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

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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

G. Aad et al. (ATLAS Collaboration)  
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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 at a center-of-mass energy of $\sqrt{s} = 8$ TeV and recorded by the ATLAS detector. Cross sections are obtained from measured $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ 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 $\sigma_{pp-H} = 33.0 \pm 5.3$ (stat) $\pm 1.6$ (syst) pb. The measurements are compared to state-of the-art predictions.

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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 $\sqrt{s} = 8$ 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 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ 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 $pp \rightarrow H$ 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 $N_{jets}$, and the transverse momentum of the leading jet $p_T^{\ell_1}$. 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 $N_{jets}$ and $p_T^{\ell_1}$ 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 $H \rightarrow \gamma\gamma$ channel and the data and background yields in the $H \rightarrow ZZ^* \rightarrow 4\ell$ 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 $m_H = 125.36 \pm 0.41$ GeV as measured by the ATLAS Collaboration [11]. The signal yield in the $H \rightarrow \gamma\gamma$ channel is obtained from fits to the diphoton mass spectra [8], and from the background subtracted data yield in a $m_\ell \ell$ mass window of 118 to 129 GeV for the $H \rightarrow ZZ^* \rightarrow 4\ell$ 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

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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 $H \to \gamma\gamma$, and 55%–59% for $H \to ZZ^* \to 4\ell$. 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 $H \to ZZ^*$ channel and 44%–53% for the $H \to ZZ^* \to 4\ell$ 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 $H \to \gamma\gamma$ event yield is modeled using a Gaussian distribution, while the event yield in the $H \to ZZ^* \to 4\ell$ 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 $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ 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 $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ 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 $p_H^1$ 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 $p_H^1$ 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 $p_T^{jets}$, 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 $pp \to H$ cross section is determined in the $H \to \gamma\gamma$ channel to be 31.4 ± 7.2 (stat) ± 1.6 (syst) pb and in the $H \to ZZ^* \to 4\ell$ channel to be 35.0 ± 8.4 (stat) ± 1.8 (syst) pb. Combining the analyses yields $\sigma_{pp\to H} = 33.0 \pm 5.3$ (stat) ± 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-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 I.
jets are reconstructed accurate multi-leg (ML) merged ggF MC event generators with state-of-the-art predictions, including NLO–NNLO total cross-section calculations. Monte Carlo event generators SHERPA 2.1 [49,50] H + 0, 1, 2 jets @NLO\(^{ij}\) MG5\_aMC@NLO [51,52] H + 0, 1, 2 jets @NLO\(^{kl}\) POWHEG NNLOPS [53,54] NNLO\(^{20,j, l,m}\) aConsiders b- (and c-) quark masses in the gg → H loop. bIncludes electroweak corrections. cBased on MSTW2008nnlo [19] (\(c_\alpha\) from PDF set). dUses \(\pi^2\)-resummed gg → H form factor. eNNLO refers to the total cross section. fBased on the CT10nnlo PDF set. gIn the notation of Ref. [28], this corresponds to NNLL’. hIncludes 1-jet resummation included at NLL’ + NLO. iBased on the CT10nlo PDF set. jUses MEPS@NLO method and CKKW merging scheme [55–57]. kSoftware version 2.2.1, NLO merged using FxFx scheme [52]. lInterfaced with PYTHIA8 for parton showering. mUses MinNLO method and \(\gamma^H\) reweighting to HNNLO [54,58,59].

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 + NNLL calculations. However, for \(N_{\text{jets}} \geq 1\), the MC predictions formally have NLO 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

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**TABLE I.** Summary of the ggF predictions used in the comparison with the measured cross sections. The second column states the order in QCD perturbation theory and which threshold resummation is applied, if any. Further details are provided in the footnotes. All predictions are for \(m_H = 125.4\) GeV and \(\sqrt{s} = 8\) TeV.

<table>
<thead>
<tr>
<th>Total cross-section calculations</th>
<th>LHC-XS [10]</th>
<th>NNLO + NNLL(^{a,b,c})</th>
<th>ADDFGHLM [34–37]</th>
<th>NNLO(^{a,b,c})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical differential cross-section predictions</td>
<td>HRES 2.2 [21,22]</td>
<td>NNLO + NNLL(^{a,f})</td>
<td>STWZ [28], BLPTW [45]</td>
<td>NNLO + NNLL(^{c,d,e,g,h})</td>
</tr>
<tr>
<td>Monte Carlo event generators</td>
<td>SHERPA 2.1 [49,50]</td>
<td>H + 0, 1, 2 jets @NLO(^{ij})</td>
<td>MG5_aMC@NLO [51,52]</td>
<td>H + 0, 1, 2 jets @NLO(^{kl})</td>
</tr>
<tr>
<td>POWHEG NNLOPS [53,54]</td>
<td>NNLO(^{20,j, l,m})</td>
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**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).
FIG. 3 (color online). Differential cross sections (left) and normalized cross-section shapes (right) for inclusive Higgs boson production measured by combining the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ 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 $p_{T}^{j_1}$ (bottom). The 0–30 GeV bin of the $p_{T}^{j_1}$ 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 $p_T^{H}$, $|y|^1$, and $p_T^{|y|}$ are shown in Fig. 3 (left). The measured $p_T^{H}$ and $|y|^1$ distributions are compared to the HRes calculation and the $p_T^{|y|}$ 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 HRes 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 $pp \rightarrow H$ production. The measurements were performed in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ 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.

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[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.
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19a Department of Physics, Bogazici University, Istanbul, Turkey
19b Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20a INFN Sezione di Bologna, Italy
20b Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, Massachusetts, USA
23 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
24a Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
24b Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
24c Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
24d Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
26a National Institute of Physics and Nuclear Engineering, Bucharest, Romania
26b National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
26c University Politehnica Bucharest, Bucharest, Romania
26d West University in Timisoara, Timisoara, Romania
27 Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa, ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
32a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
32b Departamento de Física, Universidad Técnica Federico Santa Maria, Valparaíso, Chile
33 Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington, New York, USA
36 Niels Bohr Institute, University of Copenhagen, København, Denmark
37a INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
37b Dipartimento di Fisica, Università della Calabria, Rende, Italy
38a AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
38b Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas, Texas, USA
41 Physics Department, University of Texas at Dallas, Richardson, Texas, USA
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham, North Carolina, USA
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50a INFN Sezione di Genova, Italy
50b Dipartimento di Fisica, Università di Genova, Genova, Italy
51a E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
51b High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
School of Physics, University of Sussex, Brighton, United Kingdom
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
Dipartimento di 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

*Deceased.
+Also at Department of Physics, King’s College London, London, United Kingdom.
 Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
 Also at Novosibirsk State University, Novosibirsk, Russia.
 Also at TRIUMF, Vancouver BC, Canada.
 Also at Department of Physics, California State University, Fresno, CA, USA.
 Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
 Also at Departamento de Física e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
 Also at Tomsk State University, Tomsk, Russia.
 Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
 Also at Università di Napoli Parthenope, Napoli, Italy.
 Also at Institute of Particle Physics (IPP), Canada.
 Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
 Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
 Also at Louisiana Tech University, Ruston, LA, USA.
 Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
 Also at Department of Physics, National Tsing Hua University, Taiwan.
 Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
 Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
 Also at CERN, Geneva, Switzerland.
 Also at Georgian Technical University (GTU), Tbilisi, Georgia.
 Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
 Also at Manhattan College, New York, NY, USA.