Measurements of the total and differential Higgs boson production cross sections combining the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels at $\sqrt{s} = 8$ TeV with the ATLAS detector


Published in: Physical Review Letters

DOI: 10.1103/PhysRevLett.115.091801

Link to publication

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
Measurements of the Total and Differential Higgs Boson Production
Cross Sections Combining the \( H \to \gamma\gamma \) and \( H \to ZZ^* \to 4\ell \) Decay Channels
at \( \sqrt{s} = 8 \text{ TeV} \) with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)
(Received 23 April 2015; published 27 August 2015)

Measurements of the total and differential cross sections of Higgs boson production are performed using 20.3 fb\(^{-1} \) of \( pp \) collisions produced by the Large Hadron Collider (LHC) \( [1] \) at a center-of-mass energy of \( \sqrt{s} = 8 \text{ TeV} \) and recorded by the ATLAS detector. Cross sections are obtained from measured \( H \to \gamma\gamma \) and \( H \to ZZ^* \to 4\ell \) event yields, which are combined accounting for detector efficiencies, fiducial acceptances, and branching fractions. Differential cross sections are reported as a function of Higgs boson transverse momentum, Higgs boson rapidity, number of jets in the event, and transverse momentum of the leading jet. The total production cross section is determined to be 
\( \sigma_{pp-H} = 33.0 \pm 5.3 \text{ (stat)} \pm 1.6 \text{ (syst)} \text{ pb} \). The measurements are compared to state-of-the-art predictions.

DOI: 10.1103/PhysRevLett.115.091801
PACS numbers: 14.80.Bn, 13.85.Lg, 13.85.Qk

This Letter presents measurements of the total and differential cross sections of inclusive Higgs boson production using 20.3 fb\(^{-1} \) of \( pp \) collisions produced by the Large Hadron Collider (LHC) \( [1] \) at a center-of-mass energy of \( \sqrt{s} = 8 \text{ TeV} \) and recorded by the ATLAS detector \( [2] \). The measured cross sections probe the properties of the Higgs boson and can be directly compared to the theoretical modeling of different Higgs boson production mechanisms, such as the most recent gluon fusion (ggF) QCD calculations. They can also be used to constrain new physics scenarios, for example using the effective field theory framework as proposed in Refs. \( [3–7] \). The analysis uses event yields measured in the \( H \to \gamma\gamma \) and \( H \to ZZ^* \to 4\ell \) decays and detector efficiencies, both determined as described in Refs. \( [8,9] \). The statistical uncertainties on the Higgs boson signal yields in both channels are larger than the systematic uncertainties, while the total uncertainties in the two channels are similar. Combining the analyses improves the precision of the cross-section measurements by up to 40\%, and by 25\%–30\% on average, with respect to the corresponding measurements in the most precise individual channel.

Distributions of the differential \( pp \to H \) cross sections are reported as a function of the transverse momentum \( p_T^H \) and the rapidity \( y^H \) of the Higgs boson, the jet multiplicity \( N_{\text{jets}} \), and the transverse momentum of the leading jet \( p_T^{1\ell} \). The observables \( p_T^H \) and \( y^H \) describe the kinematics of the Higgs boson. They are sensitive to perturbative QCD modeling in ggF production, which is the dominant Higgs boson production mechanism in the Standard Model (SM). The \( y^H \) distribution furthermore offers a clean probe of the gluon parton distribution function (PDF) and will play a role in future PDF fits. The \( N_{\text{jets}} \) and \( p_T^{1\ell} \) observables probe the theoretical modeling of partonic radiation in ggF production as well as the overall rate and modeling of jets in vector-boson fusion (VBF) and associated Higgs boson production (VH and \( t\bar{t}H \)). Jets produced in VBF, VH, and \( t\bar{t}H \) processes tend to have higher transverse momenta than those produced via ggF production; however, the sensitivity to measuring these contributions is weak with the current amount of data.

Cross sections are extracted using a combined likelihood built from the signal yields in the \( H \to \gamma\gamma \) channel and the data and background yields in the \( H \to ZZ^* \to 4\ell \) channel, as well as detector efficiencies, fiducial acceptances and SM branching fractions \( [10] \). A complementary approach, using a separate likelihood, measures the shape of the differential distributions by imposing a unity normalization constraint, which removes the implicit SM assumption on the branching fractions. For the extraction of the signal yields and the corrections of detector efficiencies, it is assumed that the signal in both channels is due to a narrow resonance with a mass \( m_H = 125.36 \pm 0.41 \text{ GeV} \) as measured by the ATLAS Collaboration \( [11] \). The signal yield in the \( H \to \gamma\gamma \) channel is obtained from fits to the diphoton mass spectra \( [8,9] \), and from the background subtracted data yield in a \( m_{4\ell} \) mass window of 118 to 129 GeV for the \( H \to ZZ^* \to 4\ell \) channel \( [9] \). The fiducial acceptance in both channels \( [8,9] \) is derived using a set of Monte Carlo (MC) event generators. POWHEG-BOX \( [12–14] \), interfaced with PYTHIA8 \( [15] \) for showering, is used to generate ggF and VBF events, while PYTHIA8 is used to simulate VH and...
associated production with top quarks ($t\bar{t}H$) and $b$-quarks ($bbH$). The fiducial acceptance for events with $|y^H| < 1.2$ is approximately 72% for $H \rightarrow \gamma\gamma$, and 55%–59% for $H \rightarrow ZZ^* \rightarrow 4\ell$. For higher $|y^H|$, the acceptance decreases to 35%–38% in both channels. The fiducial acceptance is more constant as a function of the other variables and is in the range 56%–62% for the $H \rightarrow \gamma\gamma$ channel and 44%–53% for the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel [16].

After correcting the differential cross sections and normalized shapes for fiducial acceptance and branching fractions, the corresponding measurements in both channels are found to be in good agreement with each other; $p$ values obtained from $\chi^2$ compatibility tests are in the range 56%–99% [16].

In the binned maximum-likelihood fit, the statistical uncertainty of the $H \rightarrow \gamma\gamma$ event yield is modeled using a Gaussian distribution, while the event yield in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel follows a Poisson distribution due to the small sample size. Experimental and theoretical systematic uncertainties affecting the signal yields, detector efficiencies, branching fractions, and fiducial acceptance corrections are taken into account in the likelihood as constrained nuisance parameters. Nuisance parameters describing the same uncertainty sources are treated as fully correlated between bins and channels. Systematic uncertainties on the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ background estimates and efficiency correction factors, as well as the uncertainty on the integrated luminosity, are described in detail in Refs. [8,9]. The branching fraction uncertainty due to the assumed quark masses and other theoretical uncertainties are evaluated following the recommendations of Ref. [17], considering uncertainty correlations between the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels. Uncertainties on the acceptance correction related to the choice of PDF set are evaluated by taking the envelope of the sum in quadratures of eigenvector variations of the baseline (CT10 [18]) and the central values of alternative (MSTW2008NLO [19] and NNPDF2.3 [20]) PDF sets. Uncertainties on the acceptance correction associated with missing higher-order corrections are evaluated by varying the renormalization and factorization scales coherently and individually by factors of 0.5 and 2 from their nominal values, and by reweighting the $p_T^H$ distribution from POWHEG-BOX to the prediction of the HRES 2.2 calculation [21,22]. The envelope of the maximum deviation of the combined scale variations and the $p_T^H$ reweighting is used as the systematic variation. To account for the uncertainty in the mass measurement, the Higgs boson mass is varied by ±0.4 GeV. To assess the systematic uncertainty due to the assumption of SM cross-section fractions of the Higgs boson production modes, the VBF and VH fractions are varied by factors of 0.5 and 2 from the SM prediction and the fraction of $t\bar{t}H$ is varied by factors of 0 and 5. These factors are based on current experimental bounds [23–27].

The total uncertainties on the acceptance correction range from 1% to 6%, depending on the channel, distribution and bin.

The total systematic uncertainties on the combined differential cross sections range from 4% to 12%, depending on the distribution and bin. For the kinematic variables $p_T^H$ and $|y^H|$, the largest systematic uncertainties on the differential cross sections are due to the luminosity and the background estimates in both channels. For the jet variables $N_{jets}$ and $p_T^j$, the largest systematic uncertainties on the differential cross sections are due to the jet energy scale and resolution. In the shape combination, the normalization uncertainties including luminosity, branching fractions, and efficiency uncertainties do not apply. Statistical uncertainties dominate all resulting distributions, ranging from 23% to 75%.

The total $pp \rightarrow H$ cross section is determined in the $H \rightarrow \gamma\gamma$ channel to be $31.4 \pm 7.2$ (stat) $\pm 1.6$ (syst) pb and in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel to be $35.0 \pm 8.4$ (stat) $\pm 1.8$ (syst) pb. Combining the analyses yields $\sigma_{pp \rightarrow H} = 33.0 \pm 5.3$ (stat) $\pm 1.6$ (syst) pb. Figure 1 presents a comparison of these measurements with two ggF predictions to which contributions from other relevant Higgs boson production modes (VBF, VH, $t\bar{t}H$, $bbH$) are added using cross sections and uncertainties from Ref. [10]. The LHC-XS ggF prediction, recommended in Ref. [10], is accurate to next-to-next-to-leading order (NNLO) in QCD and utilizes threshold resummation accurate to next-to-next-to-leading logarithms (NNLL). A significant effort has been undertaken by the theory community to provide ggF cross sections beyond this precision through various improvements in the perturbative calculations [28–33]. Recently, the ADDFGHLM group has provided a fixed-order calculation accurate to next-to-next-to-leading order (N$^3$LO) [34–37]. A PDF uncertainty

![FIG. 1 (color online). Measured total cross section of Higgs boson production compared to two calculations of the ggF cross section. Contributions from other relevant Higgs boson production modes (VBF, VH, $t\bar{t}H$, $bbH$) are added using cross sections and uncertainties from Ref. [10]. Details of the predictions are presented in Table 1.](image-url)
of $^{+7.5}_{-6.9}\%$ is assigned to the LHC-XS prediction, derived following the recommendations in Ref. [17]. This uncertainty is increased by $^{+0.3}_{-0.1}\%$ for the ADDFGHLM prediction corresponding to the change in uncertainty of the MSTW2008nnlo PDF set when changing the calculation from NNLO to N^{3}LO. The PDF uncertainty is treated as uncorrelated with the QCD scale uncertainty.

The central value of the measured total cross section is larger than the SM predictions presented in Fig. 1. A likelihood-ratio test statistic is used to quantify the agreement, using a bifurcated Gaussian to model the asymmetric theory uncertainties. The resulting $p$ values are 5.5\% and 9.0\% for the agreement between data and the predictions from LHC-XS and ADDFGHLM, respectively. The ratio of the measured cross section to the LHC-XS prediction is larger than the results presented in Refs. [23,24,38], which use an event categorization based on the expected SM yields in the different Higgs boson production modes.

The larger Higgs event yield observed in data motivates measurements of differential cross sections to investigate if the excess is localized to specific kinematic regions. Figure 2 shows the comparison of the combined cross sections in different inclusive and exclusive jet multiplicity bins with state-of-the-art predictions, including NLO-accurate multi-leg (ML) merged ggF MC event generators (further details are given in Table I). Jets are reconstructed using the anti-$k_{t}$ algorithm [39] with a radius parameter $R = 0.4$ [40], and are required to have $p_T > 30$ GeV and $|y| < 4.4$. Simulated particle-level jets are built from all particles with $c_T > 10$ mm excluding neutrinos, electrons, and muons that do not originate from hadronic decays.

Photons are excluded from jet-finding if they lie inside a cone of radius $\Delta R < 0.1$ of an electron or muon, and neither the photon nor lepton originate from a hadron decay. To allow comparisons with the unfolded measurements, the analytical calculations are corrected for effects of hadronization and multiple particle interactions. These correction factors and their associated uncertainties are obtained using the PYTHIA8 and HERWIG [41] MC event generators with different tunes [42–44]. The total cross sections from the ML merged predictions are lower than from fully inclusive NNLO + NLL calculations. However, for $N_{\text{jets}} \geq 1$, the MC predictions formally have NNLO accuracy, which is the same as the analytical calculations. Contributions from other relevant Higgs boson production modes are generated using POWHEG for VBF and PYTHIA8 for VH, $t\bar{t}H$, and $bbH$, and are scaled to the cross sections in Ref. [10]. Uncertainties are assigned to all MC predictions from QCD scale and PDF variations. The ML-merged ggF predictions also have uncertainties due to the choice of merging scale. The SHERPA uncertainties further include resummation scale variations. The measured cross sections are higher than the predictions for all measured jet multiplicities. The poorest

![FIG. 2 (color online). Measured Higgs boson production cross sections in inclusive and exclusive jet multiplicity bins compared to different theoretical predictions (see Table I for details and references).](image-url)
FIG. 3 (color online). Differential cross sections (left) and normalized cross-section shapes (right) for inclusive Higgs boson production measured by combining the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels. The measured variables are the Higgs boson transverse momentum $p_T^H$ (top) and its rapidity $y_H$ (middle), and the transverse momentum of the leading jet $p_T^j$ (bottom). The 0–30 GeV bin of the $p_T^j$ distributions corresponds to events without jets above 30 GeV. Various theoretical predictions are presented, using the same bin widths as the measurement.
agreement between data and predictions can be found in the inclusive and exclusive 1-jet bins, with local p values ranging between 0.1% and 3.6%. Normalizing the total expected cross section to the data results in an improved agreement for these bins, with local p values ranging from 4%–29%. The combined differential cross sections as a function of \( p_T^H \), \( |y^H| \), and \( p_T^{\text{j1}} \) are shown in Fig. 3 (left). The measured \( p_T^H \) and \( |y^H| \) distributions are compared to the HERES calculation and the \( p_T^{\text{j1}} \) measurement is compared to STWZ and JetVHeto predictions. Figure 3 (right) shows the comparisons of the normalized shapes to predictions from the MC event generators NNLOPS, SHERPA 2.1.1, and MG5_aMC@NLO, as well as the HERES calculation. The uncertainties on the predicted shapes are evaluated following the same approach as for the differential cross-section predictions. They are derived from the impact of QCD scale, merging scale, and PDF variations. The mean of the measured \( p_T^H \) distribution is \( 40.1 \pm 3.0 \) GeV, while the means of the MC predictions range from 34 to 37 GeV.

The p values quantifying the compatibility of the measured cross sections and predictions range from 2% to 26%, and for the shapes from 8% to 88%. For the calculation of these values, the theory uncertainties are assumed to be Gaussian distributed and fully correlated between bins [16].

In conclusion, this Letter presents the first measurements of total and differential cross sections and shapes for inclusive \( pp \to H \) production. The measurements were performed in the \( H \to \gamma\gamma \) and \( H \to ZZ^* \to 4\ell \) channels using the full 2012 data set, which consists of \( 20.3 \) fb\(^{-1} \) of \( pp \) collisions produced by the LHC at a center-of-mass energy of \( \sqrt{s} = 8 \) TeV and recorded by the ATLAS detector. The results of the two channels are compatible and have similar precision. The measurements indicate that the total production cross section of the Higgs boson is larger, and that it is produced with larger transverse momentum and more associated jets than predicted by the current most advanced SM calculations; however, more data is needed to confirm these observations.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; RGC, Hong Kong SAR, China; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNIŚW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[16] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.115.091801 for more details and numerical values of the acceptance factors, tables with the measured cross sections and their associated covariance matrices, and additional comparisons both between the Higgs decay channels as well as between data and theory predictions.

(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, AB, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Istanbul, Turkey
5Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
6LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
7High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
8Department of Physics, University of Arizona, Tucson, Arizona, USA
9Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
10Department of Physics, University of Athens, Athens, Greece
11Department of Physics, National Technical University of Athens, Zografou, Greece
12Institut de Fisica d’Altes Energies and Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain
13Institute of Physics, University of Belgrade, Belgrade, Serbia
14Department for Physics and Technology, University of Bergen, Bergen, Norway
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16Department of Physics, Humboldt University, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

PRL 115, 091801 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

091801-14
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
Department of Physics, Bogazici University, Istanbul, Turkey
Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
INFN Sezione di Bologna, Italy
Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Boston University, Boston, Massachusetts, USA
Department of Physics, Brandeis University, Waltham, Massachusetts, USA
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton, New York, USA
National Institute of Physics and Nuclear Engineering, Bucharest, Romania
National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
University Politehnica Bucharest, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa, ON, Canada
CERN, Geneva, Switzerland
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa Maria, Valparaíso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Modern Physics, University of Science and Technology of China, Anhui, China
Department of Physics, Nanjing University, Jiangsu, China
School of Physics, Shandong University, Shandong, China
Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China
Physics Department, Tsinghua University, Beijing 100084, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, København, Denmark
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Dipartimento di Fisica, Università della Calabria, Rende, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Italy
Dipartimento di Fisica, Università di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
110 Department of Physics, New York University, New York, New York, USA
111 Ohio State University, Columbus, Ohio, USA
112 Faculty of Science, Okayama University, Okayama, Japan
113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
114 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
115 Palacký University, RCPTM, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
117 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
118 Graduate School of Science, Osaka University, Osaka, Japan
119 Department of Physics, University of Oslo, Oslo, Norway
120 Department of Physics, Oxford University, Oxford, United Kingdom
121 INFN Sezione di Pavia, Italy
122 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
123 Petersburg Nuclear Physics Institute, Gatchina, Russia
124a INFN Sezione di Pavia, Italy
124b Dipartimento di Fisica, Università di Pavia, Pavia, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
126a Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
126b Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
126c Department of Physics, University of Coimbra, Coimbra, Portugal
126d Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
126e Departamento de Física, Universidade do Minho, Braga, Portugal
126f Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
127 Department of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
130 State Research Center Institute for High Energy Physics, Protvino, Russia
131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
132 INFN Sezione di Roma, Italy
133a INFN Sezione di Roma Tor Vergata, Italy
133b Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134a INFN Sezione di Roma Tor Vergata, Italy
134b Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134c INFN Sezione di Roma Tre, Italy
135 Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136a Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
136b Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
136c Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
136d Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
136e Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
139 Department of Physics, University of Washington, Seattle, Washington, USA
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144a SLAC National Accelerator Laboratory, Stanford, California, USA
144b Department of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
144c Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
144d Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
144e Department of Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
144f Department of Physics, University of Cape Town, Cape Town, South Africa
146 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
147a Department of Physics, Stockholm University, Sweden
147b The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion- Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto ON, Canada

TRIUMF, Vancouver BC, Canada

Department of Physics and Astronomy, York University, Toronto ON, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy

ICTP, Trieste, Italy

Department of Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana, Illinois, USA

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

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

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, Connecticut, USA

Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

\(^{a}\)Deceased.

\(^{b}\)Also at Department of Physics, King’s College London, London, United Kingdom.

\(^{c}\)Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

\(^{d}\)Also at Novosibirsk State University, Novosibirsk, Russia.

\(^{e}\)Also at TRIUMF, Vancouver BC, Canada.

\(^{f}\)Also at Department of Physics, California State University, Fresno, CA, USA.

\(^{g}\)Also at University of Fribourg, Fribourg, Switzerland.

\(^{h}\)Also at Departamento de Física e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.

\(^{i}\)Also at Tomsk State University, Tomsk, Russia.

\(^{j}\)Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

\(^{k}\)Also at Università di Napoli Parthenope, Napoli, Italy.

\(^{l}\)Also at Institute of Particle Physics (IPP), Canada.

\(^{m}\)Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

\(^{n}\)Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

\(^{o}\)Also at Louisiana Tech University, Ruston, LA, USA.

\(^{p}\)Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

\(^{q}\)Also at Department of Physics, National Tsing Hua University, Taiwan.

\(^{r}\)Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.

\(^{s}\)Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

\(^{t}\)Also at CERN, Geneva, Switzerland.

\(^{u}\)Also at Georgian Technical University (GTU), Tbilisi, Georgia.

\(^{v}\)Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

\(^{w}\)Also at Manhattan College, New York, NY, USA.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
\*Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
\*Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
\*Also at School of Physics, Shandong University, Shandong, China.
\*Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\*Also at Section de Physique, Université de Genève, Geneva, Switzerland.
\*Also at International School for Advanced Studies (SISSA), Trieste, Italy.
\*Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
\*Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
\*Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
\*Also at National Research Nuclear University MEPhI, Moscow, Russia.
\*Also at Department of Physics, Stanford University, Stanford, CA, USA.
\*Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
\*Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
\*Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
\*Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.