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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

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Abstract: A search for a pair of neutral, scalar bosons with each decaying into two W bosons is presented using 36.1 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 GeV $\leq m_X \leq$ 500 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 GeV $\leq m_X \leq$ 340 GeV and 135 GeV $\leq m_S \leq$ 165 GeV and the observed (expected) limits range from 2.5 (2.5) pb to 0.16 (0.17) pb.

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Contents

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, λ_{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 $H \to VV^{(*)}$ 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

JHEP05(2019)124

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 ($X \to SS$), 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:

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

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

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

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

$$WW^{(*)}WW^{(*)} \to \ell\nu + \ell\nu + 4q,$$
$$WW^{(*)}WW^{(*)} \to \ell\nu + \ell\nu + \ell\nu + 2q, \text{ or}$$
$$WW^{(*)}WW^{(*)} \to \ell\nu + \ell\nu + \ell\nu + \ell\nu$$

where ℓ is either an electron or a muon, q refers to quark and anti-quark decay products from the hadronically decaying W boson(s), and ν 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) $X \to SS$ 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 $X \to t\bar{t}$ is expected to dominate, is not considered. It is assumed that $m_S > 135\,\text{GeV}$ such that $S \to WW^{(*)}$ 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 $HH \to WW^*WW^*$ decay channel and for an extended Higgs sector with the decay of $X \to SS \to WW^{(*)}WW^{(*)}$. The analysis is divided into three independent channels depending on the number of light leptons (e or μ) 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

JHEP05(2019)124

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 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 $gg \to HH$ and resonant $gg \to X \to HH$ 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 $\mathcal{B}(X \to HH)$ is assumed to be one. Samples of $X \to SS \to WW^{(*)}WW^{(*)}$ 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 $\mathcal{B}(X \to SS)$ is assumed to be one and the branching ratio $\mathcal{B}(S \to WW^{(*)})$ 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 $E_{\mathrm{T}} > 10\,\mathrm{GeV}$ and be within the detector fiducial volume of $|\eta| < 2.47$ excluding the transition region between the barrel and end-cap calorimeter, $1.37 < |\eta| < 1.52$.[1] 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 $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ 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 $p_{\mathrm{T}} > 1\,\mathrm{GeV}$) 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 $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.5$. Jets with $p_{\mathrm{T}} < 60\,\mathrm{GeV}$ 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

[1] 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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

JHEP05(2019)124

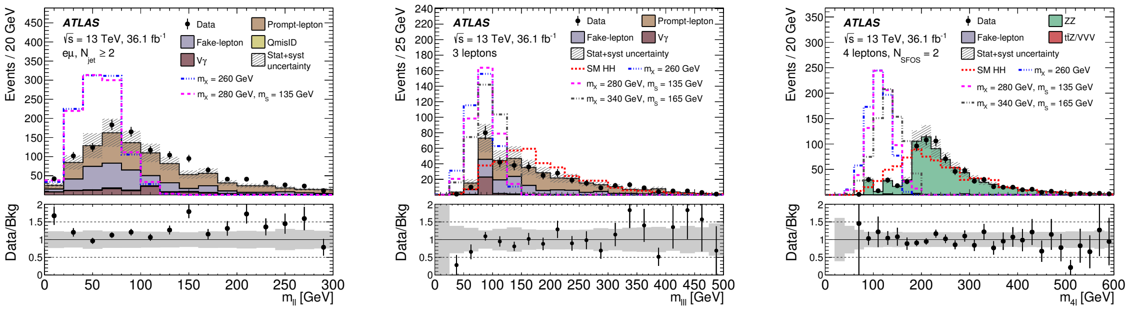
$\Delta R < \min(0.4, 0.04 + 10\,\text{GeV}/p_{\text{T}}^{\mu})$ from the nearest jet are removed if the jet has at least three tracks originating from the primary vertex; otherwise the jet is removed and the muon is kept. The missing transverse momentum, $E_{\text{T}}^{\text{miss}}$, vector is the negative of the vector sum of the transverse momenta of all electrons, muons, and jets. Tracks from the primary vertex[2] that are not associated with any objects are also taken into account in the $E_{\text{T}}^{\text{miss}}$ 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 μ). 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 $E_{\text{T}}^{\text{miss}} > 10$ (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: $|m_{\ell\ell} - m_Z| < 10\,\text{GeV}$. In order to reduce the backgrounds from non-prompt leptons, the leading (subleading) lepton is required to have $p_{\text{T}} > 30$ (20) GeV in the two lepton channel. The two leptons with the same charge are both required to have $p_{\text{T}} > 20\,\text{GeV}$ in the three lepton channel. For non-resonant production and resonant production with $m_X > 300\,\text{GeV}$, 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 $m_{\ell\ell} < 15\,\text{GeV}$ 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 betweeen 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

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



(a) (b) (c)

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_{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 $p_{\mathrm{T}} > 22\,\mathrm{GeV}$. Events that contain a SFOS lepton pair with $m_{\ell\ell} < 4\,\mathrm{GeV}$ 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,[3] 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).

[3] Leptons not from hadron decays or photon conversions.

JHEP05(2019)124

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 $Z \to ee$ 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, $E_{\text{T}}^{\text{miss}}$ 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.

JHEP05(2019)124

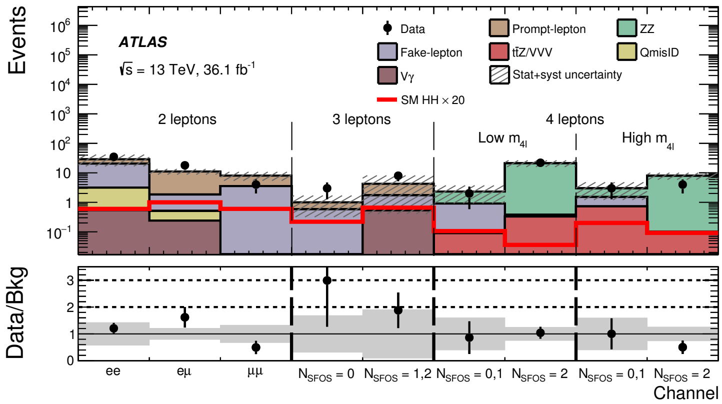


Figure 2. Expected and observed yields in each channel after all selection criteria for the non-resonant HH production searches. The label N_{SFOS} indicates the number of same-flavour, opposite-sign lepton pairs in the channel. Low and high $m_{4\ell}$ indicates $m_{4\ell} < 180\,\mathrm{GeV}$ and $m_{4\ell} > 180\,\mathrm{GeV}$, 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 $X \to SS$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ 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.

JHEP05(2019)124

Channel	Category	Background	Expected Signal	Observed
2 leptons	ee	29 ± 10	0.028 ± 0.004	35
	$e\mu$	11.1 ± 2.2	0.049 ± 0.005	18
	$\mu\mu$	8.1 ± 2.5	0.034 ± 0.004	4
3 leptons	$N_{\mathrm{SFOS}} = 0$	1.0 ± 0.7	0.011 ± 0.005	3
	$N_{\mathrm{SFOS}} = 1, 2$	4.3 ± 3.8	0.033 ± 0.010	8
4 leptons $m_{4\ell} < 180\,\mathrm{GeV}$	$N_{\mathrm{SFOS}} = 0, 1$	2.3 ± 1.4	0.005 ± 0.001	2
	$N_{\mathrm{SFOS}} = 2$	21 ± 5	0.002 ± 0.001	22
4 leptons $m_{4\ell} > 180\,\mathrm{GeV}$	$N_{\mathrm{SFOS}} = 0, 1$	3.0 ± 1.8	0.010 ± 0.002	3
	$N_{\mathrm{SFOS}} = 2$	7.9 ± 2.0	0.005 ± 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 $\sqrt{s} = 13\,\mathrm{TeV}$ of 33.4 fb. The label N_{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 $X \to SS$ 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 ($\sigma/\sigma_{\mathrm{SM}}$), are calculated using the modified frequentist $\mathrm{CL_s}$ 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 $m_X = 500\,\mathrm{GeV}$. 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 $m_X = 340\,\mathrm{GeV}$ and $m_S = 165\,\mathrm{GeV}$.

JHEP05(2019)124

	Observed	Expected limit on $\sigma/\sigma_{\mathrm{SM}}$				
	limit on $\sigma/\sigma_{\mathrm{SM}}$	Median	$+2\sigma$	$+1\sigma$	-1σ	-2σ
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 $\sqrt{s} = 13\,\mathrm{TeV}$ 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.

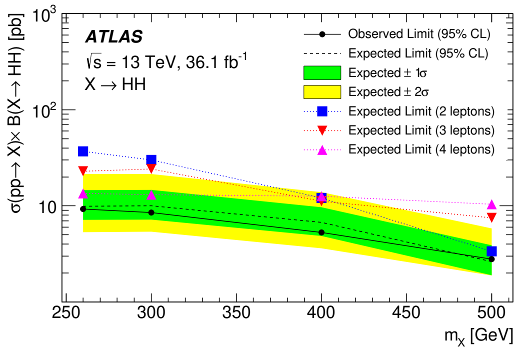
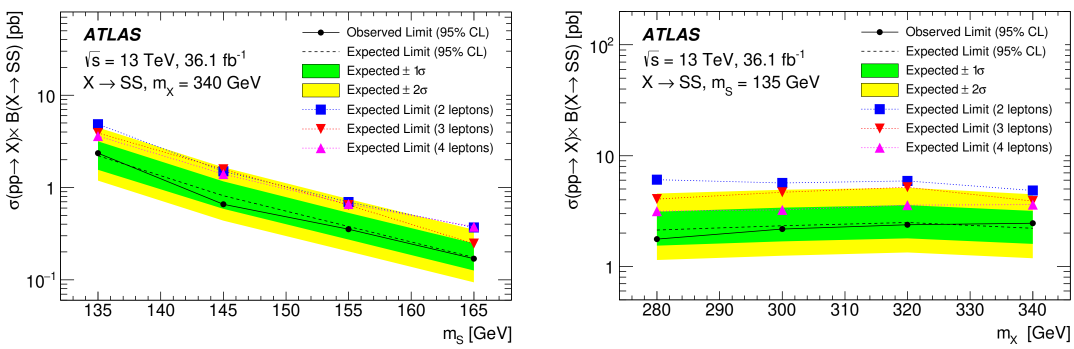


Figure 3. Expected and observed 95% CL exclusion limits set on the cross-section times branching ratio of resonant HH production as a function of m_X. Limits are shown for each channel individually as well as for the combination of the channels. Statistical and systematic uncertainties are included.



(a) **(b)**

Figure 4. Expected and observed 95% CL exclusion limits set on the cross-section times branching ratio of resonant $X \to SS$ 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.

JHEP05(2019)124

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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JHEP05(2019)124

Variable	Description
ℓ_1	Leading lepton
ℓ_2	Sub-leading lepton
$\Delta R_{\ell_N j}$	Angular distance between ℓ_N and the nearest jet
$m_{\ell\ell}$	Invariant mass of the two leptons
$m_{\ell_N jj}$	Invariant mass of ℓ_N and the two nearest jets
m_{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_{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 $X \to HH$ 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]	$m_{\ell_1 jj}$ [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 $X \to HH$ search with $m_X = 400\,\text{GeV}$ and $m_X = 500\,\text{GeV}$.

Mass	Channel	$\Delta R_{\ell_2 j}$	$\Delta R_{\ell_1 j}$	$m_{\ell\ell}$ [GeV]	$m_{\ell_1 jj}$ [GeV]
$m_S = 135\,\text{GeV}$	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]
$m_X = 340\,\text{GeV}$	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 $X \to SS$ search. The selection criteria in the first row are used for $m_S = 135\,\text{GeV}$ and $m_X = 280$, 300, and 320 GeV. The selection criteria in the second row are used for $m_X = 340\,\text{GeV}$ and $m_S = 135$, 145, 155, and 165 GeV.

Variable	Description
N_{SFOS}	Number of same-flavour opposite-sign lepton pairs
ℓ_1	Lepton with charge opposite to that of the same-sign pair
ℓ_2	Lepton from the same-sign pair that is closest to ℓ_1 in η–ϕ space
ℓ_3	Remaining lepton
$m_{\ell\ell\ell}$	Invariant mass of the three leptons
$m_{\ell_N j}$	Invariant mass of ℓ_N and the nearest jet
$m_{\ell_N jj}$	Invariant mass of ℓ_N and the two nearest jets
$m_{\ell\ell+\ell jj}$	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.

JHEP05(2019)124

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	$m_{\ell\ell\ell}$ [GeV]	[55, 100]	[25, 85]
	$m_{\ell_3 jj}$ [GeV]	[50, 145]	[50, 300]
	$m_{\ell_2 j}$ [GeV]	[35, 75]	[10, 65]
	$\Delta R_{\ell_1\ell_2}$	[0.51, 1.61]	[0.19, 1.16]
300 135	$m_{\ell\ell\ell}$ [GeV]	[55, 110]	[20, 135]
	$m_{\ell_3 jj}$ [GeV]	[50, 190]	[50, 135]
	$m_{\ell_2 j}$ [GeV]	[20, 55]	[20, 50]
	$\Delta R_{\ell_1\ell_2}$	[0.10, 1.86]	[0.46, 3.38]
320 135	$m_{\ell\ell\ell}$ [GeV]	[25, 110]	[25, 135]
	$m_{\ell_3 jj}$ [GeV]	[60, 210]	[50, 135]
	$m_{\ell_2 j}$ [GeV]	[10, 55]	[30, 60]
	$\Delta R_{\ell_1\ell_2}$	[0.24, 1.78]	[0.15, 1.53]
340 135	$m_{\ell\ell\ell}$ [GeV]	[50, 170]	[25, 180]
	$m_{\ell_3 jj}$ [GeV]	[50, 115]	[50, 115]
	$m_{\ell_2 j}$ [GeV]	[10, 40]	[25, 65]
	$\Delta R_{\ell_1\ell_2}$	[0.12, 1.68]	[0.15, 1.10]
340 145	$m_{\ell\ell\ell}$ [GeV]	[60, 110]	[40, 130]
	$m_{\ell_3 jj}$ [GeV]	[50, 350]	[50, 140]
	$m_{\ell_2 j}$ [GeV]	[10, 55]	[10, 90]
	$\Delta R_{\ell_1\ell_2}$	[0.19, 1.58]	[0.41, 1.11]
340 155	$m_{\ell\ell\ell}$ [GeV]	[30, 110]	[35, 135]
	$m_{\ell_3 jj}$ [GeV]	[50, 205]	[50, 140]
	$m_{\ell_2 j}$ [GeV]	[20, 55]	[10, 85]
	$\Delta R_{\ell_1\ell_2}$	[0.27, 2.24]	[0.50, 1.15]
340 165	$m_{\ell\ell\ell}$ [GeV]	[25, 110]	[25, 135]
	$m_{\ell_3 jj}$ [GeV]	[50, 210]	[50, 140]
	$m_{\ell_2 j}$ [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 $X \to SS$ 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.

JHEP05(2019)124

Variable	Description
p_{T}^{i}	p_{T} of lepton i
ℓ_2 and ℓ_3 ($N_{\mathrm{SFOS}} > 0$)	SFOS lepton pair with invariant mass closest to Z boson ($p_{\mathrm{T},2} > p_{\mathrm{T},3}$)
ℓ_2 and ℓ_3 ($N_{\mathrm{SFOS}} = 0$)	Different-flavour OS lepton pair with invariant mass closest to Z boson ($p_{\mathrm{T},2} > p_{\mathrm{T},3}$)
ℓ_0 and ℓ_1	Remaining lepton pair ($p_{\mathrm{T},0} > p_{\mathrm{T},1}$)

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

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

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	Non-resonant HH [%]	Resonant HH $m_X \in [280, 340]$ GeV [%]	$X \to SS$ $m_X \in [280, 340]$ 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 4.4×10^{-3} for the two same-sign lepton channel, 4.2×10^{-3} for the three lepton channel, and 5.1×10^{-4} for the four lepton channel. All numbers are given as percentages.

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JHEP05(2019)124

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Facini[92], R.M. Faisca Rodrigues Pereira[136a], R.M. Fakhrutdinov[140], S. Falciano[70a], P.J. Falke[5], S. Falke[5], J. Faltova[139], Y. Fang[15a], M. Fanti[66a,66b], A. Farbin[8], A. Farilla[72a], E.M. Farina[68a,68b], T. Farooque[104], S. Farrell[18], S.M. Farrington[175], P. Farthouat[35], F. Fassi[34e], P. Fassnacht[35], D. Fassouliotis[9], M. Faucci Giannelli[48], A. Favareto[53b,53a], W.J. Fawcett[31], L. Fayard[128], O.L. Fedin[134,o], W. Fedorko[172], M. Feickert[41], S. Feigl[130], L. Feligioni[99], C. Feng[58b], E.J. Feng[35], M. Feng[47], M.J. Fenton[55], A.B. Fenyuk[140], L. Feremenga[8], J. Ferrando[44], A. Ferrari[169], P. Ferrari[118], R. Ferrari[68a], D.E. Ferreira de Lima[59b], A. Ferrer[171], D. Ferrere[52], C. Ferretti[103], F. Fiedler[97], A. Filipčič[89], F. Filthaut[117], K.D. Finelli[25], M.C.N. Fiolhais[136a,136c,a], L. Fiorini[171], C. Fischer[14], W.C. Fisher[104], N. Flaschel[44], I. Fleck[148], P. Fleischmann[103], R.R.M. Fletcher[133], T. Flick[179], B.M. Flierl[112], L.M. Flores[133], L.R. Flores Castillo[61a], F.M. Follega[73a,73b], N. Fomin[17], G.T. Forcolin[73a,73b], A. Formica[142], F.A. Förster[14], A.C. Forti[98], A.G. Foster[21], D. Fournier[128], H. Fox[87], S. Fracchia[146], P. Francavilla[69a,69b], M. Franchini[23b,23a], S. Franchino[59a], D. Francis[35], L. Franconi[130], M. Franklin[57], M. Frate[168], M. Fraternali[68a,68b], A.N. Fray[90], D. Freeborn[92], S.M. Fressard-Batraneanu[35], B. Freund[107], W.S. Freund[78b], E.M. Freundlich[45], D.C. Frizzell[124], D. Froidevaux[35], J.A. Frost[131], C. Fukunaga[161], E. Fullana Torregrosa[171], T. Fusayasu[114], J. Fuster[171], O. Gabizon[157], A. Gabrielli[23b,23a], A. Gabrielli[18], G.P. Gach[81a], S. Gadatsch[52], P. Gadow[113], G. Gagliardi[53b,53a], L.G. Gagnon[107], C. Galea[27b], B. Galhardo[136a,136c], E.J. Gallas[131], B.J. Gallop[141], P. Gallus[138], G. Galster[39], R. Gamboa Goni[90], K.K. Gan[122], S. Ganguly[177], J. Gao[58a], Y. Gao[88], Y.S. Gao[150,l], C. García[171], J.E. García Navarro[171], J.A. García Pascual[15a], M. Garcia-Sciveres[18], R.W. Gardner[36], N. Garelli[150], V. Garonne[130], K. Gasnikova[44], A. Gaudiello[53b,53a], G. Gaudio[68a], I.L. Gavrilenko[108], A. Gavrilyuk[109], C. Gay[172], G. Gaycken[24], E.N. Gazis[10], C.N.P. Gee[141], J. Geisen[51], M. Geisen[97], M.P. Geisler[59a], K. Gellerstedt[43a,43b], C. Gemme[53b], M.H. Genest[56],

JHEP05(2019)124

C. Geng[103], S. Gentile[70a,70b], S. George[91], D. Gerbaudo[14], G. Gessner[45], S. Ghasemi[148], M. Ghasemi Bostanabad[173], M. Ghneimat[24], B. Giacobbe[23b], S. Giagu[70a,70b], N. Giangiacomi[23b,23a], P. Giannetti[69a], A. Giannini[67a,67b], S.M. Gibson[91], M. Gignac[143], D. Gillberg[33], G. Gilles[179], D.M. Gingrich[3,ar], M.P. Giordani[64a,64c], F.M. Giorgi[23b], P.F. Giraud[142], P. Giromini[57], G. Giugliarelli[64a,64c], D. Giugni[66a], F. Giuli[131], M. Giulini[59b], S. Gkaitatzis[159], I. Gkialas[9,i], E.L. Gkougkousis[14], P. Gkountoumis[10], L.K. Gladilin[111], C. Glasman[96], J. Glatzer[14], P.C.F. Glaysher[44], A. Glazov[44], M. Goblirsch-Kolb[26], J. Godlewski[82], S. Goldfarb[102], T. Golling[52], D. Golubkov[140], A. Gomes[136a,136b,136d], R. Goncalves Gama[78a], R. Gonçalo[136a], G. Gonella[50], L. Gonella[21], A. Gongadze[77], F. Gonnella[21], J.L. Gonski[57], S. González de la Hoz[171], S. Gonzalez-Sevilla[52], L. Goossens[35], P.A. Gorbounov[109], H.A. Gordon[29], B. Gorini[35], E. Gorini[65a,65b], A. Gorišek[89], A.T. Goshaw[47], C. Gössling[45], M.I. Gostkin[77], C.A. Gottardo[24], C.R. Goudet[128], D. Goujdami[34c], A.G. Goussiou[145], N. Govender[32b,b], C. Goy[5], E. Gozani[157], I. Grabowska-Bold[81a], P.O.J. Gradin[169], E.C. Graham[88], J. Gramling[168], E. Gramstad[130], S. Grancagnolo[19], V. Gratchev[134], P.M. Gravila[27f], F.G. Gravili[65a,65b], C. Gray[55], H.M. Gray[18], Z.D. Greenwood[93,ai], C. Grefe[24], K. Gregersen[94], I.M. Gregor[44], P. Grenier[150], K. Grevtsov[44], N.A. Grieser[124], J. Griffiths[8], A.A. Grillo[143], K. Grimm[150], S. Grinstein[14,y], Ph. Gris[37], J.-F. Grivaz[128], S. Groh[97], E. Gross[177], J. Grosse-Knetter[51], G.C. Grossi[93], Z.J. Grout[92], C. Grud[103], A. Grummer[116], L. Guan[103], W. Guan[178], J. Guenther[35], A. Guerguichon[128], F. Guescini[165a], D. Guest[168], R. Gugel[50], B. Gui[122], T. Guillemin[5], S. Guindon[35], U. Gul[55], C. Gumpert[35], J. Guo[58c], W. Guo[103], Y. Guo[58a,r], Z. Guo[99], R. Gupta[41], S. Gurbuz[12c], G. Gustavino[124], B.J. Gutelman[157], P. Gutierrez[124], C. Gutschow[92], C. Guyot[142], M.P. Guzik[81a], C. Gwenlan[131], C.B. Gwilliam[88], A. Haas[121], C. Haber[18], H.K. Hadavand[8], N. Haddad[34e], A. Hadef[58a], S. Hageböck[24], M. Hagihara[166], H. Hakobyan[181,*], M. Haleem[174], J. Haley[125], G. Halladjian[104], G.D. Hallewell[99], K. Hamacher[179], P. Hamal[126], K. Hamano[173], A. Hamilton[32a], G.N. Hamity[146], K. Han[58a,ah], L. Han[58a], S. Han[15d], K. Hanagaki[79,u], M. Hance[143], D.M. Handl[112], B. Haney[133], R. Hankache[132], P. Hanke[59a], E. Hansen[94], J.B. Hansen[39], J.D. Hansen[39], M.C. Hansen[24], P.H. Hansen[39], K. Hara[166], A.S. Hard[178], T. Harenberg[179], S. Harkusha[105], P.F. Harrison[175], N.M. Hartmann[112], Y. Hasegawa[147], A. Hasib[48], S. Hassani[142], S. Haug[20], R. Hauser[104], L. Hauswald[46], L.B. Havener[38], M. Havranek[138], C.M. Hawkes[21], R.J. Hawkings[35], D. Hayden[104], C. Hayes[152], C.P. Hays[131], J.M. Hays[90], H.S. Hayward[88], S.J. Haywood[141], M.P. Heath[48], V. Hedberg[94], L. Heelan[8], S. Heer[24], K.K. Heidegger[50], J. Heilman[33], S. Heim[44], T. Heim[18], B. Heinemann[44,am], J.J. Heinrich[112], L. Heinrich[121], C. Heinz[54], J. Hejbal[137], L. Helary[35], A. Held[172], S. Hellesund[130], S. Hellman[43a,43b], C. Helsens[35], R.C.W. Henderson[87], Y. Heng[178], S. Henkelmann[172], A.M. Henriques Correia[35], G.H. Herbert[19], H. Herde[26], V. Herget[174], Y. Hernández Jiménez[32c], H. Herr[97], M.G. Herrmann[112], G. Herten[50], R. Hertenberger[112], L. Hervas[35], T.C. Herwig[133], G.G. Hesketh[92], N.P. Hessey[165a], J.W. Hetherly[41], S. Higashino[79], E. Higón-Rodriguez[171], K. Hildebrand[36], E. Hill[173], J.C. Hill[31], K.K. Hill[29], K.H. Hiller[44], S.J. Hillier[21], M. Hils[46], I. Hinchliffe[18], M. Hirose[129], D. Hirschbuehl[179], B. Hiti[89], O. Hladik[137], D.R. Hlaluku[32c], X. Hoad[48], J. Hobbs[152], N. Hod[165a], M.C. Hodgkinson[146], A. Hoecker[35], M.R. Hoeferkamp[116], F. Hoenig[112], D. Hohn[24], D. Hohov[128], T.R. Holmes[36], M. Holzbock[112], M. Homann[45], S. Honda[166], T. Honda[79], T.M. Hong[135], A. Hönle[113], B.H. Hooberman[170], W.H. Hopkins[127], Y. Horii[115], P. Horn[46], A.J. Horton[149], L.A. Horyn[36], J-Y. Hostachy[56], A. Hostiuc[145], S. Hou[155], A. Hoummada[34a], J. Howarth[98], J. Hoya[86], M. Hrabovsky[126], I. Hristova[19], J. Hrivnac[128], A. Hrynevich[106], T. Hryn'ova[5], P.J. Hsu[62], S.-C. Hsu[145], Q. Hu[29], S. Hu[58c], Y. Huang[15a], Z. Hubacek[138], F. Hubaut[99], M. Huebner[24], F. Huegging[24], T.B. Huffman[131], E.W. Hughes[38], M. Huhtinen[35], R.F.H. Hunter[33], P. Huo[152], A.M. Hupe[33], N. Huseynov[77,ae], J. Huston[104], J. Huth[57], R. Hyneman[103], G. Iacobucci[52], G. Iakovidis[29], I. Ibragimov[148], L. Iconomidou-Fayard[128], Z. Idrissi[34e], P. Iengo[35], R. Ignazzi[39], O. Igonkina[118,aa], R. Iguchi[160], T. Iizawa[52], Y. Ikegami[79], M. Ikeno[79], D. Iliadis[159], N. Ilic[150], F. Iltzsche[46], G. Introzzi[68a,68b], M. Iodice[72a], K. Iordanidou[38], V. Ippolito[70a,70b], M.F. Isacson[169], N. Ishijima[129], M. Ishino[160], M. Ishitsuka[162], W. Islam[125], C. Issever[131], S. Istin[157], F. Ito[166], J.M. Iturbe Ponce[61a], R. Iuppa[73a,73b], A. Ivina[177], H. Iwasaki[79], J.M. Izen[42], V. Izzo[67a], P. Jacka[137], P. Jackson[1], R.M. Jacobs[24], V. Jain[2], G. Jäkel[179], K.B. Jakobi[97], K. Jakobs[50], S. Jakobsen[74], T. Jakoubek[137], D.O. Jamin[125], D.K. Jana[93], R. Jansky[52], J. Janssen[24], M. Janus[51], P.A. Janus[81a], G. Jarlskog[94], N. Javadov[77,ae], T. Javůrek[35], M. Javurkova[50], F. Jeanneau[142], L. Jeanty[18], J. Jejelava[156a,af], A. Jelinskas[175], P. Jenni[50,c], J. Jeong[44], N. Jeong[44], S. Jézéquel[5], H. Ji[178], J. Jia[152], H. Jiang[76], Y. Jiang[58a], Z. Jiang[150,p], S. Jiggins[50], F.A. Jimenez Morales[37], J. Jimenez Pena[171], S. Jin[15c], A. Jinaru[27b], O. Jinnouchi[162], H. Jivan[32c], P. Johansson[146], K.A. Johns[7], C.A. Johnson[63], W.J. Johnson[145], K. Jon-And[43a,43b], R.W.L. Jones[87], S.D. Jones[153], S. Jones[7], T.J. Jones[88], J. Jongmanns[59a], P.M. Jorge[136a,136b], J. Jovicevic[165a], X. Ju[18], J.J. Junggeburth[113], A. Juste Rozas[14,y], A. Kaczmarska[82], M. Kado[128], H. Kagan[122], M. Kagan[150], T. Kaji[176], E. Kajomovitz[157], C.W. Kalderon[94], A. Kaluza[97], S. Kama[41], A. Kamenshchikov[140], L. Kanjir[89], Y. Kano[160], V.A. Kantserov[110], J. Kanzaki[79], B. Kaplan[121], L.S. Kaplan[178], D. Kar[32c], M.J. Kareem[165b], E. Karentzos[10], S.N. Karpov[77], Z.M. Karpova[77], V. Kartvelishvili[87], A.N. Karyukhin[140], L. Kashif[178], R.D. Kass[122], A. Kastanas[43a,43b], Y. Kataoka[160], C. Kato[58d,58c], J. Katzy[44], K. Kawade[80], K. Kawagoe[85], T. Kawamoto[160], G. Kawamura[51], E.F. Kay[88], V.F. Kazanin[120b,120a], R. Keeler[173], R. Kehoe[41], J.S. Keller[33], E. Kellermann[94], J.J. Kempster[21], J. Kendrick[21], O. Kepka[137], S. Kersten[179], B.P. Kerševan[89], R.A. Keyes[101], M. Khader[170], F. Khalil-Zada[13], A. Khanov[125], A.G. Kharlamov[120b,120a], T. Kharlamova[120b,120a], E.E. Khoda[172], A. Khodinov[163], T.J. Khoo[52], E. Khramov[77], J. Khubua[156b], S. Kido[80], M. Kiehn[52], C.R. Kilby[91], Y.K. Kim[36], N. Kimura[64a,64c], O.M. Kind[19], B.T. King[88], D. Kirchmeier[46], J. Kirk[141], A.E. Kiryunin[113], T. Kishimoto[160], D. Kisielewska[81a], V. Kitali[44], O. Kivernyk[5], E. Kladiva[28b,*], T. Klapdor-Kleingrothaus[50], M.H. Klein[103], M. Klein[88], U. Klein[88], K. Kleinknecht[97], P. Klimek[119], A. Klimentov[29], R. Klingenberg[45,*], T. Klingl[24], T. Klioutchnikova[35], F.F. Klitzner[112], P. Kluit[118], S. Kluth[113], E. Kneringer[74], E.B.F.G. Knoops[99], A. Knue[50], A. Kobayashi[160], D. Kobayashi[85], T. Kobayashi[160], M. Kobel[46], M. Kocian[150], P. Kodys[139], P.T. Koenig[24], T. Koffas[33], E. Koffeman[118], N.M. Köhler[113], T. Koi[150], M. Kolb[59b], I. Koletsou[5], T. Kondo[79], N. Kondrashova[58c], K. Köneke[50], A.C. König[117], T. Kono[79], R. Konoplich[121,aj], V. Konstantinides[92], N. Konstantinidis[92], B. Konya[94], R. Kopeliansky[63], S. Koperny[81a], K. Korcyl[82], K. Kordas[159], G. Koren[158], A. Korn[92], I. Korolkov[14], E.V. Korolkova[146], N. Korotkova[111], O. Kortner[113], S. Kortner[113], T. Kosek[139], V.V. Kostyukhin[24], A. Kotwal[47], A. Koulouris[10], A. Kourkoumeli-Charalampidi[68a,68b], C. Kourkoumelis[9], E. Kourlitis[146], V. Kouskoura[29], A.B. Kowalewska[82], R. Kowalewski[173], T.Z. Kowalski[81a], C. Kozakai[160], W. Kozanecki[142], A.S. Kozhin[140], V.A. Kramarenko[111], G. Kramberger[89], D. Krasnopevtsev[58a], M.W. Krasny[132], A. Krasznahorkay[35], D. Krauss[113], J.A. Kremer[81a], J. Kretzschmar[88], P. Krieger[164], K. Krizka[18], K. Kroeninger[45], H. Kroha[113], J. Kroll[137], J. Kroll[133], J. Krstic[16], U. Kruchonak[77], H. Krüger[24], N. Krumnack[76], M.C. Kruse[47], T. Kubota[102], S. Kuday[4b], J.T. Kuechler[179], S. Kuehn[35], A. Kugel[59a], F. Kuger[174], T. Kuhl[44], V. Kukhtin[77], R. Kukla[99], Y. Kulchitsky[105], S. Kuleshov[144b], Y.P. Kulinich[170], M. Kuna[56], T. Kunigo[83], A. Kupco[137], T. Kupfer[45], O. Kuprash[158], H. Kurashige[80], L.L. Kurchaninov[165a], Y.A. Kurochkin[105], M.G. Kurth[15d], E.S. Kuwertz[35], M. Kuze[162], J. Kvita[126], T. Kwan[101], A. La Rosa[113], J.L. La Rosa Navarro[78d], L. La Rotonda[40b,40a], F. La Ruffa[40b,40a], C. Lacasta[171], F. Lacava[70a,70b], J. Lacey[44], D.P.J. Lack[98], H. Lacker[19], D. Lacour[132], E. Ladygin[77], R. Lafaye[5], B. Laforge[132], T. Lagouri[32c], S. Lai[51], S. Lammers[63], W. Lampl[7], E. Lançon[29], U. Landgraf[50], M.P.J. Landon[90], M.C. Lanfermann[52], V.S. Lang[44], J.C. Lange[14], R.J. Langenberg[35], A.J. Lankford[168], F. Lanni[29], K. Lantzsch[24], A. Lanza[68a], A. Lapertosa[53b,53a], S. Laplace[132], J.F. Laporte[142], T. Lari[66a], F. Lasagni Manghi[23b,23a], M. Lassnig[35], T.S. Lau[61a], A. Laudrain[128], M. Lavorgna[67a,67b], A.T. Law[143], M. Lazzaroni[66a,66b], B. Le[102], O. Le Dortz[132], E. Le Guirriec[99], E.P. Le Quilleuc[142], M. LeBlanc[7], T. LeCompte[6], F. Ledroit-Guillon[56], C.A. Lee[29], G.R. Lee[144a], L. Lee[57], S.C. Lee[155], B. Lefebvre[101], M. Lefebvre[173], F. Legger[112], C. Leggett[18], K. Lehmann[149], N. Lehmann[179], G. Lehmann Miotto[35], W.A. Leight[44], A. Leisos[159,v], M.A.L. Leite[78d], R. Leitner[139], D. Lellouch[177], B. Lemmer[51], K.J.C. Leney[92], T. Lenz[24], B. Lenzi[35], R. Leone[7],

JHEP05(2019)124

S. Leone[69a], C. Leonidopoulos[48], G. Lerner[153], C. Leroy[107], R. Les[164], A.A.J. Lesage[142], C.G. Lester[31], M. Levchenko[134], J. Levêque[5], D. Levin[103], L.J. Levinson[177], D. Lewis[90], B. Li[103], C-Q. Li[58a], H. Li[58b], L. Li[58c], M. Li[15a], Q. Li[15d], Q.Y. Li[58a], S. Li[58d,58c], X. Li[58c], Y. Li[148], Z. Liang[15a], B. Liberti[71a], A. Liblong[164], K. Lie[61c], S. Liem[118], A. Limosani[154], C.Y. Lin[31], K. Lin[104], T.H. Lin[97], R.A. Linck[63], J.H. Lindon[21], B.E. Lindquist[152], A.L. Lionti[52], E. Lipeles[133], A. Lipniacka[17], M. Lisovyi[59b], T.M. Liss[170,ao], A. Lister[172], A.M. Litke[143], J.D. Little[8], B. Liu[76], B.L Liu[6], H.B. Liu[29], H. Liu[103], J.B. Liu[58a], J.K.K. Liu[131], K. Liu[132], M. Liu[58a], P. Liu[18], Y. Liu[15a], Y.L. Liu[58a], Y.W. Liu[58a], M. Livan[68a,68b], A. Lleres[56], J. Llorente Merino[15a], S.L. Lloyd[90], C.Y. Lo[61b], F. Lo Sterzo[41], E.M. Lobodzinska[44], P. Loch[7], T. Lohse[19], K. Lohwasser[146], M. Lokajicek[137], B.A. Long[25], J.D. Long[170], R.E. Long[87], L. Longo[65a,65b], K.A. Looper[122], J.A. Lopez[144b], I. Lopez Paz[14], A. Lopez Solis[146], J. Lorenz[112], N. Lorenzo Martinez[5], M. Losada[22], P.J. Lösel[112], A. Lösle[50], X. Lou[44], X. Lou[15a], A. Lounis[128], J. Love[6], P.A. Love[87], J.J. Lozano Bahilo[171], H. Lu[61a], M. Lu[58a], N. Lu[103], Y.J. Lu[62], H.J. Lubatti[145], C. Luci[70a,70b], A. Lucotte[56], C. Luedtke[50], F. Luehring[63], I. Luise[132], L. Luminari[70a], B. Lund-Jensen[151], M.S. Lutz[100], P.M. Luzi[132], D. Lynn[29], R. Lysak[137], E. Lytken[94], F. Lyu[15a], V. Lyubushkin[77], H. Ma[29], L.L. Ma[58b], Y. Ma[58b], G. Maccarrone[49], A. Macchiolo[113], C.M. Macdonald[146], J. Machado Miguens[133,136b], D. Madaffari[171], R. Madar[37], W.F. Mader[46], A. Madsen[44], N. Madysa[46], J. Maeda[80], K. Maekawa[160], S. Maeland[17], T. Maeno[29], A.S. Maevskiy[111], V. Magerl[50], C. Maidantchik[78b], T. Maier[112], A. Maio[136a,136b,136d], O. Majersky[28a], S. Majewski[127], Y. Makida[79], N. Makovec[128], B. Malaescu[132], Pa. Malecki[82], V.P. Maleev[134], F. Malek[56], U. Mallik[75], D. Malon[6], C. Malone[31], S. Maltezos[10], S. Malyukov[35], J. Mamuzic[171], G. Mancini[49], I. Mandić[89], J. Maneira[136a], L. Manhaes de Andrade Filho[78a], J. Manjarres Ramos[46], K.H. Mankinen[94], A. Mann[112], A. Manousos[74], B. Mansoulie[142], J.D. Mansour[15a], M. Mantoani[51], S. Manzoni[66a,66b], A. Marantis[159], G. Marceca[30], L. March[52], L. Marchese[131], G. Marchiori[132], M. Marcisovsky[137], C.A. Marin Tobon[35], M. Marjanovic[37], D.E. Marley[103], F. Marroquim[78b], Z. Marshall[18], M.U.F Martensson[169], S. Marti-Garcia[171], C.B. Martin[122], T.A. Martin[175], V.J. Martin[48], B. Martin dit Latour[17], M. Martinez[14,y], V.I. Martinez Outschoorn[100], S. Martin-Haugh[141], V.S. Martoiu[27b], A.C. Martyniuk[92], A. Marzin[35], L. Masetti[97], T. Mashimo[160], R. Mashinistov[108], J. Masik[98], A.L. Maslennikov[120b,120a], L.H. Mason[102], L. Massa[71a,71b], P. Massarotti[67a,67b], P. Mastrandrea[5], A. Mastroberardino[40b,40a], T. Masubuchi[160], P. Mättig[179], J. Maurer[27b], B. Maček[89], S.J. Maxfield[88], D.A. Maximov[120b,120a], R. Mazini[155], I. Maznas[159], S.M. Mazza[143], N.C. Mc Fadden[116], G. Mc Goldrick[164], S.P. Mc Kee[103], A. McCarn[103], T.G. McCarthy[113], L.I. McClymont[92], E.F. McDonald[102], J.A. Mcfayden[35], G. Mchedlidze[51], M.A. McKay[41], K.D. McLean[173], S.J. McMahon[141], P.C. McNamara[102], C.J. McNicol[175], R.A. McPherson[173,ac], J.E. Mdhluli[32c], Z.A. Meadows[100], S. Meehan[145], T.M. Megy[50], S. Mehlhase[112], A. Mehta[88], T. Meideck[56], B. Meirose[42], D. Melini[171,g], B.R. Mellado Garcia[32c], J.D. Mellenthin[51], M. Melo[28a], F. Meloni[44], A. Melzer[24], S.B. Menary[98], E.D. Mendes Gouveia[136a], L. Meng[88], X.T. Meng[103], A. Mengarelli[23b,23a], S. Menke[113], E. Meoni[40b,40a], S. Mergelmeyer[19], C. Merlassino[20], P. Mermod[52], L. Merola[67a,67b], C. Meroni[66a], F.S. Merritt[36], A. Messina[70a,70b], J. Metcalfe[6], A.S. Mete[168], C. Meyer[133], J. Meyer[157], J-P. Meyer[142], H. Meyer Zu Theenhausen[59a], F. Miano[153], R.P. Middleton[141], L. Mijović[48], G. Mikenberg[177], M. Mikestikova[137], M. Mikuž[89], M. Milesi[102], A. Milic[164], D.A. Millar[90], D.W. Miller[36], A. Milov[177], D.A. Milstead[43a,43b], A.A. Minaenko[140], M. Miñano Moya[171], I.A. Minashvili[156b], A.I. Mincer[121], B. Mindur[81a], M. Mineev[77], Y. Minegishi[160], Y. Ming[178], L.M. Mir[14], A. Mirto[65a,65b], K.P. Mistry[133], T. Mitani[176], J. Mitrevski[112], V.A. Mitsou[171], A. Miucci[20], P.S. Miyagawa[146], A. Mizukami[79], J.U. Mjörnmark[94], T. Mkrtchyan[181], M. Mlynarikova[139], T. Moa[43a,43b], K. Mochizuki[107], P. Mogg[50], S. Mohapatra[38], S. Molander[43a,43b], R. Moles-Valls[24], M.C. Mondragon[104], K. Mönig[44], J. Monk[39], E. Monnier[99], A. Montalbano[149], J. Montejo Berlingen[35], F. Monticelli[86], S. Monzani[66a], N. Morange[128], D. Moreno[22], M. Moreno Llácer[35], P. Morettini[53b], M. Morgenstern[118], S. Morgenstern[46], D. Mori[149], M. Morii[57], M. Morinaga[176], V. Morisbak[130], A.K. Morley[35], G. Mornacchi[35],

JHEP05(2019)124

A.P. Morris[92], J.D. Morris[90], L. Morvaj[152], P. Moschovakos[10], M. Mosidze[156b], H.J. Moss[146], J. Moss[150,m], K. Motohashi[162], R. Mount[150], E. Mountricha[35], E.J.W. Moyse[100], S. Muanza[99], F. Mueller[113], J. Mueller[135], R.S.P. Mueller[112], D. Muenstermann[87], G.A. Mullier[20], F.J. Munoz Sanchez[98], P. Murin[28b], W.J. Murray[175,141], A. Murrone[66a,66b], M. Muškinja[89], C. Mwewa[32a], A.G. Myagkov[140,ak], J. Myers[127], M. Myska[138], B.P. Nachman[18], O. Nackenhorst[45], K. Nagai[131], K. Nagano[79], Y. Nagasaka[60], M. Nagel[50], E. Nagy[99], A.M. Nairz[35], Y. Nakahama[115], K. Nakamura[79], T. Nakamura[160], I. Nakano[123], H. Nanjo[129], F. Napolitano[59a], R.F. Naranjo Garcia[44], R. Narayan[11], D.I. Narrias Villar[59a], I. Naryshkin[134], T. Naumann[44], G. Navarro[22], R. Nayyar[7], H.A. Neal[103], P.Y. Nechaeva[108], T.J. Neep[142], A. Negri[68a,68b], M. Negrini[23b], S. Nektarijevic[117], C. Nellist[51], M.E. Nelson[131], S. Nemecek[137], P. Nemethy[121], M. Nessi[35,e], M.S. Neubauer[170], M. Neumann[179], P.R. Newman[21], T.Y. Ng[61c], Y.S. Ng[19], H.D.N. Nguyen[99], T. Nguyen Manh[107], E. Nibigira[37], R.B. Nickerson[131], R. Nicolaidou[142], D.S. Nielsen[39], J. Nielsen[143], N. Nikiforou[11], V. Nikolaenko[140,ak], I. Nikolic-Audit[132], K. Nikolopoulos[21], P. Nilsson[29], Y. Ninomiya[79], A. Nisati[70a], N. Nishu[58c], R. Nisius[113], I. Nitsche[45], T. Nitta[176], T. Nobe[160], Y. Noguchi[83], M. Nomachi[129], I. Nomidis[132], M.A. Nomura[29], T. Nooney[90], M. Nordberg[35], N. Norjoharuddeen[131], T. Novak[89], O. Novgorodova[46], R. Novotny[138], L. Nozka[126], K. Ntekas[168], E. Nurse[92], F. Nuti[102], F.G. Oakham[33,ar], H. Oberlack[113], T. Obermann[24], J. Ocariz[132], A. Ochi[80], I. Ochoa[38], J.P. Ochoa-Ricoux[144a], K. O'Connor[26], S. Oda[85], S. Odaka[79], S. Oerdek[51], A. Oh[98], S.H. Oh[47], C.C. Ohm[151], H. Oide[53b,53a], M.L. Ojeda[164], H. Okawa[166], Y. Okazaki[83], Y. Okumura[160], T. Okuyama[79], A. Olariu[27b], L.F. Oleiro Seabra[136a], S.A. Olivares Pino[144a], D. Oliveira Damazio[29], J.L. Oliver[1], M.J.R. Olsson[36], A. Olszewski[82], J. Olszowska[82], D.C. O'Neil[149], A. Onofre[136a,136e], K. Onogi[115], P.U.E. Onyisi[11], H. Oppen[130], M.J. Oreglia[36], G.E. Orellana[86], Y. Oren[158], D. Orestano[72a,72b], E.C. Orgill[98], N. Orlando[61b], A.A. O'Rourke[44], R.S. Orr[164], B. Osculati[53b,53a,*], V. O'Shea[55], R. Ospanov[58a], G. Otero y Garzon[30], H. Otono[85], M. Ouchrif[34d], F. Ould-Saada[130], A. Ouraou[142], Q. Ouyang[15a], M. Owen[55], R.E. Owen[21], V.E. Ozcan[12c], N. Ozturk[8], J. Pacalt[126], H.A. Pacey[31], K. Pachal[149], A. Pacheco Pages[14], L. Pacheco Rodriguez[142], C. Padilla Aranda[14], S. Pagan Griso[18], M. Paganini[180], G. Palacino[63], S. Palazzo[40b,40a], S. Palestini[35], M. Palka[81b], D. Pallin[37], I. Panagoulias[10], C.E. Pandini[35], J.G. Panduro Vazquez[91], P. Pani[35], G. Panizzo[64a,64c], L. Paolozzi[52], T.D. Papadopoulou[10], K. Papageorgiou[9,i], A. Paramonov[6], D. Paredes Hernandez[61b], S.R. Paredes Saenz[131], B. Parida[163], A.J. Parker[87], K.A. Parker[44], M.A. Parker[31], F. Parodi[53b,53a], J.A. Parsons[38], U. Parzefall[50], V.R. Pascuzzi[164], J.M.P. Pasner[143], E. Pasqualucci[70a], S. Passaggio[53b], F. Pastore[91], P. Pasuwan[43a,43b], S. Pataraia[97], J.R. Pater[98], A. Pathak[178,j], T. Pauly[35], B. Pearson[113], M. Pedersen[130], L. Pedraza Diaz[117], R. Pedro[136a,136b], S.V. Peleganchuk[120b,120a], O. Penc[137], C. Peng[15d], H. Peng[58a], B.S. Peralva[78a], M.M. Perego[142], A.P. Pereira Peixoto[136a], D.V. Perepelitsa[29], F. Peri[19], L. Perini[66a,66b], H. Pernegger[35], S. Perrella[67a,67b], V.D. Peshekhonov[77,*], K. Peters[44], R.F.Y. Peters[98], B.A. Petersen[35], T.C. Petersen[39], E. Petit[56], A. Petridis[1], C. Petridou[159], P. Petroff[128], M. Petrov[131], F. Petrucci[72a,72b], M. Pettee[180], N.E. Pettersson[100], A. Peyaud[142], R. Pezoa[144b], T. Pham[102], F.H. Phillips[104], P.W. Phillips[141], M.W. Phipps[170], G. Piacquadio[152], E. Pianori[18], A. Picazio[100], M.A. Pickering[131], R.H. Pickles[98], R. Piegaia[30], J.E. Pilcher[36], A.D. Pilkington[98], M. Pinamonti[71a,71b], J.L. Pinfold[3], M. Pitt[177], M-A. Pleier[29], V. Pleskot[139], E. Plotnikova[77], D. Pluth[76], P. Podberezko[120b,120a], R. Poettgen[94], R. Poggi[52], L. Poggioli[128], I. Pogrebnyak[104], D. Pohl[24], I. Pokharel[51], G. Polesello[68a], A. Poley[18], A. Policicchio[70a,70b], R. Polifka[35], A. Polini[23b], C.S. Pollard[44], V. Polychronakos[29], D. Ponomarenko[110], L. Pontecorvo[70a], G.A. Popeneciu[27d], D.M. Portillo Quintero[132], S. Pospisil[138], K. Potamianos[44], I.N. Potrap[77], C.J. Potter[31], H. Potti[11], T. Poulsen[94], J. Poveda[35], T.D. Powell[146], M.E. Pozo Astigarraga[35], P. Pralavorio[99], S. Prell[76], D. Price[98], M. Primavera[65a], S. Prince[101], N. Proklova[110], K. Prokofiev[61c], F. Prokoshin[144b], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[81a], A. Puri[170], P. Puzo[128], J. Qian[103], Y. Qin[98], A. Quadt[51], M. Queitsch-Maitland[44], A. Qureshi[1], P. Rados[102], F. Ragusa[66a,66b], G. Rahal[95], J.A. Raine[52], S. Rajagopalan[29], A. Ramirez Morales[90], T. Rashid[128], S. Raspopov[5],

JHEP05(2019)124

M.G. Ratti[66a,66b], D.M. Rauch[44], F. Rauscher[112], S. Rave[97], B. Ravina[146], I. Ravinovich[177], J.H. Rawling[98], M. Raymond[35], A.L. Read[130], N.P. Readioff[56], M. Reale[65a,65b], D.M. Rebuzzi[68a,68b], A. Redelbach[174], G. Redlinger[29], R. Reece[143], R.G. Reed[32c], K. Reeves[42], L. Rehnisch[19], J. Reichert[133], D. Reikher[158], A. Reiss[97], C. Rembser[35], H. Ren[15d], M. Rescigno[70a], S. Resconi[66a], E.D. Resseguie[133], S. Rettie[172], E. Reynolds[21], O.L. Rezanova[120b,120a], P. Reznicek[139], E. Ricci[73a,73b], R. Richter[113], S. Richter[44], E. Richter-Was[81b], O. Ricken[24], M. Ridel[132], P. Rieck[113], C.J. Riegel[179], O. Rifki[44], M. Rijssenbeek[152], A. Rimoldi[68a,68b], M. Rimoldi[20], L. Rinaldi[23b], G. Ripellino[151], B. Ristić[87], E. Ritsch[35], I. Riu[14], J.C. Rivera Vergara[144a], F. Rizatdinova[125], E. Rizvi[90], C. Rizzi[14], R.T. Roberts[98], S.H. Robertson[101,ac], D. Robinson[31], J.E.M. Robinson[44], A. Robson[55], E. Rocco[97], C. Roda[69a,69b], Y. Rodina[99], S. Rodriguez Bosca[171], A. Rodriguez Perez[14], D. Rodriguez Rodriguez[171], A.M. Rodríguez Vera[165b], S. Roe[35], C.S. Rogan[57], O. Røhne[130], R. Röhrig[113], C.P.A. Roland[63], J. Roloff[57], A. Romaniouk[110], M. Romano[23b,23a], N. Rompotis[88], M. Ronzani[121], L. Roos[132], S. Rosati[70a], K. Rosbach[50], P. Rose[143], N-A. Rosien[51], B.J. Rosser[133], E. Rossi[44], E. Rossi[72a,72b], E. Rossi[67a,67b], L.P. Rossi[53b], L. Rossini[66a,66b], J.H.N. Rosten[31], R. Rosten[14], M. Rotaru[27b], J. Rothberg[145], D. Rousseau[128], D. Roy[32c], A. Rozanov[99], Y. Rozen[157], X. Ruan[32c], F. Rubbo[150], F. Rühr[50], A. Ruiz-Martinez[171], Z. Rurikova[50], N.A. Rusakovich[77], H.L. Russell[101], J.P. Rutherfoord[7], E.M. Rüttinger[44,k], Y.F. Ryabov[134], M. Rybar[170], G. Rybkin[128], S. Ryu[6], A. Ryzhov[140], G.F. Rzehorz[51], P. Sabatini[51], G. Sabato[118], S. Sacerdoti[128], H.F-W. Sadrozinski[143], R. Sadykov[77], F. Safai Tehrani[70a], P. Saha[119], M. Sahinsoy[59a], A. Sahu[179], M. Saimpert[44], M. Saito[160], T. Saito[160], H. Sakamoto[160], A. Sakharov[121,aj], D. Salamani[52], G. Salamanna[72a,72b], J.E. Salazar Loyola[144b], P.H. Sales De Bruin[169], D. Salihagic[113], A. Salnikov[150], J. Salt[171], D. Salvatore[40b,40a], F. Salvatore[153], A. Salvucci[61a,61b,61c], A. Salzburger[35], J. Samarati[35], D. Sammel[50], D. Sampsonidis[159], D. Sampsonidou[159], J. Sánchez[171], A. Sanchez Pineda[64a,64c], H. Sandaker[130], C.O. Sander[44], M. Sandhoff[179], C. Sandoval[22], D.P.C. Sankey[141], M. Sannino[53b,53a], Y. Sano[115], A. Sansoni[49], C. Santoni[37], H. Santos[136a], I. Santoyo Castillo[153], A. Santra[171], A. Sapronov[77], J.G. Saraiva[136a,136d], O. Sasaki[79], K. Sato[166], E. Sauvan[5], P. Savard[164,ar], N. Savic[113], R. Sawada[160], C. Sawyer[141], L. Sawyer[93,ai], C. Sbarra[23b], A. Sbrizzi[23b,23a], T. Scanlon[92], J. Schaarschmidt[145], P. Schacht[113], B.M. Schachtner[112], D. Schaefer[36], L. Schaefer[133], J. Schaeffer[97], S. Schaepe[35], U. Schäfer[97], A.C. Schaffer[128], D. Schaile[112], R.D. Schamberger[152], N. Scharmberg[98], V.A. Schegelsky[134], D. Scheirich[139], F. Schenck[19], M. Schernau[168], C. Schiavi[53b,53a], S. Schier[143], L.K. Schildgen[24], Z.M. Schillaci[26], E.J. Schioppa[35], M. Schioppa[40b,40a], K.E. Schleicher[50], S. Schlenker[35], K.R. Schmidt-Sommerfeld[113], K. Schmieden[35], C. Schmitt[97], S. Schmitt[44], S. Schmitz[97], J.C. Schmoeckel[44], U. Schnoor[50], L. Schoeffel[142], A. Schoening[59b], E. Schopf[131], M. Schott[97], J.F.P. Schouwenberg[117], J. Schovancova[35], S. Schramm[52], A. Schulte[97], H-C. Schultz-Coulon[59a], M. Schumacher[50], B.A. Schumm[143], Ph. Schune[142], A. Schwartzman[150], T.A. Schwarz[103], Ph. Schwemling[142], R. Schwienhorst[104], A. Sciandra[24], G. Sciolla[26], M. Scornajenghi[40b,40a], F. Scuri[69a], F. Scutti[102], L.M. Scyboz[113], J. Searcy[103], C.D. Sebastiani[70a,70b], P. Seema[19], S.C. Seidel[116], A. Seiden[143], T. Seiss[36], J.M. Seixas[78b], G. Sekhniaidze[67a], K. Sekhon[103], S.J. Sekula[41], N. Semprini-Cesari[23b,23a], S. Sen[47], S. Senkin[37], C. Serfon[130], L. Serin[128], L. Serkin[64a,64b], M. Sessa[58a], H. Severini[124], F. Sforza[167], A. Sfyrla[52], E. Shabalina[51], J.D. Shahinian[143], N.W. Shaikh[43a,43b], L.Y. Shan[15a], R. Shang[170], J.T. Shank[25], M. Shapiro[18], A.S. Sharma[1], A. Sharma[131], P.B. Shatalov[109], K. Shaw[153], S.M. Shaw[98], A. Shcherbakova[134], Y. Shen[124], N. Sherafati[33], A.D. Sherman[25], P. Sherwood[92], L. Shi[155,an], S. Shimizu[79], C.O. Shimmin[180], M. Shimojima[114], I.P.J. Shipsey[131], S. Shirabe[85], M. Shiyakova[77], J. Shlomi[177], A. Shmeleva[108], D. Shoaleh Saadi[107], M.J. Shochet[36], S. Shojaii[102], D.R. Shope[124], S. Shrestha[122], E. Shulga[110], P. Sicho[137], A.M. Sickles[170], P.E. Sidebo[151], E. Sideras Haddad[32c], O. Sidiropoulou[35], A. Sidoti[23b,23a], F. Siegert[46], Dj. 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JHEP05(2019)124

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JHEP05(2019)124

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JHEP05(2019)124

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JHEP05(2019)124

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JHEP05(2019)124

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JHEP05(2019)124

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JHEP05(2019)124

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JHEP05(2019)124