Abstract
A search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ is presented. Proton-proton collision data at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector and corresponding to an average integrated luminosity of $2.1 \text{ fb}^{-1}$ are compared to the Standard Model expectations. Upper limits on the production cross section of a Standard Model Higgs boson with a mass between 110 and 600 GeV are derived. The observed (expected) 95% confidence level upper limit on the production cross section for a Higgs boson with a mass of 194 GeV, the region with the best expected sensitivity for this search, is 0.99 (1.01) times the Standard Model prediction. The Standard Model Higgs boson is excluded at 95% confidence level in the mass ranges 191–197, 199–200 and 214–224 GeV.

Keywords: LHC, ATLAS, Higgs, leptons

1. Introduction
The search for the Standard Model (SM) Higgs boson is a major goal of the Large Hadron Collider (LHC) programme. Direct searches at the CERN LEP $e^+e^-$ collider led to a lower limit on the Higgs boson mass, $m_H$, of 114.4 GeV at 95% confidence level (CL) [4]. The searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded at 95% CL the region $156 \text{ GeV} < m_H < 177$ GeV [5]. Results from the 2010 LHC run extended the search in the region $200 \text{ GeV} < m_H < 600$ GeV by excluding a Higgs boson with cross section larger than $5 - 20$ times the SM prediction [6, 7].

This letter presents a search for the SM Higgs boson in the mass range from 110 to 600 GeV in the channel $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$, where $\ell, \ell' = e, \mu$. Three distinct final states, $\mu\mu\mu\mu$ (4$\mu$), $ee\mu\mu$ (2$e\mu$), and $eeee$ (4$e$), are selected. The largest background to this search comes from continuum $ZZ^{(*)}$ production. For $m_H < 180$ GeV, contributions from $Z +$ jets and $t\bar{t}$ processes, where the additional charged leptons arise either from semi-leptonic decays of heavy flavour or from light flavour jets misidentified as leptons, are important. The $pp$ collision data were recorded with the ATLAS detector at the LHC at $\sqrt{s} = 7$ TeV and correspond to an average integrated luminosity of $2.1 \text{ fb}^{-1}$ [8].

2. The ATLAS Detector
The ATLAS detector [9] is a multi-purpose particle physics apparatus with forward-backward symmetric cylindrical geometry [4]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field. A high-granularity lead-liquid argon (LAr) sampling calorimeter measures the energy and the position of electromagnetic showers. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward rapidity regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer

---

1. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point. The x-axis is along the beam pipe, the x-axis points to the centre of the LHC ring and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity $\eta$ is defined as $\eta = -\ln[\tan(\theta/2)]$ where $\theta$ is the polar angle.
(MS) surrounds the calorimeters and consists of three large superconducting toroids, each with eight coils, a system of precision tracking chambers, and detectors for triggering. A three-level trigger system selects events to be recorded for offline analysis.

3. Data and Simulation Samples

The accumulated data are subjected to quality requirements ensuring that the relevant detector components were operating normally. The resulting average integrated luminosity of $2.1 \text{ fb}^{-1}$ corresponds to $2.28 \text{ fb}^{-1}$, $1.96 \text{ fb}^{-1}$, and $1.98 \text{ fb}^{-1}$ for the $4\mu$, $2\ell 2\mu$, and $4\ell$ final states, respectively.

The $H \rightarrow ZZ^* \rightarrow 4\ell$ signal is modelled using the POWHEG Monte Carlo (MC) event generator [10, 11], which calculates separately the gluon and vector-boson fusion production mechanisms with matrix elements up to next-to-leading order (NLO). The Higgs boson transverse momentum, $p_T$, spectrum is reweighted to the calculation of Ref. [12], providing QCD corrections up to next-to-leading order and QCD soft-gluon resummations up to next-to-next-to-leading order (NNLL). POWHEG is interfaced to PYTHIA [13] for showering and hadronization, which in turn is interfaced to PHOTOS [14] for QED radiative corrections in the final state and to TAUOLA [15, 16] for the simulation of $\tau$ decays.

The cross sections for Higgs boson production, the corresponding branching fractions, as well as their uncertainties [17], are derived to next-to-next-to-leading order (NNLO) in QCD for the gluon fusion [18, 22] and vector boson fusion [24] processes. In addition, QCD soft-gluon resummations up to NNLL are available for the gluon fusion process [25], while the NLO electroweak (EW) corrections are applied to both the gluon fusion [26, 27] and vector boson fusion [28, 29] processes. The Higgs boson decay branching ratio to the four-lepton final state is predicted by PROPHETIC [30, 31], which includes the complete NLO QCD+EW corrections, interference effects between identical final state fermions and leading two-loop heavy Higgs boson corrections to the four-fermion width. Table 1 gives the production cross sections for the $H \rightarrow 4\ell$ for several Higgs boson masses.

The $ZZ^*$ background is generated using PYTHIA, taking into account $Z\gamma$ interference. For the inclusive total cross section and the shape of the $m_{ZZ^*}$ spectrum, the MCFM [32, 33] prediction is used, which includes both quark-antiquark annihilation at QCD NLO and gluon fusion. The inclusive $Z$ boson production, $Z + \text{jets}$, is modelled using ALPGEN [34] and is divided into $Z + \text{light flavour jets}$ and $Z\bar{b}b$; overlaps between the two samples are removed. Specifically, $b\bar{b}$ pairs with separation $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \geq 0.4$ between the $b$-jets are taken from the matrix-element calculation, whereas for $\Delta R < 0.4$ the parton-shower jets are taken. PYTHIA is also used as a cross-check of the ALPGEN results. In this search the $Z + \text{jets}$ production is normalized from the data, but for comparisons the QCD NNLO FEWZ [35, 36] and the MCFM [32, 33] cross section calculations are used for the inclusive $Z$ boson and the $Z\bar{b}b$ production, respectively. The $t\bar{t}$ background is modelled using MC@NLO [37] and is normalized to the approximately NNLO cross section calculated using HATHOR [38]. Both ALPGEN and MC@NLO are interfaced to HERTWIG [39] for parton shower hadronization and to JIMMY [40] for the underlying event simulations.

All generated events undergo a full detector simulation performed using GEANT4 [41, 42]. The number of $pp$ interactions in the same bunch crossing (pileup) is included in the simulation. The MC samples are reweighted to reproduce the observed distribution in the data.

4. Physics Object Identification and Event Selection

The data considered in this analysis were selected using single-lepton triggers. For electrons the threshold on the transverse energy, $E_T$, was
20 – 22 GeV depending on the LHC instantaneous luminosity and for muons the threshold on $p_T$ was 18 GeV. Both triggers are more than 99.5% efficient for events passing the offline selection described below.

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter associated to ID tracks. The electrons must satisfy the “medium” electron criteria [43], which require the shower profiles to be consistent with those expected for electromagnetic showers and a well reconstructed ID track pointing to the corresponding cluster. The electron transverse momentum is computed from the cluster energy and the track direction.

Muon candidates are reconstructed by matching ID tracks with either full or partial tracks in the MS [43]. For the former case, the two independent momentum measurements are combined, whereas for the latter case the momentum is measured using the ID information only, with the MS providing muon identification. To reject cosmic rays, tracks are required to be consistent with having originated from the primary vertex, defined as the reconstructed vertex with the highest $\sum p_T^2$ of associated tracks.

Leptons from Higgs boson decays are expected to be isolated and to originate from a common vertex. Track and calorimeter isolation as well as transverse impact parameter significance requirements are therefore applied to further reduce the $Z +$ jets and $tt$ contributions. The sum of $p_T$ of tracks within $\Delta R < 0.2$ of the lepton divided by the lepton $p_T$ is required to be less than 0.15, while the sum $E_T$ of the calorimeter cells within $\Delta R < 0.2$ around the lepton divided by the lepton $p_T$ is required to be less than 0.3. In the case of electrons, the calorimeter cells corresponding to the electromagnetic shower are subtracted. The transverse impact parameter significance, defined as the transverse impact parameter of the lepton with respect to the primary vertex divided by its uncertainty, for the two lowest $p_T$ leptons of the quadruplet in events with $m_{4\ell} < 190$ GeV is required to be less than 3.5 and 6 for muons and electrons respectively. The selection efficiency of the isolation and impact parameter requirements has been studied using data both for isolated leptons, with $Z \to \ell\ell$ decays and non-isolated leptons from semi-leptonic $b$ and $c$–quark decays in a heavy-flavour enriched dijet sample. Good agreement is observed between data and simulation.

Higgs boson candidates are searched by selecting two same-flavoured, opposite-sign isolated lepton pairs in an event. Each lepton must satisfy $p_T > 7$ GeV and be measured in the pseudorapidity range $|\eta| < 2.47$ for electrons and $|\eta| < 2.5$ for muons. The electron $p_T$ threshold is increased to 15 GeV in the transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$). At least two leptons must have $p_T > 20$ GeV. The leptons are required to be well separated from each other with $\Delta R > 0.1$. The invariant mass of the lepton pair closest to the nominal $Z$ boson mass ($m_Z$) is denoted by $m_{12}$ and it is required that $|m_Z - m_{12}| < 15$ GeV. The invariant mass of the remaining lepton pair, $m_{34}$, is required to be lower than 115 GeV and greater than a threshold depending on the reconstructed four-lepton mass, $m_{4\ell}$, as summarized in Table 2. The final discriminating variable is $m_{4\ell}$, where the Higgs boson production would appear as a clustering of events. The width of the reconstructed Higgs boson mass distribution is dominated by experimental resolution at low $m_H$ values, with a full-width at half-maximum (FWHM) which varies according to decay mode and is between 4.5 (4$\mu$) and 6.5 (4e) GeV for $m_H = 130$ GeV. At high $m_H$ the reconstructed width is dominated by the natural width of the Higgs boson with a FWHM of approximately 35 GeV at $m_H = 400$ GeV.

5. Background Estimation

The dominant $ZZ^{(*)}$ background is estimated using MC simulation. Generated events are required to pass the complete analysis selection and the final yield is normalized to the integrated luminosity.

The $tt$ background is also estimated using MC simulation. Comparison of data to MC predictions, in a control sample of events with opposite sign electron-muon pairs consistent with the $Z$ boson mass and with one or two additional charged leptons, are used to verify that the $tt$ background is small with respect to the dominant $ZZ^{(*)}$ process and in agreement with expectation.

The $Z +$ jets background is normalized using data. The control sample is formed by selecting events with a pair of same-flavoured, opposite-sign isolated leptons consistent with the $Z$ boson mass, $|m_Z - m_{12}| < 15$ GeV, and a second same-flavoured, opposite-sign lepton pair where only kinematic, but no isolation or impact parameter, requirements are applied. At this stage, the dominant background source depends on the flavour of the second lepton.
Table 2: Thresholds applied to $m_{34}$ for reference values of $m_{4\ell}$ (see text). For other $m_{4\ell}$ values, the selection requirement is obtained via linear interpolation.

<table>
<thead>
<tr>
<th>$m_{4\ell}$ (GeV)</th>
<th>≤120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>165</th>
<th>180</th>
<th>190</th>
<th>≥200</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold (GeV)</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: The expected numbers of background events, with their systematic uncertainty, separated into “Low mass” ($m_{4\ell} < 180$ GeV) and “High mass” ($m_{4\ell} \geq 180$ GeV) regions. The expected numbers of signal events for different $m_H$ hypotheses and the observed numbers of events are also presented.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>130</th>
<th>150</th>
<th>200</th>
<th>240</th>
<th>300</th>
<th>400</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events/5 GeV</td>
<td>0.42±0.07</td>
<td>0.40±0.06</td>
<td>0.14±0.03</td>
<td>2.64±0.38</td>
<td>0.98±0.14</td>
<td>0.88±0.13</td>
<td>0.98±0.16</td>
</tr>
<tr>
<td>Events/10 GeV</td>
<td>0.42±0.07</td>
<td>0.40±0.06</td>
<td>0.14±0.03</td>
<td>2.64±0.38</td>
<td>0.98±0.14</td>
<td>0.88±0.13</td>
<td>0.98±0.16</td>
</tr>
</tbody>
</table>

Figure 1: Invariant mass distributions (a) $m_{12}$, (b) $m_{34}$, and (c) $m_{4\ell}$ for the selected candidates. The data (dots) are compared to the background expectations from the dominant $ZZ^{(*)}$ process and the sum of $t\bar{t}$, $Zb\bar{b}$ and $Z+$light flavour jets processes. Error bars represent 68.3% central confidence intervals.

pair: $Z+$light flavour jets dominates the final states with a second electron pair, while $Zb\bar{b}$ production dominates the final states with a second muon pair after the contributions from $t\bar{t}$, $ZZ^{(*)}$, and muons from in-flight $\pi$ and $K$ decays which correspond to 44% of the event yield are subtracted. The observed background, which is found to be in good agreement with expectation, is extrapolated to the signal region by means of the MC simulation.
6. Systematic Uncertainties

Uncertainties on lepton reconstruction and identification efficiency, and on the momentum resolution and momentum scale are determined using samples of $W$, $Z$ and $J/\psi$ decays. The muon efficiency uncertainty results in an acceptance uncertainty on the signal and the irreducible background which is uniform over the mass range of interest and amounts to 1.7% (1.2%) for the $4\mu$ (2$e$2$\mu$) channel. The uncertainty on the electron efficiency results in an acceptance uncertainty of 3% (2%) for the 4e (2e2$\mu$) channel at $m_{4\ell} = 600$ GeV reaching 15% (6%) at $m_{4\ell} = 110$ GeV.

A conservative theoretical uncertainty of 15% is assigned to the $ZZ^{(*)}$ background contribution [14]. The $Z +$ light flavour jets and $Zb\bar{b}$ backgrounds are evaluated using data. A systematic uncertainty between 20% and 40% is assigned on their normalisation to account for the statistical uncertainty in the control sample and the MC-based extrapolation to the signal region. The uncertainty on the $t\bar{t}$ cross section is found to be 10% by adding linearly the contributions from variations of the renormalization and factorization scales to those of the parton distribution functions.

The theoretical uncertainties on the Higgs boson production cross section are 15–20% for the gluon fusion process and 3–9% for the vector-boson fusion process [17], depending on the Higgs boson mass. They include uncertainties on the QCD scale and on the parton distribution functions [46–49]. An additional 2% uncertainty is added to the signal selection efficiency due to the modelling of the signal kinematics. This is evaluated by comparing signal samples generated with PYTHIA and the default POWHEG samples.

The overall uncertainty on the total integrated luminosity is 3.7% [8].

7. Results

The number of events observed in each final state, separately for $m_{4\ell} < 180$ GeV and $m_{4\ell} \geq 180$ GeV, are compared with the expectations for background and signal for various $m_H$ hypotheses in Table 3. In total 27 candidate events are selected by the analysis: 12 $4\mu$, 9 $2e2\mu$, and 6 4e events, while in the same mass range 24 ± 4 events are expected from the background processes. The $m_{12}$, $m_{34}$, and $m_{4\ell}$ mass spectra are shown in Fig. 1. The $m_{4\ell}$ distribution for the total background and several signal hypotheses is compared to the data in Fig. 2. The selected events have been examined visually and no evidence for reconstruction problems was identified.

Upper limits are set on the Higgs boson cross section at 95% CL, using the $CL_s$ modified frequentist formalism [50] with the profile likelihood test statistic [51]. The test statistic is evaluated with a maximum likelihood fit of signal and background models to the observed $m_{4\ell}$ distribution. Figure 3 shows the expected and observed 95% CL cross section upper limits as a function of $m_H$ and Table 3 summarizes the numerical values for selected $m_H$ points. The consistency with the background-only hypothesis is quantified using the $p$-value, the probability that a background-only experiment fluctuates more than the observation. The most significant deviation from the background-only hypothesis is observed for $m_H = 242$ GeV with a $p$-value of 4.9%. These results do not account for the so-called “look-elsewhere” effect [52]. The SM Higgs boson is excluded at 95% CL in the mass ranges 191–197, 199–200 and 214–224 GeV.

![Figure 2: $m_{4\ell}$ distribution of the selected candidates, compared to the background expectation. Error bars represent 68.3% central confidence intervals. The signal expectation for three $m_H$ hypotheses is also shown.](image-url)
Figure 3: The expected (dashed) and observed (full line) 95% CL upper limits on the Higgs boson production cross section as a function of the Higgs boson mass, divided by the expected SM Higgs boson cross section. The green and yellow bands indicate the expected sensitivity with ±1σ and ±2σ fluctuations, respectively.

8. Summary

A search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ based on 2.1 fb$^{-1}$ of data recorded by the ATLAS detector at $\sqrt{s} = 7$ TeV during the 2011 run, has been presented. No significant excess of candidates is observed in the mass range between 110 and 600 GeV with respect to the expected SM background. The observed (expected) 95% CL upper limit on the Higgs boson production cross section, in units of the SM cross section, is 0.99 (1.01) for $m_H = 194$ GeV, the region with the best expected sensitivity for this search. The SM Higgs boson is excluded at 95% CL in the mass ranges 191 − 197, 199 − 200 and 214 − 224 GeV.

9. 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, 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; DLR, DMSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and CFT, Portugal; MRSY (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, 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

Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington NY, United States of America
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas TX, United States of America
40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham NC, United States of America
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
54 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75
75 Department of Physics, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst MA, United States of America
85 Department of Physics, McGill University, Montreal QC, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
88 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
89 (a)INFN Sezione di Milano; (b)Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
93 Group of Particle Physics, University of Montreal, Montreal QC, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nippon Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science, Nagoya University, Nagoya, Japan
102 (a)INFN Sezione di Napoli; (b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
108 Department of Physics, New York University, New York NY, United States of America
109 Ohio State University, Columbus OH, United States of America
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
112 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
113 Palacky University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
120 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (c) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
124 (e) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal;
125 (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
127 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata,
134 Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
136 (c) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université
137 Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat;
138 (c) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech
139 40000; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des Sciences,
140 Université Mohammed V, Rabat, Morocco
141 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay
142 (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
143 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United
144 States of America
145 Department of Physics, University of Washington, Seattle WA, United States of America
146 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
147 Department of Physics, Shinshu University, Nagano, Japan
148 Fachbereich Physik, Universität Siegen, Siegen, Germany
149 Department of Physics, Simon Fraser University, Burnaby BC, Canada
150 SLAC National Accelerator Laboratory, Stanford CA, United States of America
151 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of
152 Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak
153 Republic
154 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University
155 of the Witwatersrand, Johannesburg, South Africa
156 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
157 Physics Department, Royal Institute of Technology, Stockholm, Sweden
158 Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of
159 America
160 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
161 School of Physics, University of Sydney, Sydney, Australia
162 Institute of Physics, Academia Sinica, Taipei, Taiwan
163 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
164 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
165 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
166 International Center for Elementary Particle Physics and Department of Physics, The University of
167 Tokyo, Tokyo, Japan
168
Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
Also at California Institute of Technology, Pasadena CA, United States of America
Also at Institute of Physics, Jagiellonian University, Krakow, Poland
Also at Department of Physics, Oxford University, Oxford, United Kingdom
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Also at Department of Physics, Nanjing University, Jiangsu, China
* Deceased