Search for the Higgs Boson in the $H\rightarrow WW\rightarrow l\nu jj$ Decay Channel in $pp$ Collisions at $\sqrt{s} = 7\text{ TeV}$ with the ATLAS Detector


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Search for the Higgs Boson in the $H \rightarrow WW \rightarrow \ell \nu jj$ Decay Channel in $pp$ Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al.*

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A search for a Higgs boson has been performed in the $H \rightarrow WW \rightarrow \ell \nu jj$ channel in 1.04 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector at the Large Hadron Collider. No significant excess of events is observed over the expected background and limits on the Higgs boson production cross section are derived for a Higgs boson mass in the range 240 GeV < $m_H$ < 600 GeV. The best sensitivity is reached for $m_H = 400$ GeV, where the 95% confidence level upper bound on the cross section for $H \rightarrow WW$ production is 3.1 pb, or 2.7 times the standard model prediction.

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The results of a similar search for $H \rightarrow WW \rightarrow \ell \nu jj$ based on 35 pb$^{-1}$ of data recorded during the 2010 LHC run were presented in Ref. [20].

The present search, based on the measured shape of the $m(\ell \nu jj)$ distribution, is restricted to $m_H > 240$ GeV, in order to ensure a smoothly varying nonresonant background, well clear of the effective kinematic cutoff $m(\ell \nu jj) \sim 160$ GeV. For $m_H \geq 600$ GeV, the jets from $W \rightarrow jj$ decay begin to overlap due to the large $W$ boost, and the natural width of the Higgs boson becomes large. A detailed treatment of these issues is beyond the scope of the present analysis. The best sensitivity in this analysis is expected for $m_H \sim 400$ GeV.

The ATLAS detector [21] is a multipurpose particle physics apparatus with forward-backward symmetric cylindrical geometry covering the pseudorapidity range $|\eta| < 2.5$ for track and $|\eta| < 4.9$ for jet measurements [22]. 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, and by a high-granularity liquid-argon (LAr) sampling electromagnetic (EM) calorimeter. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer surrounds the calorimeters and consists of three large superconducting toroids, each with eight coils, a system of precision tracking chambers, and detectors for triggering.

Detailed Monte Carlo (MC) studies of signal and backgrounds have been carried out [23]. The interaction with the ATLAS detector is modeled with GEANT4 [24] and the events are processed using the same reconstruction that is used to perform the reconstruction on data. The effect of multiple $pp$ interactions in the same bunch crossing (pileup) at the high luminosities achieved by the LHC in 2011 is modeled by superimposing, at the generation stage, several simulated minimum-bias events on the simulated signal.
and background events. MC samples were generated with different pile-up levels and subsequently reweighted to match the pile-up conditions observed in the data.

The data used in this analysis were recorded during periods when all ATLAS subdetectors were operating under nominal conditions. The events were triggered by requiring the presence of an electron candidate with transverse energy $E_T > 20$ GeV or a muon candidate with transverse momentum $p_T > 18$ GeV.

Electron candidates are selected from clustered energy deposits in the EM calorimeter with an associated track and are required to satisfy a tight set of identification cuts [25] with an efficiency of $71 \pm 1.6\%$ for electrons with $E_T > 20$ GeV. While the energy measurement is taken from the EM calorimeter, the pseudorapidity $\eta$ and azimuthal angle $\phi$ are taken from the associated track. The cluster is required to be inside the range $|\eta| < 2.47$, excluding $1.37 < |\eta| < 1.52$ and small calorimeter regions affected by temporary operational problems. The track associated with the electron candidate is required to point back to a reconstructed primary vertex with a transverse impact parameter along the beam direction $d_0/\sigma_{d_0} \leq 10$ and an impact parameter along the beam direction $z_0 \leq 10$ mm. Electrons are required to be isolated: the sum of the transverse momenta of all tracks in a cone $\Delta R < 0.3$ around [26] the cluster barycenter (excluding the electron itself) must satisfy $\Sigma(E_T)^{\text{cal}} < 4$ GeV.

Muons are reconstructed by combining tracks in the inner detector and muon spectrometer, with efficiency $92 \pm 0.6\%$ for muons with $p_T > 20$ GeV. Muons are required to pass basic quality cuts on the number and type of hits in the inner detector. They must lie in the range $|\eta| < 2.4$, and satisfy the same impact parameter cuts as electrons. They must also be isolated, with the sum of the transverse momenta of all tracks in a cone $\Delta R < 0.2$ around the muon satisfying $\Sigma(p_T^\text{track})/p_T^\mu < 0.1$.

Jets are reconstructed from topological clusters using the anti-$k_t$ algorithm [27] with radius parameter $R = 0.4$. The reconstructed jets are calibrated using $E_T$ and $\eta$ dependent correction factors based on MC simulation and validated with data [28]. They are required to have $E_T > 25$ GeV and $|\eta| < 4.5$. Jets are considered b-tagged if they contain a reconstructed displaced secondary vertex consistent with a $b$-decay [29]. The operating point chosen for this $b$-tag selection has an efficiency of 50\% for $b$-jets in $\tau$ events in MC, and the mistag rate for non-$b$-jets has been measured to be between 0.1\% and 2.0\%, depending on the $|\eta|$ and $p_T$ of the jet [29]. The event missing transverse momentum $E_T$ is reconstructed starting from topological energy clusters in the calorimeters calibrated according to the type of the object to which they are associated. The momenta of any muons in the event are also taken into account in the $E_T$ measurement.

For this analysis, events are required to have at least one vertex with at least three associated tracks with $p_T > 400$ MeV. There must be exactly one reconstructed lepton candidate (electron or muon) with $p_T > 30$ GeV. In order to ensure that this analysis is statistically independent of the ATLAS $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ analysis, events are vetoed if there is an additional lepton with $p_T > 20$ GeV, including electrons which only satisfy the looser identification cuts used in the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ analysis [30].

Events are required to have $E_T > 30$ GeV to account for an unobserved neutrino from $W \rightarrow \ell\nu$ decay. There must be exactly two jets ($H + 0$ jet sample) or exactly three jets ($H + 1$ jet sample) with $E_T > 25$ GeV and $|\eta| < 4.5$. The two jets with invariant mass ($m_{jj}$) closest to the mass of the $W$ boson are required to satisfy $71$ GeV $< m_{jj} < 91$ GeV. These two jets are taken as the $W$ decay jets and are required to lie in the range $|\eta| < 2.8$, where the jet energy scale (JES) is best known (to better than $\pm(4-8)\%$ for $E_T > 25$ GeV [28].)

After this event selection, the background is expected to be dominated by $W +$ jets production. Other important backgrounds are $Z +$ jets, multijets (MJ) from QCD processes, top quark, and diboson ($WW$, $WZ$, and $ZZ$) production. In order to further reject backgrounds from top quark production, events are rejected if any of the jets is $b$-tagged.

Although the MC is not used to model the background in the final fit used to obtain limits, a combination of MC calculations and data-driven methods is used to better understand the background yields at this intermediate stage. Backgrounds due to $W/Z +$ jets, $\tau$, and diboson production are modeled using the ALPGEN [31], MC@NLO [32], and HERWIG [33] generators, respectively. A small contribution from $W/Z + \gamma$ events is generated using MADEVENT [34]. The shape of the MJ background is modeled using histograms derived from data samples selected in an identical way to the $H \rightarrow WW \rightarrow \ell\ell\nu j$ selection except that the electron identification requirements are loosened and the isolation requirement on muons is inverted. In the loosened selection, electrons satisfying the complete set of identification criteria are not included. Expected contributions from non-QCD processes to the MJ shape histogram are subtracted using MC predictions.

To normalize the MJ shape histogram, the loose lepton control sample selection is further relaxed by removing the $E_T$ cut to construct a shape template for the $E_T$ distribution for the MJ background. The normalizations of this MJ template and the corresponding template for $W/Z +$ jets taken from MC are fit to the observed $E_T$ distribution, and the resulting scale factors are then used to normalize the MJ and $W/Z +$ jets processes in comparisons between data and expectations. Both the gluon fusion and the vector boson fusion signal production processes are simulated using the POWHEG [35,36] event generator interfaced to PYTHIA [37], normalizing to the NNLO cross sections [19] shown in Table I.
In order to reconstruct the invariant mass $m(\ell\nu jj)$ of the $WW$ system, the mass constraint $m(\ell\nu) = m(W)$ is used, where the neutrino transverse momentum $p_T^{\nu}$ is taken from the event $E_T^{\nu}$. This equation can have real or complex solutions. In the case of complex solutions, the event is rejected. This requirement rejects 45% of background events in both data and MC, but only 36% of MC signal events with $m_H = 400$ GeV. In the case of two real solutions, the solution with smaller neutrino longitudinal momentum $|p_T^{\nu}|$ is taken, based on simulation studies. Table II shows the observed and expected numbers of events for signal and background after this full selection.

Figure 1 (top) shows the $m(\ell\nu jj)$ distribution for this final sample. The expected signal for $m_H = 400$ GeV is also shown, scaled up by a factor of 2.7. The $m(\ell\nu jj)$ resolution is $(7.5 \pm 0.6\%)$ at $m_H = 400$ GeV, depending mostly on the jet energy resolution as checked in data versus MC by various jet-balance techniques [38], and shows a $1/\sqrt{m_H}$ dependence over the range of this analysis. Limits are set using a maximum likelihood fit to the observed $m(\ell\nu jj)$ distribution in the range $200 < m(\ell\nu jj) < 2000$ GeV. The nonresonant background in this fit is modeled by the sum of two exponential functions. The normalization and slope of each exponential are unconstrained parameters in the fit. The double-exponential form for the total background is well justified by fits to the $m(\ell\nu jj)$ distributions obtained by selecting events with $m_{jj}$ just below ($50 < m_{jj} < 60$ GeV) or just above ($100 < m_{jj} < 110$ GeV) the $W$ peak, respectively. As a consistency check, the background parametrization was altered to use three exponentials and the shift in signal yield as compared to the nominal background shape was found to be small as compared to other uncertainties. The $m(\ell\nu jj)$ distribution for the expected signal at each hypothesized $m_H$ is modeled using the signal MC samples.

The fit includes nuisance parameters which account for the uncertainty in the efficiency of the electron, muon, and jet reconstruction. The electron and muon efficiencies are varied within their uncertainties, leading to an uncertainty in the signal efficiency of $\pm 1.6\%$ and $\pm 0.6\%$, for electrons and muons, respectively. Varying the jet energy scale within its uncertainties yields a corresponding uncertainty of $\pm 17\%$ in the expected signal, and smearing the jet energies within the uncertainty on their resolutions results in a signal uncertainty of $\pm 8.6\%$. The limits also take into account a $\pm 3.7\%$ uncertainty on the luminosity determination [39] and a $\pm 19.4\%$ uncertainty on the predicted cross section [19], taken to be independent of mass. The off-shell effects and interference between the signal and backgrounds, which are discussed in Refs. [19,40,41], have been neglected. A conservative estimate of this uncertainty would be $150 \times m_H^3$ ($m_H$ in TeV), where the $m_H^3$ form is motivated by the scaling of the Higgs width with $m_H$ and the normalization factor is chosen to give $\sim 30\%$ at $m_H = 600$ GeV, based on Fig. 6 of Ref. [41]. If this were included, it would increase the total systematic error by less than 6% for $m_H \leq 500$ GeV, and as much as 15% for $m_H = 600$ GeV where the limit would be increased by $\sim 18\%$.

### Table II

<table>
<thead>
<tr>
<th>$H(\ell\nu jj) + 0j$</th>
<th>$H(\mu\nu jj) + 0j$</th>
<th>$H(\ell\nu jj) + 1j$</th>
<th>$H(\mu\nu jj) + 1j$</th>
<th>$H + 0j$ or $1j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Z + jets</td>
<td>5580 ± 150</td>
<td>6690 ± 430</td>
<td>3610 ± 140</td>
<td>3940 ± 360</td>
</tr>
<tr>
<td>Multijet</td>
<td>592 ± 16</td>
<td>222 ± 15</td>
<td>420 ± 16</td>
<td>195 ± 17</td>
</tr>
<tr>
<td>Top</td>
<td>87 ± 17</td>
<td>87 ± 18</td>
<td>271 ± 54</td>
<td>280 ± 56</td>
</tr>
<tr>
<td>Dibosons</td>
<td>226 ± 45</td>
<td>222 ± 45</td>
<td>89 ± 18</td>
<td>112 ± 23</td>
</tr>
<tr>
<td>Expected background</td>
<td>6490 ± 160</td>
<td>7220 ± 440</td>
<td>4390 ± 150</td>
<td>4530 ± 370</td>
</tr>
<tr>
<td>Data</td>
<td>6446</td>
<td>7201</td>
<td>4134</td>
<td>4380</td>
</tr>
<tr>
<td>Expected Signal ($m_H = 400$ GeV)</td>
<td>11 ± 3.0</td>
<td>9 ± 2.4</td>
<td>13 ± 3.5</td>
<td>10 ± 2.7</td>
</tr>
</tbody>
</table>
FIG. 1 (color online). Top: the reconstructed invariant mass \( m(l\nu jj) \) in the data summed over lepton flavor and jet multiplicity. The expected backgrounds are also shown. Bottom: the difference between data and the fitted nonresonant background. The expected contribution from Higgs boson decays for \( m_H = 400 \text{ GeV} \) in the SM is also shown, multiplied by a factor of 2.7.

Figure 1 (bottom) shows the difference between the \( m(l\nu jj) \) distribution in data and the fitted background. There is no indication of any significant excess. Limits are extracted using the Profile Likelihood [42] as a test statistic and following the \( CL_s \) procedure described in Ref. [43].

Figure 2 shows the 95% CL upper bound on the cross-section times branching ratio for Higgs production in units of the Standard Model prediction, \( \sigma \times BR_{H \to WW}/(\sigma \times BR_{H \to WW})_{\text{SM}} \), as a function of \( m_H \). The observed cross section limit for \( m_H = 400 \text{ GeV} \) is 3.1 pb, or 2.7 times the SM prediction, while the corresponding expected limits are 3.2 pb or 4.5 times the SM expectation. In the SM with an additional heavy fourth generation [44,45], the gluon fusion mechanism for production of a Higgs boson is expected to be substantially enhanced. Within the four generation context, a Higgs boson is excluded at 95% CL by the present data over the range \( m_H = 310–430 \text{ GeV} \).

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[19] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis coinciding with the axis of the beam pipe. The x axis points from the IP to the center 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 is defined in terms of the polar angle θ as η = −ln tan(θ/2).
[21] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis coinciding with the axis of the beam pipe. The x axis points from the IP to the center 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 is defined in terms of the polar angle θ as η = −ln tan(θ/2).
[26] ΔR = (∆φ)² + (∆η)², where ∆φ and ∆η are the relevant separations in φ and η, respectively.

(ATLAS Collaboration)

1 University at Albany, Albany New York, USA
2 Department of Physics, University of Alberta, Edmonton AB, Canada
3 Department of Physics, Ankara University, Ankara, Turkey
3b Department of Physics, Dumlupinar University, Kutahya, Turkey
3c Department of Physics, Gazi University, Ankara, Turkey
3d Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
3e Turkish Atomic Energy Authority, Ankara, Turkey
4 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5 High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
6 Department of Physics, University of Arizona, Tucson Arizona, USA
7 Department of Physics, The University of Texas at Arlington, Arlington Texas, USA
8 Physics Department, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12a Institute of Physics, University of Belgrade, Belgrade, Serbia
12b Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18a Department of Physics, Bogazici University, Istanbul, Turkey
18b Division of Physics, Dogus University, Istanbul, Turkey
18c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
18d Department of Physics, Istanbul Technical University, Istanbul, Turkey
19a INFN Sezione di Bologna, Italy
19b Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20 Physikalisches Institut, University of Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston Massachusetts, USA
22 Department of Physics, Brandeis University, Waltham Massachusetts, USA
23a Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
23b Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
23c Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
23d Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton New York, USA
25a National Institute of Physics and Nuclear Engineering, Bucharest, Romania
25b University Politehnica Bucharest, Bucharest, Romania
25c West University in Timisoara, Timisoara, Romania
26 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa ON, Canada
29a CERN, Geneva, Switzerland
30a Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA
31a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
31b Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32a Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32b Department of Modern Physics, University of Science and Technology of China, Anhui, China

231801-14
School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor Michigan, USA

Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, USA

INFN Sezione di 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 Massachusetts, USA

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

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

INFN Sezione di Napoli, Italy

Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

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 Illinois, USA

Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

Department of Physics, New York University, New York New York, USA

Ohio State University, Columbus Ohio, USA

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA

Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA

Palacký University, RCPTM, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene Oregon, USA

LAL, Univ. 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

INFN Sezione di Pavia, Italy

Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy

Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA

Petersburg Nuclear Physics Institute, Gatchina, Russia

INFN Sezione di Roma I, Italy

Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA

Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal

Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain

Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic

Czech Technical University in Prague, Prague, 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

Ritsumeikan University, Kusatsu, Shiga, Japan

INFN Sezione di Roma I, Italy

Dipartimento di Fisica, Università La Sapienza, Roma, Italy

INFN Sezione di Roma Tor Vergata, Italy

Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

INFN Sezione di Roma Tre, Italy

Dipartimento di Fisica, Università Roma Tre, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco

Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco

Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B. P. 2390 Marrakech 40000, Morocco
Also at Department of Physics, California State University, Fresno CA, USA.

Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.

Also at Fermilab, Batavia IL, USA.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Università di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Department of Physics, Middle East Technical University, Ankara, Turkey.

Also at Louisiana Tech University, Ruston LA, USA.

Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Manhattan College, New York, NY, USA.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at High Energy Physics Group, Shandong University, Shandong, China.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.

Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

Also at California Institute of Technology, Pasadena CA, USA.

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, USA.

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 Department of Physics, Nanjing University, Jiangsu, China.

Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.