Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the H→$\gamma\gamma$ and H→ZZ*\$→\$4 Decay Channels at $\sqrt{s}$=8 TeV with the ATLAS Detector (Postprint)

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Abstract

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Full Text

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The ATLAS Collaboration

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I. Introduction

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 → $\gamma\gamma$ and H → ZZ* → 4 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.

II. Observables

Distributions of the differential pp → 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^{j1}. 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^{j1} 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 $\bar{t}t$H). Jets produced in VBF, VH and $\bar{t}t$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.

III. Methodology

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 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 ± 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_4 mass window of 118 to 129 GeV for the H $\rightarrow$ ZZ* $\rightarrow$ 4 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 ($\bar{t}$tH) and b-quarks ($\bar{b}$bH). 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 . 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 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 ^{2} compatibility tests are in the range 56-99%.

IV. Statistical and Systematic Uncertainties

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 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 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 $\mathrm{H} \rightarrow \gamma\gamma$ and $\mathrm{H} \rightarrow \mathrm{ZZ}^* \rightarrow 4$ 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 [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 HRes 2.2 calculation [20, 21]. The envelope of the maximum deviation of the combined scale variations and the 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 $\bar{t}$tH 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_{jets} and p_T^{j1}, 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.

V. Results

The total $\mathrm{pp} \rightarrow \mathrm{H}$ cross section is determined in the $\mathrm{H} \rightarrow \gamma\gamma$ channel to be 31.4 ± 7.2 (stat) ± 1.6 (sys) pb and in the $\mathrm{H} \rightarrow \mathrm{ZZ}^* \rightarrow 4$ channel to be 35.0 ± 8.4 (stat) ± 1.8 (sys) pb. Combining the analyses yields $\sigma(\mathrm{pp} \rightarrow \mathrm{H}) = 33.0 \pm 5.3$ (stat) ± 1.6 (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, $\bar{t}$tH, $\bar{b}$bH) 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%/-6.9% is assigned to the LHC-XS prediction, derived following the recommendations in Ref. [16]. This uncertainty is increased to +7.8%/-7.0% 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, 58], 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 [52] with a radius parameter R = 0.4 [53], and are required to have p_T > 30 GeV and |y| < 4.4. Simulated particle-level jets are built from all particles with $c\tau > 10$ 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 [54] MC event generators with different tunes [55-57]. The total cross sections from the ML merged predictions are lower than from fully inclusive NNLO+NNLL calculations. However, for N_{jets} ≥ 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, $\bar{t}tH$, and $\bar{b}bH$, 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 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^{j1} are shown in Fig. 3 (left). The p_T^H and |y_H| distributions are compared to the HRes calculation and the p_T^{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 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 ± 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.

VI. Conclusion

In conclusion, this Letter presents the first measurements of total and differential cross sections and shapes for inclusive pp → H production. The measurements were performed in the $\mathrm{H} \rightarrow \gamma\gamma$ and $\mathrm{H} \rightarrow \mathrm{ZZ}^* \rightarrow 4$ 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. 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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Supplemental Material

Fiducial Acceptance The fiducial cross section σ_i in a given bin i can be expressed as:

σ_i = (n_i) / (L × B × α_i × c_i)

where n_i is the measured Higgs boson signal yield, L is the integrated luminosity (20.3 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 , = e or), *αi 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 , the signal yield is defined as the number of observed events n*{data} in a window around the Higgs boson mass peak minus the background estimate: n_i = n_{data},i - n_{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.

The fiducial acceptances for both channels and all measured distributions are presented in Fig. 4 and Tables II and III. They are based on the equation above and derived using the MC samples described in the text. For p_T^H and |y_H|, *αi is the probability for an event to pass the fiducial requirements. The acceptance is lower for H $\rightarrow$ ZZ* $\rightarrow$ 4 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^{j1} and N*{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 measurements. Figure 6 presents the same six distributions as shown in Fig. 3, but with the individual channel measurements overlaid.

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^H. The first uncertainty is statistical, the second is systematic.

Bins [GeV]	dσ/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	0.188 ± 0.090 ± 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	dσ/d
0.0–0.5	15.3 ± 5.4 ± 0.7
0.5–1.0	14.5 ± 5.6 ± 0.6
1.0–1.5	10.8 ± 5.3 ± 0.5
1.5–2.0	22.3 ± 6.7 ± 1.0
2.0–2.5	18.8 ± 7.9 ± 0.9
2.5–3.0	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	dσ/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]	dσ/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/σ) dσ/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/σ) dσ/d
0.0–0.5	0.46 ± 0.16 ± 0.00
0.5–1.0	0.43 ± 0.16 ± 0.00
1.0–1.5	0.32 ± 0.15 ± 0.00
1.5–2.0	0.66 ± 0.19 ± 0.00
2.0–2.5	0.57 ± 0.23 ± 0.00
2.5–3.0	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/σ) dσ/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/σ) dσ/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	2	3	4	5	6	7	8
1	1.00	-0.13	-0.10	-0.08	0.01	-0.16	0.01	-0.11
2	-0.13	1.00	-0.11	0.01	-0.13	0.01	-0.10	-0.08
3	-0.10	-0.11	1.00	-0.11	0.01	-0.13	0.01	-0.10
4	-0.08	0.01	-0.11	1.00	-0.11	0.01	-0.13	0.01
5	0.01	-0.13	0.01	-0.11	1.00	-0.11	0.01	-0.13
6	-0.16	0.01	-0.13	0.01	-0.11	1.00	-0.11	0.01
7	0.01	-0.10	0.01	-0.13	0.01	-0.11	1.00	-0.11
8	-0.11	-0.08	-0.10	0.01	-0.13	0.01	-0.11	1.00

TABLE XIII. Correlation matrix for the total uncertainty of the differential cross-section measurement in bins of |y_H|.

Bin	1	2	3	4	5	6
1	1.00	-0.28	0.01	-0.28	0.01	0.01
2	-0.28	1.00	-0.28	0.01	-0.28	0.01
3	0.01	-0.28	1.00	-0.28	0.01	-0.28
4	-0.28	0.01	-0.28	1.00	-0.28	0.01
5	0.01	-0.28	0.01	-0.28	1.00	-0.28
6	0.01	0.01	-0.28	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	2	3	4
1	1.00	0.03	-0.02	0.05
2	0.03	1.00	-0.04	-0.04
3	-0.02	-0.04	1.00	-0.04
4	0.05	-0.04	-0.04	1.00

TABLE XV. Correlation matrix for the total uncertainty of the differential cross-section measurement in bins of p_T^{j1}.

Bin	1	2	3	4	5
1	1.00	-0.19	0.01	-0.19	0.01
2	-0.19	1.00	-0.19	0.01	-0.19
3	0.01	-0.19	1.00	-0.19	0.01
4	-0.19	0.01	-0.19	1.00	-0.19
5	0.01	-0.19	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.

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

Bin	1	2	3	4	5	6
1	1.00	-0.09	-0.09	-0.11	-0.10	-0.21
2	-0.09	1.00	-0.09	-0.12	-0.11	-0.22
3	-0.09	-0.09	1.00	-0.11	-0.10	-0.21
4	-0.11	-0.12	-0.11	1.00	-0.13	-0.27
5	-0.10	-0.11	-0.10	-0.13	1.00	-0.66
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	2	3	4
1	1.00	-0.77	-0.37	-0.26
2	-0.77	1.00	-0.16	-0.11
3	-0.37	-0.16	1.00	-0.05
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^{j1}.

Bin	1	2	3	4	5
1	1.00	-0.63	-0.38	-0.36	-0.20
2	-0.63	1.00	-0.12	-0.11	-0.06
3	-0.38	-0.12	1.00	-0.07	-0.04
4	-0.36	-0.11	-0.07	1.00	-0.28
5	-0.20	-0.06	-0.04	-0.28	1.00

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.

Prediction	p_T^H		y_H
JetVHeto	2%	14%	-

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

Prediction	p_T^H		y_H
NNLOPS	15%	64%	10%
SHERPA 2.1.1	22%	63%	64%
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.

Observable	Correction Factor
p_T^H	99.5 ± 1.0
	y_H
N_{jets}, incl	99.9 ± 1.1
N_{jets}, excl	99.9 ± 1.4
p_T^{j1}	100.2 ± 1.4
N_{jets}, incl (0 jets)	99.9 ± 1.1
N_{jets}, incl (1 jet)	100.4 ± 1.5
N_{jets}, incl (2 jets)	100.0 ± 1.0
N_{jets}, excl (0 jets)	100.6 ± 2.1
N_{jets}, excl (1 jet)	99.8 ± 2.9
N_{jets}, excl (2 jets)	99.3 ± 5.0
N_{jets}, excl ($ $3 jets)	96.7 ± 6.7
p_T^{j1} (0-30 GeV)	100.6 ± 2.1
p_T^{j1} (30-50 GeV)	99.6 ± 2.6
p_T^{j1} (50-70 GeV)	99.2 ± 2.9
p_T^{j1} (70-100 GeV)	99.1 ± 3.2
p_T^{j1} (100-140 GeV)	98.7 ± 3.6

Note: Figure translations are in progress. See original paper for figures.

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