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Search for resonances decaying into a weak vector boson and a Higgs boson in the fully hadronic final state produced in proton – proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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A search for heavy resonances decaying into a W or Z boson and a Higgs boson produced in proton – proton collisions at the Large Hadron Collider at $\sqrt{s} = 13$ TeV is presented. The analysis utilizes the dominant $W \to q\bar{q}'$ or $Z \to q\bar{q}$ and $H \to b\bar{b}$ decays with substructure techniques applied to large-radius jets. A sample corresponding to an integrated luminosity of 139 fb^{-1} collected with the ATLAS detector is analyzed and no significant excess of data is observed over the background prediction. The results are interpreted in the context of the heavy vector triplet model with spin-1 W' and Z' bosons. Upper limits on the cross section are set for resonances with mass between 1.5 and 5.0 TeV, ranging from 6.8 to 0.53 fb for $W' \to WH$ and from 8.7 to 0.53 fb for $Z' \to ZH$ at the 95% confidence level.

DOI: 10.1103/PhysRevD.102.112008

I. INTRODUCTION

The search for physics beyond the Standard Model (SM) is a major focus of the physics program at the Large Hadron Collider (LHC). Since its discovery [1,2], the Higgs boson has become a tool in this search. In particular, one may expect new heavy resonances to couple to Higgs bosons and weak vector bosons ($V = W$ or Z). Such resonances are expected to occur in a number of theories beyond the Standard Model. Theories that aim to solve the naturalness problem predict the existence of vector resonances as expected in composite Higgs models [3,4], Little Higgs models [5], or models with extra dimensions [6,7]. Theories with extended Higgs sectors predict scalar resonances as in two-Higgs-doublet models [8].

In this article, a search for WH and ZH resonances produced in proton−proton (pp) collisions at $\sqrt{s} = 13$ TeV is reported with a sample corresponding to an integrated luminosity of 139 fb^{-1} collected with the ATLAS detector during Run 2 of the LHC in 2015–2018. The search is designed for resonances with a mass of at least 1.5 TeV and with both the V and H bosons decaying hadronically in the modes $V \to q\bar{q}^{(\prime)}$ and $H \to b\bar{b}$, as shown in Fig. 1. In this regime, the V and H bosons are produced with high transverse momentum (p_{T}), resulting in each boson being reconstructed as a single large-radius hadronic jet, and the invariant mass of this dijet system provides the final discriminating variable. Jet substructure techniques and b-tagging are then used to discriminate those jets from background jets originating from multijet, V + jets, and $t\bar{t}$ events—with QCD multijet events representing at least 85% of the total background. Due to difficulties in modeling the background from simulation, all background estimates are derived from the data.

The results of the search are interpreted in the context of the heavy vector triplet (HVT) model [9], which is a simplified model providing a broad phenomenological framework for heavy resonances coupling to SM fermions and bosons. In this model, W' and Z' vector bosons interact with quarks and the Higgs field with coupling strength of g_q and g_H, respectively.[1] Coupling to the Higgs field gives rise to interactions with longitudinally polarized W and Z bosons. Two scenarios are considered as benchmarks for interpretation in this article. Model A corresponds to the choice $g_q = -0.55$ and $g_H = -0.56$, which reproduces the phenomenology of weakly coupled models based on an extended gauge symmetry [11]. Model B corresponds to $g_q = 0.14$ and $g_H = -2.9$, which implements a strongly coupled scenario as in composite Higgs models.

Previous searches for VH resonances have been carried out at $\sqrt{s} = 13$ TeV in the semileptonic final state ($\nu\nu bb$, $\ell\nu bb$, and $\ell\ell bb$) [12–14] and fully hadronic final state ($qqbb$) [15,16]. The ATLAS and CMS collaborations

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[1]Further details about the use of the HVT model in ATLAS analyses can be found in Ref. [10].

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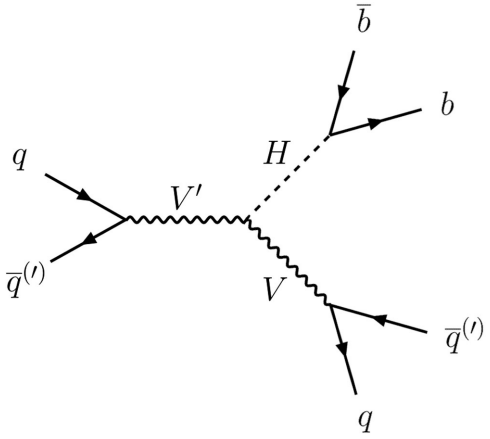

FIG. 1. Feynman diagram for the production of a V' resonance with decay into a VH pair.

report similar lower limits on the masses of W' and Z' bosons in these two sets of final states with about 36 fb^{-1} of integrated luminosity collected in 2015–2016. The strongest lower limit on the W' mass is set by CMS in the $\ell\nu bb$ channel [13] with a value of 2.9 TeV at the 95% confidence level (C.L.) in the context of HVT model B. For Z' bosons, the strongest lower limit on the mass is set by ATLAS in the combination of the $\nu\nu bb$ and $\ell\ell bb$ channels [12] with a value of 2.83 TeV at the 95% C.L. in HVT model B.

The results presented in this article differ from those previously published by ATLAS in the $qqbb$ channel [15] thanks to the following improvements. The integrated luminosity has increased by a factor of nearly four, an improved clustering algorithm combining measurements from the calorimeter and tracking systems is used to reconstruct V- and H-candidate jets, the b-tagging procedure used to identify H-candidate jets is performed on track jets with a p_{T}-dependent radius that allows double b-tagging of H-candidate jets up to considerably higher p_{T} values, and the Higgs-candidate selection has been reoptimized with increased sensitivity.

II. ATLAS DETECTOR

The ATLAS experiment [17] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[2] It consists of an inner detector (ID) for tracking surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The inner detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. An additional innermost pixel layer [18,19] inserted at a radius of 3.3 cm has been used since 2015. Liquid-argon (LAr) sampling calorimeters provide EM energy measurements with high granularity. A hadronic scintillator-tile calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end cap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and features three large air-core toroidal superconducting magnet systems with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. A two-level trigger system [20] is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to at most 100 kHz. This is followed by a software-based trigger level that reduces the accepted event rate to 1 kHz on average.

III. DATA AND MONTE CARLO SIMULATION

The data sample for the analysis was collected by the ATLAS detector with high-p_{T} single-jet triggers utilizing the anti-k_t clustering algorithm [21] with a radius $R = 1.0$. The lowest unprescaled triggers were used with the following p_{T} thresholds: 360 GeV in 2015, 420 GeV in 2016, and 460 GeV in 2017–2018. After requiring that the data were recorded with stable beam conditions and satisfied detector and data quality requirements, the integrated luminosity was measured to be 139 fb^{-1} using the methodology from Ref. [22].

The analysis relies on Monte Carlo (MC) samples to model signal events. Background MC samples are used only to optimize the signal event selection and to validate the data-driven background estimation method (Sec. V).

Signal W' and Z' events for HVT model A were produced at leading-order (LO) precision in the strong coupling constant (α_{s}) with the MadGraph5_aMC@NLO 2.2.2 [23] event generator using the NNPDF23LO parton distribution function (PDF) set [24]. Separate generation of signal events for HVT model B is not required as both models A and B give rise to dijet mass peaks with a width that is dominated by the experimental resolution. The events were interfaced with PYTHIA 8.186 [25] for parton showering, hadronization, and the underlying event, and relied on the A14 set of tuned parameters [26]. Higgs boson decays to heavy-flavor final states $H \to b\bar{b}$ and $H \to c\bar{c}$ were included, corresponding to branching fractions of 58.2% and 2.9%, respectively [27].

[2]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center 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 $\eta = -\ln\tan(\theta/2)$. The rapidity is defined relative to the beam axis as $y = (1/2)\ln[(E + p_z)/(E - p_z)]$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Multijet events were produced with the PYTHIA 8.186 event generator, the NNPDF23LO PDF set, and the A14 tune. Samples of events with top-quark pairs were produced at next-to-leading order (NLO) with POWHEG-BOX [28] and the NNPDF30 NLO PDF set, interfaced with PYTHIA 8.183 and the A14 tune. The h_{damp} parameter was set to 1.5 times the top-quark mass [29]. Samples of $W+$ jets and $Z+$ jets events were produced with SHERPA 2.1.1 [30] and the CT10 PDF set [31] for up to two partons at NLO and up to four partons at LO. The cross sections used to normalize the multijet and the $V+$ jets MC samples were computed with PYTHIA and SHERPA, respectively, and the top-quark pair cross section was taken to be 832^{+46}_{-52} pb for a top-quark mass of 172.5 GeV. This value was calculated at next-to-next-to-leading order in α_s, including the resummation of next-to-next-to-leading logarithmic soft gluon terms, with Top++2.0 [32–38]. Other SM backgrounds originating from diboson production (VV) and weak vector-boson production in association with a Higgs boson (VH) are negligible and not considered.

For all MC samples, except those produced with SHERPA, b-hadron and c-hadron decays were handled by EvtGen 1.2.0 [39]. Inelastic pp events generated using PYTHIA 8.186 with the A3 tune [40] and the NNPDF23LO PDF set were added to the hard-scattering interaction in such a way as to reproduce the effects of additional pp interactions (pileup) in each bunch crossing during data collection. The detector response was simulated with GEANT 4 [41,42], and the events were processed with the same reconstruction software as for the data. Energy/momentum scale and efficiency corrections are applied to the results of the simulation to account for small differences between the simulation and the performance measured directly from the data.

IV. EVENT RECONSTRUCTION AND SELECTION

The analysis relies on the reconstruction of charged particles with $p_{\text{T}} > 500$ MeV in the inner detector to reconstruct pp collision vertices for each crossing of the LHC beams. The primary vertex is chosen to be the vertex with the largest $\sum p_{\text{T}}^2$ for the tracks associated with the vertex.

Jets are built from a combination of tracks and calibrated clusters of energy deposits in calorimeter cells [43], with the anti-k_t clustering algorithm using a radius parameter $R = 1.0$ as implemented in FastJet [44]. The tracks are selected with the same requirements as in Ref. [45], except for the minimum p_{T} value, which has been increased to 500 MeV. By combining calorimeter and tracking information, one benefits from both the better energy resolution of the calorimeter at high energy and the superior angular resolution for the tracks. This combination becomes highly beneficial at large jet p_{T} due to the small number of clusters produced and the limited angular resolution of the calorimeter. The resulting jets are referred to as Track-CaloCluster (TCC) jets. A detailed description of the algorithm can be found in Ref. [46] and its application to a search for high-mass diboson resonances is described in Ref. [47]. A trimming algorithm [48] is applied to minimize the impact of pileup. In this algorithm, the constituents of each jet are reclustered with the k_t algorithm [49] into smaller $R = 0.2$ subjets. Trimmed large-R jets are made up of constituents of those subjets with $p_{\text{T}}^{\text{subjet}}/p_{\text{T}}^{\text{jet}} > 0.05$, where $p_{\text{T}}^{\text{subjet}}$ and $p_{\text{T}}^{\text{jet}}$ are the transverse momenta of the subjet and original untrimmed jet, respectively. The energy and mass calibration of TCC jets is based on the simulation as described in Ref. [50]. As a result of the improved angular resolution of the energy distribution within the jet, the discrimination between signal W or Z jets and background QCD jets is noticeably improved. In addition to their masses, a powerful variable to discriminate between those jets is D_2, defined as the ratio of three-point to two-point energy correlation functions that are based on the energies of the jet constituents and their pairwise angular separation [51,52]. The D_2 variable exploits the two-body structure of the $V \to q\bar{q}^{(\prime)}$ decays, absent from typical QCD jets. Another variable that provides discrimination between signal and background jets is the number of tracks (n_{trk}) matched to the jets by ghost association [53]. This quantity is significantly higher for gluon-induced jets that are a component of the background than for quark-induced jets in signal events, due to the distinct energy scales involved and the different color factors for gluons and quarks.

To identify Higgs-boson jets, a separate collection of jets is built from tracks with the anti-k_t algorithm using a p_{T}-dependent radius $R = \rho/p_{\text{T}}$ [54], where the parameter ρ is set to 30 GeV and the radius is constrained to remain in the range between 0.02 and 0.4 [55]. The track jets are assigned to specific large-R jets by ghost association with the original untrimmed large-R jets. The main advantage of using such variable-radius track jets is that one can resolve the track jets from $H \to b\bar{b}$ decays at high p_{T} and retain the ability to double b-tag the large-R Higgs-candidate jets.

Track jets are tagged as likely to contain b-hadrons if they satisfy the selection criteria of the MV2c10 algorithm [56,57] that takes advantage of the relatively long lifetime and large mass of b-hadrons. A working point corresponding to a b-tagging efficiency of 77% for true b-jets is used. For this efficiency value, rejection factors of 5 and 110 are obtained against c-quark and light-quark jets, with the efficiency and rejection factors determined in $t\bar{t}$ MC simulation [58].

Electrons are reconstructed by matching ID tracks to energy clusters in the EM calorimeter. The identification of electrons relies on a likelihood discriminant that takes the characteristic shape of electromagnetic showers into account [59]. Electrons are required to have $p_{\text{T}} > 7$ GeV and $|\eta| < 2.47$, and satisfy the *loose* identification

criteria [59]. The associated tracks must have a transverse impact parameter significance $|d_0|/\sigma_{d_0} < 5$ relative to the beam axis and a longitudinal impact parameter $|z_0 \sin\theta| < 0.5$ mm relative to the primary vertex. Muons are reconstructed and identified by matching ID and MS tracks, and performing a global fit with all ID and MS measurements, taking the energy loss in the calorimeter into account [60]. Muons are required to have $p_{\mathrm{T}} > 7$ GeV and $|\eta| < 2.5$, and satisfy the *loose* identification criteria [60]. The following track requirements are applied: $|d_0|/\sigma_{d_0} < 3$ and $|z_0 \sin\theta| < 0.5$ mm. Both the electrons and muons are required to satisfy loose isolation criteria [59,60] based on the total transverse momentum of tracks surrounding the leptons within a cone of radius $\Delta R = \min(10/p_{\mathrm{T}}^{\ell}[\mathrm{GeV}], \Delta R_{\mathrm{max}})$, where p_{T}^{ℓ} is the lepton p_{T}, and $\Delta R_{\mathrm{max}} = 0.2$ for electrons and 0.3 for muons. The isolation criteria have an efficiency of 99% with negligible dependence on the lepton p_{T} value.

Events must satisfy the trigger requirements and contain a primary vertex. In addition, noncollision backgrounds originating from calorimeter noise, beam halo interactions or cosmic rays are suppressed by rejecting events that contain any $R = 0.4$ anti-k_t calorimeter jet failing to satisfy a set of quality criteria. These are based on the LAr pulse shape, the energy profile of the jet in different parts of the calorimeter, and track variables [61]. Events with one or more charged leptons (electrons or muons) are also rejected to retain orthogonality with other VH search channels.

The signal topology requires the presence of two large-R jets with $|\eta| < 2.0$ and $p_{\mathrm{T}} > 200$ GeV. The leading (highest p_{T}) jet must satisfy $p_{\mathrm{T}} > 500$ GeV. The invariant mass of the dijet system consisting of the two highest-p_{T} jets in the event (m_{JJ}) is required to be larger than 1.3 TeV. These kinematic requirements guarantee that the trigger is fully efficient. To suppress t-channel multijet production, the difference between the rapidities of the two leading jets

TABLE I. Event selection requirements and definition of the different regions used in the analysis. Events in the signal, control, and validation regions must satisfy the preselection requirements.

Preselection	Veto non-$qqqq$ channels: No e (μ) with $p_{\mathrm{T}} > 7$ GeV and $\|\eta\| < 2.47$ (2.5) Event kinematics: $\geq$2 large-R jets with $p_{\mathrm{T}} > 200$ GeV and $\|\eta\| < 2.0$ leading large-R jet with $p_{\mathrm{T}} > 500$ GeV leading and subleading large-R jets with $m_{JJ} > 1.3$ TeV leading and subleading large-R jets with $\|\Delta y\| < 1.6$
V/H assignment	V-boson (H-boson) candidate is large-R jet with lower (higher) mass
Signal region (SRWH / SRZH)	V and H bosons: W-boson candidate within W jet mass, D_2, and n_{trk} windows Z-boson candidate within Z jet mass, D_2, and n_{trk} windows H-boson candidate within H jet mass, n_{trk} windows, with 1 or 2 b-tagged track jets
Control region (CR)	Fail both SRWH and SRZH Pass H-boson candidate n_{trk} $(m_V < 65$ GeV & $m_H < 70$ GeV) or ($m_V > 110$ GeV & $m_H > 150$ GeV) or ($m_V < 65$ GeV & $m_H > 150$ GeV)
Validation region (VR1A)	Fail both SRWH and SRZH Pass V-boson candidate n_{trk} Pass H-boson candidate n_{trk} $65 < m_V < 110$ GeV & $m_H > 150$ GeV
Validation region (VR1B)	Fail both SRWH and SRZH Fail V-boson candidate n_{trk} Pass H-boson candidate n_{trk} $65 < m_V < 110$ GeV & $m_H > 150$ GeV
Validation region (VR2A)	Fail both SRWH and SRZH Pass V-boson candidate n_{trk} Pass H-boson candidate n_{trk} $m_V < 65$ GeV & $70 < m_H < 150$ GeV
Validation region (VR2B)	Fail both SRWH and SRZH Fail V-boson candidate n_{trk} Pass H-boson candidate n_{trk} $m_V < 65$ GeV & $70 < m_H < 150$ GeV

must satisfy $|\Delta y| < 1.6$. Only the two leading-p_{T} jets are retained for further consideration.

As an initial step, the jet with the larger mass is taken to be the H-boson candidate while the other jet is taken to be the V-boson candidate. Discrimination between these V-boson or H-boson candidates and background jets relies on several properties of the large-R jets: mass, D_2, and n_{trk}. An optimization procedure is applied to adjust the selection criteria involving those variables to maximize the significance of the resonance signal under study. In the case of V-boson jets, the selection is based on the three discriminating variables as developed in the search for heavy diboson resonances in the fully hadronic channel [47], with the exception that the n_{trk} selection is loosened slightly. In the case of the H-boson candidates, the selection criteria are optimized with regard to the jet mass and n_{trk}. The successful H-boson candidate has at least one associated track jet and can be classified as either 1-tag or 2-tag, depending on the number of track jets satisfying the b-tagging requirements. Only the two highest-p_{T} associated track jets are considered for b-tagging. The variable D_2 provides little additional discrimination and is thus dropped.

The p_{T}-dependent jet mass windows for the $W(Z)$-boson candidates that result from the optimization procedure vary from 80–100 (85–110) GeV for jets with p_{T} around 500 GeV to 55–130 (65–135) GeV for jets with p_{T} around 3000 GeV. The upper bounds on D_2 for the V-boson candidates vary approximately from 1.0 to 1.5, for the same p_{T} values. The upper cut on the n_{trk} variable varies between 25 (26) and 31 (29) for $W(Z)$-boson candidates, with looser requirements for higher-p_{T} jets. Given the experimental jet mass resolution, no exclusive selection of W or Z bosons is performed and the WH and ZH final states are searched for independently. For H-boson candidates, the mass windows applied to events in the 1-tag (2-tag) category vary from 80–135 (95–150) GeV to 105–155 (100–170) GeV for jets with p_{T} of 500 and 3000 GeV, respectively. The H-boson candidates classified as 1(2)-tag are required to have an associated n_{trk} value below 32 (35) to 44 (55), looser at higher p_{T}.

The event selection defining the signal region (SR) is summarized in Table I. The resulting signal acceptance times efficiency ($\mathcal{A} \times \varepsilon$) for events in each category is shown in Figure 2. In the 1-tag category, $\mathcal{A} \times \varepsilon$ rises from approximately 3% to 10% for WH resonance masses increasing from 1.5 to 5.0 TeV. In the 2-tag category, $\mathcal{A} \times \varepsilon$ remains essentially constant at 4% for WH resonances. The different trends for the 1-tag and 2-tag selections as a function of $m(V')$ are the result of a combination of effects including the p_{T} dependence of both V- and H-tagging as well as the signal to background ratio. The $\mathcal{A} \times \varepsilon$ values are about 0.5% lower for ZH resonances due to the smaller mass separation between Z and H bosons. The experimental mass resolution for resonance masses of 2 (4) TeV is 3.5% (2.6%).

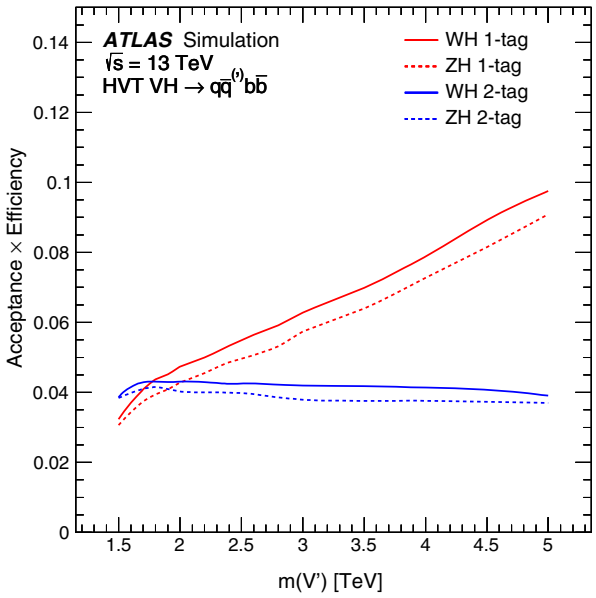

FIG. 2. Signal acceptance times efficiency as a function of the resonance mass, for events in the WH (solid lines) and ZH (dashed lines) signal regions, in the 1-tag and 2-tag categories, with respect to the total number of generated events in each sample. The HVT MC samples include only $V' \to VH$ decays with $V \to q\bar{q}^{(\prime)}$ and $H \to b\bar{b}$ or $c\bar{c}$.

V. BACKGROUND ESTIMATION AND EVENT YIELDS

The dominant background in this search comes from multijet events, corresponding to at least 85% of the total background in the signal regions, where the remaining events come from $t\bar{t}$ and V + jets processes.

The totality of the background is estimated via a data-driven method that provides template m_{JJ} distributions for the WH and ZH final states in the 1-tag and 2-tag categories. These background m_{JJ} templates are obtained in three steps: (i) background templates for the WH and ZH final states are extracted from data in the 0-tag category, where the H-boson candidate has zero associated b-tagged jets; (ii) yield and shape corrections are derived from a control region and applied to these templates; and (iii) a rebinning and smoothing of the resulting m_{JJ} distributions is performed, to ensure robustness against statistical fluctuations. All steps are described in this section.

To define the 0-tag templates from which the background in the 1-tag and 2-tag categories is extracted, additional requirements are placed on 0-tag events, such that at least 1(2) variable-radius track jet(s) is (are) associated with the H-boson jet, when estimating the background in the 1(2)-tag category. Events in the 0-tag category are not expected to directly describe either the yield or the m_{JJ} shape of the background in the 1-tag and 2-tag categories without further corrections: the b-tagging requirements enhance heavy-flavor components in the background and introduce kinematics-dependent effects.

Therefore, a control region (CR) is used to estimate the yield and shape corrections to the m_{JJ} distribution needed to extrapolate the 0-tag background events to the 1(2)-tag SRs. The CR has negligible contamination from signal. Validation regions (VR) with events that fail the SR selection are used to confirm the effectiveness of the background model and derive the associated systematic uncertainties. The definitions of the control and validation regions are shown in detail in Table I and illustrated in Fig. 3. According to simulation, multijet processes are responsible for 85% to 99% of the background composition across the different control, validation, and signal regions. This variation and its impact on the background estimate are taken into account by the uncertainties described in Sec. VI.

To define the background normalization in the 1(2)-tag category, a normalization correction $\mu_{\mathrm{CR}}^{1(2)\text{-tag}}$ is extracted from the ratio of 1(2)-tag to 0-tag yields in the control region:

$$\mu_{\mathrm{CR}}^{1(2)\text{-tag}} = \frac{N_{\mathrm{CR}}^{1(2)\text{-tag}}}{N_{\mathrm{CR}}^{0\text{-tag}}},$$

where $N_{\mathrm{CR}}^{0\text{-tag}}$ and $N_{\mathrm{CR}}^{1(2)\text{-tag}}$ are the numbers of events observed in the 0-tag and 1(2)-tag CR event categories. The values of $\mu_{\mathrm{CR}}^{1\text{-tag}}$ and $\mu_{\mathrm{CR}}^{2\text{-tag}}$ are determined to be 0.160 ± 0.014 and 0.0167 ± 0.0028, respectively, where the uncertainties are dominated by systematic effects discussed in Sec. VI. The difference in the corrections for 1-tag and 2-tag events can be understood based on studies of simulated multijet events. In 1-tag events, the two leading track jets associated with Higgs candidate large-R jets are dominated by one true b-jet accompanied by one true light-jet, whereas in 2-tag events they are dominated by two true b-jets. This indicates that different processes are at work in 1-tag and 2-tag events. The expected number of background 1(2)-tag events in the SR is calculated by applying the $\mu_{\mathrm{CR}}^{1(2)\text{-tag}}$ correction factor to the number of 0-tag events that pass all SR requirements except for the b-tagging.

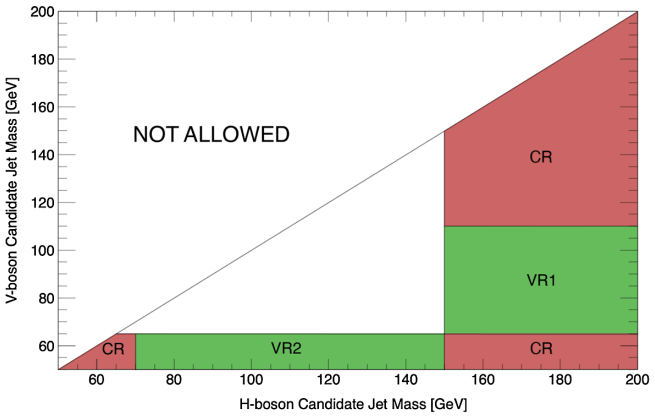

FIG. 3. Illustration of control and validation regions, defined by the masses of the H-boson and V-boson candidates. The regions VR1 and VR2 are further split into two regions each, according to the n_{trk} requirement on the V-boson candidate. The same definitions are applied across the number of b-tags (0-, 1-, and 2-tag categories).

To extract m_{JJ} background templates from the 0-tag category, a multidimensional kinematic reweighting [62] is performed using the control region events. A boosted decision tree (BDT) is used to perform the reweighting, by predicting the event weights needed to bring the shapes of kinematic distributions in the 0-tag and 1(2)-tag categories into agreement. The training is performed in the CR data and performed separately for 1-tag and 2-tag events. Variables that are sensitive to the presence of b-jets associated with the H-boson candidate and to the resulting kinematic differences are used to train the BDTs: the four-momenta of the two leading variable-radius track jets and their angular separation, the transverse momenta of the H- and V-boson jets, and the number of tracks and variable-radius track jets associated with the H-boson jet. The BDTs are built with 100 trees, a maximum depth of three layers, and a minimum of 500 events per leaf, with a learning rate set to 0.1.

In order to quantify the effectiveness of the reweighting, a binary classifier was trained to differentiate between the reweighted and target m_{JJ} distributions in the validation regions, and observed to classify them correctly at most 53% of the time, consistent with random guessing. The observed distributions of kinematic variables, including m_{JJ}, are found to be well described by the background model for 1-tag and 2-tag events in VR1A, VR1B, VR2A, and VR2B (defined in Table I).

The modeling of the m_{JJ} distributions in the VR2B region is shown in Fig. 4, for 1-tag and 2-tag events. A residual disagreement between the data and the expected background after reweighting is accounted for by a systematic uncertainty, as discussed in Sec. VI.

The numbers of 1-tag and 2-tag events observed in the control and validation regions are shown in Table II and compared with the predicted background yields.

After the normalization and reweighting corrections are applied to the events in the 0-tag category, the expected m_{JJ} background distributions in 1-tag and 2-tag categories are produced with a variable bin width that reflects the experimental mass resolution. Those distributions are then fit using a functional form that captures the smoothly falling behavior of the background:

$$f_{\mathrm{Background}}(x) = \mathrm{e}^{-p_0}(1-x)^{-p_1}x^{-p_2},$$

where $x = m_{JJ}/\sqrt{s}$ and p_0, p_1, and p_2 are the fit parameters. The results of these fits provide the background estimates that are used in the statistical analysis (described in Sec. VII) for the different signal regions.

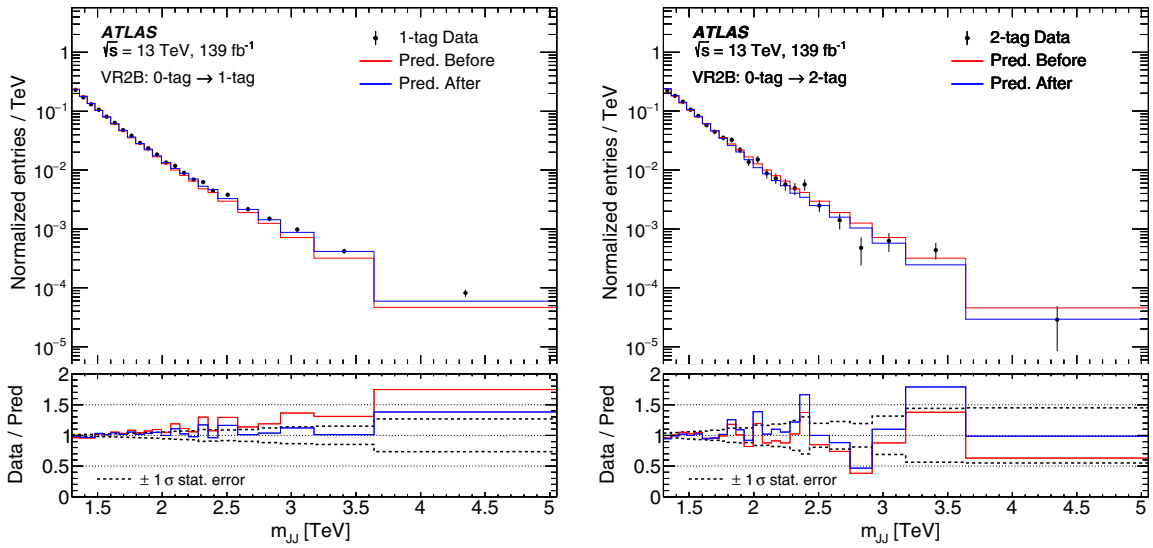

FIG. 4. Dijet mass distributions in the 1-tag (left) and 2-tag (right) VR2B regions compared with the predicted background extracted from the 0-tag events (histograms) before and after BDT reweighting.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties arise from several different sources: the data-driven background estimate, the modeling of experimental uncertainties affecting the signal, and the impact of signal theory uncertainties. At a resonance mass of 2 TeV, the background normalization and shape uncertainties dominate, while at a resonance mass of 4 TeV, the large-radius jet and boson tagging uncertainties dominate due to the small background contribution at high m_{JJ}.

The uncertainties affecting both the normalization and shape of the background predictions are determined from the validation regions. These uncertainties arise from limited sample sizes and from differences in the background composition in the various regions. The normalization uncertainty is taken to be the difference between the smallest and largest $\mu^{1(2)\text{-tag}}$ values obtained in any of the validations regions, resulting in a systematic error of 9% (17%) in the background estimate for the 1(2)-tag category. The uncertainty in the shape of the background m_{JJ} distribution is assessed from the ratio of data to prediction in the VR2B region, where the differences are the largest. This uncertainty is determined after smoothing the m_{JJ} distributions for both the data and the background prediction with the same functional form as described in Sec. V. It results in changes to the background yield of approximately 5% at m_{JJ} of 2 TeV and up to 24% at 4 TeV.

An additional shape uncertainty is assigned to account for the choice of fitting function, assessed by fitting alternate empirical functions, amounting to a maximum uncertainty of 2% (14%) at an m_{JJ} value of 2 (4) TeV.

Experimental uncertainties related to MC simulation are applicable only to signal samples, and are divided into two categories: b-tagging and large-R jets. A set of b-tagging correction factors and corresponding uncertainties are applied as a function of p_{T} and η of the variable-radius track jets to match the efficiencies for tagging b-jets measured in data, determined with $t\bar{t}$ events [58]. The uncertainties in the correction factors are extrapolated for track jets with p_{T} larger than 400 GeV. An additional extrapolation uncertainty is obtained by varying the inputs to the b-tagging algorithm according to their modeling uncertainties and by recomputing its efficiency in MC simulation [58].

Uncertainties in the p_{T} and mass scales of the large-R jet are determined with the R_{trk} method [63] adapted to the jet collection used in this article, relying on independent measurements by the calorimeter and the inner detector,

TABLE II. Data and estimated background yields for 1-tag and 2-tag events in the control and validation regions. The uncertainties correspond to the combination of statistical and systematic components. By construction, the uncertainties cover the differences between the observed and expected yields in the validation regions.

1-tag	Data	Background prediction
Control region (CR)	48668	−−
Validation region (VR1A)	4440	4290 ± 380
Validation region (VR1B)	18361	18000 ± 1600
Validation region (VR2A)	11844	12600 ± 1100
Validation region (VR2B)	29436	31200 ± 2700
2-tag	**Data**	**Background prediction**
Control region (CR)	4976	−−
Validation region (VR1A)	507	443 ± 74
Validation region (VR1B)	1922	1860 ± 310
Validation region (VR2A)	1337	1290 ± 220
Validation region (VR2B)	3065	3200 ± 540

TABLE III. Systematic uncertainties affecting the signal event yields in the WH and ZH signal regions with 1-tag or 2-tag (denoted WH-1, WH-2, ZH-1, and ZH-2, respectively). The HVT model is used with resonance masses of 2 and 4 TeV.

	Signal (2 TeV)				Signal (4 TeV)			
Source	WH-1	WH-2	ZH-1	ZH-2	WH-1	WH-2	ZH-1	ZH-2
Jet energy scale	2.8%	3.1%	1.6%	2.1%	5.2%	8.4%	6.6%	8.0%
Jet mass scale	18%	18%	9.6%	14%	20%	17%	21%	18%
Jet mass resolution	43%	45%	37%	40%	22%	21%	21%	22%
Flavor tagging	17%	8.4%	16%	8.4%	26%	12%	26%	13%
H-boson tagging	10%	10%	10%	10%	10%	10%	10%	10%
V-boson tagging	13%	13%	13%	13%	13%	13%	13%	13%
Luminosity	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%
MC statistical uncertainty	1.5%	1.4%	1.6%	1.4%	1.2%	1.4%	1.5%	1.7%

and are of the order of 5% to 10% each. These uncertainties lead to shifts in m_{JJ} of the resonant signal peak as well as differences in the signal selection efficiency. The effects of resolution uncertainties on the p_{T} and mass measurements are estimated by degrading the resolution in MC simulation according to a Gaussian smearing of width 0.02 in $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}$ and $0.20 \times \sigma(m)/m$ in $\sigma(m)/m$ [64,65].

The H- and V-boson tagging techniques are assigned dedicated uncertainties to take into account the requirements on D_2 and n_{trk}. An MC efficiency correction factor of 0.92 ± 0.13 for V-boson tagging was determined in the search for heavy diboson resonances in the fully hadronic channel [47] by taking advantage of a control region in data that is enhanced in $V+$jets events. Given that the same method for V-tagging is used in this analysis, the same scale factor and uncertainty of 14% is assigned to the signal normalization.[3] An efficiency correction and uncertainty in the n_{trk} requirement was also estimated in Ref. [66] for V jets. This uncertainty is applied to H-tagging, with an additional component to cover topology differences, based on simulation studies, corresponding to a total 10% uncertainty. In particular, these studies compare the large-radius jet mass distributions between the data and the simulation, and the impact of the n_{trk} requirement on the data-to-MC agreement in the V-mass and H-mass regions.

Signal cross sections computed at leading order are used in the interpretation of the results. The impact of uncertainties in the PDF sets, initial- and final-state radiation, and multiparton interactions on the signal acceptance are included. Uncertainties related to the PDF sets are derived by applying the methodology outlined by the PDF4LHC group [24] and considering four additional PDF sets (CT14, MMHT2014, NNPDF3.0, and ATLAS-epWZ12), resulting in $<1\%$ uncertainties in the signal acceptance. An uncertainty due to choosing the A14 tune for the signal generation is estimated by varying the scales for initial- and final-state radiation, as well as multiparton interactions, and results in an uncertainty of 2% (3%) for WH (ZH) resonances.

Finally, an uncertainty in the Run 2 integrated luminosity of 1.7% [22] is considered, as obtained by the LUCID-2 detector [67] for the main luminosity measurements. The impact of the main systematic uncertainties on signal event yields is summarized in Table III.

VII. RESULTS

The statistical analysis of the data is performed using a binned likelihood function, constructed from the m_{JJ} distributions in the 1-tag and 2-tag signal regions, using the procedure described in Ref. [1] and the ROOSTATS framework [68]. The m_{JJ} histograms derived from MC simulation are used for the HVT W' and Z' processes, while the data-driven background estimates are used for the combined $t\bar{t}$, $V+$jets, and QCD multijet processes. The input m_{JJ} distribution bounds are [1.3, 6.0] TeV.

A test statistic based on the profile likelihood ratio [69] is used to test signal hypotheses, parametrized by the signal strength value, μ, acting as a scale factor on the predicted number of signal events for each model assumption. The likelihood, L, is defined from the Poisson probability to observe N data events for a given signal s and background b expectation in each bin of the final discriminant:

$$L(\mu,\vec{\theta}) = \prod_{c=1}^{\text{categories}} \prod_{i=1}^{\text{bins}} \text{Pois}(N_{ci}|\mu s_{ci}(\vec{\theta}) + b_{ci}(\vec{\theta})) \prod_{j\in\vec{\theta}} f_j(\theta_j),$$

where the index c represents the 1-tag or 2-tag event categories and i represents the bin in the m_{JJ} distribution. Nuisance parameters $\vec{\theta}$ are included in the likelihood function with Gaussian or log-normal constraint terms, $f_j(\theta_j)$. Those nuisance parameters which produce bin variations smaller than 1% from the nominal value are neglected.

[3]The only difference is in the n_{trk} requirement, which is looser in this analysis. Studies of relative signal efficiencies for the different n_{trk} requirements show that this approximation is well motivated.

Experimental uncertainties in the signal are fully correlated between the 1-tag and 2-tag signal regions, whereas background modeling uncertainties are kept independent. In order to avoid an overconstraining of the background modeling uncertainties in the high mass region due to the higher statistical power at low masses, the m_{JJ} shape uncertainties above and below 2.5 TeV are allowed to vary independently in the fit. The postfit background expectation was found to be stable and independent of the particular choice of splitting point.

The fits are performed separately for the W' and Z' models, using data in the 1-tag and 2-tag regions from the SRWH and SRZH selections, respectively. The fit results are interpreted independently for the W' and Z' hypotheses—the WH and ZH signal regions are not orthogonal and have approximately 40% of events in common, in each category.

The pre- and postfit m_{JJ} distributions in the signal region are shown in Fig. 5 for signal resonances with a mass of 2 TeV. The numbers of data events in the signal regions are shown in Table IV, along with the predicted background and signal yields, postfit. No events with m_{JJ} values above 5 TeV are selected.

A test of the background-only hypothesis is performed by setting μ equal to zero in the likelihood fit. Deviations

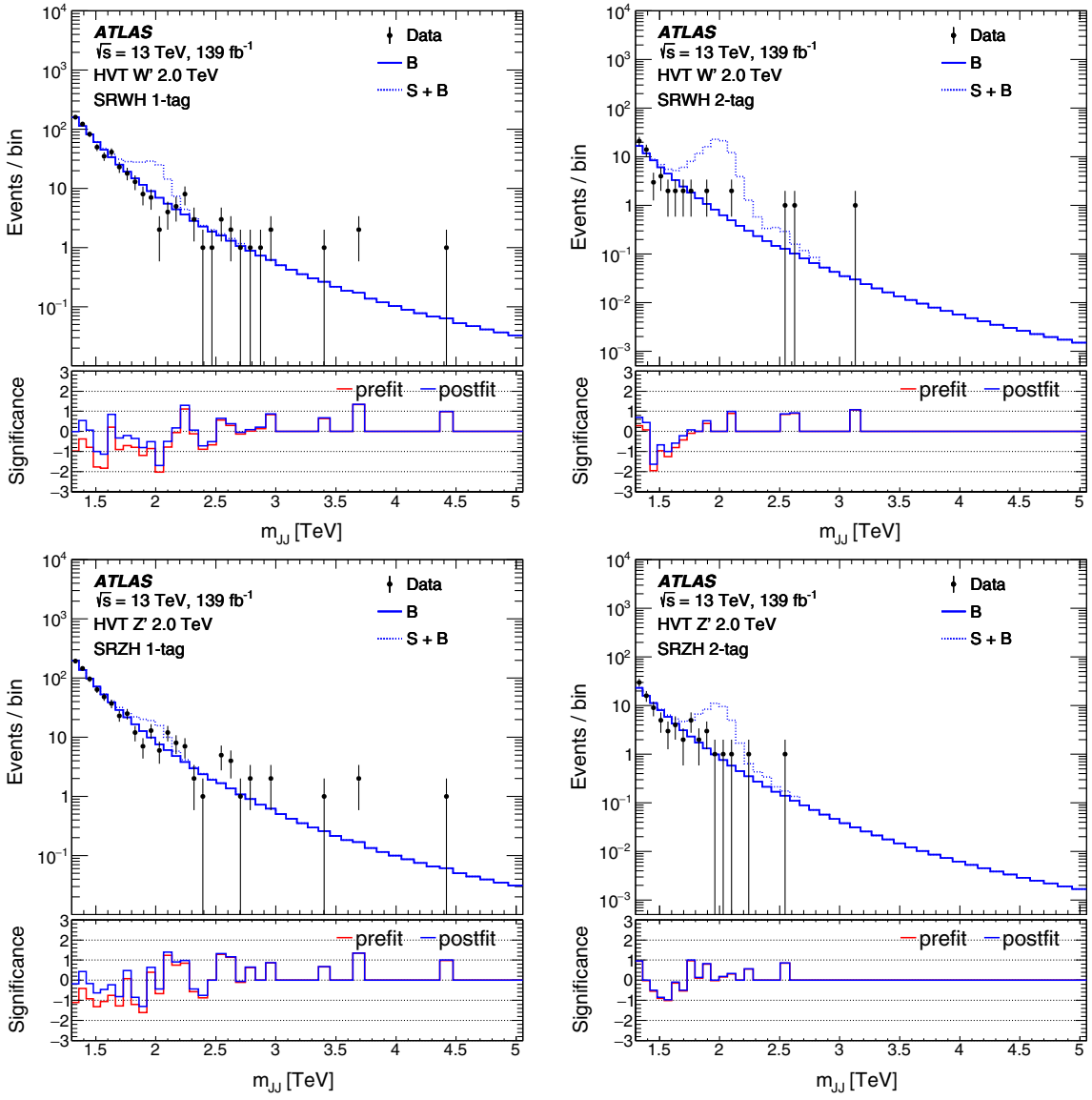

FIG. 5. Dijet mass distributions in the WH (top) and ZH (bottom) signal regions, after the likelihood fit to events in the 1-tag (left) and 2-tag (right) categories. The black points correspond to data and the solid blue histogram to the postfit background prediction. The WH and ZH signal regions are not orthogonal. The expected signal distributions for a V' boson with mass of 2 TeV are also shown (dashed histograms). The bin width varies and corresponds to the experimental mass resolution. Distributions of the significance of the observed deviations from the expected background are presented in the bottom panels before and after the fit. The significance calculation assumes Poisson probabilities and only accounts for statistical fluctuations.

TABLE IV. Event yields for the data, predicted background, and signal in each of the signal regions. The signal corresponds to that expected for HVT model B with resonance masses of 2 and 4 TeV.

Region	Data	Background	Signal (2 TeV)	Signal (4 TeV)
SRWH 1-tag	598	612 ± 46	110	2.0
SRWH 2-tag	57	61 ± 13	100	1.0
SRZH 1-tag	717	725 ± 53	47	0.80
SRZH 2-tag	84	81 ± 17	44	0.42

from the background-only hypothesis are quantified by determining the local p_0-value at each signal mass point. The largest deviation is observed in the fit to the WH signal regions and corresponds to a p_0-value of 0.03 for a resonance mass of 2.8 TeV.

The data are used to set upper limits on the production cross section of new resonances. Exclusion limits are computed using the CLs method [70], with a value of μ regarded as excluded at the 95% C.L. when the CLs value is less than 5%. The cross-section limits are shown in Fig. 6. The observed limits range from cross sections of 6.8 to 0.53 fb for WH and from 8.7 to 0.53 fb for ZH, corresponding to the exclusion of W' (Z') resonances up to a mass of 2.90 TeV (2.20 TeV) in the context of HVT model A and 3.20 TeV (2.65 TeV) in the context of HVT model B. The 2-tag category dominates the sensitivity of the search at low resonance mass while the impact of the 1-tag category increases at higher mass, surpassing the 2-tag category at masses above 3.9 TeV. As a test of the asymptotic approximation used in the statistical analysis, results are also obtained with ensembles of

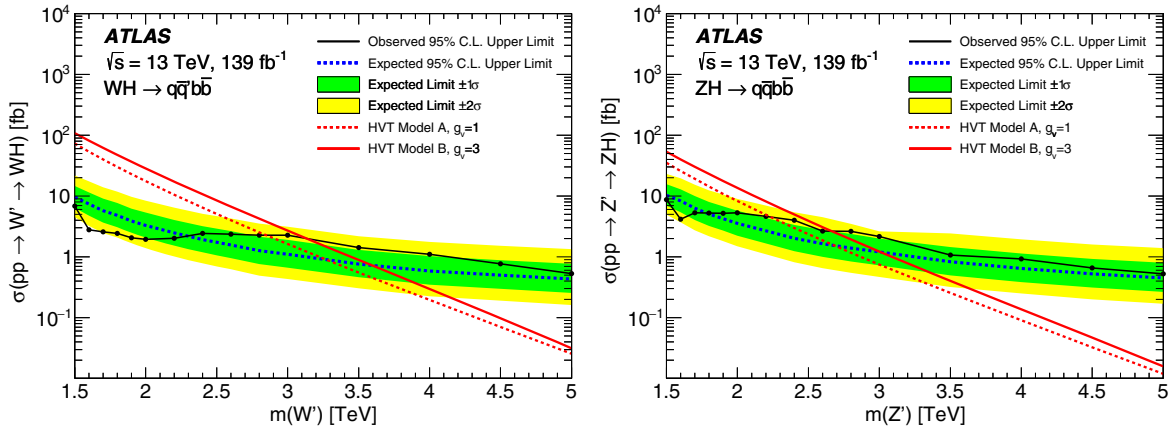

FIG. 6. Observed and expected 95% C.L. upper limits on the cross section for $pp \to V' \to VH$ in the WH (left) and ZH (right) channels. The red solid (dashed) lines show the cross-section predictions as a function of the resonance mass in the context of HVT model B (A).

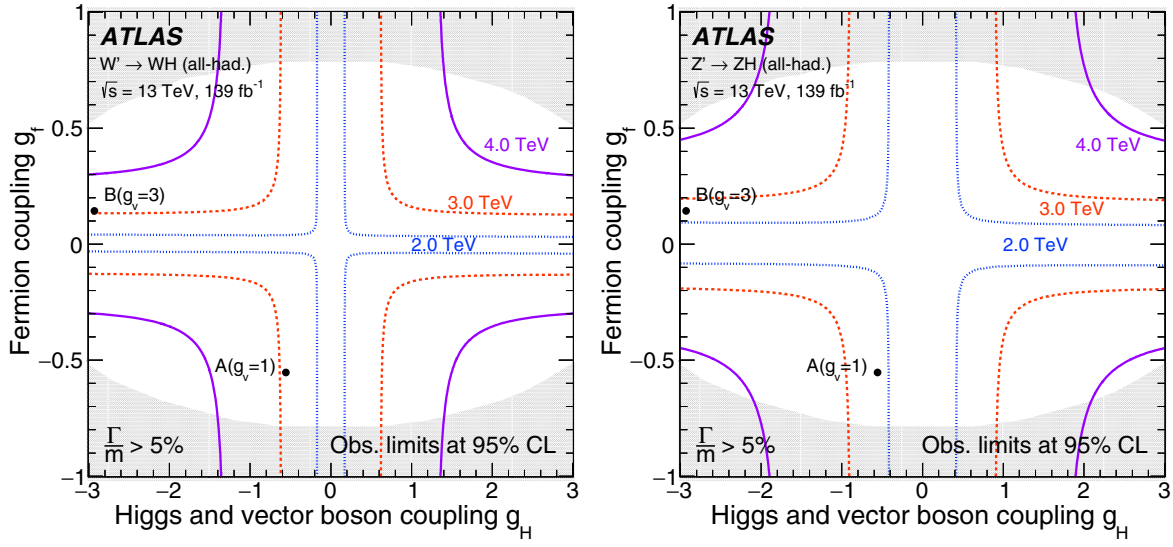

FIG. 7. Limits at 95% C.L. in the g_f vs g_H plane for resonance masses of 2, 3, and 4 TeV for the WH (left) and ZH (right) channels in the context of the HVT model. The coupling values corresponding to HVT models A and B are indicated by filled circles. The gray region indicates values of the couplings corresponding to V' resonances with Γ/m greater than 5%. In that region, the assumption that the V' signal m_{JJ} shape is dominated by the experimental resolution is no longer valid.

pseudoexperiments. The cross-section upper limits obtained in that case are looser by 10–20%, with a larger difference at high $m(V')$, and the mass limits are at most 0.05 TeV weaker.

These results can also be translated into exclusions in the $\{g_H, g_f\}$ plane, where g_f represents a universal coupling between the V' bosons and fermions. Here, g_q is taken to be equal to g_f. Figure 7 shows the 95% C.L. limits in this plane for several resonance masses.

VIII. CONCLUSION

A search for heavy resonances decaying into a W or Z boson and a Higgs boson is reported. The results are based on a sample of pp collisions at $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the Large Hadron Collider, corresponding to 139 fb^{-1} of integrated luminosity. The search exploits jet substructure techniques to study the fully hadronic $qqbb$ final state which results from the dominant decay modes of the W/Z and Higgs bosons. The main background contribution arises from multijet production, with a smaller contribution from top-quark pair and $V+$jets production. All background contributions are extracted directly from the data. Compared with the previously available results, the search benefits from an increased integrated luminosity, as well as from improvements in reconstruction and tagging of large-R jets and track jets with p_{T}-dependent radius.

No significant excess of events is observed over the expected background and the upper limits set on the cross section for $pp \to W' \to WH$ and $pp \to Z' \to ZH$ range from 6.8 fb at $m(W') = 1.5$ TeV to 0.53 fb at $m(W') = 5.0$ TeV, and from 8.7 fb at $m(Z') = 1.5$ TeV to 0.53 fb at $m(Z') = 5.0$ TeV, at 95% C.L. These results translate into lower limits on the mass of W' (Z') bosons of 2.90 TeV (2.20 TeV) in the context of the weakly coupled HVT model A and of 3.20 TeV (2.65 TeV) in the context of the strongly coupled HVT model B, at 95% C.L.

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M. Antonelli,[51] D. J. A. Antrim,[170] F. Anulli,[73a] M. Aoki,[82] J. A. Aparisi Pozo,[173] M. A. Aparo,[155] L. Aperio Bella,[46] N. Aranzabal Barrio,[36] V. Araujo Ferraz,[81a] R. Araujo Pereira,[81b] C. Arcangeletti,[51] A. T. H. Arce,[49] F. A. Arduh,[89] J-F. Arguin,[110] S. Argyropoulos,[52] J.-H. Arling,[46] A. J. Armbruster,[36] A. Armstrong,[170] O. Arnaez,[166] H. Arnold,[120] Z. P. Arrubarrena Tame,[114] G. Artoni,[134] H. Asada,[117] K. Asai,[126] S. Asai,[162] T. Asawatavonvanich,[164] N. Asbah,[59] E. M. Asimakopoulou,[171] L. Asquith,[155] J. Assahsah,[35d] K. Assamagan,[29] R. Astalos,[28a] R. J. Atkin,[33a] M. Atkinson,[172] N. B. Atlay,[19] H. Atmani,[65] K. Augsten,[141] V. A. Austrup,[181] G. Avolio,[36] M. K. Ayoub,[15a] G. Azuelos,[110,d] H. Bachacou,[144] K. Bachas,[161] M. Backes,[134] F. Backman,[45a,45b] P. Bagnaia,[73a,73b] M. Bahmani,[85] H. Bahrasemani,[151] A. J. Bailey,[173] V. R. Bailey,[172] J. T. Baines,[143] C. Bakalis,[10] O. K. Baker,[182] P. J. Bakker,[120] E. Bakos,[16] D. Bakshi Gupta,[8] S. Balaji,[156] R. Balasubramanian,[120] E. M. Baldin,[122b,122a] P. Balek,[179] F. Balli,[144] W. K. Balunas,[134] J. Balz,[100] E. Banas,[85] M. Bandieramonte,[138] A. Bandyopadhyay,[24] Sw. Banerjee,[180,e] L. Barak,[160] W. M. Barbe,[38] E. L. Barberio,[105] D. Barberis,[55b,55a] M. Barbero,[102] G. Barbour,[95] T. Barillari,[115] M-S. Barisits,[36] J. Barkeloo,[131] T. Barklow,[152] R. Barnea,[159] B. M. Barnett,[143] R. M. Barnett,[18] Z. Barnovska-Blenessy,[60a] A. Baroncelli,[60a] G. Barone,[29] A. J. Barr,[134] L. Barranco Navarro,[45a,45b] F. Barreiro,[99] J. Barreiro Guimarães da Costa,[15a] U. Barron,[160] S. Barsov,[137] F. Bartels,[61a] R. Bartoldus,[152] G. Bartolini,[102] A. E. Barton,[90] P. Bartos,[28a] A. Basalaev,[46] A. Basan,[100] A. Bassalat,[65,f] M. J. Basso,[166] R. L. Bates,[57] S. Batlamous,[35e] J. R. Batley,[32] B. Batool,[150] M. Battaglia,[145] M. Bauce,[73a,73b] F. Bauer,[144] P. Bauer,[24] H. S. Bawa,[31] A. Bayirli,[12c] J. B. Beacham,[49] T. Beau,[135] P. H. Beauchemin,[169] F. Becherer,[52] P. Bechtle,[24] H. C. Beck,[53] H. P. Beck,[20,g] K. Becker,[177] C. Becot,[46] A. Beddall,[12d] A. J. Beddall,[12a] V. A. Bednyakov,[80] M. Bedognetti,[120] C. P. Bee,[154] T. A. Beermann,[181] M. Begalli,[81b] M. Begel,[29] A. Behera,[154] J. K. Behr,[46] F. Beisiegel,[24] M. Belfkir,[5] A. S. Bell,[95] G. Bella,[160] L. Bellagamba,[23b] A. Bellerive,[34] P. Bellos,[9] K. Beloborodov,[122b,122a] K. Belotskiy,[112] N. L. Belyaev,[112] D. Benchekroun,[35a] N. Benekos,[10] Y. Benhammou,[160] D. P. Benjamin,[6] M. Benoit,[29] J. R. Bensinger,[26] S. Bentvelsen,[120] L. Beresford,[134] M. Beretta,[51] D. Berge,[19] E. Bergeaas Kuutmann,[171] N. Berger,[5] B. Bergmann,[141] L. J. Bergsten,[26] J. Beringer,[18] S. Berlendis,[7] G. Bernardi,[135] C. Bernius,[152] F. U. Bernlochner,[24] T. Berry,[94] P. Berta,[100] A. Berthold,[48] I. A. Bertram,[90] O. Bessidskaia Bylund,[181] N. Besson,[144] A. Bethani,[101] S. Bethke,[115] A. Betti,[42] A. J. Bevan,[93] J. Beyer,[115] D. S. Bhattacharya,[176] P. Bhattarai,[26] V. S. Bhopatkar,[6] R. Bi,[138] R. M. Bianchi,[138] O. Biebel,[114] D. Biedermann,[19] R. Bielski,[36] K. Bierwagen,[100] N. V. Biesuz,[72a,72b] M. Biglietti,[75a] T. R. V. Billoud,[141] M. Bindi,[53] A. Bingul,[12d] C. Bini,[73a,73b] S. Biondi,[23b,23a] C. J. Birch-sykes,[101] M. Birman,[179] T. Bisanz,[53] J. P. Biswal,[3] D. Biswas,[180,e] A. Bitadze,[101] C. Bittrich,[48] K. Bjørke,[133] T. Blazek,[28a] I. Bloch,[46] C. Blocker,[26] A. Blue,[57] U. Blumenschein,[93] G. J. Bobbink,[120] V. S. Bobrovnikov,[122b,122a] S. S. Bocchetta,[97] D. Boerner,[46] D. Bogavac,[14] A. G. Bogdanchikov,[122b,122a] C. Bohm,[45a] V. Boisvert,[94] P. Bokan,[171,171,53] T. Bold,[84a] A. E. Bolz,[61b] M. Bomben,[135] M. Bona,[93] J. S. Bonilla,[131] M. Boonekamp,[144] C. D. Booth,[94] A. G. Borbély,[57] H. M. Borecka-Bielska,[91] L. S. Borgna,[95] A. Borisov,[123] G. 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Burger,[129] B. Burghgrave,[8] J. T. P. Burr,[46] C. D. Burton,[11] J. C. Burzynski,[103] V. Büscher,[100] E. Buschmann,[53] P. J. Bussey,[57] J. M. Butler,[25] C. M. Buttar,[57] J. M. Butterworth,[95] P. Butti,[36] W. Buttinger,[36] C. J. Buxo Vazquez,[107] A. Buzatu,[157] A. R. Buzykaev,[122b,122a] G. Cabras,[23b,23a] S. Cabrera Urbán,[173] D. Caforio,[56] H. Cai,[138] V. M. M. Cairo,[152] O. Cakir,[4a] N. Calace,[36] P. Calafiura,[18] G. Calderini,[135] P. Calfayan,[66] G. Callea,[57] L. P. Caloba,[81b] A. Caltabiano,[74a,74b] S. Calvente Lopez,[99] D. Calvet,[38] S. Calvet,[38] T. P. Calvet,[102] M. Calvetti,[72a,72b] R. Camacho Toro,[135] S. Camarda,[36] D. Camarero Munoz,[99] P. Camarri,[74a,74b] M. T. Camerlingo,[75a,75b] D. Cameron,[133] C. Camincher,[36] S. Campana,[36] M. Campanelli,[95] A. Camplani,[40] V. Canale,[70a,70b] A. Canesse,[104] M. Cano Bret,[78] J. Cantero,[129] T. Cao,[160] Y. Cao,[172] M. D. M. Capeans Garrido,[36] M. Capua,[41b,41a] R. Cardarelli,[74a] F. Cardillo,[148] G. Carducci,[41b,41a] I. Carli,[142] T. Carli,[36] G. Carlino,[70a] B. T. Carlson,[138] E. M. Carlson,[175,167a] L. Carminati,[69a,69b] R. M. D. Carney,[152] S. Caron,[119] E. Carquin,[146d] S. Carrá,[46] G. Carratta,[23b,23a] J. W. S. Carter,[166] T. M. Carter,[50] M. P. Casado,[14,h] A. F. Casha,[166] E. G. Castiglia,[182] F. L. Castillo,[173] L. Castillo Garcia,[14] V. Castillo Gimenez,[173] N. F. Castro,[139a,139e] A. Catinaccio,[36] J. R. Catmore,[133] A. Cattai,[36] V. Cavaliere,[29] V. Cavasinni,[72a,72b] E. Celebi,[12b] F. Celli,[134] K. Cerny,[130] A. S. Cerqueira,[81a]

A. Cerri,[155] L. Cerrito,[74a,74b] F. Cerutti,[18] A. Cervelli,[23b,23a] S. A. Cetin,[12b] Z. Chadi,[35a] D. Chakraborty,[121] J. Chan,[180] W. S. Chan,[120] W. Y. Chan,[91] J. D. Chapman,[32] B. Chargeishvili,[158b] D. G. Charlton,[21] T. P. Charman,[93] M. Chatterjee,[20] C. C. Chau,[34] S. Che,[127] S. Chekanov,[6] S. V. Chekulaev,[167a] G. A. Chelkov,[80,i] B. Chen,[79] C. Chen,[60a] C. H. Chen,[79] H. Chen,[15c] H. Chen,[29] J. Chen,[60a] J. Chen,[39] J. Chen,[26] S. Chen,[136] S. J. Chen,[15c] X. Chen,[15b] Y. Chen,[60a] Y-H. Chen,[46] H. C. Cheng,[63a] H. J. Cheng,[15a] A. Cheplakov,[80] E. Cheremushkina,[123] R. Cherkaoui El Moursli,[35e] E. Cheu,[7] K. Cheung,[64] T. J. A. Chevalérias,[144] L. Chevalier,[144] V. Chiarella,[51] G. Chiarelli,[72a] G. Chiodini,[68a] A. S. Chisholm,[21] A. Chitan,[27b] I. Chiu,[162] Y. H. Chiu,[175] M. V. Chizhov,[80] K. Choi,[11] A. R. Chomont,[73a,73b] Y. S. Chow,[120] L. D. Christopher,[33e] M. C. Chu,[63a] X. Chu,[15a,15d] J. Chudoba,[140] J. J. Chwastowski,[85] L. Chytka,[130] D. Cieri,[115] K. M. Ciesla,[85] V. Cindro,[92] I. A. Cioară,[27b] A. Ciocio,[18] F. Cirotto,[70a,70b] Z. H. Citron,[179,j] M. Citterio,[69a] D. A. Ciubotaru,[27b] B. M. Ciungu,[166] A. Clark,[54] M. R. Clark,[39] P. J. Clark,[50] S. E. Clawson,[101] C. Clement,[45a,45b] Y. Coadou,[102] M. Cobal,[67a,67c] A. Coccaro,[55b] J. Cochran,[79] R. Coelho Lopes De Sa,[103] H. Cohen,[160] A. E. C. Coimbra,[36] B. Cole,[39] A. P. Colijn,[120] J. Collot,[58] P. Conde Muiño,[139a,139h] S. H. Connell,[33c] I. A. Connelly,[57] S. Constantinescu,[27b] F. Conventi,[70a,k] A. M. Cooper-Sarkar,[134] F. Cormier,[174] K. J. R. Cormier,[166] L. D. Corpe,[95] M. Corradi,[73a,73b] E. E. Corrigan,[97] F. Corriveau,[104,l] M. J. Costa,[173] F. Costanza,[5] D. Costanzo,[148] G. Cowan,[94] J. W. Cowley,[32] J. Crane,[101] K. Cranmer,[125] R. A. Creager,[136] S. Crépé-Renaudin,[58] F. Crescioli,[135] M. Cristinziani,[24] V. Croft,[169] G. Crosetti,[41b,41a] A. Cueto,[5] T. Cuhadar Donszelmann,[170] H. Cui,[15a,15d] A. R. Cukierman,[152] W. R. Cunningham,[57] S. Czekierda,[85] P. Czodrowski,[36] M. M. Czurylo,[61b] M. J. Da Cunha Sargedas De Sousa,[60b] J. V. Da Fonseca Pinto,[81b] C. Da Via,[101] W. Dabrowski,[84a] F. Dachs,[36] T. Dado,[47] S. Dahbi,[33e] T. Dai,[106] C. Dallapiccola,[103] M. Dam,[40] G. D'amen,[29] V. D'Amico,[75a,75b] J. Damp,[100] J. R. Dandoy,[136] M. F. Daneri,[30] M. Danninger,[151] V. Dao,[36] G. Darbo,[55b] O. Dartsi,[5] A. Dattagupta,[131] T. Daubney,[46] S. D'Auria,[69a,69b] C. David,[167b] T. Davidek,[142] D. R. Davis,[49] I. Dawson,[148] K. De,[8] R. De Asmundis,[70a] M. De Beurs,[120] S. De Castro,[23b,23a] N. De Groot,[119] P. de Jong,[120] H. De la Torre,[107] A. De Maria,[15c] D. De Pedis,[73a] A. De Salvo,[73a] U. De Sanctis,[74a,74b] M. De Santis,[74a,74b] A. De Santo,[155] J. B. De Vivie De Regie,[65] D. V. Dedovich,[80] A. M. Deiana,[42] J. Del Peso,[99] Y. Delabat Diaz,[46] D. Delgove,[65] F. Deliot,[144] C. M. Delitzsch,[7] M. Della Pietra,[70a,70b] D. Della Volpe,[54] A. Dell'Acqua,[36] L. Dell'Asta,[74a,74b] M. Delmastro,[5] C. Delporte,[65] P. A. Delsart,[58] D. A. DeMarco,[166] S. Demers,[182] M. Demichev,[80] G. Demontigny,[110] S. P. Denisov,[123] L. D'Eramo,[121] D. Derendarz,[85] J. E. Derkaoui,[35d] F. Derue,[135] P. Dervan,[91] K. Desch,[24] K. Dette,[166] C. Deutsch,[24] M. R. Devesa,[30] P. O. Deviveiros,[36] F. A. Di Bello,[73a,73b] A. Di Ciaccio,[74a,74b] L. Di Ciaccio,[5] W. K. Di Clemente,[136] C. Di Donato,[70a,70b] A. Di Girolamo,[36] G. Di Gregorio,[72a,72b] B. Di Micco,[75a,75b] R. Di Nardo,[75a,75b] K. F. Di Petrillo,[59] R. Di Sipio,[166] C. Diaconu,[102] F. A. Dias,[120] T. Dias Do Vale,[139a] M. A. Diaz,[146a] F. G. Diaz Capriles,[24] J. Dickinson,[18] M. Didenko,[165] E. B. Diehl,[106] J. Dietrich,[19] S. Díez Cornell,[46] C. Diez Pardos,[150] A. Dimitrievska,[18] W. Ding,[15b] J. Dingfelder,[24] S. J. Dittmeier,[61b] F. Dittus,[36] F. Djama,[102] T. Djobava,[158b] J. I. Djuvsland,[17] M. A. B. Do Vale,[81c] M. Dobre,[27b] D. Dodsworth,[26] C. Doglioni,[97] J. Dolejsi,[142] Z. Dolezal,[142] M. Donadelli,[81d] B. Dong,[60c] J. Donini,[38] A. D'onofrio,[15c] M. D'Onofrio,[91] J. Dopke,[143] A. Doria,[70a] M. T. Dova,[89] A. T. Doyle,[57] E. Drechsler,[151] E. Dreyer,[151] T. Dreyer,[53] A. S. Drobac,[169] D. Du,[60b] T. A. du Pree,[120] Y. Duan,[60d] F. Dubinin,[111] M. Dubovsky,[28a] A. Dubreuil,[54] E. Duchovni,[179] G. Duckeck,[114] O. A. Ducu,[36] D. Duda,[115] A. Dudarev,[36] A. C. Dudder,[100] E. M. Duffield,[18] M. D'uffizi,[101] L. Duflot,[65] M. Dührssen,[36] C. Dülsen,[181] M. Dumancic,[179] A. E. Dumitriu,[27b] M. Dunford,[61a] A. Duperrin,[102] H. Duran Yildiz,[4a] M. Düren,[56] A. Durglishvili,[158b] D. Duschinger,[48] B. Dutta,[46] D. Duvnjak,[1] G. I. Dyckes,[136] M. Dyndal,[36] S. Dysch,[101] B. S. Dziedzic,[85] M. G. Eggleston,[49] T. Eifert,[8] G. Eigen,[17] K. Einsweiler,[18] T. Ekelof,[171] H. El Jarrari,[35e] V. Ellajosyula,[171] M. Ellert,[171] F. Ellinghaus,[181] A. A. Elliot,[93] N. Ellis,[36] J. Elmsheuser,[29] M. Elsing,[36] D. Emeliyanov,[143] A. Emerman,[39] Y. Enari,[162] M. B. Epland,[49] J. Erdmann,[47] A. Ereditato,[20] P. A. Erland,[85] M. Errenst,[181] M. Escalier,[65] C. Escobar,[173] O. Estrada Pastor,[173] E. Etzion,[160] G. E. Evans,[139a,139b] H. Evans,[66] M. O. Evans,[155] A. Ezhilov,[137] F. Fabbri,[57] L. Fabbri,[23b,23a] V. Fabiani,[119] G. Facini,[177] R. M. Fakhrutdinov,[123] S. Falciano,[73a] P. J. Falke,[24] S. Falke,[36] J. Faltova,[142] Y. Fang,[15a] Y. Fang,[15a] G. Fanourakis,[44] M. Fanti,[69a,69b] M. Faraj,[67a,67c] A. Farbin,[8] A. Farilla,[75a] E. M. Farina,[71a,71b] T. Farooque,[107] S. M. Farrington,[50] P. Farthouat,[36] F. Fassi,[35e] P. Fassnacht,[36] D. Fassouliotis,[9] M. Faucci Giannelli,[50] W. J. Fawcett,[32] L. Fayard,[65] O. L. Fedin,[137,m] W. Fedorko,[174] A. Fehr,[20] M. Feickert,[172] L. Feligioni,[102] A. Fell,[148] C. Feng,[60b] M. Feng,[49] M. J. Fenton,[170] A. B. Fenyuk,[123] S. W. Ferguson,[43] J. Ferrando,[46] A. Ferrante,[172] A. Ferrari,[171] P. Ferrari,[120] R. Ferrari,[71a] D. E. Ferreira de Lima,[61b] A. Ferrer,[173] D. Ferrere,[54] C. Ferretti,[106] F. Fiedler,[100] A. Filipčič,[92] F. Filthaut,[119] K. D. Finelli,[25] M. C. N. Fiolhais,[139a,139c,n] L. Fiorini,[173] F. Fischer,[114] J. Fischer,[100] W. C. Fisher,[107] T. Fitschen,[21] I. Fleck,[150] P. Fleischmann,[106] T. Flick,[181] B. M. Flierl,[114] L. Flores,[136] L. R. Flores Castillo,[63a] F. M. Follega,[76a,76b] N. Fomin,[17]

J. H. Foo,[166] G. T. Forcolin,[76a,76b] B. C. Forland,[66] A. Formica,[144] F. A. Förster,[14] A. C. Forti,[101] E. Fortin,[102] M. G. Foti,[134] D. Fournier,[65] H. Fox,[90] P. Francavilla,[72a,72b] S. Francescato,[73a,73b] M. Franchini,[23b,23a] S. Franchino,[61a] D. Francis,[36] L. Franco,[5] L. Franconi,[20] M. Franklin,[59] G. Frattari,[73a,73b] A. N. Fray,[93] P. M. Freeman,[21] B. Freund,[110] W. S. Freund,[81b] E. M. Freundlich,[47] D. C. Frizzell,[128] D. Froidevaux,[36] J. A. Frost,[134] M. Fujimoto,[126] C. Fukunaga,[163] E. Fullana Torregrosa,[173] T. Fusayasu,[116] J. Fuster,[173] A. Gabrielli,[23b,23a] A. Gabrielli,[36] S. Gadatsch,[54] P. Gadow,[115] G. Gagliardi,[55b,55a] L. G. Gagnon,[110] G. E. Gallardo,[134] E. J. Gallas,[134] B. J. Gallop,[143] R. Gamboa Goni,[93] K. K. Gan,[127] S. Ganguly,[179] J. Gao,[60a] Y. Gao,[50] Y. S. Gao,[31,o] F. M. Garay Walls,[146a] C. García,[173] J. E. García Navarro,[173] J. A. García Pascual,[15a] C. Garcia-Argos,[52] M. Garcia-Sciveres,[18] R. W. Gardner,[37] N. Garelli,[152] S. Gargiulo,[52] C. A. Garner,[166] V. Garonne,[133] S. J. Gasiorowski,[147] P. Gaspar,[81b] A. Gaudiello,[55b,55a] G. Gaudio,[71a] P. Gauzzi,[73a,73b] I. L. Gavrilenko,[111] A. Gavrilyuk,[124] C. Gay,[174] G. Gaycken,[46] E. N. Gazis,[10] A. A. Geanta,[27b] C. M. Gee,[145] C. N. P. Gee,[143] J. Geisen,[97] M. Geisen,[100] C. Gemme,[55b] M. H. Genest,[58] C. Geng,[106] S. Gentile,[73a,73b] S. George,[94] T. Geralis,[44] L. O. Gerlach,[53] P. Gessinger-Befurt,[100] G. Gessner,[47] S. Ghasemi,[150] M. Ghasemi Bostanabad,[175] M. Ghneimat,[150] A. Ghosh,[65] A. Ghosh,[78] B. Giacobbe,[23b] S. Giagu,[73a,73b] N. Giangiacomi,[23b,23a] P. Giannetti,[72a] A. Giannini,[70a,70b] G. Giannini,[14] S. M. Gibson,[94] M. Gignac,[145] D. T. Gil,[84b] B. J. Gilbert,[39] D. Gillberg,[34] G. Gilles,[181] N. E. K. Gillwald,[46] D. M. Gingrich,[3,d] M. P. Giordani,[67a,67c] P. F. Giraud,[144] G. Giugliarelli,[67a,67c] D. Giugni,[69a] F. Giuli,[74a,74b] S. Gkaitatzis,[161] I. Gkialas,[9,p] E. L. Gkougkousis,[14] P. Gkountoumis,[10] L. K. Gladilin,[113] C. Glasman,[99] J. Glatzer,[14] P. C. F. Glaysher,[46] A. Glazov,[46] G. R. Gledhill,[131] I. Gnesi,[41b,q] M. Goblirsch-Kolb,[26] D. Godin,[110] S. Goldfarb,[105] T. Golling,[54] D. Golubkov,[123] A. Gomes,[139a,139b] R. Goncalves Gama,[53] R. Gonçalo,[139a,139c] G. Gonella,[131] L. Gonella,[21] A. Gongadze,[80] F. Gonnella,[21] J. L. Gonski,[39] S. González de la Hoz,[173] S. Gonzalez Fernandez,[14] R. Gonzalez Lopez,[91] C. Gonzalez Renteria,[18] R. Gonzalez Suarez,[171] S. Gonzalez-Sevilla,[54] G. R. Gonzalvo Rodriguez,[173] L. Goossens,[36] N. A. Gorasia,[21] P. A. Gorbounov,[124] H. A. Gordon,[29] B. Gorini,[36] E. Gorini,[68a,68b] A. Gorišek,[92] A. T. Goshaw,[49] M. I. Gostkin,[80] C. A. Gottardo,[119] M. Gouighri,[35b] A. G. Goussiou,[147] N. Govender,[33c] C. Goy,[5] I. Grabowska-Bold,[84a] E. C. Graham,[91] J. Gramling,[170] E. Gramstad,[133] S. Grancagnolo,[19] M. Grandi,[155] V. Gratchev,[137] P. M. Gravila,[27f] F. G. Gravili,[68a,68b] C. Gray,[57] H. M. Gray,[18] C. Grefe,[24] K. Gregersen,[97] I. M. Gregor,[46] P. Grenier,[152] K. Grevtsov,[46] C. Grieco,[14] N. A. Grieser,[128] A. A. Grillo,[145] K. Grimm,[31,r] S. Grinstein,[14,s] J.-F. Grivaz,[65] S. Groh,[100] E. Gross,[179] J. Grosse-Knetter,[53] Z. J. Grout,[95] C. Grud,[106] A. Grummer,[118] J. C. Grundy,[134] L. Guan,[106] W. Guan,[180] C. Gubbels,[174] J. Guenther,[36] A. Guerguichon,[65] J. G. R. Guerrero Rojas,[173] F. Guescini,[115] D. Guest,[170] R. Gugel,[100] A. Guida,[46] T. Guillemin,[5] S. Guindon,[36] J. Guo,[60c] W. Guo,[106] Y. Guo,[60a] Z. Guo,[102] R. Gupta,[46] S. Gurbuz,[12c] G. Gustavino,[128] M. Guth,[52] P. Gutierrez,[128] C. Gutschow,[95] C. Guyot,[144] C. Gwenlan,[134] C. B. Gwilliam,[91] E. S. Haaland,[133] A. Haas,[125] C. Haber,[18] H. K. Hadavand,[8] A. Hadef,[60a] M. Haleem,[176] J. Haley,[129] J. J. Hall,[148] G. Halladjian,[107] G. D. Hallewell,[102] K. Hamano,[175] H. Hamdaoui,[35e] M. Hamer,[24] G. N. Hamity,[50] K. Han,[60a,t] L. Han,[15c] L. Han,[60a] S. Han,[18] Y. F. Han,[166] K. Hanagaki,[82,u] M. Hance,[145] D. M. Handl,[114] M. D. Hank,[37] R. Hankache,[135] E. Hansen,[97] J. B. Hansen,[40] J. D. Hansen,[40] M. C. Hansen,[24] P. H. Hansen,[40] E. C. Hanson,[101] K. Hara,[168] T. Harenberg,[181] S. Harkusha,[108] P. F. Harrison,[177] N. M. Hartman,[152] N. M. Hartmann,[114] Y. Hasegawa,[149] A. Hasib,[50] S. Hassani,[144] S. Haug,[20] R. Hauser,[107] L. B. Havener,[39] M. Havranek,[141] C. M. Hawkes,[21] R. J. Hawkings,[36] S. Hayashida,[117] D. Hayden,[107] C. Hayes,[106] R. L. Hayes,[174] C. P. Hays,[134] J. M. Hays,[93] H. S. Hayward,[91] S. J. Haywood,[143] F. He,[60a] Y. He,[164] M. P. Heath,[50] V. Hedberg,[97] S. Heer,[24] A. L. Heggelund,[133] C. Heidegger,[52] K. K. Heidegger,[52] W. D. Heidorn,[79] J. Heilman,[34] S. Heim,[46] T. Heim,[18] B. Heinemann,[46,v] J. J. Heinrich,[131] L. Heinrich,[36] J. Hejbal,[140] L. Helary,[46] A. Held,[125] S. Hellesund,[133] C. M. Helling,[145] S. Hellman,[45a,45b] C. Helsens,[36] R. C. W. Henderson,[90] Y. Heng,[180] L. Henkelmann,[32] A. M. Henriques Correia,[36] H. Herde,[26] Y. Hernández Jiménez,[33e] H. Herr,[100] M. G. Herrmann,[114] T. Herrmann,[48] G. Herten,[52] R. Hertenberger,[114] L. Hervas,[36] T. C. Herwig,[136] G. G. Hesketh,[95] N. P. Hessey,[167a] H. Hibi,[83] S. Higashino,[82] E. Higón-Rodriguez,[173] K. Hildebrand,[37] J. C. Hill,[32] K. K. Hill,[29] K. H. Hiller,[46] S. J. Hillier,[21] M. Hils,[48] I. Hinchliffe,[18] F. Hinterkeuser,[24] M. Hirose,[132] S. Hirose,[168] D. Hirschbuehl,[181] B. Hiti,[92] O. Hladik,[140] J. Hobbs,[154] N. Hod,[179] M. C. Hodgkinson,[148] A. Hoecker,[36] D. Hohn,[52] D. Hohov,[65] T. Holm,[24] T. R. Holmes,[37] M. Holzbock,[115] L. B. A. H. Hommels,[32] T. M. Hong,[138] J. C. Honig,[52] A. Hönle,[115] B. H. Hooberman,[172] W. H. Hopkins,[6] Y. Horii,[117] P. Horn,[48] L. A. Horyn,[37] S. Hou,[157] A. Hoummada,[35a] J. Howarth,[57] J. Hoya,[89] M. Hrabovsky,[130] J. Hrdinka,[77] J. Hrivnac,[65] A. Hrynevich,[109] T. Hryn'ova,[5] P. J. Hsu,[64] S.-C. Hsu,[147] Q. Hu,[29] S. Hu,[60c] Y. F. Hu,[15a,15d,w] D. P. Huang,[95] X. Huang,[15c] Y. Huang,[60a] Y. Huang,[15a] Z. Hubacek,[141] F. Hubaut,[102] M. Huebner,[24] F. Huegging,[24] T. B. Huffman,[134] M. Huhtinen,[36] R. Hulsken,[58] R. F. H. Hunter,[34] P. Huo,[154] N. Huseynov,[80,x] J. Huston,[107] J. Huth,[59] R. Hyneman,[152] S. Hyrych,[28a] G. Iacobucci,[54]

G. Iakovidis,[29] I. Ibragimov,[150] L. Iconomidou-Fayard,[65] P. Iengo,[36] R. Ignazzi,[40] O. Igonkina,[120,a,y] R. Iguchi,[162] T. Iizawa,[54] Y. Ikegami,[82] M. Ikeno,[82] N. Ilic,[119,166,l] F. Iltzsche,[48] H. Imam,[35a] G. Introzzi,[71a,71b] M. Iodice,[75a] K. Iordanidou,[167a] V. Ippolito,[73a,73b] M. F. Isacson,[171] M. Ishino,[162] W. Islam,[129] C. Issever,[19,46] S. Istin,[159] J. M. Iturbe Ponce,[63a] R. Iuppa,[76a,76b] A. Ivina,[179] J. M. Izen,[43] V. Izzo,[70a] P. Jacka,[140] P. Jackson,[1] R. M. Jacobs,[46] B. P. Jaeger,[151] V. Jain,[2] G. Jäkel,[181] K. B. Jakobi,[100] K. Jakobs,[52] T. Jakoubek,[179] J. Jamieson,[57] K. W. Janas,[84a] R. Jansky,[54] M. Janus,[53] P. A. Janus,[84a] G. Jarlskog,[97] A. E. Jaspan,[91] N. Javadov,[80,x] T. Javůrek,[36] M. Javurkova,[103] F. Jeanneau,[144] L. Jeanty,[131] J. Jejelava,[158a] P. Jenni,[52,z] N. Jeong,[46] S. Jézéquel,[5] H. Ji,[180] J. Jia,[154] Z. Jia,[15c] H. Jiang,[79] Y. Jiang,[60a] Z. Jiang,[152] S. Jiggins,[52] F. A. Jimenez Morales,[38] J. Jimenez Pena,[115] S. Jin,[15c] A. Jinaru,[27b] O. Jinnouchi,[164] H. Jivan,[33e] P. Johansson,[148] K. A. Johns,[7] C. A. Johnson,[66] E. Jones,[177] R. W. L. Jones,[90] S. D. Jones,[155] T. J. Jones,[91] J. Jongmanns,[61a] J. Jovicevic,[36] X. Ju,[18] J. J. Junggeburth,[115] A. Juste Rozas,[14,s] A. Kaczmarska,[85] M. Kado,[73a,73b] H. Kagan,[127] M. Kagan,[152] A. Kahn,[39] C. Kahra,[100] T. Kaji,[178] E. Kajomovitz,[159] C. W. Kalderon,[29] A. Kaluza,[100] A. Kamenshchikov,[123] M. Kaneda,[162] N. J. Kang,[145] S. Kang,[79] Y. Kano,[117] J. Kanzaki,[82] L. S. Kaplan,[180] D. Kar,[33e] K. Karava,[134] M. J. Kareem,[167b] I. Karkanias,[161] S. N. Karpov,[80] Z. M. Karpova,[80] V. Kartvelishvili,[90] A. N. Karyukhin,[123] E. Kasimi,[161] A. Kastanas,[45a,45b] C. Kato,[60d] J. Katzy,[46] K. Kawade,[149] K. Kawagoe,[88] T. Kawaguchi,[117] T. Kawamoto,[144] G. Kawamura,[53] E. F. Kay,[175] S. Kazakos,[14] V. F. Kazanin,[122b,122a] J. M. Keaveney,[33a] R. Keeler,[175] J. S. Keller,[34] E. Kellermann,[97] D. Kelsey,[155] J. J. Kempster,[21] J. Kendrick,[21] K. E. Kennedy,[39] O. Kepka,[140] S. Kersten,[181] B. P. Kerševan,[92] S. Ketabchi Haghighat,[166] M. Khader,[172] F. Khalil-Zada,[13] M. Khandoga,[144] A. Khanov,[129] A. G. Kharlamov,[122b,122a] T. Kharlamova,[122b,122a] E. E. Khoda,[174] A. Khodinov,[165] T. J. Khoo,[54] G. Khoriauli,[176] E. Khramov,[80] J. Khubua,[158b] S. Kido,[83] M. Kiehn,[36] E. Kim,[164] Y. K. Kim,[37] N. Kimura,[95] A. Kirchhoff,[53] D. Kirchmeier,[48] J. Kirk,[143] A. E. Kiryunin,[115] T. Kishimoto,[162] D. P. Kisliuk,[166] V. Kitali,[46] C. Kitsaki,[10] O. Kivernyk,[24] T. Klapdor-Kleingrothaus,[52] M. Klassen,[61a] C. Klein,[34] M. H. Klein,[106] M. Klein,[91] U. Klein,[91] K. Kleinknecht,[100] P. Klimek,[121] A. Klimentov,[29] T. Klingl,[24] T. Klioutchnikova,[36] F. F. Klitzner,[114] P. Kluit,[120] S. Kluth,[115] E. Kneringer,[77] E. B. F. G. Knoops,[102] A. Knue,[52] D. Kobayashi,[88] M. Kobel,[48] M. Kocian,[152] T. Kodama,[162] P. Kodys,[142] D. M. Koeck,[155] P. T. Koenig,[24] T. Koffas,[34] N. M. Köhler,[36] M. Kolb,[144] I. Koletsou,[5] T. Komarek,[130] T. Kondo,[82] K. Köneke,[52] A. X. Y. Kong,[1] A. C. König,[119] T. Kono,[126] V. Konstantinides,[95] N. Konstantinidis,[95] B. Konya,[97] R. Kopeliansky,[66] S. Koperny,[84a] K. Korcyl,[85] K. Kordas,[161] G. Koren,[160] A. Korn,[95] I. Korolkov,[14] E. V. Korolkova,[148] N. Korotkova,[113] O. Kortner,[115] S. Kortner,[115] V. V. Kostyukhin,[148,165] A. Kotsokechagia,[65] A. Kotwal,[49] A. Koulouris,[10] A. Kourkoumeli-Charalampidi,[71a,71b] C. Kourkoumelis,[9] E. Kourlitis,[6] V. Kouskoura,[29] R. Kowalewski,[175] W. Kozanecki,[101] A. S. Kozhin,[123] V. A. Kramarenko,[113] G. Kramberger,[92] D. Krasnopevtsev,[60a] M. W. Krasny,[135] A. Krasznahorkay,[36] D. Krauss,[115] J. A. Kremer,[100] J. Kretzschmar,[91] P. Krieger,[166] F. Krieter,[114] A. Krishnan,[61b] M. Krivos,[142] K. Krizka,[18] K. Kroeninger,[47] H. Kroha,[115] J. Kroll,[140] J. Kroll,[136] K. S. Krowpman,[107] U. Kruchonak,[80] H. Krüger,[24] N. Krumnack,[79] M. C. Kruse,[49] J. A. Krzysiak,[85] A. Kubota,[164] O. Kuchinskaia,[165] S. Kuday,[4b] J. T. Kuechler,[46] S. Kuehn,[36] T. Kuhl,[46] V. Kukhtin,[80] Y. Kulchitsky,[108,aa] S. Kuleshov,[146b] Y. P. Kulinich,[172] M. Kuna,[58] A. Kupco,[140] T. Kupfer,[47] O. Kuprash,[52] H. Kurashige,[83] L. L. Kurchaninov,[167a] Y. A. Kurochkin,[108] A. Kurova,[112] M. G. Kurth,[15a,15d] E. S. Kuwertz,[36] M. Kuze,[164] A. K. Kvam,[147] J. Kvita,[130] T. Kwan,[104] F. La Ruffa,[41b,41a] C. Lacasta,[173] F. Lacava,[73a,73b] D. P. J. Lack,[101] H. Lacker,[19] D. Lacour,[135] E. Ladygin,[80] R. Lafaye,[5] B. Laforge,[135] T. Lagouri,[146c] S. Lai,[53] I. K. Lakomiec,[84a] J. E. Lambert,[128] S. Lammers,[66] W. Lampl,[7] C. Lampoudis,[161] E. Lançon,[29] U. Landgraf,[52] M. P. J. Landon,[93] M. C. Lanfermann,[54] V. S. Lang,[52] J. C. Lange,[53] R. J. Langenberg,[103] A. J. Lankford,[170] F. Lanni,[29] K. Lantzsch,[24] A. Lanza,[71a] A. Lapertosa,[55b,55a] J. F. Laporte,[144] T. Lari,[69a] F. Lasagni Manghi,[23b,23a] M. Lassnig,[36] V. Latonova,[140] T. S. Lau,[63a] A. Laudrain,[100] A. Laurier,[34] M. Lavorgna,[70a,70b] S. D. Lawlor,[94] M. Lazzaroni,[69a,69b] B. Le,[101] E. Le Guirriec,[102] A. Lebedev,[79] M. LeBlanc,[7] T. LeCompte,[6] F. Ledroit-Guillon,[58] A. C. A. Lee,[95] C. A. Lee,[29] G. R. Lee,[17] L. Lee,[59] S. C. Lee,[157] S. Lee,[79] B. Lefebvre,[167a] H. P. Lefebvre,[94] M. Lefebvre,[175] C. Leggett,[18] K. Lehmann,[151] N. Lehmann,[20] G. Lehmann Miotto,[36] W. A. Leight,[46] A. Leisos,[161,bb] M. A. L. Leite,[81d] C. E. Leitgeb,[114] R. Leitner,[142] D. Lellouch,[179,a] K. J. C. Leney,[42] T. Lenz,[24] S. Leone,[72a] C. Leonidopoulos,[50] A. Leopold,[135] C. Leroy,[110] R. Les,[107] C. G. Lester,[32] M. Levchenko,[137] J. Levêque,[5] D. Levin,[106] L. J. Levinson,[179] D. J. Lewis,[21] B. Li,[15b] B. Li,[106] C-Q. Li,[60c,60d] F. Li,[60c] H. Li,[60a] H. Li,[60b] J. Li,[60c] K. Li,[147] L. Li,[60c] M. Li,[15a,15d] Q. Li,[15a,15d] Q. Y. Li,[60a] S. Li,[60d,60c] X. Li,[46] Y. Li,[46] Z. Li,[60b] Z. Li,[134] Z. Li,[104] Z. Liang,[15a] M. Liberatore,[46] B. Liberti,[74a] A. Liblong,[166] K. Lie,[63c] S. Lim,[29] C. Y. Lin,[32] K. Lin,[107] R. A. Linck,[66] R. E. Lindley,[7] J. H. Lindon,[21] A. Linss,[46] A. L. Lionti,[54] E. Lipeles,[136] A. Lipniacka,[17] T. M. Liss,[172,cc] A. Lister,[174] J. D. Little,[8] B. Liu,[79] B. L. Liu,[151] H. B. Liu,[29] J. B. Liu,[60a] J. K. K. Liu,[37] K. Liu,[60d] M. Liu,[60a] M. Y. Liu,[60a] P. Liu,[15a] X. Liu,[60a] Y. Liu,[46] Y. Liu,[15a,15d]

Y. L. Liu,[106] Y. W. Liu,[60a] M. Livan,[71a,71b] A. Lleres,[58] J. Llorente Merino,[151] S. L. Lloyd,[93] C. Y. Lo,[63b] E. M. Lobodzinska,[46] P. Loch,[7] S. Loffredo,[74a,74b] T. Lohse,[19] K. Lohwasser,[148] M. Lokajicek,[140] J. D. Long,[172] R. E. Long,[90] I. Longarini,[73a,73b] L. Longo,[36] K. A. Looper,[127] I. Lopez Paz,[101] A. Lopez Solis,[148] J. Lorenz,[114] N. Lorenzo Martinez,[5] A. M. Lory,[114] P. J. Lösel,[114] A. Lösle,[52] X. Lou,[45a,45b] X. Lou,[15a] A. Lounis,[65] J. Love,[6] P. A. Love,[90] J. J. Lozano Bahilo,[173] M. Lu,[60a] Y. J. Lu,[64] H. J. Lubatti,[147] C. Luci,[73a,73b] F. L. Lucio Alves,[15c] A. Lucotte,[58] F. Luehring,[66] I. Luise,[135] L. Luminari,[73a] B. Lund-Jensen,[153] M. S. Lutz,[160] D. Lynn,[29] H. Lyons,[91] R. Lysak,[140] E. Lytken,[97] F. Lyu,[15a] V. Lyubushkin,[80] T. Lyubushkina,[80] H. Ma,[29] L. L. Ma,[60b] Y. Ma,[95] D. M. Mac Donell,[175] G. Maccarrone,[51] A. Macchiolo,[115] C. M. Macdonald,[148] J. C. Macdonald,[148] J. Machado Miguens,[136] D. Madaffari,[173] R. Madar,[38] W. F. Mader,[48] M. Madugoda Ralalage Don,[129] N. Madysa,[48] J. Maeda,[83] T. Maeno,[29] M. Maerker,[48] V. Magerl,[52] N. Magini,[79] J. Magro,[67a,67c,dd] D. J. Mahon,[39] C. Maidantchik,[81b] T. Maier,[114] A. Maio,[139a,139b,139d] K. Maj,[84a] O. Majersky,[28a] S. Majewski,[131] Y. Makida,[82] N. Makovec,[65] B. Malaescu,[135] Pa. Malecki,[85] V. P. Maleev,[137] F. Malek,[58] D. Malito,[41b,41a] U. Mallik,[78] D. Malon,[6] C. Malone,[32] S. Maltezos,[10] S. Malyukov,[80] J. Mamuzic,[173] G. Mancini,[70a,70b] I. Mandić,[92] L. Manhaes de Andrade Filho,[81a] I. M. Maniatis,[161] J. Manjarres Ramos,[48] K. H. Mankinen,[97] A. Mann,[114] A. Manousos,[77] B. Mansoulie,[144] I. Manthos,[161] S. Manzoni,[120] A. Marantis,[161] G. Marceca,[30] L. Marchese,[134] G. Marchiori,[135] M. Marcisovsky,[140] L. Marcoccia,[74a,74b] C. Marcon,[97] M. Marjanovic,[128] Z. Marshall,[18] M. U. F. Martensson,[171] S. Marti-Garcia,[173] C. B. Martin,[127] T. A. Martin,[177] V. J. Martin,[50] B. Martin dit Latour,[17] L. Martinelli,[75a,75b] M. Martinez,[14,s] P. Martinez Agullo,[173] V. I. Martinez Outschoorn,[103] S. Martin-Haugh,[143] V. S. Martoiu,[27b] A. C. Martyniuk,[95] A. Marzin,[36] S. R. Maschek,[115] L. Masetti,[100] T. Mashimo,[162] R. Mashinistov,[111] J. Masik,[101] A. L. Maslennikov,[122b,122a] L. Massa,[23b,23a] P. Massarotti,[70a,70b] P. Mastrandrea,[72a,72b] A. Mastroberardino,[41b,41a] T. Masubuchi,[162] D. Matakias,[29] A. Matic,[114] N. Matsuzawa,[162] P. Mättig,[24] J. Maurer,[27b] B. Maček,[92] D. A. Maximov,[122b,122a] R. Mazini,[157] I. Maznas,[161] S. M. Mazza,[145] J. P. Mc Gowan,[104] S. P. Mc Kee,[106] T. G. McCarthy,[115] W. P. McCormack,[18] E. F. McDonald,[105] A. E. Mcdougall,[120] J. A. Mcfayden,[18] G. Mchedlidze,[158b] M. A. McKay,[42] K. D. McLean,[175] S. J. McMahon,[143] P. C. McNamara,[105] C. J. McNicol,[177] R. A. McPherson,[175,l] J. E. Mdhluli,[33e] Z. A. Meadows,[103] S. Meehan,[36] T. Megy,[38] S. Mehlhase,[114] A. Mehta,[91] B. Meirose,[43] D. Melini,[159] B. R. Mellado Garcia,[33e] J. D. Mellenthin,[53] M. Melo,[28a] F. Meloni,[46] A. Melzer,[24] E. D. Mendes Gouveia,[139a,139e] A. M. Mendes Jacques Da Costa,[21] L. Meng,[36] X. T. Meng,[106] S. Menke,[115] E. Meoni,[41b,41a] S. Mergelmeyer,[19] S. A. M. Merkt,[138] C. Merlassino,[134] P. Mermod,[54] L. Merola,[70a,70b] C. Meroni,[69a] G. Merz,[106] O. Meshkov,[113,111] J. K. R. Meshreki,[150] J. Metcalfe,[6] A. S. Mete,[6] C. Meyer,[66] J-P. Meyer,[144] M. Michetti,[19] R. P. Middleton,[143] L. Mijović,[50] G. Mikenberg,[179] M. Mikestikova,[140] M. Mikuž,[92] H. Mildner,[148] A. Milic,[166] C. D. Milke,[42] D. W. Miller,[37] A. Milov,[179] D. A. Milstead,[45a,45b] R. A. Mina,[152] A. A. Minaenko,[123] I. A. Minashvili,[158b] A. I. Mincer,[125] B. Mindur,[84a] M. Mineev,[80] Y. Minegishi,[162] Y. Mino,[86] L. M. Mir,[14] M. Mironova,[134] K. P. Mistry,[136] T. Mitani,[178] J. Mitrevski,[114] V. A. Mitsou,[173] M. Mittal,[60c] O. Miu,[166] A. Miucci,[20] P. S. Miyagawa,[93] A. Mizukami,[82] J. U. Mjörnmark,[97] T. Mkrtchyan,[61a] M. Mlynarikova,[142] T. Moa,[45a,45b] S. Mobius,[53] K. Mochizuki,[110] P. Mogg,[114] S. Mohapatra,[39] R. Moles-Valls,[24] K. Mönig,[46] E. Monnier,[102] A. Montalbano,[151] J. Montejo Berlingen,[36] M. Montella,[95] F. Monticelli,[89] S. Monzani,[69a] N. Morange,[65] A. L. Moreira De Carvalho,[139a] D. Moreno,[22a] M. Moreno Llácer,[173] C. Moreno Martinez,[14] P. Morettini,[55b] M. Morgenstern,[159] S. Morgenstern,[48] D. Mori,[151] M. Morii,[59] M. Morinaga,[178] V. Morisbak,[133] A. K. Morley,[36] G. Mornacchi,[36] A. P. Morris,[95] L. Morvaj,[154] P. Moschovakos,[36] B. Moser,[120] M. Mosidze,[158b] T. Moskalets,[144] P. Moskvitina,[119] J. Moss,[31,ee] E. J. W. Moyse,[103] S. Muanza,[102] J. Mueller,[138] R. S. P. Mueller,[114] D. Muenstermann,[90] G. A. Mullier,[97] D. P. Mungo,[69a,69b] J. L. Munoz Martinez,[14] F. J. Munoz Sanchez,[101] P. Murin,[28b] W. J. Murray,[177,143] A. Murrone,[69a,69b] J. M. Muse,[128] M. Muškinja,[18] C. Mwewa,[33a] A. G. Myagkov,[123,i] A. A. Myers,[138] G. Myers,[66] J. Myers,[131] M. Myska,[141] B. P. Nachman,[18] O. Nackenhorst,[47] A. Nag Nag,[48] K. Nagai,[134] K. Nagano,[82] Y. Nagasaka,[62] J. L. Nagle,[29] E. Nagy,[102] A. M. Nairz,[36] Y. Nakahama,[117] K. Nakamura,[82] T. Nakamura,[162] H. Nanjo,[132] F. Napolitano,[61a] R. F. Naranjo Garcia,[46] R. Narayan,[42] I. Naryshkin,[137] M. Naseri,[34] T. Naumann,[46] G. Navarro,[22a] P. Y. Nechaeva,[111] F. Nechansky,[46] T. J. Neep,[21] A. Negri,[71a,71b] M. Negrini,[23b] C. Nellist,[119] C. Nelson,[104] M. E. Nelson,[45a,45b] S. Nemecek,[140] M. Nessi,[36,ff] M. S. Neubauer,[172] F. Neuhaus,[100] M. Neumann,[181] R. Newhouse,[174] P. R. Newman,[21] C. W. Ng,[138] Y. S. Ng,[19] Y. W. Y. Ng,[170] B. Ngair,[35e] H. D. N. Nguyen,[102] T. Nguyen Manh,[110] E. Nibigira,[38] R. B. Nickerson,[134] R. Nicolaidou,[144] D. S. Nielsen,[40] J. Nielsen,[145] M. Niemeyer,[53] N. Nikiforou,[11] V. Nikolaenko,[123,i] I. Nikolic-Audit,[135] K. Nikolopoulos,[21] P. Nilsson,[29] H. R. Nindhito,[54] A. Nisati,[73a] N. Nishu,[60c] R. Nisius,[115] I. Nitsche,[47] T. Nitta,[178] T. Nobe,[162] D. L. Noel,[32] Y. Noguchi,[86] I. Nomidis,[135] M. A. Nomura,[29] M. Nordberg,[36] J. Novak,[92] T. Novak,[92] O. Novgorodova,[48] R. Novotny,[141]

L. Nozka,[130] K. Ntekas,[170] E. Nurse,[95] F. G. Oakham,[34,d] H. Oberlack,[115] J. Ocariz,[135] A. Ochi,[83] I. Ochoa,[39] J. P. Ochoa-Ricoux,[146a] K. O'Connor,[26] S. Oda,[88] S. Odaka,[82] S. Oerdek,[53] A. Ogrodnik,[84a] A. Oh,[101] C. C. Ohm,[153] H. Oide,[164] M. L. Ojeda,[166] H. Okawa,[168] Y. Okazaki,[86] M. W. O'Keefe,[91] Y. Okumura,[162] A. Olariu,[27b] L. F. Oleiro Seabra,[139a] S. A. Olivares Pino,[146a] D. Oliveira Damazio,[29] J. L. Oliver,[1] M. J. R. Olsson,[170] A. Olszewski,[85] J. Olszowska,[85] Ö. O. Öncel,[24] D. C. O'Neil,[151] A. P. O'neill,[134] A. Onofre,[139a,139e] P. U. E. Onyisi,[11] H. Oppen,[133] R. G. Oreamuno Madriz,[121] M. J. Oreglia,[37] G. E. Orellana,[89] D. Orestano,[75a,75b] N. Orlando,[14] R. S. Orr,[166] V. O'Shea,[57] R. Ospanov,[60a] G. Otero y Garzon,[30] H. Otono,[88] P. S. Ott,[61a] G. J. Ottino,[18] M. Ouchrif,[35d] J. Ouellette,[29] F. Ould-Saada,[133] A. Ouraou,[144] Q. Ouyang,[15a] M. Owen,[57] R. E. Owen,[143] V. E. Ozcan,[12c] N. Ozturk,[8] J. Pacalt,[130] H. A. Pacey,[32] K. Pachal,[49] A. Pacheco Pages,[14] C. Padilla Aranda,[14] S. Pagan Griso,[18] G. Palacino,[66] S. Palazzo,[50] S. Palestini,[36] M. Palka,[84b] P. Palni,[84a] C. E. Pandini,[54] J. G. Panduro Vazquez,[94] P. Pani,[46] G. Panizzo,[67a,67c] L. Paolozzi,[54] C. Papadatos,[110] K. Papageorgiou,[9,p] S. Parajuli,[42] A. Paramonov,[6] C. Paraskevopoulos,[10] D. Paredes Hernandez,[63b] S. R. Paredes Saenz,[134] B. Parida,[179] T. H. Park,[166] A. J. Parker,[31] M. A. Parker,[32] F. Parodi,[55b,55a] E. W. Parrish,[121] J. A. Parsons,[39] U. Parzefall,[52] L. Pascual Dominguez,[135] V. R. Pascuzzi,[18] J. M. P. Pasner,[145] F. Pasquali,[120] E. Pasqualucci,[73a] S. Passaggio,[55b] F. Pastore,[94] P. Pasuwan,[45a,45b] S. Pataraia,[100] J. R. Pater,[101] A. Pathak,[180,e] J. Patton,[91] T. Pauly,[36] J. Pearkes,[152] B. Pearson,[115] M. Pedersen,[133] L. Pedraza Diaz,[119] R. Pedro,[139a] T. Peiffer,[53] S. V. Peleganchuk,[122b,122a] O. Penc,[140] H. Peng,[60a] B. S. Peralva,[81a] M. M. Perego,[65] A. P. Pereira Peixoto,[139a] L. Pereira Sanchez,[45a,45b] D. V. Perepelitsa,[29] E. Perez Codina,[167a] F. Peri,[19] L. Perini,[69a,69b] H. Pernegger,[36] S. Perrella,[36] A. Perrevoort,[120] K. Peters,[46] R. F. Y. Peters,[101] B. A. Petersen,[36] T. C. Petersen,[40] E. Petit,[102] V. Petousis,[141] A. Petridis,[1] C. Petridou,[161] P. Petroff,[65] F. Petrucci,[75a,75b] M. Pettee,[182] N. E. Pettersson,[103] K. Petukhova,[142] A. Peyaud,[144] R. Pezoa,[146d] L. Pezzotti,[71a,71b] T. Pham,[105] P. W. Phillips,[143] M. W. Phipps,[172] G. Piacquadio,[154] E. Pianori,[18] A. Picazio,[103] R. H. Pickles,[101] R. Piegaia,[30] D. Pietreanu,[27b] J. E. Pilcher,[37] A. D. Pilkington,[101] M. Pinamonti,[67a,67c] J. L. Pinfold,[3] C. Pitman Donaldson,[95] M. Pitt,[160] L. Pizzimento,[74a,74b] A. Pizzini,[120] M.-A. Pleier,[29] V. Plesanovs,[52] V. Pleskot,[142] E. Plotnikova,[80] P. Podberezko,[122b,122a] R. Poettgen,[97] R. Poggi,[54] L. Poggioli,[135] I. Pogrebnyak,[107] D. Pohl,[24] I. Pokharel,[53] G. Polesello,[71a] A. Poley,[151,167a] A. Policicchio,[73a,73b] R. Polifka,[142] A. Polini,[23b] C. S. Pollard,[46] V. Polychronakos,[29] D. Ponomarenko,[112] L. Pontecorvo,[36] S. Popa,[27a] G. A. Popeneciu,[27d] L. Portales,[5] D. M. Portillo Quintero,[58] S. Pospisil,[141] K. Potamianos,[46] I. N. Potrap,[80] C. J. Potter,[32] H. Potti,[11] T. Poulsen,[97] J. Poveda,[173] T. D. Powell,[148] G. Pownall,[46] M. E. Pozo Astigarraga,[36] A. Prades Ibanez,[173] P. Pralavorio,[102] M. M. Prapa,[44] S. Prell,[79] D. Price,[101] M. Primavera,[68a] M. L. Proffitt,[147] N. Proklova,[112] K. Prokofiev,[63c] F. Prokoshin,[80] S. Protopopescu,[29] J. Proudfoot,[6] M. Przybycien,[84a] D. Pudzha,[137] A. Puri,[172] P. Puzo,[65] D. Pyatiizbyantseva,[112] J. Qian,[106] Y. Qin,[101] A. Quadt,[53] M. Queitsch-Maitland,[36] M. Racko,[28a] F. Ragusa,[69a,69b] G. Rahal,[98] J. A. Raine,[54] S. Rajagopalan,[29] A. Ramirez Morales,[93] K. Ran,[15a,15d] D. M. Rauch,[46] F. Rauscher,[114] S. Rave,[100] B. Ravina,[57] I. Ravinovich,[179] J. H. Rawling,[101] M. Raymond,[36] A. L. Read,[133] N. P. Readioff,[148] M. Reale,[68a,68b] D. M. Rebuzzi,[71a,71b] G. Redlinger,[29] K. Reeves,[43] D. Reikher,[160] A. Reiss,[100] A. Rej,[150] C. Rembser,[36] A. Renardi,[46] M. Renda,[27b] M. B. Rendel,[115] A. G. Rennie,[57] S. Resconi,[69a] E. D. Resseguie,[18] S. Rettie,[95] B. Reynolds,[127] E. Reynolds,[21] O. L. Rezanova,[122b,122a] P. Reznicek,[142] E. Ricci,[76a,76b] R. Richter,[115] S. Richter,[46] E. Richter-Was,[84b] M. Ridel,[135] P. Rieck,[115] O. Rifki,[46] M. Rijssenbeek,[154] A. Rimoldi,[71a,71b] M. Rimoldi,[46] L. Rinaldi,[23b] T. T. Rinn,[172] G. Ripellino,[153] I. Riu,[14] P. Rivadeneira,[46] J. C. Rivera Vergara,[175] F. Rizatdinova,[129] E. Rizvi,[93] C. Rizzi,[36] S. H. Robertson,[104,l] M. Robin,[46] D. Robinson,[32] C. M. Robles Gajardo,[146d] M. Robles Manzano,[100] A. Robson,[57] A. Rocchi,[74a,74b] E. Rocco,[100] C. Roda,[72a,72b] S. Rodriguez Bosca,[173] A. Rodriguez Rodriguez,[52] A. M. Rodríguez Vera,[167b] S. Roe,[36] J. Roggel,[181] O. Røhne,[133] R. Röhrig,[115] R. A. Rojas,[146d] B. Roland,[52] C. P. A. Roland,[66] J. Roloff,[29] A. Romaniouk,[112] M. Romano,[23b,23a] N. Rompotis,[91] M. Ronzani,[125] L. Roos,[135] S. Rosati,[73a] G. Rosin,[103] B. J. Rosser,[136] E. Rossi,[46] E. Rossi,[75a,75b] E. Rossi,[70a,70b] L. P. Rossi,[55b] L. Rossini,[46] R. Rosten,[14] M. Rotaru,[27b] B. Rottler,[52] D. Rousseau,[65] G. Rovelli,[71a,71b] A. Roy,[11] D. Roy,[33e] A. Rozanov,[102] Y. Rozen,[159] X. Ruan,[33e] T. A. Ruggeri,[1] F. Rühr,[52] A. Ruiz-Martinez,[173] A. Rummler,[36] Z. Rurikova,[52] N. A. Rusakovich,[80] H. L. Russell,[104] L. Rustige,[38,47] J. P. Rutherfoord,[7] E. M. Rüttinger,[148] M. Rybar,[39] G. Rybkin,[65] E. B. Rye,[133] A. Ryzhov,[123] J. A. Sabater Iglesias,[46] P. Sabatini,[53] L. Sabetta,[73a,73b] S. Sacerdoti,[65] H. F-W. Sadrozinski,[145] R. Sadykov,[80] F. Safai Tehrani,[73a] B. Safarzadeh Samani,[155] M. Safdari,[152] P. Saha,[121] S. Saha,[104] M. Sahinsoy,[115] A. Sahu,[181] M. Saimpert,[36] M. Saito,[162] T. Saito,[162] H. Sakamoto,[162] D. Salamani,[54] G. Salamanna,[75a,75b] A. Salnikov,[152] J. Salt,[173] A. Salvador Salas,[14] D. Salvatore,[41b,41a] F. Salvatore,[155] A. Salvucci,[63a,63b,63c] A. Salzburger,[36] J. Samarati,[36] D. Sammel,[52] D. Sampsonidis,[161] D. Sampsonidou,[161] J. Sánchez,[173] A. Sanchez Pineda,[67a,36,67c] H. Sandaker,[133] C. O. Sander,[46] I. G. Sanderswood,[90] M. Sandhoff,[181] C. Sandoval,[22b] D. P. C. Sankey,[143] M. Sannino,[55b,55a]

Y. Sano,[117] A. Sansoni,[51] C. Santoni,[38] H. Santos,[139a,139b] S. N. Santpur,[18] A. Santra,[173] K. A. Saoucha,[148] A. Sapronov,[80] J. G. Saraiva,[139a,139d] O. Sasaki,[82] K. Sato,[168] F. Sauerburger,[52] E. Sauvan,[5] P. Savard,[166,d] R. Sawada,[162] C. Sawyer,[143] L. Sawyer,[96,gg] I. Sayago Galvan,[173] C. Sbarra,[23b] A. Sbrizzi,[67a,67c] T. Scanlon,[95] J. Schaarschmidt,[147] P. Schacht,[115] D. Schaefer,[37] L. Schaefer,[136] S. Schaepe,[36] U. Schäfer,[100] A. C. Schaffer,[65] D. Schaile,[114] R. D. Schamberger,[154] E. Schanet,[114] C. Scharf,[19] N. Scharmberg,[101] V. A. Schegelsky,[137] D. Scheirich,[142] F. Schenck,[19] M. Schernau,[170] C. Schiavi,[55b,55a] L. K. Schildgen,[24] Z. M. Schillaci,[26] E. J. Schioppa,[68a,68b] M. Schioppa,[41b,41a] K. E. Schleicher,[52] S. Schlenker,[36] K. R. Schmidt-Sommerfeld,[115] K. Schmieden,[36] C. Schmitt,[100] S. Schmitt,[46] L. Schoeffel,[144] A. Schoening,[61b] P. G. Scholer,[52] E. Schopf,[134] M. Schott,[100] J. F. P. Schouwenberg,[119] J. Schovancova,[36] S. Schramm,[54] F. Schroeder,[181] A. Schulte,[100] H-C. Schultz-Coulon,[61a] M. Schumacher,[52] B. A. Schumm,[145] Ph. Schune,[144] A. Schwartzman,[152] T. A. Schwarz,[106] Ph. Schwemling,[144] R. Schwienhorst,[107] A. Sciandra,[145] G. Sciolla,[26] M. Scornajenghi,[41b,41a] F. Scuri,[72a] F. Scutti,[105] L. M. Scyboz,[115] C. D. Sebastiani,[91] P. Seema,[19] S. C. Seidel,[118] A. Seiden,[145] B. D. Seidlitz,[29] T. Seiss,[37] C. Seitz,[46] J. M. Seixas,[81b] G. Sekhniaidze,[70a] S. J. Sekula,[42] N. Semprini-Cesari,[23b,23a] S. Sen,[49] C. Serfon,[29] L. Serin,[65] L. Serkin,[67a,67b] M. Sessa,[60a] H. Severini,[128] S. Sevova,[152] F. Sforza,[55b,55a] A. Sfyrla,[54] E. Shabalina,[53] J. D. Shahinian,[145] N. W. Shaikh,[45a,45b] D. Shaked Renous,[179] L. Y. Shan,[15a] M. Shapiro,[18] A. Sharma,[134] A. S. Sharma,[1] P. B. Shatalov,[124] K. Shaw,[155] S. M. Shaw,[101] M. Shehade,[179] Y. Shen,[128] A. D. Sherman,[25] P. Sherwood,[95] L. Shi,[95] C. O. Shimmin,[182] Y. Shimogama,[178] M. Shimojima,[116] J. D. Shinner,[94] I. P. J. Shipsey,[134] S. Shirabe,[164] M. Shiyakova,[80,hh] J. Shlomi,[179] A. Shmeleva,[111] M. J. Shochet,[37] J. Shojaii,[105] D. R. Shope,[153] S. Shrestha,[127] E. M. Shrif,[33e] M. J. Shroff,[175] E. Shulga,[179] P. Sicho,[140] A. M. Sickles,[172] E. Sideras Haddad,[33e] O. Sidiropoulou,[36] A. Sidoti,[23b,23a] F. Siegert,[48] Dj. Sijacki,[16] M. Silva Jr.,[180] M. V. Silva Oliveira,[36] S. B. Silverstein,[45a] S. Simion,[65] R. Simoniello,[100] C. J. Simpson-allsop,[21] S. Simsek,[12b] P. Sinervo,[166] V. Sinetckii,[113] S. Singh,[151] M. Sioli,[23b,23a] I. Siral,[131] S. Yu. Sivoklokov,[113] J. Sjölin,[45a,45b] A. Skaf,[53] E. Skorda,[97] P. Skubic,[128] M. Slawinska,[85] K. Sliwa,[169] R. Slovak,[142] V. Smakhtin,[179] B. H. Smart,[143] J. Smiesko,[28b] N. Smirnov,[112] S. Yu. Smirnov,[112] Y. Smirnov,[112] L. N. Smirnova,[113,ii] O. Smirnova,[97] E. A. Smith,[37] H. A. Smith,[134] M. 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Zemaityte,[134] J. C. Zeng,[172] O. Zenin,[123] T. Ženiš,[28a] D. Zerwas,[65] M. Zgubič,[134] B. Zhang,[15c] D. F. Zhang,[15b] G. Zhang,[15b] J. Zhang,[6] Kaili. Zhang,[15a] L. Zhang,[15c] L. Zhang,[60a] M. Zhang,[172] R. Zhang,[180] S. Zhang,[106] X. Zhang,[60c] X. Zhang,[60b] Y. Zhang,[15a,15d] Z. Zhang,[63a] Z. Zhang,[65] P. Zhao,[49] Z. Zhao,[60a] A. Zhemchugov,[80] Z. Zheng,[106] D. Zhong,[172] B. Zhou,[106] C. Zhou,[180] H. Zhou,[7] M. S. Zhou,[15a,15d] M. Zhou,[154] N. Zhou,[60c] Y. Zhou,[7] C. G. Zhu,[60b] C. Zhu,[15a,15d] H. L. Zhu,[60a] H. Zhu,[15a] J. Zhu,[106] Y. Zhu,[60a] X. Zhuang,[15a] K. Zhukov,[111] V. Zhulanov,[122b,122a] D. Zieminska,[66] N. I. Zimine,[80] S. Zimmermann,[52] Z. Zinonos,[115] M. Ziolkowski,[150] L. Živković,[16] G. Zobernig,[180] A. Zoccoli,[23b,23a] K. Zoch,[53] T. G. Zorbas,[148] R. Zou,[37] and L. Zwalinski[36]

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