Search for a Standard Model Higgs Boson in the $H \to ZZ \to #^+#^-#\nu\nu#$ Decay Channel with the ATLAS Detector

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th>Citation</th>
<th>G. Aad et al. &quot;Search for a Standard Model Higgs Boson in the $H \to ZZ \to #^+#^-#\nu\nu#$ Decay Channel with the ATLAS Detector.&quot; Physical Review Letters 107.22, 221802 (2011) [18 pages].</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.107.221802">http://dx.doi.org/10.1103/PhysRevLett.107.221802</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Citable link</td>
<td><a href="http://hdl.handle.net/1721.1/71147">http://hdl.handle.net/1721.1/71147</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.</td>
</tr>
</tbody>
</table>
Search for a Standard Model Higgs Boson in the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ Decay Channel with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

(Received 15 September 2011; published 22 November 2011)

A search for a heavy standard model Higgs boson decaying via $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$, where $\ell = e, \mu$, is presented. It is based on proton-proton collision data at $\sqrt{s} = 7$ TeV, collected by the ATLAS experiment at the LHC in the first half of 2011 and corresponding to an integrated luminosity of 1.04 fb$^{-1}$. The data are compared to the expected standard model backgrounds. The data and the background expectations are found to be in agreement and upper limits are placed on the Higgs boson production cross section over the entire mass window considered; in particular, the production of a standard model Higgs boson is excluded in the region $340 < m_H < 450$ GeV at the 95% confidence level.

DOI: 10.1103/PhysRevLett.107.221802

PACS numbers: 14.80.Bn, 13.85.Rm

The search for the standard model (SM) Higgs boson [1–3] is one of the most important aspects of the Large Hadron Collider (LHC) physics program. Direct searches at the CERN LEP $e^+e^-$ collider have set a lower limit of 114.4 GeV on the Higgs boson mass, $m_H$, at 95% confidence level [4]. Searches by the CDF and D0 experiments at the Fermilab Tevatron $p\bar{p}$ collider have explored the mass range up to 200 GeV and exclude the additional region $156 < m_H < 177$ GeV [5]. For $m_H$ greater than twice the Z boson mass, $m_Z$, a significant fraction of Higgs bosons decay to two Z bosons. The $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ decay channel offers a substantial branching fraction in combination with a good separation from potential background processes owing to the high transverse momentum, $p_T$, of the electron or muon pair from the leptonic Z decay and the high missing transverse momentum, $E_T^{\text{miss}}$, from the Z decaying to neutrinos.

The first cross section limits for a SM Higgs boson in the mass region $200 < m_H < 600$ GeV were set by the ATLAS and CMS collaborations in Refs. [6,7]. This letter extends the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ results therein, with a 30-fold increase in the integrated luminosity, as well as a significant improvement in the event reconstruction and background rejection.

The data sample considered in this search was recorded by the ATLAS detector during the first half of the 2011 LHC run at a center-of-mass energy $\sqrt{s} = 7$ TeV. The integrated luminosity of the data sample, considering only data-taking periods where all relevant detector subsystems were operational, is 1.04 fb$^{-1}$.

The ATLAS detector has been described elsewhere [8]. Simulated signal and background event samples are produced with Monte Carlo (MC) event generators, passed through a full GEANT4 [9] simulation of the ATLAS detector [10] and reconstructed with the same reconstruction software as the data.

$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ ($\ell = e, \mu, \tau$) events are modeled using the POWHEG [11,12] event generator, which includes matrix elements for the gluon fusion and the vector-boson fusion production mechanisms of the Higgs boson up to next-to-leading order. POWHEG is interfaced to PYTHIA [13] for the modelling of parton showers. The Higgs boson $p_T$ spectrum is reweighted to the calculation of Ref. [14], which provides QCD corrections up to next-to-leading order and QCD soft-gluon resummations up to next-to-next-to-leading logarithms. An alternative sample of signal events is produced using the PYTHIA event generator, which includes only leading order matrix elements. In both cases PHOTOS [15] is used to model final-state radiation and TAUOLA [16] for the simulation of $\tau$ decays.

$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ and $H \to ZZ \to \ell^+\ell^-q\bar{q}$ samples are also simulated using the same generators as for the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ samples, while $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ events are produced using the MC@NLO generator [17], interfaced to HERWIG [18] and JIMMY [19] in the gluon fusion channel and the SHERPA [20] generator in the vector-boson fusion channel. These channels contribute to the signal yield and are considered as part of the signal. In particular, $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ decays contribute as much as 77% to the signal expectation after the full selection for $m_H = 200$ GeV decreasing to 13% at $m_H = 300$ GeV. Independence of the analysis with respect to other ATLAS Higgs boson searches [21–23] is ensured through mutually exclusive selection requirements on the dilepton invariant mass, the number of leptons or the event missing transverse momentum.

*Full author list given at the end of the article.
The cross sections for Higgs boson production, the associated branching fractions [24], as well as their uncertainties, are compiled in Ref. [25]. They correspond to next-to-next-to-leading order in QCD for the gluon fusion [26–31] and the vector-boson fusion [32] processes. In addition, QCD soft-gluon resummations up to next-to-leading order logarithms are available for the gluon fusion process [33], while next-to-leading order electroweak corrections are applied to both the gluon fusion [34,35] and the vector-boson fusion [36,37] processes. These cross section calculations do not account for the width of the Higgs boson, which is implemented through an ad hoc Breit-Wigner line shape applied at the event generator level. Recent studies [25,38] have indicated that effects due to off-shell Higgs boson production and interferences with other SM processes may become sizeable at the highest masses ($m_H > 400$ GeV) considered in this search. In the absence of a full calculation, a conservative estimate of the possible size of such effects was made and the impact on the obtained limits in this channel was found to be less than 2% for $m_H = 400$ GeV growing to about 25% at $m_H = 600$ GeV.

Different event generators are chosen to model a range of important background processes. The ALPGEN generator [39] interfaced with HERWIG for parton showers and hadronisation is used to simulate $W/Z + j$ backgrounds. MC@NLO, interfaced to HERWIG andMUMPY, is used for the production of top-pair, single top and diboson ($WW$, $WZ$ and $ZZ$) backgrounds. PYTHIA is used to simulate $b\bar{b}$ and $c\bar{c}$ samples as well as alternative samples for the $Z$ and $ZZ$ backgrounds. All simulated background samples are scaled to the highest available precision calculations for the relevant process. An overview of the used predictions and their uncertainties is given in Ref. [40].

Data used for the search in the electron and muon channels were collected primarily using single lepton triggers with $p_T$ thresholds of 20 and 18 GeV, respectively. The expected trigger efficiency is close to 100% in the electron channel and about 95% in the muon channel for signal events passing all the selection criteria described below.

Electron candidates are reconstructed from electromagnetic calorimeter clusters, with shapes consistent with those expected from electromagnetic showers, matched to tracks reconstructed in the inner detector. Details of the electron reconstruction and identification can be found in Ref. [41]. The electron candidates are required to pass the standard ATLAS “medium” selection criteria and have $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.47$.

Muons are identified by reconstructing tracks in the muon spectrometer. These tracks are then extrapolated back to the beam line to find a matching inner detector track. Details of muon reconstruction and identification can be found in Ref. [41]. Only muons with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered.

Jets are used in this analysis to reject backgrounds from events with heavy quark decays or from events with fake $E_T^{\text{miss}}$ due to mismeasured jets. For this purpose jets are reconstructed from clusters of energy deposits in the calorimeters using the anti-$k_T$ algorithm [42] with a radius parameter $R = 0.4$. Only jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are considered.

To remove leptons associated with jets, such as those originating from semileptonic decays of $b$ hadrons, leptons are not considered in the analysis if the sum of inner detector track momenta in a cone $\Delta R < 0.2$ around the lepton direction is greater than 10% of the $p_T$ of the lepton itself or if the lepton is within a distance $\Delta R < 0.4$ of the nearest jet.

The missing transverse momentum is measured as the (negative) vectorial sum of the transverse momenta of all clusters in the calorimeters within $|\eta| < 4.5$ and all selected muons in the event. Calorimeter deposits associated with muons are subtracted to avoid double counting.

Events are required to contain a reconstructed primary vertex formed from at least 3 tracks and exactly two oppositely charged electrons or muons, consistent with originating from the primary vertex. The dilepton mass distribution is shown in Fig. 1. Inclusive $Z$ boson production is the dominant background at this stage of the analysis. To suppress backgrounds from top, $W$, and QCD multijet production, the dilepton invariant mass, $m_{\ell\bar{\ell}}$, is required to satisfy $|m_Z - m_{\ell\bar{\ell}}| < 15$ GeV.

To reduce the background from events with fake $E_T^{\text{miss}}$ due to mismeasured jets, events are rejected if the azimuthal angle between the missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$, and the leading jet in the event satisfies $\Delta \phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jett}}) < 0.3$. To reduce the background from top quark production, events with one or more $b$-tagged jets are rejected, where the $b$ tagging is based on a single

![FIG. 1 (color online). The dilepton invariant mass distribution for events with exactly two oppositely charged electrons or muons. The inset at the bottom of the figure shows the ratio between the data and the combined background expectations as well as a band corresponding to the combined systematic uncertainties of the analysis.](221802-2.png)
To exploit the mass dependent kinematic features of $H \to ZZ \to \ell^+ \ell^- \nu \bar{\nu}$ production, the search is subdivided into a low Higgs boson mass ($m_H < 280$ GeV) and a high Higgs boson mass ($m_H \geq 280$ GeV) search region, where dedicated cuts are applied to two important discriminating variables used to reduce the background contributions: $E_T^{\text{miss}}$ and the azimuthal angle between the two leptons, $\Delta \phi(\ell, \ell)$. Figure 2 shows the distributions of these variables after the application of the $m_{\ell\ell}$ window cut. Since inclusive $Z$ production gives rise to a steeply falling $E_T^{\text{miss}}$ distribution, systematic uncertainties on the $E_T^{\text{miss}}$ reconstruction are particularly important to estimate this background correctly. The dominant contributions to the $E_T^{\text{miss}}$ uncertainty come from the knowledge of the jet energy distribution, systematic uncertainties on the NEUT model, and model uncertainties. $W$ and $Z$ backgrounds are normalized in a similar way.

The background from inclusive $Z$ production is derived from MC, after checking that the simulation describes well the data in samples selected by requiring the presence of a lepton pair. The background from top events is also taken from the MC prediction. This prediction is verified to agree with data, within systematic uncertainties, in two independent control samples: the first one requires at least one identified $b$-jet, while the second selects events containing electron-muon pairs.

Additional backgrounds can arise from QCD multijet events or inclusive $W$ production due to heavy flavour decays or jets faking leptons. The normalization of the $W$ background is obtained from the ratio between data and MC in control samples of like-sign electron-electron and electron-muon events with high $E_T^{\text{miss}}$. The QCD multijet background in the electron channel is determined using a data sample based on a loosened electron selection, thus dominated by jets; this sample is scaled to describe the tails of the $m_{\ell\ell}$ distribution. In the muon channel, the background from heavy flavour decays is studied using simulation, whereas other muon sources from multijet events are constrained using a sample of like-sign muon pairs in data. In both cases the background is found to be negligible.

The efficiency for the event selection is very similar in the electron and muon channels, ranging from 3% for $m_H = 200$ GeV to about 48% for $m_H = 600$ GeV.

The boost of the $Z$ bosons originating from a Higgs boson decay increases with $m_H$, thus reducing the expected opening angle between the leptons. In the low $m_H$ region this boost is expected to be modest and a cut $1 < \Delta \phi(\ell, \ell) < 2.64$ is applied. In the high $m_H$ region an upper limit $\Delta \phi(\ell, \ell) < 2.25$ is required.

The azimuthal angle between the missing transverse momentum vector and the direction of the $Z \to \ell \ell$ boson candidate is $\Delta \phi(p_T^{\text{miss}}, \vec{p}_T^{\ell\ell}) < 1$. The efficiency of the $E_T^{\text{miss}}$ and $\Delta \phi(\ell, \ell)$ distributions for events with exactly two oppositely charged electrons or muons inside the $Z$ mass window. The insets at the bottom show the ratio between data and the combined background expectations as well as a band corresponding to the combined systematic uncertainties of the analysis.

FIG. 2 (color online). The $E_T^{\text{miss}}$ (left) and $\Delta \phi(\ell, \ell)$ (right) distributions for events with exactly two oppositely charged electrons or muons inside the $Z$ mass window. The insets at the bottom show the ratio between data and the combined background expectations as well as a band corresponding to the combined systematic uncertainties of the analysis.
therefore only combined results are presented. The numbers of candidate \( H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu} \) events selected in data and the expected yields from signal and background processes are shown in Table I.

The systematic uncertainties include experimental uncertainties related to the selection and calibration of electrons, muons, jets and \( b \) jets, which are also explicitly propagated to the \( E_T^{\text{miss}} \) calculation. Shape uncertainties for the signal and for the single \( Z \) and \( ZZ \) backgrounds are estimated using PYTHIA as an alternative MC generator.

Normalization uncertainties for signal (gluon fusion \( \pm 14\% \) and VBF \( 4\% \)) and diboson backgrounds (\( 11\% \)) are obtained from theory [25]; uncertainties for the inclusive \( Z \) boson production \( (2.5\%) \), top quark production \( (9\%) \), inclusive \( W \) boson production \( (100\%) \) and QCD multijet production in the electron channel \( (50\%) \) are estimated from data. A 3.7\% luminosity uncertainty [46] is included for those processes for which the normalization is not obtained from the data. The dominant systematic uncertainties in the analysis are the \( E_T^{\text{miss}} \) uncertainties for the \( Z \) background, the \( b \)-tagging uncertainty for the top background and the normalization uncertainties for the signal and the \( W \) and diboson backgrounds.

After the event selection, the Higgs boson search is performed by looking for an excess of data over the SM backgrounds. The number and distribution of candidate \( Z \) \( \rightarrow \ell^+ \ell^- \nu \bar{\nu} \) events observed in the data agree with the expected backgrounds within the uncertainties, with no indication of an excess. Upper limits are set on the Higgs boson production cross section relative to its predicted SM value as a function of \( m_H \). The limits are extracted from a maximum likelihood fit to the \( m_T \) distribution following the \( C_L \) modified frequentist formalism with the profile likelihood test statistic [47,48]. All systematic uncertainties are taken into account.

Figure 4 shows the expected and observed limits at the 95\% confidence level. The expected limit is lowest around \( m_H = 380 \) GeV where it is 1.1 times the SM Higgs boson cross section. Fluctuations in the background can lead to better or worse expected limits. Over the entire mass range the observed limits agree with the expectations within the \( \pm 2\sigma \) band. A SM Higgs boson in the range \( 340 < m_H < 450 \) GeV is excluded at the 95\% confidence level.

In summary, results of a search for a heavy SM Higgs boson with a mass in the range \( 200 < m_H < 600 \) GeV decaying to \( ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu} \) have been presented. These results are based on a data sample corresponding to an integrated luminosity of 1.04 fb\(^{-1}\), recorded with the ATLAS detector at the LHC. No evidence for a signal is observed and cross section limits are placed over the entire mass range, excluding the production of a SM Higgs boson in the region \( 340 < m_H < 450 \) GeV at the 95\% confidence level.

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.

![Figure 3](221802-4)

**FIG. 3** (color online). The transverse mass distribution of \( H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu} \) candidates in the high \( m_H \) search region for the data (dots), the expected backgrounds (histograms) and a Higgs boson of mass 380 GeV (filled histogram). The electron and muon channels are combined.
FIG. 4 (color online). Observed and expected 95% confidence level upper limits on the Higgs boson production cross section divided by the SM prediction. The green and yellow bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively, around the median sensitivity. The limits are based on 1.04 fb$^{-1}$ of data at $\sqrt{s} = 7$ TeV.

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; COCICIENAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC 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; MNI3W, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR, MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICCIN, 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.

18\textsuperscript{a} Department of Physics, Bogazici University, Istanbul, Turkey
18\textsuperscript{b} Division of Physics, Dogus University, Istanbul, Turkey
18\textsuperscript{c} Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
18\textsuperscript{d} Department of Physics, Istanbul Technical University, Istanbul, Turkey
19\textsuperscript{a} INFN Sezione di Bologna, Italy
19\textsuperscript{b} Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20\textsuperscript{a} Physikalisches Institut, University of Bonn, Bonn, Germany
20\textsuperscript{b} Dipartimento di Fisica, Università di Bologna, Bologna, Italy
21\textsuperscript{a} Department of Physics, Boston University, Boston Massachusetts, USA
22\textsuperscript{a} Department of Physics, Brandeis University, Waltham Massachusetts, USA
23\textsuperscript{a} Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
23\textsuperscript{b} Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
23\textsuperscript{c} Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
23\textsuperscript{d} Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
24\textsuperscript{a} Physics Department, Brookhaven National Laboratory, Upton New York, USA
25\textsuperscript{a} National Institute of Physics and Nuclear Engineering, Bucharest, Romania
25\textsuperscript{b} University Politehnica Bucharest, Bucharest, Romania
25\textsuperscript{c} West University in Timisoara, Timisoara, Romania
26\textsuperscript{a} Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27\textsuperscript{a} Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28\textsuperscript{a} Department of Physics, Carleton University, Ottawa ON, Canada
29\textsuperscript{a} CERN, Geneva, Switzerland
30\textsuperscript{a} University of Chicago, Chicago, Illinois, USA
31\textsuperscript{a} Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
31\textsuperscript{b} Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
32\textsuperscript{a} Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32\textsuperscript{b} Department of Modern Physics, University of Science and Technology of China, Anhui, China
32\textsuperscript{c} Department of Physics, Nanjing University, Jiangsu, China
32\textsuperscript{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 New York, USA
35 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
36\textsuperscript{a} INFN Gruppo Collegato di Cosenza, Italy
36\textsuperscript{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 Texas, USA
40 Physics Department, University of Texas at Dallas, Richardson Texas, USA
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 North Carolina, USA
45 SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 INFN Laboratori Nazionali di Frascati, Frascati, Italy
47 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i. Br., Germany
48 Section de Physique, Université de Genève, Geneva, Switzerland
49 INFN Sezione di Genova, Italy
49\textsuperscript{b} Dipartimento di Fisica, Università di Genova, Genova, Italy
50\textsuperscript{a} E. Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia
50\textsuperscript{b} High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
51\textsuperscript{a} II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
51\textsuperscript{b} II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
52 SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
53\textsuperscript{a} II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
54 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
55 Department of Physics, Hampton University, Hampton Virginia, USA
56 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge Massachusetts, USA
57 Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
57\textsuperscript{b} Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
57\textsuperscript{c} ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
58 Faculty of Science, Hiroshima University, Hiroshima, Japan
162 Department of Physics and Astronomy, University of California Irvine, Irvine California, USA
163 INFN Gruppo Collegato di Udine, Italy
163a Dipartimento di Fisica, Università di Udine, Udine, Italy
163b Istituto di Fisica Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
163c ICTP, Trieste, Italy
164 Department of Physics, University of Illinois, Urbana, Illinois, USA
165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
166 Department of Physics, University of British Columbia, Vancouver BC, Canada
167 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
168 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
169 Waseda University, Tokyo, Japan
170 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
171 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
172 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
173 Department of Physics, Yale University, New Haven, Connecticut, USA
174 Yerevan Physics Institute, Yerevan, Armenia
176 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

a Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal.
b Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
d Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
e Deceased.
f Also at TRIUMF, Vancouver BC, Canada.
g Also at Department of Physics, California State University, Fresno CA, USA.
h Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.
i Also at Fermilab, Batavia IL, USA.
j Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
k Also at Università di Napoli Parthenope, Napoli, Italy.
l Also at Institute of Particle Physics (IPP), Canada.
m Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
Also at Louisiana Tech University, Ruston LA, USA.
o Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
p Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
q Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
r Also at Manhattan College, New York NY, USA.
s Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
t Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.	u Also at High Energy Physics Group, Shandong University, Shandong, China.	v Also at Section de Physique, Université de Genève, Geneva, Switzerland.
w Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
x Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
y Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
z Also at California Institute of Technology, Pasadena CA, USA.
aa Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
bb Also at Department of Physics, Oxford University, Oxford, United Kingdom.
cc Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
rd Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
cc 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.
ff Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
gg Also at Department of Physics, Nanjing University, Jiangsu, China.