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Aaboud, M.; Newman, Paul; ATLAS Collaboration

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# Measurements of gluon–gluon fusion and vector-boson fusion Higgs boson production cross-sections in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay channel in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration\*



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## ABSTRACT

Higgs boson production cross-sections in proton–proton collisions are measured in the  $H \rightarrow WW^* \rightarrow e\nu\mu\nu$  decay channel. The proton–proton collision data were produced at the Large Hadron Collider at a centre-of-mass energy of 13 TeV and recorded by the ATLAS detector in 2015 and 2016, corresponding to an integrated luminosity of  $36.1 \text{ fb}^{-1}$ . The product of the  $H \rightarrow WW^*$  branching fraction times the gluon–gluon fusion and vector-boson fusion cross-sections are measured to be  $11.4_{-1.1}^{+1.2}(\text{stat.})_{-1.7}^{+1.8}(\text{syst.}) \text{ pb}$  and  $0.50_{-0.22}^{+0.24}(\text{stat.}) \pm 0.17(\text{syst.}) \text{ pb}$ , respectively, in agreement with Standard Model predictions.

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## 1. Introduction

This Letter presents a measurement of the inclusive Higgs boson production cross-sections via gluon–gluon fusion (ggF) and vector-boson fusion (VBF) through the decay  $H \rightarrow WW^* \rightarrow e\nu\mu\nu$  using  $36.1 \text{ fb}^{-1}$  of proton–proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector. Higgs boson couplings have been studied in this channel with Run-1 data by the ATLAS [1] and CMS [2] experiments and recently with Run-2 data by the CMS experiment [3]. The  $H \rightarrow WW^*$  decay channel has the second-largest branching fraction and allowed the most precise Higgs boson cross-section measurements in Run-1 [4]. The measured cross-section of the ggF production process probes the Higgs boson couplings to gluons and heavy quarks, while the VBF process directly probes the couplings to  $W$  and  $Z$  bosons. The leading-order diagrams for the ggF and VBF production processes are depicted in Fig. 1.

## 2. ATLAS detector

ATLAS is a particle detector designed to achieve a nearly full coverage in solid angle<sup>1</sup> [5,6]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electro-

magnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets. The inner tracking detector (ID) is located in a 2 T magnetic field and is designed to measure charged-particle trajectories up to a pseudorapidity of  $|\eta| = 2.5$ . Surrounding the ID are electromagnetic and hadronic calorimeters, which use liquid argon (LAr) and lead absorber for the electromagnetic central and endcap calorimeters ( $|\eta| < 3.2$ ), copper absorber for the hadronic endcap calorimeter ( $1.5 < |\eta| < 3.2$ ), and scintillator-tile active material with steel absorber for the central ( $|\eta| < 1.7$ ) hadronic calorimeter. The solid angle coverage is extended to  $|\eta| = 4.9$  with forward copper/LAr and tungsten/LAr calorimeter modules. The muon spectrometer comprises separate trigger chambers within the range  $|\eta| < 2.4$  and high-precision tracking chambers within the range  $|\eta| < 2.7$ , measuring the deflection of muons in a magnetic field generated by the three superconducting toroidal magnets. A two-level trigger system is used to select events [7].

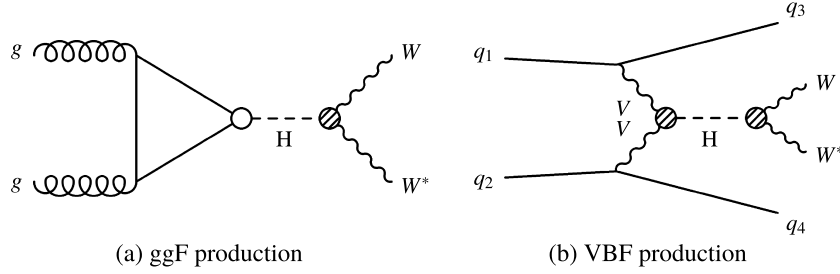
## 3. Signal and background Monte Carlo predictions

Higgs boson production via ggF was simulated at next-to-next-to-leading-order (NNLO) accuracy in QCD using the POWHEG-Box v2 NNLOPS program [8], with the PDF4LHC15 NNLO set of parton distribution functions (PDF) [9]. The simulation achieves NNLO accuracy for arbitrary inclusive  $gg \rightarrow H$  observables by reweighting the Higgs boson rapidity spectrum in HJ-MiNLO [10] to that of HNNLO [11]. The transverse momentum spectrum of the Higgs bo-

<sup>1</sup>  $\sqrt{\Delta\phi^2 + \Delta\eta^2}$ , is also used to define cone sizes. Transverse momentum and energy are defined as  $p_T = p \sin\theta$  and  $E_T = E \sin\theta$ , respectively.

\* E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in 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  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . The distance in  $(\eta, \phi)$  coordinates,  $\Delta R =$



**Fig. 1.** Diagrams for the leading production modes (ggF and VBF), where the  $VVH$  and  $qqH$  coupling vertices are marked with shaded and empty circles, respectively. The  $V$  represents a  $W$  or  $Z$  vector boson.

**Table 1**

Overview of simulation tools used to generate signal and background processes, and to model the UEPS. The PDF sets are also summarised. Alternative event generators and configurations used to estimate systematic uncertainties are shown in parentheses.

Process	Matrix element (alternative)	PDF set	UEPS model (alternative model)	Prediction order for total cross-section
ggF $H$	PowHEG-Box v2 NNLOPS [8,10,16] (MG5_AMC@NLO [47,48])	PDF4LHC15 NNLO [9]	PyTHIA 8 [14]	$N^3$ LO QCD + NLO EW [24–28]
VBF $H$	PowHEG-Box v2	PDF4LHC15 NLO	(Herwig 7 [49]) PyTHIA 8 (Herwig 7)	NNLO QCD + NLO EW [24,29–31]
$VH$	PowHEG-Box v2 [50]	PDF4LHC15 NLO	PyTHIA 8	NNLO QCD + NLO EW [51–53]
$qq \rightarrow WW$	SHERPA 2.2.2 [32,33] (PowHEG-Box v2, MG5_AMC@NLO)	NNPDF3.0NNLO [34]	SHERPA 2.2.2 [35,36] (Herwig++ [49])	NLO [37]
$gg \rightarrow WW$	SHERPA 2.1.1 [37]	CT10 [54]	SHERPA 2.1	NLO [38]
$WZ/V\gamma^*/ZZ$	SHERPA 2.1	CT10	SHERPA 2.1	NLO [37]
$V\gamma$	SHERPA 2.2.2 (MG5_AMC@NLO)	NNPDF3.0NNLO	SHERPA 2.2.2 (CSS variation [35,55])	NLO [37]
$t\bar{t}$	PowHEG-Box v2 [56] (SHERPA 2.2.1)	NNPDF3.0NLO	PyTHIA 8 (Herwig 7)	NNLO + NNLL [57]
$Wt$	PowHEG-Box v1 [58] (MG5_AMC@NLO)	CT10 [54]	PyTHIA 6.428 [59] (Herwig++)	NLO [58]
$Z/\gamma^*$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	NNLO [60,61]

son obtained with this sample was found to be compatible within uncertainties with the resummed NNLO+NNLL HRes2.3 calculation [12,13]. The parton-level events produced by the PowHEG-Box v2 NNLOPS program were passed to PyTHIA 8 [14] to provide parton showering, hadronisation and the underlying event, using the AZNLO set of data-tuned parameters [15].

Higgs boson production via VBF was simulated at next-to-leading-order (NLO) accuracy in QCD using PowHEG-Box v2 [8, 10,16,17] with the PDF4LHC15 NLO PDF set [9]. The parton-level events were passed to PyTHIA 8 [14] with the same parameters as for ggF.

The mass of the Higgs boson was set to 125 GeV, compatible with the experimental measurement [18–20]. The corresponding Standard Model (SM) branching fraction  $\mathcal{B}_{H \rightarrow WW^*}$  is calculated using HDecay v6.50 [21,22] to be 0.214 [23]. The  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  decay, where  $\ell = e$  or  $\mu$ , always includes the small contribution from  $W \rightarrow \tau\nu \rightarrow \ell\nu\nu\nu$  decays. Other production and decay modes of the Higgs boson are either fixed to SM predictions ( $VH$  production and  $H \rightarrow \tau\tau$  decay) or neglected ( $t\bar{t}H$  and  $b\bar{b}H$  associated production).

The ggF production cross-section was calculated with next-to-next-to-next-to-leading-order accuracy in QCD and includes NLO electroweak (EW) corrections [24–28]. The NLO QCD and EW calculations are used with approximate NNLO QCD corrections for the VBF production cross-section [24,29–31].

The  $WW$  background was generated separately for the  $qq \rightarrow WW$  and  $gg \rightarrow WW$  production mechanisms. The  $qq \rightarrow WW$  production process was generated using SHERPA 2.2.2 [32,33] interfaced with the NNPDF3.0 NNLO PDF set [34] and the SHERPA parton shower, hadronisation and underlying event simulation (UEPS) model [35,36]. The matrix elements were calculated for up to one

additional parton at NLO and up to three additional partons at LO precision. The loop-induced  $gg \rightarrow WW$  process was simulated by SHERPA 2.1.1 with zero or one additional jet [37]. The sample is normalised to the NLO  $gg \rightarrow WW$  cross-section [38]. Interferences with direct  $WW$  production have a negligible impact after event selection cuts have been applied and are, therefore, not considered in this analysis [39].

While NNLO cross-sections are available for diboson production processes [40–42], the SHERPA MEPS@NLO prescription [36] is used in this analysis. This procedure already captures the majority of the NNLO shape corrections.

The MC generators, PDFs, and programmes used for the UEPS are summarised in Table 1. The order of the perturbative prediction for each sample is also reported.

The generated events were passed through a GEANT 4 [43] simulation of the ATLAS detector [44] and reconstructed with the same analysis software as used for the data. Additional proton–proton interactions (pile-up) are included in the simulation for all generated events such that the distributions of the average number of interactions per bunch crossing reproduces that observed in the data. The inelastic proton–proton collisions were produced using PyTHIA 8 with the A2 set of data-tuned parameters [45] and the MSTW2008LO PDF set [46]. Correction factors are applied to account for small differences observed between data and simulation in electrons, muons, and jets identification efficiencies and energy/momentum scales and resolutions.

#### 4. Event selection and categorisations

Events are triggered using single-lepton triggers and a dilepton  $e-\mu$  trigger. The transverse momentum threshold ranges be-

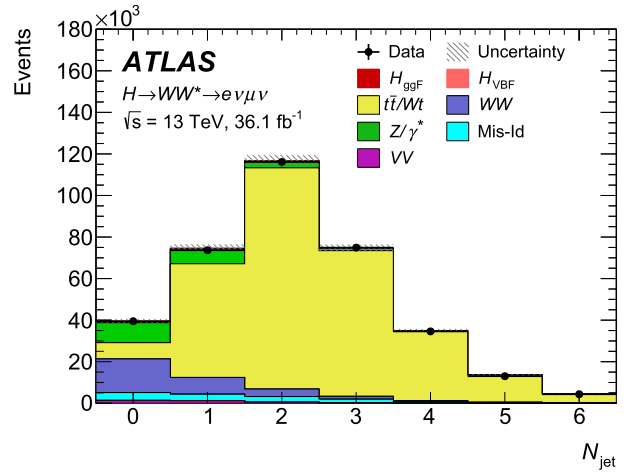
**Table 2**

Event selection criteria used to define the signal regions in the  $H \rightarrow WW^* \rightarrow e\nu\mu\nu$  analysis. For the  $N_{\text{jet}} \geq 2$  VBF signal region, the input variables used for the boosted decision tree (BDT) training are also reported.

Category	$N_{\text{jet}, (p_T > 30 \text{ GeV})} = 0$ ggF	$N_{\text{jet}, (p_T > 30 \text{ GeV})} = 1$ ggF	$N_{\text{jet}, (p_T > 30 \text{ GeV})} \geq 2$ VBF
Preselection	Two isolated, different-flavour leptons ( $\ell = e, \mu$ ) with opposite charge $p_T^{\text{lead}} > 22 \text{ GeV}, p_T^{\text{sublead}} > 15 \text{ GeV}$ $m_{\ell\ell} > 10 \text{ GeV}$ $p_T^{\text{miss}} > 20 \text{ GeV}$		
Background rejection	$\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $p_T^{\ell\ell} > 30 \text{ GeV}$	$N_{b\text{-jet}, (p_T > 20 \text{ GeV})} = 0$ $\max(m_{\tau\tau}^{\ell}) > 50 \text{ GeV}$ $m_{\tau\tau} < m_Z - 25 \text{ GeV}$	
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ topology	$m_{\ell\ell} < 55 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 1.8$		central jet veto outside lepton veto
Discriminant variable BDT input variables	$m_{\tau\tau}$		BDT $m_{jj}, \Delta y_{jj}, m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\tau\tau}, \sum_{\ell} C_{\ell}, \sum_{\ell, j} m_{\ell j}, p_T^{\text{tot}}$

tween 24 GeV and 26 GeV for single-electron triggers and between 20 GeV and 26 GeV for single-muon triggers, depending on the run period [7]. The  $e\text{-}\mu$  trigger requires a minimum  $p_T$  threshold of 17 GeV for electrons and 14 GeV for muons.

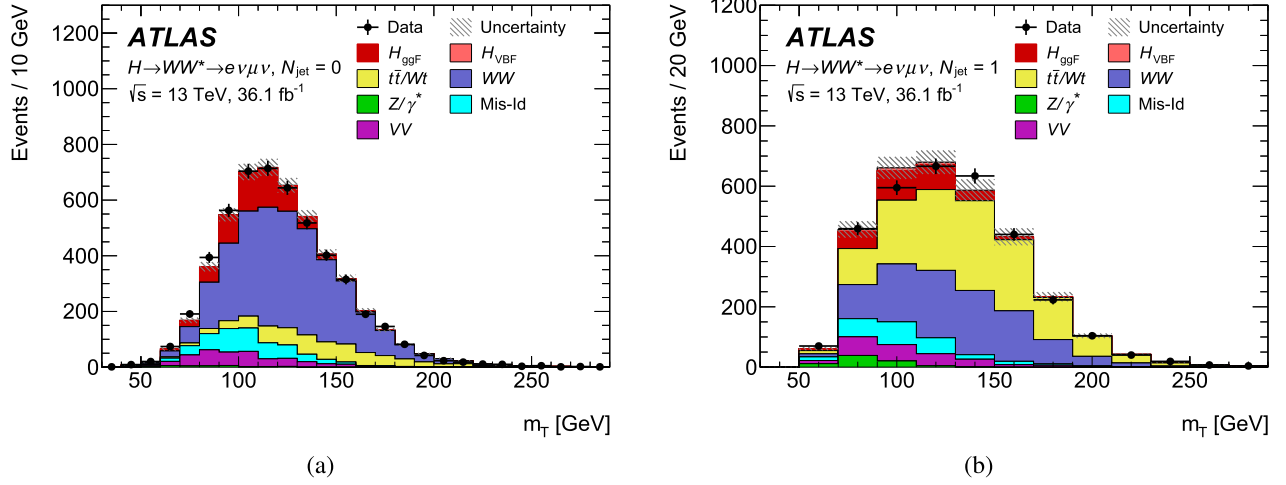
Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter with an associated well-reconstructed track [62,63]. Electrons are required to satisfy  $|\eta| < 2.47$ , excluding the transition region between the barrel and endcap calorimeters,  $1.37 < |\eta| < 1.52$ . Muon candidates are selected from tracks reconstructed in the ID matched to tracks reconstructed in the muon spectrometer [64] and are required to satisfy  $|\eta| < 2.5$ . To reject particles misidentified as leptons, several identification requirements as well as calorimeter and track isolation criteria [64, 65] are applied. The electron identification criteria applied provide an efficiency in the range 88–94% depending on electron  $p_T$  and  $\eta$ . For muons, high efficiency, close to 95%, is observed over the full instrumented  $\eta$  range. The final lepton-selection criteria require two different-flavour opposite-sign leptons, the higher- $p_T$  (leading) lepton with  $p_T > 22 \text{ GeV}$  and the subleading lepton with  $p_T > 15 \text{ GeV}$ . At least one of the leptons must correspond to a lepton that triggered the recording of the event. When the  $e\text{-}\mu$  trigger is solely responsible for the recording of the event, each lepton must be matched to one of the trigger objects. The trigger matching requires the offline  $p_T$  of the matching object to be higher than the trigger level threshold by at least 1 GeV. Jets are reconstructed using the anti- $k_r$  algorithm [66] with a radius parameter  $R = 0.4$ . The four-momenta of jets are corrected for the non-compensating response of calorimeter, signal losses due to noise threshold effects, energy lost in non-instrumented regions, and contributions from pile-up [67]. Jets are required to have  $p_T > 20 \text{ GeV}$  and  $|\eta| < 4.5$ . A multivariate selection that reduces contamination from pile-up [68] is applied to jets with  $p_T < 60 \text{ GeV}$  and  $|\eta| < 2.4$ , utilising calorimeter and tracking information to separate hard-scatter jets from pile-up jets. For jets with  $p_T < 50 \text{ GeV}$  and  $|\eta| > 2.5$ , jet shapes and topological jet correlations in pile-up interactions are exploited to reduce contamination. Jets with  $p_T > 20 \text{ GeV}$  and  $|\eta| < 2.5$  containing  $b$ -hadrons ( $b$ -jets) are identified using a multivariate technique having as input the track impact parameters and information from secondary vertices. The adopted working point provides a nominal 3% light-flavour ( $u$ -,  $d$ -,  $s$ -quark and gluon) misidentification rate and a 32%  $c$ -jet misidentification rate with an average 85%  $b$ -jet tagging efficiency, as estimated from simulated  $t\bar{t}$  events [69]. Ambiguities from overlapping reconstructed jet and lepton candidates are resolved as follows. If a reconstructed muon shares an ID track with a reconstructed electron, the electron is removed. Reconstructed jets geometrically overlapping in a cone of radius  $\Delta R = 0.2$  with electrons or muons are also removed. Electrons and muons, with transverse momentum  $p_T$ , are



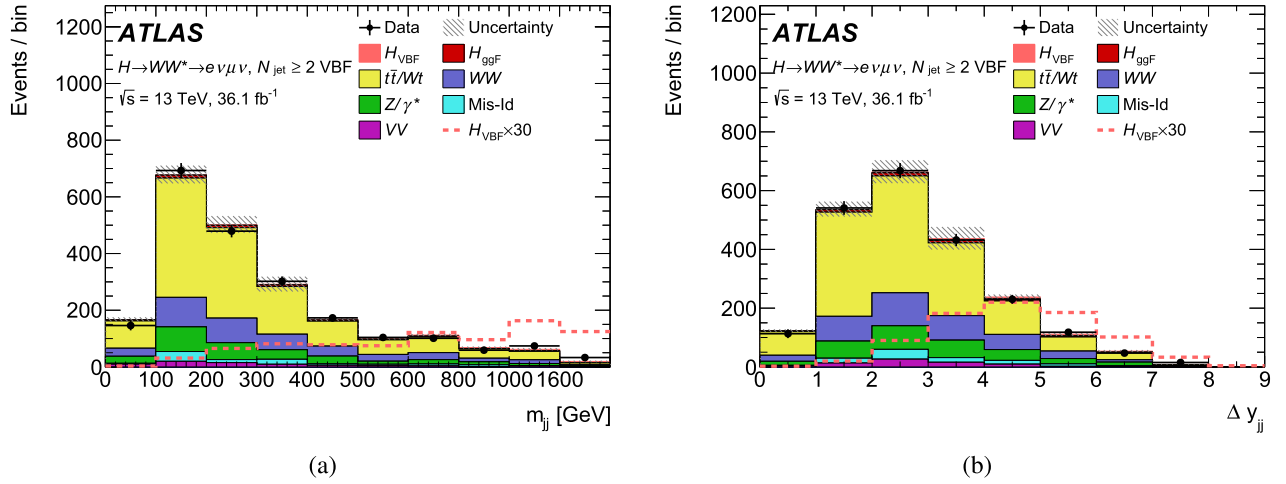
**Fig. 2.** Jet multiplicity distribution after applying the preselection criteria. The shaded band represents the systematic uncertainty and accounts for experimental uncertainties only.

removed if they are within  $\Delta R = \min(0.4, 0.04 + 10 \text{ GeV}/p_T)$  of the axis of any surviving jet. The missing transverse momentum  $E_T^{\text{miss}}$  (with magnitude  $E_T^{\text{miss}}$ ) is defined as the negative vector sum of the  $p_T$  of all the selected leptons and jets, and including reconstructed tracks not associated with these objects, and consistent with originating from the primary  $pp$  collision [70]. A second definition of missing transverse momentum (in this case denoted  $p_T^{\text{miss}}$ ) uses the tracks associated with the jets instead of the calorimeter-measured jets. It was found during the optimisation that  $p_T^{\text{miss}}$  performs better in terms of background rejection [70].

Events are classified into one of three categories based on the number of jets with  $p_T > 30 \text{ GeV}$ : events with zero jets and events with exactly one jet target the ggF production mode ( $N_{\text{jet}} = 0$  and  $N_{\text{jet}} = 1$  ggF categories), and events with at least two jets target the VBF production mode ( $N_{\text{jet}} \geq 2$  VBF category). Fig. 2 shows the jet multiplicity distribution after applying the preselection criteria defined in Table 2. The different background compositions as a function of jet multiplicity motivate the division of the data sample into the various  $N_{\text{jet}}$  categories and the definition of a signal region in each jet multiplicity bin. Details of the background estimation are provided in Section 5. To reject background from top-quark production, events containing  $b$ -jets with  $p_T > 20 \text{ GeV}$  ( $N_{b\text{-jet}, (p_T > 20 \text{ GeV})}$ ) are vetoed. The full event selection is summarised in Table 2, where  $\Delta\phi(\ell\ell, E_T^{\text{miss}})$  is defined as the azimuthal angle between  $E_T^{\text{miss}}$  and the dilepton system,  $p_T^{\ell\ell}$  is the transverse momentum of the dilepton system,  $p_T^{\text{tot}}$



**Fig. 3.** Post-fit  $m_T$  distributions with the signal and the background modelled contributions in the (a)  $N_{\text{jet}}=0$  and (b)  $N_{\text{jet}}=1$  signal regions. The hatched band shows the total uncertainty of the signal and background modelled contributions.



**Fig. 4.** Post-fit  $m_{jj}$  (a) and  $\Delta y_{jj}$  (b) distributions with signal and background modelled contributions in the  $N_{\text{jet}} \geq 2$  VBF signal region. The dashed line shows the VBF signal scaled by a factor of 30. The hatched band shows the total uncertainty of the signal and background modelled contributions.

**Table 3**

Event selection criteria used to define the control regions. Every control region selection starts from the selection labelled “Preselection” in Table 2.  $N_{b\text{-jet},(20 \text{ GeV} < p_T < 30 \text{ GeV})}$  represents the number of  $b$ -jets with  $20 \text{ GeV} < p_T < 30 \text{ GeV}$ .

CR	$N_{\text{jet},(p_T > 30 \text{ GeV})} = 0$ ggF	$N_{\text{jet},(p_T > 30 \text{ GeV})} = 1$ ggF	$N_{\text{jet},(p_T > 30 \text{ GeV})} \geq 2$ VBF
WW	$55 < m_{\ell\ell} < 110 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 2.6$ $N_{b\text{-jet},(p_T > 20 \text{ GeV})} = 0$	$m_{\ell\ell} > 80 \text{ GeV}$ $ m_{\tau\tau} - m_Z  > 25 \text{ GeV}$ $\max(m_T^\ell) > 50 \text{ GeV}$	
$t\bar{t}/Wt$	$N_{b\text{-jet},(20 \text{ GeV} < p_T < 30 \text{ GeV})} > 0$ $\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $p_T^{\ell\ell} > 30 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 2.8$	$N_{b\text{-jet},(p_T > 30 \text{ GeV})} = 1$ $N_{b\text{-jet},(20 \text{ GeV} < p_T < 30 \text{ GeV})} = 0$ $\max(m_T^\ell) > 50 \text{ GeV}$ $m_{\tau\tau} < m_Z - 25 \text{ GeV}$	$N_{b\text{-jet},(p_T > 20 \text{ GeV})} = 1$ central jet veto outside lepton veto
$Z/\gamma^*$	no $p_T^{\text{miss}}$ requirement $\Delta\phi_{\ell\ell} > 2.8$	$N_{b\text{-jet},(p_T > 20 \text{ GeV})} = 0$ $m_{\ell\ell} < 80 \text{ GeV}$ $\max(m_T^\ell) > 50 \text{ GeV}$ $m_{\tau\tau} > m_Z - 25 \text{ GeV}$	central jet veto outside lepton veto $ m_{\tau\tau} - m_Z  \leq 25 \text{ GeV}$

the invariant mass of the two leptons,  $\Delta\phi_{\ell\ell}$  is the azimuthal angle between the two leptons, and  $\max(m_T^\ell)$  is the larger of

$$m_T^\ell = \sqrt{2 p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi(\ell_i, E_T^{\text{miss}}))},$$

where  $\ell_i$  can be either the leading or the subleading lepton. The “outside lepton veto” requires the two leptons to reside within the rapidity gap spanned by the two leading jets, and the “central jet veto” rejects events with additional jets with  $p_T > 20$  GeV in the rapidity gap between the two leading jets. In the  $N_{\text{jet}}=1$  and  $N_{\text{jet}} \geq 2$  categories, the invariant mass of the  $\tau$ -lepton pair ( $m_{\tau\tau}$ ), calculated using the collinear approximation [71], is used to veto background from  $Z \rightarrow \tau\tau$  production. Signal regions (SRs) are defined in each  $N_{\text{jet}}$  category after applying all selection criteria. For both the  $N_{\text{jet}}=0$  and  $N_{\text{jet}}=1$  ggF SRs, eight regions, later used for the fit, are defined by subdividing in  $m_{\ell\ell}$  at  $m_{\ell\ell} < 30$  GeV and  $m_{\ell\ell} \geq 30$  GeV, in  $p_T$  of the subleading lepton at  $p_T^{\text{sublead}} < 20$  GeV and  $p_T^{\text{sublead}} \geq 20$  GeV, and by the flavour of the subleading lepton. For the categories with zero jets and with exactly one jet, the discriminating variable between signal and SM background processes is the dilepton

$$\text{transverse mass, defined as } m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$$

where  $E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$  and  $\mathbf{p}_T^{\ell\ell}$  is the vector sum of the lepton transverse momenta. The discriminating variable  $m_T$  is used in the ggF SRs, with eight bins for the  $N_{\text{jet}}=0$  and six bins for the  $N_{\text{jet}}=1$  regions. The bin boundaries are chosen such that approximately the same number of signal events is expected in each bin. The  $m_T$  distributions for the  $N_{\text{jet}}=0$  and  $N_{\text{jet}}=1$  SRs are shown in Fig. 3. All figures in this Letter, except Fig. 2, use signal and background normalisations as fitted by the final statistical analysis of all signal and control regions, including pulls of statistical and systematic uncertainty parameters (post-fit). For the  $N_{\text{jet}} \geq 2$  VBF selection, a boosted decision tree (BDT) [72] is used to enhance discrimination power between the VBF signal and backgrounds, including the ggF process. Kinematic variables of the two leading jets ( $j$ ) and the two leading leptons ( $\ell$ ) are used as inputs to the BDT: the invariant masses ( $m_{jj}$ ,  $m_{\ell\ell}$ ), the difference between the two jet rapidities ( $\Delta y_{jj}$ ), and the difference between the azimuthal angles of the two leptons ( $\Delta\phi_{\ell\ell}$ ). Other variables used in the BDT training are:  $m_T$ , the lepton  $\eta$ -centrality ( $\sum_\ell C_\ell$ , where  $C_\ell = |2\eta_\ell - \sum_j \eta_j| / \Delta\eta_{jj}$ ), which quantifies the positions of the leptons relative to the leading jets in pseudorapidity [73], the sum of the invariant masses of all four possible lepton–jet pairs ( $\sum_{\ell,j} m_{\ell j}$ ), and the total transverse momentum ( $p_T^{\text{tot}}$ ), which is defined as the magnitude of the vectorial sum of all selected objects. The observables providing the best discrimination between signal and background are  $m_{jj}$  and  $\Delta y_{jj}$ , and are shown in Fig. 4 after applying all selections. The BDT score reflects the compatibility of an event with VBF-like kinematics. Signal-like events would tend to have high BDT score, while background-like events tend to have low BDT score. The signal purity, therefore, increases at high values of BDT score. The BDT score is used as the discriminating variable in the statistical analysis with four bins. The bin boundaries are chosen to maximise the expected sensitivity for the VBF production mode, resulting in smaller bin widths for larger values of the BDT score. In the highest-score BDT bin, the expected signal-to-background ratio of the VBF signal is approximately 0.6. The BDT distribution for the VBF-enriched region is presented in Fig. 5.

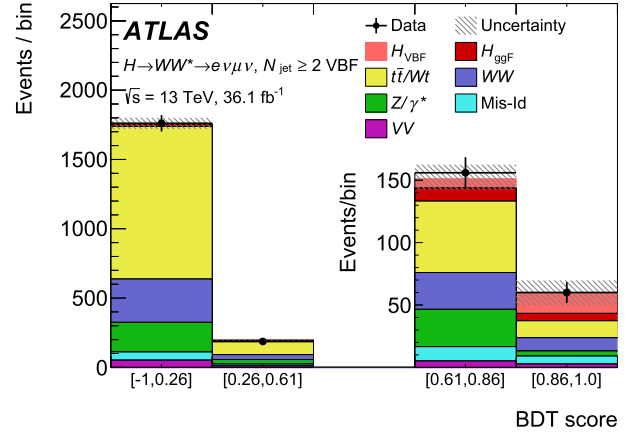
## 5. Background estimation

The background contamination in the SRs originates from various processes: non-resonant  $WW$ , top-quark pair ( $t\bar{t}$ ) and single-top-quark ( $Wt$ ), diboson ( $WZ$ ,  $ZZ$ ,  $W\gamma$  and  $W\gamma^*$ ) and Drell–Yan (mainly  $Z \rightarrow \tau\tau$ , hereafter denoted  $Z/\gamma^*$ ) production. Other back-

**Table 4**

Post-fit normalisation factors which scale the corresponding estimated yields in the signal region; the dash indicates where MC-based normalisation is used. The errors include the statistical and systematic uncertainties.

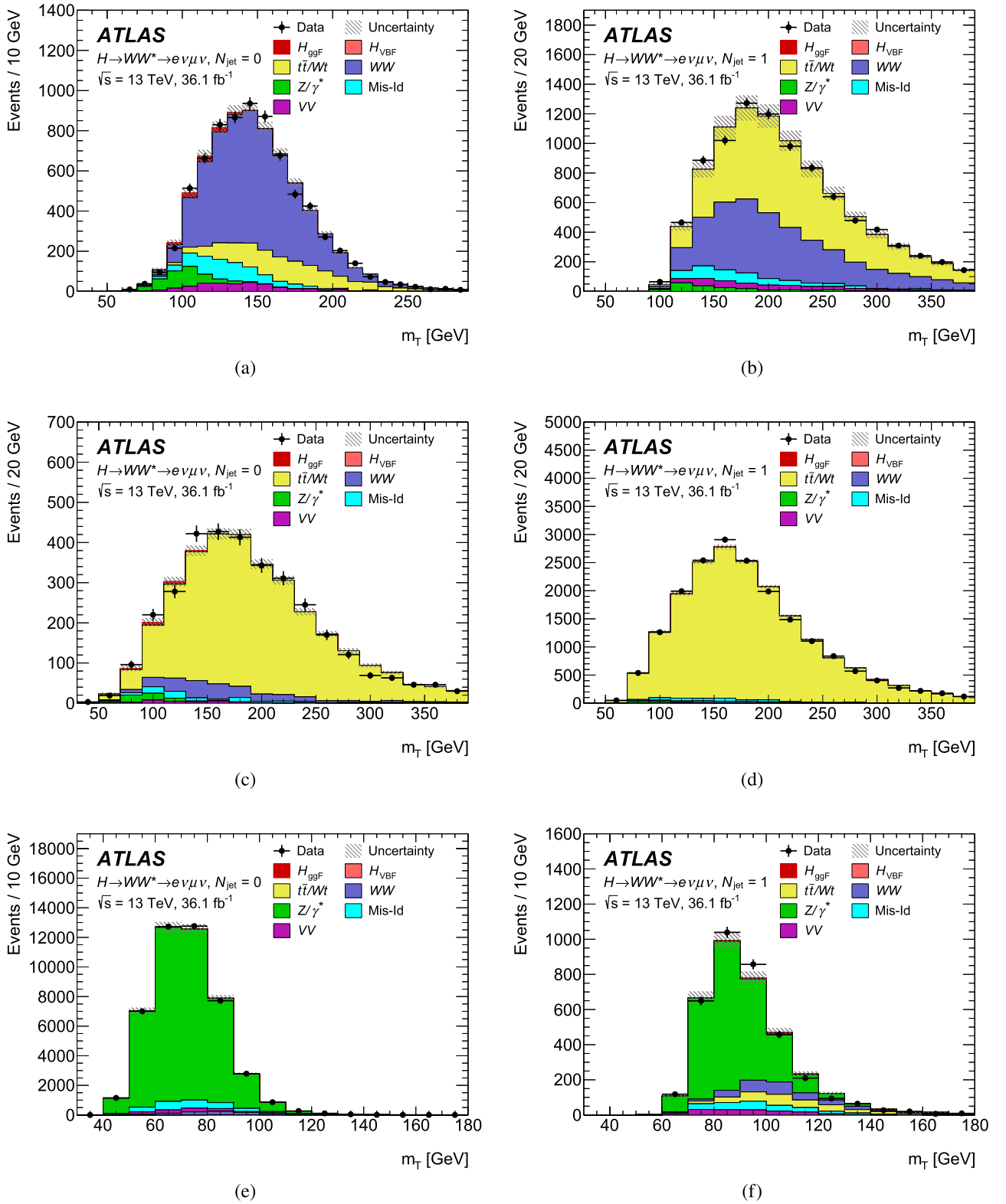
Category	$WW$	$t\bar{t}/Wt$	$Z/\gamma^*$
$N_{\text{jet},(p_T > 30 \text{ GeV})} = 0$ ggF	$1.06 \pm 0.09$	$0.99 \pm 0.17$	$0.84 \pm 0.04$
$N_{\text{jet},(p_T > 30 \text{ GeV})} = 1$ ggF	$0.97 \pm 0.17$	$0.98 \pm 0.08$	$0.90 \pm 0.12$
$N_{\text{jet},(p_T > 30 \text{ GeV})} \geq 2$ VBF	–	$1.01 \pm 0.01$	$0.93 \pm 0.07$



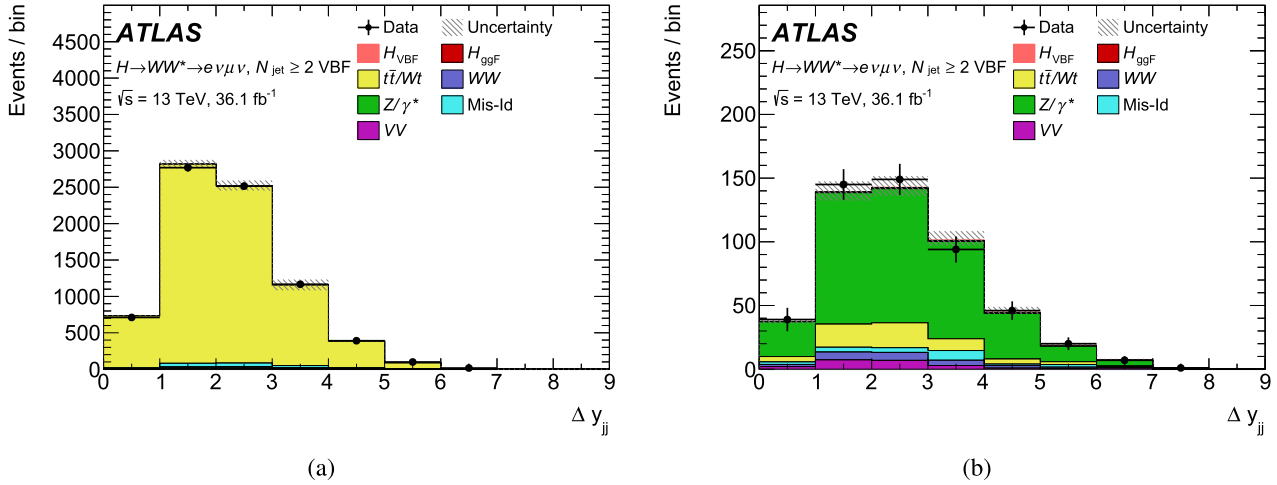
**Fig. 5.** Post-fit BDT score distribution with the signal and the background modelled contributions in the VBF signal region. The hatched band shows the total uncertainty of the signal and background modelled contributions.

ground contributions arise from  $W$  + jets and multi-jet production with misidentified leptons, which are either non-prompt leptons from decays of heavy-flavour hadrons or jets faking prompt leptons. Dedicated regions in data, identified hereafter as control regions (CRs), are used to normalise the predictions of some of the background processes. CRs are defined for the main background processes:  $WW$  (only for  $N_{\text{jet}} \leq 1$  final states),  $t\bar{t}/Wt$ , and  $Z/\gamma^*$ . Table 3 summarises the event selection for all CRs. For the  $N_{\text{jet}}=0$  and  $N_{\text{jet}}=1$   $WW$  CRs,  $m_{\ell\ell}$  selections orthogonal to those of the SRs are applied. For the  $t\bar{t}/Wt$  CRs, the  $b$ -veto is replaced with a  $b$ -tag requirement. For the  $N_{\text{jet}}=1$  and  $N_{\text{jet}} \geq 2$  VBF  $Z/\gamma^*$  CRs, the  $m_{\tau\tau}$  selection is inverted, while for the  $N_{\text{jet}}=0$   $Z/\gamma^*$  CR the  $\Delta\phi_{\ell\ell}$  selection criterion is inverted. Fig. 6 presents the post-fit  $m_T$  distributions in the  $N_{\text{jet}}=0$  and  $N_{\text{jet}}=1$  CRs.

In Fig. 7, the post-fit  $\Delta y_{jj}$  distributions in the  $N_{\text{jet}} \geq 2$  VBF CRs are shown. Data and simulation are in agreement within uncertainties for all the relevant distributions in the different CRs. The background contributions with misidentified leptons are estimated using a data-driven technique. A control sample where one of the two lepton candidates fails to meet the nominal identification and isolation criteria but satisfies looser identification criteria, referred to as an anti-identified lepton, is used. The contribution of this background in the SRs and CRs is then obtained by scaling the number of data events, after the subtraction of processes with two prompt leptons, in the control samples by an extrapolation factor. The latter is measured in a  $Z$ +jets-enriched data sample, where the  $Z$  boson decays to a pair of electrons or muons, and the misidentified lepton candidate recoils against the  $Z$  boson. The extrapolation factor is defined as the ratio of the numbers of identified and anti-identified leptons, and is measured in bins of  $p_T$  and  $\eta$ . Furthermore, a sample composition correction factor is applied separately in  $p_T < 25$  GeV and  $p_T > 25$  GeV bins, and is defined in each bin as the ratio of the extrapolation factors measured in  $W$ +jets and  $Z$ +jets MC simulation. The total uncertainty of the background with misidentified leptons includes uncertainties due to the difference in sample composition between the



**Fig. 6.** Post-fit  $m_T$  distributions with signal and background modelled contributions in the  $N_{\text{jet}} = 0$  and  $N_{\text{jet}} = 1$  control regions for the WW (a, b),  $t\bar{t}/Wt$  (c, d), and  $Z/\gamma^*$  (e, f) processes. The hatched band shows the total uncertainty of the signal and background modelled contributions. Some contributions are too small to be visible.



**Fig. 7.** Post-fit  $\Delta y_{jj}$  distribution with signal and background modelled contributions in the (a)  $t\bar{t}/Wt$  and (b)  $Z/\gamma^*$  control regions in the  $N_{\text{jet}} \geq 2$  VBF analysis category. The hatched band shows the total uncertainty of the signal and background modelled contributions. Some contributions are too small to be visible.

$W$ +jets and  $Z$ +jets control samples determined with MC simulation, the statistical uncertainty of the  $Z$ +jets control sample, and the subtraction of other processes. In the VBF regions, the background estimation is corrected for the contamination from events with two misidentified leptons, whose origin is largely multi-jet events. This contribution is negligible in other regions. Details of this method can be found in Ref. [1].

The post-fit background normalisation factors are summarised in Table 4. The  $Z/\gamma^*$  normalisation factors are affected by residual misalignments in the inner detector which distort the measurements of the track parameters for particles originating from secondary vertices e.g. leptons from  $\tau$  decays.

## 6. Systematic uncertainties

The sources of uncertainty can be classified into two categories: experimental and theoretical. The dominant experimental uncertainties are the jet energy scale and resolution [74], and the  $b$ -tagging efficiency [75]. Other sources of uncertainty are lepton energy (momentum) scale and resolution, identification and isolation [63,64,76], missing transverse momentum measurement [77], modelling of pile-up, and luminosity measurement [78]. The luminosity uncertainty is only applied to the Higgs boson signal and to background processes that are normalised to theoretical predictions. For the main processes, the theoretical uncertainties are assessed by a comparison between nominal and alternative event generators and UEPS models, as indicated in Table 1. For the prediction of  $WZ$ ,  $ZZ$ ,  $V\gamma^*$ , and  $V\gamma$  production ( $VV$ ), variations of the matching scale are considered instead of an alternative generator. In addition, the effects of QCD factorisation and renormalisation scale variations and PDF model uncertainties are evaluated.

## 7. Signal region yields and results

The ggF and VBF cross-sections are obtained from a simultaneous statistical analysis of the data samples in all SRs and CRs by maximising a likelihood function in a fit using scaling parameters multiplying the predicted total production cross-section of each signal process and applying the profile likelihood method. The CRs are used to determine the normalisation of the corresponding backgrounds. The systematic uncertainties enter the fit as nuisance parameters in the likelihood function.

Table 5 shows the post-fit yields for all of the three SRs. Yields in the highest-score VBF BDT bin are also given. The uncertainties in the total yields are smaller than those of some of the individ-

**Table 5**

Post-fit MC and data yields in the ggF and VBF SRs. Yields in the highest-score VBF BDT bin are also presented. The quoted uncertainties include the theoretical and experimental systematic sources and those due to sample statistics. The sum of all the contributions may differ from the total value due to rounding. Moreover, the total uncertainty differs from the sum in quadrature of the single-process uncertainties due to the correlations.

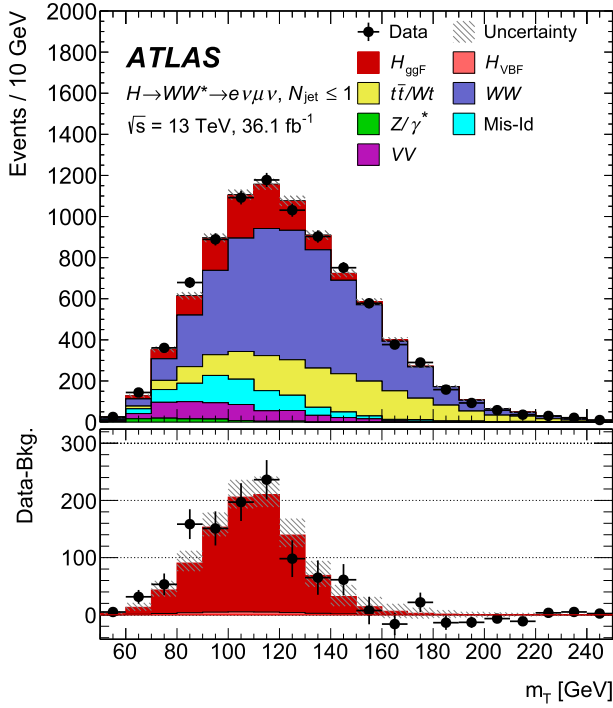
Process	$N_{\text{jet}} = 0$ ggF	$N_{\text{jet}} = 1$ ggF	$N_{\text{jet}} \geq 2$ VBF	
			Inclusive	BDT: [0.86, 1.0]
$H_{\text{ggF}}$	$639 \pm 110$	$285 \pm 51$	$42 \pm 16$	$6 \pm 3$
$H_{\text{VBF}}$	$7 \pm 1$	$31 \pm 2$	$28 \pm 16$	$16 \pm 6$
$WW$	$3016 \pm 203$	$1053 \pm 206$	$400 \pm 60$	$11 \pm 2$
$VV$	$333 \pm 38$	$208 \pm 32$	$70 \pm 12$	$3 \pm 1$
$t\bar{t}/Wt$	$588 \pm 130$	$1397 \pm 179$	$1270 \pm 80$	$14 \pm 2$
Mis-Id	$447 \pm 77$	$234 \pm 49$	$90 \pm 30$	$6 \pm 2$
$Z/\gamma^*$	$27 \pm 11$	$76 \pm 24$	$280 \pm 40$	$4 \pm 1$
Total	$5067 \pm 80$	$3296 \pm 61$	$2170 \pm 50$	$60 \pm 10$
Observed	5089	3264	2164	60

ual background processes. This effect is due to correlations among different data regions, background processes, and nuisance parameters. The correlations are imposed by the fit as it constrains the total yield to match the data. For example, for the  $b$ -tagging efficiency, which is the main source of uncertainty in the  $t\bar{t}/Wt$  yields in the SRs as well as in  $WW$  CRs, the combination of these two regions in the statistical analysis leads to an anti-correlation between the SR yields of the  $WW$  and  $t\bar{t}/Wt$  backgrounds. Changes in the  $b$ -tagging efficiency simultaneously increase/decrease the yields of  $t\bar{t}/Wt$  and  $WW$  backgrounds, resulting in a small uncertainty in the combined yields of the processes but large uncertainties in the individual components.

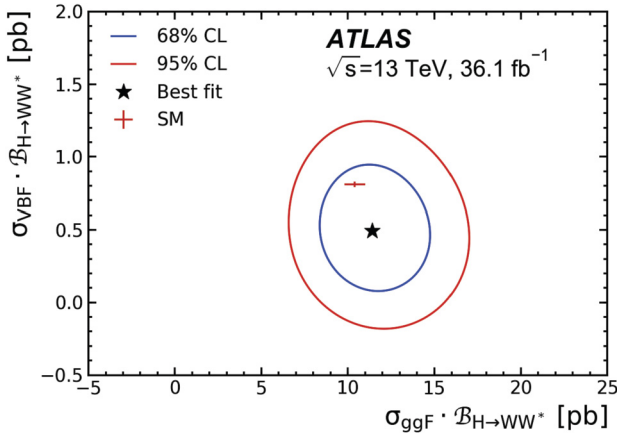
Fig. 8 shows the combined  $m_T$  distribution for  $N_{\text{jet}} \leq 1$ . The bottom panel of Fig. 8 shows the difference between the data and the total estimated background compared to the  $m_T$  distribution of a SM Higgs boson with  $m_H = 125$  GeV. The total signal observed (see Table 5) of about 1000 events is in agreement, in both shape and rate, with the expected SM signal. The cross-section times branching fractions,  $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$  and  $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$ , are simultaneously determined to be:

$$\begin{aligned} \sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 11.4_{-1.1}^{+1.2} (\text{stat.})_{-1.1}^{+1.2} (\text{theo syst.})_{-1.3}^{+1.4} (\text{exp syst.}) \text{ pb} \\ &= 11.4_{-2.1}^{+2.2} \text{ pb} \end{aligned}$$





**Fig. 8.** Post-fit combined transverse mass distribution for  $N_{\text{jet}} \leq 1$ . The bottom panel shows the difference between the data and the estimated background compared to the distribution for a SM Higgs boson with  $m_H = 125$  GeV. The signal and the background modelled contributions are fitted to the data with a floating signal strength. The hatched band shows the total uncertainty of the signal and background modelled contributions. The  $H_{\text{VBF}}$  contribution is too small to be visible.



**Fig. 9.** 68% and 95% confidence level two-dimensional likelihood contours of  $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$  vs.  $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$ , compared to the SM prediction shown by the red marker. The error bars on the SM prediction represent the ggF and VBF theory uncertainty [23], respectively.

$$\begin{aligned} \sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 0.50_{-0.22}^{+0.24}(\text{stat.}) \pm 0.10(\text{theo syst.})_{-0.13}^{+0.12}(\text{exp syst.}) \text{ pb} \\ &= 0.50_{-0.28}^{+0.29} \text{ pb.} \end{aligned}$$

The predicted cross-section times branching fraction values are  $10.4 \pm 0.6$  pb and  $0.81 \pm 0.02$  pb for ggF and VBF [23], respectively. The 68% and 95% confidence level two-dimensional contours of  $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$  and  $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$  are shown in Fig. 9 and are consistent with the SM predictions.

The signal strength parameter  $\mu$  is defined as the ratio of the measured signal yield to that predicted by the SM. The measured

**Table 6**

Breakdown of the main contributions to the total uncertainty in  $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$  and  $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$ . The individual sources of systematic uncertainties are grouped together. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components.

Source	$\Delta\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$ [%]	$\Delta\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$ [%]
Data statistics	10	46
CR statistics	7	9
MC statistics	6	21
Theoretical uncertainties	10	19
ggF signal	5	13
VBF signal	<1	4
WW	6	12
Top-quark	5	5
Experimental uncertainties	8	9
b-tagging	4	6
Modelling of pile-up	5	2
Jet	2	2
Lepton	3	<1
Misidentified leptons	6	9
Luminosity	3	3
TOTAL	18	57

signal strengths for the ggF and VBF production modes in the  $H \rightarrow WW^*$  decay channel are simultaneously determined to be

$$\begin{aligned} \mu_{\text{ggF}} &= 1.10_{-0.09}^{+0.10}(\text{stat.})_{-0.11}^{+0.13}(\text{theo syst.})_{-0.13}^{+0.14}(\text{exp syst.}) \\ &= 1.10_{-0.20}^{+0.21} \\ \mu_{\text{VBF}} &= 0.62_{-0.27}^{+0.29}(\text{stat.})_{-0.13}^{+0.12}(\text{theo syst.}) \pm 0.15(\text{exp syst.}) \\ &= 0.62_{-0.35}^{+0.36}. \end{aligned}$$

Table 6 shows the relative impact of the main uncertainties on the measured values for  $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$  and  $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*}$ . The theory uncertainties in the non-resonant WW background produce one of the largest uncertainties, of the order of 6%, in the measured ggF cross-section. The uncertainty in the ratio of  $gg \rightarrow WW$  to  $qq \rightarrow WW$  comes from the limited NLO accuracy of the  $gg \rightarrow WW$  production cross-section [38]. The resulting uncertainty in the cross-section when using acceptance criteria similar to those in this analysis was evaluated in Ref. [79] for  $N_{\text{jet}}=0$  and for  $N_{\text{jet}} \geq 2$  VBF SR, the 12% uncertainty in the WW background originates from the matching and UEPS modelling of  $qq \rightarrow WW$ . The amount of ggF contamination in the VBF region is subject to QCD scale uncertainties and this produces an uncertainty of about 13% in the measured VBF cross-section. The statistical uncertainty of the MC simulation has a relatively large impact, especially for the VBF cross-section measurement, where it contributes 21%.

The observed (expected) ggF and VBF signals have significances of 6.0 (5.3) and 1.8 (2.6) standard deviations, respectively.

## 8. Conclusions

Measurements of the inclusive cross-section of Higgs boson production via the gluon-gluon fusion (ggF) and vector-boson fusion (VBF) modes in the  $H \rightarrow WW^*$  decay channel are presented. They are based on  $36.1 \text{ fb}^{-1}$  of  $\sqrt{s} = 13$  TeV proton-proton collisions recorded by the ATLAS detector at the LHC in 2015–2016. The ggF and VBF cross-sections times the  $H \rightarrow WW^*$  branching ratio are measured to be  $11.4_{-1.1}^{+1.2}(\text{stat.})_{-1.7}^{+1.8}(\text{syst.})$  pb and  $0.50_{-0.22}^{+0.24}(\text{stat.}) \pm 0.17(\text{syst.})$  pb, respectively, in agreement with SM prediction.

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M. Aaboud<sup>34d</sup>, G. Aad<sup>99</sup>, B. Abbott<sup>124</sup>, O. Abdinov<sup>13,\*</sup>, B. Abeloos<sup>128</sup>, D.K. Abhayasinghe<sup>91</sup>, S.H. Abidi<sup>164</sup>, O.S. AbouZeid<sup>39</sup>, N.L. Abraham<sup>153</sup>, H. Abramowicz<sup>158</sup>, H. Abreu<sup>157</sup>, Y. Abulaiti<sup>6</sup>, B.S. Acharya<sup>64a,64b,n</sup>, S. Adachi<sup>160</sup>, L. Adam<sup>97</sup>, L. Adamczyk<sup>81a</sup>, J. Adelman<sup>119</sup>, M. Adersberger<sup>112</sup>, A. Adiguzel<sup>12c,ag</sup>, T. Adye<sup>141</sup>, A.A. Affolder<sup>143</sup>, Y. Afik<sup>157</sup>, C. Agheorghiesei<sup>27c</sup>, J.A. Aguilar-Saavedra<sup>136f,136a</sup>, F. Ahmadov<sup>77,ae</sup>, G. Aielli<sup>71a,71b</sup>, S. Akatsuka<sup>83</sup>, T.P.A. Åkesson<sup>94</sup>, E. Akilli<sup>52</sup>, A.V. Akimov<sup>108</sup>, G.L. Alberghi<sup>23b,23a</sup>, J. Albert<sup>173</sup>, P. Albicocco<sup>49</sup>, M.J. Alconada Verzini<sup>86</sup>, S. Alderweireldt<sup>117</sup>, M. Aleksa<sup>35</sup>, I.N. Aleksandrov<sup>77</sup>, C. Alexa<sup>27b</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>124</sup>, B. Ali<sup>138</sup>, G. Alimonti<sup>66a</sup>, J. Alison<sup>36</sup>, S.P. Alkire<sup>145</sup>, C. Allaire<sup>128</sup>, B.M.M. Allbrooke<sup>153</sup>, B.W. Allen<sup>127</sup>, P.P. Allport<sup>21</sup>, A. Aloisio<sup>67a,67b</sup>, A. Alonso<sup>39</sup>, F. Alonso<sup>86</sup>, C. Alpigiani<sup>145</sup>, A.A. Alshehri<sup>55</sup>, M.I. Alstaty<sup>99</sup>, B. Alvarez Gonzalez<sup>35</sup>, D. Álvarez Piqueras<sup>171</sup>, M.G. Alviggi<sup>67a,67b</sup>, B.T. Amadio<sup>18</sup>, Y. Amaral Coutinho<sup>78b</sup>, A. Ambler<sup>101</sup>, L. Ambroz<sup>131</sup>, C. Amelung<sup>26</sup>, D. Amidei<sup>103</sup>,

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Bartoldus <sup>150</sup>, A.E. Barton <sup>87</sup>, P. Bartos <sup>28a</sup>, A. Basalaev <sup>134</sup>, A. Bassalat <sup>128</sup>, R.L. Bates <sup>55</sup>, S.J. Batista <sup>164</sup>, S. Batlamous <sup>34e</sup>, J.R. Batley <sup>31</sup>, M. Battaglia <sup>143</sup>, M. Baucé <sup>70a,70b</sup>, F. Bauer <sup>142</sup>, K.T. Bauer <sup>168</sup>, H.S. Bawa <sup>150,l</sup>, J.B. Beacham <sup>122</sup>, T. Beau <sup>132</sup>, P.H. Beauchemin <sup>167</sup>, P. Bechtel <sup>24</sup>, H.C. Beck <sup>51</sup>, H.P. Beck <sup>20,q</sup>, K. Becker <sup>50</sup>, M. Becker <sup>97</sup>, C. Becot <sup>44</sup>, A. Beddall <sup>12d</sup>, A.J. Beddall <sup>12a</sup>, V.A. Bednyakov <sup>77</sup>, M. Bedognetti <sup>118</sup>, C.P. Bee <sup>152</sup>, T.A. Beermann <sup>35</sup>, M. Begalli <sup>78b</sup>, M. Begel <sup>29</sup>, A. Behera <sup>152</sup>, J.K. Behr <sup>44</sup>, A.S. Bell <sup>92</sup>, G. Bella <sup>158</sup>, L. Bellagamba <sup>23b</sup>, A. 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V.B. Vinogradov<sup>77</sup>, A. Vishwakarma<sup>44</sup>, C. Vittori<sup>23b,23a</sup>, I. Vivarelli<sup>153</sup>, S. Vlachos<sup>10</sup>, M. Vogel<sup>179</sup>, P. Vokac<sup>138</sup>, G. Volpi<sup>14</sup>, S.E. von Buddenbrock<sup>32c</sup>, E. Von Toerne<sup>24</sup>, V. Vorobel<sup>139</sup>, K. Vorobev<sup>110</sup>, M. Vos<sup>171</sup>, J.H. Vosseveld<sup>88</sup>, N. Vranjes<sup>16</sup>, M. Vranjes Milosavljevic<sup>16</sup>, V. Vrba<sup>138</sup>, M. Vreeswijk<sup>118</sup>, T. Šfiligoj<sup>89</sup>, R. Vuillermet<sup>35</sup>, I. Vukotic<sup>36</sup>, T. Ženiš<sup>28a</sup>, L. Živković<sup>16</sup>, P. Wagner<sup>24</sup>, W. Wagner<sup>179</sup>, J. Wagner-Kuhr<sup>112</sup>, H. Wahlberg<sup>86</sup>, S. Wahrmund<sup>46</sup>, K. Wakamiya<sup>80</sup>, V.M. Walbrecht<sup>113</sup>, J. Walder<sup>87</sup>, R. Walker<sup>112</sup>, S.D. Walker<sup>91</sup>, W. Walkowiak<sup>148</sup>, V. Wallangen<sup>43a,43b</sup>, A.M. Wang<sup>57</sup>, C. Wang<sup>58b,d</sup>, F. Wang<sup>178</sup>, H. Wang<sup>18</sup>, H. Wang<sup>3</sup>, J. Wang<sup>154</sup>, J. Wang<sup>59b</sup>, P. Wang<sup>41</sup>, Q. Wang<sup>124</sup>, R.-J. Wang<sup>132</sup>, R. Wang<sup>58a</sup>, R. Wang<sup>6</sup>, S.M. Wang<sup>155</sup>, W.T. Wang<sup>58a</sup>, W. Wang<sup>15c,ad</sup>, W.X. Wang<sup>58a,ad</sup>, Y. Wang<sup>58a</sup>, Z. Wang<sup>58c</sup>, C. Wanotayaroj<sup>44</sup>, A. Warburton<sup>101</sup>, C.P. Ward<sup>31</sup>, D.R. Wardrope<sup>92</sup>, A. Washbrook<sup>48</sup>, P.M. Watkins<sup>21</sup>, A.T. Watson<sup>21</sup>, M.F. Watson<sup>21</sup>, G. Watts<sup>145</sup>, S. Watts<sup>98</sup>, B.M. Waugh<sup>92</sup>, A.F. Webb<sup>11</sup>, S. Webb<sup>97</sup>, C. Weber<sup>180</sup>, M.S. Weber<sup>20</sup>, S.A. Weber<sup>33</sup>, S.M. Weber<sup>59a</sup>, A.R. Weidberg<sup>131</sup>, B. Weinert<sup>63</sup>, J. Weingarten<sup>51</sup>, M. Weirich<sup>97</sup>, C. Weiser<sup>50</sup>, P.S. Wells<sup>35</sup>, T. Wenaus<sup>29</sup>, T. Wengler<sup>35</sup>, S. Wenig<sup>35</sup>, N. Wermes<sup>24</sup>, M.D. Werner<sup>76</sup>, P. Werner<sup>35</sup>, M. Wessels<sup>59a</sup>, T.D. Weston<sup>20</sup>, K. Whalen<sup>127</sup>, N.L. Whallon<sup>145</sup>, A.M. Wharton<sup>87</sup>, A.S. White<sup>103</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, R. White<sup>144b</sup>, D. Whiteson<sup>168</sup>, B.W. Whitmore<sup>87</sup>, F.J. Wickens<sup>141</sup>, W. Wiedenmann<sup>178</sup>, M. Wielers<sup>141</sup>, C. Wiglesworth<sup>39</sup>, L.A.M. Wiik-Fuchs<sup>50</sup>, F. Wilk<sup>98</sup>, H.G. Wilkens<sup>35</sup>, L.J. Wilkins<sup>91</sup>, H.H. Williams<sup>133</sup>, S. Williams<sup>31</sup>, C. Willis<sup>104</sup>, S. Willocq<sup>100</sup>, J.A. Wilson<sup>21</sup>, I. Wingerter-Seez<sup>5</sup>, E. Winkels<sup>153</sup>, F. Winklmeier<sup>127</sup>, O.J. Winston<sup>153</sup>, B.T. Winter<sup>24</sup>, M. Wittgen<sup>150</sup>, M. Wobisch<sup>93</sup>, A. Wolf<sup>97</sup>, T.M.H. Wolf<sup>118</sup>, R. Wolff<sup>99</sup>, M.W. Wolter<sup>82</sup>, H. Wolters<sup>136a,136c</sup>, V.W.S. Wong<sup>172</sup>, N.L. Woods<sup>143</sup>, S.D. Worm<sup>21</sup>, B.K. Wosiek<sup>82</sup>, K.W. Woźniak<sup>82</sup>, K. Wraight<sup>55</sup>, M. Wu<sup>36</sup>, S.L. Wu<sup>178</sup>, X. Wu<sup>52</sup>, Y. Wu<sup>58a</sup>, T.R. Wyatt<sup>98</sup>, B.M. Wynne<sup>48</sup>, S. Xella<sup>39</sup>, Z. Xi<sup>103</sup>, L. Xia<sup>175</sup>, D. Xu<sup>15a</sup>, H. Xu<sup>58a</sup>, L. Xu<sup>29</sup>, T. Xu<sup>142</sup>, W. Xu<sup>103</sup>, B. Yabsley<sup>154</sup>, S. Yacoob<sup>32a</sup>, K. Yajima<sup>129</sup>, D.P. Yallup<sup>92</sup>, D. Yamaguchi<sup>162</sup>, Y. Yamaguchi<sup>162</sup>, A. Yamamoto<sup>79</sup>, T. Yamanaka<sup>160</sup>, F. Yamane<sup>80</sup>, M. Yamatani<sup>160</sup>, T. Yamazaki<sup>160</sup>, Y. Yamazaki<sup>80</sup>, Z. Yan<sup>25</sup>, H.J. Yang<sup>58c,58d</sup>, H.T. Yang<sup>18</sup>, S. Yang<sup>75</sup>, Y. Yang<sup>160</sup>, Z. Yang<sup>17</sup>, W.-M. Yao<sup>18</sup>, Y.C. Yap<sup>44</sup>, Y. Yasu<sup>79</sup>, E. Yatsenko<sup>58c,58d</sup>, J. Ye<sup>41</sup>, S. Ye<sup>29</sup>, I. Yeletsikh<sup>77</sup>, E. Yigitbasi<sup>25</sup>, E. Yildirim<sup>97</sup>, K. Yorita<sup>176</sup>, K. Yoshihara<sup>133</sup>, C.J.S. Young<sup>35</sup>, C. Young<sup>150</sup>, J. Yu<sup>8</sup>, J. Yu<sup>76</sup>, X. Yue<sup>59a</sup>, S.P.Y. Yuen<sup>24</sup>, B. Zabinski<sup>82</sup>, G. Zacharis<sup>10</sup>, E. Zaffaroni<sup>52</sup>, R. Zaidan<sup>14</sup>, A.M. Zaitsev<sup>140,ak</sup>, T. Zakareishvili<sup>156b</sup>, N. Zakharchuk<sup>33</sup>, J. Zalieckas<sup>17</sup>, S. Zambito<sup>57</sup>, D. Zanzi<sup>35</sup>, D.R. Zariповas<sup>55</sup>, S.V. Zeiřner<sup>45</sup>, C. Zeitnitz<sup>179</sup>, G. Zemaityte<sup>131</sup>, J.C. Zeng<sup>170</sup>, Q. Zeng<sup>150</sup>, O. Zenin<sup>140</sup>, D. Zerwas<sup>128</sup>, M. Zgubić<sup>131</sup>, D.F. Zhang<sup>58b</sup>, D. Zhang<sup>103</sup>, F. Zhang<sup>178</sup>, G. Zhang<sup>58a</sup>, H. Zhang<sup>15c</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>15c</sup>, L. Zhang<sup>58a</sup>, M. Zhang<sup>170</sup>, P. Zhang<sup>15c</sup>, R. Zhang<sup>58a</sup>, R. Zhang<sup>24</sup>, X. Zhang<sup>58b</sup>, Y. Zhang<sup>15d</sup>, Z. Zhang<sup>128</sup>, X. Zhao<sup>41</sup>, Y. Zhao<sup>58b,128,ah</sup>, Z. Zhao<sup>58a</sup>, A. Zhemchugov<sup>77</sup>, Z. Zheng<sup>103</sup>, D. Zhong<sup>170</sup>, B. Zhou<sup>103</sup>, C. Zhou<sup>178</sup>, L. Zhou<sup>41</sup>, M.S. Zhou<sup>15d</sup>, M. Zhou<sup>152</sup>, N. Zhou<sup>58c</sup>, Y. Zhou<sup>7</sup>, C.G. Zhu<sup>58b</sup>, H.L. Zhu<sup>58a</sup>, H. Zhu<sup>15a</sup>, J. Zhu<sup>103</sup>, Y. Zhu<sup>58a</sup>, X. Zhuang<sup>15a</sup>, K. Zhukov<sup>108</sup>, V. Zhulanov<sup>120b,120a</sup>, A. Zibell<sup>174</sup>, D. Zieminska<sup>63</sup>, N.I. Zimine<sup>77</sup>, S. Zimmermann<sup>50</sup>, Z. Zinonos<sup>113</sup>, M. Zinser<sup>97</sup>, M. Ziolkowski<sup>148</sup>, G. Zobernig<sup>178</sup>, A. Zoccoli<sup>23b,23a</sup>, K. Zoch<sup>51</sup>, T.G. Zorbas<sup>146</sup>, R. Zou<sup>36</sup>, M. Zur Nedden<sup>19</sup>, L. Zwalinski<sup>35</sup>

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany NY, United States of America

<sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

<sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America

<sup>8</sup> Department of Physics, University of Texas at Arlington, Arlington TX, United States of America

<sup>9</sup> Physics Department, National and Kapodistrian University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup> Department of Physics, University of Texas at Austin, Austin TX, United States of America

<sup>12</sup> (a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (c) Department of Physics, Bogazici University, Istanbul; (d) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

<sup>13</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>14</sup> Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain

<sup>15</sup> (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing;

(d) University of Chinese Academy of Science (UCAS), Beijing, China

<sup>16</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia

<sup>17</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>18</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

<sup>19</sup> Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany

<sup>20</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>21</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>22</sup> Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia

- 23 <sup>(a)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; <sup>(b)</sup> INFN Sezione di Bologna, Italy
- 24 Physikalisches Institut, Universität Bonn, Bonn, Germany
- 25 Department of Physics, Boston University, Boston MA, United States of America
- 26 Department of Physics, Brandeis University, Waltham MA, United States of America
- 27 <sup>(a)</sup> Transilvania University of Brasov, Brasov; <sup>(b)</sup> Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; <sup>(d)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; <sup>(e)</sup> University Politehnica Bucharest, Bucharest; <sup>(f)</sup> West University in Timisoara, Timisoara, Romania
- 28 <sup>(a)</sup> Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 29 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- 30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- 31 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- 32 <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 33 Department of Physics, Carleton University, Ottawa ON, Canada
- 34 <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l’Energie des Sciences Techniques Nucleaires (CNSTEN), Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V, Rabat, Morocco
- 35 CERN, Geneva, Switzerland
- 36 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- 37 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- 38 Nevis Laboratory, Columbia University, Irvington NY, United States of America
- 39 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- 40 <sup>(a)</sup> Dipartimento di Fisica, Università della Calabria, Rende; <sup>(b)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- 41 Physics Department, Southern Methodist University, Dallas TX, United States of America
- 42 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- 43 <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> Oskar Klein Centre, Stockholm, Sweden
- 44 Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- 45 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- 46 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- 47 Department of Physics, Duke University, Durham NC, United States of America
- 48 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- 49 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- 50 Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- 51 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- 52 Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- 53 <sup>(a)</sup> Dipartimento di Fisica, Università di Genova, Genova; <sup>(b)</sup> INFN Sezione di Genova, Italy
- 54 II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- 55 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- 56 LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- 57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- 58 <sup>(a)</sup> Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; <sup>(b)</sup> Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; <sup>(c)</sup> School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; <sup>(d)</sup> Tsung-Dao Lee Institute, Shanghai, China
- 59 <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- 60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 61 <sup>(a)</sup> Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- 62 Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- 63 Department of Physics, Indiana University, Bloomington IN, United States of America
- 64 <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 65 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 66 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- 67 <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- 68 <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 69 <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 70 <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 71 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 72 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 73 <sup>(a)</sup> INFN-TIFPA; <sup>(b)</sup> Università degli Studi di Trento, Trento, Italy
- 74 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 75 University of Iowa, Iowa City IA, United States of America
- 76 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- 77 Joint Institute for Nuclear Research, Dubna, Russia
- 78 <sup>(a)</sup> Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; <sup>(b)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(c)</sup> Universidade Federal de São João del Rei (UFSJ), São João del Rei; <sup>(d)</sup> Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
- 79 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 80 Graduate School of Science, Kobe University, Kobe, Japan
- 81 <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- 82 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- 83 Faculty of Science, Kyoto University, Kyoto, Japan
- 84 Kyoto University of Education, Kyoto, Japan
- 85 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- 86 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 87 Physics Department, Lancaster University, Lancaster, United Kingdom
- 88 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 89 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- 90 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

- <sup>91</sup> Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- <sup>92</sup> Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>93</sup> Louisiana Tech University, Ruston LA, United States of America
- <sup>94</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden
- <sup>95</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- <sup>96</sup> Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
- <sup>97</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>98</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- <sup>99</sup> CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- <sup>100</sup> Department of Physics, University of Massachusetts, Amherst MA, United States of America
- <sup>101</sup> Department of Physics, McGill University, Montreal QC, Canada
- <sup>102</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>103</sup> Department of Physics, University of Michigan, Ann Arbor MI, United States of America
- <sup>104</sup> Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- <sup>105</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- <sup>106</sup> Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
- <sup>107</sup> Group of Particle Physics, University of Montreal, Montreal QC, Canada
- <sup>108</sup> P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- <sup>109</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- <sup>110</sup> National Research Nuclear University MEPhI, Moscow, Russia
- <sup>111</sup> D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- <sup>112</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>113</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>114</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>115</sup> Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>116</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- <sup>117</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- <sup>118</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>119</sup> Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- <sup>120</sup> <sup>(a)</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk; <sup>(b)</sup> Novosibirsk State University Novosibirsk, Russia
- <sup>121</sup> Department of Physics, New York University, New York NY, United States of America
- <sup>122</sup> Ohio State University, Columbus OH, United States of America
- <sup>123</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>124</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- <sup>125</sup> Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- <sup>126</sup> Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
- <sup>127</sup> Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- <sup>128</sup> LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- <sup>129</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>130</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>131</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>132</sup> LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- <sup>133</sup> Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- <sup>134</sup> Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia
- <sup>135</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- <sup>136</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP; <sup>(b)</sup> Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Departamento de Física, Universidade de Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>137</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- <sup>138</sup> Czech Technical University in Prague, Prague, Czech Republic
- <sup>139</sup> Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- <sup>140</sup> State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia
- <sup>141</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>142</sup> IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- <sup>143</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- <sup>144</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>145</sup> Department of Physics, University of Washington, Seattle WA, United States of America
- <sup>146</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>147</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>148</sup> Department Physik, Universität Siegen, Siegen, Germany
- <sup>149</sup> Department of Physics, Simon Fraser University, Burnaby BC, Canada
- <sup>150</sup> SLAC National Accelerator Laboratory, Stanford CA, United States of America
- <sup>151</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>152</sup> Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
- <sup>153</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>154</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>155</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>156</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>157</sup> Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
- <sup>158</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>159</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>160</sup> International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
- <sup>161</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>162</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>163</sup> Tomsk State University, Tomsk, Russia
- <sup>164</sup> Department of Physics, University of Toronto, Toronto ON, Canada
- <sup>165</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada
- <sup>166</sup> Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- <sup>167</sup> Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

- <sup>168</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America  
<sup>169</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden  
<sup>170</sup> Department of Physics, University of Illinois, Urbana IL, United States of America  
<sup>171</sup> Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain  
<sup>172</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada  
<sup>173</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada  
<sup>174</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany  
<sup>175</sup> Department of Physics, University of Warwick, Coventry, United Kingdom  
<sup>176</sup> Waseda University, Tokyo, Japan  
<sup>177</sup> Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel  
<sup>178</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America  
<sup>179</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany  
<sup>180</sup> Department of Physics, Yale University, New Haven CT, United States of America  
<sup>181</sup> Yerevan Physics Institute, Yerevan, Armenia

- <sup>a</sup> Also at Borough of Manhattan Community College, City University of New York, NY; United States of America.  
<sup>b</sup> Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.  
<sup>c</sup> Also at CERN, Geneva; Switzerland.  
<sup>d</sup> Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.  
<sup>e</sup> Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.  
<sup>f</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.  
<sup>g</sup> Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); Spain.  
<sup>h</sup> Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.  
<sup>i</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.  
<sup>j</sup> Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.  
<sup>k</sup> Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.  
<sup>l</sup> Also at Department of Physics, California State University, Fresno CA; United States of America.  
<sup>m</sup> Also at Department of Physics, California State University, Sacramento CA; United States of America.  
<sup>n</sup> Also at Department of Physics, King's College London, London; United Kingdom.  
<sup>o</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.  
<sup>p</sup> Also at Department of Physics, Stanford University; United States of America.  
<sup>q</sup> Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.  
<sup>r</sup> Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.  
<sup>s</sup> Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.  
<sup>t</sup> Also at Giresun University, Faculty of Engineering, Giresun; Turkey.  
<sup>u</sup> Also at Graduate School of Science, Osaka University, Osaka; Japan.  
<sup>v</sup> Also at Hellenic Open University, Patras; Greece.  
<sup>w</sup> Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Romania.  
<sup>x</sup> Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.  
<sup>y</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.  
<sup>z</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.  
<sup>aa</sup> Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.  
<sup>ab</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.  
<sup>ac</sup> Also at Institute of Particle Physics (IPP); Canada.  
<sup>ad</sup> Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.  
<sup>ae</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.  
<sup>af</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.  
<sup>ag</sup> Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.  
<sup>ah</sup> Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.  
<sup>ai</sup> Also at Louisiana Tech University, Ruston LA; United States of America.  
<sup>aj</sup> Also at Manhattan College, New York NY; United States of America.  
<sup>ak</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.  
<sup>al</sup> Also at National Research Nuclear University MEPhI, Moscow; Russia.  
<sup>am</sup> Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.  
<sup>an</sup> Also at School of Physics, Sun Yat-sen University, Guangzhou; China.  
<sup>ao</sup> Also at The City College of New York, New York NY; United States of America.  
<sup>ap</sup> Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.  
<sup>aq</sup> Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.  
<sup>ar</sup> Also at TRIUMF, Vancouver BC; Canada.  
<sup>as</sup> Also at Università di Napoli Parthenope, Napoli; Italy.  
<sup>\*</sup> Deceased.