Measurement of the $W^+W^-$ cross section in $\sqrt{s} = 7$ TeV $pp$ collisions with ATLAS

ATLAS Collaboration

This Letter presents a measurement of the $W^+W^-$ production cross section in $\sqrt{s} = 7$ TeV $pp$ collisions by the ATLAS experiment, using $34$ pb$^{-1}$ of integrated luminosity produced by the Large Hadron Collider at CERN. Selecting events with two isolated leptons, each either an electron or a muon, 8 candidate events are observed with an expected background of $1.7 \pm 0.6$ events. The measured cross section is $41^{+16}_{-12}$ (stat.) $\pm 5$ (syst.) $\pm 1$ (lumi.) pb, which is consistent with the standard model prediction of $44 \pm 3$ pb calculated at next-to-leading order in QCD.

PACS numbers: 14.70.Fm, 13.38.Be, 13.85.Qk

The $W^+W^-$ process plays an important role in electroweak physics. The production rate and kinematic distributions of $W^+W^-$ are sensitive to the triple gauge couplings of the $W$ boson [1] and $W^+W^-$ production is an important background to standard model Higgs boson searches. For these reasons, the measurement of the $W^+W^-$ production cross section in 7 TeV $pp$ collisions is a milestone in the Large Hadron Collider (LHC) physics program. $W^+W^-$ production has been previously measured in both $e^+e^-$ collisions [1] and $p\bar{p}$ collisions [2], and was also recently measured in $pp$ collisions [3]. In the standard model, the largest production mechanisms of $W^+W^-$ proceed via s-channel and t-channel quark annihilation, followed by the gluon fusion process, which is next-to-next-to-leading order but is enhanced by the large gluon-gluon parton luminosity at the LHC.

Candidate $W^+W^-$ events are reconstructed in the leptonic $\ell\ell\nu\nu$ decay channel where each $\ell$ is either an electron or a muon; included in this selection is $W^+W^-$ production in which either or both $W$ bosons decay to $\tau\nu \rightarrow \ell\nu\nu$. This channel provides a significantly better signal to background ratio than the semileptonic or hadronic channels. Events consistent with $pp \rightarrow W^+W^- + X \rightarrow \ell\ell\nu\nu + X$ are selected by requiring two reconstructed oppositely-charged leptons and a large transverse momentum imbalance due to the neutrinos, which escape detection. There are four main backgrounds, all of comparable size: (i) $W$+jets production with a jet misidentified as a lepton; (ii) Drell-Yan production, which includes $Z/\gamma^* \rightarrow \ell\ell$ where the observed momentum imbalance is due to mismeasurements and $Z/\gamma^* \rightarrow \tau\tau \rightarrow \ell\ell + 4\nu$; (iii) top production ($t\bar{t}$ and $Wt$), which also produces two $W$ bosons, but is not considered signal and is suppressed by vetoing candidates with jets; (iv) other diboson processes, which include $WZ$ production decaying to $\ell\ell\nu\nu$ where one charged lepton is lost, $ZZ$ with one $Z$ decaying to charged leptons and one $Z$ decaying to neutrinos, and $W\gamma$ with the photon misidentified as an electron.

The ATLAS detector [4] has a cylindrical geometry [5] and consists of an inner tracking detector surrounded by a 2 T superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field. The inner detector provides precision tracking for charged particles for $|\eta| < 2.5$. It consists of silicon pixel and strip detectors surrounded by a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. For $|\eta| < 2.5$, the electromagnetic calorimeter is finely segmented and plays an important role in electron identification. The muon spectrometer has separate trigger and high-precision tracking chambers covering $|\eta| < 2.7$. The transverse energy $E_T$ is defined to be $E \sin \theta$, where $E$ is the energy associated with a calorimeter cell or energy cluster. Similarly, $p_T$ is the momentum component transverse to the beam line.

A three-level trigger system selects events to record for offline analysis. During the data-taking period, the selections for at least one electron or muon were made progressively stricter, culminating in an $E_T > 15$ GeV single electron or $p_T > 13$ GeV single muon requirement. The results presented here use a data sample corresponding to $34$ pb$^{-1}$ collected during 2010, where the subsystems described were operational.

The signal acceptance is determined from a detailed Monte Carlo simulation. The $q\bar{q} \rightarrow W^+W^-$ signal is simulated up to next-to-leading order in QCD with mc@nlo [6] and the gluon fusion process is simulated with gg2ww [7]; the CTEQ6.6 [8] and CTEQ6M [9] parton distribution functions (PDFs), respectively, are used. HERWIG [10] is used to model $W$ leptonic decays, parton showers, and hadronization, and JIMMY [11] is used to simulate the underlying event. The detector response simulation [12] is based on the GEANT4 program [13]. For the table and figures in this Letter, the standard model expectation for the $W^+W^-$ signal is normalized to $44 \pm 3$ pb, which is the sum of the quark annihilation (97%) and gluon fusion (3%) processes, as calculated by mc@nlo and gg2ww.

The luminosity in a single bunch-crossing was sufficient to produce multiple collisions, observed as multiple vertices, in the same recorded event. The vertex with the largest sum $p_T^2$ of the associated tracks is selected as the primary vertex. Additional inclusive $pp$ collisions are also simulated to reproduce the vertex multiplicity observed in data.
Electrons are reconstructed from a combination of a track found in the inner detector and an electromagnetic calorimeter energy cluster with $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ to avoid the transition region between the barrel and the end-cap electromagnetic calorimeters. Candidate electrons must satisfy the "tight" selection [14], which requires the following measured quantities to be consistent with those from a promptly produced electron: shower shape, ratio of energy deposited in the hadronic to electromagnetic calorimeters, inner-detector track quality, track-to-shower matching, ratio of calorimeter energy measurement to track momentum, and transition radiation in the straw tube tracker. The electron is required to be isolated such that the sum of $E_T$ for calorimeter energy in a cone of size $\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2}$ of 0.3 around the electron is less than 6 GeV, excluding energy associated with the electron cluster. The overall electron reconstruction and identification efficiency is measured from data using $W \to e\nu$ and $Z \to ee$ candidates. It varies from 78% for the central region ($|\eta| < 0.8$) to 64% in the forward region ($2.0 < |\eta| < 2.47$) with a statistical uncertainty of less than 0.4% and a systematic uncertainty of 5% [14] averaged over rapidity. The systematic uncertainty is due to background uncertainties in the $W$ and $Z$ samples and the consistency of efficiencies derived from the two samples.

Muon candidates are formed by associating muon spectrometer (MS) tracks with inner detector (ID) tracks after accounting for energy loss in the calorimeter. A common transverse momentum is determined using a statistical combination of the two tracks and is required to have $|\eta| < 2.4$. To reject muons from charged $\pi$ or $K$ decays and charged particles from the beam-induced backgrounds, the MS muon $p_T$ must exceed 10 GeV and be consistent with the ID measurement, $|p_T^{\text{MS}} - p_T^{\text{ID}}|/p_T^{\text{ID}} < 0.5$. To suppress muons originating from hadronic jets, the sum of the $p_T$ of other tracks with $p_T > 1$ GeV in a cone of $\Delta R = 0.2$ around the muon candidate divided by the muon $p_T$ is required to be less than 0.1. The muon reconstruction and isolation efficiencies are measured in data using $Z \to \mu\mu$ candidates to obtain a combined efficiency of $92 \pm 1\,(\text{stat}) \pm 1\,(\text{syst})\%$, where the systematic uncertainty is dominated by variations between data-taking periods due to additional collisions in the events [14].

Jets used to discriminate top from $W^+W^-$ production are reconstructed from calorimeter clusters using the anti-$k_T$ algorithm [15] with a resolution parameter of $R = 0.4$. Jets within a $\Delta R < 0.3$ of an electron are not used because the electrons are in general also reconstructed as jets. The jet energies are calibrated using $E_T\gamma$- and $\eta$-dependent correction factors [16] based on simulation and validated by test beam and collision data.

In order to suppress the Drell-Yan background, a momentum imbalance of the visible collision products in the plane transverse to the beam axis is required. For this purpose, missing transverse energy is defined as $E_T^{\text{miss}} = -\sum E_T$, where $E_T$ indicate the 2-dimensional transverse vectors for the reconstructed clusters of energy in the calorimeter in the range $|\eta| < 4.5$ and muon momenta. Since the $E_T^{\text{miss}}$ variable is sensitive to the mis-measurement of an individual lepton or jet, the relative missing transverse energy is defined as

$$E_T^{\text{rel}} \equiv \left\{ \begin{array}{ll} E_T^{\text{miss}} \times \sin (\Delta \phi) & \text{if } \Delta \phi < \pi/2 \\ E_T^{\text{miss}} & \text{if } \Delta \phi \geq \pi/2, \end{array} \right.$$
the scale factors differ from unity by at most a few percent, indicating the accuracy of the simulation, and have systematic uncertainties derived from the efficiency measurements described above. A small smearing is added to the muon $p_T$ in simulation, so that it replicates the $Z \to \mu \mu$ invariant mass distribution in data. The acceptance uncertainty due to the PDF uncertainties is 1.2%.

There are two major sources of systematic uncertainty in the jet-veto efficiency. The first is the modeling of jet production in association with $W^+W^-$ due to initial state radiation, radiation from the internal line in the $t$-channel diagram, and additional parton collisions in the same $pp$ collision. The second is the jet-energy scale, which is the correspondence between the true particle jet $p_T$ and the reconstructed jet $p_T$. To minimize the systematic uncertainty due to these two effects, control samples of $Z \to \ell\ell$ are used. These are sufficiently large and pure that the jet-veto efficiency can be directly measured and compared to simulation using the same QCD modeling as the $W^+W^-$ signal. The ratio of the observed to the simulated zero-jet fraction in the $Z \to \ell\ell$ sample to simulation is used to define a jet-veto scale factor of $0.97 \pm 0.06$. The uncertainty is due to differences between the jet-veto efficiency in $Z$ and $W^+W^-$ events which is assessed including effects from the choice of renormalization and fragmentation scales [17].

The overall selection acceptance factors for signal events are $4.1 \pm 0.1\%$ for $ee\nu\nu$, $8.6 \pm 0.1\%$ for $\mu\mu\nu\nu$, and $11.5 \pm 0.6\%$ for $e\mu\nu\nu$. The relative acceptance in event selection are lepton acceptance and identification (18%, 41%, 27%) and the $m_{\ell\ell}$ (85%, 84%, 100%), $E_{T,rel}^{miss}$ (41%, 43%, 69%), and jet-veto (64%, 59%, 61%) requirements, where the three percentages indicate the $ee$, $\mu\mu$, and $e\mu$ channels, respectively, and each factor is relative to the previous requirement. The contributions from $W^+W^-$ production where one or both $W$ bosons decays to a $\tau$ which subsequently decays to an $e$ or $\mu$ are less than 10% of the final selected $W^+W^-$ signal events in all three channels.

With the exception of $W$+jets, the backgrounds are derived from simulations, corrected with the same scale factors as applied to the modeling of the signal acceptance. The backgrounds are scaled to the data sample based on the integrated luminosity and predicted cross sections. The top and $WZ$ processes are simulated with Mc@NLO, the $ZZ$ process is simulated with HERWIG, the $W\gamma$ is simulated with MADGRAPH+PYTHIA [18], and the Drell-Yan process is simulated with ALCGEN [20] and PYTHIA [18]. The QCD jet contribution, which is not significant after the $E_{T,rel}^{miss}$ cut, is modeled with PYTHIA in Figure 1.

Like the signal acceptance, the background estimates have uncertainties due to the trigger, lepton reconstruction and identification, and jet-veto efficiencies, in addition to the uncertainties on the integrated luminosity and theoretical cross sections. The Drell-Yan and top background estimates have additional uncertainties described below. Most of the Drell-Yan events are removed by the dilepton invariant mass and $E_{T,rel}^{miss}$ requirements, but because of the large cross section some remain as background. The uncertainty on this background due to the simulation of $E_{T,rel}^{miss}$ is assessed using a control sample of $Z/\gamma^* \to ee$ and $Z/\gamma^* \to \mu\mu$ events in the $Z$ mass peak region, $|m_{\ell\ell} - m_Z| < 10$ GeV, passing a relaxed requirement of $E_{T,rel}^{miss} > 30$ GeV. Despite the $E_{T,rel}^{miss}$ requirement, this sample is still dominated by $Z \to \ell\ell$ events in which the observed momentum imbalance is due to a combination of detector resolution, limited detector coverage, and neutrinos from heavy flavor decays. A 64% systematic uncertainty is assigned based on the difference between the observed yield in data and the Monte Carlo prediction, which are statistically consistent.

The top background arises from $t\bar{t}$ and $Wt$ production where the two $W$ bosons decay leptonically. Simulation based on Mc@NLO is used to estimate the number of events passing the jet-veto requirement. Similar to the signal acceptance, there are two important sys-

FIG. 1. $E_{T,rel}^{miss}$ distributions for the selected $ee$ and $\mu\mu$ (left) and $e\mu$ (center) events and the multiplicity distribution for jets with $p_T > 20$ GeV and $|\eta| < 3.0$ for all three dilepton channels combined (right). The distributions show events with all selection criteria applied except for $E_{T,rel}^{miss}$ in the $E_{T,rel}^{miss}$ distribution and the jet veto in the jet multiplicity distribution. Simulation is used for the QCD jet and $W$+jets background contributions in these plots as opposed to the data-driven method used for $W$+jets in the signal region described in the text. The QCD jet contribution is negligible in the signal region.
dimensional uncertainties on the jet-veto efficiency: the jet-energy scale and the amount of initial and final state radiation (ISR/FSR). The jet-energy calibration uncertainty $\Delta$ corresponds to a 40% change in the top background. The uncertainty due to the ISR/FSR modeling is estimated using the HERWIG generator interfaced to PYTHIA, and varying the parameters controlling ISR and FSR in a range consistent with experimental data. The resulting uncertainty of 32% is a combination of the shift in the prediction and the statistical uncertainty on the simulation.

W bosons produced in association with a jet that is misidentified as a lepton contribute to the selected sample. The rate at which hadronic jets are misidentified as leptons may not be accurately described in the simulation, because these events are due to rare fragmentation processes or interactions with the detector. This background is therefore determined from data using control samples dominated by W+jets events and subtracting all other components using simulation. The ALPGEN+HERWIG+JIMMY simulation of the W+jets background used in Figure 1 gives comparable results to this method. The W+jets data samples are constructed by requiring one electron or muon passing the full selection criteria and a lepton-like jet, which is a reconstructed electron or muon that is selected as likely to be due to a jet. For electrons, the lepton-like jets are electromagnetic clusters matched to tracks in the inner detector that fail the full electron selection. For muons, lepton-like jets are muon candidates that fail at least one of the requirements on isolation, distance from the primary vertex, or ID and MS consistency. These events are otherwise required to pass the full event selection, treating the lepton-like jet as if it were a fully identified lepton.

The W+jets background is then estimated by scaling this control sample by a measured $p_T$-dependent factor $f$. The factor $f$ is the ratio of the probability for a jet to satisfy the full lepton identification criteria to the probability to satisfy the lepton-like jet criteria. The factor $f$ is measured in a QCD jet data sample and corrected for the small contribution of true leptons to the sample using simulation. The systematic uncertainty on $f$ is 36% for both electrons and muons, and is determined from variations of $f$ in different run periods and in data samples containing jets of different energies, which covers differences in the quark/gluon composition between the jets in the QCD jet and W+jets data samples.

The resulting signal and background expectations are shown in Table I. Eight events are observed in the data with a total expected background of 1.7 ± 0.6 events. As shown in Figure 2, the kinematic properties of the observed events are qualitatively consistent with the standard model expectation. To estimate the statistical significance of the signal, Poisson-distributed pseudo-experiments are generated, varying the expected background according to its uncertainty. The probability to observe 8 or more events in the absence of a signal is $1.2 \times 10^{-3}$, which corresponds to a significance of 3 standard deviations. The W+W− production cross section is determined using a maximum likelihood fitting method to combine the three dilepton channels. A cross section of $\sigma_{W^+W^-} = 41_{-16}^{+20}$ is measured. The luminosity uncertainty for this measurement is 3.4% [23]. The total systematic uncertainty (11.5%) includes the signal acceptance and efficiency ($\Delta A/A = 7.4\%$) and background estimation ($\Delta N_b/N_b = 33\%$) uncertainties. The dominant systematics uncertainties are due to the jet-veto (7.5%), and the lepton selection and identification (4.3%).

The measured W+W− production cross section is in good agreement with the standard model prediction of 44 ± 3 pb calculated at next-to-leading order in QCD and the recent measurement by CMS [3]. With the significantly larger integrated luminosities expected to be provided by the LHC, this signal will form the basis of a research program that will include searches for the standard model Higgs boson, anomalous triple gauge couplings, and other processes beyond the standard model.

**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;
FIG. 2. Distributions of the leading lepton $p_T$ (left), transverse momentum of the dilepton system (center), and azimuthal angle between the leptons (right) for the sum of the selected $ee$, $e\mu$, and $\mu\mu$ samples compared to the expectation. The gray band indicates the combined statistical and systematic uncertainty on the sum of the signal and background expectations.

The ATLAS Collaboration

The ATLAS Collaboration

G. Aad$^{48}$, B. Abbott$^{111}$, J. Abdallah$^{11}$, A.A. Abdelalim$^{49}$, A. Abdesselam$^{118}$, O. Abdinov$^{10}$, B. Abi$^{112}$, M. Abolins$^{89}$, H. Abramowicz$^{153}$, H. Abreu$^{115}$, E. Acerbi$^{89a,89b}$, B.S. Acharya$^{164a,164b}$, D.L. Adams$^{24}$, T.N. Addy$^{56}$, J. Adelman$^{175}$, M. Aderholz$^{99}$, S. Adomeit$^{99}$, P. Adragna$^{75}$, T. Adye$^{129}$, S. Aeby$^{22}$, J.A. Aguilar-Saavedra$^{124a,a}$, M. Aharrouche$^{81}$, S.P. Ahlen$^{21}$, F. Ahles$^{48}$, A. Ahmad$^{148}$, M. Ahsan$^{40}$, G. Aielli$^{133a,133b}$, T. Akdogan$^{18a}$, T.P.A. Åkesson$^{79}$, G. Akimoto$^{155}$, A.V. Akimov$^{94}$, A. Akiyama$^{67}$, M.S. Alam$^{1}$, M.A. Alam$^{26}$, S. Albrand$^{55}$, M. Alekseeva$^{29}$, I.N. Aleksandrov$^{65}$, F. Alessandria$^{89a}$, C. Alexa$^{25a}$, G. Alexander$^{153}$, G. Alexandrou$^{49}$, T. Alexopoulos$^{9}$, (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[5] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates ($\rho, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.
Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Science, Hiroshima University, Hiroshima, Japan
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Indiana University, Bloomington IN, United States of America
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, United States of America
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
(a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
Department of Physics, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, United States of America
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
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
Graduate School of Science, Nagoya University, Nagoya, Japan
(a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, 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 (BINP), 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
America
128 Department of Physics, University of Kentucky, Lexington KY, United States of America
127 Department of Physics, University of Edinburgh, Edinburgh, United Kingdom
126 Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
124 Laboratory of Experimental Physics, Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
123 Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
122 (a) Department of Physics, University of Science and Technology, Shizuoka, Japan; (b) Faculty of Engineering and Science, Kogakuin University, Tokyo, Japan; (c) Kindai University, Osaka, Japan
121 Department of Physics, University of Graz, Graz, Austria
120 Department of Physics, University of Hamburg, Hamburg, Germany
119 Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovakia
118 Department of Physics, Oxford University, Oxford, United Kingdom
117 Department of Physics, King’s College London, London, United Kingdom
116 Department of Physics, Faculty of Science, Masaryk University, Brno, Czech Republic
115 Institute of Physics, Faculty of Science, Charles University, Prague, Czech Republic
114 (a) Department of Physics, University of Wisconsin-Madison, Madison WI, United States of America; (b) Physics Department, University of Wisconsin-Milwaukee, Milwaukee WI, United States of America
113 Physics Department, University of Wisconsin-Milwaukee, Milwaukee WI, United States of America
112 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
111 Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
110 Department of Physics, University of Oregon, Eugene OR, United States of America
109 Graduate School of Science, Osaka University, Osaka, Japan
108 Department of Physics, University of Oslo, Oslo, Norway
107 School of Physics, University of Sydney, Sydney, Australia
106 School of Physics, University of Melbourne, Melbourne, Australia
105 Department of Physics, University of Cape Town, Cape Town, South Africa
104 Institute of Physics, University of Alberta, Edmonton AB, Canada
103 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
102 Department of Physics, University of California, Berkeley, Berkeley, California
101 Department of Physics, University of California, San Diego, La Jolla CA, United States of America
100 Department of Physics and Astronomy, University of York, York, United Kingdom
99 Department of Physics, Queen’s University, Kingston, Ontario, Canada
98 Department of Physics, University of Rochester, Rochester NY, United States of America
97 Institute for Theoretical Physics, University of Heidelberg, Heidelberg, Germany
96 Department of Physics, University of Heidelberg, Heidelberg, Germany
95 Department of Physics, University of Heidelberg, Heidelberg, Germany
94 Department of Physics, University of Heidelberg, Heidelberg, Germany
93 Department of Physics, University of Heidelberg, Heidelberg, Germany
92 Department of Physics, University of Heidelberg, Heidelberg, Germany
91 Department of Physics, University of Heidelberg, Heidelberg, Germany
90 Department of Physics, University of Heidelberg, Heidelberg, Germany
89 Department of Physics, University of Heidelberg, Heidelberg, Germany
88 Department of Physics, University of Heidelberg, Heidelberg, Germany
87 Department of Physics, University of Heidelberg, Heidelberg, Germany
86 Department of Physics, University of Heidelberg, Heidelberg, Germany
85 Department of Physics, University of Heidelberg, Heidelberg, Germany
84 Department of Physics, University of Heidelberg, Heidelberg, Germany
83 Department of Physics, University of Heidelberg, Heidelberg, Germany
82 Department of Physics, University of Heidelberg, Heidelberg, Germany
81 Department of Physics, University of Heidelberg, Heidelberg, Germany
80 Department of Physics, University of Heidelberg, Heidelberg, Germany
79 Department of Physics, University of Heidelberg, Heidelberg, Germany
78 Department of Physics, University of Heidelberg, Heidelberg, Germany
77 Department of Physics, University of Heidelberg, Heidelberg, Germany
76 Department of Physics, University of Heidelberg, Heidelberg, Germany
75 Department of Physics, University of Heidelberg, Heidelberg, Germany
74 Department of Physics, University of Heidelberg, Heidelberg, Germany
73 Department of Physics, University of Heidelberg, Heidelberg, Germany
72 Department of Physics, University of Heidelberg, Heidelberg, Germany
71 Department of Physics, University of Heidelberg, Heidelberg, Germany
70 Department of Physics, University of Heidelberg, Heidelberg, Germany
69 Department of Physics, University of Heidelberg, Heidelberg, Germany
68 Department of Physics, University of Heidelberg, Heidelberg, Germany
67 Department of Physics, University of Heidelberg, Heidelberg, Germany
66 Department of Physics, University of Heidelberg, Heidelberg, Germany
65 Department of Physics, University of Heidelberg, Heidelberg, Germany
64 Department of Physics, University of Heidelberg, Heidelberg, Germany
63 Department of Physics, University of Heidelberg, Heidelberg, Germany
62 Department of Physics, University of Heidelberg, Heidelberg, Germany
61 Department of Physics, University of Heidelberg, Heidelberg, Germany
60 Department of Physics, University of Heidelberg, Heidelberg, Germany
59 Department of Physics, University of Heidelberg, Heidelberg, Germany
58 Department of Physics, University of Heidelberg, Heidelberg, Germany
57 Department of Physics, University of Heidelberg, Heidelberg, Germany
56 Department of Physics, University of Heidelberg, Heidelberg, Germany
55 Department of Physics, University of Heidelberg, Heidelberg, Germany
54 Department of Physics, University of Heidelberg, Heidelberg, Germany
53 Department of Physics, University of Heidelberg, Heidelberg, Germany
52 Department of Physics, University of Heidelberg, Heidelberg, Germany
51 Department of Physics, University of Heidelberg, Heidelberg, Germany
50 Department of Physics, University of Heidelberg, Heidelberg, Germany
49 Department of Physics, University of Heidelberg, Heidelberg, Germany
48 Department of Physics, University of Heidelberg, Heidelberg, Germany
47 Department of Physics, University of Heidelberg, Heidelberg, Germany
46 Department of Physics, University of Heidelberg, Heidelberg, Germany
45 Department of Physics, University of Heidelberg, Heidelberg, Germany
44 Department of Physics, University of Heidelberg, Heidelberg, Germany
43 Department of Physics, University of Heidelberg, Heidelberg, Germany
42 Department of Physics, University of Heidelberg, Heidelberg, Germany
41 Department of Physics, University of Heidelberg, Heidelberg, Germany
40 Department of Physics, University of Heidelberg, Heidelberg, Germany
39 Department of Physics, University of Heidelberg, Heidelberg, Germany
38 Department of Physics, University of Heidelberg, Heidelberg, Germany
37 Department of Physics, University of Heidelberg, Heidelberg, Germany
36 Department of Physics, University of Heidelberg, Heidelberg, Germany
35 Department of Physics, University of Heidelberg, Heidelberg, Germany
34 Department of Physics, University of Heidelberg, Heidelberg, Germany
33 Department of Physics, University of Heidelberg, Heidelberg, Germany
32 Department of Physics, University of Heidelberg, Heidelberg, Germany
31 Department of Physics, University of Heidelberg, Heidelberg, Germany
30 Department of Physics, University of Heidelberg, Heidelberg, Germany
29 Department of Physics, University of Heidelberg, Heidelberg, Germany
28 Department of Physics, University of Heidelberg, Heidelberg, Germany
27 Department of Physics, University of Heidelberg, Heidelberg, Germany
26 Department of Physics, University of Heidelberg, Heidelberg, Germany
25 Department of Physics, University of Heidelberg, Heidelberg, Germany
24 Department of Physics, University of Heidelberg, Heidelberg, Germany
23 Department of Physics, University of Heidelberg, Heidelberg, Germany
22 Department of Physics, University of Heidelberg, Heidelberg, Germany
21 Department of Physics, University of Heidelberg, Heidelberg, Germany
20 Department of Physics, University of Heidelberg, Heidelberg, Germany
19 Department of Physics, University of Heidelberg, Heidelberg, Germany
18 Department of Physics, University of Heidelberg, Heidelberg, Germany
17 Department of Physics, University of Heidelberg, Heidelberg, Germany
16 Department of Physics, University of Heidelberg, Heidelberg, Germany
15 Department of Physics, University of Heidelberg, Heidelberg, Germany
14 Department of Physics, University of Heidelberg, Heidelberg, Germany
13 Department of Physics, University of Heidelberg, Heidelberg, Germany
12 Department of Physics, University of Heidelberg, Heidelberg, Germany
11 Department of Physics, University of Heidelberg, Heidelberg, Germany
10 Department of Physics, University of Heidelberg, Heidelberg, Germany
9 Department of Physics, University of Heidelberg, Heidelberg, Germany
8 Department of Physics, University of Heidelberg, Heidelberg, Germany
7 Department of Physics, University of Heidelberg, Heidelberg, Germany
6 Department of Physics, University of Heidelberg, Heidelberg, Germany
5 Department of Physics, University of Heidelberg, Heidelberg, Germany
4 Department of Physics, University of Heidelberg, Heidelberg, Germany
3 Department of Physics, University of Heidelberg, Heidelberg, Germany
2 Department of Physics, University of Heidelberg, Heidelberg, Germany
1 Department of Physics, University of Heidelberg, Heidelberg, Germany
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
(a)TRIUMF, Vancouver BC; (b)Department of Physics and Astronomy, York University, Toronto ON, Canada
Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
Science and Technology Center, Tufts University, Medford MA, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
(a)INFN Gruppo Collegato di Udine; (b)ICTP, Trieste; (c)Dipartimento di Fisica, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física 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
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
 Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
 Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
 Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
 Also at TRIUMF, Vancouver BC, Canada
 Also at Department of Physics, California State University, Fresno CA, United States of America
 Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
 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, United States of America
 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, United States of America
 Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, 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 California Institute of Technology, Pasadena CA, United States of America
 Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
 Also at Section de Physique, Université de Genève, Geneva, Switzerland
 Also at Departamento de Física, Universidade de Minho, Braga, Portugal
 Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
 Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
 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 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 à l’Energie Atomique), Gif-sur-Yvette, France
ad Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
ae Also at Department of Physics, Nanjing University, Jiangsu, China
* Deceased