

*School of Natural Sciences and Mathematics*

***Search for Higgs Boson Pair Production in the  $WW^*WW^*$   
Decay Channel Using ATLAS Data Recorded at  $\sqrt{s} = 13$  TeV***

**UT Dallas Author(s):**

Joseph M. Izen  
Bernhard Meirose  
Kendall Reeves

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# Search for Higgs boson pair production in the $WW^{(*)}WW^{(*)}$ decay channel using ATLAS data recorded at $\sqrt{s} = 13$ TeV



## The ATLAS collaboration

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

**ABSTRACT:** A search for a pair of neutral, scalar bosons with each decaying into two  $W$  bosons is presented using  $36.1 \text{ fb}^{-1}$  of proton-proton collision data at a centre-of-mass energy of 13 TeV recorded with the ATLAS detector at the Large Hadron Collider. This search uses three production models: non-resonant and resonant Higgs boson pair production and resonant production of a pair of heavy scalar particles. Three final states, classified by the number of leptons, are analysed: two same-sign leptons, three leptons, and four leptons. No significant excess over the expected Standard Model backgrounds is observed. An observed (expected) 95% confidence-level upper limit of 160 (120) times the Standard Model prediction of non-resonant Higgs boson pair production cross-section is set from a combined analysis of the three final states. Upper limits are set on the production cross-section times branching ratio of a heavy scalar  $X$  decaying into a Higgs boson pair in the mass range of  $260 \text{ GeV} \leq m_X \leq 500 \text{ GeV}$  and the observed (expected) limits range from 9.3 (10) pb to 2.8 (2.6) pb. Upper limits are set on the production cross-section times branching ratio of a heavy scalar  $X$  decaying into a pair of heavy scalars  $S$  for mass ranges of  $280 \text{ GeV} \leq m_X \leq 340 \text{ GeV}$  and  $135 \text{ GeV} \leq m_S \leq 165 \text{ GeV}$  and the observed (expected) limits range from 2.5 (2.5) pb to 0.16 (0.17) pb.

**KEYWORDS:** Hadron-Hadron scattering (experiments)

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**1 Introduction**

A scalar boson was discovered by the ATLAS and CMS collaborations [1, 2] in 2012. It has been shown to have properties consistent with those predicted for the Standard Model (SM) Higgs boson,  $H$ , through spin and coupling measurements [3, 3–10]. These measurements are based on production of the Higgs boson via gluon-gluon fusion, vector-boson fusion and in association with a  $W$  or  $Z$  boson or a top quark pair. The SM predicts non-resonant Higgs boson pair production via top quark loops as well as through self-coupling. The SM  $HH$  production cross-section is computed to be 33.4 fb [11, 12] at next-to-next-to-leading order (NNLO) in QCD, including resummation of soft-gluon emission at next-to-next-to-leading-logarithmic (NNLL) accuracy for  $m_H = 125.09$  GeV. The actual production rate could be larger than that predicted in the SM due to a variety of Beyond the Standard Model (BSM) physics effects. One such extension includes a modification to the SM Higgs self-coupling,  $\lambda_{HHH}$ , and another the existence of a new heavy resonance which decays into a pair of Higgs bosons. An important Higgs boson decay channel is  $H \rightarrow VV^{(*)}$  in which  $V$  can be either a  $W$  or  $Z$  boson, on or off-shell, and this paper focuses on the  $4W$  final state [13] in both SM and BSM  $HH$  production scenarios.

This work investigates  $HH$  production through three different processes. The first is (1.1) the SM  $HH$  production (non-resonant  $HH$ ). The second and third are both BSM processes inspired by an extended Higgs sector, such as a two-Higgs-doublet model [14], in

which a neutral heavy Higgs boson,  $X$  [15] is produced and decays either (1.2) directly into two SM Higgs bosons (resonant  $HH$ ) or (1.3) into a pair of new scalar bosons,  $S$  ( $X \rightarrow SS$ ), each of which in turn decays to other SM particles with the same mass-dependent branching ratios of the SM  $H$ . The reactions considered in this work are:

$$pp \rightarrow HH \rightarrow WW^{(*)}WW^{(*)} \text{ (non-resonant, SM),} \tag{1.1}$$

$$pp \rightarrow X \rightarrow HH \rightarrow WW^{(*)}WW^{(*)} \text{ (resonant, BSM), and} \tag{1.2}$$

$$pp \rightarrow X \rightarrow SS \rightarrow WW^{(*)}WW^{(*)} \text{ (} X \rightarrow SS, \text{ BSM).} \tag{1.3}$$

The measured final states encompass multiple combinations of leptons and hadrons:

$$\begin{aligned} WW^{(*)}WW^{(*)} &\rightarrow \ell\nu + \ell\nu + 4q, \\ WW^{(*)}WW^{(*)} &\rightarrow \ell\nu + \ell\nu + \ell\nu + 2q, \text{ or} \\ WW^{(*)}WW^{(*)} &\rightarrow \ell\nu + \ell\nu + \ell\nu + \ell\nu \end{aligned}$$

where  $\ell$  is either an electron or a muon,  $q$  refers to quark and anti-quark decay products from the hadronically decaying  $W$  boson(s), and  $\nu$  represents a neutrino, which results in missing transverse momentum. Therefore, three final states are searched for with two, three, or four leptons (plus missing energy and multiple jets), which allow any of the mentioned production modes to be probed.

The production of a new  $X$  scalar (1.2) would be seen as a local excess in the reconstructed di-Higgs mass spectrum. It is assumed in this work that  $m_X > 2m_H$  such that both  $H$  are produced on their mass shell. In the other extended Higgs sector model (1.3)  $X \rightarrow SS$  is assumed to be the dominant  $X$  decay mode. In this scenario, the  $WW^{(*)}WW^{(*)}$  channel is the dominant decay mode for the mass ranges  $270 \text{ GeV} < m_X < 2m_t$  and  $135 \text{ GeV} < m_S < m_X/2$ , where  $m_t$ ,  $m_X$  and  $m_S$  are the mass of the top quark,  $X$ , and  $S$  scalars, respectively. The mass range  $m_X > 2m_t$ , where  $X \rightarrow t\bar{t}$  is expected to dominate, is not considered. It is assumed that  $m_S > 135 \text{ GeV}$  such that  $S \rightarrow WW^{(*)}$  is the dominant decay mode. It is also assumed that  $m_S < m_X/2$  such that both  $S$  bosons are produced on their mass shell.

Previous searches were performed for resonant and non-resonant  $HH$  production using various channels, such as  $bb\gamma\gamma$  [16, 17],  $bbbb$  [18–20],  $bbVV$  [21],  $bb\tau\tau$  [22, 23] and  $WW\gamma\gamma$  [24], with data from the ATLAS and CMS experiments. Additionally, a combination of channels has been performed using data from the CMS experiment [25]. This paper describes a search for resonant and non-resonant Higgs boson pair production in the  $HH \rightarrow WW^*WW^*$  decay channel and for an extended Higgs sector with the decay of  $X \rightarrow SS \rightarrow WW^{(*)}WW^{(*)}$ . The analysis is divided into three independent channels depending on the number of light leptons ( $e$  or  $\mu$ ) from leptonic decays of  $W$  bosons, and then statistically combined to give the final result.

This paper is organised as follows. Data and simulation samples are described in section 2. The object reconstruction and selection are outlined in section 3. Section 4 details the event selection for each of the three final states analysed. The background estimation and the systematic uncertainties are described in section 5 and section 6, respectively. The

results of this analysis are presented in section 7 and summarised in section 8. Finally, the appendix lists the lepton pairing strategy used in each channel, the final event selection criteria and the corresponding acceptance and selection efficiencies.

## 2 Data and simulation samples

The data were collected with the ATLAS detector in 2015 and 2016 using  $pp$  collisions produced at  $\sqrt{s} = 13$  TeV at the Large Hadron Collider (LHC), corresponding to an integrated luminosity of  $36.1 \text{ fb}^{-1}$  [26]. The ATLAS detector is described in detail in ref. [27]. Only data-taking periods in which all relevant detector systems are operational are used.

Samples simulated using Monte Carlo (MC) techniques are used to estimate the signal acceptance and selection efficiency. Simulated samples are also used to estimate the acceptance and selection efficiency for various background processes which contribute prompt leptons from  $W$  or  $Z$  boson decay and leptons originating from photon conversion. Backgrounds due to electrons with misidentified charge and jets misidentified as leptons are estimated using data-driven techniques, as described in section 5.

The non-resonant  $gg \rightarrow HH$  and resonant  $gg \rightarrow X \rightarrow HH$  signal samples in which  $H$  is constrained to decay into  $WW^*$  are generated using MADGRAPH5\_aMC@NLO [28, 29] with the CT10 parton distribution function (PDF) set [30] and the parton shower is modelled by Herwig++ [31] with the UEEE5 set of tuned parameters (tune) for the underlying event [32] and the CTEQ6L1 PDF set [33]. In resonant production,  $X$  decays into a pair of SM Higgs bosons with a negligible width compared to the experimental mass resolution. Various resonance mass hypotheses,  $m_X$ , are considered: 260, 300, 400, and 500 GeV. The branching ratio  $\mathcal{B}(X \rightarrow HH)$  is assumed to be one. Samples of  $X \rightarrow SS \rightarrow WW^{(*)}WW^{(*)}$  events produced by gluon-gluon fusion are generated at leading order (LO) using PYTHIA 8 with the NNPDF2.3LO PDF set [34] such that both the  $X$  and  $S$  scalars are assumed to have narrow decay widths. The mass hypotheses are selected to scan a range of both  $m_X$  and  $m_S$ . In the first scan,  $m_S$  is fixed to 135 GeV for samples with  $m_X = 280, 300, 320,$  and 340 GeV. In the second scan,  $m_X$  is fixed to 340 GeV for samples with  $m_S = 135, 145, 155,$  and 165 GeV. The branching ratio  $\mathcal{B}(X \rightarrow SS)$  is assumed to be one and the branching ratio  $\mathcal{B}(S \rightarrow WW^{(*)})$  is assumed to be the mass-dependent expected branching ratios of the SM Higgs boson.

Multi-boson ( $VV/VVV$ ) and  $V\gamma$  background samples are generated at next-to-leading-order (NLO) using SHERPA 2.1 [35]. The  $V$ +jets samples are generated at NLO with SHERPA 2.2. The CT10 PDF set is used for these samples. The  $VH$  background sample is generated at leading-order (LO) using PYTHIA 8 with the NNPDF2.3LO PDF set. The  $t\bar{t}$  background sample is generated at NLO using POWHEG-BOX 2.0 [36] interfaced with PYTHIA 8 with the NNPDF2.3LO PDF set. Single-top background samples are generated at NLO using POWHEG-BOX 2.0 interfaced with PYTHIA 6.4 [37] with the CT10 PDF set. The  $t\bar{t}V$  background sample is generated at NLO using MADGRAPH5\_aMC@NLO interfaced with PYTHIA 8 with the NNPDF2.3LO PDF set. The  $t\bar{t}H$  background sample is generated at NLO using MADGRAPH5\_aMC@NLO interfaced with Herwig++ with the

NNPDF3.0 [38] PDF set. The simulated samples of  $t\bar{t}$ ,  $t\bar{t}H$ ,  $t\bar{t}V$ , and  $VV$  are described in more detail in refs. [39–41].

The standard ATLAS detector simulation [42] based on GEANT4 [43] is used for background simulated samples. For signal events, the calorimeter simulation is replaced with the fast ATLAS calorimeter simulation [44] that uses a parameterised detector response. Soft collisions generated using PYTHIA 8 [45] with the CTEQ6L1 PDF set and the A2 tune [46] are overlaid on the hard-scatter processes. The number of in-time and out-of-time collisions per bunch crossing (pileup) is adjusted to that observed in data.

### 3 Object selection

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter that are associated with tracks reconstructed in the inner detector (ID). Electrons are identified using medium (tight) criteria [47] for the four lepton channel (two and three lepton channels). Electrons are required to have a transverse energy  $E_T > 10$  GeV and be within the detector fiducial volume of  $|\eta| < 2.47$  excluding the transition region between the barrel and end-cap calorimeter,  $1.37 < |\eta| < 1.52$ .<sup>1</sup> Muon candidates are reconstructed by combining tracks reconstructed in the ID with tracks reconstructed in the muon spectrometer. Muons are identified using medium (tight) criteria [48] for the four lepton channel (two and three lepton channels). Muons are required to have a transverse momentum  $p_T > 10$  GeV and  $|\eta| < 2.5$ . Electrons are required to satisfy calorimeter and track isolation criteria and muons are required to satisfy a track isolation criterion. The calorimeter (track) isolation requires that the total sum of cluster transverse energies (transverse momenta of tracks with  $p_T > 1$  GeV) in a surrounding cone of size  $\Delta R = 0.2$  around the lepton, excluding the cluster  $E_T$  (track  $p_T$ ) of the lepton from the sum, is less than 30% (15%) of the  $p_T$  of the lepton for the four lepton selection and 6% for the two and three lepton selections.

Jets are reconstructed from calibrated topological clusters in the calorimeters [49] using the anti- $k_t$  algorithm [50] with a radius parameter  $R = 0.4$ . Jet energies are corrected for effects from the detector and from pileup [51] using simulated and *in situ* techniques [51]. Jets are required to have  $p_T > 25$  GeV and  $|\eta| < 2.5$ . Jets with  $p_T < 60$  GeV and  $|\eta| < 2.4$  are required to satisfy additional pileup rejection criteria [52]. Jets containing  $b$ -hadrons are identified ( $b$ -tagged) using the MV2c10 multivariate discriminant [53]. The  $b$ -tagging requirement results in an efficiency of 70% for jets containing  $b$ -hadrons, as determined in a simulated sample of  $t\bar{t}$  events [54]. An overlap removal procedure is applied in order to resolve ambiguities between reconstructed physics objects. Jets within  $\Delta R = 0.2$  of a reconstructed electron are removed. If the nearest remaining jet is within  $\Delta R = 0.4$  of an electron, the electron is removed. Selected muons with an angular separation of

<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 upwards. 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  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

$\Delta R < \min(0.4, 0.04 + 10 \text{ GeV}/p_T^\mu)$  from the nearest jet are removed if the jet has at least three tracks originating from the primary vertex; otherwise the jet is removed and the muon is kept. The missing transverse momentum,  $E_T^{\text{miss}}$ , vector is the negative of the vector sum of the transverse momenta of all electrons, muons, and jets. Tracks from the primary vertex<sup>2</sup> that are not associated with any objects are also taken into account in the  $E_T^{\text{miss}}$  reconstruction [55].

## 4 Event selection

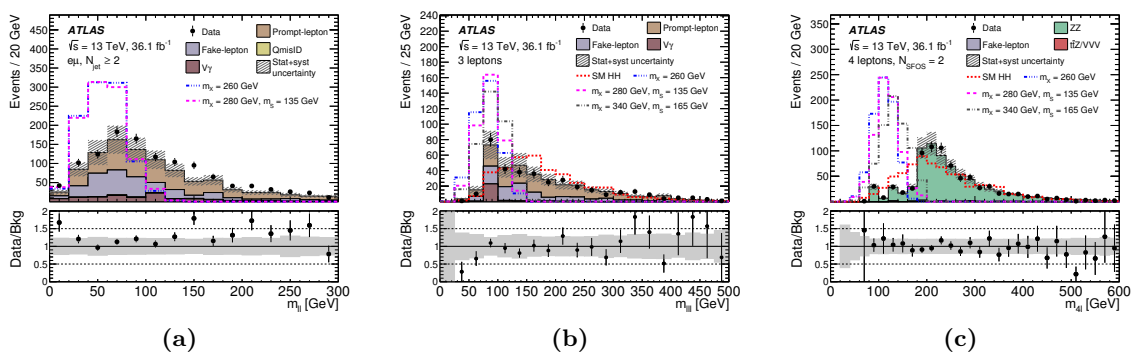
Events are required to pass single-lepton or dilepton triggers [56] with minimum  $p_T$  thresholds in the range 20–26 GeV, depending on the data collection period, and to have at least two leptons ( $e$  or  $\mu$ ). Events are also required to have at least one lepton (two leptons) to be matched to the single-lepton (dilepton) trigger signatures. A higher  $p_T$  requirement than the online trigger  $p_T$  threshold is applied to the trigger-matched lepton. Three channels are defined according to the number of reconstructed leptons (two leptons, three leptons and four leptons), and events are further classified according to the charge and flavour of the leptons. In order to suppress top quark backgrounds and to be orthogonal to other Higgs boson pair production searches ( $bb\gamma\gamma$  [16],  $bbbb$  [18], and  $bb\tau\tau$  [22]) at ATLAS, events containing  $b$ -tagged jets are rejected.

Events in the two lepton channel are required to have exactly two leptons with the same electric charge, while the three lepton channel events are required to have exactly three leptons with a summed electric charge  $\sum_{i \in \ell} q_i = \pm 1$ . Events are required to have  $N_{\text{jets}} \geq 2$  and  $E_T^{\text{miss}} > 10$  (30) GeV for the two (three) lepton channel. In order to suppress backgrounds containing a  $Z$  boson in the same-sign  $ee$  channel (due to the misidentification of an electron’s charge) and in the three lepton channel, events are removed if they contained a same-flavour lepton pair with an invariant mass,  $m_{\ell\ell}$ , near the  $Z$  boson mass:  $|m_{\ell\ell} - m_Z| < 10$  GeV. In order to reduce the backgrounds from non-prompt leptons, the leading (subleading) lepton is required to have  $p_T > 30$  (20) GeV in the two lepton channel. The two leptons with the same charge are both required to have  $p_T > 20$  GeV in the three lepton channel. For non-resonant production and resonant production with  $m_X > 300$  GeV, signal events tend to have jets with larger  $p_T$  compared to low  $m_X$  resonant production scenarios and thus  $N_{\text{jets}} \geq 3$  is required in the two lepton channel to account for more jets passing the  $p_T$  requirement. Additionally, events containing a same-flavour opposite-sign (SFOS) lepton pair with an invariant mass  $m_{\ell\ell} < 15$  GeV are also removed in order to suppress backgrounds from hadron resonances or virtual photons. Following this preselection, a number of observables are considered and four variables are chosen based on the ranking of the generic algorithm [57] and the correlations between variables. These four variables that consist of the angular separation between each lepton and the nearest jet as well as invariant masses among different combinations of the leptons and jets are used for further selection. The final selections on these variables are optimised in order to maximise signal

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<sup>2</sup>Proton-proton collision vertices are reconstructed by requiring that at least two tracks with  $p_T > 0.4$  GeV are associated with a given vertex. The primary vertex is defined as the vertex with the largest  $\sum p_{T,\text{track}}^2$ .





**Figure 1.** Distributions of the invariant mass of (a) two, (b) three, and (c) four leptons for the two, three, and four lepton channels after preselection. The charge misidentification background in the two lepton channel and the non- $ZZ$  backgrounds in the four lepton channel are non-zero but are too small to be seen in the distributions. The shaded band in the ratio plot shows the systematic uncertainty in the background estimate. Resonant  $HH$  signal samples are denoted by  $m_X$ . The integral of each signal sample distribution is scaled to that of the expected background.

significance. One of these variables is the invariant mass of two (three) leptons in the two (three) lepton channel and is shown in figure 1a (1b) to illustrate its discriminating power. The optimisation procedure using all four variables is performed separately for each analysis channel, each signal mass point, each lepton flavour category (for the two lepton channel), and each number of same-flavour opposite-sign ( $N_{\text{SFOS}}$ ) lepton pairs (for the three lepton channel). The optimised selection criteria are listed in tables 3–9 in the appendix.

Events in the four lepton channel are required to have exactly four leptons with  $\sum_{i \in \ell} q_i = 0$ . At least one of the leptons is required to have  $p_T > 22 \text{ GeV}$ . Events that contain a SFOS lepton pair with  $m_{\ell\ell} < 4 \text{ GeV}$  are removed. Following this preselection, selections on the invariant masses and angular separation of lepton pairs are implemented to reject backgrounds containing a  $Z$  boson or non-prompt leptons or other objects incorrectly identified as leptons, known as fake leptons. A summary of the selection criteria used in the four lepton channel is shown in tables 10–11 in the appendix. Figure 1c shows the kinematic distribution of the four lepton invariant mass.

## 5 Background estimation

The backgrounds in this search all have final states that contain leptons that can be classified according to their origin into prompt leptons,<sup>3</sup> leptons with misidentified charges, and fake leptons (including non-prompt and misidentified jets). The backgrounds in the two and three lepton channels are dominated by irreducible prompt-lepton processes, including  $VV$  ( $WZ$  and  $ZZ$ ),  $t\bar{t}Z$  and  $VVV$ , with a significant contribution from fake leptons. The background in the four lepton channel is almost exclusively due to  $ZZ$  production (including both on-shell and off-shell production).

<sup>3</sup>Leptons not from hadron decays or photon conversions.

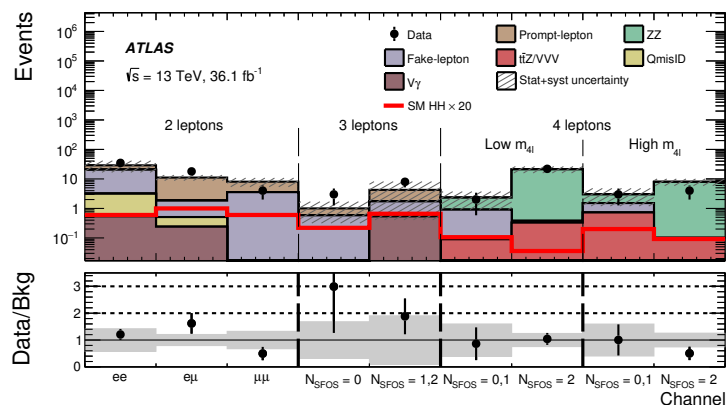


Prompt-lepton backgrounds are modelled using simulated samples described in section 2. Control regions containing one pair (two pairs) of SFOS leptons with invariant mass  $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$  in the three (four) lepton channel are used to check the modelling of  $WZ$  ( $ZZ$ ) background. A data-driven method [7, 58] is used to estimate the charge misidentification rate for electrons from a sample of  $Z \rightarrow ee$  events with  $m_{ee}$  in a narrow window around  $m_Z$ . The corresponding same-sign charge misidentification (QmisID) background is evaluated by scaling the opposite-sign events by this rate. The probability of misidentifying the charge of a muon is checked in both data and simulation, and found to be negligible in the kinematic ranges relevant to this analysis.

In the two and three lepton channels non-prompt-lepton contributions from the conversion of prompt photons are estimated using  $V\gamma$  simulated samples. Fake-lepton and non-prompt-lepton contributions from misidentification of hadronic jets as leptons, semileptonic decay of heavy-flavour hadrons and photon conversions from neutral pion decays are estimated using data with a fake-factor method [59]. The method defines “tight” leptons as leptons passing all requirements described in section 3 and “anti-tight” leptons as leptons failing the isolation or identification requirements. The fake factor is calculated as the ratio of events with tight leptons to events with one tight lepton replaced by an anti-tight lepton in the data control samples. The control samples of the two and three lepton channels are ensured to be largely orthogonal to corresponding preselection samples by requiring a lower jet multiplicity. A control sample containing three leptons with enriched  $Z$ +jets processes is used in the four lepton channel to extract the fake factors. All simulated prompt-lepton contributions are subtracted from the data before measuring the fake factor. The fake-lepton background contributions are estimated by applying the fake factors to events with the same selection as for the signal regions but with at least one anti-tight lepton replacing one of the prompt leptons. The fake factors in the four lepton channel are applied to events in two control samples, one with three tight leptons and one anti-tight lepton and the other with two tight leptons and two anti-tight leptons.

## 6 Systematic uncertainties

Experimental systematic uncertainties are evaluated. They include uncertainties related to the electron and jet energy measurements [51], muon momentum measurement,  $E_T^{\text{miss}}$  modelling [55], and lepton reconstruction, identification, and isolation efficiencies. The dominant systematic uncertainty in the fake-lepton background estimations arises from a closure test of the fake-factor method and the relative contributions from heavy-flavour hadron decays and photon conversions. Pileup modelling,  $b$ -tagging efficiencies, and jet pileup rejection modelling are also included. Theoretical uncertainties are evaluated for all simulated samples. These include uncertainties in PDF, QCD scale, and parton shower modelling that impact efficiency times acceptance for signal samples and uncertainties in the production cross-sections for simulated background samples. The statistical uncertainties in MC signal and background samples as well as in data control regions are included as systematic uncertainties.



**Figure 2.** Expected and observed yields in each channel after all selection criteria for the non-resonant  $HH$  production searches. The label  $N_{\text{SFOS}}$  indicates the number of same-flavour, opposite-sign lepton pairs in the channel. Low and high  $m_{4\ell}$  indicates  $m_{4\ell} < 180$  GeV and  $m_{4\ell} > 180$  GeV, respectively. The shaded band in the ratio plot shows the systematic uncertainty in the background estimate. The signal is scaled by a factor of 20.

The systematic uncertainties with the largest impact on the  $HH$  production cross-section (times branching ratio) limits come from the jet energy scale and resolution with a relative impact compared to the total systematic plus statistical uncertainty of 45% (29%–55%) and fake-lepton background estimations with a relative impact of 42% (31%–54%) for the non-resonant (resonant) production searches. Theoretical uncertainties are found to have a relative impact of 23% (24%–36%) for the non-resonant (resonant) production searches. The relative impact of jet energy measurements, fake-lepton background estimations, and theoretical uncertainties in the  $X \rightarrow SS$  analysis are 38%–51%, 37%–52% and 25%–32%, respectively. Other experimental uncertainties due to lepton, pileup,  $b$ -tagging, pileup jet rejection, prompt-lepton background estimations, and  $E_T^{\text{miss}}$  modelling are found to have a small impact on the results. The uncertainty in the combined 2015+2016 integrated luminosity is 2.1%. It is derived, following a methodology similar to that detailed in ref. [26], and using the LUCID-2 detector for the baseline luminosity measurements [60], from calibration of the luminosity scale using  $x$ - $y$  beam-separation scans. It has a 5%–10% relative impact due to its simultaneous effect on the signal and background estimates. All simulated processes except  $ZZ$  are affected by the uncertainty in the luminosity measurement. The relative impact of all systematic uncertainties is found to be 71% (60%–79%) for the non-resonant (resonant) production searches. In addition to the systematic effects, the statistical uncertainties are found to have a relative impact of 71% (61%–80%) for the non-resonant (resonant) production searches.

## 7 Results

The expected and observed yields in each channel after all selection criteria for the non-resonant  $HH$  production searches are shown in figure 2 and table 1.

Channel	Category	Background	Expected Signal	Observed
2 leptons	$ee$	$29 \pm 10$	$0.028 \pm 0.004$	35
	$e\mu$	$11.1 \pm 2.2$	$0.049 \pm 0.005$	18
	$\mu\mu$	$8.1 \pm 2.5$	$0.034 \pm 0.004$	4
3 leptons	$N_{\text{SFOS}} = 0$	$1.0 \pm 0.7$	$0.011 \pm 0.005$	3
	$N_{\text{SFOS}} = 1, 2$	$4.3 \pm 3.8$	$0.033 \pm 0.010$	8
4 leptons $m_{4\ell} < 180$ GeV	$N_{\text{SFOS}} = 0, 1$	$2.3 \pm 1.4$	$0.005 \pm 0.001$	2
	$N_{\text{SFOS}} = 2$	$21 \pm 5$	$0.002 \pm 0.001$	22
4 leptons $m_{4\ell} > 180$ GeV	$N_{\text{SFOS}} = 0, 1$	$3.0 \pm 1.8$	$0.010 \pm 0.002$	3
	$N_{\text{SFOS}} = 2$	$7.9 \pm 2.0$	$0.005 \pm 0.001$	4

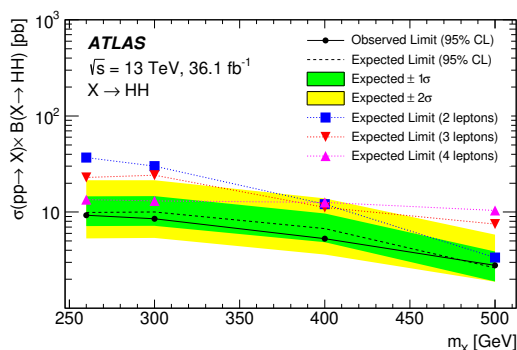
**Table 1.** Expected and observed yields in each channel after all selection criteria and the profile-likelihood fit for the non-resonant  $HH$  production searches. The expected signal refers to the SM non-resonant  $HH$  production, corresponding to its calculated cross-section at  $\sqrt{s} = 13$  TeV of 33.4fb. The label  $N_{\text{SFOS}}$  indicates the number of same-flavour, opposite-sign lepton pairs in the channel. Systematic uncertainties on the signal and background estimates are shown.

A statistical analysis using a profile-likelihood-ratio test statistic [61] for the two, three, and four lepton channels, separately, as well as the combination of the three channels is performed. The expected and observed yields in each of the nine signal regions shown in figure 2 as well as the  $ZZ$  control region in the four lepton channel are used as the input parameters to the likelihood. No significant excess over the estimated backgrounds is observed in data. Upper limits at 95% confidence level (CL) are set on the production cross-section for non-resonant SM  $HH$  production and on the production cross-section times branching ratio for resonant  $HH$  production as well as  $X \rightarrow SS$  production. The expected and observed limits on the signal strength of non-resonant SM  $HH$  production, defined as the ratio of the signal cross-section to the Standard Model prediction ( $\sigma/\sigma_{\text{SM}}$ ), are calculated using the modified frequentist  $\text{CL}_s$  method [62] using the asymptotic approximation and are shown in table 2. All systematic uncertainties are included in the profile-likelihood fit as Gaussian nuisance parameters and are treated as correlated across all signal regions. The combined observed (expected) upper limit on the non-resonant SM  $HH$  production cross-section is found to be 5.3 (3.8) pb, which corresponds to a limit on the signal strength of 160 (120).

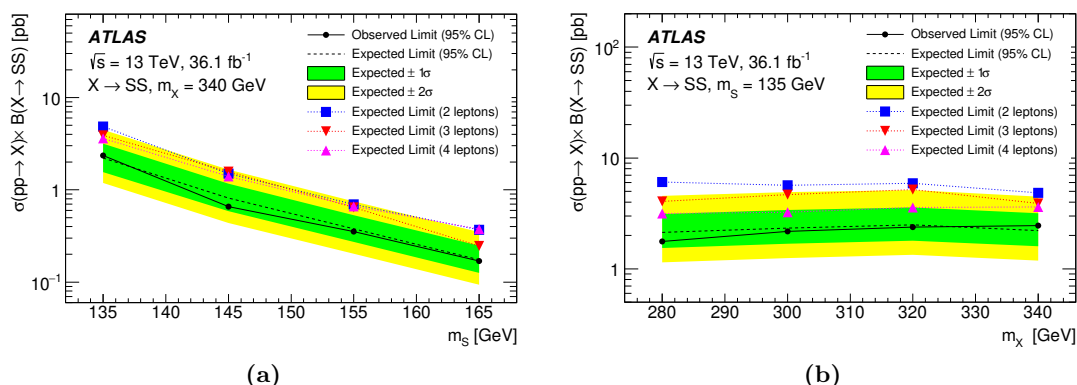
Upper limits at 95% CL on the production cross-section times branching ratio are set for a scalar resonance decaying into either a pair of SM Higgs bosons (shown in figure 3) or into a pair of heavy scalars (shown in figure 4). The observed (expected) upper limits on resonant  $HH$  production vary with the resonance mass  $m_X$  and range from 9.3 (10) pb to 2.8 (2.6) pb, with the smallest limit set for  $m_X = 500$  GeV. Upper limits on resonant  $SS$  production vary with the resonance mass  $m_X$  and the scalar mass  $m_S$ . The observed (expected) limits range from 2.5 (2.5) pb to 0.16 (0.17) pb, with the smallest limit set for  $m_X = 340$  GeV and  $m_S = 165$  GeV.

	Observed	Expected limit on $\sigma/\sigma_{SM}$				
	limit on $\sigma/\sigma_{SM}$	Median	+2 $\sigma$	+1 $\sigma$	-1 $\sigma$	-2 $\sigma$
2 leptons	170	150	290	210	100	78
3 leptons	420	270	690	420	200	150
4 leptons	340	400	880	590	290	210
Combined	160	120	230	170	83	62

**Table 2.** Expected and observed 95% CL exclusion limits set on the non-resonant  $HH$  signal strength. The SM non-resonant  $HH$  cross-section at  $\sqrt{s} = 13$  TeV is calculated to be 33.4 fb. Limits are shown for each channel individually as well as for the combination of the channels. Statistical and systematic uncertainties are included.



**Figure 3.** Expected and observed 95% CL exclusion limits set on the cross-section times branching ratio of resonant  $HH$  production as a function of  $m_X$ . Limits are shown for each channel individually as well as for the combination of the channels. Statistical and systematic uncertainties are included.



**Figure 4.** Expected and observed 95% CL exclusion limits set on the cross-section times branching ratio of resonant  $X \rightarrow SS$  production as a function of (a)  $m_S$  and (b)  $m_X$ . Limits are shown for each channel individually as well as for the combination of the channels. Statistical and systematic uncertainties are included.

## 8 Conclusions

A search for resonant and non-resonant Higgs boson pair production as well as for a heavy scalar pair production has been performed in the  $WW^{(*)}WW^{(*)}$  decay channel using  $36.1 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  proton-proton collision data collected by the ATLAS experiment at the LHC in 2015 and 2016. The analysis is performed separately in three channels based on the number of leptons in the final state: two same-sign leptons, three leptons, and four leptons. No significant excesses over the expected backgrounds are observed in data and the results from the three channels are statistically combined. An observed (expected) 95% CL upper limit of 160 (120) is set on the signal strength for the non-resonant Higgs boson pair production. Upper limits are set on the production cross-section times branching ratio of a heavy scalar  $X$  that decays into two Higgs bosons for a mass range of  $260 \text{ GeV} \leq m_X \leq 500 \text{ GeV}$  and the observed (expected) limits range from 9.3 (10) pb to 2.8 (2.6) pb. Upper limits are also set on the production cross-section times branching ratio of a heavy scalar  $X$  that decays into two heavy scalars  $S$  for mass ranges of  $280 \text{ GeV} \leq m_X \leq 340 \text{ GeV}$  and  $135 \text{ GeV} \leq m_S \leq 165 \text{ GeV}$  and the observed (expected) limits range from 2.5 (2.5) pb to 0.16 (0.17) pb.

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Variable	Description
$\ell_1$	Leading lepton
$\ell_2$	Sub-leading lepton
$\Delta R_{\ell_N j}$	Angular distance between $\ell_N$ and the nearest jet
$m_{\ell\ell}$	Invariant mass of the two leptons
$m_{\ell_N jj}$	Invariant mass of $\ell_N$ and the two nearest jets
$m_{\text{all}}$	Invariant mass of all objects that pass the selection criteria

**Table 3.** Description of the notation used in the two lepton analysis.

$m_X$	Channel	$\Delta R_{\ell_1 j}$	$m_{\ell\ell}$ [GeV]	$m_{\ell_1 jj}$ [GeV]	$m_{\text{all}}$ [GeV]
260 GeV	$ee$	[0.35, 1.85]	< 100	< 145	< 1100
	$e\mu$	[0.25, 1.80]	< 85	< 135	< 650
	$\mu\mu$	[0.25, 2.10]	< 80	< 115	< 700
300 GeV	$ee$	[0.35, 1.75]	< 120	< 160	< 1400
	$e\mu$	[0.20, 1.80]	< 135	< 160	< 800
	$\mu\mu$	[0.20, 1.75]	< 115	< 185	< 1000

**Table 4.** Optimised selection criteria used in the two lepton channel in the  $X \rightarrow HH$  search with  $m_X = 260$  GeV and  $m_X = 300$  GeV.

(Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [63].

## A Final selection criteria

Tables 3–6 list the final selection criteria in the two lepton channel. Tables 7–9 present the final selection criteria in the three lepton channel. Table 10 defines the variables and table 11 lists the selection criteria in the four lepton channel.

The lepton pairing strategy in the four leptons channel is designed to identify the decay of a  $Z$  boson in order to efficiently reject the dominant  $ZZ$  background in events with at least one SFOS lepton pair. Events are classified based on the number of SFOS lepton pairs they contain in order to account for the different background composition in each signal region.

Table 12 shows the final acceptance and selection efficiencies for the signal samples.

$m_X$	Channel	$\Delta R_{\ell_2 j}$	$\Delta R_{\ell_1 j}$	$m_{\ell\ell}$ [GeV]	$m_{\ell_1 j j}$ [GeV]
400 GeV	$ee$	[0.35, 1.50]	[0.30, 1.25]	[45, 235]	[40, 285]
	$e\mu$	[0.20, 1.50]	[0.20, 1.05]	[35, 195]	[30, 235]
	$\mu\mu$	[0.20, 1.20]	[0.20, 1.20]	[40, 215]	[30, 260]
500 GeV	$ee$	[0.20, 1.15]	[0.20, 1.15]	[100, 270]	[40, 285]
	$e\mu$	[0.20, 1.00]	[0.20, 0.80]	[75, 250]	[35, 350]
	$\mu\mu$	[0.20, 1.05]	[0.20, 0.75]	[60, 250]	[30, 310]
Non-res.	$ee$	[0.20, 1.40]	[0.20, 1.15]	[55, 270]	[40, 285]
	$e\mu$	[0.20, 1.15]	[0.20, 0.80]	[75, 250]	[35, 350]
	$\mu\mu$	[0.20, 1.05]	[0.20, 0.75]	[60, 250]	[30, 310]

**Table 5.** Optimised selection criteria used in the two lepton channel in the non-resonant  $HH$  search and the  $X \rightarrow HH$  search with  $m_X = 400$  GeV and  $m_X = 500$  GeV.

Mass	Channel	$\Delta R_{\ell_2 j}$	$\Delta R_{\ell_1 j}$	$m_{\ell\ell}$ [GeV]	$m_{\ell_1 j j}$ [GeV]
$m_S = 135$ GeV	$ee$	[0.35, 2.5]	[0.4, 1.65]	$< 80$	[50, 150]
	$e\mu$	[0.25, 1.7]	[0.25, 1.65]	$< 95$	[50, 150]
	$\mu\mu$	[0.25, 2.05]	[0.2, 1.85]	$< 95$	[50, 150]
$m_X = 340$ GeV	$ee$	[0.35, 1.85]	[0.2, 1.65]	$< 130$	[50, 190]
	$e\mu$	[0.25, 1.6]	[0.25, 1.6]	$< 150$	[50, 150]
	$\mu\mu$	[0.2, 2.0]	[0.2, 1.65]	$< 115$	[50, 185]

**Table 6.** Optimised selection criteria used in the two lepton channel in the  $X \rightarrow SS$  search. The selection criteria in the first row are used for  $m_S = 135$  GeV and  $m_X = 280, 300,$  and  $320$  GeV. The selection criteria in the second row are used for  $m_X = 340$  GeV and  $m_S = 135, 145, 155,$  and  $165$  GeV.

Variable	Description
$N_{\text{SFOS}}$	Number of same-flavour opposite-sign lepton pairs
$\ell_1$	Lepton with charge opposite to that of the same-sign pair
$\ell_2$	Lepton from the same-sign pair that is closest to $\ell_1$ in $\eta$ - $\phi$ space
$\ell_3$	Remaining lepton
$m_{\ell\ell\ell}$	Invariant mass of the three leptons
$m_{\ell_N j}$	Invariant mass of $\ell_N$ and the nearest jet
$m_{\ell_N j j}$	Invariant mass of $\ell_N$ and the two nearest jets
$m_{\ell\ell+ljj}$	The minimum sum of the invariant mass of two opposite-sign leptons and the invariant mass of the remaining lepton and the two leading jets
$\Delta R_{\ell\ell}$	Angular distance between two leptons

**Table 7.** Description of the notation used in the three lepton analysis.



$m_X$	Variable	$N_{\text{SFOS}} = 0$	$N_{\text{SFOS}} = 1, 2$
Non-res.	$\Delta R_{\ell_2 \ell_3}$	[2.47, 5.85]	[2.16, 3.50]
	$m_{\ell_2 \ell_3}$ [GeV]	[10, 70]	[10, 70]
	$m_{\ell_3 jj}$ [GeV]	[50, 110]	[50, 115]
	$m_{\ell_3 j}$ [GeV]	[15, 50]	[15, 45]
260	$m_{\ell \ell \ell}$ [GeV]	[30, 105]	[20, 85]
	$m_{\ell \ell + \ell jj}$ [GeV]	[65, 200]	[85, 360]
	$m_{\ell_2 j}$ [GeV]	[20, 75]	[10, 60]
	$\Delta R_{\ell_1 \ell_2}$	[0.58, 1.66]	[0.41, 1.77]
300	$m_{\ell \ell \ell}$ [GeV]	[20, 110]	[20, 130]
	$m_{\ell \ell + \ell jj}$ [GeV]	[55, 195]	[75, 175]
	$m_{\ell_2 j}$ [GeV]	[35, 70]	[15, 85]
	$\Delta R_{\ell_1 \ell_2}$	[0.08, 1.49]	[0.42, 1.14]
400	$m_{\ell_1 \ell_2}$ [GeV]	[20, 60]	[15, 45]
	$m_{\ell_3 j}$ [GeV]	[15, 50]	[15, 50]
	$m_{\ell \ell + \ell jj}$ [GeV]	[50, 240]	[80, 270]
	$\Delta R_{\ell_2 \ell_3}$	[1.97, 6.24]	[2.09, 4.60]
500	$m_{\ell \ell \ell}$ [GeV]	[130, 320]	[150, 295]
	$\Delta R_{\ell_2 \ell_3}$	[2.68, 3.47]	[2.54, 6.19]
	$\Delta R_{\ell_1 \ell_2}$	[0.12, 0.68]	[0.11, 1.08]
	$m_{\ell_3 j}$ [GeV]	[15, 90]	[20, 50]

**Table 8.** Optimised selection criteria for non-resonant and resonant  $HH$  searches in the three lepton channel. The selection criteria are chosen to ensure constant signal selection efficiency between the  $N_{\text{SFOS}} = 0$  and  $N_{\text{SFOS}} = 1, 2$  categories.

$m_X/m_S$	Variable	$N_{\text{SFOS}} = 0$	$N_{\text{SFOS}} = 1, 2$
280 135	$m_{\ell\ell}$ [GeV]	[55, 100]	[25, 85]
	$m_{\ell_3jj}$ [GeV]	[50, 145]	[50, 300]
	$m_{\ell_2j}$ [GeV]	[35, 75]	[10, 65]
	$\Delta R_{\ell_1\ell_2}$	[0.51, 1.61]	[0.19, 1.16]
300 135	$m_{\ell\ell}$ [GeV]	[55, 110]	[20, 135]
	$m_{\ell_3jj}$ [GeV]	[50, 190]	[50, 135]
	$m_{\ell_2j}$ [GeV]	[20, 55]	[20, 50]
	$\Delta R_{\ell_1\ell_2}$	[0.10, 1.86]	[0.46, 3.38]
320 135	$m_{\ell\ell}$ [GeV]	[25, 110]	[25, 135]
	$m_{\ell_3jj}$ [GeV]	[60, 210]	[50, 135]
	$m_{\ell_2j}$ [GeV]	[10, 55]	[30, 60]
	$\Delta R_{\ell_1\ell_2}$	[0.24, 1.78]	[0.15, 1.53]
340 135	$m_{\ell\ell}$ [GeV]	[50, 170]	[25, 180]
	$m_{\ell_3jj}$ [GeV]	[50, 115]	[50, 115]
	$m_{\ell_2j}$ [GeV]	[10, 40]	[25, 65]
	$\Delta R_{\ell_1\ell_2}$	[0.12, 1.68]	[0.15, 1.10]
340 145	$m_{\ell\ell}$ [GeV]	[60, 110]	[40, 130]
	$m_{\ell_3jj}$ [GeV]	[50, 350]	[50, 140]
	$m_{\ell_2j}$ [GeV]	[10, 55]	[10, 90]
	$\Delta R_{\ell_1\ell_2}$	[0.19, 1.58]	[0.41, 1.11]
340 155	$m_{\ell\ell}$ [GeV]	[30, 110]	[35, 135]
	$m_{\ell_3jj}$ [GeV]	[50, 205]	[50, 140]
	$m_{\ell_2j}$ [GeV]	[20, 55]	[10, 85]
	$\Delta R_{\ell_1\ell_2}$	[0.27, 2.24]	[0.50, 1.15]
340 165	$m_{\ell\ell}$ [GeV]	[25, 110]	[25, 135]
	$m_{\ell_3jj}$ [GeV]	[50, 210]	[50, 140]
	$m_{\ell_2j}$ [GeV]	[15, 55]	[20, 60]
	$\Delta R_{\ell_1\ell_2}$	[0.20, 2.12]	[0.39, 1.95]

**Table 9.** Optimised selection criteria for the  $X \rightarrow SS$  searches in the three lepton channel. The selection criteria are chosen to ensure constant signal selection efficiency between the  $N_{\text{SFOS}} = 0$  and  $N_{\text{SFOS}} = 1, 2$  categories.

Variable	Description
$p_{\text{T}}^i$	$p_{\text{T}}$ of lepton $i$
$\ell_2$ and $\ell_3$ ( $N_{\text{SFOS}} > 0$ )	SFOS lepton pair with invariant mass closest to $Z$ boson ( $p_{\text{T},2} > p_{\text{T},3}$ )
$\ell_2$ and $\ell_3$ ( $N_{\text{SFOS}} = 0$ )	Different-flavour OS lepton pair with invariant mass closest to $Z$ boson ( $p_{\text{T},2} > p_{\text{T},3}$ )
$\ell_0$ and $\ell_1$	Remaining lepton pair ( $p_{\text{T},0} > p_{\text{T},1}$ )

**Table 10.** Description of the notation used in the four lepton analysis.

<b>Event selection in the four lepton channel</b>	
4 leptons with $p_{\text{T}} > 10$ GeV and $\sum q_i = 0$	
Trigger	
Trigger matched lepton	
$p_{\text{T}}^{\ell_{\text{matched}}} > 22, 25, 27$ GeV (depending on data period trigger)	
$m_{\ell\ell} > 4$ GeV (for all SFOS pairs)	
$N_{b\text{-tag}} = 0$	
$m_{\ell_0\ell_1} > 10$ GeV	
<b><math>N_{\text{SFOS}} = 0, 1</math> selection</b>	
$ m_{\ell_2\ell_3} - m_Z  > 5$ GeV	
$m_{4\ell} < 180$ GeV	$m_{4\ell} > 180$ GeV
<b><math>N_{\text{SFOS}} = 2</math> selection</b>	
$m_{\ell_2\ell_3} < 70$ GeV, $m_{\ell_2\ell_3} > 110$ GeV	
$m_{4\ell} < 180$ GeV	$m_{4\ell} > 180$ GeV
$\Delta\phi_{\ell_2\ell_3} < 2.6$ rad	$m_{\ell_0\ell_1} < 70$ GeV, $m_{\ell_0\ell_1} > 110$ GeV

**Table 11.** Summary of the selection criteria used in the four lepton channel. All events are required to pass the common selection and then category-dependent selection criteria are applied according to the number of same-flavour opposite-sign lepton pairs in the event.

Channel	Category	$X \rightarrow SS$		
		Non-resonant $HH$ [%]	Resonant $HH$ $m_X \in [280, 340]$ GeV [%]	$m_X \in [280, 340]$ GeV $m_S \in [135, 165]$ GeV [%]
Two lepton	$ee$	0.60	0.30–0.55	0.41–0.82
	$e\mu$	1.05	0.52–1.32	1.12–2.31
	$\mu\mu$	0.66	0.35–1.10	0.88–1.94
Three lepton	$N_{\text{SFOS}} = 0$	0.32	0.07–0.24	0.09–0.5
	$N_{\text{SFOS}} = 1, 2$	0.94	0.18–0.61	0.27–1.2
Four lepton	$N_{\text{SFOS}} = 0, 1$	2.94	2.08–3.32	2.65–3.66
	$N_{\text{SFOS}} = 2$	1.23	0.73–1.34	0.85–1.46

**Table 12.** The final acceptance times selection efficiencies in the  $4W$  channel for non-resonant, resonant, and  $SS$  signal samples after all selection criteria are applied. Acceptance times selection efficiency is defined as the ratio of reconstructed signal events passing all selection criteria to the number of generated signal events that are filtered for the corresponding channel. The generator filter efficiencies are  $4.4 \times 10^{-3}$  for the two same-sign lepton channel,  $4.2 \times 10^{-3}$  for the three lepton channel, and  $5.1 \times 10^{-4}$  for the four lepton channel. All numbers are given as percentages.

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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>, S.P. Amor Dos Santos<sup>136a,136c</sup>, S. Amoroso<sup>44</sup>, C.S. Amrouche<sup>52</sup>, C. Anastopoulos<sup>146</sup>, L.S. Ancu<sup>52</sup>, N. Andari<sup>142</sup>, T. Andeen<sup>11</sup>, C.F. Anders<sup>59b</sup>, J.K. Anders<sup>20</sup>, K.J. Anderson<sup>36</sup>, A. Andreazza<sup>66a,66b</sup>, V. Andrei<sup>59a</sup>, C.R. Anelli<sup>173</sup>, S. Angelidakis<sup>37</sup>, I. Angelozzi<sup>118</sup>, A. Angerami<sup>38</sup>, A.V. Anisenkov<sup>120b,120a</sup>, A. Annovi<sup>69a</sup>, C. Antel<sup>59a</sup>, M.T. Anthony<sup>146</sup>, M. Antonelli<sup>49</sup>, D.J.A. Antrim<sup>168</sup>, F. Anulli<sup>70a</sup>, M. Aoki<sup>79</sup>, J.A. Aparisi Pozo<sup>171</sup>, L. Aperio Bella<sup>35</sup>, G. Arabidze<sup>104</sup>, J.P. Araque<sup>136a</sup>, V. Araujo Ferraz<sup>78b</sup>, R. Araujo Pereira<sup>78b</sup>, A.T.H. Arce<sup>47</sup>, R.E. Ardell<sup>91</sup>, F.A. Arduh<sup>86</sup>, J-F. Arguin<sup>107</sup>, S. Argyropoulos<sup>75</sup>, A.J. Armbruster<sup>35</sup>, L.J. Armitage<sup>90</sup>, A. Armstrong<sup>168</sup>, O. Arnaez<sup>164</sup>, H. Arnold<sup>118</sup>, M. Arratia<sup>31</sup>, O. Arslan<sup>24</sup>, A. Artamonov<sup>109,\*</sup>, G. Artoni<sup>131</sup>, S. 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Bandyopadhyay<sup>24</sup>, S. Banerjee<sup>178,j</sup>, A.A.E. Bannoura<sup>179</sup>, L. Barak<sup>158</sup>, W.M. Barbe<sup>37</sup>, E.L. Barberio<sup>102</sup>, D. Barberis<sup>53b,53a</sup>, M. Barbero<sup>99</sup>, T. Barillari<sup>113</sup>, M-S. Barisits<sup>35</sup>, J. Barkeloo<sup>127</sup>, T. Barklow<sup>150</sup>, R. Barnea<sup>157</sup>, S.L. Barnes<sup>58c</sup>, B.M. Barnett<sup>141</sup>, R.M. Barnett<sup>18</sup>, Z. Barnovska-Blenessy<sup>58a</sup>, A. Baroncelli<sup>72a</sup>, G. Barone<sup>26</sup>, A.J. Barr<sup>131</sup>, L. Barranco Navarro<sup>171</sup>, F. Barreiro<sup>96</sup>, J. Barreiro Guimarães da Costa<sup>15a</sup>, R. Bartoldus<sup>150</sup>, A.E. Barton<sup>87</sup>, P. Bartos<sup>28a</sup>, A. Basalae<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. Bauce<sup>70a,70b</sup>, F. Bauer<sup>142</sup>, K.T. 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J.S. Bonilla<sup>127</sup>, M. Boonekamp<sup>142</sup>, A. Borisov<sup>140</sup>, G. Borissov<sup>87</sup>, J. Bortfeldt<sup>35</sup>, D. Bortoletto<sup>131</sup>,  
 V. Bortolotto<sup>71a,71b</sup>, D. Boscherini<sup>23b</sup>, M. Bosman<sup>14</sup>, J.D. Bossio Sola<sup>30</sup>, K. Bouaouda<sup>34a</sup>,  
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 A. Brandt<sup>8</sup>, G. Brandt<sup>179</sup>, O. Brandt<sup>59a</sup>, F. Braren<sup>44</sup>, U. Bratzler<sup>161</sup>, B. Brau<sup>100</sup>, J.E. Brau<sup>127</sup>,  
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 G. Brooijmans<sup>38</sup>, T. Brooks<sup>91</sup>, W.K. Brooks<sup>144b</sup>, E. Brost<sup>119</sup>, J.H. Broughton<sup>21</sup>,  
 P.A. Bruckman de Renstrom<sup>82</sup>, D. Bruncko<sup>28b</sup>, A. Bruni<sup>23b</sup>, G. Bruni<sup>23b</sup>, L.S. Bruni<sup>118</sup>,  
 S. Bruno<sup>71a,71b</sup>, B.H. Brunt<sup>31</sup>, M. Bruschi<sup>23b</sup>, N. Bruscinò<sup>135</sup>, P. Bryant<sup>36</sup>, L. Bryngemark<sup>44</sup>,  
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 M.K. Bugge<sup>130</sup>, O. Bulekov<sup>110</sup>, D. Bullock<sup>8</sup>, T.J. Burch<sup>119</sup>, S. Burdin<sup>88</sup>, C.D. Burgard<sup>118</sup>,  
 A.M. Burger<sup>5</sup>, B. Burghgrave<sup>119</sup>, K. Burka<sup>82</sup>, S. Burke<sup>141</sup>, I. Burmeister<sup>45</sup>, J.T.P. Burr<sup>131</sup>,  
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 P. Butti<sup>35</sup>, W. Buttinger<sup>35</sup>, A. Buzatu<sup>155</sup>, A.R. Buzykaev<sup>120b,120a</sup>, G. Cabras<sup>23b,23a</sup>,  
 S. Cabrera Urbán<sup>171</sup>, D. Caforio<sup>138</sup>, H. Cai<sup>170</sup>, V.M.M. Cairo<sup>2</sup>, O. Cakir<sup>4a</sup>, N. Calace<sup>52</sup>,  
 P. Calafiura<sup>18</sup>, A. Calandri<sup>99</sup>, G. Calderini<sup>132</sup>, P. Calfayan<sup>63</sup>, G. Callea<sup>40b,40a</sup>, L.P. Caloba<sup>78b</sup>,  
 S. Calvente Lopez<sup>96</sup>, D. Calvet<sup>37</sup>, S. Calvet<sup>37</sup>, T.P. Calvet<sup>152</sup>, M. Calvetti<sup>69a,69b</sup>,  
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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>45</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. Zaripovas<sup>55</sup>, S.V. Zeifner<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. Zgubic<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>, P. Zhao<sup>47</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> <sup>(a)</sup> *Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;* <sup>(b)</sup> *Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;* <sup>(c)</sup> *Department of Physics, Bogazici University, Istanbul;* <sup>(d)</sup> *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> <sup>(a)</sup> *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* <sup>(b)</sup> *Physics Department, Tsinghua University, Beijing;* <sup>(c)</sup> *Department of Physics, Nanjing University, Nanjing;* <sup>(d)</sup> *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*
- <sup>23</sup> <sup>(a)</sup> *Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna;* <sup>(b)</sup> *INFN Sezione di Bologna; Italy*
- <sup>24</sup> *Physikalisches Institut, Universität Bonn, Bonn; Germany*
- <sup>25</sup> *Department of Physics, Boston University, Boston MA; United States of America*
- <sup>26</sup> *Department of Physics, Brandeis University, Waltham MA; United States of America*
- <sup>27</sup> <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*
- <sup>28</sup> <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*
- <sup>29</sup> *Physics Department, Brookhaven National Laboratory, Upton NY; United States of America*
- <sup>30</sup> *Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina*
- <sup>31</sup> *Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom*
- <sup>32</sup> <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*
- <sup>33</sup> *Department of Physics, Carleton University, Ottawa ON; Canada*
- <sup>34</sup> <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 (CNESTEN), Rabat;* <sup>(c)</sup> *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;* <sup>(d)</sup> *Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda;* <sup>(e)</sup> *Faculté des sciences, Université Mohammed V, Rabat; Morocco*
- <sup>35</sup> *CERN, Geneva; Switzerland*
- <sup>36</sup> *Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America*
- <sup>37</sup> *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*
- 91 *Department of Physics, Royal Holloway University of London, Egham; United Kingdom*
- 92 *Department of Physics and Astronomy, University College London, London; United Kingdom*
- 93 *Louisiana Tech University, Ruston LA; United States of America*
- 94 *Fysiska institutionen, Lunds universitet, Lund; Sweden*
- 95 *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France*
- 96 *Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain*
- 97 *Institut für Physik, Universität Mainz, Mainz; Germany*
- 98 *School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom*
- 99 *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France*
- 100 *Department of Physics, University of Massachusetts, Amherst MA; United States of America*
- 101 *Department of Physics, McGill University, Montreal QC; Canada*
- 102 *School of Physics, University of Melbourne, Victoria; Australia*
- 103 *Department of Physics, University of Michigan, Ann Arbor MI; United States of America*
- 104 *Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America*
- 105 *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus*
- 106 *Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus*
- 107 *Group of Particle Physics, University of Montreal, Montreal QC; Canada*
- 108 *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia*
- 109 *Institute for Theoretical and Experimental Physics (ITEP), Moscow; Russia*
- 110 *National Research Nuclear University MEPhI, Moscow; Russia*
- 111 *D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia*
- 112 *Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany*
- 113 *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany*
- 114 *Nagasaki Institute of Applied Science, Nagasaki; Japan*
- 115 *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan*
- 116 *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America*

- 117 *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands*
- 118 *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands*
- 119 *Department of Physics, Northern Illinois University, DeKalb IL; United States of America*
- 120 <sup>(a)</sup> *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk;* <sup>(b)</sup> *Novosibirsk State University Novosibirsk; Russia*
- 121 *Department of Physics, New York University, New York NY; United States of America*
- 122 *Ohio State University, Columbus OH; United States of America*
- 123 *Faculty of Science, Okayama University, Okayama; Japan*
- 124 *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America*
- 125 *Department of Physics, Oklahoma State University, Stillwater OK; United States of America*
- 126 *Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic*
- 127 *Center for High Energy Physics, University of Oregon, Eugene OR; United States of America*
- 128 *LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France*
- 129 *Graduate School of Science, Osaka University, Osaka; Japan*
- 130 *Department of Physics, University of Oslo, Oslo; Norway*
- 131 *Department of Physics, Oxford University, Oxford; United Kingdom*
- 132 *LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France*
- 133 *Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America*
- 134 *Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg; Russia*
- 135 *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America*
- 136 <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*
- 137 *Institute of Physics, Academy of Sciences of the Czech Republic, Prague; Czech Republic*
- 138 *Czech Technical University in Prague, Prague; Czech Republic*
- 139 *Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic*
- 140 *State Research Center Institute for High Energy Physics, NRC KI, Protvino; Russia*
- 141 *Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom*
- 142 *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France*
- 143 *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America*
- 144 <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*
- 145 *Department of Physics, University of Washington, Seattle WA; United States of America*
- 146 *Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom*
- 147 *Department of Physics, Shinshu University, Nagano; Japan*
- 148 *Department Physik, Universität Siegen, Siegen; Germany*
- 149 *Department of Physics, Simon Fraser University, Burnaby BC; Canada*
- 150 *SLAC National Accelerator Laboratory, Stanford CA; United States of America*
- 151 *Physics Department, Royal Institute of Technology, Stockholm; Sweden*
- 152 *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America*
- 153 *Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom*
- 154 *School of Physics, University of Sydney, Sydney; Australia*



- 155 *Institute of Physics, Academia Sinica, Taipei; Taiwan*
- 156 <sup>(a)</sup> *E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia*
- 157 *Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel*
- 158 *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel*
- 159 *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece*
- 160 *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan*
- 161 *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan*
- 162 *Department of Physics, Tokyo Institute of Technology, Tokyo; Japan*
- 163 *Tomsk State University, Tomsk; Russia*
- 164 *Department of Physics, University of Toronto, Toronto ON; Canada*
- 165 <sup>(a)</sup> *TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON; Canada*
- 166 *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan*
- 167 *Department of Physics and Astronomy, Tufts University, Medford MA; United States of America*
- 168 *Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America*
- 169 *Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden*
- 170 *Department of Physics, University of Illinois, Urbana IL; United States of America*
- 171 *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC, Valencia; Spain*
- 172 *Department of Physics, University of British Columbia, Vancouver BC; Canada*
- 173 *Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada*
- 174 *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany*
- 175 *Department of Physics, University of Warwick, Coventry; United Kingdom*
- 176 *Waseda University, Tokyo; Japan*
- 177 *Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel*
- 178 *Department of Physics, University of Wisconsin, Madison WI; United States of America*
- 179 *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany*
- 180 *Department of Physics, Yale University, New Haven CT; United States of America*
- 181 *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, Iliia 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
- \* Deceased