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# Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration [*]

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## ABSTRACT

Measurements of fiducial and differential cross sections of Higgs boson production in the $H \to ZZ^* \to 4\ell$ decay channel are presented. The cross sections are determined within a fiducial phase space and corrected for detection efficiency and resolution effects. They are based on 20.3 fb$^{-1}$ of $pp$ collision data, produced at $\sqrt{s} = 8$ TeV centre-of-mass energy at the LHC and recorded by the ATLAS detector. The differential measurements are performed in bins of transverse momentum and rapidity of the four-lepton system, the invariant mass of the subleading lepton pair and the decay angle of the leading lepton pair with respect to the beam line in the four-lepton rest frame, as well as the number of jets and the transverse momentum of the leading jet. The measured cross sections are compared to selected theoretical calculations of the Standard Model expectations. No significant deviation from any of the tested predictions is found.

## 1. Introduction

In 2012 the ATLAS and CMS Collaborations announced the discovery of a new particle [1,2] in the search for the Standard Model (SM) Higgs boson [3–8] at the CERN Large Hadron Collider (LHC) [9]. Since this discovery, the particle's mass $m_H$ was measured by the ATLAS and CMS Collaborations [10–12]. The result of the ATLAS measurement based on 25 fb$^{-1}$ of data collected at centre-of-mass energies of 7 TeV and 8 TeV is $125.36 \pm 0.41$ GeV. Tests of the couplings and spin/CP quantum numbers have been reported by both collaborations [11,13,14] and show agreement with the predicted scalar nature of the SM Higgs boson.

In this Letter, measurements of fiducial and differential production cross sections for the $H \to ZZ^* \to 4\ell$ decay channel are reported and compared to selected theoretical calculations. The event selection and the background determination are the same as in Ref. [15], where a detailed description is given. For this measurement, an integrated luminosity of 20.3 fb$^{-1}$ of $pp$ collisions is analyzed. The data were collected at the LHC at a centre-of-mass energy of $\sqrt{s} = 8$ TeV and recorded with the ATLAS detector [16].

The ATLAS detector covers the pseudorapidity range $|\eta| < 4.9$ and the full azimuthal angle $\phi$.[1] It consists of an inner tracking detector covering the pseudorapidity range $|\eta| < 2.5$ surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer with large superconducting toroidal magnets.

Fiducial cross sections are quoted to minimize the model dependence of the acceptance corrections related to the extrapolation to phase-space regions not covered by the detector. The measured fiducial cross sections are corrected for detector effects to be directly compared to theoretical calculations.

The differential measurements are performed in several observables related to the Higgs boson production and decay. These include the transverse momentum $p_{\mathrm{T},H}$ and rapidity $|y_H|$ of the Higgs boson, the invariant mass of the subleading lepton pair $m_{34}$ (the leading and subleading lepton pairs are defined in Section 3) and the magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame with respect to the beam axis $|\cos\theta^*|$. The number of jets $n_{\mathrm{jets}}$ and the transverse momentum of the leading jet $p_{\mathrm{T,jet}}$ are also included. The distribution of the $p_{\mathrm{T},H}$ observable is sensitive to the Higgs boson production mechanisms as well as spin/CP quantum numbers, and can be used to test perturbative QCD predictions. This distribution

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[*] *E-mail address:* atlas.publications@cern.ch.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) at the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln[\tan(\theta/2)]$.

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has been studied extensively and precise predictions exist (see e.g. Refs. [17–21]), including the effect of finite quark masses. The distribution of the $|y_H|$ observable can be used to probe the parton distribution functions (PDFs) of the proton. The distributions of the decay variables $m_{34}$ and $|\cos\theta^*|$ are sensitive to the Lagrangian structure of Higgs boson interactions, e.g. spin/CP quantum numbers and higher-dimensional operators. The jet multiplicity and transverse momentum distributions are sensitive to QCD radiation effects and to the relative rates of Higgs boson production modes. The distribution of the transverse momentum of the leading jet probes quark and gluon radiation.

## 2. Theoretical predictions and simulated samples

The Higgs boson production cross sections and decay branching fractions as well as their uncertainties are taken from Refs. [21,22]. The cross sections for the gluon-fusion (ggF) process have been calculated to next-to-leading order (NLO) [23–25], and next-to-next-to-leading order (NNLO) [26–28] in QCD with additional next-to-next-to-leading logarithm (NNLL) soft-gluon resummation [29]. The cross section values have been modified to include NLO electroweak (EW) radiative corrections, assuming factorization between QCD and EW effects [30–34]. The cross sections for the vector-boson fusion (VBF) processes are calculated with full NLO QCD and EW corrections [35–37], and approximate NNLO QCD corrections are included [38]. The cross sections for the associated $WH/ZH$ production processes ($VH$) are calculated at NLO [39] and at NNLO [40] in QCD, and NLO EW radiative corrections [41] are applied. The cross sections for associated Higgs boson production with a $t\bar{t}$ pair ($t\bar{t}H$) are calculated at NLO in QCD [42–45].

The Higgs boson branching fractions for decays to four-lepton final states are provided by Prophecy4f [46,47], which implements the complete NLO QCD + EW corrections and interference effects between identical final-state fermions.

The $H \rightarrow ZZ^* \rightarrow 4\ell$ signal is modelled using the Powheg Monte Carlo (MC) event generator [48–52], which calculates separately the ggF and VBF production mechanisms with matrix elements up to NLO. The description of the Higgs boson transverse momentum spectrum in the ggF process is adjusted to follow the calculation in Refs. [19,20], which includes QCD corrections up to NLO and QCD soft-gluon resummations up to NNLL, as well as finite quark masses [53]. Powheg is interfaced to Pythia8 [54] for showering and hadronization, which in turn is interfaced to Photos [55,56] to model photon radiation in the final state. Pythia8 is used to simulate $VH$ and $t\bar{t}H$ production. The response of the ATLAS detector is modelled in a simulation [57] based on GEANT4 [58].

The measured fiducial cross-section distributions are compared to three ggF theoretical calculations: Powheg without the adjustments to the $p_{\mathrm{T},H}$ spectrum described above, Powheg interfaced to Minlo (Multi-scale improved NLO) [59] and HRes2 (v.2.2) [19,20]. Powheg with Minlo provides predictions for jet-related variables at NLO for Higgs boson production in association with one jet. The HRes2 program computes fixed-order cross sections for ggF SM Higgs boson production up to NNLO. All-order resummation of soft-gluon effects at small transverse momenta is consistently included up to NNLL, using dynamic factorization and resummation scales. The program implements top- and bottom-quark mass dependence up to NLL + NLO. At NNLL + NNLO level only the top-quark contribution is considered. HRes2 does not perform showering and QED final-state radiation effects are not included.

The contributions from the other production modes are added to the ggF predictions. At a centre-of-mass energy of 8 TeV and for a Higgs boson mass of 125.4 GeV, their relative contributions to the total cross section are 87.3% (ggF), 7.1% (VBF), 3.1% ($WH$), 1.9% ($ZH$) and 0.6% ($t\bar{t}H$), respectively.

All theoretical predictions are computed for a SM Higgs boson with mass 125.4 GeV. They are normalized to the most precise SM inclusive cross-section predictions currently available [60], corrected for the fiducial acceptance derived from the simulation.

The $ZZ$, $WZ$, $t\bar{t}$ and $Z$ + jets background events are modelled using the simulated samples and cross sections described in Ref. [15].

## 3. Event selection

The detector level physics object definitions of muons, electrons, and jets, and the event selection applied in this analysis are the same as in Ref. [15], with the exception of the jet selection and the additional requirement on the four-lepton invariant mass described below. A brief overview is given in this section.

Events with at least four leptons are selected with single-lepton and dilepton triggers. The transverse momentum and transverse energy thresholds for the single-muon and single-electron triggers are 24 GeV. Two dimuon triggers are used, one with symmetric thresholds at 13 GeV and the other with asymmetric thresholds at 18 GeV and 8 GeV. For the dielectron trigger the symmetric thresholds are 12 GeV. Furthermore there is an electron–muon trigger with thresholds at 12 GeV (electron) and 8 GeV (muon).

Higgs boson candidates are formed by selecting two same-flavour opposite-sign (SFOS) lepton pairs (a lepton quadruplet). The leptons must satisfy identification, impact parameter, and track-based and calorimeter-based isolation criteria. Each muon (electron) must satisfy transverse momentum $p_{\mathrm{T}} > 6$ GeV (transverse energy $E_{\mathrm{T}} > 7$ GeV) and be in the pseudorapidity range $|\eta| < 2.7$ (2.47). The highest-$p_{\mathrm{T}}$ lepton in the quadruplet must satisfy $p_{\mathrm{T}} > 20$ GeV, and the second (third) lepton in $p_{\mathrm{T}}$ order must satisfy $p_{\mathrm{T}} > 15$ (10) GeV. The leptons are required to be separated from each other by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.1$ (0.2) when having the same (different) lepton flavours.

Multiple quadruplets within a single event are possible: for four muons or four electrons there are two ways to pair the masses, and for five or more leptons there are multiple combinations. The quadruplet selection is done separately in each channel: $4\mu$, $2e2\mu$, $2\mu 2e$, $4e$, keeping only a single quadruplet per channel. Here the first flavour index refers to the leading lepton pair, which is the pair with the invariant mass $m_{12}$ closest to the $Z$ boson mass [61]. The invariant mass $m_{12}$ is required to be between 50 GeV and 106 GeV. The subleading pair of each channel is chosen as the remaining pair with mass $m_{34}$ closest to the $Z$ boson mass and satisfying the requirement $12 < m_{34} < 115$ GeV. Finally, if more than one channel has a quadruplet passing the selection, the channel with the highest expected signal rate is kept, in the order: $4\mu$, $2e2\mu$, $2\mu 2e$, $4e$. A $J/\psi$ veto is applied: $m(\ell_i, \ell_j) > 5$ GeV for SFOS lepton pairs. Only events with a four-lepton invariant mass in the range 118–129 GeV are kept. This requirement defines the signal mass window and was chosen by minimizing the expected uncertainty on the total signal yield determination, taking into account the experimental uncertainty on the Higgs boson mass.

Jets are reconstructed from topological clusters of calorimeter cells using the anti-$k_t$ algorithm [62] with the distance parameter $R = 0.4$. In this analysis, jets [63] are selected by requiring $p_{\mathrm{T}} > 30$ GeV, $|y| < 4.4$ and, in order to avoid double counting of electrons that are also reconstructed as jets, $\Delta R(\text{jet, electron}) > 0.2$.

The events are divided into bins of the variables of interest, which are computed with the reconstructed four-momenta of the selected lepton quadruplets or from the reconstructed jets: the transverse momentum $p_{\mathrm{T},H}^{\mathrm{reco}}$ and the rapidity $|y_H^{\mathrm{reco}}|$ of the four-lepton system, the invariant mass of the subleading lepton pair

**Table 1**
List of selection cuts which define the fiducial region of the cross section measurement. The same flavour opposite sign lepton pairs are denoted as SFOS, the leading lepton pair mass as $m_{12}$, and the subleading lepton pair mass as $m_{34}$.

| | |
|---|---|
| Lepton selection | |
| Muons: | $p_{\mathrm{T}} > 6$ GeV, $\lvert\eta\rvert < 2.7$ |
| Electrons: | $p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$ |
| Lepton pairing | |
| Leading pair: | SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$ |
| Subleading pair: | Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$ |
| Event selection | |
| Lepton kinematics: | $p_{\mathrm{T}} > 20, 15, 10$ GeV |
| Mass requirements: | $50 < m_{12} < 106$ GeV, $12 < m_{34} < 115$ GeV |
| Lepton separation: | $\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons |
| $J/\psi$ veto: | $m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs |
| Mass window: | $118 < m_{4\ell} < 129$ GeV |

$m_{34}^{\mathrm{reco}}$, the magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame with respect to the beam axis $\lvert\cos\theta^{*\mathrm{reco}}\rvert$, the number of jets $n_{\mathrm{jets}}^{\mathrm{reco}}$, and the transverse momentum of the leading jet $p_{\mathrm{T,jet}}^{\mathrm{reco}}$. In order to distinguish them from the unfolded variables used in the cross section bin definition, they are labelled with "reco".

## 4. Definition of the fiducial region

The fiducial selection, outlined in Table 1, is designed to replicate at simulation level, before applying detector effects, the analysis selection as closely as possible in order to minimize model-dependent acceptance effects on the measured cross sections.

The fiducial selection is applied to electrons and muons originating from vector-boson decays before they emit photon radiation, referred to as Born-level leptons. An alternative approach would be to correct the lepton momenta by adding final-state radiation photons within a cone of size $\Delta R < 0.1$ around each lepton (dressing). For this analysis the acceptance difference between Born and dressed-lepton definitions is less than 0.5%. Particle-level jets are reconstructed from all stable particles except muons and neutrinos using the anti-$k_t$ algorithm with the distance parameter $R = 0.4$.

Jets are selected by requiring $p_{\mathrm{T}} > 30$ GeV, $|y| < 4.4$ and $\Delta R(\text{jet, electron}) > 0.2$. Muons (electrons) must satisfy $p_{\mathrm{T}} > 6$ (7) GeV and $|\eta| < 2.7$ (2.47). Events in which at least one of the $Z$ bosons decays into $\tau$ leptons are removed. Quadruplets are formed from two pairs of SFOS leptons. The leptons are paired as in Section 3, including the possibility of incorrectly pairing the leptons, which happens in about 5% of the selected events for a SM Higgs boson with mass 125.4 GeV. The leading pair is defined as the SFOS lepton pair with invariant mass $m_{12}$ closest to the $Z$ boson mass and the subleading pair is defined as the remaining SFOS lepton pair with invariant mass $m_{34}$ closest to the $Z$ boson mass.

The three highest-$p_{\mathrm{T}}$ leptons in the quadruplet are required to have $p_{\mathrm{T}} > 20, 15, 10$ GeV, respectively, and the lepton pairs must have $50 < m_{12} < 106$ GeV and $12 < m_{34} < 115$ GeV.

The separation between the leptons is required to be $\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons. A $J/\psi$ veto is applied: $m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs. Furthermore, the mass of the four-lepton system $m_{4\ell}$ must be close to $m_H$, i.e. $118 < m_{4\ell} < 129$ GeV.

For a SM Higgs boson mass of 125.4 GeV, the acceptance of the fiducial selection (with respect to the full phase space of $H \to ZZ^* \to 2\ell 2\ell'$, where $\ell, \ell' = e, \mu$) is 45.7%. The number of events passing the event selection divided by the number of events passing the fiducial selection is 55.3%; about 1% of the events passing the event selection do not pass the fiducial selection.

## 5. Background estimate

The background estimates used in this analysis are described in detail in Ref. [15]. The irreducible $ZZ$ and the reducible $WZ$ background contributions are estimated using simulated samples normalized to NLO predictions. For the jet-related variables, the simulation predictions are compared to data for $m_{4\ell} > 190$ GeV where the $ZZ$ background process is dominant; shape differences between the distributions in data and simulation are used to estimate systematic uncertainties.

The reducible $Z+$jets and $t\bar{t}$ background contributions are estimated with data-driven methods. Their normalizations are obtained from data control regions and extrapolated to the signal region using transfer factors. The $\ell\ell + \mu\mu$ final state is dominated by $Z$ + heavy-flavour jets and the $\ell\ell + ee$ final state by $Z$ + light-flavour jets. The misidentification of light-flavour jets as electrons is difficult to model in the simulation. Therefore the distributions for $\ell\ell + ee$ are taken from data control regions and extrapolated to the signal region, while the background distributions for $\ell\ell + \mu\mu$ are taken from simulated samples.

After the analysis selection about 9 background events are expected: 6.7 events from irreducible $ZZ$ and 2.2 events from the reducible background.

The observed distributions compared to the signal and background expectations for the six reconstructed observables $p_{\mathrm{T},H}^{\mathrm{reco}}$ $|y_H^{\mathrm{reco}}|$, $m_{34}^{\mathrm{reco}}$, $\lvert\cos\theta^{*\mathrm{reco}}\rvert$, $n_{\mathrm{jets}}^{\mathrm{reco}}$, and $p_{\mathrm{T,jet}}^{\mathrm{reco}}$ are shown in Fig. 1. The signal prediction includes VBF, $ZH$, $WH$, $t\bar{t}H$, and the POWHEG ggF calculation for a Higgs boson with $m_H = 125$ GeV and is normalized to the most precise SM inclusive cross-section calculation currently available [60].

## 6. Observed differential yields and unfolding

The extraction of the signal yield for the measurement of the fiducial cross section is performed through a fit to the $m_{4\ell}$ distribution using shape templates for the signal and background contributions [15]. In this fit, the Higgs boson mass is fixed to 125.4 GeV and the parameter of interest is the total number of signal events. The extracted number of observed signal events in the mass window is $23.7^{+5.9}_{-5.3}(\text{stat.}) \pm 0.6(\text{syst.})$.

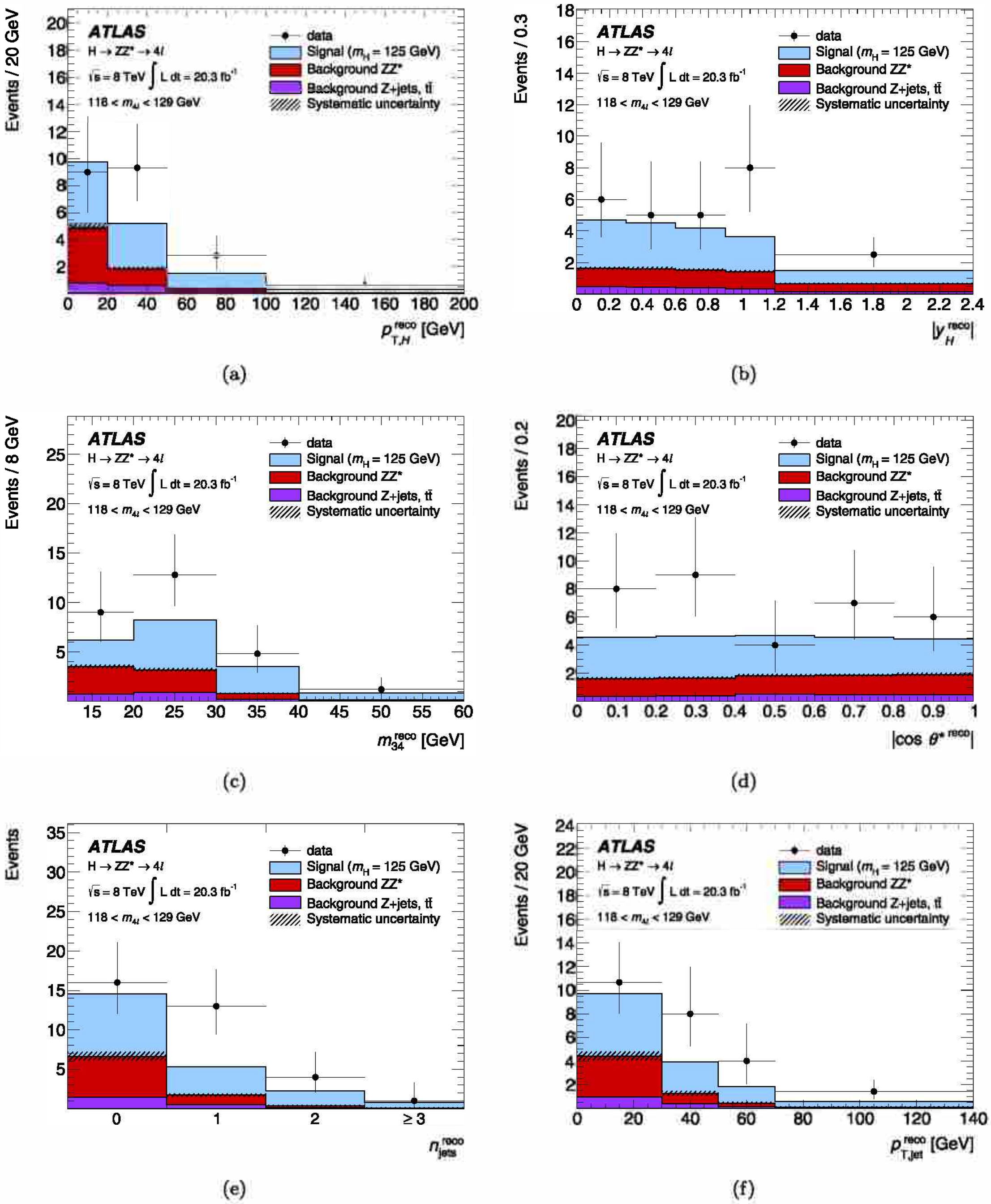
In the differential cross-section measurements, given the low number of signal events expected in each measured bin $i$, the signal yields $n_i^{\mathrm{sig}}$ are determined by subtracting the expected number of background events from the observed number of events. This is done within the mass window for each bin of the observable of interest. The total number of observed events in the mass window is 34 and the extracted signal yield is $25.1^{+6.3}_{-5.4}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.})$ events.

The difference between the number of signal events extracted with the two methods is mainly due to fixing the Higgs boson mass to 125.4 GeV in the fit method. As reported in Ref. [10], the best fit mass in the $H \to ZZ^* \to 4\ell$ channel alone is 124.5 GeV, causing smaller weights for some events in the fit.

After subtracting the background, the measured signal yields are corrected for detector efficiency and resolution effects. This unfolding is performed using correction factors derived from simulated SM signal samples. The correction factor in the $i$-th bin is calculated as

$$c_i = \frac{N_i^{\mathrm{reco}}}{N_i^{\mathrm{fid}}},$$

where $N_i^{\mathrm{reco}}$ is the number of reconstructed events in the $i$-th bin of the observed distribution and $N_i^{\mathrm{fid}}$ is the number of events in



(a) (b)

(c) (d)

(e) (f)

**Fig. 1.** Data yield distributions for the transverse momentum $p_{\mathrm{T},H}^{\mathrm{reco}}$ and the rapidity $|y_H^{\mathrm{reco}}|$ of the four-lepton system, the invariant mass of the subleading lepton pair $m_{34}^{\mathrm{reco}}$, the magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame with respect to the beam axis $|\cos\theta^{*\mathrm{reco}}|$, the number of jets $n_{\mathrm{jets}}^{\mathrm{reco}}$, and the transverse momentum of the leading jet $p_{\mathrm{T,jet}}^{\mathrm{reco}}$ compared to signal and background expectations. The signal prediction includes VBF, $ZH$, $WH$, $t\bar{t}H$, and the POWHEG ggF calculation for a Higgs boson with $m_H = 125$ GeV and is normalized to the most precise SM inclusive cross-section calculation currently available [60]. The hatched areas denote the systematic uncertainties on the backgrounds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the $i$-th bin of the particle-level distribution, within the fiducial region.

The unfolded signal yield in each bin is then converted into a differential fiducial cross section via

$$\frac{d\sigma_{\mathrm{fid},i}}{dx_i} = \frac{n_i^{\mathrm{sig}}}{c_i \cdot \mathcal{L}_{\mathrm{int}} \cdot \Delta x_i},$$

where $\Delta x_i$ is the bin width and $\mathcal{L}_{\mathrm{int}}$ the integrated luminosity.

The correction factors used in this analysis are obtained from simulated samples for all SM Higgs production modes, using the relative rates as predicted by the SM. The inclusive correction factor is $c = 0.553 \pm 0.002(\mathrm{stat.}) \pm 0.015(\mathrm{syst.})$. The correction factors for the different production modes are 0.553 (ggF), 0.572 (VBF), 0.535 ($WH$), 0.551 ($ZH$) and 0.417 ($t\bar{t}H$). In $t\bar{t}H$ production the Higgs boson is accompanied by light- and heavy-flavour jets as well as possible additional leptons from the top-quark decays. Since lepton isolation is applied to the reconstructed but not the

**Table 2**
Summary of the relative systematic uncertainties on the total background contribution (top rows) and on the parameters that enter the signal extraction (bottom rows). The ranges indicate the variation across observables and bins.

| Systematic uncertainties (%) | |
|---|---|
| *Background* | |
| Luminosity | 1.4–2.3 |
| Reducible background | 1.6–34 |
| Experimental, leptons | 1.3–2.3 |
| PDF/scale | 3.0–24 |
| *Correction factors/conversion to $\sigma$* | |
| Luminosity | 2.8 |
| Experimental, leptons | 2.1–2.6 |
| Experimental, jets | 2.7–13 |
| Production process | 0.1–15 |
| Higgs boson mass | 0.4–2.7 |

fiducial objects, the correction factors for $t\bar{t}H$ differ from those for the other production modes.

For each bin, the number of expected background events, the number of observed events, the luminosity, and the correction factors are used to calculate a profile likelihood ratio [64]. The likelihood includes shape and normalization uncertainties of backgrounds and correction factors as nuisance parameters. For each variable all bins are included in the likelihood and correlations of uncertainties between the different bins and between backgrounds and correction factors are taken into account. The cross sections are extracted for each bin by minimizing twice the negative logarithm of the profile likelihood ratio $-2\ln\Lambda$. The uncertainties on the cross sections are also estimated using $-2\ln\Lambda$ by evaluating its variation as a function of the parameter of interest (the cross section value in each bin). Under the asymptotic assumption [64], $-2\ln\Lambda$ behaves as a $\chi^2$ distribution with one degree of freedom. For some of the fitted intervals, due to the low number of events, the distribution of the profile likelihood ratio does not follow a $\chi^2$ distribution and the uncertainties are derived using pseudo-experiments.

The compatibility between the measured cross sections and the theoretical predictions is evaluated by computing the difference between the value of $-2\ln\Lambda$ at the best-fit value and the value obtained by fixing the cross sections in all bins to the ones predicted by theory. Under the asymptotic assumption [64], this statistical observable behaves as a $\chi^2$ with the number of degrees of freedom equal to the number of bins; it is used as a test statistic to compute the $p$-values quantifying the compatibility between the observed distributions and the predictions. For all measured observables the asymptotic assumption is verified with pseudo-experiments.

## 7. Systematic uncertainties

Systematic uncertainties are calculated for the estimated backgrounds, the correction factors, and the SM theoretical predictions; the latter only have an impact on the quantitative comparison of the measurements with different predictions. An overview of the systematic uncertainties on the total background prediction and the correction factors is shown in Table 2.

The uncertainty on the integrated luminosity is propagated in a correlated way to the backgrounds evaluated from the MC predictions and to the unfolding, where it is used when converting the estimated unfolded signal yield into a fiducial cross section. This uncertainty is derived following the same methodology as that detailed in Ref. [65] from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

Systematic uncertainties on the data-driven estimate of the reducible backgrounds are assigned both to the normalization and the shapes of the distributions by varying the estimation methods [15].

The systematic uncertainties on the lepton trigger, reconstruction and identification efficiencies [66,67] are propagated to the signal correction factors and the $ZZ^*$ background, taking into account correlations. For the correction factors, systematic uncertainties are assigned on the jet resolution and energy scales. The largest systematic uncertainty is due to the uncertainty in the jet flavour composition [63,68,69].

The uncertainties on the correction factors due to PDF choice as well as QCD renormalization and factorization scale variations are evaluated in signal samples using the procedure described in Ref. [15] and found to be negligible. A similar procedure is followed for most variables for the irreducible $ZZ$ background. For the jet-related observables an uncertainty is derived instead by comparing the data with the predicted $ZZ$ distributions for $m_{4\ell} > 190$ GeV, after normalizing the MC estimate to the observed data yield. The systematic uncertainty is estimated as the larger of the data-MC difference and the statistical uncertainty on the data. This systematic uncertainty accounts for both the theoretical and experimental uncertainties in the modelling of the $ZZ$ jet distributions. Systematic uncertainties due to the modelling of QED final-state radiation are found to be negligible with respect to the total uncertainty.

The correction factors are calculated assuming the predicted relative cross sections of the different Higgs production modes. The corresponding systematic uncertainty is evaluated by varying these predictions within the current experimental bounds [14]. The VBF and $VH$ fractions are varied by factors of 0.5 and 2 with respect to the SM prediction and the $t\bar{t}H$ fraction is varied by factors of 0 and 5.

The experimental uncertainty on $m_H$ [10] is propagated to the correction factors by studying their dependence on the Higgs boson mass.

The systematic uncertainties on the theoretical predictions include the PDF and QCD scale choices as well as the uncertainty on the $H \to ZZ^*$ branching fraction [60]. The procedure described in Ref. [70] is used to evaluate the scale uncertainties of the predicted $n_{\text{jets}}$ distribution.

The upper edges of the uncertainty ranges in Table 2 are in most cases due to the highest bins in the $n_{\text{jets}}$ and $p_{\text{T,jet}}$ distributions. The background systematic uncertainties are large in some bins due to the limited statistics in the data control regions.

## 8. Results

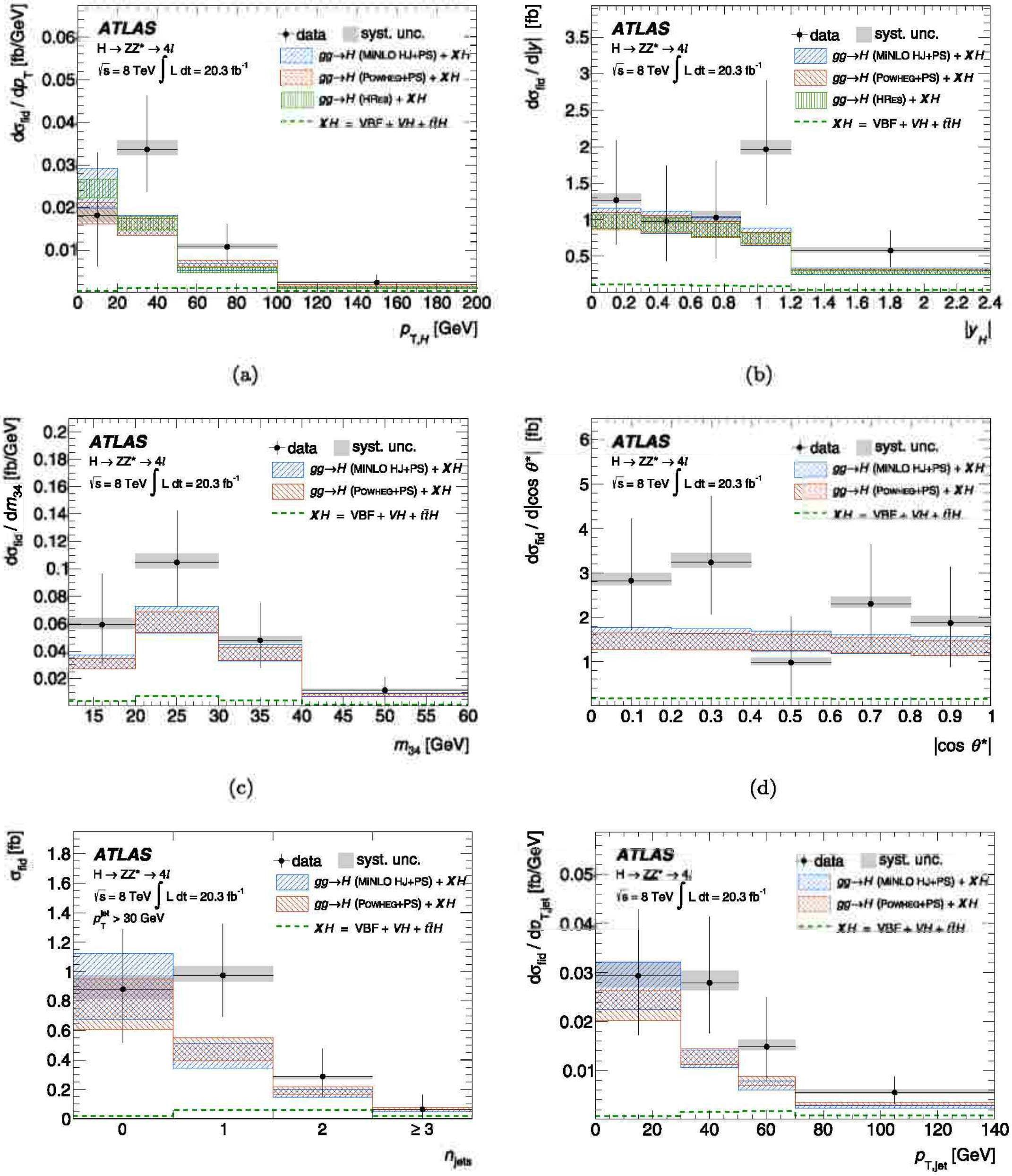
The cross section in the fiducial region described in Table 1 is

$$\sigma_{\text{tot}}^{\text{fid}} = 2.11^{+0.53}_{-0.47}(\text{stat.}) \pm 0.08(\text{syst.})\ \text{fb}.$$

The theoretical prediction from Ref. [60] for a Higgs boson mass of 125.4 GeV is $1.30 \pm 0.13$ fb.

The differential cross sections as a function of $p_{\text{T},H}$, $y_H$, $m_{34}$, $|\cos\theta^*|$, $n_{\text{jets}}$, and $p_{\text{T,jet}}$ are shown in Fig. 2. For all variables and bins the total uncertainties on the cross-section measurements are dominated by statistical uncertainties. Powheg, Minlo and HRes2 calculations of ggF, added to VBF, $ZH/WH$ and $t\bar{t}H$ (see Section 2), are overlaid. The HRes2 calculation was developed for modelling the Higgs kinematic variables and is only used for $p_{\text{T},H}$ and $y_H$. The theoretical calculations are normalized to the most precise SM inclusive cross-section predictions currently available [60].

The $p$-values quantifying the compatibility between data and predictions, computed with the method described in Section 6, are shown in Table 3. No significant discrepancy is observed.



(a) (b) (c) (d) (e) (f)

**Fig. 2.** Differential unfolded cross sections for the transverse momentum $p_{\mathrm{T},H}$ and rapidity $y_H$ of the Higgs boson, the invariant mass of the subleading lepton pair $m_{34}$, the magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame with respect to the beam axis $|\cos\theta^*|$, the number of jets $n_{\mathrm{jets}}$, and the transverse momentum of the leading jet $p_{\mathrm{T,jet}}$ in the $H \to ZZ^* \to 4\ell$ decay channel compared to different theoretical calculations of the ggF process: Powheg, Minlo and HRes2. The contributions from VBF, $ZH/WH$ and $t\bar{t}H$ are determined as described in Section 2 and added to the ggF distributions. All theoretical calculations are normalized to the most precise SM inclusive cross-section predictions currently available [60]. The error bars on the data points show the total (stat. $\oplus$ syst.) uncertainty, while the grey bands denote the systematic uncertainties. The bands of the theoretical prediction indicate the total uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 9. Conclusion

Measurements of fiducial and differential cross sections in the $H \to ZZ^* \to 4\ell$ decay channel are presented. They are based on 20.3 $\mathrm{fb}^{-1}$ of $pp$ collision data, produced at $\sqrt{s} = 8$ TeV centre-of-mass energy at the LHC and recorded by the ATLAS detector. The cross sections are corrected for detector effects and compared to selected theoretical calculations. No significant deviation from the theoretical predictions is observed for any of the studied variables.

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**Table 3**
Compatibility tests of data with Powheg, Minlo and HRes2 ggF calculations of SM Higgs boson production. The compatibility $p$-values are obtained, as explained in the text, from the difference between $-2\ln\Lambda$ at the best-fit value and $-2\ln\Lambda$ with the cross sections fixed to the theory computations.

| Variable | $p$-values | | |
|---|---|---|---|
| | Powheg | Minlo | HRes2 |
| $p_{\mathrm{T},H}$ | 0.30 | 0.23 | 0.16 |
| $\lvert y_H \rvert$ | 0.37 | 0.45 | 0.36 |
| $m_{34}$ | 0.48 | 0.60 | – |
| $\lvert\cos\theta^*\rvert$ | 0.35 | 0.45 | – |
| $n_{\mathrm{jets}}$ | 0.37 | 0.28 | – |
| $p_{\mathrm{T,jet}}$ | 0.33 | 0.26 | – |

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Y. Yang[111], S. Yanush[93], L. Yao[33a], W-M. Yao[15], Y. Yasu[66], E. Yatsenko[42], K.H. Yau Wong[21], J. Ye[40], S. Ye[25], I. Yeletskikh[65], A.L. Yen[57], E. Yildirim[42], M. Yilmaz[4b], R. Yoosoofmiya[125], K. Yorita[173], R. Yoshida[6], K. Yoshihara[157], C. Young[145], C.J.S. Young[30], S. Youssef[22], D.R. Yu[15], J. Yu[8], J.M. Yu[89], J. Yu[114], L. Yuan[67], A. Yurkewicz[108], I. Yusuff[28,am], B. Zabinski[39], R. Zaidan[63], A.M. Zaitsev[130,z], A. Zaman[150], S. Zambito[23], L. Zanello[134a,134b], D. Zanzi[88], C. Zeitnitz[177], M. Zeman[128], A. Zemla[38a], K. Zengel[23], O. Zenin[130], T. Ženiš[146a], D. Zerwas[117], G. Zevi della Porta[57], D. Zhang[89], F. Zhang[175], H. Zhang[90], J. Zhang[6], L. Zhang[153], X. Zhang[33d], Z. Zhang[117], Z. Zhao[33b], A. Zhemchugov[65], J. Zhong[120], B. Zhou[89], L. Zhou[35], N. Zhou[165], C.G. Zhu[33d], H. Zhu[33a], J. Zhu[89], Y. Zhu[33b], X. Zhuang[33a], K. Zhukov[96], A. Zibell[176], D. Zieminska[61], N.I. Zimine[65], C. Zimmermann[83], R. Zimmermann[21], S. Zimmermann[21], S. Zimmermann[48], Z. Zinonos[54], M. Ziolkowski[143], G. Zobernig[175], A. Zoccoli[20a,20b], M. zur Nedden[16], G. Zurzolo[104a,104b], V. Zutshi[108], L. Zwalinski[30]

[1] *Department of Physics, University of Adelaide, Adelaide, Australia*
[2] *Physics Department, SUNY Albany, Albany, NY, United States*
[3] *Department of Physics, University of Alberta, Edmonton, AB, Canada*
[4] *(a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Istanbul Aydin University, Istanbul; (d) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[5] *LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*
[6] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States*
[7] *Department of Physics, University of Arizona, Tucson, AZ, United States*
[8] *Department of Physics, The University of Texas at Arlington, Arlington, TX, United States*
[9] *Physics Department, University of Athens, Athens, Greece*
[10] *Physics Department, National Technical University of Athens, Zografou, Greece*
[11] *Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[12] *Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*
[13] *(a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[14] *Department for Physics and Technology, University of Bergen, Bergen, Norway*
[15] *Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States*
[16] *Department of Physics, Humboldt University, Berlin, Germany*
[17] *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[18] *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[19] *(a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[20] *(a) INFN Sezione di Bologna; (b) 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, MA, United States*
[23] *Department of Physics, Brandeis University, Waltham, MA, United States*
[24] *(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[25] *Physics Department, Brookhaven National Laboratory, Upton, NY, United States*
[26] *(a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania*
[27] *Departamento de Física, 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, IL, United States*
[32] *(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[33] *(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China*
[34] *Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France*
[35] *Nevis Laboratory, Columbia University, Irvington, NY, United States*
[36] *Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[37] *(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[38] *(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[39] *The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[40] *Physics Department, Southern Methodist University, Dallas, TX, United States*
[41] *Physics Department, University of Texas at Dallas, Richardson, TX, United States*
[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, NC, United States*
[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*
[50] *(a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51] *(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) 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*

[56] *Department of Physics, Hampton University, Hampton, VA, United States*
[57] *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States*
[58] (a) *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* (b) *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* (c) *ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany*
[59] *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
[60] (a) *Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong;* (b) *Department of Physics, The University of Hong Kong, Hong Kong;* (c) *Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[61] *Department of Physics, Indiana University, Bloomington, IN, United States*
[62] *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
[63] *University of Iowa, Iowa City, IA, United States*
[64] *Department of Physics and Astronomy, Iowa State University, Ames, IA, United States*
[65] *Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
[66] *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[67] *Graduate School of Science, Kobe University, Kobe, Japan*
[68] *Faculty of Science, Kyoto University, Kyoto, Japan*
[69] *Kyoto University of Education, Kyoto, Japan*
[70] *Department of Physics, Kyushu University, Fukuoka, Japan*
[71] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[72] *Physics Department, Lancaster University, Lancaster, United Kingdom*
[73] (a) *INFN Sezione di Lecce;* (b) *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[74] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[75] *Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
[76] *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[77] *Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
[78] *Department of Physics and Astronomy, University College London, London, United Kingdom*
[79] *Louisiana Tech University, Ruston, LA, United States*
[80] *Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
[81] *Fysiska institutionen, Lunds universitet, Lund, Sweden*
[82] *Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*
[83] *Institut für Physik, Universität Mainz, Mainz, Germany*
[84] *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[85] *CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
[86] *Department of Physics, University of Massachusetts, Amherst, MA, United States*
[87] *Department of Physics, McGill University, Montreal, QC, Canada*
[88] *School of Physics, University of Melbourne, Victoria, Australia*
[89] *Department of Physics, The University of Michigan, Ann Arbor, MI, United States*
[90] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States*
[91] (a) *INFN Sezione di Milano;* (b) *Dipartimento di Fisica, Università di Milano, Milano, Italy*
[92] *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
[93] *National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus*
[94] *Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States*
[95] *Group of Particle Physics, University of Montreal, Montreal, QC, Canada*
[96] *P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
[97] *Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[98] *National Research Nuclear University MEPhI, Moscow, Russia*
[99] *D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
[100] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[101] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[102] *Nagasaki Institute of Applied Science, Nagasaki, Japan*
[103] *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
[104] (a) *INFN Sezione di Napoli;* (b) *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
[105] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States*
[106] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[107] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[108] *Department of Physics, Northern Illinois University, DeKalb, IL, United States*
[109] *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
[110] *Department of Physics, New York University, New York, NY, United States*
[111] *Ohio State University, Columbus, OH, United States*
[112] *Faculty of Science, Okayama University, Okayama, Japan*
[113] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States*
[114] *Department of Physics, Oklahoma State University, Stillwater, OK, United States*
[115] *Palacký University, RCPTM, Olomouc, Czech Republic*
[116] *Center for High Energy Physics, University of Oregon, Eugene, OR, United States*
[117] *LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France*
[118] *Graduate School of Science, Osaka University, Osaka, Japan*
[119] *Department of Physics, University of Oslo, Oslo, Norway*
[120] *Department of Physics, Oxford University, Oxford, United Kingdom*
[121] (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*
[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*
[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 Fisica, Universidade do Minho, Braga;* (f) *Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain);* (g) *Dep 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] Physics Department, University of Regina, Regina, SK, Canada
[133] Ritsumeikan University, Kusatsu, Shiga, Japan
[134] (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[135] (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[136] (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[137] (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
[138] 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
[139] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
[140] Department of Physics, University of Washington, Seattle, WA, United States
[141] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[142] Department of Physics, Shinshu University, Nagano, Japan
[143] Fachbereich Physik, Universität Siegen, Siegen, Germany
[144] Department of Physics, Simon Fraser University, Burnaby, BC, Canada
[145] SLAC National Accelerator Laboratory, Stanford, CA, United States
[146] (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
[147] (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
[148] (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
[149] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[150] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
[151] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[152] School of Physics, University of Sydney, Sydney, Australia
[153] Institute of Physics, Academia Sinica, Taipei, Taiwan
[154] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[155] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[156] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[157] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[158] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[159] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[160] Department of Physics, University of Toronto, Toronto, ON, Canada
[161] (a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
[162] Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[163] Department of Physics and Astronomy, Tufts University, Medford, MA, United States
[164] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[165] Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
[166] (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
[167] Department of Physics, University of Illinois, Urbana, IL, United States
[168] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[169] 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
[170] Department of Physics, University of British Columbia, Vancouver, BC, Canada
[171] Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
[172] Department of Physics, University of Warwick, Coventry, United Kingdom
[173] Waseda University, Tokyo, Japan
[174] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[175] Department of Physics, University of Wisconsin, Madison, WI, United States
[176] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[177] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[178] Department of Physics, Yale University, New Haven, CT, United States
[179] Yerevan Physics Institute, Yerevan, Armenia
[180] Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

[a] Also at Department of Physics, King's College London, London, United Kingdom.
[b] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[c] Also at Novosibirsk State University, Novosibirsk, Russia.
[d] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[e] Also at TRIUMF, Vancouver, BC, Canada.
[f] Also at Department of Physics, California State University, Fresno, CA, United States.
[g] Also at Tomsk State University, Tomsk, Russia.
[h] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[i] Also at Università di Napoli Parthenope, Napoli, Italy.
[j] Also at Institute of Particle Physics (IPP), Canada.
[k] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[l] Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[m] Also at Louisiana Tech University, Ruston, LA, United States.
[n] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[o] Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.
[p] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[q] Also at CERN, Geneva, Switzerland.
[r] Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
[s] Also at Manhattan College, New York, NY, United States.
[t] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[u] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

[v] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[w] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[x] Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
[y] Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
[z] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[aa] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[ab] Also at International School for Advanced Studies (SISSA), Trieste, Italy.
[ac] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[ad] Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
[ae] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
[af] Also at National Research Nuclear University MEPhI, Moscow, Russia.
[ag] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[ah] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[ai] Also at Department of Physics, Nanjing University, Jiangsu, China.
[aj] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[ak] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
[al] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
[am] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
[*] Deceased.