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The Higgs boson in the

\[ H \rightarrow ZZ(\ast) \rightarrow 4l \]

decay channel with the

ATLAS detector at the LHC

Antonio Salvucci
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\[ H \rightarrow ZZ^(*) \rightarrow 4l \]
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ATLAS detector at the LHC

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The Higgs boson in the
\[ H \rightarrow ZZ(*) \rightarrow 4l \]
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ATLAS detector at the LHC

Proefschrift

ter verkrijging van de graad van doctor
aan de Radboud Universiteit Nijmegen
op gezag van de rector magnificus prof. mr. S.C.J.J. Kortmann,
volgens besluit van het college van decanen
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Introduction

Since ancient times, humanity has tried to give an answer to the question: “What are we made of?” The first attempt to answer this question occurred in the Greek Age, when the philosopher Democritus suggested that matter was made up of basic elements, called atoms, considered as homogeneous and indivisible quantities. Later in time, physicists extended this intuition: atoms are not the basic elements and matter is made up of elementary particles, quarks and leptons. In recent centuries, both theoretical and experimental efforts have been spent on the study of the properties and the interaction of these particles, organizing everything in a theoretical model. The Standard Model of particles physics is such a theoretical model widely accepted and confirmed by experimental efforts. It explains and unifies three of the four fundamental forces of nature and describes all the known elementary particles. The last decades of high energy physics experiments have verified the predictions of the Standard Model to a high level of accuracy, up to the energies explored at the electron-positron collider LEP and the proton-antiproton collider Tevatron.

In the Standard Model theoretical framework, the Higgs-Brout-Englert mechanism, also simply called Higgs mechanism, describes how the elementary particles acquire mass. This mechanism postulates the existence of a scalar field which gives mass to fermions and vector bosons via Yukawa couplings and spontaneous breaking of the underlying symmetry of the standard theory, leading to the emergence of a physical scalar particle, the Higgs boson.

The Higgs boson is therefore the keystone particle of the Standard Model. It has been hunted for decades using different experiments at both the LEP and Tevatron colliders, but no experimental evidence was found. The search has been continued by the experiments installed on the Large Hadron Collider (LHC). The LHC is the world’s largest particle accelerator built at CERN. It collides proton beams at unprecedented centre-of-mass energies. Seven experiments are located along its ring. ATLAS and CMS are the two general-purpose detectors whose main goal is to either confirm or reject experimentally the existence of the Higgs boson.

The Higgs boson search culminated in July 4th 2012 when both the ATLAS [1] and CMS [2] collaborations announced the observation of a new particle [3] [4] with a mass around 125 GeV for a combined significance against background of more than 5 standard deviations. In order to verify if the newly observed particle is the Standard Model Higgs boson or not, its properties have

1
been measured. The study of its quantum number, by means the determination of the spin and parity, is a crucial step in its confirmation or rejection as a Standard Model Higgs boson, which is predicted to have spin 0 and even parity.

This thesis is aiming to present the work contributed by the author in the context of the ATLAS experiment and the search for the Standard Model Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel using the proton-proton collision data collected during 2011 and 2012. This decay channel is one of the main channels where the discovery of the Higgs boson has been made. It provides a very clean final state signature and the possibility to fully reconstruct the Higgs mass with excellent detector resolution. Moreover, it is the most suitable instrument to study the spin and parity state of the Higgs boson, since one can reconstruct the full decay chain and derive the intrinsic properties of the $H \rightarrow ZZ$ decay amplitude from angular and invariant mass distribution of the final state.

This thesis is organized as follow. In Chapter 1 an introduction of the theoretical aspects of the Standard Model and the spontaneous symmetry breaking are presented. The constraints on the Higgs boson mass, its mechanisms and decay channels in the LHC are described.

In Chapter 2 the LHC and the ATLAS detector are introduced. The scope and features of the ATLAS experiment are described, emphasizing the basic components of the detector. For the search for the Higgs boson in the four lepton decay channel, electrons and muons are used.

In Chapter 3 a description of the lepton and event identification and reconstruction techniques is presented. Due to the better identification and reconstruction of the muons with respect to the electrons, the $4\mu$ final state is the most promising one for measuring the Higgs-boson mass. For this reason it is very important to know the resolution of the ATLAS muon system well. In Chapter 4 a detailed description of the determination of the muon momentum resolution of the ATLAS detector is provided. The muon momentum resolution is studied by the author using data-driven techniques. Since the ATLAS experiment is equipped with a Muon Spectrometer and an Inner Detector, both providing the measurement of the muon momentum, the muon resolution is studied for both and compared for the two muon reconstruction algorithms performance.

In Chapter 5 the observation of a new particle in the search for the Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel is presented. The optimization of the analysis selection, extensively studied by the author, is presented. This optimization has significantly increased the sensitivity of $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel. The background estimation, studied by the author mainly in final state involving muons, and the results using collision data are presented. The combination with all other Higgs boson decay channel analyses in ATLAS is also presented.

Chapter 6 presents an update of the analysis in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel using the full data sample collected in 2011 and 2012. Here further studies concerning the event selection and background composition are presented along with the mass measurement and the limits for the production cross section.

In Chapter 7 the description of the spin and parity measurement of the newly observed particle is provided. Various spin and parity hypotheses have been taken into account. The multivariate
approach with BDT is introduced and results on testing the Standard Model hypothesis against different models are shown. The work of the author extends to many parts of the spin and parity determination analysis: the Monte Carlo production and validation studies, the modelling of the spin and parity, the multivariate approach and the related systematic uncertainties. In the whole manuscript the natural units system, in which $\hbar = c = 1$, is used: as consequence, GeV is the unit for energy, mass and momentum.
Chapter 1

The Standard Model and the Higgs Boson

The Standard Model of particle physics is a theory that describes the known matter in terms of its elementary constituents and their interactions. Three out of the four fundamental interactions are described in a coherent Quantum Field Theory (QFT) framework: the electromagnetic interaction, responsible for the interactions between charged particles; the weak interaction, responsible for the existence of atomic nuclei and radioactive decays; and the strong interaction, responsible for binding quarks together to form protons and neutrons and consequently nuclei. Gravity is too weak at the scales with which particle physics is concerned and is not incorporated in the Standard Model. The elementary particles - Tables 1.1 and 1.2 - are basically divided in two groups:

i) **bosons**, which have integer spin. In the SM, the gauge bosons have spin 1 and mediate the fundamental interactions. The photon is the mediator of the electromagnetic interaction, the $W^+$, $W^-$ and $Z^0$ mediate the weak interaction and the gluons deal with the strong interaction. Apart from the weak force carriers ($W$ and $Z$), the bosons are massless and only
the $W$ bosons have electric charge. The gluons carry an additional quantum number, the
colour, similar to the electric charge;

\begin{table}
\centering
\begin{tabular}{|l|l|l|l|l|}
\hline
Force & Particle & Charge & Spin & Mass \\
\hline
Electromagnetic & photon ($\gamma$) & 0 & 1 & 0 \\
Weak & $W^\pm$ bosons & $\pm 1$ & 1 & 80.40 GeV \\
& $Z$ boson & 0 & 1 & 91.19 GeV \\
Strong & gluon & 0 & 1 & 0 \\
\hline
\end{tabular}
\caption{The fundamental interactions and the related gauge bosons properties.}
\end{table}

ii) \textbf{fermions}, which have semi-integer spin and are the constituents of the matter. They are
divided in two groups depending whether they couple to the gluons or not: leptons, colourless
and not interacting through the strong force, and quarks, carrying colour and involved in the
strong interaction. They are grouped in three families or generations, each composed of two
quarks and two leptons: the lightest and most stable particles make up the first generation,
whereas the heavier and less stable particles belong to the second and third generations.
Neutrinos are weakly interacting only and assumed to be massless\footnote{Recent experimental evidence of neutrino oscillations\cite{6,7} suggests that they have non-zero masses: anyway, this does not affect the physics phenomenology at the LHC.}

\begin{table}
\centering
\begin{tabular}{|l|l|l|l|l|}
\hline
 & Generation I & Generation II & Generation III & Charge \\
\hline
leptons & $e^-$ & 0.511 MeV & $\mu^-$ & 105.7 MeV & $\tau^-$ & 1.777 GeV & -1 \\
 & $\nu_e$ & $\sim 0$ & $\nu_\mu$ & $\sim 0$ & $\nu_\tau$ & $\sim 0$ & 0 \\
quarks & u & 2.3 MeV & c & 1.27 GeV & t & 173.5 GeV & 2/3 \\
 & d & 4.8 MeV & s & 95 MeV & b & 4.18 GeV & -1/3 \\
\hline
\end{tabular}
\caption{The three generations of fermions and their properties.}
\end{table}

Each boson and fermion is associated with an anti-particle with the same mass and spin but
with opposite charge; particles without electric charge, such as the photon, the $Z$ and gluons, are
identical to their anti-particles.

All these elementary particles are the building blocks of the known matter. In particular hadrons
are composed by quarks. They are organized in two groups depending on the number of the
constituent quarks: baryons, made up of three quarks and having half-integer spin, and mesons,
made up of a quark and an anti-quark pair and having integer spin.
1.1. THE STANDARD MODEL OF PARTICLE PHYSICS

1.1.2 Gauge symmetries

The Standard Model is a renormalizable field theory [8] which finds its basis in the context of
gauge symmetries [9]. Both the electroweak sector, developed in the 1960s by Glashow, Weinberg
and Salam [10] [11] [12], and the strong sector, developed by Gell-Man and Zweig [13] [14] with
the quark hypothesis, are summarized in the gauge principle, introduced by Weyl in 1929 [15]. In
these theories, the particles and their interaction are described by irreducible representations of
certain groups of symmetry.

The symmetry is a fundamental point in gauge theories: from a mathematical point of view, a
symmetry arises when the solutions of a set of equations are unchanged if a transformation is
applied. Depending on the parameters of the transformation, the symmetries can be classified into
discrete or continuous. The second class of symmetries can be divided in space-time symmetries,
acting on space-time coordinates, and internal symmetries, acting on internal quantum numbers.
The latter ones can be further divided in two groups: global symmetries, when a transformation is
applied in the same way everywhere in the space-time, and local or gauge symmetries, when the
transformation can be chosen independently in each point of space-time.

In non-relativistic quantum mechanics, a system is described by its state represented by the wave
function \( \psi \), whereas in the quantum field theories each particle is described as an excitation of
a local quantum field \( \phi(x) \). In classical field theory, the properties and the interactions of the
field \( \phi(x) \) are determined by the Lagrangian density \( L \), containing the field and its space-time
derivatives

\[
L(x) = L(\phi, \partial_{\mu}\phi).
\]  

(1.1)

According to the Noether’s theorem, every continuous symmetry of the Lagrangian yields a con-
servation law. Then, if a Lagrangian satisfies a symmetry, there is a corresponding conserved
quantity. So it is always possible to describe conservation laws through symmetries of the La-
grangian. Based on the Euler-Lagrange equation, a transformation \( \phi \rightarrow \phi + \epsilon \Delta \phi \), where \( \epsilon \) is an
infinitesimal parameter, can be a symmetry of the system only if the Lagrangian is invariant under
this transformation up to a four-divergence

\[
L \rightarrow L + \epsilon \partial_{\mu}J^{\mu}.
\]  

(1.2)

Given Noether’s theorem, the current

\[
j^{\mu}(x) = \frac{\partial L}{\partial(\partial_{\mu}\phi)} \Delta \phi - J^{\mu}
\]  

(1.3)
is conserved. Moreover, the principle of relativity states that any observer in the space-time is
equivalent. It can happen that the transformation that preserves the symmetry of the Lagrangian
can be freely chosen in any point of the space-time, or better, that the Lagrangian must be
invariant under local transformations. In order to achieve this, gauge fields have to be introduced:
the number of associated gauge fields is equal to the number of generators of the symmetry group. The quantum field theories describing the fundamental interactions considered in the SM are based on gauge symmetries and so they are called gauge theories.

The Standard Model is a gauge field theory based on the symmetries of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ group, where the interactions are generated from the requirement of local gauge invariance. $SU(3)_C$ is the symmetry group of the strong sector and on its gauge symmetry is based the quantum chromodynamics (QCD) theory which describes the strong interaction: the $C$ refers to the colour quantum number and the 3 to the number of the possible colour states. Quarks are objects living in the fundamental representation of this group and gluons are the gauge bosons that mediate the interactions. The subgroup $SU(2)_L \times U(1)_Y$ is the symmetry group of the electroweak sector and describes quantum electrodynamics (QED) and weak interactions as a whole: the electroweak interaction. To the group $SU(2)_L$, connected to a conserved quantum number, the weak isospin $T_i$, are associated three gauge fields $W^i$. Here the $L$ refers to left-handed fermions. To the group $U(1)_Y$, connected to the conserved quantum number called weak hypercharge $Y$, only one gauge field $B$ is associated. Fermions are objects living in the fundamental representation of the group and the interactions are mediated by the previously mentioned gauge fields. The observed physical states ($\gamma, W^\pm, Z$) are linear combinations of the gauge fields $B$ and $W_i$.

1.1.3 Quantum electrodynamics

Quantum electrodynamics is an abelian gauge theory describing a fermion field $\psi$ and its electromagnetic field. As mentioned, the field’s Lagrangian must be invariant under the local gauge transformation. Consider a transformation under the unitary abelian group $U(1)$, i.e. a phase transformation

$$\psi \rightarrow U\psi = e^{i\alpha(x)}\psi,$$

where $\alpha(x)$ is an arbitrary parameter depending on the space and time coordinates, and take the Dirac Lagrangian for a fermion of mass $m$

$$\mathcal{L} = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi,$$

where $\bar{\psi} = \psi^\dagger\gamma^0$ and $\gamma^\mu$ are the Dirac matrices. This theory is not gauge invariant, because, applying the transformation the first term transforms as

$$\partial_\mu \psi \rightarrow e^{i\alpha(x)}\partial_\mu \psi + e^{i\alpha(x)}\psi \partial_\mu \alpha.$$

According to the gauge principle, the local gauge invariance can be satisfied only adding a vector boson field $A_\mu$, the photon field, which interacts with the fermionic field $\psi$ and transforms as

$$A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu \alpha.$$
1.1. THE STANDARD MODEL OF PARTICLE PHYSICS

Then, substituting the normal derivative $\partial_\mu$ with the covariant derivative $D_\mu$

$$D_\mu = \partial_\mu - ieA_\mu,$$

where $e$ is the electric charge, the Lagrangian can be written as

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi - m\bar{\psi}\psi.$$  \hspace{1cm} (1.9)

In this way, the fermionic field $\psi$ is now transforming as

$$D_\mu \psi \rightarrow e^{i\alpha(x)}D_\mu \psi$$ \hspace{1cm} (1.10)

and the Lagrangian has a term, $e\bar{\psi}\gamma^\mu A_\mu \psi$, which describes the interaction between the vector field $A_\mu$ and the electromagnetic current $J^\mu$, defined by

$$J^\mu = e\bar{\psi}\gamma^\mu \psi.$$ \hspace{1cm} (1.11)

Although the Lagrangian obtained is locally invariant, it is not complete because a kinetic term for the gauge field is needed. This additional term comes from the Proca Lagrangian density

$$\mathcal{L} = -\frac{1}{4} F^\mu_\nu F^\mu_\nu + \frac{1}{4} m_A^2 A_\mu A^\mu,$$ \hspace{1cm} (1.12)

where $F^\mu_\nu$ is the electromagnetic field strength tensor. Then, in order to satisfy the gauge principle, the vector boson field is required to be massless: the final QED Lagrangian is

$$\mathcal{L}_{QED} = \bar{\psi} (i\gamma^\mu D_\mu \psi - m) \psi - \frac{1}{4} F^\mu_\nu F^\mu_\nu.$$ \hspace{1cm} (1.13)

1.1.4 Quantum chromodynamics

The structure of quantum chromodynamics is based on local gauge invariance in an analogous way as for QED. In this case, the abelian $U(1)$ group is replaced with the non-abelian $SU(3)$ group, related to transformations of the quark fields.

Consider the Lagrangian describing a single quark flavour

$$\mathcal{L} = \bar{q} (i\gamma^\mu \partial_\mu - m) q$$ \hspace{1cm} (1.14)

and apply a $SU(3)$ transformation such as

$$q(x) \rightarrow Uq(x) = e^{-ig_\alpha(x)T_\alpha}q(x),$$ \hspace{1cm} (1.15)

2The Lagrangian should include all the six quark flavours: a summation over $j = 1, \ldots, 6$ should be present. For simplicity only a single quark flavour is considered.
where $g$ is the strong coupling constant, $U$ is an arbitrary $3 \times 3$ special unitary matrix, $\alpha_a$ are arbitrary parameters and $T_a$ are the generators of the $SU(3)$ group. The resulting Lagrangian does not satisfy the $SU(3)$ local gauge invariance. In order to do this, as for the QED case, eight gauge fields $G_a^\mu$, the gluon fields, have to be introduced. Knowing that these fields transform as

$$G_a^\mu \rightarrow G_a^\mu - \frac{1}{g} \partial_\mu \alpha_a - f_{abc} \alpha_b G_c^\mu ,$$

(1.16)

and using the covariant derivative

$$D_\mu = \partial_\mu + igT_a G_a^\mu ,$$

(1.17)

where $T_a G_a^\mu$ is in analogy to $A_\mu$ in QED, the resulting Lagrangian has a term, $g\bar{q}\gamma^\mu T_a G_a^\mu q$, which describes the interaction between the gluon field $G_a^\mu$ and the currents $J^{\mu,a}$, defined by

$$J^{\mu,a} = g\bar{q}\gamma^\mu T^a q .$$

(1.18)

Then, adding the kinematic term for each gluon field, the resulting final QCD Lagrangian is

$$\mathcal{L}_{QCD} = \bar{q} (i\gamma^\mu D^\mu - m) q - \frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} ,$$

(1.19)

where $G_{\mu\nu}^a$ is the gluon field-strength tensor.

### 1.1.5 Electroweak Theory

The electroweak unification is the heart of the Standard Model and it was first formalized in 1960 by Glashow and then refined in 1967 by Weinberg and Salam: they discovered a way to combine the electromagnetic and weak interactions.

Weak interactions include both charged and neutral currents: charged currents are involved in transitions between up-type and down-type quarks or charged leptons and the corresponding neutrinos, whereas neutral currents conserve flavour. As already mentioned in Section 1.1.1 weak interactions are mediated by the vector bosons $W$ and $Z$: the ones mediated by the two $W$ vector bosons are known as weak Charged Current interactions (CC), while those mediated by the $Z$ are known as weak Neutral Current interactions (NC).

The electroweak theory is based on the same principle of gauge invariance as QED and QCD, and treats the weak and electromagnetic interactions as different manifestations of the same force. The problem of different structures of electromagnetic, $\gamma^\mu$, and charged weak, $\gamma^\mu (1 - \gamma^5)$, vertex factors was solved by absorbing the axial vector part to the particle spinor. In this way, it is possible

---

3This, in analogy to the fine structure constant in QED, is often expressed in term of $\alpha_s = \frac{g^2}{4\pi}$.

4$T_a = \frac{\lambda_a}{2}$ (with $a = 1, \ldots, 8$) where $\lambda_a$ are the Gell-Mann matrices, a set of linearly independent traceless $3 \times 3$ matrices: the generators satisfy the commutation relation $[T_a, T_b] = if_{abc} T_c$, where $f_{abc}$ are the structure constants of $SU(3)$, manifesting the non-Abelian character of the theory.
to define both left-handed and right-handed spinors as

\[ \psi_L = P_L \psi = \frac{1}{2} (1 - \gamma^5) \psi \]

\[ \psi_R = P_R \psi = \frac{1}{2} (1 + \gamma^5) \psi, \]

where \( P_{L,R} \) are the chirality operators and \( \gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 \). Thus, fermions are divided in left-handed and right-handed components. The \( W \) bosons couple only to left-handed particles, while the \( Z \) boson and the photon couple to both left-handed and right-handed particles. Left-handed fields are grouped in order to form isospin doublets (\( T = \frac{1}{2} \))

\[
\begin{pmatrix}
(u \\
d)
\end{pmatrix}_L, \quad 
\begin{pmatrix}
\nu_e \\
e
\end{pmatrix}_L, \quad 
\begin{pmatrix}
(c) \\
s
\end{pmatrix}_L, \quad 
\begin{pmatrix}
(\nu_\mu) \\
\mu
\end{pmatrix}_L, \quad 
\begin{pmatrix}
(t) \\
b
\end{pmatrix}_L, \quad 
\begin{pmatrix}
(\nu_\tau) \\
\tau
\end{pmatrix}_L,
\]

while right-handed fields form isospin singlets (\( T = 0 \))

\[
\begin{pmatrix}
u_R \\
d_R \\
e_R \\
c_R \\
s_R \\
\mu_R \\
t_R \\
b_R \\
\tau_R
\end{pmatrix}
\]

and are invariant under weak isospin transformations. The electroweak gauge symmetry group is \( SU(2)_L \times U(1)_Y \). \( SU(2)_L \) refers to the weak isospin, \( T \), with the subscript \( L \) indicating that it involves left-handed fields: under \( SU(2)_L \) the left-handed fields transform as doublets, while the right-handed ones do not transform at all. \( U(1)_Y \) refers to the weak hypercharge, \( Y \), which is connected to the weak isospin by the relation

\[ Q = T_3 + \frac{1}{2} Y, \]

where \( T_3 \) is the third component of the weak isospin. The \( U(1)_Y \) transformation, when applied to a left-handed doublet or right-handed singlet, corresponds to a multiplication by a phase factor \( e^{i\alpha Y/2} \).

Applying the gauge principle, four gauge fields are introduced: \( B_\mu \), associated to \( U(1)_Y \) and coupling to both left-handed and right-handed components, and a massless field triplet \( W^i_\mu \), associated to \( SU(2)_L \) and coupling only with left-handed components. As for QED and QCD, before defining the electroweak Lagrangian, the covariant derivative expression for this gauge theory is needed

\[ D_\mu = \partial_\mu + igW^i_\mu T_i + ig' B_\mu Y/2, \]

where \( T_i \) are the generators of \( SU(2)_L \), \( Y/2 \) is the generator of \( U(1)_Y \) and \( g \) and \( g' \) are respectively the coupling constants of \( SU(2)_L \) and \( U(1)_Y \). In this way the resulting electroweak Lagrangian is

\[ \mathcal{L}_{EW} = -\frac{1}{4} W^i_\mu W^{i\mu} - \frac{1}{4} B_\mu B^{\mu} + i\bar{\psi}\gamma^\mu D_\mu \psi, \]
where $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field tensors

$$W_{\mu\nu} = \partial_{\mu} W_{\nu} - \partial_{\nu} W_{\mu} - g_\epsilon^{ijk} W_{\mu}^i W_{\nu}^j$$

$$B_{\mu\nu} = \partial_{\mu} B_{\nu} - \partial_{\nu} B_{\mu}$$

with $\epsilon^{ijk}$ structure constants of $SU(2)$. The interaction terms between the fermions and the gauge fields are

$$L_{int} = i \bar{\psi}_L \gamma^\mu \left( g_\tau_i \frac{1}{2} W_{\mu}^i + g' \frac{1}{2} B_{\mu} Y \right) \psi_L + i \bar{\psi}_R \gamma^\mu \left( g' \frac{1}{2} B_{\mu} Y \right) \psi_R,$$

where the coupling of the $W_{\mu}^i$ only to the left-handed components is visible.

### 1.2 Spontaneous symmetry breaking

Looking to the expression for the electroweak Lagrangian - Equation 1.26 - there are no fermion mass terms. This is because $\bar{\psi} \psi = \psi_L \psi_R + \psi_R \psi_L$ would mix left-handed and right-handed fields and, consequently, breaks $SU(2)_L$ gauge invariance. Also adding the term $\frac{1}{2} m^2 V^\mu V_\mu$ for the gauge bosons will break the gauge invariance and then the theory is non-renormalizable. The developed solution to this problem is the generation of masses through the spontaneous breaking of the gauge symmetry, usually known as the Higgs mechanism.

F. Englert and R. Brout [16], P. Higgs [17] [18] [19] and independently G. Guralnik, C. R. Hagen and T. Kibble [20] [21] conjectured that the universe is filled with a scalar field - the Higgs field - which is a doublet in $SU(2)$ space, has a non-zero $U(1)$ hypercharge and is a $SU(3)$ singlet.

According to this mechanism, the gauge bosons acquire mass by interacting with the Higgs field and fermion masses will be generated dynamically by gauge invariant Yukawa interactions with the Higgs field. Since states with a Higgs field are not orthogonal to the vacuum state, the $SU(2)$ and $U(1)$ quantum numbers of the vacuum are non-zero. This means that the symmetry is still valid for the Lagrangian but not for the vacuum state: a symmetry like this is called a spontaneously broken symmetry.

Adding the Higgs mechanism, the full electroweak Lagrangian will consist of several terms: the fermion and gauge terms, as in Equation 1.26 and the additional Yukawa and Higgs terms

$$L_{EW} = L_{gauge, fermions} + L_{Higgs} + L_{Yukawa}.$$

### 1.2.1 The Higgs mechanism

In the context of the $SU(2)_L \times U(1)_Y$ symmetry, the Higgs mechanism is implemented through an additional $SU(2)_L$ isospin doublet of complex scalar fields with hypercharge $Y = 1$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}.$$
1.2. SPONTANEOUS SYMMETRY BREAKING

The Higgs contribution to the electroweak Lagrangian is

$$L_H = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi),$$  \hspace{1cm} (1.32)

where the potential $V(\phi)$ is parameterized using two arbitrary parameters, $\lambda$ and $\mu$,

$$V(\phi) = \mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2$$

$$= \mu^2 |\phi|^2 + \lambda |\phi|^4.$$ \hspace{1cm} (1.33)

The potential shape is strictly determined by the values of the potential parameters. The ground state expectation $\phi_0$ is determined minimizing the potential

$$\frac{\partial V}{\partial \phi} = 2\phi (\mu^2 + 2\lambda \phi^2) = 0,$$  \hspace{1cm} (1.34)

where $\lambda$ is the strength of the quartic self-coupling of the scalar field, shown by the term $|\phi|^4$, and $\mu$ is the mass parameter. $\lambda$ is required to be positive so that the energy is bounded from below: this requirement ensures the existence of stable ground states.

Depending on the value of the mass parameter $\mu$, there are two qualitatively different cases:

i) $\mu^2 > 0$: in this case the potential has a unique minimum at $\phi = 0$ that corresponds to the ground state, i.e. the vacuum. In terms of quantum field theory this means that the field $\phi$ has zero vacuum expectation value and $L_{\text{Higgs}}$ is the Lagrangian for a scalar particle of mass $\mu$ and massless gauge bosons. The vacuum is thus invariant under $SU(2)_L \times U(1)_Y$ and the gauge bosons have to be massless in order to respect this symmetry.

ii) $\mu^2 < 0$: in this case a non vanishing vacuum expectation value for $\phi^2$ in the physical vacuum state has been obtained: the Lagrangian has a mass term with negative sign for the field $\phi$ and the minimum energy is not at $\phi = 0$. The potential assumes a shape known as the “Mexican hat”, with a local maximum at $\phi = 0$.

The shape of the potential, for both the cases, is shown in Figure 1.1. The potential parameters are then set to $\mu^2 < 0$ and $\lambda > 0$ and the ground state expectation value is

$$\phi_0^2 = -\frac{\mu^2}{\lambda} - \frac{\nu^2}{2},$$  \hspace{1cm} (1.35)

Choosing one of the non-zero ground states - Equation 1.35 - the $SU(2)_L \times U(1)_Y$ symmetry is spontaneously broken because the ground state is no more symmetric under $SU(2)_L \times U(1)_Y$. The minimum of the potential is no longer a unique value of $\phi$ but there are an infinite number of states. The fields are expressed with quantum fluctuations about this minimum and the scalar doublet $\phi$ can be written as

$$\phi(x) = e^{i\xi(x)x^i} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix},$$  \hspace{1cm} (1.36)
Figure 1.1. Forms of the Higgs potential due to the sign of $\mu^2$: (a) $\mu^2 > 0$ and (b) $\mu^2 < 0$. The degeneracy of the vacuum state in this 2-dimensional graph is represented by $+\nu$ and $-\nu$ which are the states of minimum energy for the Higgs potential, with $\nu = v/\sqrt{2}$.

where $\xi_i(x)$, with $i = 1, 2, 3$, are the massless real fields - the massless scalar fields (Goldstone bosons) - and $H(x)$ is the real scalar Higgs field - the massive Higgs field. The scalar field describes radial excitations from the ground state changing the potential energy while the massless scalar fields correspond to angular excitations without potential energy change. The three massless scalar bosons correspond to the three broken symmetry generators.

In this way, the Lagrangian is locally $SU(2)_L$ invariant and by using the freedom of gauge transformations the $\xi_i(x)$ disappear from the Lagrangian and $\phi$ can be replaced by

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}.$$ \hspace{1cm} (1.37)

Then, taking into account the covariant derivative

$$D_\mu = \partial_\mu + ig\frac{\tau^i}{2} W^i_\mu + ig'\frac{1}{2} B_\mu,$$ \hspace{1cm} (1.38)

the kinetic part of the Lagrangian $\mathcal{L}_H$ - the term $(D_\mu \phi)\dagger (D^\mu \phi)$ in Equation 1.32 - results in

$$\frac{1}{2} \partial^\mu H \partial_\mu H + \frac{1}{8} g^2 (v + H)^2 \left| W^1_\mu + iW^2_\mu \right|^2 + \frac{1}{8} (v + H)^2 \left| g' W^3_\mu - g B_\mu \right|^2.$$ \hspace{1cm} (1.39)

In this way, four physical fields are obtained: two charged physical fields $W^{\pm}_\mu$, corresponding to the $W^\pm$ bosons and defined as a combination of the fields $W^1_\mu$ and $W^2_\mu$

$$W^{\pm}_\mu = \frac{1}{\sqrt{2}} \left( W^1_\mu \mp iW^2_\mu \right),$$ \hspace{1cm} (1.40)
and two neutral physical fields, $Z_\mu$ and $A_\mu$, corresponding to the $Z$ boson and the photon, defined as an orthogonal combination of the fields $B_\mu$ and $W^3_\mu$

$$Z_\mu = \frac{g'W^3_\mu - gB_\mu}{\sqrt{g'^2 + g^2}}$$  \hspace{0.5cm} (1.41)$$

$$A_\mu = \frac{g'W^3_\mu + gB_\mu}{\sqrt{g'^2 + g^2}}.$$  \hspace{0.5cm} (1.42)

Then, introducing the weak mixing angle $\theta_w$, known as the Weinberg’s angle, the neutral physical fields can be written as

$$Z_\mu = -B_\mu \sin \theta_W + W^3_\mu \cos \theta_W$$  \hspace{0.5cm} (1.43)$$

$$A_\mu = B_\mu \cos \theta_W + W^3_\mu \sin \theta_W.$$  \hspace{0.5cm} (1.44)

Taking into account the kinetic term of the Lagrangian - Equation 1.39 - the boson masses are extracted from its mass terms; the charged $W$ bosons acquire a mass

$$M_W = \frac{gv}{2},$$  \hspace{0.5cm} (1.45)$$

while for the $Z$ boson the mass is

$$M_Z = \frac{v}{2} \sqrt{g'^2 + g^2}$$  \hspace{0.5cm} (1.46)$$

and the photon remains massless, $M_\gamma = 0$. Also the Higgs boson mass can be extracted from the kinetic terms of the Lagrangian (see Section 1.3)

$$M_H = \sqrt{2\lambda v^2} = 2\sqrt{-\mu^2}.$$  \hspace{0.5cm} (1.47)$$

It is important to observe that the Higgs boson mass is not fixed but depends on the free parameter of the theory $\lambda$, which represents the Higgs self-coupling, while the masses of the vector bosons are fixed once $g^2$ and $v$ are known.

In addition, it is possible to define the relation between the boson masses and the Weinberg’s angle

$$M_Z = \frac{M_W}{\cos \theta_W}.$$  \hspace{0.5cm} (1.48)$$

In this way, the fundamental parameters of the Standard Model are reduced to four: the coupling constants $g$ and $g'$ and the Higgs potential parameters $\lambda$ and $\mu$.

### 1.2.2 Fermion masses: the Yukawa coupling

As already mentioned, the fermions acquire mass interacting with the Higgs field $H$.

Since adding mass terms in the Lagrangian will break $SU(2)_L$ gauge invariance, the only way to assign mass to the fermion is introducing an invariant coupling term, called Yukawa coupling. This
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coupling allows to describe the interactions between the Higgs and the fermion fields through the coupling constant \( g_f \). For a single generation, the Yukawa contribution to the Lagrangian is

\[
\mathcal{L}_{\text{Yukawa}} = -g_l \bar{L}^c L \phi_l d_R - g_d \bar{Q}^c L \phi_d u_R - g_u \bar{Q}^c L \tilde{\phi} u_R + \text{h.c.},
\]

(1.49)

where \( L_L = (\nu_L, l_L)^T \) and \( Q_L = (u_L, d_L)^T \) stand for the left-handed lepton and quark doublets, \( l \) is the charged lepton and \( \tilde{\phi} = -i\tau_2 \phi^* \) is the charge conjugate of the Higgs doublet.

For simplicity, in the following only leptons will be considered. Given a leptonic family and substituting \( \phi \) with the one obtained after the spontaneous symmetry breaking - Equation 1.37 - the Yukawa contribution to the Lagrangian becomes

\[
\mathcal{L}_{\text{Yukawa}}^l = -\frac{g^l v}{\sqrt{2}} \bar{\psi}^l \psi^l - \frac{g^l v}{\sqrt{2}} \bar{\psi}^l \psi^l H = -M^l \bar{\psi}^l \psi^l - \frac{g^l v}{\sqrt{2}} \bar{\psi}^l \psi^l H.
\]

(1.50)

The first term corresponds to the mass term of the considered lepton, \( M^l = g^l v / \sqrt{2} \), while the second one describes the interaction between the Higgs field and a lepton-antilepton pair (or more in general a fermion-antifermion pair). The vertex of this interaction is

\[
H f \bar{f} \rightarrow iM^f \frac{1}{2M_W^2}
\]

(1.51)

and so the coupling of the Higgs boson with fermions is proportional to the fermion mass.

1.3 Higgs mass constraints

Although it predicts the existence of a Higgs boson, the Standard Model does not provide a value for its mass, since it is a free parameter of the SM. The Higgs boson mass can be extracted from the Lagrangian, considering the kinetic term \( \frac{1}{2} (\partial_{\mu} H)^2 \) and the terms coming from the Higgs potential, defined in Equation 1.33. Substituting \( \phi(x) \) with the one obtained after the spontaneous symmetry breaking - Equation 1.37 - the potential becomes

\[
V(\phi) \rightarrow V(H) = \frac{\mu^2}{2} (v + H)^2 + \frac{\lambda}{4} (v + H)^4,
\]

(1.52)

so the Lagrangian corresponding to the Higgs boson only will be

\[
\mathcal{L}_H = \frac{1}{2} (\partial_{\mu} H)^2 - \frac{2\lambda v^2}{2} H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4 + \frac{\lambda v^4}{4}.
\]

(1.53)

Then, the Higgs boson mass is \( M_H = \sqrt{2\lambda v^2} \), but, since it depends on the free parameter of the theory, \( \lambda \), its value cannot be fixed. Interesting theoretical constraints can be derived from assumptions on the energy range in which the SM is valid before perturbation theory breaks down and new phenomena emerge. These constraints are based on perturbative unitarity in scattering amplitudes, triviality and vacuum stability.
1.3. HIGGS MASS CONSTRAINTS

1.3.1 Unitarity

Interactions of the longitudinal components of the massive gauge bosons grow with their momenta; thus, the calculation of the scattering cross section for longitudinally polarized $W$ and $Z$ bosons would violate unitary, since it increases with the energy of the process. This problem can be solved adding two new diagrams, which take into account the interaction between the weak vector boson and the Higgs boson. For instance, from the calculations of the amplitude for the scattering of $W$ bosons involving the Higgs boson, it follows that $M_H^2 \leq 2\pi\sqrt{2}/G_F \sim (870 \text{ GeV})^2$ \[23\]. Moreover, large values of the Higgs mass are not the best “choice” for the perturbation theory of the SM. Just to make an example, consider the decays of Higgs into massive gauge bosons and assume a very large Higgs mass $M_H > 1 \text{ TeV}$: this leads to two-loop contributions at the same importance as one-loop contribution and the perturbative series is not convergent. In order to keep the convergence, perturbative unitarity requires a Higgs boson mass below 1 TeV.

1.3.2 Triviality

Consider the one-loop radiative corrections to the Higgs boson quartic coupling $\lambda$ with contributions of the Higgs boson itself only. This leads to a logarithmic dependence of $\lambda$ on the energy scale squared, $Q^2$. At very small energies the quartic coupling vanishes, making the theory trivial, non-interacting. On the other hand, for very large energies it can become infinite. In addition, besides the fact that $\lambda$ grows to infinity, no well-defined theory would exist, since the Higgs potential would be reduced to an infinitesimally thin band with a vacuum expectation value equal to zero and infinitely strong interactions. In particular, it is possible to see that $\lambda(Q^2)$ becomes infinite at the Landau pole, corresponding to the energy
\[ \Lambda^2 = v^2 e^{\frac{4\pi^2}{\lambda^2}} = v^2 e^{\frac{4\pi^2}{8\pi^2 M_H^2}}. \] (1.54)

Hence, it is required that the quartic coupling $\lambda$ is finite up to a large scale $\Lambda$ until which no new physics appears. From Equation (1.54), it is possible to derive the upper bound on the Higgs mass
\[ M_H^2 = \frac{8\pi^2 v^2}{3\ln\frac{\Lambda^2}{v^2}}. \] (1.55)

This means that the Higgs boson mass upper bound depends on the energy scale. Thus, a cut-off energy $\Lambda_C$ can be established, below which the self-coupling $\lambda$ remains finite. If $\Lambda_C$ is large, the Higgs boson mass should be small to avoid $\lambda$ becoming infinite, while in the opposite case the Higgs boson mass can be heavy.

Lattice simulations of gauge theories, including non-perturbative effects, have led to an upper limit

---

\[6\] In scalar field theories, the Landau pole is a singularity in the running coupling constant that indicates a mass scale at which the theory breaks down and new physics must appear.
CHAPTER 1. THE STANDARD MODEL AND THE HIGGS BOSON

for the Higgs mass of 750 GeV, for $\Lambda_C \sim 1$ TeV \[24\]; on the other hand, if $\Lambda_C$ is set at the Planck scale, $\sim 10^{19}$ GeV, the Higgs boson mass will be small, $M_H < 190$ GeV.

1.3.3 Vacuum Stability

Taking into account the top quark loops, they tend to drive the Higgs quartic coupling $\lambda$ to negative values: in this case the vacuum is no more stable since it has no minimum.

In order to avoid this instability, the Higgs boson mass must exceed a minimum value for a given top quark mass: this permits to set a lower bound depending on the cut-off energy $\Lambda$.

In addition, requiring the Standard Model to be extended to the Great Unification Theory (GUT) scale, $\Lambda_{GUT} \sim 10^{16}$ GeV, and including the effect of top quark loops on the running coupling $\lambda$, the Higgs boson mass should roughly be in the range between 130 and 180 GeV \[25\].

1.4 The Higgs boson at the LHC

The Large Hadron Collider, described later in Chapter 2 is providing $p$-$p$ collisions at very high energies. The search for the Standard Model Higgs boson is one of the main physics goals at this collider: it is therefore crucial to know the production modes of the Higgs boson in $p$-$p$ collisions and its decay channels.

1.4.1 Proton-proton collisions

A proton is not an elementary particle, but it consists of three valence quarks (two up-quark and one down-quark), sea quarks and gluons: this means that $p$-$p$ collisions are described by the interactions between the constituents of the two protons. In such an interaction, not only valence and sea quarks participate, but also gluons are involved. Defining as $p$ the momentum of each proton, each constituent carries a fraction of this momentum, $x_i$.

Depending on the factorization scale, $\mu^2$, the scattering processes between hadrons are factorized in hard scattering processes, with high momentum transfer $Q^2$ and defined by perturbative QCD, and soft interactions defined by non-perturbative QCD.

Given two colliding partons, $a$ and $b$, in two protons, the cross section, $\sigma$, of the process $pp \to c + X$, where $c$ is a massive particle (i.e. the Higgs boson), depends on the scattering cross section of the two partons, $\sigma_{a+b \to c}$, and their parton density functions, $f_{a/A}(x_a, \mu^2)$ and $f_{b/B}(x_b, \mu^2)$, called PDF\[7\],

\[
\sigma_{pp \to c + X} = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu^2)f_{b/B}(x_b, \mu^2)\sigma_{a+b \to c}(x_a x_b, \mu^2),
\]  

\[1.56\]

These functions correspond to the density for finding a parton with a fraction $x$ of the momentum of the starting proton at a given factorization scale $\mu^2$. 

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where the sum extends to all partonic processes leading to the production of the particle $c$. 

In a hard scattering process, many quarks and gluons are produced: the quarks then radiate gluons which further radiate or create new quark-antiquark pairs forming a parton shower. These can also be produced from the initial state partons not participating in the hard scattering process. Since a coloured hadron cannot exist freely\(^8\), the resulting partons form colourless hadrons. When a bunch of hadrons are produced in a narrow cone, they are reconstructed as a jet.

### 1.4.2 Production modes

There are four main production mechanisms of the SM Higgs boson at the LHC.

i) **Gluon fusion** (ggF): in this case the process is $gg \rightarrow H$, via a loop which, in principle, includes all quarks, but, since the Higgs coupling to fermions is proportional to the fermion mass, the dominant one is the top quark loop. Concerning the cross section of this process, its dynamic is mainly controlled by the strong interactions with the leading order (LO) contribution \([26]\). Then, next-to-leading order (NLO) QCD radiative corrections \([27]\) and NLO electroweak (EW) radiative corrections \([28]\) are applied.

ii) **Vector boson fusion** (VBF): in this case the process is $q\bar{q} \rightarrow q\bar{q}H$ in which two virtual $W$ or $Z$ bosons, radiated off the two quarks in the initial state, fuse to create a Higgs boson. The cross section of this process is evaluated using full NLO QCD and EW corrections \([29]\).

iii) **Associated production with a vector boson** (VH): the vector boson can be a $W$ or $Z$ and the process is $q\bar{q} \rightarrow W/ZH$. The cross sections of the process are evaluated with precision at NLO and at next-to-next-to-leading order (NNLO) \([30]\) in QCD, applying NLO EW radiative corrections.

\(^8\)According to the colour confinement principle only colourless particles can exist freely.

\(^9\)Also called **Higgs-strahlung**.
iv) **Associated production with a pair of heavy quarks**\(^{10}\) \((qqH)\): in this case there are two processes, \(q\bar{q} \rightarrow q\bar{q}H\) and \(gg \rightarrow q\bar{q}H\). In the scenario of associated Higgs production with a pair of top quarks, the cross sections are evaluated at NLO QCD \(^{31}\).

Figure 1.3 shows the corresponding Feynman diagrams of the processes.

![Feynman Diagrams](image)

**Figure 1.3.** Standard Model Higgs boson main production processes at the LHC: (a) gluon fusion, (b) vector boson fusion, (c) associated production with \(W\) or \(Z\) bosons, (d) associated production with top quarks.

![Graphs](image)

**Figure 1.4.** Standard Model Higgs boson production cross sections in \(p-p\) collisions at \(\sqrt{s} = 7\) TeV (a) and \(\sqrt{s} = 8\) TeV (b) as a function of the Higgs boson mass. The coloured bands indicate the total theoretical uncertainties \(^{32}\) \(^{33}\).

In Figure 1.4 the fully inclusive Standard Model Higgs boson production cross sections \(^{32}\) \(^{33}\) for each of the production modes at both \(\sqrt{s} = 7\) TeV and \(\sqrt{s} = 8\) TeV, together with the theoretical uncertainties, are shown.

\(^{10}\)Also called *Higgs bremsstrahlung of heavy quarks*. 
1.4. THE HIGGS BOSON AT THE LHC

1.4.3 Decay channels

According to the Standard Model, the Higgs boson can decay into pairs of fermions or bosons. As already mentioned, the Higgs couplings to fermions are proportional to the fermion masses, and the coupling to bosons are proportional to the boson masses: the heavier is the particle, the stronger the coupling with the Higgs boson and thus the higher the branching fraction of the Higgs in this channel. Figure 1.5 shows the Feynman diagrams of the Higgs boson decay modes.

![Feynman diagrams](image)

Figure 1.5. Feynman diagrams of the Higgs boson decay modes: tree level (first diagram from the left) and loop processes (last two on the right).

The Higgs couplings to fermions and boson are determined by their masses

\[ g_{ffH} = \left( \sqrt{2} G_F \right)^{1/2} \frac{1}{m_f} \quad \text{and} \quad g_{VVH} = \left( \sqrt{2} G_F \right)^{1/2} m_V, \quad (1.57) \]

where \( m_f \) and \( m_V \) are the fermion mass and the boson mass, respectively. The total decay width, the mean lifetime and the branching ratios (BRs) for each decay channel are determined by the parameters set in Equation 1.57. The theoretical prediction of the Higgs boson decay width \( \Gamma_H \) for a mass of 125 GeV is \( \Gamma_H = 6.1 \) MeV, as shown in Figure 1.6a. This means that the Higgs boson has a short lifetime, \( 6.8 \times 10^{-22} \) s and only its decay products can be experimentally detected. The branching ratios (BRs) for each decay channel of the SM Higgs boson are shown in Figure 1.6b, together with their theoretical uncertainties, as a function of its mass. The BRs are known at NLO including both QCD and electroweak corrections.

In the low mass range - \( m_H < 130 \) GeV - the most important decay of the Higgs boson is the one to a pair of \( b \)-quarks \( (H \rightarrow b\bar{b}) \), which has a branching ratio of about 75%-50% in the case of \( m_H \approx 115 - 130 \) GeV. In the same range, there are other final states whose BR is one order of magnitude smaller: \( H \rightarrow \tau\tau \) with BR \( \sim 4-5\% \), \( H \rightarrow gg \) with BR \( \sim 7\% \), \( H \rightarrow c\bar{c} \) with BR \( \sim 2-3\% \) and \( H \rightarrow \gamma\gamma \) and \( H \rightarrow Z\gamma \) with BR \( \sim 0.2-0.3\% \). The decays to a pair of \( W \) or \( Z \) boson are also important in the low mass range and become dominant in the mass range above 140 GeV. Below the two vector bosons pair mass threshold, at least one of the gauge bosons must be virtual. Finally, at higher masses, the \( t\bar{t} \) decay channel is important, with a BR \( \sim 10\% \).

In the gluon fusion production process the best channel are \( H \rightarrow \gamma\gamma \), \( H \rightarrow WW^{(*)} \) and \( H \rightarrow ZZ^{(*)} \). In this work, the last process is considered, with the leptonic decay of the two \( Z \) bosons.
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Figure 1.6. (a) The total decay width, $\Gamma(H)$, of the Higgs boson as a function of its mass. (b) The main branching ratios of the Standard Model Higgs boson decay channels together with their theoretical uncertainties (bands) as a function of the Higgs mass [32] [33].

The $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons decay channel

This Higgs decay channel is rather clean and usually it is referred to as the golden channel at the experiments at the LHC. The $Z$ boson decays to a fermion-antifermion pair, two hadrons or two leptons. The decay mode with the highest branching ratio is the decay to hadrons, $\text{BR} \sim 70\%$, which is not easy to detect due to QCD background. A large fraction of the leptonic decays are to a pair of neutrinos, $\text{BR} \sim 20\%$, while the decay to pairs of electrons, muons and taus have a BR of about 10% of the total. The Higgs boson decays to a pair of $Z$ bosons, one of each decay to a pair of leptons: this process is relevant at 125 GeV and the cross section multiplied by the BR is around 2.5 fb. In the low mass range, at least one of the $Z$ bosons has to be virtual, i.e. off-shell.

Figure 1.7. Feynman diagram of the $H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l'^+l'^-$ process.
1.4. THE HIGGS BOSON AT THE LHC

In Figure 1.7 the Feynman diagram of the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel is presented. In this work only the decay to muons and electrons pairs will be considered: although $\tau$ leptons can also be used, the reconstruction of a Higgs boson mass peak with pairs of tau leptons is difficult and relatively inefficient. In fact, the tau life time is very short, $3 \cdot 10^{-13}$ s, so it can be reconstructed only from its decaying products: tau leptons decay to one or more hadrons and a neutrino, BR $\sim 65\%$, or to a lepton and a pair of neutrinos, BR $\sim 35\%$. Because of the presence of neutrinos, which escape detection, the efficiency of identifying a $\tau$-pair is rather low. In this way, four different final states can be detected: $4e$ and $4\mu$, in which both the $Z$ bosons decay to a pair of electrons or muons, and $2\mu 2e$ and $2e 2\mu$, in which the on-shell $Z$ boson decay to a pair of muons (electrons) and the off-shell one to a pair of electrons (muons). The presence of a real $Z$ provides two high $p_T$ leptons in the final state together with other two leptons coming from the virtual $Z$.

In order to identify the Higgs boson decay the main backgrounds need to be considered. Background processes can be divided into irreducible backgrounds, when background events cannot be distinguished from the signal, because they have the same experimental signature, and reducible backgrounds otherwise. The most important reducible backgrounds to this decay channel are $t\bar{t}$ and $Zbb$ events which result in a four-lepton final state, while the irreducible background is dominated by the continuum $(Z^{(*)}/\gamma^{(*)})(Z^{(*)}/\gamma^{(*)})$ production.

In this channel, the Higgs mass can be fully reconstructed - Chapter 5 - and it provides also the best resolution in the mass distribution - Chapter 6 - really important since the Higgs width is predicted to be very small. Since a spin and parity analysis will be shown in this work, the theoretical background needed to study the Higgs boson spin and parity is given in Chapter 7.
Chapter 2

The ATLAS experiment at the LHC

The Large Hadron Collider (LHC) \cite{35} is currently the world’s largest hadron collider, where protons are accelerated in a 27 km circumference synchrotron and colliding at very high energy. ATLAS is one of the experiments installed along the LHC ring. In this chapter the description of the LHC accelerator complex and the ATLAS detector is presented.

2.1 The Large Hadron Collider

The LHC was built by the European Organization for Nuclear Research (CERN), in the tunnel which previously hosted the Large Electron Positron (LEP) collider, from 1998 to 2008. Its first collisions, delivered in 2009, were at injection energy of 450 GeV per proton beam, corresponding to a centre of mass energy of 900 GeV. Afterwards, in 2010 and 2011, it provided collisions at a centre of mass of 7 TeV, while in 2012 the energy was increased at 8 TeV.

The LHC was designed to collide protons on protons at a centre of mass energy of 14 TeV in order to study the still open issues of the Standard Model and to reveal possible new physics beyond it. Two transfer tunnels connect the LHC to the CERN accelerator complex which is used as injector. As shown in Figure 2.1, the protons are pre-accelerated in several stages before being injected in the LHC. Firstly a linear accelerator, LINAC2, brings the protons to an energy of 50 MeV and injects them into the Proton Synchrotron Booster (PSB), where they are accelerated to 1.4 GeV. After that, the protons are injected into the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS), where their energy is increased to 26 GeV and 450 GeV, respectively.
2.1. THE LARGE HADRON COLLIDER

Finally, once injected into the LHC, the protons get ramped up to their operating energy 4. Here, the two beams, containing $\sim 10^{11}$ protons each, collide every 50 ns with an incidence angle of 300 µrad, in 4 points, where the operating experiments are.

The system of 1232 dipoles is used to bend the two proton beam trajectories. An LHC dipole has a length of 14.3 m and is made of superconducting magnets which operate at a temperature of 1.9 K: these dipoles provide a magnetic field of 0.533 T in the injection stage up to 8.33 T for the nominal 7 TeV energy per beam, corresponding to an average magnetic field of 5.3 T along the whole collider length.

The LHC is also designed to collide lead (Pb) ions, in order to study ions collisions at the centre of mass energies up to 1150 TeV. The general LHC design parameters are reported in Table 2.1.

The number of events per second for a given process, $N_{ev}$, generated in the LHC collisions is related to the machine luminosity, $\mathcal{L}$ and to the cross section of the event under study, $\sigma_{ev}$, by the following relationship:

$$N_{ev} = \mathcal{L}\sigma_{ev}. \quad (2.1)$$

In the case of a Gaussian beam distribution, the machine luminosity can be written as

$$\mathcal{L} = \frac{N_b n_b f_{rev} \gamma_r}{4\pi \epsilon_\alpha \beta^*} F; \quad (2.2)$$

Figure 2.1. Schematic view of the Large Hadron Collider and the CERN accelerator complex.

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1 It was 3.5 TeV in 2010 and 2011 and 4 TeV in 2012.
2 The bunch separation for the first years of operations (RUN1) is 50 ns, but its design value is 25 ns.
3 For a beam energy of 450 GeV.
4 It depends only on the beam parameters.
where

- $N_b$ is the number of particles per bunch;
- $n_b$ is the number of bunches per beam;
- $f_{rev}$ is the revolution frequency;
- $\gamma_r$ is the relativistic gamma factor;
- $\epsilon_n$ is the normalized transverse beam emittance;
- $\beta^*$ is the beta function at the interaction point;
- $F$ is the geometric luminosity reduction factor due to the crossing angle at the interaction point.

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Table 2.1. General LHC design parameters.

According to the design parameters, the expected instantaneous luminosity is $\mathcal{L} \sim 10^{34}$ cm$^{-2}$s$^{-1}$, that is 2 orders of magnitude larger than the one reached at the Tevatron [37] proton-antiproton ($p$-$\bar{p}$) collider, operating at Fermilab, in the United States, until September 2011.
2.1. THE LARGE HADRON COLLIDER

Equation 2.2 expresses the instantaneous luminosity which decreases with time as the number of protons decreases after every collision. The beams can in principle collide for multiple hours. The total number of events produced is proportional to the integrated luminosity all over the time, expressed in units of inverse barns. Figure 2.2 shows the delivered luminosity to the ATLAS experiment during stable beams for p-p collisions in 2010, 2011 and 2012. In 2010 and 2011, when the p-p collisions were at $\sqrt{s} = 7$ TeV centre-of-mass energy, the ATLAS detector recorded 45 pb$^{-1}$ and 5.25 fb$^{-1}$ respectively, while in 2012 the ATLAS detector recorded 21.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV.

![Figure 2.2. Cumulative luminosity versus day delivered to ATLAS during stable beams and for p-p collisions for 2010 (green), 2011 (red) and 2012 (blue) running][1]


ATLAS[1] and CMS[2] are the two general purpose experiments covering the wide range of physics that can be studied at the LHC. The main goal for these two experiments is to search for the Higgs boson and physics beyond the Standard Model, like the discovery of new heavy particles predicted for instance in supersymmetric theories. Other purposes are precision measurements related to some fundamental Standard Model quantities, like the top quark mass.

LHCb[39] is an experiment that, using a lower luminosity ($\mathcal{L} = 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$) focuses on b-quark physics: in particular, it is studying CP-symmetry violation in heavy b-quark systems,

---

[5] Total Elastic and diffractive cross section measurement
[6] Large Hadron Collider forward
[7] Monopole and Exotics Detector at the LHC
such as $B_s$ and $B_d$ mesons, and their branching fractions.

**ALICE** [40] is the LHC experiment dedicated to heavy-ion physics and it is designed to study the phase transition to the quark-gluon plasma. For this kind of studies, LHC will provide lead-lead ion collisions with a peak luminosity of $\mathcal{L} = 2 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

**TOTEM** [41] is located near the collision point of the CMS detector. It measures the total $p\bar{p}$ cross section and studies elastic scattering and diffractive dissociation at the LHC.

**LHCf** [42] is located 140 m away from the interaction point of the ATLAS detector. It consists of two calorimeters and studies forward production of neutral particles in $p\bar{p}$ collisions.

**MoEDAL** [43] is located in the LHCb cavern and it was designed to search for magnetic monopoles and other highly ionizing stable massive particles (SMPs).

### 2.1.1 Proton-proton collisions

In Section 1.4.1 the phenomenology of proton-proton collisions was described. Here, the production cross-sections at the energy scale of the LHC will be considered.

![Figure 2.3. $p\bar{p}$ and $p\bar{p}$ cross sections and the number of produced events for a luminosity of $\mathcal{L} = 10^{34}$ cm$^{-2}$ s$^{-1}$ as a function of $\sqrt{s}$ [44].](image)
2.1. THE LARGE HADRON COLLIDER

For a centre of mass energy of 14 TeV and a luminosity of $L \sim 10^{34}$ cm$^{-2}$s$^{-1}$, the inelastic cross section of $p$-$p$ processes is expected to be $\sigma \sim 80$ mb, corresponding to $10^9$ collisions per second. Most of the events have a high longitudinal momentum, while the transverse momentum, $p_T$, has a value of about 500 MeV: these events, called minimum bias events, are not so relevant for LHC studies. As discussed in Section 1.4, the most important events are the ones called hard scattering events, where partons collide elastically: these events are characterized by a high transverse momentum. The effective energy in the centre of mass, $\sqrt{s}$, of these collisions is smaller than the one reached in $p$-$p$ interactions:

$$\sqrt{s} = \sqrt{x_a x_b s}, \quad (2.3)$$

where $x_a$ and $x_b$ are the momentum fractions of the colliding partons. Assuming $x_a \sim x_b$ and $\sqrt{s} = 14$ TeV, the energy is $\sqrt{s} \sim x \sqrt{s}$, so to produce a particle with 100 GeV of mass the two colliding partons should have 1% of the momentum of the proton ($x = 0.001$), while, in order to produce a particle with 5 TeV of mass, the two partons should collide with $x = 0.36$. The cross section of such a process is given previously in Equation 1.56. In Figure 2.3 the cross sections for some hard scattering processes as a function of the centre of mass energy are shown.

**Figure 2.4.** Theoretical predictions and experimental measurements of the production cross sections of several processes at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with the ATLAS experiment [45].

Measurements of the production cross sections of some physics processes have been performed by the experiments running at the LHC. Figure 2.4 shows the ATLAS results on the theoretical and experimental production cross sections of several processes at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.
2.2 The ATLAS detector

The ATLAS detector [46], shown in Figure 2.5, has been designed to be a multi-purpose particle physics detector in order to detect physics signals with a wide range of signatures. It has been designed to explore the high physics potential of the LHC $p$-$p$ interactions. The main physics goals of this experiment are:

i) a precise measurement of Standard Model parameters, with particular focus on the top quark properties, such as the mass, the couplings and the spin; measurement of production cross section of $W$ and $Z$ vector bosons at the new energy regime; $WW$, $ZZ$ and triple gauge boson couplings.

ii) Exploration of the origin of the electroweak symmetry breaking mechanism: ATLAS is designed to be able to discover the Standard Model Higgs boson, associated with the mass mechanism, over a large range of potential Higgs masses.

iii) The search for physics beyond the Standard Model: the supersymmetric extensions of the Standard Model, the possible existence of Extra Dimensions and the presence of new neutral ($Z'$) and charged ($W'$) vector bosons.

Figure 2.5. The ATLAS detector.
The search for the SM Higgs boson has been used as a benchmark for the design of the ATLAS detector: since the dominant decay channel of the Higgs boson was unknown, due to its unknown mass, the detector was designed to detect all the possible decay scenarios. These requirements, the high luminosity and the beam energy lead to the following main design requirements for ATLAS:

- fast detectors with high granularity, in order to handle the large number of particles and to reduce the influence of overlapping events;
- large acceptance in pseudo-rapidity with almost full azimuthal angle coverage;
- good charged-particle momentum resolution and reconstruction efficiency;
- excellent electromagnetic calorimeter for electron and photon identification and energy measurements and a full coverage hadronic calorimeter for accurate jet and missing transverse energy measurements;
- good muon identification and momentum resolution;
- highly efficient triggering on low transverse momentum objects with sufficient background rejection.

The ATLAS detector is located in a hall about 100 m underground, known as the “Point 1” of the LHC ring; it is cylindric, weighs approximately 7000 t, is 44 m long and 25 m high and wide. It is nominally forward-backward symmetric with respect to the interaction point. The detector is divided in three longitudinal regions, one central, the barrel region, and two lateral, the end-cap region.
regions. The sub-detectors installed in those regions are named using the prefix _barrel_ and _end-cap_, respectively. As shown in Figure 2.6 the ATLAS detector consists of four main elements: in the central part, close to the beam line, the _Inner Detector_ is located, which tracks charged particles in order to reconstruct those coming from the interaction vertex; outside the ID is the _Calorimeter_, divided in an electromagnetic and a hadronic part, which is able to measure the energy and the position of electromagnetic showers; the _Muon Spectrometer_, which surrounds the calorimetric system, is used to detect and identify muons providing an accurate tracking and the trigger; the _Magnet System_, which deflects the charged particles in order to measure their momentum. All these systems will be described in detail later.

The ATLAS experiment uses a right-handed coordinate system, with the origin centered to the nominal position of the interaction point. The _z_-axis is defined as the beam direction, having the same orientation of the counter-clock wise rotating proton beam; the _x_-axis points from the interaction point towards the centre of the LHC ring and the _y_-axis is defined as pointing vertically upwards. A cylindrical coordinate system is used, defined by

i) \( R = \sqrt{x^2 + y^2} \), the radial vector from the interaction point;

ii) \( \phi = [-\pi, \pi] \), the azimuthal angle, which is measured from the positive _x_-axis in the clockwise direction when looking at the positive _z_-direction;

iii) \( \theta = [0, \pi] \), the polar angle, formed by the direction of the emitted particle with the positive _z_-axis: it is measured from the beam axis.

![Figure 2.7. The pseudo-rapidity \( \eta \) according to different directions from the coordinate system’s origin (lower left corner). The polar angle \( \theta \) is measured from the horizontal axis, positive upwards. The dark and light blue boxes are the muon spectrometer’s barrel and end-cap modules, respectively.](image-url)
Another important quantity to consider is the pseudo-rapidity $\eta$, defined as
\[
\eta = - \ln \left( \tan \frac{\theta}{2} \right).
\] (2.4)

In Figure 2.7 an illustration of the pseudo-rapidity values, corresponding to different directions from the coordinate system’s origin, is shown. In the case of massive objects, such as jets, the rapidity $y$ is used instead, defined as
\[
y = \frac{1}{2} \ln \left( \frac{E + p_Z}{E - p_Z} \right).
\] (2.5)

In order to describe the track of a particle, some variables, defined in the $x$-$y$ plane are needed: the transverse momentum $p_T$, which corresponds to the momentum component orthogonal to the beam axis ($p_T = p \sin \theta$); the transverse energy $E_T$ and the missing transverse energy ($E_{T,\text{miss}}$). Additional parameters are the transverse impact parameter, $d_0$ (Figure 2.8), corresponding to the distance of the track’s point of the closest approach to the beam axis in the transverse plane, and $z_0$, corresponding the longitudinal distance of this particular point. The angular separation of two particle tracks, pointing to the primary vertex, is expressed in terms of $\Delta R$ and defined as
\[
\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}.
\] (2.6)

Figure 2.8. Schematic view of the transverse impact parameter $d_0$ associated to the particle trajectory. The primary vertex coincides with the origin of the coordinate system.

2.2.1 The magnet system

The magnet system [47], shown in Figure 2.9 is divided in four independent subsets. In the barrel region a thin superconducting solenoid and an air-core superconducting toroid are located: the
CHAPTER 2. THE ATLAS EXPERIMENT AT THE LHC

former provides a bending power of $\langle BL \rangle \sim 2.3 \text{ T m}$, the latter consists of eight coils and provides a bending power of $\langle BL \rangle \sim 3.2 \text{ T m}$. In the end-cap regions there are two air-core superconducting toroids, providing a bending power of $\langle BL \rangle \sim 6.3 \text{ T m}$. The power of the magnets is provided by generators of 21 kA, in the case of toroids, and 8 kA, in the case of solenoid. A liquid helium cooling system is used to keep the magnets at a temperature of 4.5 K in order to stay in the superconducting regime.

![ATLAS magnets system view](image1.png)

**Figure 2.9.** ATLAS magnets system view: the superconducting solenoid (left) and the air-core superconducting toroid (right).

2.2.2 The Inner Detector

The Inner Detector (ID) [48], shown in Figure 2.10, is totally contained in the central solenoid which provides a 2 T axial magnetic field oriented in the direction of the beam axis, to bend the particles in the $x$-$y$ plane.

![The ATLAS Inner Detector view](image2.png)

**Figure 2.10.** The ATLAS Inner Detector view.
2.2. THE ATLAS DETECTOR

This detector identifies the primary interaction vertices and the secondary ones, measures the impact parameter with high resolution and measures the $p_T$ of charged particles with a resolution of 30% at $p_T = 500$ GeV. Its coverage in pseudo-rapidity is $|\eta| < 2.51$.

The high track density expected for the collision events in the LHC imposed a high granularity for this detector. Moreover, it has to work in a high-radiation environment and represent a minimal amount of material to limit multiple scattering effects on the track momentum resolution. It is shown in Figure 2.11 and consists of:

- **pixel detectors**: semiconductor detectors used in the region closest to the interaction point. They are placed on three concentric layers around the beam axis in the barrel region and on five discs orthogonal to the $z$ axis for each end-cap region (1-13 cm). The pixel size is $50 \times 400 \, \mu m$. These detectors provide a resolution of $\sigma_{R-\phi} = 12 \, \mu m$, in the radial direction, and of $\sigma_z = 60 \, \mu m$ in the $z$ direction;

- **microstrip detectors**: named SCT\textsuperscript{12} they are microstrip detectors used in the intermediate radial region (24-55 cm). In the barrel region they are placed in four concentric layers, while in the end-cap regions they are placed in nine discs orthogonal to the $z$ axis. The strip pitch is 80$\mu m$. The resolution provided is $\sigma_{R-\phi} = 16 \, \mu m$ and $\sigma_z = 580 \, \mu m$;

- **tubes detectors**: named TRT\textsuperscript{13} they are transition radiation detectors, composed of straw tubes and filled with Xe/CO$_2$/O$_2$ gas mixture (70%/27%/3%). They are placed parallel to

\textsuperscript{12}SemiConductor Tracker  
\textsuperscript{13}Transition Radiation Tracker
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the beam direction in the barrel region and radially in the end-cap regions (55-108 cm). They are able to provide a resolution of 170 µm per straw tube and a combined resolution of about 50 µm.

The gaseous tracker, introduced to limit the multiple scattering and the energy loss of the incoming particles, is also able to measure a higher number of space points along the particles’ tracks and exploit the transition radiation phenomenon to identify electrons and charged pions. To maintain an adequate noise performance after radiation damage, the silicon sensors are kept at a temperature between 5 °C and 10 °C. The TRT is operated at room temperature.

2.2.3 The calorimeters

The ATLAS calorimeter system [49], shown in Figure 2.12, is composed of an electromagnetic calorimeter, with a coverage in pseudo-rapidity of |η| ≤ 3.2, and a hadronic calorimeter, which provides a pseudo-rapidity coverage up to |η| ≤ 4.9.

Figure 2.12. The ATLAS calorimetric system.

- **Electromagnetic calorimeter**: this is a sampling calorimeter that measures the energy and the position of electromagnetic showers with |η| < 3.2. It is composed of two identical half cylinders in the barrel region and in each end-cap region of two coaxial wheels covering respectively the pseudo-rapidity range of 1.4 ≤ |η| ≤ 2.5 and 2.5 ≤ |η| ≤ 3.2. This calorimeter is a liquid argon (LAr) detector with lead (Pb) absorber plates, both placed following an accordion geometry. Kapton electrodes, placed in the region filled with LAr, have the same
2.2. THE ATLAS DETECTOR

geometry of the alternating layers of Pb and LAr: in this way, the segmentation of the calorimetric cells is fixed to $\Delta \eta \times \Delta \phi = 0.025 \times 0.025 \ (4 \times 4 \text{ cm}^2 \text{ at } \eta = 0)$. The thickness of the lead layers is not fixed: it varies as a function of $\eta$ from 1.5 mm for $|\eta| \leq 0.8$ up to 2.2 mm for $0.8 \leq |\eta| \leq 3.2$. The thickness of the LAr volumes is 2.1 mm in the barrel region and goes from 0.9 mm up to 3.1 mm in the end-cap regions. So, the total active thickness is around 22 radiation lengths ($X_0$) in the barrel region and from 22 $X_0$ up to 38 $X_0$ in the end-cap regions. Such a structure allows to obtain a good energy resolution and an almost full coverage along the azimuthal direction ($\phi$). This is needed to have the maximum geometrical acceptance.

The design energy resolution is given by the relation

$$\frac{\sigma(E)}{E} = a \sqrt{E(\text{GeV})} \oplus b E(\text{GeV}) \oplus c,$$

(2.7)

where $a = 10\%$ is the stochastic term, $b = 0.5\%$ takes into account the electronic noise, $c = 0.7\%$ is the constant term which reflects the systematic effects and the operator $\oplus$ represents the quadratic sum.

- **Hadronic calorimeter:** this detector covers a pseudo-rapidity range of $|\eta| < 4.9$ and it is built using different technologies, depending on the $\eta$ value. In the region $|\eta| < 1.7$ a sampling calorimeter, called Tile Calorimeter, is installed. It is made of steel layers with thickness of 14 mm and scintillator tiles with thickness of 4 mm for the active medium. In this region the granularity is $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$. In the end-cap regions - $1.5 \leq |\eta| \leq 3.2$ - layers of copper are used as absorber, with a thickness that goes from 25 mm in the innermost region up to 50 mm in the outer one, alternated with volumes filled with LAr. In the forward region - $3.2 \leq |\eta| \leq 4.9$ - volumes of LAr alternating with copper or tungsten layers are used. The ATLAS hadronic calorimeter is able to provide a good hadronic shower containment, a good accuracy in measuring the missing transverse energy, $E_T^{\text{miss}}$, and a consistent reduction of the punch-through effect in the muon spectrometer. For the hadronic calorimeter there are two different energy resolution functions, depending on $\eta$

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E(\text{GeV})}} \oplus 3\%, \quad \text{for } |\eta| \leq 3, \quad (2.8)$$

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E(\text{GeV})}} \oplus 10\%, \quad \text{for } 3 \leq |\eta| \leq 5. \quad (2.9)$$

The resolution of the combined electromagnetic and hadronic calorimeter system measured at a test beam is shown in Figure 2.13.

\[14\] Hadrons create showers in the absorbers: these, if too thin, can allow to some particles to escape and to be detected as muons in the muon spectrometer.
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Figure 2.13. Resolution of the combined ECAL/HCAL calorimetric system. The weighted data (black) show a better resolution than the uncorrected one (grey). A calibration procedure (see Reference [50]) is done to get an equal response for the electromagnetic as well as the pure hadronic component of a hadronic shower: a calibration coefficient has to be applied to the signals determined on the corresponding electromagnetic scale.

2.2.4 The muon spectrometer

The muon spectrometer [51] is located in the outer part of the ATLAS detector and provides a precise tracking of high \( p_T \) muons with a good transverse momentum resolution and as well as a muon trigger for the experiment. This system has been designed optimizing the following parameters:

- **resolution**: a good resolution for \( p_T \) of the order of few percent is needed for a reliable muon charge identification and for a good reconstruction of final state decays in two muons (i.e. \( Z \rightarrow \mu^+\mu^- \)) or four muons (i.e. \( H \rightarrow ZZ^{(*)} \rightarrow 4\mu \)). It is designed to provide a uniform transverse momentum resolution along the whole \( \eta \) coverage;

- **second coordinate measurement**: to obtain a better track reconstruction, it is necessary to detect the muons also in the non-bending direction, with a resolution smaller than 10 mm;

- **rapidity coverage**: in order to study all the physics processes with muons in the final state, a coverage in pseudo-rapidity up to \( |\eta| \leq 3 \) is needed;

- **bunch crossing identification**: the limit on the trigger time resolution is set by the time interval between two bunch crossing. In the first years of run, the bunch crossing interval was 50 ns.
2.2. THE ATLAS DETECTOR

This detector is designed to be able to detect muons that will pass the barrel and end-cap calorimeters and measure their momenta in the pseudo-rapidity range of $|\eta| \leq 2.7$, providing a $p_T$ resolution with an uncertainty of about 3% for 100 GeV tracks and about 10% for 1 TeV tracks. It is also able to trigger muons in a pseudo-rapidity range of $|\eta| \leq 2.4$, using different $p_T$ thresholds.

![Figure 2.14. The transverse (left) and lateral (right) sections of the ATLAS muon spectrometer.](image)

The muon sub-detectors composing the muon spectrometer are mounted in three concentric cylinders in the barrel regions and in four concentric disks in the end-cap regions, placed with the axis coincident with the beam axis and at different radii from the interaction point (Figure 2.14). These groups of chambers are called stations. Groups of three chambers at different radii forms projective towers that point to the interaction point. Using this geometry, muons from the interaction point will cross at least three precision chambers that measure the particle momentum from the measurement of the trajectory sagitta. The stations are named Inner, Middle and Outer according to the distance to the interaction point: in the barrel region they are labelled with BI, BM and BO, while in the end-cap regions they are called EI, EM and EO. An additional layer of chambers, Extra End-cap chambers, EE, is also used. Each station is able to measure the trajectory with an accuracy of 50 $\mu$m. Along the azimuthal direction the spectrometer is divided in 16 sectors, following the octagonal symmetry of the toroidal magnetic system; these sectors are classified in Large Sectors, placed between two coils of the toroidal magnet, and Small Sectors, smaller and placed along the coil of the toroidal magnet.

In order to obtain an accurate measurement of the muon tracks and taking into account the rate capability, the ageing properties and radiation hardness of the detectors, the Monitored Drift Chamber (MDT) and the Cathode Strip Chamber (CSC) detectors - only in the innermost region of the end-cap - have been chosen for whole muon spectrometer. The trigger is provided by Resistive Plate Chamber (RPC) detectors, in the barrel region, and Thin Gap Chamber (TGC) detectors, in the end-cap regions.
• **Monitored Drift Chambers**: are made from multi-layers of tubes filled with Ar/CO₂ gas mixture (97%/3%). They are chosen for their good ageing properties and placed on either side of a special support structure (spacer). Each multi-layer is made by 3 or 4 layers of tubes, depending on the chamber topology. This structure provides a correct relative positioning of the tubes and the chamber’s integrity under the effect of the temperature and the gravity. The tubes are arranged in 2 × 4 monolayers for the inner stations and 2 × 3 for the outer stations to form a station that can be rectangular in the barrel and trapezoidal in the end-cap. Each tube has a diameter of 30 mm, a thickness of 400 µm and a length varying from 70 cm to 630 cm. In the axis a tungsten-rhenium wire, with a diameter of 50 µm, is placed: it is maintained at a potential of 3080 V in order to work in avalanche regime. This provides a maximum drift time of the electrons of 700 ns. The tube resolution is of the order of 80 µm and depends on the drift-time, \( t \), and on the drift-distance, \( r \). The MDTs have a pseudo-rapidity coverage of \(|\eta| \leq 2.0\). The schematic view of a MDT chamber is shown in Figure 2.15.

• **Cathode Strip Chambers**: are multi-wire proportional chambers that substitute the MDT detectors in the innermost layer of the end-cap regions, covering the pseudo-rapidity range

![Figure 2.15. Schematic view of a MDT chamber.](image)

![Figure 2.16. Schematic view of a CSC chamber.](image)
2.2. THE ATLAS DETECTOR

of $2.0 \leq |\eta| \leq 2.7$. The wires are oriented in the radial direction, while the cathodes are segmented: one has the strips perpendicular to the wires, the other parallel to them. The cathode-anode spacing corresponds to 2.54 mm, equal to the anode wire pitch. The position of the track is obtained by interpolation between the charges induced on neighbouring cathode strips. The spatial resolution is about $60 \mu m$. The drift-time of the electrons is of the order of 30 ns and the time resolution is about 7 ns. The operating voltage is 1900 V and the gas mixture used is Ar/CO$_2$ (80%/20%). Figure 2.16 shows the schematic view of a CSC chamber.

- **Resistive Plate Chambers**: are gaseous detectors made of two resistive plates of phenolic-melaminic plastic laminate with a volume resistivity of $10^{10}$ $\Omega$ cm. The two plates are kept at an inter-distance of 2 mm by insulating spacers. Their outside surface is coated with a thin layer of graphite paint (100 k$\Omega$ cm) to assure the HV and the ground connection of the resistive electrodes. The volume is filled with the gas mixture of C$_2$H$_4$/Iso-C$_4$H$_{10}$/SF$_6$ (94.7%/5%/0.3%) which is not flammable and allows to work in avalanche mode, offering a high rate capability ($\sim 1$ kHz cm$^2$). An electric field of 4.9 kV mm$^{-1}$ is applied. The signal is read out by copper strips, mounted on the outer faces of the resistive plates. The spatial resolution is about 1 cm while the time resolution is about 1 ns. These detectors are used in

- **Thin Gap Chambers**: have a structure very similar to the one of the multi-wire proportional chamber: the anode wire pitch (1.8 mm) is larger than the anode-cathode distance

![Figure 2.17. Schematic view of a RPC chamber.](image)
(1.4 mm). The volume is filled with the gas mixture CO$_2$/n-C$_5$H$_{12}$ (55%/45%) which permits these detectors to work in a saturated regime, in order to have a lower sensitivity to mechanical deformations. The cathode strips are separated from the gas volume by graphite layers, placed orthogonally to the wires (anodes). The TGC detectors are mounted in two concentric rings located in the end-cap regions, covering the pseudo-rapidity range of $1.05 \leq |\eta| \leq 2.7$.

Figure 2.18 shows the schematic view of a TGC chamber.

\section{The trigger system}

At the design luminosity, the $p$-$p$ interaction rate is of the order of 40 MHz. The ATLAS trigger system has been designed to trim this rate down to a more manageable data flow. It is organized in three level, called L1 or LVL1 (Level1), L2 or LVL2 (Level 2) and EF (Event Filter), each one based on fast reconstruction of physics objects (like muons, electrons, photons and jets) and refining the decision made by the previous level.

- **Level 1**: is the first level \cite{52} of the ATLAS trigger chain. This level is a hardware-based trigger and makes a first selection using the RPC and TGC chambers to identify muons with a high $p_T$ and the calorimeters for high $E_T$ photons, electrons, jets and taus decaying in hadrons. Cuts on $E_T$ and $p_T$ are applied: the events passing the L1 trigger selection are transferred to the next trigger level. The output rate of the L1 trigger cannot exceed 75 kHz with a maximum latency of 2.5 $\mu$s to make the final decision: in this time window, the information coming from all the detectors are temporarily stored in local memories, called Read Out Buffer, ROB, located in integrated circuits near the detectors. Moreover, the L1 trigger defines some Regions-of-Interest, RoIs, corresponding to the $\eta$-$\phi$ region of the detector where the object passing a certain trigger is present and which will be given to the second trigger level.
2.2. THE ATLAS DETECTOR

- **Level 2**: is the second level of the ATLAS trigger chain. This is a software-based trigger which is seeded by the RoI information provided by the L1. The information is used to reconstruct within a RoI only those events that satisfy the requirements of this trigger level: if the requirements are satisfied, the complete event is reconstructed and passed to the last trigger level. The event rate is reduced to 2 kHz, with an event processing time of about 40 ms.

- **Event Filter**: is the final stage of the ATLAS trigger chain, which reduces the event rate to 500 Hz. Here only events that pass at least one of the L2 trigger algorithms are processed. This level has access to the whole event using the full information of the ATLAS detector. The EF uses the off-line analysis procedure, such as detailed reconstruction algorithms. The mean processing time for one event at the event filter is around 4 s. This last step of the ATLAS trigger runs on a dedicated computer farm, located near the ATLAS cavern. The events passing this final stage are written to the mass storage and made available for further off-line analysis.

The L2 and EF trigger levels are referred to collectively as the High-Level Trigger (HLT) system. The L1 and HLT share an overall trigger selection framework and differ mostly in the amount of event data they access and in the complexity and speed of the algorithms. The L1 uses only coarse-grained calorimeter and muon information, while the HLT restricts itself to the RoIs, using, for these regions, full data from all detectors, combining the information from different sub-detectors. The ATLAS trigger system provides also di-lepton triggers. Using the same selection logic of the single object case, each trigger level requires two leptons candidate to each pass the specific trigger level requirements. In the case of muons and electrons, all possible combinations are considered: two muons, two electrons, a muon and an electron.

**The muon trigger**

The muons are reconstructed in the trigger using the information of the detectors installed in the ATLAS muon spectrometer. It is organized in three levels: an hardware one, the L1, which uses the information of the RPC and the TGC chambers, and a software one, HLT, comprising the L2 and the EF, which uses also the information of the other detectors of the muon spectrometer. The L1 muon trigger is designed to operate at two different threshold working points - Figure 2.19:

i) **Low-\(p_T\) trigger** \((p_T < 20 \text{ GeV})\): in this case only the information of the two innermost RPC stations and the outermost TGC stations are used.

ii) **High-\(p_T\) trigger** \((p_T > 20 \text{ GeV})\): in this case the information of last two RPC stations and the first and the third TGC stations are used.
For sake of simplicity, consider the RPC only. Call the first station of RPC as the Low-$p_T$ coincidence plane, the second station as the Pivot plane and the third station as the High-$p_T$ coincidence plane. In the case of Low-$p_T$ trigger, for each hit in the Pivot plane, every time a hit inside the coincidence window corresponding to the Low-$p_T$ plane is found, the trigger is fired. In the second case, the trigger is fired when a hit in the Pivot plane corresponds to a hit in the High-$p_T$ plane inside the coincidence window. This system is optimized to apply the low-$p_T$ thresholds (i.e. 6, 8, 10 GeV) and the high-$p_T$ thresholds (i.e. 20, 40 GeV) at the same time.

The L1 trigger operates through coincidence matrices, which use the information of the detector’s layers in order to verify the coincidence between the hits in the two planes considered within a fixed time-window. In order to measure track’s quantities, several coincidence matrices are defined, providing information for a single RoI. One matrix of the Low-$p_T$ trigger and the corresponding one of the High-$p_T$ forms a LocalLogical (LL), which selects muons inside a region of $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$. The Pad Logical Board, PL, combines the information from four LLs in order to select the muon candidate with the highest $p_T$. For each $p_T$ threshold more than a muon candidate can be found and the final decision for the L1 trigger is taken by the Central Trigger Processor, CTP. The L1 provides rough estimate of the muons position and $p_T$ to the HLT trigger.

The HLT muon trigger tries to confirm the L1 muons and reject fakes. The L2 standalone algorithm runs on the full granularity of the data within the RoI defined by the L1. Hits from the MDT chambers, within a region where the L1 trigger is fired, are selected and a linear track fit is
2.2. THE ATLAS DETECTOR

performed in each station. The trigger efficiency is about 90% for muons with a $p_T$ above the trigger threshold. At this stage, the L1 rate is reduced by factors of 2 (10) for the low (high)-$p_T$ case. In addition, a specialized algorithm is used to discriminate between isolated and non-isolated muon candidates by examining energy deposits in the calorimeter and the ID tracks in the region of the muon candidate. By applying isolation criteria another significant reduction is achieved. If all selection criteria are satisfied, the information are sent to the EF, which has access to the full event with full granularity. Here the results of the L2 are combined with information of the precision tracker. Two alternative algorithms are used: one algorithm starts from tracks reconstructed in the MS and extrapolates them back to the interaction point; the second algorithm starts from the ID tracks and performs muon identification outward. Both the algorithms confirm or discard L2 candidates: if confirmed, the event is acquired.

The electron trigger

The electrons are reconstructed in the trigger in $|\eta| < 2.5$, using the information of the two layers of the EM calorimeter and the ID of the ATLAS detector.

At L1 trigger level, electrons are selected using calorimeter information with the reduced granularity of the so called trigger towers (TT) which have a dimension of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. In each trigger tower all the cells of the calorimeter are summed and the clustering is done by looking for local maxima with a sliding window algorithm using $4 \times 4$ trigger towers. The most energetic of the four $1 \times 2$ or $2 \times 1$ combinations of the $2 \times 2$ core has to pass the electromagnetic cluster threshold. At this stage most events are already rejected by applying $E_T$ and shower-shape criteria.

Seeded by the position of the L1 cluster, in the L2 trigger level the electron selection is done using a fast calorimeter reconstruction algorithm and a fast track reconstruction. Concerning the reconstruction in the calorimeter, around the L1 seed position, cells are retrieved in a region of $\Delta\eta \times \Delta\phi = 0.4 \times 0.4$ and the cluster seed finding is done using the hottest cell in the second EM layer in the smaller region $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$. The defined window cluster size is $3 \times 7$. The cell energies provided by the Read-out Driver Boards (ROD), which reconstruct the deposited energy, are used as input by the trigger. Concerning the track reconstruction, a track search in the ID in the vicinity of the cluster is performed, requiring matching of $E_T/p_T$ and position of cluster and track. A large rejection against photons from $\pi_0$ decays is achieved. In addition, hypothesis algorithms are also used in order to reject fakes coming predominantly from jets.

At the EF trigger level, the reconstruction is done using a sliding window algorithm acting on towers containing the energy summed in depth by regions. After this, fixed window clusters of size $3 \times 7$ are built starting from the second layer of the EM calorimeter using cell energies provided by the RODs. The track reconstruction is done by combining hits in the silicon detectors and the TRT standalone tracking. At this stage, the information of the transition-radiation tracker are
used to better discriminate electrons from pions: bremsstrahlung (for $\text{e}^{-}$) and conversion recovery (for $\gamma$) are also performed.

Although the selection efficiency is generally higher when using the EF for rejection, this has to be weighted against the increased rate and bandwidth out of L2. The common HLT selection software used in both systems provides the flexibility to optimize the overall HLT system taking into account both physics and system parameters. The L1 EM-cluster trigger rate is of about 22 kHz and the HLT reduces it to about 114 Hz.
Chapter 3

Object and event identification
and reconstruction

In any ATLAS analysis it is crucial to reconstruct and identify the physics objects resulting from
\( p-p \) collisions. In particular, it is very important to reconstruct the tracks and the vertex of an
event well, and correctly identify the particles. In the context of the \( H \rightarrow ZZ(\ast) \rightarrow 4l \) analysis, this
chapter describes the tracking and vertex reconstruction and identification of the leptons considered
in the analysis. Since jets are not used extensively, but only to categorize \( H \rightarrow ZZ(\ast) \rightarrow 4l \)
candidates (see Section 6.2.1), only an overview of their identification, reconstruction and energy
measurements is given: additional information can be found in References [55] [56] [57].

3.1 Tracks and vertices

In ATLAS, the reconstruction of a track [58] [59] starts from clusters and space points defined using
the information from the sub-detectors composing the ID. To reconstruct a track two approaches
are used [58]:

i) \textit{inside-out}, in which the search for and reconstruction of a track starts from the pixel layers
and adds hits from the other detectors moving away from the interaction point. It is designed
for the efficient reconstruction of primary charged particles, defined as particles with a mean
lifetime greater than \( 3 \times 10^{-11} \) s directly produced in a \( p-p \) interaction.

ii) \textit{outside-in}, in which the search for and reconstruction of a track is done in the opposite way,
from TRT segments and extending them inwards by adding silicon hits. It is designed to
reconstruct secondary particles, which are produced in the interactions of the primary ones.
In the first approach, a track seed is formed using a combination of space points from three pixel layers and the first SCT layer and then extended to all the other SCT layers in order to search for additional hits. The hits are classified in three ways: a *hit* with good properties, an *outlier* that provides a reduction of the fit quality and a *hole*, a hit not found when expected. According to this classification, a track candidate has to satisfy a set of quality cuts \[58\], based on the number of good hits, outliers and holes. Once the track candidates are found, the eventual ambiguities between the tracks are resolved, a more refined fit procedure is performed and then the tracks are extended to the TRT layers, in order to find the last hits. Figure 3.1 shows the number of track candidates in data (markers) and simulation (lines) as a function of $\eta$ for different categories of the ambiguity solver algorithm.

![Figure 3.1](image)

**Figure 3.1.** Number of track candidates as a function of $\eta$ for different track categories of the ambiguity solver algorithm: all entering the ambiguity solver (black), rejected because they are assigned a track score of zero (blue), rejected because of quality cuts (red) and accepted as resolved tracks (green). Data (markers) and simulation (lines) are shown.

The track reconstruction efficiency depends on the pile-up conditions \[59\]: in a high pile-up scenario the detector occupancy increases and this affects the number of tracks without corresponding primary and secondary particles, called “fake tracks”. Figure 3.2a shows the track reconstruction efficiency as a function of $\eta$ for different quality cuts and in different pile-up scenarios. In the default scenario, tracks are selected requiring at least 7 hits in the silicon detector and allowing at most two holes in the pixel detector. In the robust scenario, tracks are selected requiring 2 more hits in the silicon detectors and zero holes in the pixel detectors. Using more robust quality cuts the number of fake tracks is minimized, but, at the same time, they decrease the efficiency by 5% for tracks associated to the primary vertices. Figure 3.2b show the non-primary fraction, which is the sum of the contributions from secondaries and from fake tracks, as a function of $\eta$ for different quality cuts and in different pile-up scenarios. The non-primary fraction with the default requirements increases by a factor of 3-5 with increasing pile-up: this can be attributed
3.1. TRACKS AND VERTICES

to an increase of fakes. Using the robust requirements the non-primary fraction is reduced by a factor of 2-5 and becomes almost independent of the amount of pile-up.

(a) Primary track reconstruction efficiency vs $\eta$

(b) Non-primary fraction vs $\eta$

Figure 3.2. Track reconstruction efficiency (a) and non-primary fraction (b) as a function of $\eta$ for different pile-up conditions.

Once the track candidates are reconstructed, it is important to reconstruct the primary vertices (the interaction points) and the secondary vertices, i.e. particle decays. The vertices are identified using two algorithms [60]: a vertex finding algorithm, which associates the tracks to vertex candidates, and a vertex fitting algorithm, which reconstructs the vertex parameters. To find the correct association of tracks with vertices, the first algorithm selects the reconstructed tracks that are compatible with originating from the interaction region and selects a vertex seed. Then the vertex position is found through a $\chi^2$ based fitting procedure: any track that does not satisfy the fit is then used to set a new seed and the procedure starts again until no tracks are left. It is clearly possible that an event has more than one vertex: in this case, the primary vertex is defined as the one that has the highest sum of $p_T^2$ of the associated tracks.

As for the track reconstruction efficiency, the vertex reconstruction efficiency depends on the pile-up scenario: it decreases when pile-up increases, since the number of fake tracks increases as well and the accuracy in reconstructing the vertex position is lower.

Figures 3.3a and 3.3b show the number of reconstructed tracks per events and the number of reconstructed primary vertices, respectively, in data for different pile-up scenarios. The degradation of the reconstruction efficiency starts from pile-up scenario with $\mu \geq 15$ [59] [61]. When comparing the number of reconstructed vertices from data and MC prediction a disagreement is found in the minimum bias vertex multiplicity. In order to take into account this effect, the expected average number of interactions per bunch crossing is multiplied by a factor, called $\mu$-rescaling [62]. Figures 3.4a and 3.4b show the distributions of the transverse and longitudinal impact parameters, respectively, with respect to the primary vertex: the tails of these distributions are dominated by
secondary tracks. Each track is satisfying the robust requirements and has $p_T > 400$ MeV.

Figure 3.3. (a) Comparison of the number of reconstructed tracks per event in data containing different amounts of pile-up; (b) the number of reconstructed vertices with the robust track requirements in data containing different amounts of pile-up. In both (a) and (b) the requirement on the transverse momentum is $p_T > 400$ MeV.

Figure 3.4. (a) The impact parameter distributions at medium and high pile-up for tracks satisfying the robust requirements and (b) the distributions of the longitudinal impact parameter, $z_0 \sin \theta$, with respect to the primary vertex. In both (a) and (b) the requirement on the transverse momentum is $p_T > 400$ MeV.
3.2 Leptons

The ATLAS detector is able to identify and reconstruct muons, electrons and taus. Since no taus are used in this analysis, this section focuses on the identification and reconstruction of muons and electrons. Information concerning the performance of the identification and the reconstruction of taus can be found in references [63] [64].

3.2.1 Muons

The ATLAS detector has been designed in order to be able to reconstruct muons with an efficiency of at least 95% and a relative resolution in $p_T$ of about 3% around 100 GeV and 10% around 1 TeV. The evaluation of the muon momentum resolution will be described later in Chapter 4.

A muon track is reconstructed both in the ID and the MS; the information of the two systems can be combined in order to provide the best performance in terms of resolution over the entire $p_T$ range. As schematically shown in Figure [3.5] in ATLAS four types of muon candidates are distinguished depending on the way they are reconstructed [65]. The muon identification is in fact performed using the available information from the ID, the MS and the calorimeter sub-detector systems. The different types are:

i) **Stand-alone muons** (SA): are muons with a track reconstructed only using the hits in the Muon Spectrometer and then extrapolated to the beam line. The reconstruction of a stand-alone muon track starts from the trigger chambers, where a region of interest, RoI, is identified; then for each muon station contained in the RoI a track segment is found. Combining these segments a track is formed and a global fit of the muon track is performed. The reconstruction of stand-alone muons can be done up to $|\eta| < 2.7$.

ii) **Combined muons** (CB): are muons with tracks reconstructed in both the Inner Detector and the Muon Spectrometer and combining the information from the two systems. The combination method is based on the match $\chi^2$, as the difference between the inner and the outer track parameters weighted by their combined covariance matrix. A cut on the $\chi^2$ match is applied. These type of muons are the standard muon objects for physics analysis and provide candidates of highest purity. The reconstruction of these muons is limited to $|\eta| < 2.5$ by the ID coverage and their momentum is defined as a weighted combination between the $p_T$ measurements done by the ID and the MS.

iii) **Segment tagged muons** (ST): are muons that have a track reconstructed in the Inner Detector and some hits on the first station of the Muon Spectrometer. The ID track is associated to straight track segments in the precision muon chambers of the MS. The match
quality is defined as a tag $\chi^2$, where the difference between the MS track segment and the extrapolated ID track is used. These muons adopt the measured parameters of the associated ID track (i.e. $p_T$) and are used to recover efficiency for low $p_T$ muons. The reconstruction of these muons is limited to $|\eta| < 2.5$.

iv) **Calorimeter tagged muons** (CT): are muons with a track reconstructed in the ID and associated to energy depositions in the calorimeters if these are compatible with the hypothesis of minimum ionizing particle. These muons have the lowest purity of all muon types, but are used to recover inefficiencies in the regions of $|\eta| \sim 0$ where the MS is only partially equipped with muons chambers to provide space for services of the ID and the calorimeter. The identification and reconstruction criteria of this type of muons are optimized for the pseudo-rapidity region $|\eta| < 0.1$ and a momentum $p_T > 15$ GeV.

In the first years of the LHC operation, ATLAS uses two reconstruction algorithms [66] following two independent and complementary strategies:

- Staco or “Chain 1” [67] performs a statistical combination of the track parameters of the MS and ID muon tracks using the covariance matrices of both track parameter measurements;

- Muid or “Chain 2” [68] performs a global refit of the muon track using the hits from both the ID and MS sub-detectors.

The reconstruction efficiency [69] [70] [71] of the different muon types can be decomposed as the product of the reconstruction efficiency in the ID, the reconstruction efficiency in the MS, and the matching efficiency between the ID and MS measurements. The reconstruction efficiency in the MS is not uniform and varies with $\eta$ and $\phi$. In particular, there are two regions in $\eta$ with decreased reconstruction efficiency: one around $\eta \sim 0$, as described before, and the transition region between the barrel and the end-cap regions, around $|\eta| \sim 1.2$, where only one muon chamber is used for the track reconstruction. For each muon type, the reconstruction efficiency is defined by

$$
\epsilon(\text{Type}) = \epsilon(\text{Type}|\text{ID}) \cdot \epsilon(\text{ID}) ,
$$

(3.1)

where $\epsilon(\text{Type}|\text{ID})$ is the MS reconstruction and the matching efficiency for a specific muon type measured with CT probes and $\epsilon(\text{ID})$ is the ID reconstruction efficiency which is the fraction of the MS track probes associated to an ID track. In particular, for CB muons the reconstruction efficiency can be written as the product of three independent sub-efficiencies

$$
\epsilon_{\text{reco}}^{CB} = \epsilon_{\text{ID}} \times \epsilon_{\text{MS}} \times \epsilon_{\text{match}} ,
$$

(3.2)

where $\epsilon_{\text{ID}}$ is the efficiency that the ID reconstructs a muon track, $\epsilon_{\text{MS}}$ is the efficiency of the MS a muon track and $\epsilon_{\text{match}}$ is the efficiency of combining the two tracks in one.
3.2. LEPTONS

(a) Combined muon: a track in the MS (blue), extrapolated through the calorimeter (orange) and matched with a track in the ID (yellow).

(b) Segment tagged muon: an ID track (yellow) matched with one hit segment in the MS (blue).

(c) Stand-alone muon: a track in the MS (blue), extrapolated through the calorimeter (orange) but without a matching ID track (dashed line).

(d) Calorimeter tagged muon: an ID track (yellow) extrapolated into the calorimeter (orange) and compatible with the signature of a minimum ionizing particle.

Figure 3.5. The four types of muons defined in ATLAS: combined (a), segment tagged (b), stand-alone (c) and calorimeter tagged (d).

A Tag-and-Probe \[69\] method is used to measure the muon reconstruction efficiency of all muon types within the acceptance of the ID, \(|\eta| < 2.5\). This method uses any known correlation between two separately reconstructed objects and is sensitive to the ID and MS reconstruction efficiency together with the matching efficiency. With stringent selection criteria on the tag objects and the correlation to the probe, the identity of the probe object is ensured without direct and hard cuts on this object. To perform these efficiency measurements \(Z \to \mu\mu\) decays are used: events are selected by requiring two opposite charge isolated\[1\] muons, with \(p_T > 20\) GeV, and a di-muon invariant mass within 10 GeV from the \(Z\) boson mass. One of the muons is required to be a CB muon candidate and it is selected using information from the whole detector and tight selection criteria: this muon is called the ‘Tag’. Then, the other muon, called ‘Probe’, is selected depending on the desired sub-efficiency: i.e. it has to be a SA track when the ID muon efficiency is to be measured, or an ID track when the MS and the matching efficiency is to be measured. Once the tag-and-probe pairs are selected, the probe is matched to a reconstructed muon, requiring that

---

\[1\] A muon is considered isolated when the sum of the momenta of the tracks with \(p_T > 1\) GeV detected in a cone of \(\Delta R = 0.4\) around the muon track is less than 0.1 times the muon momentum itself.
they have the same measured charge and are close in the $\eta$-$\phi$ plane\footnote{For ID probes $\Delta R < 0.01$, while for MS probes $\Delta R < 0.05.$}. 

![Efficiency vs $\eta$](image1.png) ![Efficiency vs $\langle \mu \rangle$](image2.png)

**Figure 3.6.** (a) Muon reconstruction efficiency as a function of $\eta$ for muons with $p_T > 20$ GeV and for CB+ST (circles) and CT (triangles); (b) measured reconstruction efficiency for CB+ST muons with $p_T > 20$ GeV as a function of the average number of inelastic $p$-$p$ collisions per bunch crossing, $\langle \mu \rangle$. In both (a) and (b) the panel on the bottom shows the ratio between measured and predicted efficiencies for 2012 data taking.

![Efficiency vs $\eta$](image3.png) ![Efficiency vs $\eta$](image4.png)

**Figure 3.7.** ID muon reconstruction efficiency as a function of $\eta$ for muons with $p_T > 20$ GeV. The efficiency is measured using muons satisfying standard quality cuts (a) and muons passing relaxed requirements (b). In both (a) and (b) the panel on the bottom show the ratio between measured and predicted efficiencies for 2012 data taking.
3.2. LEPTONS

In Figure 3.6a the muon reconstruction efficiencies as a function of $\eta$ for all muon types are shown: their combination gives an uniform muon reconstruction efficiency of about 98% over all the detector regions. In Figure 3.6b the reconstruction efficiency for CB+ST muons as a function of the average number of inelastic $p$-$p$ interactions per bunch crossing, $\langle \mu \rangle$, is shown, displaying a high value, around 99.9%, and a good stability. More details concerning the pile-up dependence of the reconstruction efficiency can be found in reference [72]. Figure 3.7 shows the reconstruction efficiency as a function of $\eta$ for only ID muons passing the standard requirements (a) and relaxed ones (b). The level of agreement between measured and predicted muon efficiencies is evaluated: calling $\epsilon_{\text{Data}}$ the measured and $\epsilon_{\text{MC}}$ the predicted efficiency, the Data/MC agreement is called ‘efficiency scale factor’ (SF) and defined as

$$SF = \frac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}}.$$  

The muon trigger efficiency [73] [74] relative to reconstructed muons is measured using the Tag-and-Probe method, using, as before, $Z \rightarrow \mu\mu$ events. The approach is the same as used for the reconstruction efficiency measurement, with the difference that reconstructed muons are used as probes. In ATLAS, two kind of muon trigger efficiencies are measured:

i) $\epsilon(L1|\text{rec})$, corresponding to the probability that a reconstructed muon passes the L1 trigger;

ii) $\epsilon(L2&EF|L1&\text{rec})$, corresponding to the probability for a reconstructed muon accepted by the L1 trigger to pass a particular $p_T$ threshold at L2 and in the EF.

The trigger efficiencies are computed measuring the performance of the various algorithms existing for any trigger level [75]. For the analysis, relevant are the muon trigger efficiencies measured starting from the EF, where two complementary strategies are used. The “outside-in” algorithm selects the muon candidate starting from the MS and extrapolates the track inward to the ID. The “inside-out” algorithm selects the muon candidate from the ID and extrapolates outward to the MS. Both the algorithms are used to obtain the final decision of the EF trigger level.

Figure 3.8 shows the measured efficiencies of data and MC in the barrel and end-cap regions as a function of the offline reconstructed muon $p_T$ for the “outside-in” (top) and the “inside-out” (bottom) algorithms, considering the mu18_medium trigger chain of the ATLAS trigger. Both algorithms show similar efficiencies in the barrel and end-cap regions: the triggers reach their efficiency plateau at $p_T \sim 20$ GeV. The difference of the efficiencies in the barrel and end-cap regions is due to the geometric acceptance of the L1 trigger chambers.

As for the reconstruction efficiency, also in this case the scale factor is defined by the formula

$$SF = \frac{1 - \prod_{n=1}^{N} (1 - \epsilon_{\text{Data},n})}{1 - \prod_{n=1}^{N} (1 - \epsilon_{\text{MC},n})},$$  

where $N$ is the number of offline objects satisfying specific object selection criteria and $\epsilon_{\text{Data},n}$ and $\epsilon_{\text{MC},n}$ are the trigger efficiencies for the offline objects determined with data and MC. Equation
3.4 assumes the existence of at least one offline object in an event which has an associated trigger object, required to pass all the steps of the trigger chain, in a cone of $\Delta R = 0.15$ around the offline object.

Figure 3.8. Efficiencies of the mu18 medium trigger chain as a function of the offline reconstructed muon $p_T$. (a) and (b) show the muon trigger efficiencies with the “outside-in” algorithm in the barrel and end-cap regions, respectively. (c) and (d) show the muon trigger efficiencies with the “inside-out” algorithm in the barrel and end-cap regions, respectively. In all plots, circles and rectangles show data and MC, respectively, while the panels on the bottom show the ratio between measured and predicted efficiencies for 2011 data taking. The difference of the efficiencies in the barrel and end-cap regions is due to the geometric acceptance of the L1 trigger chambers.
3.2. LEPTONS

3.2.2 Electrons

The identification and reconstruction of electrons is done using the EM calorimeter and the ID. In particular, the EM calorimeter measures the energy in three longitudinal layers: the first layer is made of strips and has the finest segmentation in $\eta$ in order to separate photon from $\pi^0$ decays; the second layer has a coarser segmentation - eight times the first layer in $\eta$ - and contains most of the shower energy; the third layer completes the measurement of the shower energy.

First energy deposits in the EM calorimeter are found by a sliding window algorithm [76] which finds energy deposits in cells within a fixed-size rectangular window with a local transverse energy maximum. If found, these energy deposits become seed clusters and they are matched with ID tracks. The matching criteria are very loose, since they have to take into account all the radiative effects, such as bremsstrahlung of high energy electrons. These losses in energy can change the trajectories of the electrons when they traverse the magnetic field. An important role is played by the fitting track procedure: in ATLAS, electrons are reconstructed using the Gaussian Sum Filter (GSF) algorithm [77]. In absence of bremsstrahlung, the distribution $p_{\text{true}}/p_{\text{reco}}$ is supposed to be a Gaussian, but with bremsstrahlung present this is not the case. This algorithm takes into account the non-Gaussian noise by modelling it as a weighted sum of Gaussian components. In a event, all tracks with transverse momentum $p_T > 400$ MeV and $|\eta| < 2.5$ that are identified as electrons can be refitted. The re-defined track parameters are then used in the matching with the calorimeter clusters. In the case of a track-cluster match, the cluster is considered and calibrated as an electron, otherwise as a photon. Because of the bremsstrahlung, the electron and the photon clusters are calibrated differently as the electromagnetic shower starts earlier for electrons than for photons. Once reconstructed, the electron objects have to satisfy more selection criteria in order to reject as much as possible fake contributions. The identification is done in $|\eta| < 2.47$ with a cut-based selection approach, which defines four sets of cuts with different background rejection power:

i) **loose** selection criteria feature cuts on the detector acceptance and the hadronic leakage as well as constraints on the shower shape in the second sampling of the calorimeter;

ii) **medium** selection criteria are stricter than loose criteria, requiring additional cuts on the first sampling shower shape variables, cuts on the quality of the tracks (i.e. hits in the Pixels and in the SCT) and track-cluster matching requirements;

iii) **tight** selection criteria imply additional identification cuts: the agreement between the energy $E$, measured in the calorimeter, and the momentum $p$, measured in the ID, is tested and the particle identification uses also the information of the TRT to discriminate against photon conversions;

iv) **multilepton** selection criteria, developed in the context of searches with multi lepton final
states analysis, exploit specific cuts on high/low bremsstrahlung categories using the GSF information. In this case relaxed cuts on the pile-up sensitive variables and additional cuts on the track matching variables, when the track had a significant energy loss, are used. This strategy allows to have selection criteria more pile-up robust and to achieve an almost constant background rejection.

On top of these identification criteria, constraints on the calorimeter and track isolation are imposed. While for 2011 the calorimetric isolation is measured using the calorimeter cells, for 2012 it is measured through the topological clusters \([76]\) that are found inside a cone of \(\Delta R = 0.3\) around the cluster seed and built from clusters with a energy greater than a threshold value depending on the expected noise. The topological clusters are defined to have a greater efficiency in noise suppression and in higher pile-up conditions with respect to the calorimeter cells.

The electron reconstruction efficiency \([78, 79, 80]\) is measured using a Tag-and-Probe method \([78]\) similar to the one described in Section 3.2.1, but using \(Z \to ee\) events. First one electron candidate is selected if satisfying the standard selection and is called ‘Tag’; then a second electron candidate is selected if satisfying some looser criteria. For the 2012 data taking, the electron reconstruction algorithm has been improved. An electron recovery procedure is executed around each electromagnetic energy cluster passing very loose shower shape requirements. This consists of a modified pattern recognition that allows for energy loss at each material surface and an optimized electron track fitter. Furthermore, the track-cluster matching procedure was improved to favour the primary electron track in case of cascades due to bremsstrahlung.

![Figure 3.9](image_url)

(a) Electron reconstruction efficiency vs \(\eta\)  
(b) Electron reconstruction efficiency vs \(E_{T,\text{cluster}}\)

Figure 3.9. The electron reconstruction efficiency as a function of \(\eta_{\text{cluster}}\) (a) and as a function of \(E_{T,\text{cluster}}\) (b). Electrons are required to satisfy track quality criteria (at least one hit in the pixel detector and at least 7 hits in the pixel and SCT detectors). Both measurements (filled triangles) and MC predictions (open triangles) are shown, for 2011 (red) and 2012 (blue) data taking.
Figure 3.9 shows the reconstruction efficiency as a function of $\eta$ measured in the cluster (a) and as a function of $E_T$ measured in the cluster (b) for both 2011 (red) and 2012 (blue) data taking. Over the $E_T$ range, the 2012 reconstruction efficiency is increased by about 2% (8%) in the barrel (end-cap) region with respect to the one achieved in 2011. Averaging over the $\eta$ coverage, the increase is of about 2% (7%) at high (low) $E_T$.

Figure 3.10. The identification efficiency for the electron quality criteria as a function of $E_T$ (a) and as a function of the number of reconstructed primary vertices (b) for the loose (red), multilepton (violet), medium (green) and tight (blue) quality cuts. Measurements (full markers) and MC predictions (open markers) are shown for 2012 data taking.
The electron identification efficiency \cite{78,79,80} is also measured with the same Tag-and-Probe method that uses $J/\psi \rightarrow ee$ events in addition to $Z \rightarrow ee$ events. In this case, backgrounds are either subtracted using functional fits (from $J/\psi$ measurements) or are based on normalized templates either in the mass or the isolation distributions (from $Z$ measurements). Figure 3.10 shows the electron identification efficiency as a function of $E_T$ (a) and as a function of the number of primary vertices (b) for the loose (red), multilepton (violet), medium (green) and tight (blue) quality cuts for the 2012 data taking. The level of agreement between the measured and predicted electron efficiencies can be translated into an efficiency scale factor, SF, as defined in Equation 3.3.

The electron trigger efficiencies \cite{81} are computed using electrons identified by the offline reconstruction software. Depending on the electron $E_T$, three types of trigger efficiencies, all using a Tag-and-probe or similar technique, are defined \cite{81}.

- **Low-$E_T$ electron trigger efficiencies using $J/\psi \rightarrow ee$ events**: defined for electrons with $E_T < 15$ GeV and evaluated using a single offline electron passing a particular trigger as ‘Tag’ and all remaining offline electrons in the events to probe the efficiency of other triggers. The tag-and-probe electrons must satisfy each the offline tight selection and have an invariant mass within $2.6 \text{ GeV} < m_{ee} < 3.2 \text{ GeV}$. Additional cuts are applied to ensure quality tracks in the ID and no contamination from fakes. The probe-electron is used to measure the $e_{5,\text{tight}}$ trigger chain efficiency, which reaches a plateau around 7 GeV: the L2 and EF efficiencies measured above this threshold are 97% and 94%, respectively.

- **High-$E_T$ electron trigger efficiencies using $W \rightarrow e\nu$ events**: defined for electrons with $E_T > 15$ GeV and evaluated with a technique similar to the Tag-and-Probe; the ‘Tag’ is the neutrino and the ‘Probe’ is the electron. The events are required to pass $E_T^{\text{miss}}$ triggers with thresholds between 20 and 40 GeV, to have a large missing transverse energy, $E_T^{\text{miss}} > 25$ GeV and to be isolated. The additional requirement of large transverse mass, $m_T > 40$ GeV, reduces contamination from fake electrons. The electron is required to pass the offline tight selection and $Z$ events are vetoed, following the same electron identification criteria as in the inclusive $W$ analysis \cite{82}. The efficiencies of the $e_{15,\text{medium}}$ and $e_{20,\text{loose}}$ trigger chains are measured as a function of $E_T$ and $\eta$.

- **High-$E_T$ electron trigger efficiencies using $Z \rightarrow ee$ events**: defined for electrons with $E_T > 15$ GeV and evaluated with the Tag-and-Probe technique. The two opposite charge identified electrons must satisfy tight requirements, have $E_T > 20$ GeV and an invariant mass between $80 \text{ GeV} < m_{ee} < 100 \text{ GeV}$. The ‘Tag’ electron must pass the $e_{15,\text{medium}}$ trigger and match an offline tight electron with $\Delta R < 0.15$ \cite{82}. The efficiencies of the $e_{15,\text{medium}}$ and $e_{20,\text{loose}}$ triggers are measured as a function of $E_T$ and $\eta$ and are similar to those obtained in $W \rightarrow e\nu$ analysis.
3.3. JETS

Figure 3.11 shows the efficiency of the e15\_medium and e20\_loose trigger chains with respect to offline tight electrons as a function of $E_T$ (a) and $\eta$ (b), respectively, using $W \rightarrow e\nu$ (filled markers) and $Z \rightarrow ee$ (open markers) events. Above the plateau, reached around 20 GeV (25 GeV), the e15\_medium (e20\_loose) efficiency is 99.08% (99.36%) and 98.97% (99.26%) at the EF level when using $W \rightarrow e\nu$ events and $Z \rightarrow ee$ events, respectively. The results from $Z \rightarrow ee$ and $W \rightarrow e\nu$ events are very compatible, giving a robust estimate of the electron-trigger efficiency.

![Graph](image)

(a) Electron trigger efficiency vs $E_T$

(b) Electron trigger efficiency vs $\eta$

**Figure 3.11.** Efficiencies measured for the e15\_medium (red) and e20\_loose (blue) trigger chains measured with $W \rightarrow e\nu$ events (filled markers) and $Z \rightarrow ee$ events (open markers). The efficiencies are measured at the EF level with respect to the offline tight electron as a function of $E_T$ (a) and $\eta$ (b).

3.3 Jets

Jets can be defined as composite objects contained in narrow cones in $\eta$-$\phi$. The identification and reconstruction of an object as a jet starts on the topological cell clusters [76] in the calorimeter, used as input for the jet finding algorithms. The jets used in the analysis are identified using an anti-$k_T$ algorithm [55] with a distance parameter $R = 0.4$. The topological clusters are then corrected from the electromagnetic scale to hadronic energy scale using a $p_T$ and $\eta$-dependent jet energy scale (JES) determined from Monte Carlo simulation [83] [84]. To reject jets not associated to real energy deposits in the calorimeters, they are also required to pass the standard “looser” quality cuts for ATLAS jets [83]. Jets originating from pile-up are removed by requiring that a certain amount of the tracks associated to the jet (within $\Delta R = 0.4$ around the jet axis) must originate from the primary vertex. This is implemented as a cut on the value of the “jet vertex fraction”: it is JVF > 0.75 for $\sqrt{s} = 7$ TeV data and JVF > 0.5 for $\sqrt{s} = 8$ TeV data.
Chapter 4

Muon momentum resolution of the ATLAS detector

The ATLAS detector is designed to provide an efficient muon detection and a good momentum resolution. It is equipped with the Muon Spectrometer (MS), which is able to provide a muon momentum resolution with a relative precision of about 3% over a wide $p_T$ range and of 10% for at $p_T = 1$ TeV, and the Inner Detector (ID), which provides another precise determination of the muon momentum.

The composition of the MS and the ID is given in Section 2.2.4 and Section 2.2.2 respectively. In both the systems, the muon momentum is measured from the deflection of the muon trajectory in the magnetic field, generated by the air-core toroid coils in the MS and by a superconducting solenoid in the ID. Among all muon types distinguished by the ATLAS detector (see Section 3.2.1) the ones with the best resolution are the combined muons.

Since the muon identification follows the principle that first separate tracks are measured in the ID and the MS before combining both tracks to reconstruct a single trajectory, the resolution is studied in both the ID and the MS. The combined track has a higher momentum resolution than each individual one: the ID measurement dominates the combination up to a $p_T \sim 80$ GeV, the ID and the MS measurements have similar weights for $80 < p_T < 100$ GeV and the MS dominates for a $p_T > 100$ GeV. In this chapter a determination of the muon momentum resolution using data driven techniques is described.
4.1 Parameterization of the momentum resolution

The relative momentum resolution, $\sigma(p_T)/p_T$ originates from different effects: the amount of material traversed by the muons, the spatial resolution of the individual track points and the relative internal alignment of the ID [87] [88] and MS [89] [90].

The MS is designed to provide a uniform momentum resolution as a function of $\eta$. The resolution can be parameterized as a function of $p_T$

$$\frac{\sigma(p_T)}{p_T} = \frac{p_{0}^{MS}}{p_T} + p_{1}^{MS} + p_{2}^{MS} \cdot p_T,$$

where $p_{0}^{MS}$ is a coefficient related to the energy loss fluctuations in the calorimeter material, $p_{1}^{MS}$ takes into account the multiple scattering and $p_{2}^{MS}$ is the intrinsic resolution term (chamber alignment and tube resolution).

![Diagram of muon momentum resolution](image)

Figure 4.1. Expected muon momentum resolution [89] of the ATLAS MS as a function of muon $p_T$ (red triangles). All contributions are shown: multiple scattering (black squares), chamber alignments (pink circles), tube resolution and autocalibration (green triangles) and energy loss fluctuations (light blue circles).

Figure 4.1 shows the designed muon momentum resolution of the Muon Spectrometer as a function of muon $p_T$ together with all its contributions: it is evident that the coefficients $p_{0}^{MS}$ and $p_{1}^{MS}$ are...
dominant at low $p_T$, while $p_{\text{MS}}^2$ is dominant at high $p_T$.

In the ID the track length of the muon in the active material, on which the curvature measurement depends, is reduced close to the edge of the TRT fiducial volume. This means that the momentum resolution is uniform up to the TRT coverage, $|\eta| < 1.9$, and it rapidly gets worse beyond this region. The parameterizations as a function of $p_T$ used are:

$$\frac{\sigma(p_T)}{p_T} = p_{\text{ID}}^1 \oplus p_{\text{ID}}^2 \cdot p_T,$$

for $|\eta| < 1.9$, \hfill (4.2)

$$\frac{\sigma(p_T)}{p_T} = p_{\text{ID}}^1 \oplus p_{\text{ID}}^2 \cdot \frac{p_T}{\tan^2 \theta},$$

for $|\eta| > 1.9$, \hfill (4.3)

where $p_{\text{ID}}^1$ is the term taking into account the multiple scattering, $p_{\text{ID}}^2$ is the intrinsic resolution term and $\theta$ is the polar angle. As for the MS case, $p_{\text{ID}}^1$, dominates at low $p_T$, while the $p_{\text{ID}}^2$ term is dominant at high $p_T$.

Since the muon momentum resolution is evaluated using combined muons, the analysis is limited to the ID geometrical acceptance $|\eta| < 2.5$. Within this range in pseudo-rapidity, four main regions are distinguished, as shown in Table 4.1. This choice was made mainly to have sufficient statistics over the pseudo-rapidity range in order to perform the fit procedure also in cases with a smaller number of events (i.e. 2010 analysis). Each region can be then divided into two or more regions, up to a total of 16 regions, and each of these is studied individually using $Z \rightarrow \mu\mu$ decays. This allows to probe for a possible $\eta$ asymmetry in the momentum resolution before combining the results. In the MS, the muon momentum resolution varies also with the azimuthal angle $\phi$, but this variation is neglected and the resolution is integrated over $\phi$.

<table>
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<tr>
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<th>Coverage</th>
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<tr>
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<tr>
<td>Transition</td>
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</tr>
<tr>
<td>End-cap</td>
<td>$1.70 &lt;</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>$2.0 &lt;</td>
</tr>
</tbody>
</table>

Table 4.1. Regions in pseudo-rapidity of the ATLAS detector chosen for the evaluation of the muon momentum resolution.

4.2 Data and Monte Carlo samples

The results presented in this chapter are obtained from the analysis of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV $p-p$ collision data collected by ATLAS with LHC stable beams in 2010, 2011 and 2012 and corresponding to an integrated luminosity of $40 \text{pb}^{-1}$, $4.7 \text{fb}^{-1}$ and $20.4 \text{fb}^{-1}$, respectively.
The online event selection is performed by the trigger system described in Section 2.2.5 and the events are accepted only if the MS and the ID were in good data taking conditions and both solenoidal and toroidal magnet systems were on. Experimental data are compared to Monte Carlo simulations of signal and background processes. The simulated processes are generated with Pythia [89] and Powheg [91], passed through the full Geant4 [92] simulation of the ATLAS detector, the trigger simulation and the same reconstruction chain used for data. For the 2010 and 2011 analyses, the simulation describes the performance of a perfectly calibrated and aligned ATLAS detector, while for the 2012 analysis it includes a realistic evaluation of the misalignments of the MS, obtained by studying straight muon tracks from cosmic ray events [93] and from special runs of data taking performed in conditions with the toroidal magnetic field off [94].

The muon momentum resolution and the correction parameters needed for simulation are evaluated in each \( \eta \) region of the detector using the \( Z \) boson decay into muons (\( Z \rightarrow \mu\mu \)). For the 2010 analysis only, in order to obtain a sample large enough to be able to perform the fit procedure, \( W \) boson decays into muons (\( W \rightarrow \mu\nu \)) are also used. The different background sources include Drell-Yan di-muon production, \( Z \) and \( W \) decays into taus (\( Z \rightarrow \tau\tau \) and \( W \rightarrow \tau\nu \)), \( t\bar{t} \) production process and heavy flavour decays (\( b\bar{b} \) and \( c\bar{c} \)).

In all of the analyses, collision events are selected by requiring at least one reconstructed Primary Vertex (PV) with a position \(|z_{PV}| < 150 \text{ mm}\) with respect to the nominal interaction point and at least 3 ID tracks associated with the PV, each one satisfying the requirement of at least 2 hits in the pixel detector and at least 6 hits in the SCT. In addition, for both data and simulation, each event is required to be triggered by the ATLAS trigger system and muons have to be reconstructed as combined with \( p_T \) exceeding a given trigger threshold. Both muon reconstruction algorithms, “Chain 1” (Staco) and “Chain 2” (Muid), described in Section 3.2.1, are used. Specific requirements for the 2010, 2011 and 2012 analyses are described below:

- **2010 event selection**: a trigger \( p_T \) threshold of 10 GeV is applied to muon candidates to guarantee an unbiased determination of the correction parameters. Each muon track has to satisfy the requirements of at least 2 hits in the pixel detector, at least 6 hits in the SCT and at least 5 hits in the TRT. The muon track is also required to be in the pseudo-rapidity range \(|\eta| < 2.5\).

\( Z \rightarrow \mu\mu \) decays are selected requiring two combined muons, with opposite electric charge. Both muons must satisfy the muon quality requirements and have a transverse momentum \( p_T > 20 \text{ GeV} \). They also have to satisfy a track isolation requirement: a muon is considered isolated if the sum of the transverse momenta of the non-muon tracks in a cone \( \Delta R = 0.4 \) around the muon is less than 20% of the muon \( p_T \) (\( \Sigma p_T/pt < 0.2 \)). Finally the di-muon invariant mass has to be larger than 15 GeV. This selection allows to have a background fraction, estimated using MC simulation, of few percent.
The selection of the $W \rightarrow \mu \nu$ decays has been optimized for the measurement of the $W$-production cross section from leptonic decays \cite{95}, requiring at least an isolated muon with $p_T > 10$ GeV, a missing transverse energy of at least 25 GeV and a reconstructed $W$-boson mass larger than 40 GeV. This selection suppresses the muon background from decays in flight and heavy flavour decays in jets.

- **2011 event selection**: in this case muons and $Z \rightarrow \mu \mu$ decays are selected in the same way as discussed for the 2010 analysis. The only changes consist in the trigger $p_T$ threshold of 18 GeV applied to the muon candidates and the $\Delta R$ definition used to evaluate the muon track isolation: it has been changed from 0.4 to 0.2. $W \rightarrow \mu \nu$ decays are not used.

- **2012 event selection**: in this case muons are selected requiring a trigger $p_T$ threshold of 24 GeV. Each muon track has to satisfy the requirement of at least 1 hit in the pixel detector, at least 5 hits in the SCT and at least 5 hits in the TRT. $Z \rightarrow \mu \mu$ decays are almost selected in the same way as discussed for the 2011 analysis, but with a $p_T$ cut of 25 GeV instead of 20 GeV. In addition, the reconstructed di-muon invariant mass has to be in a window of ±15 GeV around the $Z$-boson mass: this gives a very pure sample where the background fraction, estimated using MC simulation, is of the order of 0.1%. Also in this case $W \rightarrow \mu \nu$ decays are not used.

### 4.3 Combined fit to the muon resolution components

The analysis of the $Z \rightarrow \mu \mu$ decay is sensitive to the momentum resolution through two quantities:

i) the width of the reconstructed di-muon invariant mass peak at the $Z$ pole, which is a convolution of the natural width of the $Z$ boson and the muon momentum resolution;

ii) the difference between the independent momentum measurements of the ID and the MS for combined muons, which is sensitive to the quadratic sum of the ID and the MS momentum resolutions. This difference is signed by the muon electric charge, $(q/p_T^{ID} - q/p_T^{MS})$, which disentangles systematic effects of the curvature due to local misalignments from the overall intrinsic resolution, reducing the bias on the estimation of the resolution and correction parameters.

These quantities are used in a combined fit procedure, described in Section 4.3.3, in order to determine the overall resolution from the data. Once the resolution parameters are measured, correction parameters are provided for the simulated muon $p_T$ to reproduce the data: these corrections are needed in order to accurately measure analysis-level quantities based on the muon $p_T$.

Before going into details of the technique to parameterize the quantities with a single resolution function for each tracking system, the individual input quantities to the fit will be explained.
4.3. COMBINED FIT TO THE MUON RESOLUTION COMPONENTS

4.3.1 Di-muon invariant mass distribution at the Z pole

The di-muon invariant-mass distribution at the Z pole can also be used to study the resolution contribution to the relative invariant-mass width. It is done as a function of the pseudo-rapidity interval of the decay muons, which both are required to lie in the same interval. The di-muon invariant-mass distributions are obtained separately from ID and MS track parameters and then fitted by using a convolution of the Z lineshape and two Gaussian functions modelling the detector resolution effects. The Z lineshape, including the Z boson natural width, a photon radiation and the interference term [96], is given by the formula

\[ f(x) = A \left( \frac{1}{x^2} \right) + B \left( \frac{x^2 - \bar{x}^2}{(x^2 - \bar{x}^2)^2 + \Gamma_Z^2 \bar{x}^2} \right) + C \left( \frac{x^2}{(x^2 - \bar{x}^2)^2 + \Gamma_Z^2 \bar{x}^2} \right), \]

where \( x \) represents the di-muon invariant mass \( M_{\mu\mu} \), \( \Gamma_Z \) is the width of the Z boson fixed to its world average value \( \Gamma_Z = 2.4952 \text{ GeV} \) [97], the coefficients A, B and C are fixed and determined from the invariant mass of the muon pair at the particle level before detector simulation, and \( \bar{x} \) is a free parameter of the fit.

The detector effects are modelled by a double Gaussian function: a narrow Gaussian describing the core momentum resolution and a broad Gaussian describing the tails (energy loss effects). These two Gaussian functions have a common mean value, \( \mu \), fixed to 0: the muon momentum scale is assumed to be correct and any scale correction is determined only after applying the muon resolution corrections. The value for \( \sigma \) of the broader Gaussian is fixed to twice the value for the narrow one, in order to correctly describe the tails. In addition, while the full fit range is from 60 GeV to 120 GeV, the core Gaussian in constrained to contain 85% of the di-muon pairs: this corresponds to the fraction of muons contained within the core Gaussian in the simulation, where the fit was applied without constraint. The ratio of di-muon pairs contained in the core Gaussian was found to be correct also in the data. In this way, the measured lineshape will be

\[ f_M(x) = N(x) \otimes \left[ \frac{0.85}{\sqrt{2\pi}\sigma^2} \cdot e^{-\frac{x^2}{2\sigma^2}} + \frac{0.15}{\sqrt{2\pi}(2\sigma)^2} \cdot e^{-\frac{x^2}{2(2\sigma)^2}} \right], \]

where \( \sigma \) represents the mass resolution.

Figure 4.2 shows the di-muon invariant mass resolution at the Z pole for ID tracks as a function of the pseudo-rapidity interval of the decay muons, obtained using the “Chain 1” (a) and “Chain 2” (b) algorithms and 40 pb\(^{-1}\) of 2010 collision data. For both reconstruction algorithms, the ID mass resolution is best in the barrel region, around 2 GeV, then just below 3 GeV for \( |\eta| < 2.0 \) and it degrades to about 6 GeV for \( |\eta| > 2.0 \). The degradation of the resolution with increasing of \( \eta \) is caused by the fact that as \( \eta \) increases there are fewer hits and a lower field integral per track. The resolution measured in data is worse than the predicted one because of the residual internal misalignment of the ID.
CHAPTER 4. MUON MOMENTUM RESOLUTION OF THE ATLAS DETECTOR

Figure 4.2. ID di-muon invariant mass resolution in $Z \rightarrow \mu\mu$ decays for data (black points) and simulation (red points) in 2010 analysis for “Chain 1” (a) and “Chain 2” (b) algorithms.

Figure 4.3. MS di-muon invariant mass resolution in $Z \rightarrow \mu\mu$ decays for data (black points) and simulation (red points) in 2010 analysis for “Chain 1” (a) and “Chain 2” (b) algorithms.

Figure 4.3 shows the di-muon invariant mass resolution at the $Z$ pole for MS tracks, obtained using the “Chain 1” (a) and “Chain 2” (b) algorithms and $40 \text{pb}^{-1}$ of 2010 collision data. For both
4.3. COMBINED FIT TO THE MUON RESOLUTION COMPONENTS

algorithms, the MS mass resolution is worse in data than in simulation for two reasons:

i) an asymmetry of the magnetic field integrals: in the simulation a perfect alignment is assumed, but the positions of the two end-cap toroid system are not symmetric with respect to the plane orthogonal to the major axis of the ID;

ii) residual internal misalignments of the MS.

The best MS mass resolution is achieved in the barrel region at about 3 GeV. Comparing the ID and MS mass resolution obtained for the two algorithms, small differences can be observed. These differences arise from the different way of combining tracks used by the two reconstruction algorithms (see Section 3.2.1). In general, when selecting di-muon pairs, it can happen that the two algorithms do not select the same combined muons: for this reason small differences for the two algorithms are observed.

Figure 4.4 shows the di-muon invariant mass resolution at the $Z$ pole as a function of the $\eta$ obtained using combined muons in the “Chain 1” (a) and “Chain 2” (b) algorithms and 40 pb$^{-1}$ of 2010 collision data. In this case the mass resolution is between 1.4 GeV and 2.5 GeV, almost independent of $\eta$. In some detector regions, the different way of combining tracks used by the two algorithms is reflected in the CB invariant mass resolution.

(a) CB mass resolution: “Chain 1”

(b) CB mass resolution: “Chain 2”

**Figure 4.4.** CB di-muon invariant mass resolution in $Z \rightarrow \mu\mu$ decays for data (black points) and simulation (red points) in 2010 analysis for “Chain 1” (a) and “Chain 2” (b) algorithms.

In the 2011 analysis, similar results are obtained. The MS, ID and CB di-muon invariant mass resolution as a function of $\eta$ are shown in Figures 4.5, 4.6 and 4.7 respectively, for both algorithms.
CHAPTER 4. MUON MOMENTUM RESOLUTION OF THE ATLAS DETECTOR

using 4.7 fb$^{-1}$ of 2011 collision data. In this case the ID mass resolution, for both algorithms, is

\begin{align*}
\begin{array}{c}
\eta \in [-2.5, 2.5) \\
\eta \in [-1.7, -1.05) \\
\eta \in [-1.05, 1.05) \\
\eta \in [1.05, 1.7) \\
\eta \in [1.7, 2.0) \\
\eta \in [2.0, 2.5)
\end{array}
\end{align*}

\[
\text{Z resolution at } m_{\mu \mu} = 7 \text{ TeVs}
\]

**Figure 4.5.** ID di-muon invariant mass resolution in $Z \rightarrow \mu\mu$ decays for data (black points) and simulation (red points) in 2011 analysis for “Chain 1” (a) and “Chain 2” (b) algorithms.

\begin{align*}
\begin{array}{c}
\eta \in [-2.5, 2.5) \\
\eta \in [-1.7, -1.05) \\
\eta \in [-1.05, 1.05) \\
\eta \in [1.05, 1.7) \\
\eta \in [1.7, 2.0) \\
\eta \in [2.0, 2.5)
\end{array}
\end{align*}

\[
\text{Z resolution at } m_{\mu \mu} = 7 \text{ TeVs}
\]

**Figure 4.6.** MS di-muon invariant mass resolution in $Z \rightarrow \mu\mu$ decays for data (black points) and simulation (red points) in 2011 analysis for “Chain 1” (a) and “Chain 2” (b) algorithms.
4.3. COMBINED FIT TO THE MUON RESOLUTION COMPONENTS

Best in the barrel region, about 2 GeV, and then deteriorating with increasing of $\eta$ up to 6 GeV. The MS mass resolution is instead improved in all the $\eta$ regions with respect to the 2010 analysis due to a better alignment of the Muon Spectrometer. Concerning the CB mass resolution, results obtained are compatible with those achieved in the 2010 analysis: the mass resolution is almost independent of $\eta$ and the best value is achieved in the barrel region at about 1.4 GeV.

Figure 4.7. CB di-muon invariant mass resolution in $Z \rightarrow \mu\mu$ decays for data (black points) and simulation (red points) in 2011 analysis for “Chain 1” (a) and “Chain 2” (b) algorithms.

Figure 4.8. CB di-muon invariant mass resolution in $Z \rightarrow \mu\mu$ decays for data (black points) and simulation (red points) in 2012 analysis for “Chain 1” algorithm.
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Figure 4.8 shows the CB di-muon invariant mass resolution as a function of $\eta$ for “Chain 1” algorithm using 20.4 TeV$^{-1}$ of 2012 collision data. In this case, the simulation includes a realistic alignment of the detectors and the mass resolution is studied in 16 detector regions. It ranges from 1.5 GeV to 3 GeV.

4.3.2 Difference between momentum measurements of the ID and the MS

The ATLAS detector is able to reconstruct muons in both the ID and the MS. This redundancy in the ATLAS tracking system can also be used to measure the muon momentum resolution, by comparing the independent momentum measurements of the muons. The difference between the two measurements is defined as

$$\rho = \frac{q}{p_{T}^{\text{ID}}} - \frac{q}{p_{T}^{\text{MS}}},$$

where $p_{T}^{\text{ID}}$ and $p_{T}^{\text{MS}}$ denote the momentum measurement in the ID and the MS, respectively, and $q$ is the muon electric charge. This quantity, sensitive to the quadratic sum of the ID and the MS momentum resolutions, is dominated by the ID or MS contribution, depending on the muon $p_{T}$: the ID contribution dominates the combination at lower $p_{T}$, while the MS contribution dominates at higher $p_{T}$.

The resolution as a function of the muon $p_{T}$ and $\eta$ is then extracted fitting the $\rho$ distribution with a normal distribution, in a range of $\pm$ 1 r.m.s from the mean of the data distribution. The fitting procedure is performed in various $p_{T}$ bins: six for the 2010 analysis and eight for both the 2011 and 2012 analyses. Their definition is reported in Table 4.2 for the 2010 analysis and in Table 4.3 for the 2011 and 2012 analyses.

<table>
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**Table 4.2.** $p_{T}$ bins definition for 2010 analysis.

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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.3.** $p_{T}$ bins definition for 2011 and 2012 analyses.
4.3. COMBINED FIT TO THE MUON RESOLUTION COMPONENTS

4.3.3 Global fit technique

The measurements of the MS and the ID momentum resolution are obtained using a Monte Carlo template technique, based on an iterative “global” fit procedure \[98\] \[99\] \[100\] \[101\]. Performing the fit, the muon momentum smearing is allowed in the simulation, for both the ID and the MS, in order to reproduce the data. At the first iteration, the corrections to the resolution parameters $\Delta p_{\text{ID,MS}}^i$ are set to their initial values. Then, in a $\chi^2$ minimization fit, their final values are obtained rescaling in any iteration the simulated muon $p_T$ with the corrections values obtained in the previous iteration. The transformation of the muon $p_T$ is defined as:

$$p'_T = p_T \left( 1 + g \Delta p_{\text{ID,MS}}^1 + g \Delta p_{\text{ID,MS}}^2 p_T \right),$$

(4.7)

where $p'_T$ indicates the simulated muon $p_T$ after applying the corrections $\Delta p_{\text{ID,MS}}^i$ and $g$ is a normally distributed random number with mean 0 and width 1.

The “global” fit is built up using:

i) a template fit to the reconstructed $Z$ lineshape:
   at this stage, a momentum resolution smearing is allowed in the fit to the $Z$ lineshape obtained from the MS and ID tracks. The $Z$ lineshape distributions of the MS and ID are fit separately. This template is able to perform the fit either using only a single detector region or using two detector regions simultaneously. The first case results into two $Z$ lineshape distributions, one for the ID and one for the MS, where both muons lie in the same pseudo-rapidity interval. The second case gives six $Z$ lineshape distributions, three for each tracking system: both muons coming from the first region; both muons coming from the second region; one muon coming from the first region and the other from the second.
   This template fit is mainly sensitive to the quadratic sum of the multiple scattering and the intrinsic alignment resolution terms, $\sigma_{\text{mult.scatt.}} \oplus \sigma_{\text{intrinsic}}$.

ii) the above, plus a template fit to the $(q/p_T^\text{ID} - q/p_T^\text{MS})$ distribution:
   also in this case, the momentum resolution smearing is allowed in the fit. The fit is done in various $p_T$ bins, see Section 4.3.2, and the total number of distributions corresponds to the number of bins. As in the previous case, the template fit can be performed either using only one detector region or using two regions simultaneously; when using two regions, these are kept separate and the total number of distributions is two times the number of the bins. This template fit is also sensitive to the quadratic sum of the ID and MS resolutions, $\sigma_{\text{ID}} \oplus \sigma_{\text{MS}}$.

iii) external constraints on MS alignment and multiple scattering in ID and MS:
   they consist of additional knowledge introduced to take into account additional independent studies, both for the ID and the MS \[93\] \[94\]. This reduces the correlation among the multiple scattering and the detector resolution terms in the fit, resulting in smaller uncertainties on the fitted parameters. Details are described in Section 4.3.4.
The muon momentum corrections are derived for each region following an iterative procedure: first the $p_T$ of single muons and the pair of muons from the $Z$ boson decay in the barrel region are corrected; then the additional corrections are extracted for events in which one of the two muons or both fall in the other regions, $|\eta| > 1.05$. This means that corrections are derived for the barrel region first and then for the other regions, keeping those of the barrel region fixed.

4.3.4 External constraints to the combined fit

The additional knowledge of the performance of the two tracking systems is applied differently depending on the year of data taking. This information is translated into constraints applied to the fit parameters: in some cases one or more fit parameters are fixed to 0, reducing the number of free parameters of the fit.

For the MS, the energy loss of muons is mainly concentrated in the calorimeter and has been well measured with commissioning studies [93] on a large sample of cosmic ray events. Its contribution to the overall MS resolution in the $p_T$ range from 20 GeV to 100 GeV is negligible: no additional contribution for the energy loss, $\Delta p_0^{MS}$, is included, as shown by equation [4.7]. The correction to the multiple scattering term, $\Delta p_1^{MS}$, is always a free parameter of the fit and no constraints are applied. For the correction to the intrinsic resolution term, $\Delta p_2^{MS}$, alignment constraints are applied in the 2010 and 2011 analyses. These constraints are derived by the best estimate of the alignment accuracy, studied with samples of straight tracks obtained with cosmic rays and in data taken with no magnetic field in the muon system [93] [94]. The estimated alignment accuracy for the 2010 and 2011 analyses is shown in Table 4.4.

<table>
<thead>
<tr>
<th>$\eta$ region</th>
<th>Alignment accuracy [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Barrel</td>
<td>100 ± 20</td>
</tr>
<tr>
<td>Transition</td>
<td>160 ± 30</td>
</tr>
<tr>
<td>End-cap</td>
<td>100 ± 30</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>200 ± 30</td>
</tr>
</tbody>
</table>

Table 4.4. Alignment accuracy for 2010 and 2011 analyses.

This information can be translated into a constraint on the correction to the intrinsic resolution term using the formula of the track sagitta

$$\Delta s[\mu m] \propto \frac{0.3}{8} B[T] L[m]^2 \Delta p_2^{MS}[TeV^{-1}] \times 10^3,$$

(4.8)

where $\Delta s$ is the difference in sagitta from a correction $\Delta p_2^{MS}$ in a magnetic field of intensity $B$ given a track length $L$. The uncertainty on $\Delta p_2^{MS}$ is propagated directly from the uncertainty on
the alignment accuracy using the above formula. The resulting constraints for the 2010 and 2011 analyses are summarized in Table 4.5. In the 2012 analysis the correction to the intrinsic resolution term is instead fixed to 0 since the simulation includes a realistic evaluation of the misalignments of the MS.

<table>
<thead>
<tr>
<th>η region</th>
<th>Constraint on $\Delta p_{2}^{\text{MS}}$ [TeV$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Barrel</td>
<td>0.143 ± 0.030</td>
</tr>
<tr>
<td>Transition</td>
<td>0.312 ± 0.050</td>
</tr>
<tr>
<td>End-cap</td>
<td>0.200 ± 0.050</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>0.408 ± 0.050</td>
</tr>
</tbody>
</table>

Table 4.5. Constraints on the intrinsic resolution term, $\Delta p_{2}^{\text{MS}}$, applied for 2010 and 2011 analyses.

For the ID, in the 2010 analysis, the correction to the multiple scattering term, $\Delta p_{1}^{\text{ID}}$, is constrained around an expected value of zero, using the uncertainty on the ID material budget. The amount of material is probed by the results on the $K_{S}^{0}$ reconstructed mass [102], the $J/\psi$ width measurement [103] and the resolution on the transverse impact parameter for low $p_{T}$ tracks [104]. This information is then transformed in a 5% uncertainty on the multiple scattering correction term for $|\eta| < 2.0$ and 10% for $|\eta| > 2.0$. For the 2011 and 2012 analyses, the correction to the multiple scattering term is fixed at 0 due to the precise knowledge of the ID material budget to a level of 0.05% [105]. The correction to the intrinsic resolution term, $\Delta p_{2}^{\text{ID}}$, is always a free parameter of the fit and no constraints are applied.

## 4.4 Combined fit results

The constraints on the $\Delta p_{i}$ parameters are applied in the combined fit by adding a penalty term $\sum_{i} \left( \frac{\Delta p_{i} - a_{i}}{\sigma a_{i}} \right)^{2}$ to the total $\chi^{2}$ being minimized, where $a_{i}$ is the expectation value and $\sigma a_{i}$ the associated uncertainty for each of the constrained $\Delta p_{i}$ parameters.

The fitted corrections parameters are provided in Tables 4.6, 4.7 and 4.8 together with their statistical and systematic uncertainties. Results for both reconstruction algorithms are reported. For the $\Delta p_{2}^{\text{ID}}$ parameter, Equation 4.3 is used in any CSC/No-TRT region, while in all other regions Equation 4.2 is used.

The results of the resolution fit are tested by constraining the multiple scattering contribution to the expectation from the material budget in the ID. This effect is evaluated by performing the fit for the other three parameters after fixing $\Delta p_{1}^{\text{ID}}$ to a value increased by 5% (10%), for $|\eta| < 2.0$ ($|\eta| > 2.0$), with respect to the one obtained in the previous fit. The systematic uncertainty on the other corrections is taken as the difference of each fitted value with respect to the baseline case.
CHAPTER 4. MUON MOMENTUM RESOLUTION OF THE ATLAS DETECTOR

Table 4.6. Values of the corrections to the $p_T$ parameterization of the simulated resolution in the MS and ID to reproduce the one in data for the 2010 analysis. The first uncertainty is statistical, the second one is the quadratic sum of all systematic uncertainties.

<table>
<thead>
<tr>
<th>$\eta$ region</th>
<th>$\Delta p_1^{MS}$ (%)</th>
<th>$\Delta p_2^{MS}$ (TeV$^{-1}$)</th>
<th>$\Delta p_1^{ID}$ (%)</th>
<th>$\Delta p_2^{ID}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>2.99 ± 0.06 ± 0.07</td>
<td>0.165 ± 0.017 ± 0.003</td>
<td>2.05 ± 0.04 ± 0.06</td>
<td>0.148 ± 0.015 ± 0.009</td>
</tr>
<tr>
<td>Transition</td>
<td>8.74 ± 0.19 ± 0.09</td>
<td>0.315 ± 0.069 ± 0.014</td>
<td>4.96 ± 0.25 ± 0.68</td>
<td>0.327 ± 0.052 ± 0.066</td>
</tr>
<tr>
<td>End-cap</td>
<td>3.44 ± 0.31 ± 0.02</td>
<td>0.178 ± 0.078 ± 0.004</td>
<td>3.18 ± 0.16 ± 0.09</td>
<td>0.191 ± 0.043 ± 0.008</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>2.92 ± 0.38 ± 0.02</td>
<td>0.407 ± 0.041 ± 0.019</td>
<td>2.78 ± 0.49 ± 0.36</td>
<td>0.437 ± 0.053 ± 0.014</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\eta$ region</th>
<th>$\Delta p_1^{ID}$ (%)</th>
<th>$\Delta p_2^{ID}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.16 ± 0.37</td>
<td>0.216 ± 0.048 ± 0.018</td>
</tr>
<tr>
<td>Transition</td>
<td>1.36 ± 0.38 ± 0.68</td>
<td>0.593 ± 0.054 ± 0.130</td>
</tr>
<tr>
<td>End-cap</td>
<td>0.64 ± 0.54</td>
<td>0.684 ± 0.072 ± 0.084</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>0.50 ± 0.79</td>
<td>0.063 ± 0.003 ± 0.002</td>
</tr>
</tbody>
</table>

Table 4.7. Values of the corrections to the $p_T$ parameterization of the simulated resolution in the MS and ID to reproduce the one in data for the 2011 analysis. The first uncertainty is statistical, the second one is the systematic uncertainty. Apart from the barrel region, the others are divided in two sub-regions for negative (top) and positive (bottom) $\eta$.

<table>
<thead>
<tr>
<th>$\eta$ region</th>
<th>$\Delta p_1^{MS}$ (%)</th>
<th>$\Delta p_2^{MS}$ (TeV$^{-1}$)</th>
<th>$\Delta p_1^{ID}$ (%)</th>
<th>$\Delta p_2^{ID}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>1.83 ± 0.21 ± 0.08</td>
<td>0.150 ± 0.073 ± 0.065</td>
<td>2.36 ± 0.12 ± 0.06</td>
<td>0.135 ± 0.019 ± 0.058</td>
</tr>
<tr>
<td>Transition</td>
<td>5.19 ± 0.36 ± 0.07</td>
<td>0.335 ± 0.095 ± 0.087</td>
<td>5.83 ± 0.27 ± 0.05</td>
<td>0.342 ± 0.080 ± 0.078</td>
</tr>
<tr>
<td>End-cap</td>
<td>4.86 ± 0.24 ± 0.10</td>
<td>0.341 ± 0.072 ± 0.065</td>
<td>5.63 ± 0.23 ± 0.09</td>
<td>0.369 ± 0.093 ± 0.076</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>2.97 ± 0.25 ± 0.14</td>
<td>0.183 ± 0.064 ± 0.062</td>
<td>4.06 ± 0.20 ± 0.06</td>
<td>0.194 ± 0.076 ± 0.054</td>
</tr>
<tr>
<td></td>
<td>2.90 ± 0.35 ± 0.12</td>
<td>0.203 ± 0.069 ± 0.071</td>
<td>3.96 ± 0.12 ± 0.09</td>
<td>0.137 ± 0.096 ± 0.069</td>
</tr>
<tr>
<td></td>
<td>2.47 ± 0.18 ± 0.18</td>
<td>0.107 ± 0.026 ± 0.021</td>
<td>2.60 ± 0.32 ± 0.11</td>
<td>0.208 ± 0.061 ± 0.029</td>
</tr>
<tr>
<td></td>
<td>1.87 ± 0.51 ± 0.13</td>
<td>0.156 ± 0.076 ± 0.065</td>
<td>2.07 ± 0.26 ± 0.09</td>
<td>0.167 ± 0.064 ± 0.055</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\eta$ region</th>
<th>$\Delta p_1^{ID}$ (%)</th>
<th>$\Delta p_2^{ID}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0</td>
<td>0.220 ± 0.018 ± 0.021</td>
</tr>
<tr>
<td>Transition</td>
<td>0</td>
<td>0.080 ± 0.013 ± 0.012</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.352 ± 0.042 ± 0.019</td>
</tr>
<tr>
<td>End-cap</td>
<td>0</td>
<td>0.426 ± 0.032 ± 0.021</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.500 ± 0.025 ± 0.015</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>0</td>
<td>0.019 ± 0.005 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.028 ± 0.003 ± 0.004</td>
</tr>
</tbody>
</table>

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4.4. COMBINED FIT RESULTS

<table>
<thead>
<tr>
<th>η region</th>
<th>Chain 1</th>
<th></th>
<th>Chain 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Δp1 MS (%)</td>
<td>Δp2 MS (TeV⁻¹)</td>
<td></td>
</tr>
<tr>
<td><strong>Barrel</strong></td>
<td></td>
<td>0.34 ± 0.07 ± 0.25</td>
<td>0</td>
<td>1.10 ± 0.05 ± 0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30 ± 0.06 ± 0.09</td>
<td>0</td>
<td>0.78 ± 0.05 ± 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.98 ± 0.05 ± 0.09</td>
<td>0</td>
<td>1.13 ± 0.03 ± 0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.03 ± 0.03 ± 0.09</td>
<td>0</td>
<td>1.26 ± 0.03 ± 0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.11 ± 0.08 ± 0.47</td>
<td>0</td>
<td>1.00 ± 0.04 ± 0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.52 ± 0.07 ± 0.08</td>
<td>0</td>
<td>1.11 ± 0.05 ± 0.06</td>
</tr>
<tr>
<td><strong>Transition</strong></td>
<td></td>
<td>2.07 ± 0.06 ± 0.06</td>
<td>0</td>
<td>2.56 ± 0.03 ± 0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.35 ± 0.05 ± 0.09</td>
<td>0</td>
<td>1.73 ± 0.06 ± 0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.83 ± 0.08 ± 0.12</td>
<td>0</td>
<td>1.62 ± 0.04 ± 0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.15 ± 0.05 ± 0.15</td>
<td>0</td>
<td>2.37 ± 0.03 ± 0.08</td>
</tr>
<tr>
<td><strong>End-cap</strong></td>
<td></td>
<td>1.64 ± 0.03 ± 0.15</td>
<td>0</td>
<td>1.64 ± 0.03 ± 0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.53 ± 0.03 ± 0.09</td>
<td>0</td>
<td>1.69 ± 0.03 ± 0.05</td>
</tr>
<tr>
<td><strong>CSC/No-TRT</strong></td>
<td></td>
<td>1.58 ± 0.05 ± 0.15</td>
<td>0</td>
<td>1.62 ± 0.03 ± 0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.57 ± 0.06 ± 0.12</td>
<td>0</td>
<td>1.63 ± 0.04 ± 0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.45 ± 0.03 ± 0.14</td>
<td>0</td>
<td>1.55 ± 0.03 ± 0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.22 ± 0.07 ± 0.19</td>
<td>0</td>
<td>1.32 ± 0.04 ± 0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>η region</th>
<th>Chain 1</th>
<th></th>
<th>Chain 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Δp1 ID (%)</td>
<td>Δp2 ID (TeV⁻¹)</td>
<td></td>
</tr>
<tr>
<td><strong>Barrel</strong></td>
<td></td>
<td>0.248 ± 0.008 ± 0.040</td>
<td>0</td>
<td>0.234 ± 0.008 ± 0.021</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.206 ± 0.007 ± 0.017</td>
<td>0</td>
<td>0.204 ± 0.006 ± 0.012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.228 ± 0.006 ± 0.011</td>
<td>0</td>
<td>0.237 ± 0.007 ± 0.018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.208 ± 0.006 ± 0.015</td>
<td>0</td>
<td>0.220 ± 0.006 ± 0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.203 ± 0.008 ± 0.014</td>
<td>0</td>
<td>0.215 ± 0.008 ± 0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.237 ± 0.006 ± 0.003</td>
<td>0</td>
<td>0.233 ± 0.007 ± 0.015</td>
</tr>
<tr>
<td><strong>Transition</strong></td>
<td></td>
<td>0.310 ± 0.007 ± 0.020</td>
<td>0</td>
<td>0.293 ± 0.007 ± 0.008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.275 ± 0.007 ± 0.014</td>
<td>0</td>
<td>0.278 ± 0.007 ± 0.018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.269 ± 0.011 ± 0.007</td>
<td>0</td>
<td>0.283 ± 0.004 ± 0.026</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.283 ± 0.012 ± 0.019</td>
<td>0</td>
<td>0.300 ± 0.007 ± 0.033</td>
</tr>
<tr>
<td><strong>End-cap</strong></td>
<td></td>
<td>0.339 ± 0.005 ± 0.027</td>
<td>0</td>
<td>0.339 ± 0.009 ± 0.015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.378 ± 0.006 ± 0.008</td>
<td>0</td>
<td>0.371 ± 0.006 ± 0.021</td>
</tr>
<tr>
<td><strong>CSC/No-TRT</strong></td>
<td></td>
<td>0.007 ± 0.001 ± 0.008</td>
<td>0</td>
<td>0.006 ± 0.001 ± 0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.028 ± 0.001 ± 0.004</td>
<td>0</td>
<td>0.029 ± 0.002 ± 0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.031 ± 0.001 ± 0.005</td>
<td>0</td>
<td>0.028 ± 0.001 ± 0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.005 ± 0.001 ± 0.003</td>
<td>0</td>
<td>0.006 ± 0.001 ± 0.002</td>
</tr>
</tbody>
</table>

Table 4.8. Values of the corrections to the p_T parameterization of the simulated resolution in the MS and ID to reproduce the one in data for the 2012 analysis. The first uncertainty is statistical, the second one is the systematic uncertainty. Each region is divided in many sub-regions; from the top to the bottom there are six barrel regions (η=[-1.05,-0.8],[-0.8,-0.4],[-0.4,0.0],[0.0,0.4],[0.4,0.8],[0.8,1.05]), four transition regions (η=[-1.7,-1.5],[-1.5,-1.05],[1.05,1.5],[1.5,1.7]), two end-cap regions (η=[-2.0,-1.7],[1.7,2.0]) and four CSC/No-TRT regions (η=[-2.5,-2.25],[-2.25,-2.0],[2.0,2.25],[2.25,2.5]).
For the 2010 analysis an additional source of systematic uncertainty is used. In the transition region some chambers in the MS were known to be less well aligned than others. About 30% of the muons are in the region where the mis-aligned chambers are, $1.05 < |\eta| < 1.2$. To assess the correctness of the alignment accuracy assumed for the whole region, all muons in the range $1.05 < |\eta| < 1.2$ are removed and the fit is repeated. The systematic uncertainty for all the corrections is taken as the difference of each fitted value with respect to the baseline case.

As discussed in Section 4.3.4, for the 2011 analysis the $\Delta p_{1}^{ID}$ correction parameter is fixed to zero, while for the 2012 analysis $\Delta p_{1}^{ID}$ and $\Delta p_{2}^{MS}$ are fixed to zero.

The values of the correction parameters quantify the increase in momentum resolution in data when compared to the simulation: the smaller the corrections are, the closer to the expectation the resolution is. In the analyses, it is evident that the smallest values for the correction parameters are obtained in the barrel regions, while with the increase of $\eta$ the values of the corrections are larger and the overall resolution becomes worse with respect to the barrel regions. The values of the corrections for the 2012 analysis are smaller since the simulation includes a realistic evaluation of the misalignments of the MS, while in the 2010 and 2011 analyses the simulation describes the performance of a perfectly aligned detector.

The full parameterization of the experimental momentum resolution is obtained by adding quadratically the uncorrected simulated resolution terms, derived on the simulation using the parameterization functions defined in Equations 4.1, 4.2 and 4.3, and the corresponding corrections from Tables 4.6, 4.7 and 4.8. The results for the full parameterization are reported in Tables 4.9, 4.10 and 4.11. The parameterization is reported for each region of the detector for both reconstruction algorithms. Looking at the resolution parameters in the tables, it is evident that both the reconstruction algorithms, “Chain 1” and “Chain 2”, show similar performance.

<table>
<thead>
<tr>
<th>$\eta$ region</th>
<th>$p_{0}^{MS}$ (TeV)</th>
<th>$p_{1}^{MS}$ (%)</th>
<th>$p_{2}^{MS}$ (TeV$^{-1}$)</th>
<th>$p_{0}^{ID}$† (TeV)</th>
<th>$p_{1}^{ID}$ (%)</th>
<th>$p_{2}^{ID}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.17 ± 0.01</td>
<td>3.98 ± 0.10</td>
<td>0.195 ± 0.018</td>
<td>0.26 ± 0.01</td>
<td>3.53 ± 0.09</td>
<td>0.222 ± 0.030</td>
</tr>
<tr>
<td>Transition</td>
<td>0</td>
<td>8.78 ± 0.92</td>
<td>0.366 ± 0.108</td>
<td>0</td>
<td>8.39 ± 0.59</td>
<td>0.277 ± 0.128</td>
</tr>
<tr>
<td>End-cap</td>
<td>0</td>
<td>4.78 ± 0.35</td>
<td>0.198 ± 0.147</td>
<td>0</td>
<td>5.27 ± 0.34</td>
<td>0.143 ± 0.140</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>0</td>
<td>4.09 ± 0.43</td>
<td>0.413 ± 0.170</td>
<td>0</td>
<td>3.60 ± 1.17</td>
<td>0.675 ± 0.190</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>$\eta$ region</th>
<th>$p_{0}^{ID}$† (TeV)</th>
<th>$p_{1}^{ID}$ (%)</th>
<th>$p_{2}^{ID}$ (TeV$^{-1}$)</th>
<th>$p_{0}^{ID}$† (TeV)</th>
<th>$p_{1}^{ID}$ (%)</th>
<th>$p_{2}^{ID}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>n.a</td>
<td>1.56 ± 0.38</td>
<td>0.375 ± 0.052</td>
<td>n.a</td>
<td>1.55 ± 0.37</td>
<td>0.396 ± 0.040</td>
</tr>
<tr>
<td>Transition</td>
<td>n.a</td>
<td>2.91 ± 0.96</td>
<td>0.673 ± 0.141</td>
<td>n.a</td>
<td>2.53 ± 0.64</td>
<td>0.625 ± 0.189</td>
</tr>
<tr>
<td>End-cap</td>
<td>n.a</td>
<td>3.37 ± 0.54</td>
<td>1.070 ± 0.111</td>
<td>n.a</td>
<td>3.39 ± 0.57</td>
<td>0.925 ± 0.161</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>n.a</td>
<td>4.70 ± 0.82</td>
<td>0.081 ± 0.005</td>
<td>n.a</td>
<td>4.62 ± 0.71</td>
<td>0.078 ± 0.008</td>
</tr>
</tbody>
</table>

Table 4.9. Resolution parameterization in the MS and ID for the 2010 analysis. † n.a is used to indicate that for the ID no energy loss term is present.
4.5. MEASURED RESOLUTION AS A FUNCTION OF $p_T$

The parameterized resolution as a function of $p_T$ for each detector region is obtained using the values of the parameters reported in Tables 4.9, 4.10 and 4.11. Figures 4.9 and 4.10 show the MS and the ID muon resolution curves, respectively, for the barrel region, obtained for 2010 (a), 2011 (b) and 2012 (c) analyses. The former show results using the “Chain 1” algorithm, the latter results obtained with “Chain 2” algorithm.

Table 4.10. Resolution parameterization in the MS and ID for the 2011 analysis. † n.a is used to indicate that for the ID no energy loss term is present.

<table>
<thead>
<tr>
<th>η region</th>
<th>$p_0^{\text{MS}}$ (TeV)</th>
<th>$p_1^{\text{MS}}$ (%)</th>
<th>$p_2^{\text{MS}}$ (TeV$^{-1}$)</th>
<th>$p_0^{\text{ID}}$ † (TeV)</th>
<th>$p_1^{\text{ID}}$ (%)</th>
<th>$p_2^{\text{ID}}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.12 ± 0.01</td>
<td>3.43 ± 0.17</td>
<td>0.182 ± 0.053</td>
<td>0.24 ± 0.01</td>
<td>3.31 ± 0.12</td>
<td>0.144 ± 0.019</td>
</tr>
<tr>
<td>Transition</td>
<td>0</td>
<td>6.84 ± 1.60</td>
<td>0.381 ± 0.165</td>
<td>0</td>
<td>6.01 ± 0.26</td>
<td>0.510 ± 0.114</td>
</tr>
<tr>
<td>End-cap</td>
<td>0</td>
<td>4.45 ± 0.13</td>
<td>0.211 ± 0.076</td>
<td>0</td>
<td>4.24 ± 0.12</td>
<td>0.216 ± 0.076</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>0</td>
<td>3.66 ± 0.43</td>
<td>0.153 ± 0.064</td>
<td>0</td>
<td>3.20 ± 0.26</td>
<td>0.159 ± 0.061</td>
</tr>
</tbody>
</table>

Table 4.11. Resolution parameterization in the MS and ID for the 2012 analysis. † n.a is used to indicate that for the ID no energy loss term is present.

<table>
<thead>
<tr>
<th>η region</th>
<th>$p_0^{\text{MS}}$ (TeV)</th>
<th>$p_1^{\text{MS}}$ (%)</th>
<th>$p_2^{\text{MS}}$ (TeV$^{-1}$)</th>
<th>$p_0^{\text{ID}}$ † (TeV)</th>
<th>$p_1^{\text{ID}}$ (%)</th>
<th>$p_2^{\text{ID}}$ (TeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>n.a</td>
<td>1.62 ± 0.01</td>
<td>0.372 ± 0.048</td>
<td>n.a</td>
<td>1.61 ± 0.01</td>
<td>0.363 ± 0.040</td>
</tr>
<tr>
<td>Transition</td>
<td>n.a</td>
<td>2.60 ± 0.01</td>
<td>0.388 ± 0.069</td>
<td>n.a</td>
<td>2.59 ± 0.01</td>
<td>0.412 ± 0.069</td>
</tr>
<tr>
<td>End-cap</td>
<td>n.a</td>
<td>3.36 ± 0.02</td>
<td>0.653 ± 0.052</td>
<td>n.a</td>
<td>3.39 ± 0.02</td>
<td>0.662 ± 0.039</td>
</tr>
<tr>
<td>CSC/No-TRT</td>
<td>n.a</td>
<td>4.64 ± 0.21</td>
<td>0.056 ± 0.009</td>
<td>n.a</td>
<td>5.12 ± 0.21</td>
<td>0.044 ± 0.005</td>
</tr>
</tbody>
</table>

4.5 Measured resolution as a function of $p_T$

The parameterized resolution as a function of $p_T$ for each detector region is obtained using the values of the parameters reported in Tables 4.9, 4.10 and 4.11. Figures 4.9 and 4.10 show the MS and the ID muon resolution curves, respectively, for the barrel region, obtained for 2010 (a), 2011 (b) and 2012 (c) analyses. The former show results using the “Chain 1” algorithm, the latter results obtained with “Chain 2” algorithm.
Figure 4.9. Resolution curve from the fitted parameter values of the barrel MS in collision data and simulation as a function of the muon $p_T$. “Chain 1” algorithm is considered. The solid blue line shows determination based on data and is continued as dashed line for the extrapolation to $p_T$ range not accessible in the analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
4.5. MEASURED RESOLUTION AS A FUNCTION OF $p_T$

Figure 4.10. Resolution curve from the fitted parameter values of the barrel ID in collision data and simulation as a function of the muon $p_T$. “Chain 2” algorithm is considered. The solid blue line shows determination based on data and is continued as dashed line for the extrapolation to $p_T$ range not accessible in the analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
In both figures, the solid blue line shows the determination based on data, the dashed blue line represents its extrapolation to \( p_T \) ranges not accessible in the analysis, the shaded band represents the sum in quadrature of the statistical and systematic uncertainty and the solid red line shows the expected resolution curve obtained from the simulation.

Comparing the muon resolution obtained in the three analyses, it is evident that the muon momentum resolution is significantly improved during the three years of data taking. In particular, comparing the 2010 and 2011 results, in which the simulation assumes a perfectly aligned detector, the muon resolution obtained from 2011 data is closer to the expected one with respect to the one obtained from 2010 data: this reflects a better alignment of the detector during 2011 data taking than in 2010 one. In the 2012 analysis, where the knowledge of the alignment of the ATLAS detector is improved and included in the simulation, the muon resolution obtained from data is very close to the expected one: this reflects an excellent knowledge of the performance of the ATLAS detector. Differences are observed between the uncertainties obtained for the two algorithms: those arise from the correlation values between the resolution correction parameters that have been taken into account to compute the uncertainty bands. The full set of muon momentum resolution curves for all detector regions are reported in Appendix A.

![Figure 4.11](image)

**Figure 4.11.** Di-muon invariant mass for “Chain 1” (a) and “Chain 2” (b) algorithms, obtained using combined tracks. The invariant mass for 2010 data (black points) and simulation (green) of \( Z \to \mu\mu \) plus background events, after applying the corrections, are shown.

Starting from the corrected ID and MS \( p_T \) measurements in MC, it is possible to correct the combined muon \( p_T^{\text{CB}} \) in the simulation and obtain a new measurements \( p_T^{\text{CB}} \), defined as a linear
4.5. MEASURED RESOLUTION AS A FUNCTION OF $P_T$

![Di-muon invariant mass: Chain 1](image1)

![Di-muon invariant mass: Chain 2](image2)

**Figure 4.12.** Di-muon invariant mass for “Chain 1” (a) and “Chain 2” (b) algorithms, obtained using combined tracks. The invariant mass for 2011 data (black points) and simulation (green) of $Z \rightarrow \mu\mu$ plus background events, after applying the corrections, are shown.

![Di-muon invariant mass: Chain 1](image3)

![Di-muon invariant mass: Chain 2](image4)

**Figure 4.13.** Di-muon invariant mass for “Chain 1” (a) and “Chain 2” (b) algorithms, obtained using combined tracks. The invariant mass for 2012 data (black points) and simulation (green) of $Z \rightarrow \mu\mu$ plus background events, after applying the corrections, are shown.
combination of the MS and the ID contributions and weighted by the MS and the ID resolutions

\[ p_{\text{CB}}^{'T} = p_{\text{CB}}^T \left[ 1 + \frac{\Delta(MS)}{\sigma^2(MS)} + \frac{\Delta(ID)}{\sigma^2(ID)} \right] \left( 1 + \frac{1}{\sigma^2(MS)} + \frac{1}{\sigma^2(ID)} \right) \] (4.9)

where \( \Delta(MS, ID) \) is the overall correction to the simulated MS or ID \( p_T \), from Equation 4.7, and \( \sigma(MS, ID) \) are the values of the resolution at \( p_T^{MS,ID} \).

Due to the different way of combining tracks used by the two reconstruction algorithms, the correction formula for combined tracks, given by equation 4.9, works better for “Chain 1” algorithm. However it results a good approximation for “Chain 2” algorithm, too.

Figures 4.11, 4.12 and 4.13 show the di-muon invariant mass distributions around the Z pole for combined tracks, after applying the corrections from Tables 4.6, 4.7 and 4.8, to the simulation. The corrected simulation (green) and the data (black points) are in good agreement, within few percent, giving the goodness of the simulation correction provided in Section 4.4.
Chapter 5

The Higgs boson discovery

In the context of the Standard Model the Brout-Englert-Higgs mechanism is the source of electroweak symmetry breaking and results in the appearance of the Higgs boson. The Higgs decay to four leptons is one of the main channels where the search for the SM Higgs Boson has been performed. It is usually referred to as the golden channel at the experiments at the LHC due to the clean final state signature and the possibility to fully reconstruct the Higgs mass with excellent detector resolution. However, it has a relatively low branching ratio especially at lower masses.

The search for the SM Higgs boson through the decay $H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l'^+l'^-$, where $l,l' = e$ or $\mu$, provides a good sensitivity over a wide mass range. Four distinct final states are selected: $\mu^+\mu^-\mu^+\mu^- (4\mu)$, $e^+e^-e^+e^- (4e)$, $\mu^+\mu^-e^+e^- (2\mu 2e)$, $e^+e^-\mu^+\mu^- (2e 2\mu)$; the last two differ by the flavour of the lepton pair having a reconstructed invariant mass closest to the $Z$ mass. The largest background in this search comes from continuum ($Z^{(*)}/\gamma^{*}$)($Z^{(*)}/\gamma^{*}$) production, referred to as $ZZ^{(*)}$ hereafter, which includes the single resonance $Z \rightarrow 4l$. For four-lepton masses below around 160 GeV, there are also important background contributions from $Z$+jets and $tt$ production, where the additional charged lepton candidates arise either from decays of hadrons with $b$ or $c$ quark content, from photon conversions or from mis-identification of jets.

This chapter presents a search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l'^+l'^-$. The analysis is done using $p$-$p$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV recorded with the ATLAS detector in 2011 and in the first half of 2012, respectively. The results obtained [106] are combined with those of other Higgs boson searches [3].

In order to maximize the expected signal significance for a low mass Higgs boson, in the beginning of 2012 an optimization of the analysis selection with respect to the previous published analysis [107] has been performed. This optimization has significantly increased the sensitivity of this channel and thus played an important role in the Higgs discovery.
CHAPTER 5. THE HIGGS BOSON DISCOVERY

5.1 Data and Monte Carlo samples

In this section, data and Monte Carlo samples used in the analysis are described.

Data samples
The analysis is based on p-p collision data collected in 2011 and the first half of 2012. The data are subjected to quality requirements: events recorded during periods when the relevant detector components were not operating properly are rejected. The resulting integrated luminosity is 4.8 fb$^{-1}$ for $\sqrt{s} = 7$ TeV and 5.8 fb$^{-1}$ for $\sqrt{s} = 8$ TeV, for a total of about 10.6 fb$^{-1}$.

Monte Carlo signal samples
The $H \rightarrow ZZ^{(*)} \rightarrow 4l$ signal is modelled using the Powheg [91] Monte Carlo generator. This generator calculates separately the gluon fusion and the vector-boson fusion production mechanisms with matrix elements up to the next-to-leading order (NLO). The Higgs boson $p_T$ spectrum in the gluon fusion process is re-weighted to follow the calculation of Reference [108], which includes QCD corrections up to NLO and QCD soft-gluon re-summations up to next-to-next-to-leading logarithm (NNLL). Powheg is interfaced with Pythia [89] [90] for showering and hadronization, which in turn is interfaced with Photos [109] for QED radiative corrections in the final state and with Tauola [110] [111] for the simulation of $\tau$ lepton decay. The simulation of the production of a Higgs boson in association with a $W$ or a $Z$ boson is done using Pythia.

The cross sections for the Higgs boson production, the corresponding branching fractions, as well as their uncertainties, have been calculated by the LHC Higgs Cross Section Working Group [32] [33]. The cross sections for the exclusive production mechanisms and the branching ratios for some generated $m_H$ are reported in Table 5.1 for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

The cross sections for the gluon fusion process have been calculated at next-to-next-to-leading order (NNLO) in QCD [112] [113] [114]. In addition, for the gluon fusion process, QCD soft-gluon resummations up to NNLL [115] and NLO electroweak (EW) radiative corrections [116] are applied. The cross sections for vector-boson fusion processes are calculated at NNLO in QCD [117] and NLO EW corrections [29] [118] are applied. The cross sections for the associated $WH/ZH$ production processes are calculated at NNLO in QCD [119] and NLO EW corrections [120] are applied. These cross-section calculations do not take into account the width of the Higgs boson, which is implemented through a Breit-Wigner lineshape applied at the event generator level. The Higgs boson decay branching ratio to the four-lepton final state is predicted by Prophecy4f [121] [122] including the complete NLO QCD and EW corrections with all interference and leading two-loop heavy Higgs boson corrections to the four-fermion width.

Monte Carlo background samples
The $ZZ^{(*)}$ continuum background is modelled using Powheg for quark-antiquark annihilation
### 5.1. DATA AND MONTE CARLO SAMPLES

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\sigma(gg \rightarrow H)$ [pb]</th>
<th>$\sigma(qq' \rightarrow Hqq')$ [pb]</th>
<th>$\sigma(q\bar{q} \rightarrow WH)$ [pb]</th>
<th>$\sigma(q\bar{q} \rightarrow ZH)$ [pb]</th>
<th>BR $[10^{-3}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>125</td>
<td>$15.3 \pm 2.3$</td>
<td>$1.22 \pm 0.03$</td>
<td>$0.57 \pm 0.02$</td>
<td>$0.32 \pm 0.02$</td>
<td>$0.125$</td>
</tr>
<tr>
<td>130</td>
<td>$14.1^{+2.7}_{-2.1}$</td>
<td>$1.15 \pm 0.03$</td>
<td>$0.50 \pm 0.02$</td>
<td>$0.28 \pm 0.01$</td>
<td>$0.19$</td>
</tr>
<tr>
<td>190</td>
<td>$5.9^{+1.0}_{-0.9}$</td>
<td>$0.69 \pm 0.02$</td>
<td>$0.125 \pm 0.005$</td>
<td>$0.074 \pm 0.004$</td>
<td>$0.94$</td>
</tr>
<tr>
<td>400</td>
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<td>$0.162^{+0.009}_{-0.005}$</td>
<td>-</td>
<td>-</td>
<td>$1.21$</td>
</tr>
<tr>
<td>600</td>
<td>$0.37 \pm 0.06$</td>
<td>$0.058^{+0.005}_{-0.002}$</td>
<td>-</td>
<td>-</td>
<td>$1.23$</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
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</tr>
<tr>
<td>125</td>
<td>$19.5 \pm 2.9$</td>
<td>$1.58 \pm 0.04$</td>
<td>$0.70 \pm 0.03$</td>
<td>$0.39 \pm 0.02$</td>
<td>$0.125$</td>
</tr>
<tr>
<td>130</td>
<td>$18.1 \pm 2.6$</td>
<td>$1.49 \pm 0.04$</td>
<td>$0.61 \pm 0.03$</td>
<td>$0.35 \pm 0.02$</td>
<td>$0.19$</td>
</tr>
<tr>
<td>190</td>
<td>$7.9 \pm 1.1$</td>
<td>$0.91^{+0.03}_{-0.02}$</td>
<td>$0.156 \pm 0.007$</td>
<td>$0.094 \pm 0.006$</td>
<td>$0.94$</td>
</tr>
<tr>
<td>400</td>
<td>$2.9 \pm 0.4$</td>
<td>$0.25 \pm 0.01$</td>
<td>-</td>
<td>-</td>
<td>$1.21$</td>
</tr>
<tr>
<td>600</td>
<td>$0.5 \pm 0.1$</td>
<td>$0.097 \pm 0.004$</td>
<td>-</td>
<td>-</td>
<td>$1.23$</td>
</tr>
</tbody>
</table>

Table 5.1. Higgs boson production cross sections for gluon fusion, vector-boson fusion and associated production with a $W$ or $Z$ boson in $p\bar{p}$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV for several Higgs boson masses. The quoted uncertainties correspond to the total theoretical systematic uncertainties with a linear sum of QCD scale and PDF+$\alpha_s$ uncertainties (see Section 5.4). The production cross section for associated production with a $W$ or $Z$ boson is negligible for $m_H > 300$ GeV. The decay branching ratio (BR) for $H \rightarrow ZZ^{(*)} \rightarrow 4l$, with $l = e$ or $\mu$, is also reported.

[123] and $ggZZ$ [123] for gluon fusion. It is normalized to the prediction given by mcfm [125], which computes the cross section at LO and NLO for the process $qq \rightarrow ZZ$ including $ZZ$, $Z\gamma^*$ and their interference, for the double resonant (or $t$-channel) and single resonant (or $s$-channel) diagrams, and for the process $gg \rightarrow ZZ$ including both quark-antiquark annihilation at QCD NLO and gluon fusion. As with the signal samples, POWHEG is then interfaced with PYTHIA and PHOTOS. The simulation of $\tau$ decays is done by TAUOLA.

The inclusive $Z$ boson and $Zb\bar{b}$ productions are modelled using ALPGEN [126], while for the $t\bar{t}$ production MC@NLO [127] is used. Both the MC generators are interfaced with HERWIG [128] for parton shower and hadronization, and JIMMY [129] for simulation of the underlying events. For the inclusive $Z$ boson and $Zb\bar{b}$ processes, overlaps between the two samples are removed. In particular, $b\bar{b}$ pairs with separation $\Delta R \geq 0.4$ between the jets are taken from the matrix-element calculation, while for $\Delta R < 0.4$ the parton-shower jets are used. The QCD NNLO prediction by FEWZ [130] and the MCFM cross sections calculations are used for the inclusive $Z$ boson and $Zb\bar{b}$ production, respectively. The $t\bar{t}$ background is normalized to the approximate NNLO cross section calculated using HATHOR [131]. The cross sections for the background processes are reported in Table 5.2 for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.
### Table 5.2. Background processes and the corresponding cross sections for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

<table>
<thead>
<tr>
<th>process name</th>
<th>Cross section [fb]</th>
</tr>
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<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>$\sqrt{s} = 8$ TeV</td>
</tr>
<tr>
<td>$Z \to ll + \text{jets} (l = e$ or $\mu)$</td>
<td>3182875 344745</td>
</tr>
<tr>
<td>$Z \to ll + bb (l = e$ or $\mu, m_{ee}/m_{\mu\mu} &gt; 30$ GeV)</td>
<td>116.95 152.04</td>
</tr>
<tr>
<td>$Z \to ll + bb (l = e$ or $\mu, m_{ee}/m_{\mu\mu} &gt; 30$ GeV at least 3l)</td>
<td>4053.7 5269.81</td>
</tr>
<tr>
<td>$tt (\text{at least one lepton})$</td>
<td>91550.6 154262.9</td>
</tr>
<tr>
<td>$t\bar{t} (m_{tt} &gt; 60$ GeV and $m_{tt} &gt; 12$ GeV)</td>
<td>515.2 761.2</td>
</tr>
<tr>
<td>$gg \to ZZ \to 4l (l = e, \mu$ or $\tau, m_{ll} &gt; 4$ GeV, 3l with $p_T &gt; 5$ GeV)</td>
<td>192.3 $-$</td>
</tr>
<tr>
<td>$gg \to ZZ \to 4l (l = e, \mu$ or $\tau, m_{ll} &gt; 4$ GeV, 2l with $p_T &gt; 5$ GeV)</td>
<td>$-$ 499.14</td>
</tr>
<tr>
<td>$gg \to ZZ \to 4l (l = e$ or $\mu)$</td>
<td>1.72 2.69</td>
</tr>
</tbody>
</table>

The leading di-lepton pair mass is required to be $m_{ll} > 60$ GeV, while the sub-leading one is required to be $m_{ll} > 12$ GeV. $^\dagger$ The $m_{ll}$ requirements of $^\dagger$ are vetoed.

Generated events are fully simulated using the ATLAS detector simulation within Geant4 framework [92]. During the data taking the LHC machine parameters were continuously evolving resulting in increasing values for the average number of interactions in every bunch crossing. To take this effect into account, a pile-up re-weighting is applied to the MC samples in order to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data.

#### 5.2 Event selection

In the $H \to ZZ^{(*)} \to 4l$ analysis, quality data are selected and trigger requirements are applied. Event candidates must have a reconstructed primary vertex with at least three tracks. In these events, leptons are selected to form quadruplets, which have to satisfy specific requirements. In order to reject most of the reducible background processes, additional selections are applied. Before going through the event selection details, the optimization of the kinematic selection is described.

#### 5.2.1 Data quality and trigger requirements

The collected data are divided into Luminosity Blocks (LB), which consist of one or two minutes of approximately constant instantaneous luminosity and data taking conditions, such as detector status and the trigger menu. Only LB where the LHC has declared “stable beams” and having components of the detector declared to be operating as expected have been used. A specific ‘Good Run List’ (GRL) for each final state is applied.

Events passing the quality requirements have to satisfy the trigger requirements. They are selected
only if satisfying the single-lepton or the di-lepton trigger thresholds.

Concerning the single-lepton trigger, for collision data at $\sqrt{s} = 7$ TeV, the $p_T$ threshold of the single muon trigger is 18 GeV, while for the single-electron trigger the $E_T$ threshold varies from 20 GeV to 22 GeV, depending on the LHC data taking period\footnote{The trigger selection evolves into using higher thresholds as the machine parameters tunings result to higher instantaneous luminosity.}. For collision data at $\sqrt{s} = 8$ TeV, a single muon $p_T$ threshold of 24 GeV and a single electron $E_T$ threshold of 25 GeV are applied. Concerning the di-lepton triggers, the threshold is applied to both the leptons firing the trigger. The threshold for electrons is 12 GeV for each electron in the full period. For muons this is 10 GeV and 13 GeV for collision data at $\sqrt{s} = 7$ TeV and at $\sqrt{s} = 8$ TeV, respectively. In addition an asymmetric di-muon trigger is also used for 2012 collision data: in this case the $p_T$ thresholds are 18 GeV for one muon and 8 GeV for the other.

5.2.2 Event selection optimization

In the beginning of 2012, when the Higgs boson was not yet discovered, the kinematic selection of the analysis has been optimized, focusing on the low mass region, between 120 GeV and 130 GeV. In fact, the combination of the Higgs boson searches performed in 2011\footnote{The trigger selection evolves into using higher thresholds as the machine parameters tunings result to higher instantaneous luminosity.} showed a hint for the possible value of the Higgs boson mass in that region.

The optimization was done in order to increase the signal-background discrimination power and to reach a higher sensitivity to signal events. It has been performed on the assumption of an expected total integrated luminosity of 20 fb$^{-1}$ at a centre-of-mass energy of 7 TeV, compared to the previous published analysis\footnote{The trigger selection evolves into using higher thresholds as the machine parameters tunings result to higher instantaneous luminosity.} with 4.8 fb$^{-1}$ of 2011 collision data at $\sqrt{s} = 7$ TeV.

Optimization for the four muons final state

The optimization procedure is based on a scan of the six main kinematic variables:

- $m_{12}$: the opposite-charge di-muon invariant mass closer to the PDG $Z$ mass;
- $m_{34}$: the other opposite-charge di-muon invariant mass;
- $p_T$: the transverse momenta of muons ordered in $p_T$. 

Since the kinematic variables are correlated, the optimization procedure was performed in an iterative way looking for minima in the six dimensional variable space. The idea is to perform a scan for each variable by considering the value of the remaining $N-1$ variables fixed. In particular, in the first step, the value for the $N-1$ remaining variables is set to those of the previous analysis. Once all the minima for each variable are found, to verify they are the optimal values, another scan
is performed in the same way as before: in this case the values of the variables out of the scan are fixed to those found during the first iteration. The signal sensitivity is quantified by the $p_0$ value, corresponding to the probability that the expected background in a window of 6 GeV around the signal mass fluctuates to an observed number of events which is greater or equal to the sum of the expected signal plus background events in the same mass window. This probability is computed from the expected MC signal and background events.

The expected $p_0$ is estimated using the $\chi^2$ asymptotic approximation, given by the formula

$$ Z_0 = \sqrt{2 \left( (s + b) \ln \left(1 + \frac{s}{b}\right) - s \right)}, $$

(5.1)

where $s$ is the number of signal events, $b$ the number of background events and $Z_0$ represents the equivalent number of Gaussian standard deviations. The background estimates are taken from simulation: the reducible background is expected to be small with respect to the irreducible one and therefore the optimization procedure is less sensitive to its systematics. The trigger requirements, described in Section 5.2.1 have been taken into account.

Figures 5.1 and 5.2 give the local expected $Z_0$, for the four muons final state, as a function of the cut value for the different kinematic variables and considering a 125 GeV Higgs signal.

![Figure 5.1](image_1.png)

(a) $Z_0$ as a function of $m_{12}$ cut

![Figure 5.2](image_2.png)

(b) $Z_0$ as a function of $m_{34}$ cut

**Figure 5.1.** Dependence of the expected $Z_0$ on the mass of the leading pair (a) and on the mass of the sub-leading pair (b). A 125 GeV Higgs signal and an integrated luminosity of $20 \text{fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$ have been considered.

According to the results obtained, it is clear that the most sensitive variables for the optimization are $m_{12}$ and $p_T$, while the dependence on the other variables is weaker. The selected cut value for the minimum $m_{12}$ has been chosen at 50 GeV, much relaxed compared to the previous one set at 15 GeV around the $Z$ mass, $|m_Z - m_{12}| < 15 \text{ GeV}$. The cut on $p_T$ has been loosened to 6 GeV from 7 GeV in the previous analysis. The $p_T$ of the second muon is the third most sensitive variable:
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Figure 5.2. Dependence of the expected \( Z_0 \) on on the \( p_T \) of the muons in the quadruplet, ordered from the leading (a) to the lowest one (d). A 125 GeV Higgs signal and an integrated luminosity of 20 fb\(^{-1} \) at \( \sqrt{s} = 7 \) TeV have been considered.

The cut value for \( p_T_2 \) has been relaxed from 20 GeV to 15 GeV. The sensitivity of the search is not affected strongly by the requirements on \( p_T_1 \) and \( p_T_3 \): the cut on \( p_T_1 \) has been kept at 20 GeV and the one on \( p_T_3 \) has been tightened from 7 GeV to 10 GeV. Also the cut on \( m_{34} \), which is dependent on the four-lepton invariant mass (see Section 5.2.4), has been tightened by 2.5 GeV with respect to the previous analysis: this results in a small increase in the expected significance. In general, if a small dependence of the expected significance is observed, the choice was made to be conservative and reduce the reducible background contribution. The set of cuts found considering the 125 GeV Higgs signal has been verified to be optimal also for other Higgs mass hypotheses between 120 GeV and 130 GeV. The cuts as results of the optimization procedure are summarized in Table 5.3.

The impact of extending the muon acceptance by adding stand-alone (SA) and calo-tagged (CT) muons has been investigated. As discussed in section 3.2.1 SA muons are reconstructed outside the ID coverage (2.5 < |\( \eta \) | < 2.7), while CT muons are considered for |\( \eta \) | < 0.1 where the MS is
CHAPTER 5. THE HIGGS BOSON DISCOVERY

not equipped with detectors.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Optimal Cut</th>
<th>2011 Published Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{12}$</td>
<td>50 GeV</td>
<td>15 GeV around the Z mass</td>
</tr>
<tr>
<td>$m_{34}$</td>
<td>20 GeV (at $m_{4\mu} = 125$ GeV)</td>
<td>17.5 GeV (at $m_{4\mu} = 125$ GeV)</td>
</tr>
<tr>
<td>$p_T^1$</td>
<td>20 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>$p_T^2$</td>
<td>15 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>$p_T^3$</td>
<td>10 GeV</td>
<td>7 GeV</td>
</tr>
<tr>
<td>$p_T^4$</td>
<td>6 GeV</td>
<td>7 GeV</td>
</tr>
</tbody>
</table>

Table 5.3. Value of the cut position for a 125 GeV Higgs signal obtained from the optimization procedure for the four muons final state.

In Table 5.4 the numbers of expected signal and background events together with the corresponding sensitivity for the two different selections are reported. The values are computed considering the four muons final state only and a 125 GeV Higgs-mass signal, for an assumed integrated luminosity of 20 fb$^{-1}$ at $\sqrt{s} = 7$ TeV. By adding the SA and CT muons, the signal efficiency for a 125 GeV Higgs mass is improved by about 9% using the optimized kinematic variables described above. In term of standard deviation ($\sigma$), by adding SA and CT muons, the sensitivity of the four muons final state only increases from 1.67$\sigma$, in the previous analysis, to 2.16$\sigma$. Therefore, SA and CT muons are included in the analysis.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Signal</th>
<th>Irred. bkg</th>
<th>Red. bkg</th>
<th>$Z_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Published without SA and CT muons</td>
<td>2.33</td>
<td>1.22</td>
<td>0.08</td>
<td>1.67</td>
</tr>
<tr>
<td>Optimized with SA and CT muons</td>
<td>3.75</td>
<td>1.71</td>
<td>0.26</td>
<td>2.16</td>
</tr>
</tbody>
</table>

Table 5.4. Numbers of expected signal and background events in a window of 6 GeV around the signal mass, together with the corresponding local signal significance for different selections from simulation. An integrated luminosity of 20 fb$^{-1}$ at $\sqrt{s} = 7$ TeV is assumed. A 125 GeV Higgs signal and the four muons final state only are considered.

**Optimization for final states with electrons**

Due to a different background composition, a separate kinematic cut optimization study is performed for sub-channels with sub-leading electrons in the final states, $4e$ and $2\mu2e$. For these final states the contribution of the $Z+\text{jets}$ background is quite relevant. In this case, the optimization procedure is similar to the one performed for the four muons final state. It is done for an integrated luminosity of 4.8 fb$^{-1}$ at $\sqrt{s} = 7$ TeV. In fact, due to the very
5.2. EVENT SELECTION

low number of simulated events passing the analysis cuts \[ \text{107} \], the evaluation of the \( Z + \text{jets} \) background cannot be based only on MC. Its normalization is derived using MC events in the control region where isolation and impact parameter cuts are removed. The normalization is obtained relatively to the selections of the previous analysis, where the data driven estimation of the \( Z + \text{jets} \) contribution to the signal region was used to give an absolute reference.

The kinematic cuts in the quadruplet selection were studied in detail after fixing the minimum transverse momentum for electrons, \( p_T > 7 \text{ GeV} \), as for the previous analysis, in order to obtain a better electron reconstruction efficiency and to avoid fakes. The selection criteria considered in these final states are \( m_{12}, p_T^2 \) and \( p_T^3 \), while \( m_{34} \) is kept at the same value fixed by the optimization done for the four muons final state. The acceptance of the MC signal and background events for a given set of cuts is evaluated using the expected number of events and the local significances estimated with Equation 5.1 in a mass window of 6 GeV around the signal mass.

Figure 5.3 gives the dependence of the local significance on the cut value of \( m_{12} \) for final states with electrons and for an integrated luminosity of 4.8 fb\(^{-1}\). It is clear that lowering the value of \( m_{12} \) the significance increases considerably, reaching a plateau below 50 GeV: as for the four muons final state, the cut is then fixed at 50 GeV instead of 15 GeV around the \( Z \) mass.

**Figure 5.3.** Dependence of the expected \( Z_0 \) on \( m_{12} \). A 125 GeV Higgs signal and an integrated luminosity of 4.8 fb\(^{-1}\) at \( \sqrt{s} = 7 \text{ TeV} \) are considered. The lower box shows the difference with respect to the previous published analysis.

Figure 5.4 shows the dependence of the local significance on the cut value of \( p_T^2 \). In this case by lowering the minimum value from 20 GeV to 15 GeV a small improvement on the local significance is achieved. Figure 5.4 shows the dependence of the local significance on the cut value of \( p_T^3 \). By
increasing the minimum value from 7 GeV to 10/12 GeV a further improvement can be reached: for simplicity, the minimum value of $p_T$ is fixed at 10 GeV as in the case of the 4$\mu$ final state.

![ATLAS Simulation](image1)

![ATLAS Simulation](image2)

(a) $Z_0$ as a function of the $p_{T2}$ cut

(b) $Z_0$ as a function of the $p_{T3}$ cut

Figure 5.4. Dependence of the expected $Z_0$ on $p_{T2}$ (a) and on $p_{T3}$ (b) of the electrons composing the quadruplet. A 125 GeV Higgs signal and an integrated luminosity of 4.8 fb$^{-1}$ at $\sqrt{s} = 7$ TeV are considered. The lower boxes show the difference with respect to the previous published analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Optimal Cut</th>
<th>2011 Published Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{12}$</td>
<td>50 GeV</td>
<td>15 GeV around the $Z$ mass</td>
</tr>
<tr>
<td>$m_{34}$</td>
<td>20 GeV (at $m_{4f} = 125$ GeV)</td>
<td>17.5 GeV (at $m_{4f} = 125$ GeV)</td>
</tr>
<tr>
<td>$p_{T1}$</td>
<td>20 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>$p_{T2}$</td>
<td>15 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>$p_{T3}$</td>
<td>10 GeV</td>
<td>7 GeV</td>
</tr>
<tr>
<td>$p_{T4}$</td>
<td>7 GeV</td>
<td>7 GeV</td>
</tr>
</tbody>
</table>

Table 5.5. Value of the cut position for a 125 GeV Higgs signal obtained from the optimization procedure for the final states with electrons.

In Table 5.5 the choice of the cuts as results of the optimization procedure for the final states with electrons is summarized. This set of cuts has been applied also to the 2$e$2$\mu$ final state. In Table 5.6 the number of expected signal and background events are reported together with the corresponding sensitivity for the two different selections. The values are computed considering the four electrons final state and the 2$e$2$\mu$ and 2$\mu$2$e$ final states together for a 125 GeV Higgs signal.
5.2. EVENT SELECTION

and assuming an integrated luminosity of $20 \text{fb}^{-1}$ at $\sqrt{s} = 7$ TeV. Considering the four electrons final state only, using the optimized set of cuts the expected local significance for an integrated luminosity of $20 \text{fb}^{-1}$ increases from $0.99\sigma$ to $1.18\sigma$, while for the $2e2\mu$ and $2\mu2e$ final states and taking in account also SA and CT muons, the expected significance increases from $1.78\sigma$ to $2.20\sigma$.

<table>
<thead>
<tr>
<th>Final state</th>
<th>Selection</th>
<th>Signal</th>
<th>Irred. bkg</th>
<th>Red. bkg</th>
<th>$Z_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4e$</td>
<td>Published</td>
<td>0.95</td>
<td>0.56</td>
<td>0.08</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Optimized</td>
<td>1.27</td>
<td>0.72</td>
<td>0.09</td>
<td>1.18</td>
</tr>
<tr>
<td>$2e2\mu+$</td>
<td>Published without SA and CT muons</td>
<td>3.01</td>
<td>1.69</td>
<td>0.33</td>
<td>1.78</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>Optimized with SA and CT muons</td>
<td>4.02</td>
<td>1.82</td>
<td>0.41</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Table 5.6. Numbers of expected signal and background events in a window of 6 GeV around the signal mass and the corresponding local signal significance for different selections from simulation. An integrated luminosity of $20 \text{fb}^{-1}$ at $\sqrt{s} = 7$ TeV is assumed. A 125 GeV Higgs signal and the $4e$ final state only and $2e2\mu$ and $2\mu2e$ final states together are considered.

5.2.3 Lepton selection

Once the events pass the data quality and trigger requirements, an additional requirement at event level is applied. In order to assure a good vertex quality, collision events are selected by requiring at least one reconstructed primary vertex with at least three ID tracks associated with it. Then individual leptons are selected. Electron candidates consist of electromagnetic clusters matched with an ID track using the distance between the cluster position and the extrapolated position of the track at the calorimeter. The electron reconstruction and identification proceeds as described in Section 3.2.2. The electron selection criteria used in the analysis are different for events at $\sqrt{s} = 7$ TeV and at $\sqrt{s} = 8$ TeV: for the former loose selection criteria are used, while for the latter multilepton selection criteria are used instead. The electrons should have a transverse energy $E_T > 7$ GeV and a pseudo-rapidity $|\eta| < 2.47$.

Muon candidates are reconstructed by matching ID tracks with either complete or partial tracks reconstructed in the MS. As a result of the optimization studies described in Section 5.2.2, also stand-alone and calo-tagged muons are considered in the analysis. Their identification and reconstruction proceeds as described in Section 3.2.1, but only considering the “Chain 1” muon reconstruction algorithm. In order to obtain good tracks, quality requirements have to be applied. For the $\sqrt{s} = 7$ TeV analysis, each muon track has to satisfy the requirement of at least 2 hits in the pixel detector, at least 6 hits in the SCT and at least 5 hits in the TRT, while for the $\sqrt{s} = 8$ TeV analysis the requirements are relaxed: at least 1 hit in the pixel detector, at least 5 hits in the SCT and at least 5 hits in the TRT. All muons should have a transverse momentum $p_T > 6$ GeV and a pseudo-rapidity $|\eta| < 2.7$. In order to reject cosmic muons, the transverse impact parameter
of the muons with respect to the primary vertex is required to be $|d_0| < 1 \text{ mm}$.

To ensure association with the primary vertex, each lepton ID track must satisfy a requirement on the longitudinal impact parameter of $|z_0| < 10 \text{ mm}$. Possible overlaps between lepton tracks are also removed. When two electrons share the same ID track, the one with the highest $E_T$ is kept. When an electron shares the same track with a muon, the electron is removed.

### 5.2.4 Lepton quadruplet selection

The candidate quadruplet is formed by selecting two opposite sign and same flavour di-lepton pairs in an event. The leptons forming the quadruplet, once ordered in $p_T$, must satisfy the transverse momentum cuts as described in Section 5.2.2: the quadruplet should contain a lepton with $p_T > 20 \text{ GeV}$, one with $p_T > 15 \text{ GeV}$ and another one with $p_T > 10 \text{ GeV}$. In addition, the four leptons are required to be well separated: for same flavour leptons a $\Delta R > 0.10$ cut is applied, while for different flavour leptons the cut is $\Delta R > 0.20$.

Within the quadruplet, the same flavour and opposite sign di-lepton pair having an invariant mass, $m_{12}$, closest to the nominal $Z$ boson mass is called the leading di-lepton pair, while the second di-lepton pair of the quadruplet, with invariant mass $m_{34}$, is called the sub-leading one. According to the optimization procedure, $m_{12}$ is required to be between 50 GeV and 106 GeV, while $m_{34}$ is required to be in the range $m_{\text{threshold}} < m_{34} < 115 \text{ GeV}$, where $m_{\text{threshold}}$ varies as a function of the four-lepton invariant mass, $m_{4l}$, as described in Table 5.7. In order to avoid a possible $J/\psi$ selection, all possible same flavour opposite charge di-lepton combinations in the quadruplet must satisfy $m_{ll} > 5 \text{ GeV}$. In the case that more than one quadruplet survives the kinematic selection, the quadruplet with $m_{12}$ closest to $m_Z$ and with the most energetic $m_{34}$ is selected.

\[
\begin{array}{cccccc}
| m_{4l} | & 120 & 130 & 150 & 165 & 180 & \geq 190 \\
| m_{\text{threshold}} | & 17.5 & 22.5 & 30 & 35 & 40 & 50 \\
\end{array}
\]

**Table 5.7.** The sub-leading di-lepton invariant mass, $m_{34}$, is required to exceed a threshold based on the reconstructed four-lepton invariant mass, $m_{4l}$. For other $m_{4l}$ values, the selection requirement is obtained via linear interpolation.

### 5.2.5 Additional requirements

Once a good quadruplet is found, additional requirements are applied to the leptons composing the quadruplet. The signal events are expected to be found with a quadruplet having leptons well isolated and directly associated with the primary vertex. In order to reject background contributions, characterized by non-isolated leptons and leptons from secondary vertices, cuts on the relative tracking isolation, the relative calorimetric isolation and the significance of the
transverse impact parameter are applied to each lepton of the quadruplet. 

The relative track isolation discriminant is defined as the sum of the transverse momenta of tracks, \( \sum p_T \), inside a cone of \( \Delta R < 0.2 \) around the lepton, divided by the lepton \( p_T \). In the sum, any contribution arising from other leptons of the quadruplet is subtracted. Each lepton of the quadruplet is required to have a relative track isolation smaller than 15%.

The relative calorimetric isolation discriminant is defined as the sum of the transverse energy deposits in calorimeter cells, for 2011 analysis, or in topological clusters, for 2012 analysis, \( \sum E_T \), inside a cone of \( \Delta R < 0.2 \) around the lepton, divided by the lepton \( p_T \). The algorithm for topological clustering suppresses noise by keeping cells with a significant energy deposit and their neighbours. As for the track isolation, in the sum any contribution arising from other leptons of the quadruplet is subtracted. For events at \( \sqrt{s} = 7 \text{ TeV} \), both electrons and muons are required to have a relative calorimetric isolation smaller than 30%, while for events at \( \sqrt{s} = 8 \text{ TeV} \) the requirement on electrons is tightened, smaller than 20%. SA muons are required to have a relative calorimetric isolation smaller than 15%.

The impact parameter significance of the leptons, \( d_0/\sigma_{d_0} \), is a good discriminant to remove leptons originating from \( b \) or \( c \) quarks and associated to displaced vertices. Each muon of the quadruplet is required to have an impact parameter significance smaller than 3.5, while for each electron it has to be smaller than 6.5, since bremsstrahlung smears the \( d_0 \) distribution and the discrimination power of the selection is reduced. This requirement is not applied to SA muons.

### 5.2.6 Selection efficiency and mass resolution

At this stage the global analysis efficiency to reconstruct \( H \rightarrow ZZ^{(*)} \rightarrow 4l \) final states is evaluated. In Table 5.8 the combined signal reconstruction and selection efficiencies for each final state for both 2011 and 2012 analyses are reported. Two Higgs boson mass hypotheses, \( m_H = 130 \text{ GeV} \) and \( m_H = 360 \text{ GeV} \), are considered.

<table>
<thead>
<tr>
<th>( m_H ) [GeV]</th>
<th>( \sqrt{s} = 7 \text{ TeV} )</th>
<th>( \sqrt{s} = 8 \text{ TeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>42% 23% 17% 40%</td>
<td>23% 25% 23%</td>
</tr>
<tr>
<td>360</td>
<td>71% 58% 47% 68%</td>
<td>59% 52%</td>
</tr>
</tbody>
</table>

Table 5.8. Combined signal reconstruction efficiency, for each final state and for two signal MC samples, \( m_H = 130 \text{ GeV} \) and \( m_H = 360 \text{ GeV} \), at \( \sqrt{s} = 7 \text{ TeV} \) and \( \sqrt{s} = 8 \text{ TeV} \).

The width of the signal peak is dominated by the detector resolution. In order to enhance the mass resolution, the \( Z \) mass constraint method is used: it adjusts the lepton momenta according to their uncertainties so that the invariant mass of the leading pair equals a constraint mass \( m_c \). Due to
the non-negligible decay width of the Z boson, the constrained mass is estimated by maximizing the likelihood consisting of the product of the Z lineshape and the detector mass resolution. The use of the Z mass constraint gives another important improvement with respect to the previous published analysis.

**Figure 5.5.** The invariant mass distributions for a simulated MC sample with \( m_H = 130 \text{ GeV} \) in the 4\( \mu \) (a), 4\( e \) (b) and 2\( \mu \)2\( \mu \) and 2\( \mu \)2\( e \) (c) final states. The Gaussian fit (red) to the \( m_H \) peak is superimposed: the fitted range is chosen to be \(-2\sigma\) to \(2\sigma\) \((-1.5\sigma\) to \(2.5\sigma\)) for the 4\( \mu \) (2\( \mu \)2\( \mu \)/4\( e \)) final state. The slightly reduced mean values arise from radiative losses which are more explicit in final states involving electrons [78]. In (d), (e) and (f) the corresponding results after applying the Z mass constraint are shown.

In Figure 5.5 the invariant mass distributions for the four-lepton final states are shown, considering a \( m_H = 130 \text{ GeV} \) Higgs signal. Results without applying the Z mass constraint are on top, while the corresponding results after applying it are on the bottom. The improvement on the resolution is 15% for the 4\( \mu \), 13% for the 2\( \mu \)2\( \mu \)/2\( \mu \)2\( e \) and 10% for the 4\( e \) final state.
5.3 Background estimation

In this section the expected background yield and its composition are described. The irreducible background, the $ZZ^{(*)}$ process, is estimated using Monte Carlo simulation normalized to its theoretical cross section, while the reducible background, $ll+jets$ and $tt$ processes, is estimated by data-driven methods. The background composition depends on the flavour of the sub-leading pair: due to the different nature of the background sources for electrons and muons, two different approaches are taken for the $ll+\mu\mu$ and the $ll+ee$ final states.

5.3.1 $ll+\mu\mu$ background

The amount of $tt$ and $Z+jets$, mostly dominated by $Zb\bar{b}$ background events, in the signal region is estimated using a control region in which the $b\bar{b}$ contribution is enhanced. In this region, the $m_{12}$ distribution shows a peak at the $Z$ mass, due to $Zb\bar{b}$ events along with flat distribution of $tt$ events.

The control region is obtained by applying the selection criteria with some exceptions: no isolation requirement is applied to the leptons of the sub-leading pair and at least one of them is required to fail the impact parameter significance. In this way, the $ZZ^{(*)}$ contributions are removed and both $tt$ and $Z+jets$ background can be simultaneously estimated.

![Figure 5.6](image)

Figure 5.6. Distribution of $m_{12}$ for $\sqrt{s} = 7$ TeV (a) and $\sqrt{s} = 8$ TeV (b) in the control region with enhanced $b\bar{b}$ contribution. The fit (blue) is presented together with the MC expectations.

The $m_{12}$ distribution is then fitted using a second order Chebychev polynomial for the $tt$ contri-
bution and a Breit-Wigner lineshape convoluted with a Crystal Ball resolution function for the $Z$+jets component. Figure 5.6 shows the results of the fit for both $\sqrt{s} = 7$ TeV (a) and $\sqrt{s} = 8$ TeV (b) analyses. The shapes used in the fit are obtained from MC and the parameters are allowed to fluctuate within 10\% of their nominal values. The fit results are compatible with the MC expectations. The number of expected background events in the signal region is extrapolated from the yields in the control region by applying a transfer factor, derived from MC and defined as

$$f_{\text{transfer}} = \frac{\epsilon_{\text{iso}}}{1 - \epsilon_{d_0}},$$

(5.2)

where $\epsilon_{\text{iso}}$ and $\epsilon_{d_0}$ are the efficiencies of the sub-leading leptons to satisfy the impact parameter (IP) significance requirement and the isolation criteria. Table 5.9 reports the transfer factors and related IP significance and isolation efficiencies for both the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV analyses.

<table>
<thead>
<tr>
<th>process</th>
<th>IP efficiency (%)</th>
<th>isolation efficiency (%)</th>
<th>$f_{\text{transfer}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>$Z$+jets 56.9 ± 1.5</td>
<td>21.9 ± 1.3</td>
<td>2.3 ± 0.3 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$ 44.2 ± 1.7</td>
<td>9.6 ± 1.6</td>
<td>0.2 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td>$Z$+jets 49.6 ± 1.5</td>
<td>21.9 ± 1.3</td>
<td>1.6 ± 0.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$ 46.1 ± 1.7</td>
<td>10.5 ± 1.5</td>
<td>0.3 ± 0.1 ± 0.1</td>
</tr>
</tbody>
</table>

Table 5.9. Efficiencies of the IP significance and isolation requirements and corresponding transfer factors for $Z$+jets and $t\bar{t}$ processes in events that satisfy the $l\ell + \mu\mu$ selection.

The MC description of the selection efficiency has been verified with data in a control region obtained by selecting $Z + \mu$ events, where the $Z$ is selected applying the same selection criteria of the analysis to the leading di-lepton pair and exactly one extra muon is required. The efficiencies
of the isolation and IP significance requirements, shown in Figure 5.7, are derived using the extra muon: data and MC agree well.

The $t\bar{t}$ background is cross-checked and validated in a control region defined by selecting $e\mu + \mu\mu$ events, from which it possible get another estimate of the number of expected $t\bar{t}$ events in the signal region to be compared to the one found using the $m_{12}$ fit procedure. In this case the leading pair is formed by an opposite-charge $e\mu$ pair, which should have an invariant mass satisfying the same selection cuts applied to $m_{12}$, accompanied by an opposite-charge di-muon pair. In this way, events with a $Z$ candidate decaying to a pair of electrons or muons are excluded. The leptons of the quadruplet should satisfy the analysis selection criteria and the $p_T$ requirements are the same applied for the search analysis. Isolation and IP significance requirements are applied only to the leptons of the $e\mu$ pair. The number of expected and observed $e\pm\mu\mp + \mu\pm\mu\mp$ events for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV analyses are reported in Table 5.10.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ = 7 TeV</th>
<th>$\sqrt{s}$ = 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>8</td>
</tr>
<tr>
<td>MC</td>
<td>$11.0 \pm 0.6$</td>
</tr>
</tbody>
</table>

Table 5.10. Expected and observed $e\pm\mu\mp + \mu\pm\mu\mp$ events in 4.8 fb$^{-1}$ and 5.8 fb$^{-1}$ collision data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively.

The number of $t\bar{t}$ events in the signal region is extrapolated from the $e\mu + \mu\mu$ yield by applying a transfer factor derived from $t\bar{t}$ simulation as the ratio of yields in the kinematic region of the control region of $ee/\mu\mu + \mu\mu$ events to the $e\mu + \mu\mu$ yield. It is estimated to be $0.53 \pm 0.03$ and $0.57 \pm 0.03$ for the $ee/\mu\mu$ and $\mu\mu/\mu\mu$ final states, respectively. Also the efficiency of the application of IP significance and isolation requirements on the sub-leading pair are estimated from simulation.

It is found to be $(7.2 \pm 2.0) \cdot 10^{-5}$, averaging the $ee\mu\mu$ and $\mu\mu\mu\mu$ final states.

The expected $l\ell + \mu\mu$ background yields in the signal regions are summarized in Tables 5.11 and 5.12 for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV analyses, respectively.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$4\ell$</td>
</tr>
<tr>
<td>$m_{12}$ fit: $Z+\text{jets}$</td>
<td>$0.25 \pm 0.10 \pm 0.08$</td>
</tr>
<tr>
<td>$m_{12}$ fit: $t\bar{t}$</td>
<td>$0.022 \pm 0.010 \pm 0.011$</td>
</tr>
<tr>
<td>$t\bar{t}$ from $e^\pm\mu^\mp + \mu^\mp\mu^\mp$</td>
<td>$0.025 \pm 0.009 \pm 0.014^\dagger$</td>
</tr>
</tbody>
</table>

Table 5.11. Summary of the $l\ell + \mu\mu$ background estimates for the $\sqrt{s} = 7$ TeV data. The first uncertainty is statistical, while the second is systematic. $^\dagger$ indicates the cross-checked number of expected events not used for the background normalization.
CHAPTER 5. THE HIGGS BOSON DISCOVERY

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{12}$ fit: $Z$+jets</td>
<td>$4\mu$: $0.51 \pm 0.13 \pm 0.16$ $2e2\mu$: $0.41 \pm 0.10 \pm 0.13$</td>
</tr>
<tr>
<td>$m_{12}$ fit: $t\bar{t}$</td>
<td>$0.044 \pm 0.015 \pm 0.015$ $0.040 \pm 0.013 \pm 0.013$</td>
</tr>
<tr>
<td>$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}e^{\mp}$</td>
<td>$0.058 \pm 0.015 \pm 0.019$ $0.051 \pm 0.013 \pm 0.017$</td>
</tr>
</tbody>
</table>

Table 5.12. Summary of the $ll+\mu\mu$ background estimates for the $\sqrt{s} = 8$ TeV data. The first uncertainty is statistical, while the second is systematic. † indicates the cross-checked number of expected events not used for the background normalization.

Figure 5.8 shows the invariant mass distribution for $m_{12}$ (a) and $m_{34}$ (b) in the $ll+\mu\mu$ control sample, combining the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets. The leading and sub-leading pairs are required to satisfy the kinematic selection of the analysis, while the isolation and the IP significance requirements are applied only to the leptons of the leading pair. The $Z$+jets and $t\bar{t}$ contributions are normalized to the data-driven background estimates, while the $ZZ(\ast)$ background is normalized to its theoretical cross section. Data and simulation are in good agreement both for large values of $m_{34}$, where the $ZZ(\ast)$ background dominates, and for low $m_{34}$ values.

Figure 5.8. Invariant mass distribution of $m_{12}$ (a) and $m_{34}$ (b) in the $ll+\mu\mu$ control region defined by a $Z$-boson candidate and an additional di-muon pair, for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets combined. The kinematic selection of the analysis is applied. The isolation and IP parameter significance requirements are applied to the leading di-lepton pair only. The MC is normalized as described in the text.
5.3. BACKGROUND ESTIMATION

5.3.2 $ll + ee$ background

The $ll + ee$ background is estimated in a control region obtained by selecting $Z + ee$ events. The same selection criteria are applied to the leading pair, while the electron selection criteria are relaxed for the electrons of the sub-leading pair: the isolation and IP significance requirements are not applied. The $Z + ee$ sample is then divided into regions based on the classification of the two sub-leading electron candidates. In fact, these electron candidates can be either true isolated electrons, electrons from heavy flavour semi-leptonic decays ($Q$), electrons from photon conversions ($\gamma$) or light jets mis-reconstructed as electrons and denoted as fakes (f). Consequently, the different sources of electron background are classified in reconstruction categories, which are electron-like (E), conversion-like (C) and fake-like (F). These categories are defined using discriminating variables that are not used in the electron identification [133]: the number of b-layer hits, $n_{b\text{-layer}}$, the fraction of high-threshold hits in the TRT detectors, $R_{\text{TRT}}$, the energy in the first layer of the electromagnetic calorimeter, $f_1$, and the lateral containment cluster along $\phi$ in the second layer of the electromagnetic calorimeter $R_\phi$. The first variable is used to identify converted photons, while the latter three ones are used to discriminate electrons from hadrons. The three categories are selected as follows:

- **electron-like** (E): $f_1 > 0.1$, b-layer required (if expected), $R_{\text{TRT}} > 0.1$ within the TRT coverage ($|\eta| < 2.0$) or $R_\phi > 0.9$ elsewhere;

- **conversion-like** (C): no b-layer required (if expected) or number of pixel hits smaller than 2 (if a b-layer hit is not expected);

- **fake-like** (F): everything else.

A total of nine categories of sub-leading pairs are defined (i.e. EE, EC, EF, etc) and the categorization depends on the $p_T$ of the electron candidates, which are ordered in $p_T$. The numbers of observed events in each category of the control region are reported in Table 5.13 for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, together with the MC expectations. The total number of $ll + ee$ background events is the sum of the contributions of each category after extrapolation to the signal region.

For each category, the extrapolation to the signal region is done using toy pseudo-experiments [107], which have as inputs the number of events of the corresponding category and a transfer factor, defined as the product of efficiencies of each electron in the sub-leading pair to pass the IP significance and isolation criteria. For each experiment the individual background components are generated independently using Poisson statistics. The efficiencies for each electron category are obtained from $Z + e$ events: the leading pair should satisfy the same selection criteria of the search analysis, while relaxed electron requirements are applied to the additional electron, but requiring

\[ R_\phi \text{ defined as the ratio of the energy deposited in a } \Delta\eta \times \Delta\phi = 3 \times 7 \text{ cluster to that in } \Delta\eta \times \Delta\phi = 7 \times 7 \text{ cluster.} \]
CHAPTER 5. THE HIGGS BOSON DISCOVERY

<table>
<thead>
<tr>
<th>Cat.</th>
<th>4e</th>
<th>2μ2e</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>√s = 7 TeV</td>
<td>√s = 8 TeV</td>
</tr>
<tr>
<td>Data</td>
<td>MC</td>
<td>Data</td>
</tr>
<tr>
<td>EE</td>
<td>11</td>
<td>11.2±0.6</td>
</tr>
<tr>
<td>EC</td>
<td>4</td>
<td>2.5±0.8</td>
</tr>
<tr>
<td>EF</td>
<td>6</td>
<td>9.7±1.4</td>
</tr>
<tr>
<td>CE</td>
<td>5</td>
<td>1.5±0.7</td>
</tr>
<tr>
<td>CC</td>
<td>2</td>
<td>1.4±0.7</td>
</tr>
<tr>
<td>CF</td>
<td>7</td>
<td>4.7±1.2</td>
</tr>
<tr>
<td>FE</td>
<td>5</td>
<td>3.1±0.6</td>
</tr>
<tr>
<td>FC</td>
<td>5</td>
<td>3.0±1.0</td>
</tr>
<tr>
<td>FF</td>
<td>12</td>
<td>11.0±1.9</td>
</tr>
</tbody>
</table>

Table 5.13. The observed yields in the various categories in the l+l+ee control region for both √s = 7 TeV and √s = 8 TeV. Events are classified according to whether the sub-leading electrons are: electron-like (E), conversion-like (C) and fake-like (F). MC expectations are shown for comparison. The di-lepton categorization in reconstruction categories is ordered in pT.

The number of l+l+ee background events in the signal region is cross-checked in several control regions. One is defined selecting Z + ee events by requiring same sign sub-leading electron pairs. In this case the analysis selection criteria are applied to the leading pair, while relaxed selection criteria are applied to the electron candidates of the sub-leading pair. Also in this case, the categorization of the sub-leading pair is based on the classification of electron candidates and the extrapolation to the signal region is done using toy pseudo-experiments as described in the previous case. The results obtained are in agreement with those from the previous case.

Another check is done using a control region named 3l + l, in which same-sign sub-leading di-electron pairs are required. This control region has only to deal with the composition for the last lepton. Quadruplets are built as in the analysis and the three highest pT leptons have to satisfy all the analysis criteria. The remaining electron is required to satisfy the standard silicon hit requirements, consisting in at least one hit in the pixel detector and at least 7 hits in the silicon detector. The yields for the different components (f, γ, Q) are obtained from a simultaneous fit to templates obtained from the n^b-layer_ hits and the R_{TRT} distributions. The template fit is first applied
5.3. BACKGROUND ESTIMATION

![Figure 5.9](image)

**Figure 5.9.** The results of the simultaneous fit to \( n_{\text{hits}}^{\text{b-layer}} \) (a) and \( R_{\text{TRT}} \) (b) for the background components in the 2\( \mu \)2\( e \) final state at \( \sqrt{s} = 7 \text{ TeV} \). In (c) and (d) the corresponding results for the 4\( e \) final state at \( \sqrt{s} = 8 \text{ TeV} \) are shown.

Only to MC distributions and then extended to the data, where the requirement on the lateral containment of the cluster energy along \( \eta \) has been applied to decrease the hadronic component with respect to the others. In Figure 5.9 the results of the simultaneous fit to \( n_{\text{hits}}^{\text{b-layer}} \) and \( R_{\text{TRT}} \) for the 2\( \mu \)2\( e \) final state at \( \sqrt{s} = 7 \text{ TeV} \) and for the 4\( e \) final state at \( \sqrt{s} = 8 \text{ TeV} \) are shown. Additional
checks are performed substituting $R_{\text{TRT}}$ with $f_1$ and the difference in results (small) is taken into account as a systematic error. As for the other control regions, the expected background in the signal region is extrapolated using the corresponding selection efficiencies from $Z + e$ events and a relative systematic uncertainty of 5% is assigned. The number of events derived from this control region confirm the consistency of the ones derived for the first case.

The last check is done performing the full analysis and selecting same-sign electron pairs for the sub-leading pair. For data at $\sqrt{s} = 7$ TeV, 4 (2) events below $m_{4l} = 160$ GeV in the $4e$ ($2\mu2e$) final state are found, while for data at $\sqrt{s} = 8$ TeV, 4 (3) events in the $4e$ ($2\mu2e$) final state are found. In Figure 5.10 the invariant mass distributions ($m_{4l}$, $m_{12}$ and $m_{34}$) for the two same-sign events in the $2\mu2e$ final state, in data and MC at $\sqrt{s} = 7$ TeV, are shown.

The expected $ll+ee$ background yields in the signal region are summarized in Table 5.14 for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{s} = 7$ TeV</td>
</tr>
<tr>
<td></td>
<td>$4e$</td>
</tr>
<tr>
<td></td>
<td>$4e$</td>
</tr>
<tr>
<td>$ll + e^\pm e^\mp$</td>
<td>$3.1 \pm 0.6 \pm 0.5$</td>
</tr>
<tr>
<td>$ll + e^\pm e^\pm$</td>
<td>$3.2 \pm 0.6 \pm 0.5$</td>
</tr>
<tr>
<td>$3l + l$ (same sign)</td>
<td>$2.2 \pm 0.5 \pm 0.3$</td>
</tr>
</tbody>
</table>

Table 5.14. Summary of the $ll + ee$ background estimates for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data. The first uncertainty is statistical, while the second is systematic.† indicates the cross-checked number of expected events not used for the background normalization.
5.3. BACKGROUND ESTIMATION

Figure 5.11 shows the invariant mass distribution for $m_{12}$ (a) and $m_{34}$ (b) in the $ll + ee$ control sample, combining the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets. As for $ll + \mu\mu$ events, the leading and sub-leading pairs are required to satisfy the kinematic selection of the analysis, while the isolation and the IP significance requirements are applied only to the leptons of the leading pair. Also in this case, the shape and normalization of the background are in good agreement with the data.

![Graphs showing invariant mass distributions](image)

(a) $ll + ee$ background: $m_{12}$  
(b) $ll + ee$ background: $m_{34}$

**Figure 5.11.** Invariant mass distribution of $m_{12}$ (a) and $m_{34}$ (b) in the $ll + ee$ control region defined by a Z-boson candidate and an additional di-electron pair, for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets combined. The kinematic selection of the analysis is applied. The isolation and IP parameter significance requirements are applied to the leading di-lepton pair only. The MC is normalized as described in the text.

### 5.3.3 Summary of the background estimation

The background estimation from data-driven techniques was described, keeping the final state $ll + \mu\mu$ and $ll + ee$ separated. From the former the contribution of Z+jets and $t\bar{t}$ is extracted separately from different control regions, while from the latter their combined contribution is extracted. Considering each final state, the data-driven background estimates are summarized in Table 5.15 for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets. In Figure 5.12 the invariant mass distribution of the leading di-lepton pair, $m_{12}$, and the sub-leading one, $m_{34}$, are shown combining all final states, $ll + \mu\mu$ and $ll + ee$, and including the contribution of the Higgs boson signal with mass $m_{H} = 125$ GeV. The data samples at $\sqrt{s} = 7$ TeV and at $\sqrt{s} = 8$ TeV are combined and compared to the simulation. The Z+jets and $t\bar{t}$ contributions are normalized to the data-driven background
CHAPTER 5. THE HIGGS BOSON DISCOVERY

<table>
<thead>
<tr>
<th>Final state</th>
<th>Background</th>
<th>Estimated numbers of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$√s = 7$ TeV</td>
<td>$√s = 8$ TeV</td>
</tr>
<tr>
<td>$4µ$</td>
<td>$Z+$jets $t\bar{t}$</td>
<td>$0.3 \pm 0.1 \pm 0.1$ $0.5 \pm 0.1 \pm 0.2$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$</td>
<td>$0.02 \pm 0.02 \pm 0.02$ $0.04 \pm 0.02 \pm 0.02$</td>
</tr>
<tr>
<td>$2\mu 2\mu$</td>
<td>$Z+$jets $t\bar{t}$</td>
<td>$0.2 \pm 0.1 \pm 0.1$ $0.4 \pm 0.1 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$</td>
<td>$0.02 \pm 0.01 \pm 0.01$ $0.04 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$2\mu 2e$</td>
<td>$Z+$jets $t\bar{t}$</td>
<td>$2.6 \pm 0.4 \pm 0.4$ $4.9 \pm 0.8 \pm 0.7$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$</td>
<td>$3.1 \pm 0.6 \pm 0.5$ $3.9 \pm 0.7 \pm 0.8$</td>
</tr>
</tbody>
</table>

Table 5.15. Summary of the estimated number of $Z+$jets and $t\bar{t}$ background events, for $√s = 7$ TeV and $√s = 8$ TeV. The backgrounds are combined for the $2\mu 2e$ and $4e$ final states, as discussed in the text. The first uncertainty is statistical, while the second is systematic.

Figure 5.12. Invariant mass distributions of the lepton pairs in a sample defined by a $Z$ boson candidate and an additional same-flavour di-lepton pair, for the $√s = 7$ TeV and $√s = 8$ TeV datasets combined: $m_{12}$ (a) and $m_{34}$ (b) distributions for all events ($ll + \mu\mu$ and $ll + ee$) are shown. The kinematic selection of the analysis is applied, while isolation and IP significance requirements are applied to the first di-lepton pair only. The MC is normalized as described in the text.

estimates, while the $ZZ^{(*)}$ one is normalized to its theoretical cross section. As expected, in the background control region the contribution of the $m_H = 125$ GeV Higgs signal is small. Data and simulation show a good agreement.
5.3. BACKGROUND ESTIMATION

5.3.4 Single resonant \( pp \rightarrow Z \rightarrow 4l \)

In order to verify the background estimation methods also at a lower mass range, a special check is done in reconstructing the single resonant \( pp \rightarrow Z \rightarrow 4l \) process (Figure 5.13).

![Feynman diagram of the single resonant \( pp \rightarrow Z \rightarrow 4l \) process.](image)

To increase the acceptance of the \( Z \rightarrow 4l \) events the kinematic requirements have been relaxed with respect to the ones of the search analysis: \( m_{12} \) should have a value between 30 GeV and 106 GeV, \( m_{34} \) should be in the range 5-115 GeV, and the \( p_T \) requirement on the softest lepton is relaxed to 4 GeV. Only for the \( 4\mu \) final state the requirement on the third lepton has been relaxed to 8 GeV. Figure 5.14 shows the \( m_{4l} \) distributions, combining all the final states, for the single resonant peak \( Z \rightarrow 4l \). The comparisons between data and MC are shown for the \( \sqrt{s} = 7 \) TeV (a) and \( \sqrt{s} = 8 \) TeV (b).

![Invariant mass of the four leptons, combining all the final states, demonstrating the single resonant peak \( pp \rightarrow Z \rightarrow 4l \).](image)

(a) \( pp \rightarrow Z \rightarrow 4l : \sqrt{s} = 7 \) TeV

(b) \( pp \rightarrow Z \rightarrow 4l : \sqrt{s} = 8 \) TeV

Figure 5.14. Invariant mass of the four leptons, combining all the final states, demonstrating the single resonant peak \( pp \rightarrow Z \rightarrow 4l \). The comparison between data and simulation is shown for \( \sqrt{s} = 7 \) TeV (a) and \( \sqrt{s} = 8 \) TeV (b). The comparisons between data and MC are shown for the \( \sqrt{s} = 7 \) TeV (a) and the \( \sqrt{s} = 8 \) TeV (b) datasets. Figure 5.15 shows the same distribution but combining the two datasets. A good agreement between data and MC is found.
5.4 Systematic uncertainties

There are many sources of systematic error that have to be taken into account. One of them is the theoretical uncertainty of the Higgs-boson cross section. As discussed in Section 5.1, it has been extensively studied by the LHC Higgs cross section working group. The QCD scale uncertainties for $m_H = 125$ GeV amount to $+7\%$ to $-8\%$ for the gluon-fusion process, while for the vector-boson fusion and associated production with a $W$ or $Z$ boson they are $\pm 1\%$. The uncertainty on the production cross section due to uncertainties on the PDF and $\alpha_s$ is $\pm 8\%$ for gluon-initiated processes and $\pm 4\%$ for quark-initiated processes: these uncertainties have been estimated following the prescription in Reference [134] and by using the PDF sets of CTEQ [135], MSTW [136] and NNPDF [137]. The uncertainties on the predicted branching ratios are $\pm 5\%$.

Concerning the SM $ZZ^{(*)}$ background, the QCD scale uncertainty gives an uncertainty of $\pm 5\%$ on the total yield. The PDF and $\alpha_s$ uncertainties give an effect of $\pm 4\%$ and $\pm 8\%$ for processes initiated by quarks and gluons, respectively. Also the dependence of these uncertainties on the four-lepton invariant mass spectrum has been taken into account. In addition the theoretical constraints on the $ZZ^*$ yield on the search for a Higgs boson has been used: its impact has been studied [106] and found to be negligible. Also the impact of the interference between a Higgs signal and the non-resonant $gg \rightarrow ZZ$ background is small and becomes negligible for $m_H < 2m_Z$ [138]. The uncertainty on the integrated luminosity has to be taken into account. It has been determined to be $\pm 1.8\%$ for the $\sqrt{s} = 7$ TeV data and $\pm 3.6\%$ for the $\sqrt{s} = 8$ TeV data. The uncertainties on the lepton reconstruction and identification efficiencies and on momentum
resolution and scale are determined using samples of $W$, $Z$ and $J/\psi$ decays, as described in Chapter 3. The uncertainties on the muon and electron identification and reconstruction efficiency result in a relative acceptance uncertainty for the signal and the $ZZ^{(*)}$ background, which is uniform over the mass range. From the muon side the uncertainty amounts to $\pm 0.7\%$ ($\pm 0.5\%/\pm 0.5\%$) for the $4\mu$ ($2e2\mu/2\mu2e$) final state for $m_{4\ell} = 600$ GeV and increases to $\pm 0.9\%$ ($\pm 0.8%/\pm 0.5\%$) for $m_{4\ell} = 115$ GeV. Similarly, from the electron side, this relative acceptance uncertainty is $\pm 2.6\%$ ($\pm 1.7%/\pm 1.8\%$) for the $4e$ ($2e2\mu/2\mu2e$) final state for $m_{4\ell} = 600$ GeV and reaches $\pm 8.0\%$ ($\pm 2.3%/\pm 7.6\%$) for $m_{4\ell} = 115$ GeV. The impact of the uncertainties on the electron energy resolution and on the muon momentum resolution and scale are found to be negligible. The effect of the uncertainty on the electron energy scale results instead in an uncertainty of $\pm 0.7\%$ ($\pm 0.5%/\pm 0.2\%$) on the mass scale of the $m_{4\ell}$ distribution for the $4e$ ($2e2\mu/2\mu2e$) final state.

### 5.5 Results

After applying the selection cuts, the expected $m_{4\ell}$ distributions for the total background and several signal hypotheses are compared to the data. Figure 5.16 shows the $m_{4\ell}$ distributions for data and simulation for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

![Figure 5.16](image)

(a) $\sqrt{s} = 7$ TeV

(b) $\sqrt{s} = 8$ TeV

**Figure 5.16.** The $m_{4\ell}$ distributions for the selected candidates compared to the background expectations in the range 80-600 GeV for $\sqrt{s} = 7$ TeV (a) and $\sqrt{s} = 8$ TeV (b). The signal expectations for several $m_{4\ell}$ hypotheses are also shown.

In Table 5.16 the observed numbers of events for each final state are summarized and compared
to the expected backgrounds and to various signal hypotheses, for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The expected background events are divided in two mass regions: “Low Mass”, defined as $m_4l < 160$ GeV, and “High mass”, defined as $m_4l \geq 160$ GeV. The number of observed events in the “High mass” region is greater than the MC expectation. The $ZZ(\ast)$ background in this region is underestimated by simulation. This has no effect for the “Low Mass” region.

<table>
<thead>
<tr>
<th>$4\mu$</th>
<th>2e$2\mu$/2$\mu$2e</th>
<th>4e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low mass</td>
<td>High mass</td>
<td>Low mass</td>
</tr>
<tr>
<td>Data</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>$ZZ(\ast)$</td>
<td>4.6±0.2</td>
<td>18.6±1.3</td>
</tr>
<tr>
<td>$Z$+jets and $t\bar{t}$</td>
<td>0.2±0.1</td>
<td>0.07±0.03</td>
</tr>
<tr>
<td>Total Background</td>
<td>4.8±0.2</td>
<td>18.6±1.3</td>
</tr>
<tr>
<td>$m_H = 125$ GeV</td>
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<td>1.0±0.2</td>
</tr>
<tr>
<td>$m_H = 150$ GeV</td>
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<td>3.4±0.5</td>
</tr>
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<td>$m_H = 190$ GeV</td>
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<td>7.4±1.1</td>
</tr>
<tr>
<td>$m_H = 400$ GeV</td>
<td>2.3±0.3</td>
<td>3.8±0.6</td>
</tr>
</tbody>
</table>

| $5.8$ fb$^{-1}$ at $\sqrt{s} = 8$ TeV |
| Data | 4 | 34 | 11 | 61 | 7 | 25 |
| $ZZ(\ast)$ | 6.3±0.3 | 27.3±2.0 | 3.9±0.2 | 41.4±3.1 | 2.9±0.3 | 17.7±1.4 |
| $Z$+jets and $t\bar{t}$ | 0.4±0.2 | 0.15±0.07 | 3.9±0.9 | 1.4±0.3 | 2.9±0.8 | 1.0±0.3 |
| Total Background | 6.7±0.3 | 27.4±2.0 | 7.8±1.0 | 42.8±3.1 | 5.8±0.8 | 18.7±1.4 |
| $m_H = 125$ GeV | 1.4±0.2 | 1.7±0.2 | 0.8±0.1 |
| $m_H = 150$ GeV | 4.5±0.6 | 5.9±0.8 | 2.7±0.4 |
| $m_H = 190$ GeV | 8.2±1.0 | 12.5±1.7 | 5.3±0.8 |
| $m_H = 400$ GeV | 3.9±0.5 | 6.6±0.9 | 2.9±0.4 |

Table 5.16. The observed numbers of events and the final estimates for the expected backgrounds, divided into “Low mass” ($m_4l < 160$ GeV) and “High mass” ($m_4l \geq 160$ GeV) regions, together with the expected numbers of signal events for various Higgs boson mass hypotheses. The corresponding total uncertainty is also given.

Table 5.17. The numbers of observed and expected signal and background events in a window of ±5 GeV around the $m_H = 125$ GeV Higgs boson mass hypothesis for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets as well as for their combination.
5.5. RESULTS

Table 5.17 presents the observed and expected events, for signal and background, in a window of ±5 GeV around the $m_H = 125$ GeV Higgs boson mass hypothesis for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets and their combination. The expected signal and background events are reported with their corresponding uncertainties.

Figure 5.17. The $m_4l$ distributions for each final state, $4\mu$ (a), $2\mu2e$ (b), $2e2\mu$ (c) and $4e$ (d), in the mass range 80-250 GeV for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV combined. The signal expectations for several $m_H$ hypotheses are also shown.
CHAPTER 5. THE HIGGS BOSON DISCOVERY

Figure 5.17 shows the $m_{4\ell}$ mass distributions for each final state, $4\mu$ (a), $2\mu2e$ (b), $2e2\mu$ (c) and $4e$ (d), in the mass range 80-250 GeV for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV combined. Figure 5.18a shows the same distribution but combining all the final states.

![Figure 5.17](image1)

![Figure 5.18a](image2)

Figure 5.18. (a) The $m_{4\ell}$ distribution in the mass range 80-250 GeV combining all final states at both energies. (b) Distribution of the $m_{34}$ versus the $m_{12}$ invariant mass for the selected candidates in the $m_{4\ell}$ range 120-130 GeV. The expected distributions for a SM Higgs with $m_H = 125$ GeV (boxes) and for the total background (shading) are also shown.

High-$p_T$ photon emission from final-state radiation (FSR) is not taken into account explicitly in the lepton reconstruction and affects the reconstructed invariant mass rarely. Anyway, all selected candidates have been checked and no appreciable FSR activity has been found.

A likelihood function $L$ that depends on the Higgs boson mass, $m_H$, and the signal strength, $\mu$, which acts as a scale factor on the total number of events predicted by the SM for each of the Higgs boson signal processes, is constructed using the signal and background model

$$L(m_H, \mu, \theta) = \prod_\text{year} \prod_\text{final state} \text{Pois}(N_{i,j} | \mu \cdot S_{i,j}(m_H, \theta) + B_{i,j}(\theta)) \cdot \prod_{k=1}^{N_{i,j}} F_{i,j}(m_{4\ell}^k, m_H, \mu, \theta). \quad (5.3)$$

This represents the product of the Poisson distribution corresponding to the observation of $N_{i,j}$ events for 2011 and 2012 datasets and each of the four final states, given the expectation for the signal $S_{i,j}$ and background $B_{i,j}$. This is also multiplied by the product of the values of the pdf $F_{i,j}$, constructed using the signal and background pdf, for each $k$ event. $\theta$ represents the set of...
nuisance parameters used for the systematic uncertainties.

The statistical test used is the likelihood ratio \( \Lambda(\alpha) \) \[^{139}\] that depends on one or more parameters of interest \( \alpha \) (i.e. the Higgs boson mass or the signal strength) and on nuisance parameters \( \theta \):

\[
\Lambda(\vec{\alpha}) = \ln \frac{L(\vec{\alpha}, \hat{\theta}(\vec{\alpha}))}{L(\hat{\alpha}, \theta)}.
\]

(5.4)

The likelihood fit to the data is then performed for the parameter of interest: \( \hat{\theta} \) denotes the unconditional maximum likelihood estimate of a parameter and \( \hat{\theta} \) corresponds to the conditional maximum likelihood estimate for given fixed values of the parameters of interest. In the case of the signal strength measurement, \( \mu \) is the only parameter of interest: this means that the measurements is done as a function of the hypothesised Higgs boson mass \( m_H \).

Figure 5.19 shows the observed and expected 95% CL cross section upper limits, as a function of \( m_H \), for the combination of the 2011 and 2012 data. The upper limits are set using the \( CL_s \) modified frequentist formalism \[^{140}\] with the profile likelihood ratio test statistic. The test statistic is evaluated using a maximum-likelihood fit of signal and background models to the observed \( \sigma_4l \) distributions. Combining the two datasets, the SM Higgs boson is excluded at 95% confidence level (CL) in the mass ranges 131-162 GeV and 170-460 GeV. The expected exclusion ranges are 124-164 GeV and 176-500 GeV.

Figure 5.19. The expected (dashed) and observed (full line) 95% CL upper limits on the SM Higgs boson production cross section as function of \( m_H \), divided by the expected SM Higgs boson cross section, for the combination of the \( \sqrt{s} = 7 \) TeV and \( \sqrt{s} = 8 \) TeV data samples. The green (yellow) band indicates the expected limits with \( \pm 1\sigma \) \((\pm 2\sigma)\).
The significance of an excess is given by the probability, $p_0$, that a background-only experiment is more signal-like in terms of the test statistic than the observed data. The probability to observe an excess at a fixed mass is called local $p_0$. Figure 5.20 shows the local $p_0$ using the asymptotic approximation [139] as a function of $m_H$ for the combination of the 2011 and 2012 datasets. The most significant upward deviations from the background-only hypothesis are observed at $m_H = 125$ GeV with a local $p_0$ of 0.018%, corresponding to 3.6 standard deviations.

Figure 5.20. The observed local $p_0$ for the combination of the 2011 and 2012 datasets (solid black line) and for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets separately (blue and red respectively). The dashed curves show the expected median local $p_0$ for the signal hypothesis when tested at the corresponding $m_H$.

Figure 5.21 shows the signal strength parameter $\mu = \sigma/\sigma_{SM}$ as a function of $m_H$ for the combination of the 2011 and 2012 datasets (a) and the corresponding result in the case where a SM Higgs signal of $m_H = 125$ GeV is injected (b). The profile likelihood ratio $\Lambda(\mu)$ used for the inclusive signal strength measurement is given by Equation 5.4 where $\mu$ is the parameter of interest, $m_H$ is profiled and the others are the nuisance parameters. The value of the signal strength at 125 GeV is $\mu = 1.4^{+0.6}_{-0.5}$.

5.6 Combination with other Higgs boson searches

In addition to the $H \rightarrow ZZ(\rightarrow 4l)$ search, the other searches of SM Higgs boson in ATLAS show the same conclusions. This search is combined [3] with the results from the other decay channels:
5.6. COMBINATION WITH OTHER HIGGS BOSON SEARCHES

Figure 5.21. (a) The signal strength parameter $\mu = \sigma/\sigma_{SM}$ as a function of $m_H$ obtained from a fit to the data for the combined fit to the 2011 and 2012 datasets. (b) The corresponding result when a SM Higgs signal with $m_H = 125$ GeV is injected.

$H \to \gamma\gamma$ and $H \to WW^{(*)}$, both obtained using the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets, and $H \to bb$ and $H \to \tau\tau$, both obtained using the $\sqrt{s} = 7$ TeV dataset.

Figure 5.22 shows the combined 95% CL exclusion limits on the production of the SM Higgs boson, expressed in terms of the signal strength parameter $\mu$, as a function of $m_H$. The observed 95% CL exclusion regions are between 111 GeV and 122 GeV and between 131 GeV and 559 GeV. The mass regions between 113-114 GeV, 117-121 GeV and 132-527 GeV are excluded at 99% CL.

Figure 5.23a shows the observed local $p_0$ as a function of $m_H$ in the low mass range. The largest local significance combining the 2011 and 2012 datasets and all decay channels is found for a SM Higgs boson mass hypothesis of $m_H = 126.5$ GeV, where it reaches 6 standard deviations, with an expected value in the presence of a SM Higgs boson signal at that mass of 4.9 standard deviations.

The mass of the observed new particle is estimated using the profile likelihood ratio $\lambda(m_H)$ of the two channels with the highest mass resolution, $H \to ZZ^{(*)} \to 4l$ and $H \to \gamma\gamma$. The resulting estimate for the mass of the observed particle is $m_H = 126.0 \pm 0.4$ (stat) $\pm 0.4$ (syst) GeV.

The best-fit signal strength $\mu$ is shown in Figure 5.23b as a function of $m_H$. The observed excess corresponds to $\mu = 1.4 \pm 0.3$ for $m_H = 126$ GeV, which is consistent with the SM Higgs boson hypothesis $\mu = 1$. 

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Figure 5.22. The observed (solid) 95% CL upper limits on the signal strength as a function of $m_H$ and the expectation (dashed) under the background-only hypothesis, for all decay channels combined. The green (yellow) band shows the ±1σ (±2σ) uncertainties on the background-only expectation.

Figure 5.23. (a) The observed (solid) local $p_0$ as a function of $m_H$ and (b) the best-fit signal strength as a function of $m_H$, for the full combination of the 2011 and 2012 data.
Chapter 6

Updated results of the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ analysis

In Chapter 5 the discovery of a Higgs-like boson by the ATLAS collaboration has been presented. At that time, the analysis of the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel was done using an integrated luminosity of 4.8 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 5.8 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. This chapter presents an update of the analysis in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel [141] [142] [143] using the full data sample collected in 2012, corresponding to an integrated luminosity of 20.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV, combined with the full data sample collected in 2011. The analysis remains largely the same as the one described in Chapter 5 with only few changes (see Section 6.2). The updated results focus on the background estimation, the limits on the production cross section, and the measurement of the signal strength and of the mass of the SM Higgs boson candidate.

An important step in the confirmation of the new particle as the SM Higgs boson is the measurement of its properties. The SM makes precise predictions for the couplings of the Higgs boson to all other known particles, which influence the production and the decay rates of the Higgs boson. To explore further the coupling structure of the Higgs boson, each event can be classified into one of three production mode categories according to their jet activity or extra lepton: vector-boson fusion production mode (VBF-like), vector-boson associated production mode (VH-like) and gluon-fusion production mode (ggF-like). Moreover, the SM predicts the Higgs boson to be a scalar particle (spin 0) with even parity. The measurements of the spin and parity of the newly observed particle will be discussed in Chapter 7.
CHAPTER 6. UPDATED RESULTS OF THE $H \rightarrow ZZ^{(*)} \rightarrow 4l$ ANALYSIS

6.1 Data and Monte Carlo samples

Data samples
As discussed in Section 5.1, the data are subjected to quality requirements. For this updated analysis and the spin and parity measurements 2011 and 2012 collision data are used, corresponding to 4.6 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 20.7 fb$^{-1}$ for $\sqrt{s} = 8$ TeV, for a total integrated luminosity of about 25 fb$^{-1}$. Due to different data quality requirements, the integrated luminosity of 2011 collision data decreased from 4.8 fb$^{-1}$ to 4.6 fb$^{-1}$ with respect to the previous analysis.

Monte Carlo signal samples
The $H \rightarrow ZZ^{(*)} \rightarrow 4l$ signal is modelled using the same Monte Carlo generators and using the same procedure as described in Section 5.1. For this updated analysis, the contribution of the associated production with a $t\bar{t}$ pair ($t\bar{t}H$) is included; its simulation has been done using Pythia. The $p_T$ re-weighting of the gluon fusion process is applied at the analysis level to the simulated events of 2011 MC samples, while for 2012 MC samples it is included in the event generation. The cross sections for the exclusive production mechanisms and the branching ratios for three generated $m_H$ are reported in Table 6.1 for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$\sigma(gg \rightarrow H)$ (pb)</th>
<th>$\sigma(qq' \rightarrow Hqq')$ (pb)</th>
<th>$\sigma(q\bar{q} \rightarrow WH)$ (pb)</th>
<th>$\sigma(q\bar{q} \rightarrow ZH)$ (pb)</th>
<th>$\sigma(q\bar{q}/gg \rightarrow t\bar{t}H)$ (pb)</th>
<th>BR [10$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123</td>
<td>15.8$^{+2.3}_{-2.4}$</td>
<td>1.25 ± 0.03</td>
<td>0.60$^{+0.02}_{-0.03}$</td>
<td>0.33 ± 0.02</td>
<td>0.09$^{+0.01}_{-0.02}$</td>
<td>0.103</td>
</tr>
<tr>
<td>125</td>
<td>15.3 ± 2.3</td>
<td>1.22 ± 0.03</td>
<td>0.57 ± 0.02</td>
<td>0.32 ± 0.02</td>
<td>0.09$^{+0.01}_{-0.02}$</td>
<td>0.125</td>
</tr>
<tr>
<td>127</td>
<td>14.9 ± 2.2</td>
<td>1.20 ± 0.03</td>
<td>0.54 ± 0.02</td>
<td>0.30 ± 0.02</td>
<td>0.08 ± 0.01</td>
<td>0.148</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123</td>
<td>20.2 ± 3.0</td>
<td>1.61 ± 0.05</td>
<td>0.73 ± 0.03</td>
<td>0.42 ± 0.02</td>
<td>0.14 ± 0.02</td>
<td>0.103</td>
</tr>
<tr>
<td>125</td>
<td>19.5 ± 2.9</td>
<td>1.58$^{+0.04}_{-0.05}$</td>
<td>0.70 ± 0.03</td>
<td>0.39 ± 0.02</td>
<td>0.13 ± 0.02</td>
<td>0.125</td>
</tr>
<tr>
<td>127</td>
<td>18.9 ± 2.8</td>
<td>1.55 ± 0.05</td>
<td>0.66$^{+0.02}_{-0.03}$</td>
<td>0.37 ± 0.02</td>
<td>0.12$^{+0.01}_{-0.02}$</td>
<td>0.148</td>
</tr>
</tbody>
</table>

Table 6.1. Higgs boson production cross sections for gluon fusion, vector-boson fusion and associated production with a $W$ or $Z$ boson or a $t\bar{t}$ pair in $p$-$p$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV for several Higgs boson masses around 125 GeV. The quoted uncertainties correspond to the total theoretical systematic uncertainties, with a linear sum of QCD scale and PDF+$\alpha_s$ uncertainties. The decay branching ratio (BR) for $H \rightarrow ZZ^{(*)} \rightarrow 4l$, with $l = e$ or $\mu$, is also reported.

Monte Carlo background samples
The background processes are modelled using the MC generators and using the same procedure as described in Section 5.1.
6.2 Event selection

In this section the changes in the event selection with respect to the previous analysis will be discussed. Concerning data quality requirements, a standard ‘Good Run List’ (GRL) is applied to each final state, instead of a specific one used in the previous analysis: this results in a reduced integrated luminosity for \(\sqrt{s} = 7\) TeV collision data, from 4.8 fb\(^{-1}\) to 4.6 fb\(^{-1}\). The trigger requirements for the single-lepton and the di-lepton triggers remain the same as discussed in Section 5.2.1.

In this updated analysis, electron-muon triggers are also applied. For collision data at \(\sqrt{s} = 7\) TeV, the electron-muon trigger has an \(E_T\) threshold of 10 GeV for the electron and a \(p_T\) threshold of 6 GeV for the muon, while for collision data at \(\sqrt{s} = 8\) TeV the thresholds are 12 GeV or 24 GeV for the electron \(E_T\) and 8 GeV for the muon \(p_T\). The efficiency for events to be selected by at least one of the triggers considered is greater than 97% for events with muons and around 100% for events with four electrons.

The lepton identification for the \(\sqrt{s} = 7\) TeV data remains unchanged, while for \(\sqrt{s} = 8\) TeV the multi-lepton electron identification has been tightened for \(E_T < 15\) GeV to improve the \(Z+\)jets background rejection. The selection of electrons in the calorimeter has been tightened around the crack region (1.37 < \(|\eta|\) < 1.52), where there was a large contribution to the background, and a stricter pixel hit requirement to limit conversions has been imposed everywhere. This results in a increased reducible background rejection of the order of 40%. Then, the selection criteria applied to muons and electrons are the same as described in Section 5.2.3.

The lepton quadruplet selection criteria follow the ones given in Section 5.2.4 with only two changes: a loosened cut on the mass of the sub-leading pair, \(m_{34}\), at lower \(m_{4l}\) values and a different choice of the lepton pairing in order to reduce the mis-pairing in the 4\(\mu\) and 4\(e\) final states. The value of \(m_{34}\) is required to be in the range \(m_{\text{min}} < m_{34} < 115\) GeV, where \(m_{\text{min}}\) is 12 GeV for \(m_{4l} < 140\) GeV, then it rises linearly to 50 GeV at \(m_{4l} = 190\) GeV and stays at this value for \(m_{4l} > 190\) GeV. Within the same event multiple quadruplets are possible: for four or more muons or electrons there are multiple ways to choose the lepton pairs. In this analysis, only the quadruplet with the same-flavour and opposite-sign di-lepton pair closest to the \(Z\) boson mass is kept within the event. The discovery analysis retained events where the pairing with \(m_{12}\) closest to the \(Z\) boson mass does not have an \(m_{34}\) passing the mass requirements, but another pairing with \(m_{12}\) and \(m_{34}\) passing the requirements. The present approach reduces the mis-pairing in the 4\(\mu\) and 4\(e\) final states to below 10% from around 20% in the previous analysis. All other additional requirements (i.e. isolation criteria, IP significance) remain the same as discussed in Section 5.2.5.

6.2.1 Event categorization

Each Higgs-boson candidate satisfying the selection criteria is assigned to one of three production mode categories depending on its characteristics. Events falling in the VBF-like category should
have two high $p_T$ jets widely separated in pseudo-rapidity. The jets are reconstructed from topological clusters and the ones within the ID acceptance ($|\eta| < 2.47$) are required to have more than 50% of the sum of the scalar $p_T$ of their associated tracks coming from the primary vertex, in order to reduce the background from pile-up. The jets should satisfy the requirement of $p_T > 25$ (30) GeV for $|\eta| < 2.5$ (2.5 $< |\eta| < 4.5$), be separated by more than 3 units in pseudo-rapidity and have an invariant mass greater than 350 GeV. Events satisfying these requirements are classified as VBF-like, others are considered for the VH-like category. Events are classified as VH-like if there is an additional lepton (e or $\mu$) to the four ones forming the Higgs boson candidate. This additional lepton should have $p_T > 8$ GeV and satisfy the same lepton requirements applied to the ones of the quadruplet. Finally, events that are not classified as VBF-like or VH-like are assigned to the ggF-like category.

### Table 6.2

<table>
<thead>
<tr>
<th>Category</th>
<th>$gg \to H$</th>
<th>$q\bar{q}/gg \to t\bar{t}H$</th>
<th>$q\bar{q}' \to Hqq'$</th>
<th>$q\bar{q} \to W/ZH$</th>
<th>$ZZ^{(*)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>ggF-like 2.20</td>
<td>0.14</td>
<td>0.11</td>
<td>57.5</td>
<td></td>
</tr>
<tr>
<td>VBF-like</td>
<td>0.03</td>
<td>0.06</td>
<td>-</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>VH-like</td>
<td>0.01</td>
<td>-</td>
<td>0.03</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td>ggF-like 13.5</td>
<td>0.79</td>
<td>0.65</td>
<td>320.4</td>
<td></td>
</tr>
<tr>
<td>VBF-like</td>
<td>0.28</td>
<td>0.43</td>
<td>0.01</td>
<td>3.58</td>
<td></td>
</tr>
<tr>
<td>VH-like</td>
<td>0.06</td>
<td>-</td>
<td>0.14</td>
<td>0.69</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2. The expected number of events in each category, after applying all selection criteria, for each signal production mechanism at $m_H = 125$ GeV and the $ZZ^{(*)}$ background. The numbers of events are reported for $4.6$ fb$^{-1}$ at $\sqrt{s} = 7$ TeV and $20.7$ fb$^{-1}$ at $\sqrt{s} = 8$ TeV. The requirement $m_{4l} > 100$ GeV is applied.

Table 6.2 shows the expected number of events in each category for each Higgs boson production mechanism, with mass $m_H = 125$ GeV, and the $ZZ^{(*)}$ background. The number of expected events for the VBF and VH production mechanisms is very low: most events are classified as ggF-like.

### 6.2.2 Selection efficiency and mass resolution

The combined signal reconstruction and selection efficiencies are reported in Table 6.3.

In the analysis the effect on the reconstructed invariant mass due to photon emission from final state radiation (FSR) is evaluated and modelled by the MC. Only di-muon $Z_1$ candidates having $m_{12}$ in the range 66-89 GeV are corrected for FSR by including in the invariant mass a reconstructed
6.2. EVENT SELECTION

<table>
<thead>
<tr>
<th></th>
<th>4µ</th>
<th>2µ2e/2e2µ</th>
<th>4e</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>39%</td>
<td>21%</td>
<td>15%</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td>39%</td>
<td>26%</td>
<td>19%</td>
</tr>
</tbody>
</table>

Table 6.3. Combined signal reconstruction efficiency for each final state and for a $m_H = 125$ GeV signal MC at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

A photon with $E_T > 1$ GeV and lying close to one of the two muon tracks. In the case of one FSR candidate for each muon, the one with the highest $E_T$ is kept. The $\Delta R$ between the photon and one of the two muons should be $\Delta R < 0.08$ to 0.15, depending on the photon $E_T$. The corrected invariant mass should be $m_{\mu\mu\gamma} < 100$ GeV. For FSR photon energies below 3.5 GeV topological clusters are used to reconstruct and identify an FSR photon in the vicinity of a muon [144].

\[ \text{Table 6.3. Combined signal reconstruction efficiency for each final state and for a } m_H = 125 \text{ GeV signal MC at } \sqrt{s} = 7 \text{ TeV and } \sqrt{s} = 8 \text{ TeV.} \]

\[ \text{photon with } E_T > 1 \text{ GeV and lying close to one of the two muon tracks. In the case of one FSR candidates for each muon, the one with the highest } E_T \text{ is kept. The } \Delta R \text{ between the photon and one of the two muons should be } \Delta R < 0.08 \text{ to 0.15, depending on the photon } E_T. \text{ The corrected invariant mass should be } m_{\mu\mu\gamma} < 100 \text{ GeV. For FSR photon energies below 3.5 GeV topological clusters are used to reconstruct and identify an FSR photon in the vicinity of a muon [144].} \]

\[ \text{Figure 6.1. (a) Mass distribution of } Z \rightarrow \mu^+\mu^- \text{ events in data before (triangles) and after (bullets) FSR correction. Only events with } 66 \text{ GeV} < m_{\mu\mu} < 89 \text{ GeV and with } m_{\mu\mu\gamma} < 100 \text{ GeV are corrected for FSR. The MC prediction is shown before (red) and after (blue) FSR correction and for events without FSR photons (black) at generator level. (b) Mass distribution of simulated } H \rightarrow ZZ^{(*)} \rightarrow 4\mu \text{ events with mass } m_H = 125 \text{ GeV in which an FSR photon has been identified. The mass distributions before (solid blue) and after the FSR correction (dotted purple) are shown. The effect of applying the } Z \text{ mass constraint for these two cases is also shown (dashed black and solid red).} \]

The effect of the FSR correction is shown in Figure 6.1, where the invariant mass distributions
of the $Z \rightarrow \mu^+\mu^-$ candidate events with and without FSR correction are shown. The FSR reconstruction algorithm recovers 70% of the FSR photons within the selected fiducial region and about 85% of the corrected events have genuine FSR photons, with the remaining misidentified photons coming from pile-up and muon ionization. According to the MC simulation, about 4% of all $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ candidate events should have the FSR correction applied.

Then the $Z$ mass constraint is applied as described in Section 5.2.6. Figure 6.1b shows the mass distribution for $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ events, with mass $m_H = 125$ GeV, where an FSR photon has been identified. The mass resolution is clearly improved after applying first the FSR correction and then the $Z$ mass constraint (solid red) with respect of the case in which no corrections are applied (solid blue).

![Figure 6.2](image)

**Figure 6.2.** The invariant mass distribution for a simulated MC sample with $m_H = 125$ GeV in the $4\mu$ (a), $4e$ (b) and $2\mu2\mu$ and $2\mu2e$ (c) final states. The Gaussian fit (red) to the $m_{4\ell}$ peak is superimposed: the fit range is $-2\sigma$ to $2\sigma$ ($-1.5\sigma$ to $2.5\sigma$) for the $4\mu$ ($2\mu2\mu/4e$) final state. (d), (e) and (f) show the corresponding results after applying the $Z$ mass constraint.
In Figure 6.2 the invariant mass distributions for the four-lepton final states are shown. Results without applying the Z mass constraint are on top, while the corresponding results after applying it are on the bottom. The predicted natural width of the Higgs boson is approximately 4 MeV at $m_H = 125$ GeV.

6.3 Background estimation

The background estimation follows the methods discussed in Section 5.3. The $ZZ^{(*)}$ background is estimated using Monte Carlo simulation normalized to its theoretical cross section, while the reducible background, composed of $ll$+jets and $t\bar{t}$, is estimated by data-driven methods. As in the discovery analysis, the background composition is studied selecting the $ll + \mu\mu$ and the $ll + ee$ final states.

6.3.1 $ll + \mu\mu$ background

The number of $Z$+jets and $t\bar{t}$ background events in the signal region is extrapolated from a control region, as defined in Section 5.3.1 in which the $b\bar{b}$ contribution is enhanced. The yields of the two background processes are obtained through a fit on the $m_{12}$ distribution, where the fit function used contains a second order Chebychev polynomial, for the $t\bar{t}$ contribution, and a Breit-Wigner line-shape convoluted with a Crystal Ball resolution function, for the $Z$+jets contribution. The extrapolation to the signal region is done by using transfer factors derived using Equation 5.2 and computing the isolation and IP significance efficiencies of the two sub-leading muons.

For the $\sqrt{s} = 7$ TeV data sample, due to the limited data, the fit is performed in the inclusive $ll + \mu\mu$ final state, keeping together the 4$\mu$ and 2$e$2$\mu$ final states. The fit is instead performed separately for each of the two final state for the $\sqrt{s} = 8$ TeV data sample. In Figure 6.3 the results are presented. In Table 6.4 the transfer factors and related IP significance and isolation efficiencies are reported.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>process</th>
<th>IP efficiency (%)</th>
<th>isolation efficiency (%)</th>
<th>$f_{\text{transfer}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>$Z$+jets</td>
<td>55.7 ± 1.3</td>
<td>21.3 ± 1.1</td>
<td>2.8 ± 0.2 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$</td>
<td>44.2 ± 1.2</td>
<td>10.2 ± 1.0</td>
<td>0.3 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>8</td>
<td>$Z$+jets</td>
<td>48.3 ± 0.5</td>
<td>23.7 ± 0.5</td>
<td>3.06 ± 0.46 ± 0.77</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$</td>
<td>42.3 ± 0.7</td>
<td>9.0 ± 0.5</td>
<td>0.18 ± 0.02 ± 0.04</td>
</tr>
</tbody>
</table>

Table 6.4. Efficiencies of the IP significance and isolation requirements and corresponding transfer factors for $Z$+jets and $t\bar{t}$ processes in events that satisfy the $ll + \mu\mu$ selection.
The MC description of the selection efficiency has been verified using a control region of $Z + \mu$ events, as defined in Section 5.3.1. A good agreement between data and MC has been found, as shown in Figure 6.4.

**Figure 6.3.** Distribution of $m_{12}$ for $ll + \mu\mu$ final states at $\sqrt{s} = 7$ TeV (a) and for the $4\mu$ (b) and $2e2\mu$ (c) final states at $\sqrt{s} = 8$ TeV, in the control region with enhanced $b\bar{b}$ contribution. The fit (blue and green) is presented together with the MC expectations.
6.3. BACKGROUND ESTIMATION

In this updated analysis, the $t\bar{t}$ contribution is cross-checked and validated only for $\sqrt{s} = 8$ TeV. This is done in a control region in which $e\mu + \mu\mu$ events are selected. The selection criteria are the same described in Section 5.3.1 for the corresponding control region. The number of observed $e^\pm\mu^\mp + \mu^+\mu^-$ events in data is 85, compared to 53.9 $\pm$ 2.2 of expected events from simulation: the excess in data has been taken into account as a correction factor when extrapolating the $t\bar{t}$ contribution. The transfer factors, derived from $t\bar{t}$ simulation as the ratio of yields of $ee/\mu\mu + \mu\mu$ and the $e\mu + \mu\mu$ events, are estimated to be 1.09 $\pm$ 0.06 and 0.89 $\pm$ 0.05 for the $2e2\mu$ and $4\mu$ final states, respectively. The estimate of the $t\bar{t}$ contribution from this control region is consistent with the one derived using the $m_{12}$ fit method.

The expected $ll + \mu\mu$ background yields in the signal region are summarized in Table 6.5.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{s} = 7$ TeV</td>
</tr>
<tr>
<td></td>
<td>4$\mu$</td>
</tr>
<tr>
<td>$m_{12}$ fit: $Z+$jets</td>
<td>0.22 $\pm$ 0.07 $\pm$ 0.02</td>
</tr>
<tr>
<td>$m_{12}$ fit: $t\bar{t}$</td>
<td>0.03 $\pm$ 0.01 $\pm$ 0.01</td>
</tr>
<tr>
<td>$t\bar{t}$ from $e\mu + \mu\mu$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.5. Summary of the $ll + \mu\mu$ background estimates in the signal region for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples. The first uncertainty is statistical, while the second is systematic. $^1$ indicates the cross-checked number of expected events not used for the background normalization.
Figure 6.5 shows the invariant mass distributions for $m_{12}$ (a) and $m_{34}$ (b) in the $ll + \mu\mu$ control region including the contribution of the SM Higgs boson signal at $m_H = 125$ GeV. The data samples at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV are combined and compared to the simulation. The $Z + $ jets and $t\bar{t}$ contributions are normalized to the data-driven background estimates, while the $ZZ^{(*)}$ is normalized to its theoretical cross section. Data and simulation are in good agreement.

6.3.2 $ll + ee$ background

The $ll + ee$ background estimation is based on the electron candidates categorization. While in the previous analysis (see Section 5.3.2) electrons from photon conversions and fake ones were classified in two different categories, in this updated analysis they are kept together and the number of categories is then reduced from three to two: electron-like (E) and fake-like (F).

The control region is formed by relaxing the selection criteria on the sub-leading electron pair. Taking advantage of the higher statistics, for the $\sqrt{s} = 8$ TeV analysis the number of expected
6.3. BACKGROUND ESTIMATION

events in the signal region is extracted in a different way. While for $\sqrt{s} = 7$ TeV toy pseudo-
experiments are used (see Section 5.3.2), in the $\sqrt{s} = 8$ TeV analysis the number of expected
background events in the signal region is extrapolated using transfer factors derived as a function
of $\eta$ and $p_T$. First the number of events in each category of sub-leading pairs (EE, EF, FE, FF)
is evaluated in four $\eta$ regions: “All”, in which the whole $\eta$ range is considered, “BB”, with both
electrons in the barrel region ($|\eta| < 1.37$), “C”, with at least one electron in the crack region
(1.37 < $|\eta|$ < 1.52) and “E”, all other options when “BB” and “C” cases are not satisfied. Then,
the efficiencies needed to obtain the transfer factors are computed in bins of $\eta$ and $p_T$ of the
additional electron in $Z + e$ events. Both the pseudo-rapidity and the $p_T$ range are divided in three

<table>
<thead>
<tr>
<th>Category</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
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<td>MC</td>
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<td>MC</td>
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<td></td>
<td>12</td>
<td>12.97±3.46</td>
<td>36</td>
<td>25.91±4.36</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>17.70±4.06</td>
<td>40</td>
<td>25.73±4.48</td>
</tr>
<tr>
<td>EF</td>
<td>9</td>
<td>13.51±3.52</td>
<td>28</td>
<td>25.48±4.44</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>16.33±3.84</td>
<td>42</td>
<td>33.10±5.30</td>
</tr>
<tr>
<td>FE</td>
<td>9</td>
<td>6.38±2.39</td>
<td>18</td>
<td>8.22±2.30</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9.43±2.92</td>
<td>25</td>
<td>24.02±4.62</td>
</tr>
<tr>
<td>FF</td>
<td>12</td>
<td>19.64±4.39</td>
<td>27</td>
<td>53.99±7.29</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>26.30±5.06</td>
<td>44</td>
<td>63.43±7.90</td>
</tr>
</tbody>
</table>

Table 6.6. Observed yields in the various categories in the $ll + ee$ control region for both $\sqrt{s} = 7$ TeV
and $\sqrt{s} = 8$ TeV. Events are classified according to whether the sub-leading electrons are:
electron-like (E) and fake-like (F). MC expectations are shown for comparison. The di-
lepton categorization in reconstruction categories is ordered in $p_T$. Numbers are reported
for the whole $\eta$ coverage of the two sub-leading electrons.

The number of observed events in data for each category is reported together with the MC ex-
pectations in Table 6.6. The whole $\eta$ range is considered for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.
Figure 6.6 shows some examples of the resulting transfer factors obtained from $Z + e$ events in
bins of $p_T$ and $\eta$, for the $\sqrt{s} = 8$ TeV analysis. The total of $ll + ee$ background events is the sum
of the contributions of each category after the extrapolation to the signal region.
The estimate of the $ll + ee$ background is then cross-checked and validated using several control
regions. One is obtained inverting the isolation and IP significance requirements for the electrons
of the sub-leading pair, with respect to the ones in the analysis. This check is done for $\sqrt{s} = 8$
TeV data only. Also in this case events are classified following the reconstruction categories and
the transfer factors are derived in bins of $p_T$ and $\eta$ from $Z + e$ events, where the additional electron
should satisfy the same selection criteria of the two sub-leading electrons.
Another check is done in the control region called 3ll, defined as described in Section 5.3.2.
In this case the yield for the different components ($f, \gamma, Q$) depends on the last lepton and it is
CHAPTER 6. UPDATED RESULTS OF THE $H \rightarrow ZZ^{(*)} \rightarrow 4L$ ANALYSIS

0.494 0.425  
0.27 0.265  
0.069 0.056  
0.045 0.061
E  F

e  b  
c  f

(a) 7-15 GeV Barrel  
(b) 15-25 GeV Crack  
(c) $>25$ GeV End-cap

Figure 6.6. Examples of resulting transfer factors obtained from $Z + e$ events in bins of $p_T$ and $\eta$, for the $\sqrt{s} = 8$ TeV analysis. Capital letters denote the reconstruction categories, while small letters denote true categories of electron candidates.

extracted from a simultaneous fit to the $n^{b\text{-layer}}$ and $R_{\text{TRT}}$ distributions. The number of expected events in the signal region is obtained using the fit results and the corresponding selection efficiencies extracted from $Z + e$ events. In Figure 6.7 the results of the simultaneous fit to $n^{b\text{-layer}}$ and $R_{\text{TRT}}$ distributions for the $2\mu 2e$ final state at $\sqrt{s} = 8$ TeV and the $4e$ final state at $\sqrt{s} = 7$ TeV are shown. In Table 6.7 the fit results for the yields of the individual components - f, $\gamma$ and Q - estimated from data are reported for the $4e$ and $2\mu 2e$ final states.

<table>
<thead>
<tr>
<th>Type</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>179.00$^{+11.20}<em>{-13.00}$ 0.0095$^{+0.0005}</em>{-0.0005}$ 178.00$^{+13.90}<em>{-13.40}$ 0.0090$^{+0.0004}</em>{-0.0004}$</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>3.12$^{+1.44}<em>{-1.43}$ 0.1506$^{+0.0013}</em>{-0.0013}$ 1.63$^{+0.99}<em>{-0.99}$ 0.1094$^{+0.0021}</em>{-0.0021}$</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>12.00$^{+15.54}<em>{-5.69}$ 0.0521$^{+0.0003}</em>{-0.0003}$ 12.70$^{+5.03}<em>{-4.57}$ 0.0526$^{+0.0004}</em>{-0.0004}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>4e</th>
<th>2$\mu 2e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data fit Efficiency</td>
<td>Data fit Efficiency</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>179.00$^{+11.20}<em>{-13.00}$ 0.0095$^{+0.0005}</em>{-0.0005}$ 178.00$^{+13.90}<em>{-13.40}$ 0.0090$^{+0.0004}</em>{-0.0004}$</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td>418.00$^{+22.20}<em>{-22.60}$ 0.0059$^{+0.0006}</em>{-0.0006}$ 480.00$^{+23.40}<em>{-22.80}$ 0.0061$^{+0.0006}</em>{-0.0006}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.7. Fit results for the yield of each component estimated from data, for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.

Results obtained from the validation methods are consistent with those found in the control region. An additional check is done performing the analysis selection and requiring two same-sign electrons for the sub-leading pair. In this case, for the 2011 analysis only 2 events below $m_{4l} < 160$ GeV in the $4e$ final state are found, while for the 2012 analysis the number of events in the same $m_{4l}$
region are 3 (4) in the 4e (2µ2e) final state.

![Graph](image)

Figure 6.7. The results of simultaneous fit to $n_{\text{hits}}^{b-\text{layer}}$ (a) and $R_{\text{TRT}}$ (b) for the background components in 2e/2µ final state at $\sqrt{s} = 8$ TeV. In (c) and (d) the corresponding results for the 4e final state at $\sqrt{s} = 7$ TeV are given.

The expected $l + ee$ background yields in the signal region are summarized in Table 6.8. Figure 6.8 shows the invariant mass distributions for $m_{12}$ (a) and $m_{34}$ (b) in the $l + ee$ control region including the contribution of the SM Higgs boson signal at $m_H = 125$ GeV. The shape and normalization
of the background are in good agreement with data.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated number of events $\sqrt{s} = 7$ TeV</th>
<th>Estimated number of events $\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$4e$</td>
<td>$2\mu 2e$</td>
</tr>
<tr>
<td>$ll + e^\pm e^\mp$ (relaxed cuts)</td>
<td>$1.4 \pm 0.3 \pm 0.4$</td>
<td>$3.2 \pm 0.5 \pm 0.4$</td>
</tr>
<tr>
<td>$ll + e^\pm e^\mp$ (inverted cuts)</td>
<td>$-\text{-}$</td>
<td>$3.6 \pm 0.6 \pm 0.6$</td>
</tr>
<tr>
<td>$3l + l$ (same sign)</td>
<td>$2.5 \pm 0.3 \pm 0.5$ $^\dagger$</td>
<td>$3.9 \pm 0.4 \pm 0.6$ $^\dagger$</td>
</tr>
</tbody>
</table>

Table 6.8. Summary of the $ll + ee$ background estimates for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data. The first uncertainty is statistical, while the second is systematic. $^\dagger$ indicates the cross-checked number of expected events not used for the background normalization.

Figure 6.8. Invariant mass distribution of the lepton pair in the control sample defined by a $Z$ boson candidate and an additional di-electron pair, for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets combined. $m_{12}$ (a) and $m_{34}$ (b) for $ll + ee$ events are shown. The kinematic selection of the analysis is applied. The isolation and IP parameter significance requirements are applied to the leading di-lepton pair only. The MC is normalized as described in the text. The expected contribution of the SM Higgs boson signal at $m_H = 125$ GeV is also shown.
6.3. BACKGROUND ESTIMATION

6.3.3 Single resonant $pp \rightarrow Z \rightarrow 4l$

To verify the background estimation and to understand better the $ZZ^*$ background in the lower mass range a specific check is performed reconstructing the single resonant process.

Figure 6.9. Invariant mass of the $4e$ (a), $4\mu$ (b), $2\mu 2\mu$ (c) and $2\mu 2e$ (d) final states, demonstrating the single resonant peak $pp \rightarrow Z \rightarrow 4l$. The acceptance is improved relaxing the kinematic selection as described in the text. The comparison between data and simulation is shown combining the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.
CHAPTER 6. UPDATED RESULTS OF THE H → ZZ(∗) → 4L ANALYSIS

Events are selected in the same way as described in Section 5.3.4 but relaxing even more the requirements on $m_{12}$ and $m_{34}$: they are required to be in the range 20-160 GeV and 1-115 GeV, respectively. Figure 6.9 shows the $m_{4l}$ distribution for each final state, while Figure 6.10 shows the same distribution combining all the final states. The predicted amount of reducible background is very small and a good agreement between data and simulation is found.

Figure 6.10. Invariant mass of four leptons, combining all the final states, demonstrating the single resonant peak $pp \rightarrow Z \rightarrow 4l$. The acceptance is improved relaxing the kinematic selection as described in the text. The comparison between data and simulation is shown combining the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.

6.4 Systematic Uncertainties

In this updated analysis the theoretical uncertainties on the Higgs boson cross section and the SM ZZ(∗) background remain the same described in Section 5.4. The same is true for the uncertainty on the integrated luminosity for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data.

The systematic uncertainties on the lepton reconstruction and identification are evaluated by comparing the nominal event yield with the one after having modified the quantity of interest by applying varied weights or scale factors ($\pm 1\sigma$ from the nominal value). The relative systematic uncertainty is evaluated as $|\Sigma A - \Sigma B|/\Sigma A$, where $\Sigma A$ is the nominal yield and $\Sigma B$ the modified one. The uncertainty on the muon momentum scale is found to be about $\pm 0.1\%$ and is considered negligible, while the one on the muon momentum resolution affects the mass scale of the $m_{4l}$ distribution: it amounts to $\pm 0.2\%$ ($\pm 0.1\%$) for the $4\mu$ ($2\mu2e$) final state and is negligible for the $2e2\mu$ final state. The uncertainty on the muon reconstruction and identification efficiency amounts to...
±0.8%, ±0.4% and ±0.4% for the 4µ, 2µ2e and 2e2µ final states, respectively, at \( m_{4\ell} = 125 \text{ GeV} \). The uncertainty on the electron energy resolution is found to be negligible, while the one on the electron energy scale affects the mass scale of the \( m_{4\ell} \) distribution: it is less than ±0.4% (±0.2%) for the 4e (2e2µ) final state and negligible for the 2µ2e final state. The uncertainty on the electron reconstruction and identification efficiency amounts to ±9.4%, ±8.7% and ±2.4% for the 4e, 2µ2e and 2e2µ final states, respectively, at \( m_{4\ell} = 125 \text{ GeV} \).

6.5 Results

Once the selection cuts are applied, the expected \( m_{4\ell} \) distribution for the total background and the \( m_H = 125 \text{ GeV} \) signal hypothesis are compared to the data. Figure 6.11 shows these distributions in two ranges of \( m_{4\ell} \): 80-250 GeV (a) and 170-900 GeV (b).

![Figure 6.11](image_url)

(a) 80 < \( m_{4\ell} < 250 \text{ GeV} \)

(b) 170 < \( m_{4\ell} < 900 \text{ GeV} \)

**Figure 6.11.** The \( m_{4\ell} \) distributions for the selected candidates compared to the background expectation in the range 80-250 GeV (a) and 170-900 GeV (b) combining the \( \sqrt{s} = 7 \text{ TeV} \) and \( \sqrt{s} = 8 \text{ TeV} \) data samples and all the final states. The signal expectation for the \( m_H = 125 \text{ GeV} \) hypothesis is also shown.

In Table 6.9 the numbers of observed events are summarized and compared to the expected backgrounds and to various signal hypotheses in two different \( m_{4\ell} \) regions: “low mass” (100 GeV < \( m_{4\ell} < 160 \text{ GeV} \)) and “high mass” (\( m_{4\ell} \geq 160 \text{ GeV} \)). The numbers of events are reported for each final states and for the \( \sqrt{s} = 7 \text{ TeV} \) and \( \sqrt{s} = 8 \text{ TeV} \) data samples.
CHAPTER 6. UPDATED RESULTS OF THE $H \to ZZ^{(*)} \to 4L$ ANALYSIS

<table>
<thead>
<tr>
<th></th>
<th>4µ Low mass</th>
<th>4µ High mass</th>
<th>2eµ/µµ2e Low mass</th>
<th>2eµ/µµ2e High mass</th>
<th>4e Low mass</th>
<th>4e High mass</th>
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<tr>
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<td>5</td>
<td>23</td>
<td>2</td>
<td>13</td>
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<tr>
<td>$ZZ^{(*)}$</td>
<td>2.2±0.1</td>
<td>16.8±1.2</td>
<td>2.5±0.2</td>
<td>26.6±2.0</td>
<td>0.8±0.1</td>
<td>9.4±0.8</td>
</tr>
<tr>
<td>$Z+$jets and $t\bar{t}$</td>
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<td>0.5±0.1</td>
</tr>
<tr>
<td>Total Background</td>
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<tr>
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<td>0.3±0.1</td>
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<td>1.1±0.2</td>
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<td>1.2±0.2</td>
<td>0.4±0.1</td>
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</tbody>
</table>

4.6 fb$^{-1}$ at $\sqrt{s} = 7$ TeV

<table>
<thead>
<tr>
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<th>2eµ/µµ2e Low mass</th>
<th>2eµ/µµ2e High mass</th>
<th>4e Low mass</th>
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<td>28</td>
<td>169</td>
<td>13</td>
<td>55</td>
</tr>
<tr>
<td>$ZZ^{(*)}$</td>
<td>12.4±0.6</td>
<td>92.6±6.7</td>
<td>14.7±0.9</td>
<td>144.0±11.0</td>
<td>5.4±0.5</td>
<td>55.9±4.5</td>
</tr>
<tr>
<td>$Z+$jets and $t\bar{t}$</td>
<td>1.9±0.6</td>
<td>0.5±0.2</td>
<td>6.1±1.5</td>
<td>1.5±0.4</td>
<td>2.5±0.6</td>
<td>0.6±0.2</td>
</tr>
<tr>
<td>Total Background</td>
<td>14.3±0.8</td>
<td>93.1±6.7</td>
<td>20.8±1.8</td>
<td>145.0±11.0</td>
<td>8.0±0.8</td>
<td>56.5±4.5</td>
</tr>
<tr>
<td>$m_H = 123$ GeV</td>
<td>4.4±0.6</td>
<td></td>
<td>5.4±0.8</td>
<td></td>
<td>2.2±0.4</td>
<td></td>
</tr>
<tr>
<td>$m_H = 125$ GeV</td>
<td>5.8±0.7</td>
<td></td>
<td>7.0±0.9</td>
<td></td>
<td>2.9±0.4</td>
<td></td>
</tr>
<tr>
<td>$m_H = 127$ GeV</td>
<td>6.7±0.9</td>
<td></td>
<td>8.4±1.2</td>
<td></td>
<td>3.4±0.5</td>
<td></td>
</tr>
</tbody>
</table>

20.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV

Table 6.9. The observed numbers of events and the final estimate for the expected backgrounds, separated into "Low mass" (100 GeV < $m_{4\ell}$ < 160 GeV) and "High mass" ($m_{4\ell}$ ≥ 160 GeV) regions, together with the expected numbers of signal events for various Higgs boson mass hypotheses. The corresponding total uncertainty is also given.

<table>
<thead>
<tr>
<th></th>
<th>signal</th>
<th>$ZZ^{(*)}$</th>
<th>$Z+$jets, $t\bar{t}$</th>
<th>obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>2.2±0.3</td>
<td>1.17±0.07</td>
<td>1.12±0.17</td>
<td>5</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td>13.7±1.8</td>
<td>6.2±0.4</td>
<td>2.62±0.34</td>
<td>27</td>
</tr>
<tr>
<td>Combined</td>
<td>15.9±2.1</td>
<td>7.4±0.4</td>
<td>3.74±0.93</td>
<td>32</td>
</tr>
</tbody>
</table>

(a) Total number of events

<table>
<thead>
<tr>
<th></th>
<th>signal</th>
<th>$ZZ^{(*)}$</th>
<th>$Z+$jets, $t\bar{t}$</th>
<th>obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>4µ</td>
<td>6.3±0.8</td>
<td>2.8±0.1</td>
<td>0.55±0.15</td>
<td>13</td>
</tr>
<tr>
<td>2µ2e</td>
<td>3.0±0.4</td>
<td>1.4±0.1</td>
<td>1.56±0.33</td>
<td>5</td>
</tr>
<tr>
<td>2eµ/µµ2e</td>
<td>4.0±0.5</td>
<td>2.1±0.1</td>
<td>0.55±0.17</td>
<td>8</td>
</tr>
<tr>
<td>4e</td>
<td>2.6±0.4</td>
<td>1.2±0.1</td>
<td>1.11±0.28</td>
<td>6</td>
</tr>
</tbody>
</table>

(b) Number of events per final state

Table 6.10. The numbers of observed and expected signal and background events in a window of ±5 GeV around the $m_{H} = 125$ GeV Higgs boson mass hypothesis. Numbers are reported combining all final states for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets and their combination (a) and for each final state for the combined dataset (b).
6.5. RESULTS

In Table 6.10 the observed and expected events, for the signal and the backgrounds, in a window of ±5 GeV around the $m_H = 125$ GeV Higgs boson mass hypothesis are reported. These numbers of events are given combining all final states for $4.6 \, fb^{-1}$ at $\sqrt{s} = 7$ TeV and $20.7 \, fb^{-1}$ at $\sqrt{s} = 8$ TeV and their combination (a) and separately for each final state for the combined dataset (b).

![Figure 6.12](image-url)

**Figure 6.12.** The $m_4\ell$ distributions for each final state, $4\mu$ (a), $2\mu2e$ (b), $2e2\mu$ (c) and $4e$ (d), in the mass range 80-170 GeV for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV combined. The signal expectation for $m_H = 125$ GeV hypothesis is also shown.
CHAPTER 6. UPDATED RESULTS OF THE $H \to ZZ^{(*)} \to 4L$ ANALYSIS

Figure 6.12 shows the $m_{4l}$ mass distribution for each final state, $4\mu$ (a), $2\mu 2e$ (b), $2e 2\mu$ (c) and $4e$ (d), in the mass range 80-170 GeV for the combination of the 2011 and 2012 data samples. Compared to the results of the discovery analysis (see Section 5.5), due to the changes in the kinematic selection and the pairing criteria, the amount of $ZZ^{(*)}$ has been reduced by around 15% in the $4\mu$ and $4e$ final states. Also the overall signal/background ratio (S/B) has improved from 1.1 to 1.4, due to improved electron identification and background rejection.

Seven of the 225 events with a leading di-muon pair are affected by FSR and only one of them is in the mass range 120-130 GeV: this is in good agreement with the 4% expected from simulation. Figure 6.13 shows the distributions of the $m_{34}$ versus $m_{12}$ invariant mass for the selected candidates in the $m_{4l}$ range 120-130 GeV, before applying the $Z$ mass constrained kinematic fit. The distribution of the selected candidates is compatible with a Higgs boson with $m_H = 125$ GeV in addition to the estimated background distribution.

Figure 6.14a shows the observed and expected 95% CL cross section limits, as a function of $m_H$, for the combination of the 2011 and 2012 data samples. The limits are set using the same methods described in Section 5.5. The observed exclusion starts at around 130 GeV due to the excess at 125 GeV. Figure 6.14b shows the local $p_0$ as a function of $m_H$ for the combined dataset. In Table 6.11 the lowest observed local $p_0$-values, the corresponding mass and the expected local $p_0$ quoted at the mass of the observed minimum, are summarized for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples and their combination. In the combined analysis, an excess of events is found around $m_H = 124.3$ GeV, with a local $p_0$ value of $2.7 \times 10^{-11}$, corresponding to a significance of 6.6$\sigma$: 

Figure 6.13. Distributions of the $m_{34}$ versus the $m_{12}$ invariant mass for the selected candidates in the $m_{4l}$ range 120-130 GeV. The expected distributions for a SM Higgs with $m_H = 125$ GeV (boxes) and for the total background (shading) are also shown.
the $H \to ZZ^(*) \to 4l$ channel alone surpasses the $5\sigma$ discovery significance and the single channel discovery is therefore reached.

Figure 6.14. (a) The expected (dashed) and observed (solid line) 95% CL upper limit on the SM Higgs boson production cross section as a function of $m_H$ divided by the expected SM Higgs boson cross section. The green (yellow) band indicates the expected limits with $\pm 1\sigma$ ($\pm 2\sigma$). The combination of the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets is used. (b) The observed local $p_0$ for the combination of the 2011 and 2012 datasets (solid black line) and for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets separately (blue and red respectively). The dashed curves show the expected median local $p_0$ for the signal hypothesis when tested at the corresponding $m_H$.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_0$</td>
<td>$m_H(p_0)$</td>
</tr>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$125.6$ GeV</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td>$8.8 \times 10^{-10}$</td>
<td>$124.1$ GeV</td>
</tr>
<tr>
<td>Combined</td>
<td>$2.7 \times 10^{-11}$</td>
<td>$124.3$ GeV</td>
</tr>
</tbody>
</table>

Table 6.11. Summary of the observed $p_0$-values for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples and their combination. The expected significance, quoted at the mass of the observed minimum, is also reported.
6.5.1 Signal strength and mass measurement

Figure 6.15 shows the signal strength $\mu = \sigma/\sigma_{SM}$ as a function of $m_H$ (a) and the corresponding result in the case where a SM Higgs boson signal of $m_H = 125$ GeV is injected into simulated and predicted backgrounds (b). The bands illustrate the $\mu$ interval of the test statistic $-2\ln \Lambda(\mu) < 1$, where $\Lambda$ is the profile likelihood ratio, as defined in Section 5.5. An approximate $\pm 1\sigma$ variation is reported. Since the expected SM rate rises rapidly with increasing $m_H$ in the low mass region, the expected $\mu$ is increased below the injected signal mass and slightly exceeds one over a small mass range.

In order to measure the Higgs boson mass, the signal shapes and signal systematic uncertainties need to be continuously parameterized in $m_H$. The signal mass distributions are obtained from simulation after applying a smoothing procedure [145] which reduces the statistical fluctuations in the shapes. The shapes and uncertainties are parameterized as continuous functions of the Higgs mass obtained from simulation at various values of $m_H$. The detector level $m_{4l}$ distribution for the signal is obtained event-by-event through the convolution of an analytic description of the single lepton detector response with a Breit-Wigner function that describes the Higgs mass lineshape at truth level. The intermediate distributions are obtained by interpolation. The form of the background shapes is taken from MC and varied from the nominal expectation to allow for shape
systematics. Figure 6.16a shows the profile likelihood as a function of $m_H$ for the combined data samples and combining all the final states. The solid curve represents the profile likelihood with the mass systematic uncertainties from electrons and muons (MSS$_e$ and MSS$_\mu$ respectively) applied and the dashed curve without applying them. The profile likelihood ratio $\Lambda(m_H)$ used for the Higgs boson mass measurement is defined as in Equation 5.4 where the parameter of interest is the Higgs boson mass $m_H$, $\mu$ is profiled and $L$ is the likelihood given by Equation 5.3.

The value of the fitted mass is $m_H = 124.3^{+0.6}_{-0.5} \ (\text{stat})^{+0.5}_{-0.3} \ (\text{syst}) \ \text{GeV}$, where the systematic uncertainty is dominated by the energy and momentum scale uncertainties. The values of the systematic error is evaluated as the quadratic difference between the two values of the curves, the one containing the mass systematic uncertainties (solid) and the one without (dashed), when crossing the 68% CL uncertainty line ($-2 \ln \Lambda = 1$).

In Table 6.12 the fitted mass values for each final state are reported. The $4\mu$ and $2\mu 2e$ final states, where the muons dominate the mass scale, agree reasonably well with the $4e$ and $2e 2\mu$ final states.
CHAPTER 6. UPDATED RESULTS OF THE $H \rightarrow ZZ^{(*)} \rightarrow 4L$ ANALYSIS

<table>
<thead>
<tr>
<th>Final state</th>
<th>Fitted Higgs mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>$123.8^{+0.8}_{-0.3}$ (stat) +0.2−0.3 (syst) GeV</td>
</tr>
<tr>
<td>$2\mu 2e$</td>
<td>$122.6^{+1.9}_{-1.1}$ (stat) +0.5−0.5 (syst) GeV</td>
</tr>
<tr>
<td>$2e 2\mu$</td>
<td>$125.0^{+1.0}_{-0.9}$ (stat) +0.5−0.6 (syst) GeV</td>
</tr>
<tr>
<td>$4e$</td>
<td>$126.2^{+1.2}_{-1.3}$ (stat) +0.8−0.8 (syst) GeV</td>
</tr>
</tbody>
</table>

Table 6.12. Values of the fitted mass for each final state using the combination of the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.

where the electrons dominate the mass scale, within their total uncertainties.

Figure 6.16b shows the best $\mu$ and $m_H$ fit values and the profile likelihood contours, corresponding to 68% and 95% CL, with mass scale systematics applied (darker colour) and without applying them (lighter colour). In this case, the likelihood ratio used has two parameters of interest: the Higgs boson mass $m_H$ and the signal strength $\mu$. The value of the signal strength at the best fit value for $m_H$ (124.3 GeV) is $\mu = 1.7^{+0.5}_{-0.4}$.

6.5.2 Higgs boson couplings

The Higgs-boson couplings can be explored by classifying the selected candidates in one of the three production mode categories. Applying the categorization criteria (see Section 6.2.1), eight VBF-like candidates and one VH-like candidate are selected. In a mass window of ±5 GeV around 125 GeV, one VBF-like candidate is found with mass 123.5 GeV: this is in agreement with 0.71±0.10 expected events for the VBF production mode in the same mass window. Above 160 GeV, six VBF-like candidates are found, in agreement with 3.8±1.3 expected events from the $ZZ^{(*)}$ production. The one observed VH-like candidate, with mass 270.3 GeV, is in agreement with 0.9±0.3 expected events for the $ZZ^{(*)}$ production. The amount of $Z$+jets and $t\bar{t}$ background for VBF-like and VH-like categories is estimated using similar techniques as described in Section 6.3. The estimated yields in the signal region for the 2012 (2011) analysis are 0.3±0.09 (0.15±0.07) events for the VBF-like category and 0.08±0.04 (0.03±0.02) events for the VH-like category.

Information concerning the Higgs-boson couplings can be extracted measuring the signal strength for specific production modes. In this analysis, the production modes are grouped as “fermionic”, containing the ggF and $t\bar{t}H$ modes, and “bosonic”, containing VBF and VH modes: the corresponding signal strengths are $\mu_{ggF+t\bar{t}H}$ and $\mu_{VBF+VH}$, respectively.

Figure 6.17a shows their best fit values, both multiplied by the factor $B/B_{SM}$, which represents the scale factor of the branching ratio with respect to the SM value. This factor is included since the source of potential deviations from the SM expectation cannot be resolved between production and decay with a single channel analysis. The measured values are $\mu_{ggF+t\bar{t}H} \times B/B_{SM} =$
6.5. RESULTS

\[ \text{Figure 6.17. (a) Likelihood contours in the } (\mu_{ggF+tH}/\mu_{VBF+VH}) \text{ plane including the branching ratio factor } B/B_{SM}. \text{ Only the part of the plane where the expected numbers of signal events in each category is positive is considered. The best fit to the data (×) and the SM expectation (+) are shown. (b) Results of a likelihood scan for } \mu_{ggF+tH}/\mu_{VBF+VH}, \text{ where the factor } B/B_{SM} \text{ cancels out.} \]

1.8^{+0.8}_{-0.5} \text{ and } \mu_{VBF+VH} \times B/B_{SM} = 1.2^{+1.4}_{-1.8}: \text{ the results are consistent with the SM expectation within the total uncertainty. Figure 6.17(b) shows the profile likelihood as a function of the ratio } \mu_{ggF+tH}/\mu_{VBF+VH}. \text{ In this case the ambiguity between production and decay is removed and the measured value is } \mu_{ggF+tH}/\mu_{VBF+VH} = 0.7^{+2.4}_{-0.7}. \]
Chapter 7

Spin and parity measurement

In Chapter 6 the updated results of the event selection in the $H \to ZZ^{(*)} \to 4l$ channel have been discussed. The measurement of spin and parity of the recently discovered particle plays a central role in its confirmation or rejection as a SM Higgs boson, which is predicted to have spin 0 and even parity. However, the possibility of Higgs look-alikes with higher spins cannot be excluded a priori. Moreover, some theories beyond the SM allow for CP mixing in the Higgs sector.

The decay of a heavy boson like the SM Higgs into a pair of vector bosons which finally decay into electrons or muons allows for a determination of the spin and parity of the parent particle. In this chapter an analysis probing the spin and the parity ($J^P$) using the $H \to ZZ^{(*)} \to 4l$ decay is presented. The determination of the spin and parity is done through the observed distributions of the two $Z^{(*)}$ masses, one production angle and four decay angles. Since the Landau-Yang theorem forbids the decay of spin-1 particles into a photon-pair, the spin-1 hypothesis is strongly disfavoured by the observed decay of the new particle into two photons. This conclusion can be altered however in the case when the observed $H \to \gamma\gamma$ events are produced in the decays of a different resonance having very similar mass. The spin 2 case is disfavoured in the case of the observation of the Higgs decay in a pair of fermions.

The $J^P$ states explored in this analysis, which uses the same selection criteria as in Section 6.2, are spin 0, 1 and 2 with even and odd parity. Before going through the details of the analysis, the general idea behind the measurement and an introduction of the spin and parity states under study are given. The production of the Monte Carlo samples and the corresponding validation is also presented. Then, the multivariate approach used to evaluate the spin and parity of the Higgs boson is explained. Finally, the results are presented.
7.1 Characterization of the spin and parity states

Consider the production of a resonance $X$ at the LHC in gluon-gluon and quark-antiquark partonic collisions, with the subsequent decay of $X$ into two $Z$ bosons which in turn decay leptonically. In this way the final state can be fully and accurately reconstructed. Considering the most general couplings of the particle $X$ to relevant SM fields, the spin and parity of $X$ can be extracted from angular distributions of four leptons in the final state. In the following, the intermediate $Z$ bosons will be labelled $Z_1$, the one having the mass closest the nominal PDG value, and $Z_2$, the other, and their masses $m_{12}$ and $m_{34}$ respectively. The observables sensitive to underlying spin and parity are the masses of the $Z$ bosons ($m_{12}$ and $m_{34}$), one production angle ($\theta^*$) and four decay angles ($\phi_1$, $\phi$, $\theta_1$ and $\theta_2$). The shapes of $m_{12}$ and $m_{34}$ are sensitive to the spin and parity in the low mass region only (above 180 GeV both $Z$ are on-shell).

![Diagram](image)

**Figure 7.1.** Definitions of production and decay angles in $X \rightarrow ZZ^{(*)} \rightarrow 4l$, where $X$ is produced in gluon-gluon or quark-antiquark partonic collisions.

The production and decay angles, illustrated in Figure 7.1, are defined in the following way:

- $\theta_1$ and $\theta_2$ are the angles between the negatively charged final state leptons and the direction of flight of their respective $Z$ boson, evaluated in the rest frame of the corresponding $Z$ boson;

- $\phi$ is the angle between the decay planes of the four final state leptons expressed in the four-lepton rest frame;

- $\phi_1$ is the angle defined between the decay plane of the first lepton pair (the one related to $Z_1$) and a plane defined by the vector of the $Z_1$ in the four lepton rest frame and the positive direction of the collision axis;
Consider the most general parameterization of the particle $X$ couplings to SM fields. Such parameterizations, well known for spin-zero, spin-one, and spin-two particles interacting with the SM gauge bosons \[151\], are used in the following.

In the interaction of a colour- and charge-neutral particle $X$ with two spin-one bosons $V$ (two $Z$ bosons in this case) the spin of the particle $X$ can be zero, one, or two. For a generic Higgs-like spin-zero resonance of arbitrary parity, the scattering amplitude describing its interaction with two spin-one gauge bosons is

$$A(X \rightarrow V_1V_2) = v^{-1} \left[ g_1 M_V^2 \varepsilon_1^+ \varepsilon_2^+ + g_2 f_{\mu\nu}^{(1)} f^{*(2)\mu\nu} + g_3 f_{\mu\nu}^{(1)} f^{*(2)\mu\nu} q_1^\alpha q_2^\alpha + g_4 f_{\mu\nu}^{(1)} \tilde{f}^{*(2)\mu\nu} \right], \quad (7.1)$$

where $X$ represents the Higgs-like resonance, $V_{1,2}$ the two $Z$ bosons, $g_{1,2,3,4}$ the coupling constants, $\varepsilon_{1,2}$ the polarization vectors of the $Z$ bosons, $v$ the SM vacuum expectation value of the Higgs field and $\Lambda$ the scale at which the physics beyond the SM could appear. The field strength tensor and the conjugate tensor of the gauge boson are given by

$$f^{(i)\mu\nu} = \varepsilon^\mu i_\nu - \varepsilon^\nu i_\mu \quad \text{and} \quad \tilde{f}^{(i)\mu\nu} = \varepsilon_{\mu\nu\alpha\beta} \varepsilon^{\alpha i} q_{\beta}^i, \quad (7.2)$$

where $q_i$ and $\varepsilon_i$ are its momentum and polarization, respectively, while $\varepsilon_{\mu\nu\alpha\beta}$ is the Levi-Civita tensor. Equation (7.1) is sufficiently general to accommodate all radiative corrections to Higgs interactions with gauge bosons, massive or massless, in the SM. The coupling of the spin-zero particle to massless gauge bosons can be described setting $M_V = 0$ in Equation (7.1). Considering the coupling constants $g_{1,2,3,4}$, a SM Higgs boson is expected to have $g_1 = 1$ and all other coupling constant equal to zero ($g_i \neq 1 = 0$), whereas a pseudo-scalar Higgs would have $g_4 \neq 0$. Assuming the SM couplings, Higgs production through $q\bar{q}$ annihilation for spin 0 is negligible and therefore ignored in this study.

In the case of a generic Higgs-like spin-1 particle $X$ of arbitrary parity, as a consequence of the Landau-Yang theorem, it cannot interact with two identical massless bosons. For this reason, a spin-one colour-singlet particle cannot be produced in gluon fusion, or decay to two photons. The scattering amplitude describing its interaction with two massive spin-one gauge bosons is

$$A(X \rightarrow V_1V_2) = g_1 [(\varepsilon_1^+ q)(\varepsilon_2^+ \varepsilon_X) + (\varepsilon_2^+ q)(\varepsilon_1^+ \varepsilon_X)] + g_2 \varepsilon_\alpha \varepsilon_\beta \varepsilon_X^+ \varepsilon_1^+ \varepsilon_2^+ q^\beta. \quad (7.3)$$

where $\varepsilon_X$ is the polarization vector of the resonance $X$, $g_i$ are the coupling constants, $q$ is the four-momentum of the particle $X$ and $\bar{q} = q_1 - q_2$, where $q_1$ and $q_2$ are the four-momenta of the two gauge bosons. In the case when $X$ has positive parity, $J^P = 1^+$, the first term violates parity and the second one conserves it. Alternatively, the two terms correspond to parity-conserving and parity violating interactions of a $1^-$ particle, respectively. So, assuming parity conserving

\[1\] In the case of two gluons, a trivial colour factor needs to be introduced.
7.1. CHARACTERIZATION OF THE SPIN AND PARITY STATES

interactions, the case \( g_1 \neq 0 \) corresponds to a vector resonance, while \( g_2 \neq 0 \) to a pseudo-vector. Even if the decay of such a resonance to two massless bosons is not allowed, this model is still interesting to study the presence of different resonances with different helicities and couplings in the low mass region (below 180 GeV).

In the case of spin two, the properties of the resonance \( X \) are model dependent. The most general amplitude for the decay of a spin-2 resonance into two identical vector gauge bosons contains 10 different terms and 10 coupling constants \([150]\), which are in general complex numbers \([150]\).

\[
A(X \rightarrow V_1 V_2) = \Lambda^{-1} \left[ 2g_1 X_{\mu\nu} f^{*\alpha}(1) f^{\beta}(2) \eta^{\alpha\beta} + 2g_2 X_{\mu\nu} \frac{q_{\gamma} \eta^{\mu\nu} f^{*\nu}(1) f^{\alpha}(2) \eta^{\alpha\beta}}{\Lambda^2} \right. \\
+ g_3 \frac{q^\alpha q^\beta}{\Lambda^2} X_{\mu\nu} \left( f^{*\alpha}(1) f^{\alpha}(2) + f^{*\alpha}(2) f^{\alpha}(1) \right) + g_4 \frac{q^\alpha q^\beta}{\Lambda^2} X_{\mu\nu} f^{*\nu}(1) f^{\alpha}(2) \\
+ m_X^2 X_{\mu\nu} \left( 2g_5 \epsilon_{\alpha\beta} \epsilon^{\alpha\beta} + 2g_6 \frac{q^\alpha q^\beta}{\Lambda^2} \left( \epsilon_{\alpha\beta} \epsilon^{\alpha\beta} \right) \right) \\
+ g_7 \frac{q^\alpha q^\beta}{\Lambda^2} X_{\mu\nu} f^{*\nu}(1) f^{\alpha}(2) \\
+ m_X^2 X_{\mu\alpha} \eta^{\beta\nu} \epsilon_{\mu\nu\rho} \left( g_9 \frac{q^\rho}{\Lambda^2} \epsilon_{\alpha\beta} \epsilon^{\alpha\beta} + g_{10} \frac{q^\rho}{\Lambda^2} ( \epsilon_{\alpha\beta} \epsilon^{\alpha\beta} + \epsilon^{\alpha\beta} (q \epsilon_{\alpha\beta}) ) \right) \right]. \tag{7.4}
\]

The \( X \) resonance wave function is given by a symmetric traceless tensor \( X_{\mu\nu} \). The first seven coupling constants, \( g_1, \ldots, g_7 \), correspond to the \( J^P = 2^+ \) particle parity-conserving interaction, while the last three, \( g_8, \ldots, g_{10} \), correspond to its parity-violating interaction. Alternatively, they correspond to parity-violating and parity-conserving interactions of the \( J^P = 2^- \) particle, respectively.

Moreover, both groups can contribute to the same amplitude and then CP-mixing is possible.

Therefore, the number of allowed spin-2 states is very large. In this study, since it is not possible to address all spin-2 states, two minimal models, corresponding to the lowest dimension operators, are considered: a graviton-like tensor with minimal coupling \( (2^+_m) \), equivalent to a Kaluza-Klein graviton \([152]\), and a pseudo-tensor \( (2^-) \).

<table>
<thead>
<tr>
<th>( J^P )</th>
<th>Production configuration</th>
<th>Decay configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^+</td>
<td>( gg \rightarrow X )</td>
<td>( g_1 = 1, g_2 = g_3 = g_4 = 0 )</td>
</tr>
<tr>
<td>0^-</td>
<td>( gg \rightarrow X )</td>
<td>( g_4 = 1, g_1 = g_2 = g_3 = 0 )</td>
</tr>
<tr>
<td>1^+</td>
<td>( q\tilde{q} \rightarrow X )</td>
<td>( g_1 = 0, g_2 = 1 )</td>
</tr>
<tr>
<td>1^-</td>
<td>( q\tilde{q} \rightarrow X )</td>
<td>( g_1 = 1, g_2 = 0 )</td>
</tr>
<tr>
<td>2^+_m</td>
<td>( gg \rightarrow X ) and ( q\tilde{q} \rightarrow X )</td>
<td>( g_1 = g_3 = 0, g_2 = 1 )</td>
</tr>
<tr>
<td>2^-</td>
<td>( gg \rightarrow X ) and ( q\tilde{q} \rightarrow X )</td>
<td>( g_8 = g_9 = 1 )</td>
</tr>
</tbody>
</table>

| Table 7.1. Spin and parity states, together with the choice of couplings parameters, considered in the analysis. |

In Table 7.1 the spin and parity states considered in this study are summarized, together with the
corresponding couplings parameters \[150\] \[153\]. For spin-2 states, both gluon-gluon and quark-antiquark production mechanisms have been considered. Since the relative fraction of the $gg$ and $q\bar{q}$ production mechanisms for spin-2 boson is a priori unknown, different admixtures are considered in order to obtain a model independent estimate. All the admixtures considered in this study are summarized in Table 7.2.

<table>
<thead>
<tr>
<th>Label</th>
<th>$gg$ fraction</th>
<th>$q\bar{q}$ fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{q\bar{q}}=0$</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>$f_{q\bar{q}}=25$</td>
<td>75%</td>
<td>25%</td>
</tr>
<tr>
<td>$f_{q\bar{q}}=50$</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>$f_{q\bar{q}}=75$</td>
<td>25%</td>
<td>75%</td>
</tr>
<tr>
<td>$f_{q\bar{q}}=100$</td>
<td>0%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 7.2. Different $gg$ and $q\bar{q}$ admixtures cases considered for spin-2 state.

7.2 Simulation of the spin and parity models

For the spin and parity analysis the JHU \[150\] leading-order generator is used to simulate the decay of the Higgs boson with a mass of 125 GeV. While POWHEG can only generate the SM hypothesis, $0^+$, the JHU generator allows the generation of various spin and parity combinations. The parton showers are done using PYTHIA, with the PDF set CTEQ6L1 \[135\] and the ATLAS underlying event tune \[154\] \[155\].

7.2.1 JHU Monte Carlo validation

Validation studies of the JHU Monte Carlo samples have been performed. The POWHEG NLO generator is chosen as reference since it provides the best prediction for a SM Higgs $p_T$ spectrum, being in very good agreement with the NNLL+NLO predictions \[108\]. Validation studies have been performed after the parton shower. Considering the SM hypothesis, $J^P = 0^+$, the validation is performed applying the following acceptance cuts:

- the invariant mass of the leading di-lepton pair should satisfy the requirement $50 \text{ GeV} < m_{12} < 106 \text{ GeV}$;
- the invariant mass of the sub-leading di-lepton pair should be greater than $17.5 \text{ GeV}$;
- the pseudo-rapidity and the $p_T$ of the leptons should be $|\eta| < 2.7$ and $p_T > 20, 15, 10, 6 \text{ GeV}$, respectively.
Figure 7.2. JHU (blue) and POWHEG (red) comparison at generator level after parton shower for some of the relevant kinematic and angular distributions, for a SM Higgs $J^P = 0^+$. 

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In Figure 7.2 some of the relevant kinematic and angular distributions predicted by JHU and Powheg, assuming the SM hypothesis \( J^P = 0^+ \), are shown together with the ratio between the two predictions. All distributions agree within the statistical errors: the JHU simulation results in good agreement with the Powheg one.

Since JHU is a LO generator and Powheg is a NLO one, some differences in the Higgs \( p_T \) distributions are expected, as shown in Figure 7.3. This discrepancy has no large impact on the spin-parity states separation as long as the Higgs \( p_T \) is not used as discriminant in the analysis.

7.2.2 JHU \( p_T \) re-weighting

For gluon-fusion production the Higgs \( p_T \) spectrum generated by JHU is found to be slightly harder than the one from Powheg. While the mis-modelling of the transverse momenta by JHU does not affect the spin-dependent observables, it might have an important impact on the event selection. In order to avoid this, the JHU Higgs boson \( p_T \) spectrum is re-weighted to that of Powheg at the fully simulated event level. This re-weighting has no effect on the expected separation of the spin and parity states: this has been verified performing dedicated studies.

In order to correctly re-weight the JHU sample, weights are determined by the differential cross section ratio between Powheg and JHU, as defined by the expression

\[
 f_w = \frac{d\sigma/dp_T^4(\text{Powheg})}{d\sigma/dp_T^4(\text{JHU})}.
\]

(7.5)

where \( p_T^4 \) is the transverse momentum of the four leptons final state. The resulting weight distribution calculated for the JHU \( J^P = 0^+ \) sample is shown in Figure 7.4k. The largest systematic uncertainties on the event weights come from the QCD scale and the PDF uncertainties. These uncertainties are estimated by varying the QCD scale and the PDF set in Powheg and by evaluating the respective variations in the weights distribution.

Figure 7.3. Higgs \( p_T \) distribution for JHU (blue) and Powheg (red), for a SM Higgs \( J^P = 0^+ \).
Concerning the QCD scale, its uncertainty is determined by varying simultaneously the factorization scale, $\mu_F$, and the renormalization scale, $\mu_R$, by a factor two up and down. The PDF uncertainty is estimated using two PDF sets, CTEQ and NNPDF. Then, for each $p_T$ bin, the systematic uncertainty is taken as the largest deviation of the weights. The systematic uncertainties on the calculated weights are shown in Figure 7.4 for $\sqrt{s} = 8$ TeV. The same procedure is applied to other spin-parity samples for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

Figure 7.5. Higgs $p_T$ distribution for the spin-2$^+$ graviton-like resonance with minimal couplings produced via $gg$ (black) and $q\bar{q}$ (red) production mechanisms, using JHU.
CHAPTER 7. SPIN AND PARITY MEASUREMENT

As already discussed, a spin-2 particle can be produced also via s-channel $q\bar{q}$ production mechanisms. The spectrum of $p_T$ for the $q\bar{q}$ production is expected to be softer than the $gg$ production, as shown in Figure 7.5. Since no better prediction of this spectrum is currently available, no re-weighting procedure is applied to the $q\bar{q} p_T$ spectrum.

7.3 Event Selection

The event selection is the same as the one described in Section 6.2. For the spin and parity determination, a fully inclusive study is performed: events candidates are not classified in categories by their production mechanism (see Section 6.2.1). The VBF contamination is small and, since it does not bias observables sensitive to the spin and parity determination (see Appendix B), it is not taken into account in this study. The same is true for the VH production, which contribution is even smaller than the VBF production. Only the events falling in the signal region $115 \text{ GeV} < m_{4l} < 130 \text{ GeV}$ are retained in the analysis.

7.3.1 Kinematic binning

The goal of this analysis is to find the $J^P$ hypothesis which is preferred over all other hypotheses to an extend comparable to the expected sensitivity given the amount of data. Thus, the hypotheses are tested in pairs, attempting to exclude one against the other. To improve the sensitivity, the signal region is split in two regions, depending on $m_{4l}$, of high and low signal over background ($S/B$). The former is defined as $121 \text{ GeV} < m_{4l} < 127 \text{ GeV}$, the latter as $115 \text{ GeV} < m_{4l} < 121 \text{ GeV}$ and $127 \text{ GeV} < m_{4l} < 130 \text{ GeV}$. The use of these two regions allows an increase in the sensitivity of the separation of individual hypothesis of 6% in each case.

<table>
<thead>
<tr>
<th>Final state and bin</th>
<th>$\sqrt{s} = 7 \text{ TeV}$</th>
<th>$\sqrt{s} = 8 \text{ TeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>$ZZ^{(*)}$</td>
</tr>
<tr>
<td>4$\mu$ high</td>
<td>0.83</td>
<td>0.27</td>
</tr>
<tr>
<td>4$\mu$ low</td>
<td>0.17</td>
<td>0.40</td>
</tr>
<tr>
<td>2$\mu$2$\mu$ high</td>
<td>0.33</td>
<td>0.11</td>
</tr>
<tr>
<td>2$\mu$2$\mu$ low</td>
<td>0.09</td>
<td>0.17</td>
</tr>
<tr>
<td>2$e$2$\mu$ high</td>
<td>0.51</td>
<td>0.20</td>
</tr>
<tr>
<td>2$e$2$\mu$ low</td>
<td>0.13</td>
<td>0.28</td>
</tr>
<tr>
<td>4$e$ high</td>
<td>0.24</td>
<td>0.09</td>
</tr>
<tr>
<td>4$e$ low</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 7.3. The expected yields for signal, $ZZ^{(*)}$ and reducible backgrounds for $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ data samples in the high and low $S/B$ bins for each final state.
7.4. MULTIVARIATE APPROACH WITH BDT

The background estimates for the signal region are obtained using the data-driven and Monte Carlo
techniques described in Section 6.3. In Table 7.3 the expected yields for signal and background
processes in the high and low \( S/B \) bins, for each final state, are reported for both \( \sqrt{s} = 7 \) TeV
and \( \sqrt{s} = 8 \) TeV data samples.

### 7.4 Multivariate approach with BDT

In order to separate the states with different spin and parity, a multivariate discriminant for each
spin-parity pair can be used. For each spin-parity state, the discriminant is built using as input the
seven experimental observables \( (m_{12}, m_{34}, \theta^*, \phi, \phi_1, \theta_1 \) and \( \theta_2) \) sensitive to the spin and parity of
the underlying state. The resulting shape of the discriminant is different for the individual states
composing the spin-parity pair. By using such discriminant, the problem is reduced from a \( N \)-
dimensional one, where \( N \) is the number of observables, to the comparison of two one-dimensional
distributions.

In order to perform a multivariate analysis the Boosted Decision Tree (BDT) with Gradient Boost,
implemented in the Toolkit for Multivariate Analysis (TMVA) [156], is used for this study. The
BDT algorithm is mainly chosen because it offers the best performance with limited available
statistics for the training and in the presence of non-linear correlations between the observables.

The general structure of the multivariate analysis is organized in three steps:

i) After applying the selection cuts to all signal MC samples for different spin and parity and to
the \( ZZ^{(*)} \) background MC samples, the distributions of the seven sensitive observables are
reconstructed in the signal region \( (115 \text{ GeV} < m_{4l} < 130 \text{ GeV}) \). Then, the obtained set of
observables is used to train the BDT discriminants and each of them is trained to distinguish
between one pair of spin and parity states. Discriminants are created for all possible pairs of
spin-parity states.

ii) Once the discriminants are created, their responses are calculated for each event in all signal
and background samples. The obtained values for the BDT discriminants are separated in
two sub-sets, low and high \( S/B \) bins, according to the value of \( m_{4l} \). This procedure is done
separately for all final states considered in the analysis.

iii) At the final stage, the eight bins are considered separately as different channels and in each
one the yields for signal and background are estimated. These channels are therefore treated
as independent measurements which are combined during the statistical test. For each \( J^P \)
hypothesis the expected and the observed exclusion for all other hypotheses are calculated.
The exclusion is achieved by comparing the response shape of the BDT discriminants calcu-
lated for the signal and background samples to those observed in data with the statistical
treatment described in Section 7.5.
7.4.1 BDT discriminants

The BDT discriminants are derived for all possible pairs of spin-parity states, testing each hypothesis against all the others and considering for the spin-2 case only the $gg$ production (100% $gg$ admixture). The BDT discriminants are also evaluated to separate $0^+$ versus spin-2, with both even and odd parity, for different $gg/q\bar{q}$ admixtures (see Table 7.2). Since there is no interference between the $gg$ and $q\bar{q}$ production processes, spin-2 samples with different admixtures are obtained starting from the two having pure $gg$ production (100% $gg$) and pure $q\bar{q}$ production (100% $q\bar{q}$) and mixing them at generator level. These additional samples have been used as well to train the BDT. Some examples of distributions of the sensitive variables, after the selection cuts, used for the training of the BDT discriminants are presented in Figure 7.6, when comparing $J^P = 0^+$ (red) with $J^P = 0^-$ (black), in Figure 7.7a, where the comparison is between $J^P = 0^+$ (red) with $J^P = 1^+$ (black), and in Figure 7.7b, where the $J^P = 0^+$ (red) is compared to $J^P = 2^-$ (black) for $gg$ production only.

![Graphs showing distributions for different spin-parity states](image-url)

**Figure 7.6.** $m_{12}$, $m_{34}$, $\phi$, $\cos(\theta_1)$, $\cos(\theta_2)$, $\phi_1$, $\cos(\theta^*)$ distributions, after selection cuts, for $J^P = 0^+$ (red) and $J^P = 0^-$ (black) used for the training of the BDT discriminants.

In Figure 7.8 some examples of distributions of the BDT response are shown. On the left (a) the distributions are shown for $J^P = 0^+$ (blue) and $J^P = 0^-$ (red) for test and training samples, while on the right (b) the same distributions are shown for $J^P = 0^+$ (blue) and $J^P = 2^+$ for $f_{q\bar{q}=50}$ (red).
7.4. MULTIVARIATE APPROACH WITH BDT

![Graphs showing distributions of various variables](image)

(a) $J^P = 0^+$ (red) vs $J^P = 1^+$ (black)

(b) $J^P = 0^+$ (red) vs $J^P = 2^-$ (black), 100% $gg$

Figure 7.7. $m_{12}$, $m_{34}$, $\phi$, $\cos(\theta_1)$, $\cos(\theta_2)$, $\phi_1$, $\cos(\theta^*)$ distributions, after selection cuts, used for the training of the BDT discriminants. (a) $J^P = 0^+$ (red) and $J^P = 1^+$ (black). (b) $J^P = 0^+$ (red) and $J^P = 2^-$ (black), for $gg$ production only.
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The BDT response distributions for the 0\(^+\) vs 0\(^-\) (a) and 0\(^+\) vs 2\(^+\)\(q\bar{q}\) = 50 (b) states separation are shown in Figure 7.8. The response of the BDT for the reducible background 155

7.4.2 Reducible background

Due to limited statistics, the determination of the reducible background shape is problematic. Since the reducible background is estimated using a control region (see Section 6.3), its shape is determined applying a smoothing procedure to the BDT output for reducible background events in the control region. This has been done using a Kernel Density Estimator (KDE) with a Gaussian kernel.

Figure 7.9. Smoothed distribution of the 0\(^+\) vs 0\(^-\) BDT discriminant for reducible background.

An example of BDT output for the reducible background distribution for 0\(^+\)/0\(^-\) spin-parity hypotheses separation is shown in Figure 7.9. The response of the BDT for the reducible background
events in the signal region is expected to be the same obtained for those in the control region.

### 7.4.3 Systematic uncertainties

Since the events used in this multivariate analysis are obtained using the selection criteria described in Section 6.2, most of the systematics uncertainties, such as theoretical uncertainties, background normalization and luminosity uncertainties, are exactly the same as those described in Section 6.4.

In addition, shape systematics, corresponding to the variation of the shape of the BDT discriminant due to systematic effects, and the uncertainties on the fraction of events falling in the high and low $S/B$ bins have to be taken into account.

Concerning the Higgs $p_T$ modeling, the systematic uncertainties originating from the $p_T$ reweighting procedure, as described in Section 7.2.2, are taken into account both for shape variation and for the variation of the fraction of events in the two $S/B$ bins. The impact of these systematics on the BDT shape responses has been found negligible.

In order to evaluate the impact of the mis-pairing effect on the same flavour final states ($4\mu$ and $4e$), some specific tests have been performed. Using the $0^+$ hypothesis and knowing the fraction of mis-paired events ($\sim 10\%$) in the signal region, the effect on the BDT output has been studied increasing and reducing the amount of mis-pairing by 7%. As shown in Figure 7.10, the variation of the mis-pairing effect has negligible effects on the BDT output shape. Therefore, it has been neglected.

**Figure 7.10.** BDT response for JHU $0^+$ signal sample for $4\mu$ final state (a) and for $ZZ^{(*)}$ background for $4e$ final state (b). Black points represents the BDT response using the nominal fraction of events with wrong pairing, while red and blue lines represent the BDT response when the mis-pairing fraction is respectively decreased and increased by 7%.

Systematic uncertainties related to the lepton identification and reconstruction have been con-
CHAPTER 7. SPIN AND PARITY MEASUREMENT

considered both for shape variation and for the variation on the number of events in the S/B bins. Systematics due to the electron energy resolution have been taken into account as shape systematic uncertainty only, since they do not affect the S/B bin migration. The ones due to electron energy scale are considered both for shape systematics and bin migration (10%). The systematics due to muon momentum resolution and trigger efficiency have been considered as shape systematic as well, since the bin migration for these effects is small. Mass resolution and signal mis-modelling has been taken as an additional source of systematic uncertainty (10%) for the high and low S/B normalization by applying a ±500 MeV shift in the m_{4l} distribution for the signal.

Figure 7.11 shows some summary plots examples of systematic uncertainties on the fraction of events in the high S/B bin for various spin-parity hypotheses and four lepton final states.

Even if it is not a source of systematic errors, the impact of the BDT “over-training” is also studied. Having limited statistics in the training, the MVA can learn statistical fluctuations from

Figure 7.11. Examples of systematic uncertainties on the fraction of events in the high S/B bin for various spin-parity hypotheses and four lepton final states, corresponding to “up” and “down” variation of the systematic sources considered.
the training sample that can be absent or different in the test sample, leading to inefficiencies in the separation of the hypotheses. To evaluate the magnitude of this effect, the expected separation between spin-parity hypotheses was compared for the case when the full data sample and the test sample were used in the BDT: no significant differences have been observed in the BDT response.

7.5 Statistical treatment

Given two hypotheses with different spin and parity called $H_0$ and $H_1$, the expected distribution of events in either high or low $S/B$ bin when comparing the two hypotheses using a defined BDT discriminant is defined as

$$P^i = \mu^{\text{sig}} L \cdot f^{\text{sig}} N^{\text{sig}} [\varepsilon \cdot \text{PDF}^{H_0}_i + (1 - \varepsilon) \cdot \text{PDF}^{H_1}_i] + \sum_{\text{bkg}(k)} f^{\text{bkg}} k N^{\text{bkg}} k \cdot \text{PDF}^{\text{bkg}} k,$$

where $L$ is the total luminosity, $\mu^{\text{sig}}$ is the signal strength, $N^{\text{sig}}$ is the number of expected SM signal events in the mass region $115 \text{ GeV} < m_{\ell\ell} < 130 \text{ GeV}$, $f^{\text{sig}}_i$ is the signal fraction in the $i$th $S/B$ bin and $\varepsilon$ is the fraction of the $H_0$ signal hypothesis represented by $\text{PDF}^{H_i}_i$ for the $J^P$ discriminant. Similarly, $N^{\text{bkg}}_k$, $f^{\text{bkg}}_k$ and $\text{PDF}^{\text{bkg}}_k$ represent the number of expected background events, the background fraction in the $i$th $S/B$ bin and the PDF, respectively, for the $k$th background.

The parameters $L$, $N^{\text{sig}}$ and $N^{\text{bkg}}_k$ are nuisance parameters which are constrained by Gaussian terms and their uncertainties are determined from the nominal analysis. The fractions of events in each of the two mass regions (low and high) are constrained to sum to unity. The parameter $\mu^{\text{sig}}$ is left free while the parameter of interest is $\varepsilon$.

For the spin-parity analysis, the signal and background shapes are obtained from their respective responses to the training of the $H_0$ and $H_1$ samples. The test statistic used is the ratio of profile likelihood $q = \log \left[ \frac{L(H_1)}{L(H_0)} \right]$, where the parameter $\varepsilon$ is 0 for the assumed $H_0$ hypothesis and 1 for the tested $H_1$ hypothesis. The probability model is fitted to the data to obtain a maximum likelihood estimate for the nuisance parameters. Then, using a series of pseudo-experiments, the sampling distributions for the two hypotheses, sharing the same background, are built.

7.6 Expected exclusion

In Table 7.4 the expected exclusion for different spin and parity hypotheses with respect to each other are presented. For the spin 2 case, only the $gg$ production is considered ($f_{qq} = 0\%$). The exclusions are given in term of $p$-value with the corresponding number of standard deviations in parentheses for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples. By using a total integrated luminosity of about 25 fb$^{-1}$, it is expect to distinguish the Standard Model hypothesis from all other states except $2^+_m$, for which the expected exclusion is around 1 $\sigma$. 

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### Table 7.4. Expected exclusion for different spin and parity hypotheses with respect to each other.

The exclusion is given in terms of $p$-value with the corresponding standard deviations in parentheses and combining the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples. For the spin 2 case, only the $gg$ production is considered ($f_{qq} = 0\%$).

<table>
<thead>
<tr>
<th>$J^p$</th>
<th>Assumed hypothesis</th>
<th>$0^+$</th>
<th>$0^-$</th>
<th>$1^+$</th>
<th>$1^-$</th>
<th>$2^+_m$</th>
<th>$2^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td></td>
<td>0.0156 (2.155)</td>
<td>0.0225 (2.005)</td>
<td>0.0181 (2.094)</td>
<td>0.1381 (1.089)</td>
<td>0.0221 (2.013)</td>
<td></td>
</tr>
<tr>
<td>$0^-$</td>
<td></td>
<td>0.0152 (2.166)</td>
<td>0.0035 (2.699)</td>
<td>0.0065 (2.484)</td>
<td>0.0151 (2.168)</td>
<td>0.0389 (1.763)</td>
<td></td>
</tr>
<tr>
<td>$1^+$</td>
<td></td>
<td>0.0115 (2.274)</td>
<td>0.0012 (3.032)</td>
<td>0.0623 (1.536)</td>
<td>0.0077 (2.422)</td>
<td>0.0017 (2.934)</td>
<td></td>
</tr>
<tr>
<td>$1^-$</td>
<td></td>
<td>0.0142 (2.192)</td>
<td>0.0034 (2.709)</td>
<td>0.0540 (1.607)</td>
<td>0.0057 (2.531)</td>
<td>0.0101 (2.324)</td>
<td></td>
</tr>
<tr>
<td>$2^+_m$</td>
<td></td>
<td>0.1382 (1.088)</td>
<td>0.0208 (2.038)</td>
<td>0.0189 (2.076)</td>
<td>0.0098 (2.335)</td>
<td>0.0101 (2.321)</td>
<td></td>
</tr>
<tr>
<td>$2^-$</td>
<td></td>
<td>0.0197 (2.059)</td>
<td>0.0362 (1.797)</td>
<td>0.0045 (2.611)</td>
<td>0.0178 (2.102)</td>
<td>0.0076 (2.426)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.5 shows the expected exclusion of $0^+ (2^+_m)$ in favour of $2^+_m (0^+)$ hypothesis (a) and of $0^+ (2^-)$ in favour of $2^- (0^+)$ hypothesis (b) for different spin-2 $gg/qq$ admixtures and combining the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.

#### Table 7.5 (a) Expected exclusion of $2^+_m (0^+)$ in favour of $0^+ (2^+_m)$ and (b) expected exclusion of $2^- (0^+)$ in favour of $0^+ (2^-)$ for different $gg/qq$ admixtures. The exclusion is given in terms of $p$-value with the corresponding standard deviations in parentheses and combining $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.

All $p_0$ values are obtained studying the discrimination between the different hypotheses using MC pseudo-experiments in which the number of signal and background events is fixed to their expectations. The separations are evaluated assuming the Standard Model hypothesis ($\mu = 1$).
7.7 Results

In Figure 7.12 the distributions of some of the spin and parity sensitive observables for events satisfying the event selection criteria and falling in the signal region $115 \text{ GeV} < m_{4l} < 130 \text{ GeV}$ are shown. The distributions of the $0^+$ (light blue line) and $0^-$ (dashed green line) signal hypotheses expectation are shown together with the irreducible $ZZ^{(*)}$ background (red), the reducible background (violet) and the data (black point) for the combined $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ data. 

![Distributions of some spin and parity sensitive observables](image)

**Figure 7.12.** Distributions of some of the spin and parity sensitive observables for events passing the full selection in the signal mass window $115 \text{ GeV} < m_{4l} < 130 \text{ GeV}$, combining the $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ data samples. The expected contributions from the Higgs signal (light blue), the $ZZ^{(*)}$ background (red) as well as the measured contribution from reducible background (violet) are shown together with the data (black points).

Figure 7.13 presents some distributions of the BDT discriminants, where the SM hypothesis, $0^+$, is
CHAPTER 7. SPIN AND PARITY MEASUREMENT

compared with 0− (a), 1+ (b), 1− (c), 2+ (d) and 2− (e). The response of the data (black points), the assumed 0+ signal hypothesis (light blue line), the tested hypothesis (dashed green line), the ZZ(+) background (red) and the reducible background (violet) are reported combining the 2011 and 2012 data samples.

![Diagram of BDT discriminant distributions](image)

(a) $J^P = 0^+ \text{ vs } J^P = 0^-$
(b) $J^P = 0^+ \text{ vs } J^P = 1^+$
(c) $J^P = 0^+ \text{ vs } J^P = 1^-$
(d) $J^P = 0^+ \text{ vs } J^P = 2_0^+$
(e) $J^P = 0^+ \text{ vs } J^P = 2^-$

Figure 7.13. Distributions of the BDT analysis discriminants for data and MC expectations, combining $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples. Each discriminant is shown for a pair of spin and parity hypotheses: (a) $J^P = 0^+$ versus $J^P = 0^-$, (b) $J^P = 0^+$ versus $J^P = 1^+$, (c) $J^P = 0^+$ versus $J^P = 1^-$, (d) $J^P = 0^+$ versus $J^P = 2_0^+$ and (e) $J^P = 0^+$ versus $J^P = 2^-$. For the spin-2 hypothesis, the 100% $gg$ production is assumed.

Before quoting the final $p_0$ values to exclude the tested spin and parity hypotheses, the discrimination between the different hypotheses has been studied using more than 500k MC pseudo-experiments. In each experiment the expected number of signal and background events are fixed to the observed yields. Examples of resulting distributions of the ratio of profile likelihood are shown in Figure 7.14 and compared to the response from the data (vertical black line). The dis-
7.7. RESULTS

tributions of the assumed $0^+$ hypothesis (blue) is compared to the one for the tested hypothesis (red) for the combined data samples: $0^-$ (a), $1^+$ (b), $1^-$ (c), $2^+_m$ (d) and $2^-$ (e). The medians of each of the expected distributions are indicated by dashed lines, blue and red for the assumed and tested hypothesis, respectively. The shaded areas correspond to the observed $p_0$ values, representing the compatibility with the tested hypothesis $H_1$ (red shaded area) and the assumed hypothesis $H_0$ (blue shaded area). These distributions are obtained taking into account all the systematic uncertainties and show where the observed events are located with respect to the expected PDF of the discriminant.

Figure 7.14. Distributions of the ratio of profile likelihood generated with more than 500k MC pseudo-experiments when assuming the SM hypothesis, $0^+$, and testing the $0^-$ (a), $1^+$ (b), $1^-$ (c), $2^+_m$ (d) and $2^-$ (e) hypotheses.

Table 7.6 shows the observed exclusion for different spin and parity hypotheses with respect to each other, given in terms of $p$-value for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.
Table 7.6. Observed exclusion for different spin and parity hypotheses with respect to each other, given in term of \( p \)-value and combining the \( \sqrt{s} = 7 \) TeV and \( \sqrt{s} = 8 \) TeV data samples.

Figure 7.15 presents a comparison of the \( 0^+ \) hypothesis with the \( 2^+_{\text{m}} \) hypothesis as a function of the \( gg/qq \) admixtures. Each distribution of the two signal hypotheses is obtained generating more than 500k MC pseudo-experiments, where the expected numbers of signal and background events are fixed to the observed yields. The median value for the \( 0^+ \) (blue points) and \( 2^+_{\text{m}} \) (red points) hypotheses are compared to the ratio of profile likelihood values observed in data (black points).

Figure 7.15. Values of the ratio of profile likelihood as a function of the \( gg/qq \) admixtures \( (f_{q\bar{q}}) \). The \( 2^+_{\text{m}} \) hypothesis is tested when assuming the SM one, \( 0^+ \). The expected values are obtained generating more than 500k MC pseudo-experiments. The blue and red points correspond to the expected median values for \( 0^+ \) and \( 2^+_{\text{m}} \), respectively, while the black points represent the observed values in data. The green and yellow bands correspond, respectively, to one and two standard deviations around the spin-0 median curve.
7.8. SUMMARY

In Table 7.7 the observed exclusion of $0^+ \ (2^+_m)$ in favour of the $2^+_m \ (0^+)$ hypothesis (a) and $0^+ \ (2^-)$ in favour of the $2^- \ (0^+)$ hypothesis (b) for different spin-2 $gg/qq$ admixtures are reported for the combined data samples.

<table>
<thead>
<tr>
<th>Observed exclusion of $2^+_m$ hypothesis</th>
<th>$f_{qq} = 0%$</th>
<th>$f_{qq} = 25%$</th>
<th>$f_{qq} = 50%$</th>
<th>$f_{qq} = 75%$</th>
<th>$f_{qq} = 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^+_m$ in favour of $0^+$</td>
<td>0.079</td>
<td>0.002</td>
<td>0.002</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>$0^+$ in favour of $2^+_m$</td>
<td>0.532</td>
<td>0.944</td>
<td>0.943</td>
<td>0.923</td>
<td>0.962</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>Observed exclusion of $2^-$ hypothesis</th>
<th>$f_{qq} = 0%$</th>
<th>$f_{qq} = 25%$</th>
<th>$f_{qq} = 50%$</th>
<th>$f_{qq} = 75%$</th>
<th>$f_{qq} = 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^-$ in favour of $0^+$</td>
<td>0.249</td>
<td>0.482</td>
<td>0.448</td>
<td>0.591</td>
<td>0.465</td>
</tr>
<tr>
<td>$0^+$ in favour of $2^-$</td>
<td>0.034</td>
<td>0.010</td>
<td>0.018</td>
<td>0.007</td>
<td>0.012</td>
</tr>
</tbody>
</table>

(b)

Table 7.7. Observed exclusion of $2^+_m \ (0^+)$ in favour of the $0^+ \ (2^+_m)$ hypothesis (a) and of $2^- \ (0^+)$ in favour of the $0^+ \ (2^-)$ hypothesis (b) for different $gg/qq$ admixtures, given in term of $p$-value and combining $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples.

7.8 Summary

The goal of this analysis was to test the spin and parity hypotheses, one against the other, in order to evaluate the most favoured one. A successful support of the SM Higgs hypothesis requires that the $0^+$ state is preferred over all the other.

In Table 7.8 the summary of the expected and observed exclusion, given in term of $p$-value, is given for the cases when assuming $0^+$ hypothesis and testing the other. The corresponding exclusion when assuming the alternative hypotheses and testing the $0^+$ one are also given. In addition, the statistical separation between the pairs of hypotheses expressed as a CL$_s$ confidence level is also provided. The CL$_s$ is calculated using the following

$$CL_s = \frac{p_0(\text{alternative } J^P)}{1 - p_0(0^+)},$$

where the numerator corresponds to the observed $p_0$-value for each alternative $J^P$ hypothesis when $0^+$ is assumed and the denominator to the one of the $0^+$ hypothesis when assuming the alternative. The results correspond to the combined statistics of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data samples. The profile likelihood is computed including all sources of systematics and allowing the signal
strength $\mu$ to vary. The expected sensitivity to discriminate between the SM $0^+$ hypothesis and $0^-, 1^+, 1^-$ and $2^-\text{m}$ is above the $2.5\sigma$ level, while the expected discrimination against $2^+_\text{m}$ is approximately $1.5\sigma$. The observed $p_0$-values clearly favour the SM hypothesis with respect to $0^-, 1^+, 1^-$ and $2^+_\text{m}$. Concerning the $2^-$ hypothesis, although the expected separation is above $2.6\sigma$ in favour of the $0^+$ hypothesis, the data appear to prefer the $2^-$ hypothesis.

<table>
<thead>
<tr>
<th>$J^P$ hypotheses</th>
<th>Tested $J^P$ for an assumed $0^+$</th>
<th>Tested $0^+$ for an assumed $J^P$</th>
<th>CL$_\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>$0^-$</td>
<td>0.0037</td>
<td>0.015</td>
<td>0.0072</td>
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<tr>
<td>$1^+$</td>
<td>0.0016</td>
<td>0.001</td>
<td>0.0059</td>
</tr>
<tr>
<td>$1^-$</td>
<td>0.0038</td>
<td>0.051</td>
<td>0.0040</td>
</tr>
<tr>
<td>$2^\tau^\text{m}$</td>
<td>0.0920</td>
<td>0.079</td>
<td>0.0992</td>
</tr>
<tr>
<td>$2^-$</td>
<td>0.0053</td>
<td>0.249</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

Table 7.8. Values of the expected and observed $p_0$ values for an assumed $0^+$ hypothesis for different $J^P$ hypotheses when the $0^+$ hypothesis is assumed. The $p_0$-values are also given when the $0^+$ hypothesis is tested and the alternative hypothesis is assumed. The two observed $p_0$-values are combined to provide the CL$_\alpha$ confidence level for each hypothesis.

The $0^-, 1^+, 1^-$ and $2^+$ hypotheses are excluded at the 97.8%, 99.8%, 94% and 83.2% CL$_\alpha$ confidence levels in favour of the SM $0^+$ hypothesis: the Higgs-like boson is therefore found to be compatible with the SM hypothesis [141] [142]. The combination with the other ATLAS results will be discussed in the next section.
Conclusions

The search for the Standard Model Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel in the context of the ATLAS experiment at the LHC has been presented. After discussing the Standard Model theoretical framework, the ATLAS detector and the event selection criteria, the discovery of a new particle using $4.8 \text{ fb}^{-1}$ and for $5.8 \text{ fb}^{-1}$ of $p$-$p$ collision data at $\sqrt{s} = 7$ TeV and at $\sqrt{s} = 8$ TeV, respectively, has been presented. In the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel an excess of data events over the background-only prediction has been observed at $m_H = 125$ GeV with a local $p_0$ of 0.018%, corresponding to 3.6 standard deviations. Combined results from all ATLAS searches show an excess at $m_H = 126.5$ GeV, with a significance of 6 standard deviations. The estimated mass is $m_H = 126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)}$ GeV, while the signal strength is $\mu = 1.4 \pm 0.3$.

Using the full available dataset of $p$-$p$ collision data collected in 2011 and 2012, corresponding to a total integrated luminosity of about $25 \text{ fb}^{-1}$, the mass of the new particle has been measured. In particular, since the $4\mu$ final state is the most promising one for the mass measurement, the performance of the ATLAS muon system have been extensively studied, focusing on the muon momentum resolution. The value of the measured mass is $m_H = 124.3^{+0.6}_{-0.5} \text{ (stat)}^{+0.5}_{-0.3} \text{ (syst)}$ GeV. The resulting signal strength at the best fit value for $m_H$ is $\mu = 1.7^{+0.5}_{-0.4}$, compatible with the Standard Model expectation of unity. A first attempt of the coupling measurement has been also presented. Grouping the production modes as “fermionic”, containing the ggF and $t\bar{t}H$ modes, and “bosonic”, containing VBF and VH modes, the ratio between their corresponding signal strength has been measured to be $\mu_{ggF+t\bar{t}H}/\mu_{VBF+VH} = 0.7^{+2.4}_{-0.3}$.

To verify if the new discovered particle was the Standard Model Higgs boson or not, the Standard Model prediction for its spin and parity, $J^P = 0^+$, has been tested against different alternative hypotheses. The multivariate technique approach based on the Boosted Decision Tree has been presented. The hypothesis testing method against $J^P = 0^-, 1^+, 1^-, 2^+_m$ and $2^-_m$ specific models has been described. Results show that the Standard Model hypothesis, $0^+$, is clearly preferred. The $0^-, 1^+$ and $1^-$ hypotheses are excluded at more than 95% confidence level while the $2^+_m$ hypothesis is excluded at 83% confidence level. The $2^-_m$ hypothesis appears to be preferred by the data when compared to the $0^+$ hypothesis, although the expected separation in favour of the $0^+$ hypothesis is above 2.6$\sigma$.
Combining the results in the search in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay with the searches in the other sensitive channels, the $H \rightarrow \gamma\gamma$ and $H \rightarrow WW \rightarrow l\nu l\nu$, allows to achieve a high level of accuracy in the confirmation of the new particle as the Standard Model Higgs boson. Using the two channels with the best mass resolution, $H \rightarrow ZZ^{(*)} \rightarrow 4l$ and $H \rightarrow \gamma\gamma$, where the fitted mass is $m_H = 126.8 \pm 0.2$ (stat) $\pm 0.7$ (syst) GeV, the mass of the new particle is

$m_H = 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (syst) GeV [157]. The consistency between the two fitted masses, $m_{H\gamma\gamma}$ and $m_{H4l}$, is quantified fitting the data with the profile likelihood ratio $\Lambda(\Delta m_H)$. The parameter of interest is $\Delta m_H = m_{H\gamma\gamma} - m_{H4l}$, which is found to be $\Delta m_H = 2.3^{+0.6}_{-0.7}$ (stat) $\pm 0.6$ (stat) GeV. From the value of the likelihood at $m_H = 0$, the probability for a single Higgs boson to give a value of $\Lambda(\Delta m_H)$ disfavouring the $\Delta m_H = 0$ hypothesis more strongly than observed in the data is found to be at the level of 1.2% (2.5σ) using the asymptotic approximation. This means that the two mass measurements are compatible, providing the evidence for the observation of the same particle in two different decay modes.

Using the three decay channels, the signal production strength at the best fit, normalized to the SM expectation, is $\mu = 1.33 \pm 0.14$ (stat) $\pm 0.15$ (syst) [157].

The measurements of the spin-parity, $J^P$, properties of the new particle have been also combined [158]. All alternative models ($J^P = 0^-, 1^+, 1^-, 2^+_m, 2^-$) when compared to the Standard Model hypothesis, $J^P = 0^+$, are excluded at confidence level above 97.8%. This provides the evidence for the Standard Model nature of the Higgs boson, with spin 0 and positive parity.

Another important confirmation of the new particle as the Standard Model Higgs boson will be the observation of its fermionic decay channels ($\tau\tau, b\bar{b}$) and the measurement of the Yukawa coupling with fermions. Only an evidence for Higgs fermionic decays has been achieved [159] so far.

Starting from 2015, the LHC will provide $p-p$ collisions at higher centre-of-mass energy, $\sqrt{s} = 13$ TeV. These collisions will allow future analyses to measure the Higgs boson mass, its spin and parity and the couplings to fermions and bosons with very high precision. In particular, the LHC RUN2 will allow the measurement of the couplings in $\tau\tau$ and $b\bar{b}$ production modes, separately, and maybe even $\mu\mu$. In addition, possible CP violating contributions in the parity nature of the Higgs boson will be investigated.

All these further measurements will be necessary to confirm if the newly discovered Higgs boson is indeed the Standard Model one or if theories beyond the Standard Model are required to explain its properties, although the measured value of the Higgs mass and the fact that the couplings are Standard Model like has ruled out a significant number of Super Symmetric (SUSY) models [160].
Appendix A

Muon momentum resolution curves

As mentioned in Section 4.5, the parameterized resolution as a function of $p_T$ for each detector region is obtained using the values of the parameters reported in Tables 4.9, 4.10, and 4.11. Here a full set of resolution curves for 2010, 2011 and 2012 analyses is given. In all the following figures, the solid blue line shows the determination based on data, the dashed blue line represents its extrapolation to $p_T$ ranges not accessible in the analysis, the shaded band represents the sum in quadrature of the statistical and systematic uncertainty and the solid red line shows the expected resolution curve obtained from the simulation.

Figures A.1 and A.2 show the muon resolution curves for ID and MS, respectively, for the “Chain 1” algorithm using 40 pb$^{-1}$ of 2010 collision data. The corresponding results for the “Chain 2” algorithm are presented in Figures A.3 and A.4.

Figures A.5 and A.6 show the muon resolution curves for ID and MS, respectively, for the “Chain 1” algorithm using 4.7 fb$^{-1}$ of 2011 collision data, while Figures A.7 and A.8 show the corresponding results for the “Chain 2” algorithm.

Figures A.9 and A.10 show the muon resolution curves for ID and MS, respectively, for the “Chain 1” algorithm using 20.4 fb$^{-1}$ of 2012 collision data, while the corresponding results for the “Chain 2” algorithm are presented in Figures A.11 and A.12.

The muon resolution is significantly improved during the three years of data taking. Improvements from the 2010 to the 2011 analysis reflect a better alignment of the detector, since the simulation assumes a perfectly aligned ATLAS detector. Further improvements in the 2012 analysis reflect an excellent knowledge of the performance of the ATLAS detector, since the simulation includes the knowledge of the performance of the ATLAS detector.
Figure A.1. Resolution curve from the fitted parameter values of the ID in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 1” algorithm and 2010 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
APPENDIX A. MUON MOMENTUM RESOLUTION CURVES

Figure A.2. Resolution curve from the fitted parameter values of the MS in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 1” algorithm and 2010 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.3. Resolution curve from the fitted parameter values of the ID in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 2” algorithm and 2010 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
APPENDIX A. MUON MOMENTUM RESOLUTION CURVES

Figure A.4. Resolution curve from the fitted parameter values of the MS in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 2” algorithm and 2010 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.5. Resolution curve from the fitted parameter values of the ID in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 1” algorithm and 2011 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.6. Resolution curve from the fitted parameter values of the MS in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 1” algorithm and 2011 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.7. Resolution curve from the fitted parameter values of the ID in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 2” algorithm and 2011 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.8. Resolution curve from the fitted parameter values of the MS in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 2” algorithm and 2011 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.9. Resolution curve from the fitted parameter values of the ID in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 1” algorithm and 2012 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.10. Resolution curve from the fitted parameter values of the MS in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 1” algorithm and 2012 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
APPENDIX A. MUON MOMENTUM RESOLUTION CURVES

Figure A.11. Resolution curve from the fitted parameter values of the ID in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 2” algorithm and 2012 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Figure A.12. Resolution curve from the fitted parameter values of the MS in collision data and simulation as a function of the muon $p_T$, for different detector regions. The “Chain 2” algorithm and 2012 data are considered. The solid blue line shows the determination based on data and is continued as dashed line for the extrapolation to the $p_T$ range not accessible in analysis. The red line represents the expected resolution and the shaded band represents the sum in quadrature of the statistical and systematic uncertainty.
Appendix B

Gluon fusion and VBF Higgs production mechanism

The JHU generator implements only the Higgs production mechanism via gluon fusion, while for a SM Higgs boson with a mass of 125 GeV about 7% of the total production cross section is due to vector-boson fusion (VBF) processes. Figures B.1 and B.2 show the distributions of the spin and parity sensitive variables for gluon fusion (blue) and VBF (red) production, obtained using the Powheg MC generator and applying the same selection cuts described in Section 7.2.1. The SM hypothesis is considered. All the distributions are in reasonable agreement between the two production modes. This means that neglecting the VBF production mechanism does not introduce a significant bias in the spin and parity analysis.

Figure B.1. Comparison between Powheg gluon fusion (blue) and VBF (red) predictions for $m_{12}$ (a) and $m_{34}$ (b) for the $0^+$ Higgs hypothesis.
APPENDIX B. GLUON FUSION AND VBF HIGGS PRODUCTION MECHANISM

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<th>Events/0.5 GeV</th>
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<th>10^-1</th>
<th>10^0</th>
<th>10^1</th>
<th>10^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powheg gg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powheg VBF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) $m_{4l}$

(b) $\cos \theta^*$

(c) $\cos \theta_1$

(d) $\cos \theta_2$

(e) $\phi$

(f) $\phi_1$

Figure B.2. Comparison between POWHEG gluon fusion (blue) and VBF (red) predictions for $m_{4l}$ (a), $\cos \theta^*$ (b), $\cos \theta_1$ (c), $\cos \theta_2$ (d), $\phi$ (e) and $\phi_1$ (f) for the $0^+$ Higgs hypothesis.
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BIBLIOGRAPHY


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Summary

The Standard Model of particle physics is a very successful theory that describes the known matter in terms of its elementary constituents and their interactions. It describes and unifies three out of the four fundamental interactions: the electromagnetic interaction, responsible for the interactions between charged particles; the weak interaction, responsible for the existence of atomic nuclei; and the strong interaction, responsible for binding quarks together to form protons and neutrons and consequently nuclei. The gravitational interaction acts on macroscopic scale and it cannot be unified with the other three forces in the Standard Model theoretical framework.

In the Standard Model particles acquire mass through the Higgs-Brout-Englert mechanism, usually called the Higgs mechanism, which postulates the existence of a scalar field, the Higgs field. Then, the gauge bosons and the fermions acquire mass by interacting with the Higgs field. This leads to the emergence of a physical scalar particle, the Higgs boson. It has been hunted for decades in different experiments at both the LEP and Tevatron colliders without having any experimental evidence. The search continued when the world’s largest proton-proton collider, the Large Hadron Collider, started its operations. The first evidence of the Higgs boson was achieved in July 4th 2012 when the collaborations of the ATLAS and CMS experiments announced the observation of a new particle with a mass around 125 GeV, with a combined significance of more than 5 standard deviations.

The analyses presented in this thesis focus on the search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$ in the context of the ATLAS experiment at the LHC. This decay channel is one of the most sensitive one and provides a clean final state signature and the possibility to fully reconstruct the Higgs mass with excellent detector resolution.

Only muons and electrons are considered in the final state. Electrons are reconstructed and identified by combining the information from the Inner Detector and the calorimeter, whereas for the muons the Inner Detector and the Muon Spectrometer are used. In particular, since the $4\mu$ final state is the most promising one for measuring the Higgs-boson mass, it is very important to know the muon performance of the ATLAS detector. In order to achieve this, the muon momentum resolution of the ATLAS detector has been studied using $Z$ decays in two muons using data-driven techniques. The muon momentum resolution as a function of the muon $p_T$ is provided for both
SUMMARY

the Inner Detector and the Muon Spectrometer.

Then, the observation of a new particle in the search for the Standard Model Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel has been presented. The analysis has been performed using 4.8 $fb^{-1}$ and for 5.8 $fb^{-1}$ of $p$-$p$ collision data at $\sqrt{s} = 7$ TeV and at $\sqrt{s} = 8$ TeV, respectively. An excess of data events over the background-only prediction has been observed at $m_H = 125$ GeV with a local $p_0$ of 0.018%, corresponding at 3.6 standard deviations. The combination with the other searches of SM Higgs boson in ATLAS has been presented. The significance of the combined excess at $m_H = 126.5$ GeV reached 6 standard deviations, with an expected value in the presence of a SM Higgs boson signal at that mass of 4.9 standard deviations. The resulting estimate for the mass of the new observed particle is $m_H = 126.0 \pm 0.4$ (stat) $\pm 0.4$ (syst) GeV, while the observed best-fit signal strength parameter $\mu$, defined as the ratio of the observed and expected number of events, is $\mu = 1.4 \pm 0.3$ which is consistent with a Standard Model Higgs boson.

The analysis in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel has been updated with the full 2011 and 2012 datasets corresponding to a total integrated luminosity of about 25 $fb^{-1}$ of $p$-$p$ collision data. Using the full available dataset, the excess of events is found around $m_H = 124.3$ GeV with a local $p_0$ value of $2.7 \times 10^{-11}$, corresponding to a significance of 6.6$\sigma$: the single channel discovery is therefore reached. The value of the estimated mass is $m_H = 124.3^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV, while the signal strength at this best fit value for $m_H$ is $\mu = 1.7^{+0.5}_{-0.4}$.

To verify if the new discovered particle is the Standard Model Higgs boson or not, its spin and parity have been measured. In order to test the Standard Model hypothesis, spin zero and even parity, against other spin and parity, $J^P$, hypotheses, a multivariate technique using Boosted Decision Trees has been developed. The $J^P$ states explored in this analysis are spin 0, 1 and 2 with even and odd parity. Expect the 2$^-$ hypothesis, which appears to be preferred by the data when compared to the 0$^+$ hypothesis, the 0$^-$, 1$^+$, 1$^-$ and 2$^+$ hypotheses are excluded at the 97.8%, 99.8%, 94% and 83.2% CLs confidence levels in favour of the SM 0$^+$ hypothesis. The Higgs-like boson is therefore found to be compatible with the SM hypothesis.

The results obtained in the search in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel have been combined with the results from the other two most sensitive decay channels in ATLAS, $H \rightarrow \gamma\gamma$ and the $H \rightarrow WW \rightarrow l\nu l\nu$. In the combination, the excess of events has been found at $m_H = 125.5$ GeV with a local significance of 10$\sigma$. The mass and the signal strength are measured to be $m_H = 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (syst) GeV and $\mu = 1.33 \pm 0.14$ (stat) $\pm 0.15$ (syst), respectively.

The measurements of the spin-parity properties of the new boson performed using the three decay channels have been combined too. The Standard Model hypothesis, when compared to alternative spin-parity hypotheses ($J^P = 0^-, 1^+, 1^-, 2^m, 2^-$), has been found strongly favoured: all the other hypotheses have been excluded with a confidence level above 97.8%.

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Samenvatting

Het Standaardmodel van de deeltjesfysica is een bijzonder succesvolle theorie die alle bekende vormen van materie beschrijft in termen van elementaire deeltjes en hun interacties. Het beschrijft drie van de vier fundamentele krachten: de electromagnetische kracht, verantwoordelijk voor interacties tussen geladen deeltjes; de zwakke kernkracht, verantwoordelijk voor het bestaan van atoomkernen en de sterke kernkracht die de quarks bindt in de vorm van protonen en neutronen. De zwaartekracht werkt op een macroscopische schaal en kan niet binnen het Standaardmodel beschreven worden.


De analyses in dit proefschrift beschrijven de zoektocht naar het Standaardmodel Higgsdeeltje in het vervalskanaal $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ in de ATLAS detector bij de LHC versneller. Dit vervalkanaal is een van de meest gevoelige. Het heeft een eindtoestand met weinig achtergrond en biedt de mogelijkheid de massa van het Higgsdeeltje precies te bepalen. In deze eindtoestand worden alleen elektronen en muonen gebruikt. Elektronen worden gereconstrueerd door informatie van de Inner Detector en de calorimeter te combineren. Voor muonen worden de Inner Detector en Muon Spectrometer gebruikt. De $4\mu$ eindtoestand biedt potentieel de beste bepaling van de Higgs massa. Daarom is het bijzonder belangrijk de kwaliteit van de muon-reconstructie van de ATLAS detector te begrijpen. Daarvoor wordt de muon-impulsresolutie van ATLAS bestudeerd met $Z$-deeltjes die naar twee muonen vervallen. Uit data wordt de resolutie als functie van de muon $p_T$ bepaald voor zowel de Inner Detector als de Muon Spectrometer.

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Vervolgens is de observatie van een nieuw deeltje in de zoektocht naar het Standaardmodel Higgsboson in het $H \rightarrow ZZ^{(*)} \rightarrow 4l$ vervalskanaal gepresenteerd. De analyse is uitgevoerd op een dataset van 4.8 fb$^{-1}$ proton-proton botsingen bij $\sqrt{s} = 7$ TeV en 5.8 fb$^{-1}$ bij $\sqrt{s} = 8$ TeV. Een signaal boven de achtergrond wordt waargenomen met een locale $p_0$-waarde van 0.018%, wat overeenkomt met 3.6 standaarddeviaties. De combinatie met de zoektocht in de andere vervalskanalen in ATLAS bereikt een significantie van 6 standaarddeviaties voor $m_H = 126.5$ GeV. De verwachte significantie voor een Standaardmodel Higgsboson bij deze massa is 4.9 standaarddeviaties. De gecombineerde meting van de massa van het nieuwe deeltje wordt nu $m_H = 126.0 \pm 0.4$ (stat) $\pm 0.4$ (sys) GeV. Voor de signaalsterkte parameter $\mu$ die gedefinieerd wordt als de verhouding van het gemeten signaal en het verwachte signaal, wordt gevonden $\mu = 1.4 \pm 0.3$, in overeenstemming met het Standaardmodel.

De analyse in het $H \rightarrow ZZ^{(*)} \rightarrow 4l$ kanaal is uitgebreid met de volledige dataset van 2011 en 2012, een geïntegreerde luminositeit van 25 fb$^{-1}$ proton-proton botsingen. In deze dataset is het maximale signaal te zien bij een massa van $m_H = 124.3$ GeV met een $p_0$-waarde van $2.7 \times 10^{-11}$ wat overeenkomt met een significantie van 6.6 standaarddeviaties. Hiermee is het deeltje ook in dit individuele vervalskanaal aangetoond. De gemeten massa is $m_H = 124.3^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (sys) GeV en de waarde van $\mu$ bij deze massa is $\mu = 1.7^{+0.4}_{-0.5}$.

Door de spin en pariteit te meten, kan bepaald worden of het nieuwe deeltje daadwerkelijk het Higgsboson is. Het Standaardmodel voorspelt een boson met spin nul en even pariteit. Deze hypothese is vergeleken met alternatieve mogelijkheden voor $J^P$ met behulp van Boosted Decision Trees, een multivariate analysetechniek. In deze analyse zijn de $J^P$ toestanden met spin 0, 1 en 2 en even en oneven pariteit getest. Met uitzondering van de $2^-$ hypothese, die de data lijkt te verkiezen boven de standaard $0^+$ hypothese, worden $0^-, 1^+, 1^-$ en $2^+$ hypotheses uitgesloten met een confidence level van respectievelijk 97.8%, 99.8%, 94% en 83.2%. Het Higgs-achtige boson heeft daarmee eigenschappen in overeenstemming met die van het Standaardmodel Higgs.

Het resultaat van het $H \rightarrow ZZ^{(*)} \rightarrow 4l$ kanaal is gecombineerd met die van de andere twee meest gevoelige metingen in ATLAS: $H \rightarrow \gamma\gamma$ en $H \rightarrow WW \rightarrow l\nu l\nu$. Het signaal bereikt nu een significantie van 10 standaarddeviaties bij een massa van $m_H = 125.5$ GeV. De meting van de massa en de signaalsterke $\mu$ geven respectievelijk $m_H = 125.5 \pm 0.2$ (stat) $^{+0.4}_{-0.3}$ (sys) GeV en $\mu = 1.33 \pm 0.14$ (stat) $^{+0.15}_{-0.15}$ (sys).

De gecombineerde meting van de spin en pariteit van het nieuwe boson heeft een sterke voorkeur voor de waarden als in het Standaardmodel. Bij een directe vergelijking met de alternatieven $(J^P = 0^-, 1^+, 1^-, 2^+, 2^-)$ worden alle met een confidence level van meer dan 97.8% uitgesloten.
About the author

Antonio Salvucci was born on July 13th, 1983 in Latina, Italy. He studied at the university of Rome “Tor Vergata”, where he obtained his bachelor degree in October 2010, studying possible violations of the Pauli Exclusion Principle through the analysis of the data collected with the VIP experiment installed at the Gran Sasso National Laboratory (LNGS) in Italy. In the same university, he obtained his master degree in physics in September 2010. The research that led to his master thesis focused on the study of the detector performance, mainly oriented on the status of the alignment and the effects of the misalignments on the physics analyses, and on the study of a possible new massive neutral boson ($Z'$) in the context of the ATLAS experiment at the LHC. It was carried out in the Frascati National Laboratory (LNF) where he obtained a scholarship of one year starting on February 2009.

Before starting is PhD in February 2011 at the Radboud University of Nijmegen, he spent two months (November-December 2010) at CERN in Geneva working on the first pass of the determination of the muon momentum resolution of the ATLAS detector. During his PhD he carried out his research under the supervision of prof. Nicolo de Groot and dr. Frank Filthaut. He went to several international particle physics school: two Belgian Dutch German (BND) graduate schools (September 2011 and 2012) and one CERN physics school in Hungary (June 2012).

In the first year he continued his work on the muon momentum resolution of the ATLAS detector, showing the results to the Dutch national conference of Lunteren (November 2011) and the international HCP conference in Paris (November 2011). Then he started the search analysis for the Standard Model Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channel. During the two years of work he strongly contributed to the Higgs boson discovery (July 2012) and the measurements of its spin and parity. He presented the results of the analysis, which led to the writing of this thesis, at the Dutch national conference ’Physics@FOM’ in Veldhoven (January 2013) and at the ’La Thuile’ (February 2013) and EPS (July 2013 in Stockholm) international conferences. The analysis framework developed in the context of the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ analysis was then used to investigate a new computing framework based on the PROOF system and using the ATLAS Grid facilities [161]. This work has been presented in the 20th International Conference on Computing in High Energy and Nuclear Physics (October 2013 in Amsterdam).
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Once again I am writing the last pages of a manuscript, which, each time, represents the “end” of an additional chapter of my life’s book. In this moment I can only retrace what were the last three years of my life, definitely filled with strong feelings.

I still remember, like it was yesterday, the night when I prepared my luggage to start a new life in The Netherlands. Leaving was for sure not easy, especially when I saw some tears falling down from my parents’ eyes. As well, the first months in a new country were difficult: new society, new habits, new friends and no more solid “stones”. Sometimes I felt alone even with lots of people around me or when the huge number of tasks left me no time for a bit of rest. All those feelings are now only memories: this is a real proof how much way I did.

A long trip of a bit more than three years is almost over. Along my “journey” I met many people who in some way have been important, giving me encouragement when I had no more. First of all I would thank once more a dear friend, Claudio Gatti, for the support and the knowledge and tricks he provided me: these have been so important for my PhD career.

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(my fault!!) - barbecues and dinners. We had very amazing moments (Geert-Jan, do you still remember my jokes concerning fruits?).

Through my superhero, flatmate and second father Ruggero (Hey dad, your son Gianluca is still waiting you at home!) I met lots of amazing people around the city. With you guys - Shankar, Helene, Manuela, Marta, Jordan, Mariam, Vania, Daniel, Florian, Simone, Anna, Simone and Virginia - I had crazy moments dancing, drinking, cooking, making jokes and whatever our brains were able to think: you have been really nice fellows and I hope to meet all of you once again.

Thanks for making brighter and happier my Dutch life.

My last three years were spent not only in Nijmegen, but visiting most of the European countries. I went several times to Nikhef, in Amsterdam, to attend physics lessons and to several international schools and conferences. In those trips I met nice people which enriched my life with memorable moment. In this case it is quite impossible (and probably also not correct) to try to remember all your names, but probably it is nicer to describe some of the most beautiful moments. For those were in Bonn, I would remember the hours spent playing guitar and singing song: Pantso - my dear and sweet "son": your father (me, Zeus) will never forget you:) - Andrea and Enrico (also called “Er Cicoria”) played amazing song with the guitar and most of us were singing (with terrible voices I would say!). In Bonn as well Davide still remembers that night when we were smoking just outside the hotel: I would look at your face in the moment in which you will read about this!!!

In that city I also met a girl that is becoming one of the most important people of my life (or at least I hope it will be somehow). Lucia, I guess you well remember most of the moments in which we spent our time together - I could make an infinite list of all amazing moments we spent together, along with some not so nice ones - but I would focus on a particular one when in Saint Genis my car was not working properly (probably “Betty” was already planning something strange ... don’t you agree?). During the last two years (more or less) we realized that life is not a dream and everything must be built step by step, with patience, sweat and sometimes tears (“perché ogni lacrima nasconde sempre qualcosa di buono”). I would thank you for just being in my life, making it better. You showed me that I am still able to give more than I have to see other people happy: this is probably the best gift I had. Because of you, I often visited Brussels, the cool city in which you are living and I met some new friends: Federico, a nice guy and a great fellow for making jokes and good food (“anche se rimani uno zozzo teorico!”), Alberto and Matteo (we need to organize another PES tournament!!!).

During the last three years I also spent more than one year at CERN, working on the Higgs boson physics analysis. There I worked really hard, sometimes also during the night, especially just before the Higgs discovery, announced in July 2012. I guess I will never forget exciting moments when we found the first Higgs candidates: me, Roberto, Fabio, Ludovico, Stefano, Mario (someone called us the “Italian Mafia”) spent most of our energies to improve the Higgs analysis and give a strong contribution to the Higgs boson discovery. I really would thank my team for the great job done: we worked very hard all together enjoying every single moment we spent on the Higgs boson
analysis (trying to smile even if things were not going in the correct direction). That team earned other two members some weeks after the Higgs boson discovery, Giada and Andrea. In particular I have memorable moments with Andrea: since he is as much idiot as me, we had a lot of fun during our working time, trying also to save ourself from all the “strange” situations in which we were involved. Andrea, I guess you still remember (and unfortunately not only you) the first approval of the spin and parity analysis: that one was one of the most epic moments of my PhD, without any doubt. For this and many other moments I would thank you: you were supporting me for any idiotic idea I had - BIG BIG MISTAKES MAN! - even when some situations became too embarrassing (“Come Scusi??”). Fortunately, we had a serious guy (or at least more than us) which helped us to avoid our TOTAL DESTRUCTION: both of us should thank Roberto (“A proposito Rob, ma ’Manine de Fata’ te lo ricordi?”) more than once.

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