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

The ATLAS Collaboration

Abstract

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 $\sigma_{pp \rightarrow H} = 33.0 \pm 5.3$ (stat) $\pm 1.6$ (sys) pb. The measurements are compared to state-of-the-art predictions.
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The ATLAS Collaboration
(Dated: April 23, 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 $\sqrt{s} = 8$ 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 $\sigma_{pp\to H} = 33.0 \pm 5.3$ (stat) $\pm 1.6$ (sys) pb. The measurements are compared to state-of-the-art predictions.

PACS numbers: 13.85.Lg,13.85.Qk,14.80.Bn

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 $H \to \gamma\gamma$ 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 $p_T^{j_1}$. 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 $N_{\text{jets}}$ distribution is sensitive to the relative contributions of different production mechanisms. The observable $p_T^{j_1}$ probes the theoretical modeling of partonic radiation in ggF production as well as the modeling of jets in events with Higgs boson production by vector-boson fusion (VBF) and associated production (VH). Jets produced in VBF and VH processes tend to have higher transverse momenta than those produced in the ggF production mode.

Cross sections are extracted using a combined likelihood that takes into account 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, combines the differential distributions normalized to unity, referred to as shapes, which removes the implicit SM assumption on the branching fractions. For the extraction of the yields, the detector efficiencies, fiducial acceptances, and branching fractions, the Higgs boson mass is set to the value measured by the ATLAS Collaboration of $m_H = 125.36 \pm 0.41$ GeV [11]. The signal yield in the $H \to \gamma\gamma$ channel is obtained from fits to the diphoton mass spectra [8], while in the $H \to ZZ^* \to 4\ell$ channel, the estimated background is subtracted from the data yields in each bin in a mass window around $m_H$, defined by the reconstructed four-lepton mass [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 (ttH) 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 $H \to \gamma\gamma$ channel and 44–53% for the $H \to ZZ^* \to 4\ell$ channel.

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%.

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. [16], 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 eigenvalue variations of the baseline (CT10 [17]) and the central values of alternative (MSTW2008NLO [18] and NNPDF2.3 [19]) 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 HERwig 2.2 calculation [20, 21]. 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 [22–26]. 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 $N_{\text{jets}}$ 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.
1.8 (sys) pb. Combining the analyses yields \( \sigma_{pp\to H} = 33.0 \pm 5.3 \text{(stat)} \pm 1.6 \text{(sys)} \) 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 utilises 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 [31, 47–51]. Recently, the ADDFGHLM group has provided a fixed-order calculation accurate to next-to-next-to-next-leading order (N^3LO) [27–30]. A PDF uncertainty of \( +7.5\% \) is assigned to the LHC-XS prediction, derived following the recommendations in Ref. [16]. This uncertainty is increased by \( +6.9\% \) for the ADDFGHLM prediction corresponding to the change in uncertainty of the MSTW2008nnlo PDF set when changing the calculation from NNLO to N^3LO. 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 higher than the results presented in Refs. [22, 23], which use an event categorization based on the expected SM yields in the different Higgs boson production modes.

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 [52] with a radius parameter \( R = 0.4 \) [53], and are required to have \( p_T > 30 \text{ GeV} \) and \( |y| < 4.4 \). Simulated particle-level jets are built from all particles with \( \Delta r > 10 \text{ mm} \) 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 [54] MC event generators with different tunes [55–57]. The obtained 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 agreement with data can be found in the inclusive and exclusive 1-jet bins, with \( p \)-values ranging between 0.1\% and 3.6\%.

The combined differential cross sections as a function of \( p_T^1 \), \( |y|^1 \), and \( p_T^3 \) are shown in Fig. 3 (left). The measured \( p_T^1 \) and \( |y|^1 \) distributions are compared to the HRES calculation and the \( p_T^1 \) 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 \( p_T^1 \) distribution is \( 40.1 \pm 3.0 \text{ GeV} \), while the means of the MC predictions range from 34 to 37 GeV.

![FIG. 2. 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. 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 $p_T^H$ distributions corresponds to events without jets above 30 GeV. Various theoretical predictions are presented, using the same bin widths as the measurement.
The $p$-values quantifying the compatibility of the measured shapes and the predictions range from 8% to 88%. For the calculation of these values, the theory uncertainties are assumed to be Gaussian distributed and fully correlated between bins.

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 dataset, 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. While the measured total cross section is higher than the tested predictions, $p$-values indicate fair agreement between the current best predictions and the data for all studied differential cross sections and shapes.

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; 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.
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Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, 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 Matematica e 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
School of Physics and Astronomy, 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
Louisiana Tech University, Ruston LA, United States of America
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
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. 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 and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, 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, SB RAS, 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
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
121 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
122 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
123 Petersburg Nuclear Physics Institute, Gatchina, Russia
124 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
126 (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teorica y del Cosmos and CAPEF, Universidad de Granada, Granada (Spain); (g) Dept Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
127 Institute 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 Ritsumeikan University, Kusatsu, Shiga, Japan
133 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) 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 CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of America
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
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
147 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
163 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, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, 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

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 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

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

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, United States of America

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, United States of America

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, United States of America

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, United States of America

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, United States of America

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, United States of America

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
$^a_j$ Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

$^a_k$ Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

$^a_l$ Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

* Deceased
SUPPLEMENTAL MATERIAL

The fiducial cross section $\sigma_i$ in a given bin $i$ can be expressed as

$$\sigma_i = \frac{n_i}{L_i B \alpha_i c_i} = \frac{\sigma_{\text{fid},i}}{B \alpha_i}, \quad (1)$$

where $n_i$ is the measured Higgs boson signal yield, $L$ is the integrated luminosity ($20.3 \text{ fb}^{-1}$ for this analysis), $B$ is the branching ratio ($0.228\%$ for $H \rightarrow \gamma\gamma$ and $0.0129\%$ for $H \rightarrow ZZ^* \rightarrow 4\ell$, $\ell = e$ or $\mu$), $\alpha_i$ is the fiducial acceptance and $c_i$ is a correction factor for detector effects, primarily accounting for reconstruction efficiency but also for bin-to-bin migration. For $H \rightarrow ZZ^* \rightarrow 4\ell$, the signal yield is defined as the number of observed events $n_{\text{data}}$ in a window around the Higgs boson mass peak minus the background estimate: $n_i = n_{\text{data},i} - n_{\text{bkg},i}$, while for $H \rightarrow \gamma\gamma$, the signal yield is extracted from a simultaneous signal+background fit of the $m_{\gamma\gamma}$ distribution. The correction factors for detector effects $c_i$, along with their systematic uncertainties are taken from the differential cross section measurements in the individual channels [8, 9]. The differential cross section is defined as the fiducial cross section divided by the bin width.

| Bin | 1  | 2  | 3  | 4  | 5  |
|-----|----|----|----|----|----|
| Incl. | 46.7 ± 1.1 |
| $N_{\text{jets}}$ | 45.0 ± 1.1 | 47.8 ± 1.0 | 49.8 ± 1.3 | 50.0 ± 1.9 |
| $p_T^H$ | 45.0 ± 1.1 | 46.2 ± 0.8 | 47.7 ± 0.8 | 50.3 ± 0.7 |
| $|y^H|$ | 57.9 ± 0.8 | 59.3 ± 0.6 | 34.8 ± 0.8 |
| $p_H^H$ | 44.4 ± 1.0 | 45.2 ± 0.9 | 47.6 ± 0.7 | 52.9 ± 0.7 |

TABLE II. Fiducial acceptance factors in percent for the $H \rightarrow ZZ^* \rightarrow 4\ell$ measurement with associated uncertainties. The binning is the same as in Fig. 4.

Fiducial acceptance

For each bin $i$, the acceptance factor for each decay channel is defined as

$$\alpha_i = \frac{\sigma_{\text{fid},i}}{\sigma_{\text{incl},i}}, \quad (2)$$

The fiducial acceptances for both channels and all measured distributions are presented in Fig. 4 and Tables II and III. They are based on Eq. 2 and derived using the Higgs MC samples described in the text. For $p_T^H$ and $|y^H|$, $\alpha_i$ is the probability for an event to pass the fiducial requirements. The acceptance is lower for $H \rightarrow ZZ^* \rightarrow 4\ell$ than for $H \rightarrow \gamma\gamma$ since it is less likely for four decay products to fulfill the fiducial requirements. For the jet variables $p_T^H$ and $N_{\text{jets}}$, an additional migration effect enters due to overlap between jets and the Higgs boson decay products, which affects the fiducial regions differently than the total phase space, where no Higgs boson decay products need to be considered. The fiducial acceptance falls off steeply as the Higgs boson rapidity increases, as both fiducial definitions include pseudo-rapidity requirements on the Higgs boson decay products.

Additional figures

Figure 5 presents the measured jet multiplicity distributions. The lower two subfigures include the individual $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements. Figure 6 presents the same six distributions as shown in Fig. 3, but with the individual channel measurements overlaid.

| Bin | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-----|----|----|----|----|----|----|----|----|
| Incl. | 60.4 ± 1.2 |
| $N_{\text{jets}}$ | 62.1 ± 1.4 | 59.1 ± 0.7 | 58.4 ± 1.4 | 55.9 ± 3.5 |
| $p_T^H$ | 62.1 ± 1.4 | 58.9 ± 0.9 | 57.4 ± 0.9 | 57.2 ± 0.9 | 58.3 ± 1.6 |
| $|y^H|$ | 71.5 ± 1.2 | 71.7 ± 1.2 | 71.5 ± 1.2 | 71.5 ± 1.2 | 67.7 ± 1.3 | 37.7 ± 0.5 |
| $p_H^H$ | 62.2 ± 1.1 | 62.2 ± 1.2 | 60.6 ± 1.3 | 59.3 ± 1.1 | 57.9 ± 1.2 | 57.5 ± 0.9 | 56.7 ± 1.1 | 58.6 ± 1.0 |

TABLE III. Fiducial acceptance factors in percent for the $H \rightarrow \gamma\gamma$ measurement with associated uncertainties. The binning is the same as in Fig. 4.
FIG. 4. Fiducial acceptances mapping each measured bin of the $p_T^H$, $|y^H|$, $N_{jets}$, and $p_T^{j1}$ distributions from the inclusive phase space to the respective fiducial regions. The factors are derived using POWHEG for ggF and VBF production and PYTHIA8 for VH, $t\bar{t}H$, and $bbH$. The width of the band indicates the uncertainty from five sources: missing higher order corrections, PDF variations, changing the Higgs boson mass and the production mode composition, and variations of the hadronization/underlying event tunes (see main text for further details). The PDF uncertainty is the largest individual contribution to the total uncertainty.
FIG. 5. Absolute and fractional cross sections in bins of jet multiplicity for inclusive Higgs boson production at √s = 8 TeV measured by combining the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{*} \rightarrow 4l$ analyses using 20.3 fb$^{-1}$ of pp collisions. The top plot shows the cross section in inclusive jet bins, while the other plots have exclusive jet binning (except for the ≥ 3 jets bin). In the lower two plots, the cross sections of the two channels are shown individually, defined by the fiducial cross sections corrected for acceptance and branching ratio (see Eq. 1). These cross sections have partially correlated systematic uncertainties that are considered in the combined measurement.
FIG. 6. Differential cross sections (left) and shapes (right) of the Higgs boson transverse momentum (top), absolute rapidity (middle) and leading jet transverse momentum (bottom) of inclusive Higgs boson production at $\sqrt{s} = 8$ TeV measured in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ final states using 20.3 fb$^{-1}$ of pp collisions. Both the combined measurements as well as the individual channels are shown.
Result tables

Tables IV–VII present the measured differential cross sections and Tables VIII–XI report the corresponding shape measurements.

### TABLE IV. Measured cross section in bins of $p_T$. The first uncertainty is statistical, the second is systematic.

| Bins [GeV] | $d\sigma/dp_T^H$ [pb/GeV] |
|------------|----------------------------|
| 0–20       | 0.20 ± 0.15 ± 0.01        |
| 20–30      | 0.88 ± 0.27 ± 0.04        |
| 30–40      | 0.46 ± 0.23 ± 0.02        |
| 40–50      | 0.56 ± 0.20 ± 0.03        |
| 50–60      | 0.28 ± 0.18 ± 0.01        |
| 60–80      | 0.18 ± 0.09 ± 0.009       |
| 80–100     | 0.136 ± 0.067 ± 0.006     |
| 100–200    | 0.0214 ± 0.0091 ± 0.0010  |

### TABLE V. Measured cross section in bins of $|y_H|$. The first uncertainty is statistical, the second is systematic.

| Bins | $d\sigma/d|y_H|$ [pb] |
|------|------------------|
| 0.0–0.3 | 15.3 ± 5.4 ± 0.7 |
| 0.3–0.6 | 14.5 ± 5.6 ± 0.6 |
| 0.6–0.9 | 10.8 ± 5.3 ± 0.5 |
| 0.9–1.2 | 22.3 ± 6.7 ± 1.0 |
| 1.2–1.6 | 18.8 ± 7.9 ± 0.9 |
| 1.6–2.4 | 9.4 ± 5.3 ± 0.4 |

### TABLE VI. Measured cross section in bins of $N_{jets}$. The first uncertainty is statistical, the second is systematic.

| Bins | $d\sigma/dN_{jets}$ [pb] |
|------|--------------------------|
| 0    | 15.3 ± 4.3 ± 0.8        |
| 1    | 11.9 ± 2.7 ± 0.6        |
| 2    | 4.1 ± 1.5 ± 0.3         |
| ≥ 3  | 2.57 ± 0.97 ± 0.32      |

### TABLE VII. Measured cross section in bins of $p_T^{j1}$. The first uncertainty is statistical, the second is systematic.

| Bins [GeV] | $d\sigma/dp_T^{j1}$ [pb/GeV] |
|------------|-------------------------------|
| 0–30       | 0.51 ± 0.14 ± 0.03            |
| 30–50      | 0.36 ± 0.11 ± 0.02            |
| 50–70      | 0.156 ± 0.069 ± 0.009         |
| 70–100     | 0.111 ± 0.050 ± 0.006         |
| 100–140    | 0.055 ± 0.026 ± 0.004         |

### TABLE VIII. Measured fractions in bins of $p_T^H$. The first uncertainty is statistical, the second is systematic.

| Bins [GeV] | $1/\sigma d\sigma/dp_T^H$ [1/GeV] |
|------------|----------------------------------|
| 0–20       | 0.0055 ± 0.0036 ± 0.0006         |
| 20–30      | 0.0258 ± 0.0077 ± 0.0003         |
| 30–40      | 0.0133 ± 0.0068 ± 0.0002         |
| 40–50      | 0.0166 ± 0.0060 ± 0.0002         |
| 50–60      | 0.0079 ± 0.0053 ± 0.0001         |
| 60–80      | 0.0055 ± 0.0027 ± 0.0001         |
| 80–100     | 0.0041 ± 0.0021 ± 0.0000         |
| 100–200    | 0.00060 ± 0.00026 ± 0.00001     |

### TABLE IX. Measured fractions in bins of $|y_H|$. The first uncertainty is statistical, the second is systematic.

| Bins | $1/\sigma d\sigma/d|y_H|$ |
|------|--------------------------|
| 0.0–0.3 | 0.46 ± 0.16 ± 0.00       |
| 0.3–0.6 | 0.43 ± 0.16 ± 0.00       |
| 0.6–0.9 | 0.32 ± 0.15 ± 0.00       |
| 0.9–1.2 | 0.66 ± 0.19 ± 0.00       |
| 1.2–1.6 | 0.57 ± 0.23 ± 0.00       |
| 1.6–2.4 | 0.27 ± 0.13 ± 0.00       |

### TABLE X. Measured fractions in bins of $N_{jets}$. The first uncertainty is statistical, the second is systematic.

| Bins | $1/\sigma d\sigma/dN_{jets}$ |
|------|-----------------------------|
| 0    | 0.447 ± 0.078 ± 0.010       |
| 1    | 0.353 ± 0.071 ± 0.005       |
| 2    | 0.123 ± 0.043 ± 0.003       |
| ≥ 3  | 0.077 ± 0.029 ± 0.007       |

### TABLE XI. Measured fractions in bins of $p_T^{j1}$. The first uncertainty is statistical, the second is systematic.

| Bins [GeV] | $1/\sigma d\sigma/dp_T^{j1}$ [1/GeV] |
|------------|----------------------------------|
| 0–30       | 0.0162 ± 0.0027 ± 0.0003         |
| 30–50      | 0.0117 ± 0.0032 ± 0.0002         |
| 50–70      | 0.0051 ± 0.0022 ± 0.0001         |
| 70–100     | 0.0035 ± 0.0016 ± 0.0001         |
| 100–140    | 0.00180 ± 0.00088 ± 0.00007     |
Uncertainty correlation tables

Tables XII–XV contain the correlation matrices of the differential cross section measurements and Tables XVI–XIX those of the differential shape measurements.

### TABLE XII. Correlation matrix for the total uncertainty of the differential cross-section measurement in bins of $p_T^H$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | 0.01  | 0.01  | 0.01  | 0.02  | 0.01  | 0.01  | 1.00  |
| Bin 2 | 0.01  | 1.00  | -0.13 | -0.10 | 0.01  | 0.01  | 0.01  | 0.01  |
| Bin 3 | 0.01  | -0.13 | 1.00  | -0.08 | 0.01  | 0.01  | 0.01  | 0.01  |
| Bin 4 | 0.01  | -0.10 | -0.08 | 1.00  | 0.01  | 0.01  | 0.01  | 0.01  |
| Bin 5 | 0.00  | 0.01  | 0.01  | 0.01  | 1.00  | -0.16 | -0.11 | 0.01  |
| Bin 6 | 0.01  | 0.01  | 0.01  | 0.01  | -0.16 | 1.00  | -0.11 | 0.01  |
| Bin 7 | 0.01  | 0.01  | 0.01  | 0.01  | -0.11 | -0.11 | 1.00  | 0.01  |
| Bin 8 | 0.01  | 0.02  | 0.01  | 0.01  | 0.01  | 0.01  | 0.01  | 1.00  |

### TABLE XIII. Correlation matrix for the total uncertainty of the differential cross-section measurement in bins of $|y^H|$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 |
|-------|-------|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | 0.01  | 0.01  | 0.02  | 0.01  | 0.01  |
| Bin 2 | 0.01  | 1.00  | 0.01  | 0.02  | 0.01  | 0.01  |
| Bin 3 | 0.01  | 0.01  | 1.00  | 0.01  | 0.01  | 0.01  |
| Bin 4 | 0.02  | 0.02  | 0.01  | 1.00  | 0.02  | 0.01  |
| Bin 5 | 0.01  | 0.01  | 0.01  | 0.02  | 1.00  | -0.28 |
| Bin 6 | 0.01  | 0.01  | 0.01  | 0.01  | -0.28 | 1.00  |

### TABLE XIV. Correlation matrix for the total uncertainty of the differential cross-section measurement in bins of $N_{jets}$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 |
|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | 0.03  | -0.02 | 0.02  |
| Bin 2 | 0.03  | 1.00  | -0.04 | 0.05  |
| Bin 3 | -0.02 | -0.04 | 1.00  | -0.04 |
| Bin 4 | 0.02  | 0.05  | -0.04 | 1.00  |

### TABLE XV. Correlation matrix for the total uncertainty of the differential cross-section measurement in bins of $p_T^{H,1}$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 |
|-------|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | 0.03  | 0.02  | 0.02  | 0.01  |
| Bin 2 | 0.03  | 1.00  | 0.02  | 0.02  | 0.02  |
| Bin 3 | 0.02  | 0.02  | 1.00  | 0.02  | 0.01  |
| Bin 4 | 0.02  | 0.02  | 0.02  | 1.00  | -0.19 |
| Bin 5 | 0.01  | 0.02  | 0.01  | -0.19 | 1.00  |

### TABLE XVI. Correlation matrix for the total uncertainty of the differential shape measurement in bins of $p_T^{H,1}$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | -0.28 | -0.22 | -0.18 | -0.16 | -0.17 | -0.11 | -0.12 |
| Bin 2 | -0.28 | 1.00  | -0.34 | -0.28 | -0.11 | -0.11 | -0.08 | -0.08 |
| Bin 3 | -0.22 | -0.34 | 1.00  | -0.21 | -0.08 | -0.09 | -0.06 | -0.06 |
| Bin 4 | -0.18 | -0.28 | -0.21 | 1.00  | -0.07 | -0.07 | -0.05 | -0.05 |
| Bin 5 | -0.16 | -0.11 | -0.08 | -0.07 | 1.00  | -0.26 | -0.18 | -0.04 |
| Bin 6 | -0.17 | -0.11 | -0.09 | -0.07 | -0.26 | 1.00  | -0.18 | -0.05 |
| Bin 7 | -0.11 | -0.08 | -0.06 | -0.05 | -0.18 | -0.18 | 1.00  | -0.03 |
| Bin 8 | -0.12 | -0.08 | -0.06 | -0.05 | -0.04 | -0.05 | -0.03 | 1.00  |

### TABLE XVII. Correlation matrix for the total uncertainty of the differential shape measurement in bins of $|y^{H,1}|$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 |
|-------|-------|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | -0.09 | -0.09 | -0.11 | -0.10 | -0.21 |
| Bin 2 | -0.09 | 1.00  | -0.09 | -0.12 | -0.11 | -0.22 |
| Bin 3 | -0.09 | -0.09 | 1.00  | -0.11 | -0.10 | -0.21 |
| Bin 4 | -0.11 | -0.12 | -0.11 | 1.00  | -0.13 | -0.27 |
| Bin 5 | -0.10 | -0.11 | -0.10 | -0.13 | 1.00  | -0.66 |
| Bin 6 | -0.21 | -0.22 | -0.21 | -0.27 | -0.66 | 1.00  |

### TABLE XVIII. Correlation matrix for the total uncertainty of the differential shape measurement in bins of $N_{jets}$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 |
|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | -0.77 | -0.37 | -0.26 |
| Bin 2 | -0.77 | 1.00  | -0.16 | -0.11 |
| Bin 3 | -0.37 | -0.16 | 1.00  | -0.05 |
| Bin 4 | -0.26 | -0.11 | -0.05 | 1.00  |

### TABLE XIX. Correlation matrix for the total uncertainty of the differential shape measurement in bins of $p_T^{H,1}$.

|       | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 |
|-------|-------|-------|-------|-------|-------|
| Bin 1 | 1.00  | -0.63 | -0.38 | -0.36 | -0.20 |
| Bin 2 | -0.63 | 1.00  | -0.12 | -0.11 | -0.06 |
| Bin 3 | -0.38 | -0.12 | 1.00  | -0.07 | -0.04 |
| Bin 4 | -0.36 | -0.11 | -0.07 | 1.00  | -0.28 |
| Bin 5 | -0.20 | -0.06 | -0.04 | -0.28 | 1.00  |
Gluon fusion cross section

Figure 7 shows the measurement of the Higgs boson production cross section compared to a range of theory predictions, including LHC-XS, the result used by the ATLAS and CMS collaboration in Run 1, for which the ggF part is accurate to NNLO+NNLL in QCD [10], as well as ggF cross section calculations that attempt to go beyond NNLO, including the recently completed full N^3LO prediction. Details about the various predictions are presented in Table XX, and the central values and a breakdown of the uncertainties of the calculations as well as the measurement are reported in Table XXI.

![Figure 7. Measured total cross section of Higgs boson production compared to different theoretical calculations.](image)

TABLE XX. 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 \( m_H = 125.4 \text{ GeV} \) and \( \sqrt{s} = 8 \text{ TeV} \).

| Name                      | \( \sigma_{gg \to H} \) [pb] |
|---------------------------|-------------------------------|
| Data–XH                   | 30.0 ±5.3 (stat) ±1.6 (sys)   |
| LHC-XS                    | 19.15 ±1.38 (scale) ±1.44 (pdf) |
| ADDFGHLM                  | 20.55 ±0.04 (scale) ±1.60 (pdf) |
| ABNY                      | 19.54 ±0.55 (scale) ±1.47 (pdf) ±0.78 (appr.) |
| STWZ                      | 20.41 ±1.18 (scale) ±1.53 (pdf) |
| dFMMV                     | 21.12 ±0.29 (scale) ±1.58 (pdf) ±0.56 (appr.) |
| BBFMR                     | 21.32 ±0.45 (scale) ±1.60 (pdf) ±1.39 (appr.) |

\( ^{a} \) Non-ggF cross section
\( \sigma_{XH} = 3.01^{+0.05}_{-0.06} \text{ (scale) } \pm 0.09 \text{ (pdf) \, pb, subtracted from the measured inclusive cross section: } 33.0 ±5.3 \text{ (stat) ±1.6 \, (sys) \, pb.} \)

For the predictions, uncertainties from renormalization, factorization and, where appropriate, resummation scale variations as well as uncertainties due to approximation or missing terms beyond NNLO are pro-

TABLE XXI. Central values and uncertainties for the different ggF predictions and the data.

| Name                      | \( \sigma_{gg \to H} \) [pb] |
|---------------------------|-------------------------------|
| Data–XH                   | 30.0 ±5.3 (stat) ±1.6 (sys)   |
| LHC-XS                    | 19.15 ±1.38 (scale) ±1.44 (pdf) |
| ADDFGHLM                  | 20.55 ±0.04 (scale) ±1.60 (pdf) |
| ABNY                      | 19.54 ±0.55 (scale) ±1.47 (pdf) ±0.78 (appr.) |
| STWZ                      | 20.41 ±1.18 (scale) ±1.53 (pdf) |
| dFMMV                     | 21.12 ±0.29 (scale) ±1.58 (pdf) ±0.56 (appr.) |
| BBFMR                     | 21.32 ±0.45 (scale) ±1.60 (pdf) ±1.39 (appr.) |

\( ^{a} \) Non-ggF cross section
\( \sigma_{XH} = 3.01^{+0.05}_{-0.06} \text{ (scale) } \pm 0.09 \text{ (pdf) \, pb, subtracted from the measured inclusive cross section: } 33.0 ±5.3 \text{ (stat) ±1.6 \, (sys) \, pb.} \)

\( ^{a} \) Considers b- (and c-) quark masses in the \( gg \to H \) loop
\( ^{b} \) Includes electroweak corrections
\( ^{c} \) Based on MSTW2008nlo [18] (\( \alpha_s \) from PDF set)
\( ^{d} \) Uses \( \pi \) resummed \( gg \to H \) form factor
\( ^{e} \) In the counting of Ref. [47], the result has N^3LL accuracy

For the predictions, uncertainties from renormalization, factorization and, where appropriate, resummation scale variations as well as uncertainties due to approximation or missing terms beyond NNLO are pro-

The calculations take different approaches to approximately evaluate the ggF cross section beyond NNLO. Therefore the preferred scale for each calculation differs, and the choice of scale and the precise scale variations applied was left to the authors of the calculations. The LHC-XS, ABNY, STWZ, and BBFMR predictions use a central scale of \( \mu = m_H \) as their overall scale, while dFMMV and ADDFGHLM use \( \mu_0 = m_H/2 \).
Compatibility between predictions and data

Tables XXII and XXIII present compatibility tests between the differential predictions and the measured cross sections and shapes respectively. The theory uncertainties are assumed to be Gaussian and to be fully correlated between bins.

**TABLE XXII.** \( p \)-values quantifying the compatibility between predictions and the data for the differential cross sections. The theory uncertainties are assumed to be Gaussian and to be fully correlated between bins.

|          | \( p^H_T \) | \( |y^H| \) | \( p^J_T \) |
|----------|-------------|-------------|-------------|
| HRes     | 2\% 14\%    | -           | -           |
| STWZ     | -           | - 26\%     | -           |
| JetVHeto | -           | - 24\%     | -           |

**TABLE XXIII.** \( p \)-values quantifying the compatibility between predictions and the data for the differential shapes. The theory uncertainties are assumed to be Gaussian distributed and fully correlated between bins.

|          | \( p^H_T \) | \( |y^H| \) | \( p^J_T \) |
|----------|-------------|-------------|-------------|
| HRes     | 15\% 64\%  | -           | -           |
| NNLOPS   | 10\% 64\%  | 64\%        | -           |
| SHERPA 2.1.1 | 22\% 63\% | 88\%        | -           |
| MG5_aMC@NLO | 8\% 60\% | 88\%        | -           |

Non-perturbative correction factors

Table XXIV presents multiplicative non-perturbative correction factors and associated uncertainties that are applied to correct analytical parton-level predictions presented in this Letter to particle level. These corrections account for hadronization and multiple parton interactions, and are derived based on a number of underlying event and showering tunes applied to the Higgs boson production MC samples used in the analysis.

**TABLE XXIV.** Non-perturbative factors in percent with systematic uncertainties, accounting for the impact of hadronization and underlying event.

| Bin | \( p^H_T \)          | \( |y^H| \) | \( N_{jets, \text{excl}} \) excl | \( N_{jets, \text{incl}} \) incl | \( p^J_T \)          |
|-----|----------------------|-------------|----------------------------------|----------------------------------|----------------------|
| 1   | 99.5 ± 1.0           | 100.5 ± 1.3 | 100.6 ± 2.1                      | 100.2 ± 1.4                     | 100.0 ± 1.0          |
| 2   | 99.9 ± 1.1           | 100.1 ± 0.7 | 99.8 ± 0.7                       | 100.1 ± 0.8                     | 100.0 ± 0.7          |
| 3   | 99.9 ± 1.1           | 100.1 ± 0.8 | 99.8 ± 0.7                       | 100.0 ± 0.7                     | 99.8 ± 0.6           |
| 4   | 99.9 ± 1.1           | 100.1 ± 0.8 | 99.8 ± 0.7                       | 100.0 ± 0.7                     | 99.8 ± 0.6           |
| 5   | 99.9 ± 1.1           | 100.1 ± 0.8 | 99.8 ± 0.7                       | 100.0 ± 0.7                     | 99.8 ± 0.6           |
| 6   | 99.9 ± 1.1           | 100.1 ± 0.8 | 99.8 ± 0.7                       | 100.0 ± 0.7                     | 99.8 ± 0.6           |
| 7   | 99.9 ± 1.1           | 100.1 ± 0.8 | 99.8 ± 0.7                       | 100.0 ± 0.7                     | 99.8 ± 0.6           |
| 8   | 99.9 ± 1.1           | 100.1 ± 0.8 | 99.8 ± 0.7                       | 100.0 ± 0.7                     | 99.8 ± 0.6           |