The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/132621

Please be advised that this information was generated on 2017-09-02 and may be subject to change.
Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector

The ATLAS Collaboration

Abstract

A search is reported for Higgs boson decay to $\mu^+\mu^-$ using data with an integrated luminosity of 24.8 fb$^{-1}$ collected with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV at the CERN Large Hadron Collider. The observed dimuon invariant mass distribution is consistent with the Standard Model background-only hypothesis in the 120–150 GeV search range. For a Higgs boson with a mass of 125.5 GeV, the observed (expected) upper limit at the 95% confidence level is 7.0 (7.2) times the Standard Model expectation. This corresponds to an upper limit on the branching ratio $\text{BR}(H \to \mu^+\mu^-)$ of $1.5 \times 10^{-3}$. 

© 2014 CERN for the benefit of the ATLAS Collaboration.

Reproduction of this article or parts of it is allowed as specified in the CC-BY-3.0 license.
Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector

Abstract

A search is reported for Higgs boson decay to $\mu^+\mu^-$ using data with an integrated luminosity of 24.8 fb$^{-1}$ collected with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV at the CERN Large Hadron Collider. The observed dimuon invariant mass distribution is consistent with the Standard Model background-only hypothesis in the 120–150 GeV search range. For a Higgs boson with a mass of 125.5 GeV, the observed (expected) upper limit at the 95% confidence level is 7.0 (7.2) times the Standard Model expectation. This corresponds to an upper limit on the branching ratio $\text{BR}(H \rightarrow \mu^+\mu^-)$ of $1.5 \times 10^{-3}$.

1. Introduction

The Standard Model (SM) describes a wide range of particle physics phenomena to a high degree of precision. In the SM, the Brout–Englert–Higgs (BEH) mechanism [1–3] spontaneously breaks the electroweak (EW) gauge symmetry and generates masses for the $W$ and $Z$ gauge bosons as well as for the charged fermions via Yukawa couplings [4–6]. In searches for the Higgs boson predicted by the BEH mechanism, the ATLAS and CMS collaborations have discovered a new particle, via decays into gauge bosons [7, 8], with a mass of approximately 125.5 GeV and measured properties consistent with those predicted by the SM [9–12].

Higgs boson decays to $b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$ can be measured at the LHC with their SM branching ratios proportional to the squares of the fermion masses. The SM branching ratio for the $H \rightarrow \mu^+\mu^-$ decay is $21.9 \times 10^{-3}$ for a Higgs boson mass ($m_H$) of 125 GeV [13, 14]. The $H \rightarrow \mu^+\mu^-$ decay has a clean final state signature that allows a measurement of the Higgs boson coupling to second-generation fermions. The dominant irreducible background is the $Z/\gamma^* \rightarrow \mu^+\mu^-$ process, which has an approximately three orders of magnitude higher production rate compared to that of the expected signal.

In this Letter a search for the $H \rightarrow \mu^+\mu^-$ decay of the SM Higgs boson is presented. This search for the presence of a narrow $H \rightarrow \mu^+\mu^-$ resonance, with a signal width determined by experimental resolution, is performed by fitting the invariant mass distribution in the 110–160 GeV region. This range allows determining background shape and normalisation and setting a limit on the dimuon decay of the SM Higgs boson with a mass of 125.5 GeV. Section 2 gives a description of the experimental setup and summarises the data sample and Monte Carlo (MC) simulation samples used to model the signal process and to develop an analytical model for the background processes. Sections 3 and 4 describe the event selections and categorisation. Analytical models used to describe invariant mass distributions for signal and background processes are discussed in Section 5, and systematic uncertainties are detailed in Section 6. The results are presented in Section 7.

2. Experimental setup, data and simulated samples

This search is performed on the data sample recorded in 2011 and 2012 by the ATLAS detector in $pp$ collisions at the LHC at $\sqrt{s} = 7$ and 8 TeV, respectively. ATLAS [15] is a general-purpose particle detector with a cylindrical geometry and consists of several subdetectors surrounding the interaction point and covering almost the full solid angle [1]. The trajectories and momenta of charged particles are measured within the pseudorapidity range of $|\eta| < 2.5$ by multi-layer silicon pixel and microstrip detectors as well as a transition radiation tracker. The tracking system is immersed in a 2 T magnetic field produced by a superconducting solenoid.
and is surrounded by a high-granularity liquid-argon (LAr) electromagnetic sampling calorimeter covering $|\eta| < 3.2$. An iron and scintillator tile hadronic calorimeter provides coverage in the range $|\eta| < 1.7$. The LAr calorimeters also provide measurements of electromagnetic and hadronic energy deposits in the region $1.5 < |\eta| < 4.9$. The muon spectrometer surrounds the calorimeters and consists of three large air-core superconducting magnets with a toroidal field of 0.5 T in the barrel region and 1 T in the forward regions, and a system of precision tracking chambers; it provides coverage for $|\eta| < 2.7$. The muon spectrometer also includes fast detectors for triggering covering $|\eta| < 2.4$.

Events were recorded with a trigger requiring at least one muon candidate with transverse momentum $p_T > 18$ GeV for 7 TeV data and $p_T > 24$ GeV for 8 TeV data. This trigger is approximately 70% efficient for muons with $|\eta| < 1.05$ and approximately 90% efficient for muons with $|\eta| > 1.05$. The differences in the efficiency are mostly due to the different geometrical acceptance of the muon trigger system in these regions. For 8 TeV data, events were also recorded with a dimuon trigger requiring at least two muon candidates with transverse momenta of $p_T > 18$ GeV and $p_T > 8$ GeV. Applying data quality requirements, the total integrated luminosity of the selected data sample is $4.5 \pm 0.1$ fb$^{-1}$ for 7 TeV data and $20.3 \pm 0.6$ fb$^{-1}$ for 8 TeV data. The associated systematic uncertainties are summarised in Section 6.

At the LHC, SM Higgs boson production is dominated by the gluon fusion (ggF) process with the next two most important contributions arising from the vector boson fusion (VBF) process and production in association with vector bosons (VH). The signal MC samples are generated in 5 GeV steps of the Higgs boson mass from 120 GeV to 150 GeV. The ggF and VBF samples are generated at next-to-leading-order (NLO) in QCD with Powheg [17, 18] with the parton showering modelled by Pythia8 [19] for the 8 TeV samples and Pythia [20] for the 7 TeV samples. The CT10 [21] parton distribution functions (PDFs) are used in Powheg, with the ATLAS Underlying Event Tune, AU2 [22]. The ggF Higgs boson $p_T$ spectrum in Powheg is tuned to agree with the prediction from HRES [23, 24]; this procedure shifts the Higgs boson $p_T$ spectrum to slightly smaller values. The VH samples are generated with Pythia8, using AU2 and the CTEQ6 [25] PDFs.

The predicted SM Higgs boson cross-sections and branching ratios are compiled in Refs. [13, 14, 26]. The cross section for the ggF process is calculated at next-to-next-to-leading-order (NNLO) [27, 32] in QCD and NLO electroweak (EW) corrections are applied [33, 34], assuming that the QCD and EW corrections factorise. The cross section for the VBF process is calculated with full NLO QCD and EW corrections [35-37] and approximate NNLO QCD corrections [38]. The cross section for the VH process is calculated at NNLO [39, 40] in QCD, and NLO EW radiative corrections [41] are applied. The branching ratios for $H \rightarrow \mu^+\mu^-$ decays as a function of $m_H$ are calculated using HDECAY [42].

The following MC event generators are used to simulate background processes: ALPGEN [43]+HERWIG [44] for W+jets, MC@NLO [45]+HERWIG for $t\bar{t}$, $tW$ and $tb$, ASEM@MC [46]+PYTHIA for $tq\bar{t}$, POWHEG+PYTHIA8 for $Z/\gamma^* + q\bar{q} \rightarrow WW$, gg2WW [47]+HERWIG for $gg \rightarrow WW$, POWHEG [48]+PYTHIA for $WZ$ and $ZZ$ and MG-GRAPH [49, 50]+PYTHIA for $WY^*$, $WW$, $WZ$, $ZZ$ and $WY^*$ production are referred to as diboson production later in the text. In addition, contributions from $W$ boson production in association with one or more jets ($W$+$j$ets), where one of the jets is misidentified as a muon, are estimated using a data control region containing same-sign dimuon events as described in Ref. [9].

The signal and background MC samples are processed through the ATLAS detector simulation [51] based on Geant4 [52], followed by the same reconstruction algorithms that are used for collision data. The effects arising from multiple collisions in the same or neighbouring bunch crossings (pile-up) are included in the MC simulation, matching the pile-up conditions of the selected data sample.

3. Event selection

Events are required to contain at least one reconstructed $pp$ collision vertex candidate with at least three associated tracks each with $p_T > 0.4$ GeV. The vertex with the largest sum of $p_T^2$ of tracks is considered to be the primary vertex. Muon candidates are reconstructed by matching tracks in the inner detector to tracks reconstructed in the muon spectrometer. In addition to stringent track quality requirements imposed for muon identification, the muon tracks must be consistent with having originated from the primary vertex. All selected muon candidates are required to be within $|\eta| < 2.5$. Muon candidates must pass track and calorimeter isolation requirements that scale with the $p_T$ of the muon track. The isolation is calculated as the scalar sum of the $p_T$ of additional tracks or the $E_T$ of calorimeter energy deposits within cone of radius $AR = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon track, normalised by $p_T^\mu$. For 8 TeV data, each muon with $p_T^\mu > 20$ (15) GeV is required to have a normalised track isolation smaller than
Jets are reconstructed from clusters of calorimeter cells using the anti-$k_t$ algorithm \cite{53,54} with a radius parameter of 0.4. The selected jets must satisfy $E_T > 25$ GeV for $|\eta| < 2.4$ and $E_T > 30$ GeV for $2.4 \leq |\eta| < 4.5$. Muon candidates overlapping with the selected jets within a cone of radius $AR = 0.4$ are removed from the analysis. In the pseudorapidity range $|\eta| < 2.5$, jets originating from $b$-quarks are identified using a $b$-tagging algorithm \cite{55,56} with an efficiency of approximately 80%, determined from $t\bar{t}$ MC events, and with a misidentification rate for selecting light-quark or gluon jets of less than 1%. The missing transverse momentum \cite{57}, $E^\text{miss}_T$, is the magnitude of the vector sum of the $p_T$ of muons, electrons, photons, jets and clusters of calorimeter cells with $|\eta| < 4.9$ not associated with these objects.

Corrections are applied to simulated MC samples in order to account for differences between data and MC simulation for the trigger and identification efficiency and for the muon momentum scale and resolution. The trigger and reconstruction efficiency corrections are measured using $Z \rightarrow \mu^+\mu^-$ events and are found to be within 2\% of unity. The muon momentum corrections are determined by comparing the reconstructed invariant mass distribution of $Z \rightarrow \mu^+\mu^-$ events in data with that from simulated events; these corrections are within 0.1\% of unity.

$H \rightarrow \mu^+\mu^-$ candidate events are selected by requiring exactly two oppositely charged muons with transverse momentum $p_T^{\mu} > 25$ GeV and $p_T^{\mu} > 15$ GeV for the leading and subleading muon, respectively. Selected events must contain at least one muon identified by the trigger system within a cone of radius $AR = 0.15$ centred on the reconstructed muon candidate. The dominant background in this search is $Z/\gamma^* \rightarrow \mu^+\mu^-$ production, followed by smaller backgrounds from single and pair production of top quarks and dibosons processes. To suppress backgrounds from top quark pair production and diboson processes, events are required to have $E^\text{miss}_T < 80$ GeV. The dimuon invariant mass distribution $m_{\mu^+\mu^-}$ and the dimuon transverse momentum $p_T^{\mu^+\mu^-}$ for data and MC events passing all the selection requirements so far are shown in Fig.\cite{1}. The number of expected signal events for $m_H = 125$ GeV, the expected background contributions, and the number of observed data events in the $m_{\mu^+\mu^-}$ region from 122.5 to 127.5 GeV are shown in Table\cite{1}. The MC background yields are given to illustrate the expected background composition. The selection efficiency times acceptance for signal events with $m_H = 125$ GeV after all selection criteria described thus far is approximately 55\%.

The expected background processes produce smooth $m_{\mu^+\mu^-}$ distributions in the search window, allowing the total background normalisation and shape in each category to be derived from fitting the data as described in Section\cite{5}. The $m_{\mu^+\mu^-}$ distribution is examined in the range 110–160 GeV. This range is larger than the 120–150 GeV search window in order to account for signal resolution effects and to allow sufficient sidebands for background normalisation.

4. Event categorisation

To increase sensitivity to the Higgs boson signal, the selected events are separated into seven mutually exclusive categories with different signal-to-background ratios based on their muon pseudorapidity ($\eta_{\mu}$), $p_T^{\mu^+\mu^-}$, and VBF dijet signature. Events produced in the VBF

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{The distribution of the dimuon invariant mass (top) and dimuon momentum (bottom) for 7 TeV and 8 TeV data with all the selection requirements described in Section\cite{5}. The expected signal is shown for $m_H = 125$ GeV.}
\end{figure}
process are characterised by two forward jets with little hadronic activity between them. The VBF category is thus defined by requiring the events to have at least two jets with an invariant mass greater than 500 GeV, $|\eta_{\text{jet}}| > 3$ and $\eta_{	ext{jet}} \times \eta_{\text{jet}} < 0$. In events with more than two jets, those with the highest $p_T$ are used in the selection. Events with at least one jet identified as originating from a $b$-quark are excluded from the VBF category.

The events that are not selected for the VBF category are classified using $p_T^{\mu}$. Signal events have on average larger values of $p_T^{\mu}$ than the $Z/\gamma^*$ background events. Therefore, the remaining events are separated into three $p_T^{\mu}$ categories: low (< 15 GeV), medium (15–50 GeV) and high (> 50 GeV). To further improve the search sensitivity, each of these three categories is also subdivided into a central category with $|\eta_{\mu}| < 1$ and $|\eta_{\mu}| > 1$ and a non-central category containing all remaining events. This value for the $\eta_{\mu}$ boundary has been chosen by scanning a range of $\eta_{\mu}$ values and selecting a value with the highest signal sensitivity. The muon momentum measurement for the central muons is more precise, producing a narrower $m_{\mu\nu}$ distribution for signal events in the central category and thus resulting in a higher overall signal sensitivity. Table 2 shows the signal event yields, $N_S/\sqrt{N_B}$ ratios, approximate signal width and results of the fits to the data, described in Section 5 for all analysis categories.

5. Signal and background models

Analytical models are used to describe the $m_{\mu\nu}$ distributions for signal and background processes. The simulated samples detailed in Section 2 are used to develop background models which are designed to describe essential features of the background $m_{\mu\nu}$ distributions, dominated by $Z/\gamma^*$, while having sufficient flexibility to describe different categories and to absorb potential differences between data and MC simulation.

The background model selected for the $p_T^{\mu}$ categories is the sum of a Breit–Wigner (BW) function convolved with a Gaussian function (GS), and an exponential function divided by $x^3$:

$$P_B(x) = f \cdot [BW(M_{BW}, \Gamma_{BW}) \ast GS(\sigma_{BS}^B)](x) + (1-f) \cdot C \cdot e^{A/x^3},$$

where $x$ represents $m_{\mu\nu}$ and $f$ represents the fraction of the BW component when each individual component is normalised to unity. $C$ is an overall normalisation coefficient. The $\sigma_{BS}^B$ parameters in each category are fixed to the average $m_{\mu\nu}$ resolution in that category as determined from the MC simulation of $Z/\gamma^*$. The background model for the VBF category is the product of a Breit–Wigner and an exponential function:

$$P_B(x) = BW(M_{BW}, \Gamma_{BW}, x) \cdot e^{A/x^3}.$$
determined from fits to the data, as shown in Fig. 2 for the central medium $p_T^{\mu^+\mu^-}$ category. Similar fit quality is observed for all other categories.

![Figure 2: The background model fits to the $m_{\mu^+\mu^-}$ distribution for the central medium $p_T^{\mu^+\mu^-}$ category for 7 TeV (top) and 8 TeV (bottom) data. The statistical uncertainties are given for the data points. The expected signal is shown for $m_H = 125$ GeV and is scaled by a factor of 50.](image)

The signal model is obtained from simulated Higgs boson signal samples, where contributions from the ggF, VBF and VH Higgs boson production processes are added together. This model is the sum of a Crystal Ball (CB) and a Gaussian function:

$$P_S(x) = f_{CB} \cdot \text{CB}(x, m, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \cdot \text{GS}(x, m, \sigma_{GS}^S),$$  

(3)

where $x$ represents $m_{\mu^+\mu^-}$ and $f_{CB}$ represents the fraction of the CB contribution when each individual component is normalised to unity. The parameters $\alpha$ and $n$ define the power-law tail of the CB distribution. The parameters $\sigma_{CB}$ and $\sigma_{GS}^S$ denote the widths of the CB and GS distributions, respectively. The parameters $m$, $\sigma_{CB}$ and $\sigma_{GS}^S$ are determined from the fits to the simulated Higgs boson samples. In order to improve stability of the fits, the remaining parameters $f_{CB}$, $\alpha$ and $n$ are fixed to values determined from empirical tests where a range of possible values have been tested.

![Figure 3: The signal model fit to the $m_{\mu^+\mu^-}$ distribution for the central (top) and non-central (bottom) simulated Higgs boson events for $m_H = 125$ GeV in the medium $p_T^{\mu^+\mu^-}$ category for $\sqrt{s} = 8$ TeV.](image)

To derive the results presented in Section 7, a binned maximum likelihood fit to the observed $m_{\mu^+\mu^-}$ distributions in the range 110–160 GeV is performed using the sum of the signal and background model. The fit is done simultaneously in all seven categories with separate distributions for 7 TeV and 8 TeV data. In addition to the background model parameters described earlier, a background normalisation in each category and the $H \to \mu^+\mu^-$ signal strength $\mu_S$ are free parameters of the fit, where $\mu_S$ is defined such that $\mu_S = 0$ corresponds to the background-only hypothesis and $\mu_S = 1$ corresponds to the SM $H \to \mu^+\mu^-$ signal.
6. Systematic uncertainties

The main theoretical and experimental sources of uncertainty on the number of expected signal events are shown in Table 2. The uncertainty on the integrated luminosity is ±1.8% for 7 TeV data [58] and ±2.8% for 8 TeV data; it is obtained following the same methodology as that detailed in Ref. [58], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

Sources of experimental uncertainty include the efficiency of the muon trigger, reconstruction, identification, and isolation requirements, as well as the muon momentum scale and resolution. Uncertainties on the jet energy scale and resolution affect the selection of jets used in the VBF category definitions. Smaller uncertainties arise from pile-up and the primary vertex selection.

The theoretical uncertainties on the production and $H \rightarrow \mu^+ \mu^-$ decay of a SM Higgs boson of mass $m_H = 125$ GeV are taken from Refs. [13, 14]. The uncertainty on the relative populations of the $p_T^{\mu^+\mu^-}$ categories, due to the uncertainty on the description of the Higgs boson $p_T$ spectrum arising from missing higher-order corrections, is determined by varying the QCD renormalisation, factorisation and resummation scales used in the HRES program. To evaluate these uncertainties, the scales are independently varied up and down by a factor of two while keeping their ratio between 0.5 and 2.0. The ggF contribution to the VBF category has large uncertainties due to missing higher-order corrections; they are estimated using the method described in Ref. [26]. The uncertainties associated with the modelling of multi-parton interactions (MPI) are estimated by turning off the MPI modelling in the event generation, according to the recommendations in Ref. [26].

In addition to the samples described in Section 2, samples of the dominant Z/γ* background are generated with Powheg+Pythia8 and parameterised with a detector response measured using simulated MC events. These samples contain approximately 170 times more events than expected in the data and are used to validate the background models and to derive systematic uncertainties due to potential mismodelling bias. This bias is estimated by fitting the parameterised signal plus background model to the simulated $m_{\mu^+\mu^-}$ background distribution in the mass range 110–160 GeV where the signal strength $\mu_s$ is a free parameter. The bias is then defined as the root mean square of the signal yield obtained from the fit for Higgs boson masses in the range 120–150 GeV. This uncertainty varies from 3% to 20% of the statistical uncertainty on the signal strength $\mu_s$, depending on the selection category and data-taking period.

Table 3: Main sources of experimental and theoretical uncertainty on the signal yield, excepting the error from mismodelling bias. “QCD scale” indicates the theoretical uncertainty on the Higgs boson production due to missing higher-order corrections estimated by varying the QCD renormalisation and factorisation scales, while “PDFs + $\alpha_s$” indicates uncertainty due to parton distribution functions, as described in Ref. [13, 14]. The ranges for the uncertainties cover the variations among different categories and data-taking periods.

<table>
<thead>
<tr>
<th>Source (experimental)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>±1.8 (7 TeV), ±2.8 (8 TeV)</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>±1</td>
</tr>
<tr>
<td>Muon momentum res.</td>
<td>±1</td>
</tr>
<tr>
<td>Muon trigger</td>
<td>±1.5</td>
</tr>
<tr>
<td>Muon isolation</td>
<td>±1.1</td>
</tr>
<tr>
<td>Pile-up reweighting</td>
<td>±1</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>±1.4 (VBF)</td>
</tr>
<tr>
<td>Source (theory)</td>
<td>Uncertainty (%)</td>
</tr>
<tr>
<td>Higgs boson branching ratio</td>
<td>±7</td>
</tr>
<tr>
<td>QCD scale</td>
<td>±8 (ggF), ±1 (VBF, VH)</td>
</tr>
<tr>
<td>PDFs + $\alpha_s$</td>
<td>±8 (ggF), ±4 (VBF, VH)</td>
</tr>
<tr>
<td>ggF uncert. in VBF</td>
<td>±22</td>
</tr>
<tr>
<td>Multi-parton inter. in VBF</td>
<td>±9 (ggF), ±4 (VBF)</td>
</tr>
</tbody>
</table>

7. Results and conclusions

The statistical procedure used to interpret the data is summarised in Ref. [7]. The observed data is consistent with the expected backgrounds and no evidence for a signal is found. Upper limits are computed on the signal strength $\mu_s$ using a modified frequentist CL$_s$ method [59, 60] based on a Poisson log-likelihood ratio statistical test.

The observed and expected 95% confidence level (CL) limits on the $H \rightarrow \mu^+ \mu^-$ signal strength are shown in Fig. 4. Table 4 summarises the observed and expected limits for different values of $m_H$. Including the systematic uncertainties described in Section 6 changes the expected limit by approximately 2% for $m_H = 125$ GeV.

Table 4: Observed and expected 95% CL upper limits on the $H \rightarrow \mu^+ \mu^-$ signal strength $\mu_s$ for different values of $m_H$.

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
<th>145</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs.</td>
<td>9.5</td>
<td>7.1</td>
<td>6.5</td>
<td>8.3</td>
<td>14.7</td>
<td>16.5</td>
<td>16.8</td>
</tr>
<tr>
<td>Exp.</td>
<td>6.7</td>
<td>7.2</td>
<td>7.9</td>
<td>9.1</td>
<td>11.3</td>
<td>16.0</td>
<td>26.6</td>
</tr>
</tbody>
</table>

To conclude, a search for Higgs boson decay to $\mu^+ \mu^-$ in 24.8 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV at the
LHC has been performed with the ATLAS experiment. The observed data is consistent with the expected backgrounds. No evidence for a signal is observed and upper limits are set on the signal strength of the Higgs boson mass. For a SM Higgs boson with a mass of 125.5 GeV, the observed (expected) limit on the signal strength $\mu_S$ at the 95% CL is 7.0 (7.2) times the SM prediction. Assuming a Higgs boson mass of 125 GeV and the SM production cross section, which is allowed to vary within its uncertainty, the 95% CL upper limit on the $H \rightarrow \mu^+\mu^-$ branching ratio is $1.5 \times 10^{-3}$.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNISW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR, MSTD, Serbia; MSSR, Slovakia; ARRS and MIŽS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

References

[arXiv:1207.7214]
[arXiv:1207.7235]
[arXiv:1307.1427]
[arXiv:1307.1432]
[arXiv:1401.6527]
[arXiv:1305.4571]
[arXiv:1101.0593]
[arXiv:1201.3084]


Division of Physics, TOBB University of Economics and Technology, Ankara; *(d) Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 *(a) Institute of Physics, University of Belgrade, Belgrade; *(b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 *(a) Department of Physics, Bogazici University, Istanbul; *(b) Department of Physics, Dogus University, Istanbul; *(c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 *(a) INFN Sezione di Bologna; *(b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 *(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; *(b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; *(c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; *(d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 *(a) National Institute of Physics and Nuclear Engineering, Bucharest; *(b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; *(c) University Politehnica Bucharest, Bucharest; *(d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 *(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; *(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 *(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; *(b) Department of Modern Physics, University of Science and Technology of China, Anhui; *(c) Department of Physics, Nanjing University, Jiangsu; *(d) School of Physics, Shandong University, Shandong; *(e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 *(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; *(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 *(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; *(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
Petersburg Nuclear Physics Institute, Gatchina, Russia
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina SK, Canada
132 Ritsumeikan University, Kusatsu, Shiga, Japan
133 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of America
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
147 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
165 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana IL, United States of America
167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
168 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Micro electrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
169 Department of Physics, University of British Columbia, Vancouver BC, Canada
170 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
171 Department of Physics, University of Warwick, Coventry, United Kingdom