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Authors

Aad, G
Abajyan, T
Abbott, B
[et al.](#)

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Search for resonant diboson production in the $WW/WZ \rightarrow \ell\nu jj$ decay channels with the ATLAS detector at $\sqrt{s} = 7$ TeV

G. Aad *et al.**

(ATLAS Collaboration)

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A search for resonant diboson production using a data sample corresponding to 4.7 fb^{-1} of integrated luminosity collected by the ATLAS experiment at the Large Hadron Collider in pp collisions at $\sqrt{s} = 7$ TeV is presented. The search for a narrow resonance in the WW or WZ mass distribution is conducted in a final state with an electron or a muon, missing transverse momentum, and at least two jets. No significant excess is observed and limits are set using three benchmark models: WW resonance masses below 940 and 710 GeV are excluded at 95% confidence level for spin-2 Randall–Sundrum and bulk Randall–Sundrum gravitons, respectively; WZ resonance masses below 950 GeV are excluded at 95% confidence level for a spin-1 extended gauge model W' boson.

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I. INTRODUCTION

Many extensions to the Standard Model (SM) predict new massive particles that can decay to WW , WZ , or ZZ final states [1–3]. In some extensions, the branching ratios of the new particles to these diboson final states greatly exceed their branching ratios to light fermions or photons [4–7]. An analysis of WW , WZ , and ZZ events is therefore a central element in the search for physics beyond the SM.

This article describes a search for a narrow resonance decaying to either a WW or WZ diboson intermediate state with subsequent decays to an $\ell\nu jj$ final state, i.e. a charged lepton (electron or muon), large missing transverse momentum (E_T^{miss}), and at least two jets. Data corresponding to 4.7 fb^{-1} collected by the ATLAS experiment at the Large Hadron Collider (LHC) in pp collisions at $\sqrt{s} = 7$ TeV are used. The search is complementary to other direct searches by the ATLAS Collaboration for a WW or WZ resonance using events from the $\ell\nu\ell\nu$ [8] or $\ell\nu\ell\ell$ [9] final state and has the additional advantage of the hadronically decaying W or Z boson in the final state, which leads to a higher branching ratio. Also, the $\ell\nu jj$ final state allows the reconstruction of the invariant mass of the system, under certain assumptions for neutrino momentum from a W boson decay. Such a reconstruction is not possible in the $\ell\nu\ell\nu$ final state due to the presence of two neutrinos in each event. A separate search for a ZZ resonance has been performed using events with a $\ell\ell\ell\ell$ or $\ell\ell jj$ final state at $\sqrt{s} = 7$ TeV [10].

Three benchmark signal models are used to interpret the $\ell\nu jj$ results. A spin-2 Randall–Sundrum graviton (G^*) is

used to model a narrow resonance decaying to WW in two distinct warped extra-dimension models: the original Randall–Sundrum (RS) model [1] (commonly called RS1) and the bulk RS model [11] which allows all SM particles to propagate into the extra dimension. The WZ resonance is modeled by a sequential standard model W' boson with the $W'WZ$ coupling strength set by the extended gauge model (EGM) [12]. In the EGM model, the $W'WZ$ coupling is equal to the SM WWZ coupling strength scaled by a factor $c_{\text{EGM}} \times (m_W/m_{W'})^2$, producing a partial width proportional to $m_{W'}$. In the nominal EGM, the coupling strength scaling factor c_{EGM} is set to one. However, this analysis derives exclusion limits for a range of values of this parameter as a function of the invariant mass of the $\ell\nu jj$ system. This particle is referred to as the EGM W' boson below.

The aforementioned direct WW resonance search by the ATLAS Collaboration using $\ell\nu\ell\nu$ final-state events in 4.7 fb^{-1} pp collision data at $\sqrt{s} = 7$ TeV excludes an RS1 graviton with mass less than 1.23 TeV and a bulk RS graviton with mass below 840 GeV [8]. Previous searches for a WW resonance by the D0 Collaboration in Run II at the Tevatron exclude an RS1 graviton with mass less than 760 GeV [13]. Similar searches, mentioned above, for a ZZ resonance by the ATLAS Collaboration exclude an RS1 graviton with mass below 845 GeV [10]. The CMS Collaboration reports a ZZ resonance search in the $\ell\ell jj$ final state and excludes an RS1 graviton with mass below 945 TeV [14]. Previous direct searches for a WZ resonance at $\sqrt{s} = 7$ TeV by the ATLAS and CMS Collaborations exclude the EGM W' benchmark with mass below 760 GeV [9] and 1143 GeV [15], respectively.

II. THE ATLAS DETECTOR

ATLAS [16] is a general-purpose particle detector used to investigate a broad range of different physics processes. Its cylindrical construction is forward-backward

*Full author list given at the end of the article.

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symmetric and provides nearly complete Hermeticity. The detector is composed of three main subsystems: the inner detector, the calorimeter system, and the muon spectrometer. The inner detector (ID) is used for tracking and measuring the momentum of charged particles within the pseudorapidity range $|\eta| < 2.5$ [17] and is composed of a silicon pixel detector, a silicon microstrip detector and, for $|\eta| < 2.0$, a transition radiation tracker. A uniform 2 T magnetic field is provided by a superconducting solenoid surrounding the ID. The calorimeter system forms the next layer of the detector, spanning the region $|\eta| < 4.9$ and providing three-dimensional reconstruction of particle showers. The inner calorimeter is a high-granularity lead-liquid-argon (LAr) electromagnetic (EM) sampling calorimeter covering $|\eta| < 3.2$. Surrounding the EM calorimeter is an iron-scintillator-tile sampling calorimeter providing hadronic coverage in the range $|\eta| < 1.7$, extended to $|\eta| < 3.2$ with copper-LAr technology. The EM and hadronic calorimeters both have LAr-based forward detectors reaching up to $|\eta| = 4.9$. Outside the calorimeters, the muon spectrometer (MS) is used to identify muons and measure their momenta. The MS is composed of three large air-core superconducting toroid systems (one barrel and two endcaps) each with eight azimuthally symmetric superconducting coils. Three layers of precision tracking chambers, consisting of drift tubes and cathode strip chambers, allow muon track reconstruction for $|\eta| < 2.7$, and fast resistive plate and thin-gap trigger chambers provide trigger signals in the region $|\eta| < 2.4$.

The ATLAS detector uses a three-level trigger system to select events for offline analysis. For this search, events are required to have at least one lepton satisfying trigger requirements, the details of which are presented in Sec. IV.

III. MONTE CARLO SIMULATION

Monte Carlo (MC) simulations are used to model the benchmark signal samples and most SM background processes. The RS1 G^* and EGM W' boson production and decay are simulated using PYTHIA 6.4 [18] with the modified leading-order (LO*) parton distribution function (PDF) set MRST2007LO* [19]. RS1 G^* samples are generated for resonance masses between 500 and 1500 GeV in 250 GeV steps. In these samples the warping parameter, $\tilde{k} \equiv k/\tilde{M}_{\text{Pl}}$, is set to 0.1, where $\tilde{M}_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8\pi}$ is the reduced Plank mass. EGM W' samples are generated with resonance masses from 500 to 1500 GeV in 100 GeV steps, and the production cross sections are calculated at next-to-next-to-leading order (NNLO) in α_S using ZWPROD [20]. The EGM coupling strength scaling factor c_{EGM} is set to 1.0 in these samples, which produces a resonance width of $0.032 \times m_{W'}$ GeV.

The bulk RS model is implemented in CALCHEP [21], allowing simulation of the $2 \rightarrow 4$ production and decay of the graviton with transfer of spin information to the final-state particles. The CTEQ6L LO PDF set [22] is used

TABLE I. Production cross sections times branching ratios for $G^* \rightarrow WW$ or $W' \rightarrow WZ$ for the RS1 G^* , bulk RS G^* , and the EGM W' , for resonance masses equal to 500 GeV, 1000 GeV, and 1500 GeV. All cross sections are given in picobarns.

Mass [GeV]	RS1 G^*	Bulk RS G^*	
		$\sigma \times \text{BR}$ [pb]	EGM W'
500	13.0	3.0	2.6
1000	0.23	0.023	0.10
1500	0.017	0.0011	0.011

for these events. Because the bulk RS G^* graviton has negligible coupling to light fermions, only gluonic initial states are considered. These events are processed with PYTHIA to simulate the parton shower, hadronization, and underlying event. Samples are generated with \tilde{k} of 1.0 and resonance masses from 500 to 1500 GeV in 100 GeV steps, with cross sections taken from the CALCHEP calculation. For three representative resonance masses, the production cross sections times branching ratios to WW/WZ for each sample are given in Table I.

Templates with 50 GeV spacing in the mass of the $\ell\nu jj$ system, $m_{\ell\nu jj}$, are constructed to ensure a signal prediction if no signal MC sample is generated at that mass. These templates are created by first fitting the fully simulated $m_{\ell\nu jj}$ distribution with a crystal ball function [23]. The shape parameters from these fits are interpolated across the mass range 500–1500 GeV and used to construct crystal ball functions, the signal templates, at the intermediate mass points. The acceptances for these signal templates are also interpolated from fits to the acceptances of the fully simulated samples.

For SM background processes, the production of a W or Z boson in association with jets is simulated with ALPGEN [24] using the CTEQ6L LO PDF set. These events are processed with HERWIG [25] for parton showering and hadronization, and JIMMY [26] to simulate the underlying event. The samples are initially normalized to the NNLO production cross section computed with FEWZ [27,28]. The prediction of the W boson transverse momentum, p_T , by ALPGEN is reweighted to agree with the shape predicted by SHERPA [29], which is observed to agree more closely with data at high p_T [30]. Single top quark (tb , tqb , tW) and top quark pair ($t\bar{t}$) production are simulated with the next-to-leading-order (NLO) generator MC@NLO [31–33] interfaced to HERWIG and JIMMY and using the CT10 [34] NLO PDF set. A sample of $t\bar{t}$ events generated with POWHEG [35–37] interfaced to HERWIG and JIMMY is used to cross-check the MC@NLO $t\bar{t}$ production model, and a POWHEG $t\bar{t}$ sample interfaced to PYTHIA is generated to study the dependence on the parton shower and hadronization model. The ACERMC event generator [38] interfaced with PYTHIA is employed to study the effect of initial- and final-state radiation in $t\bar{t}$ events. Both $t\bar{t}$ and single top quark samples are generated assuming a top quark mass, m_t , of

172.5 GeV, but two MC@NLO $t\bar{t}$ samples are generated with $m_t = 170$ and 175 GeV to determine the dependence of the background prediction on the top quark mass. The $t\bar{t}$ cross section is normalized to the approximate NNLO value [39,40]. Single top quark production cross sections are taken from an NNLO calculation for the $t\bar{b}$ process [41], and approximate NNLO calculations for the $tq\bar{b}$ and tW processes [42]. SM diboson production (WW , WZ , ZZ) is modeled using HERWIG and normalized to the NLO production cross sections computed by MCFM [43,44] with the MRST2007LO* PDF set. In all samples, PHOTOS [45] is employed to simulate final-state photon radiation and TAUOLA [46] to take into account polarization in τ lepton decays.

All MC samples include the effect of multiple pp interactions (pileup) per bunch crossing and are reweighted so as to match the distribution of the number of interactions per bunch crossing to that observed in the data. The detector response is simulated using a GEANT4-based model [47] of the ATLAS detector [48]. Finally, events are reconstructed using the same software used for collision data.

IV. OBJECT RECONSTRUCTION AND EVENT SELECTION

The events recorded by the ATLAS detector for this analysis are selected by single-electron or single-muon triggers. The electron trigger requires an electronlike object [49] with transverse energy (E_T) greater than 20 or 22 GeV depending on the LHC instantaneous luminosity. The muon trigger requires a muon candidate with $p_T > 18$ GeV. The data sample used, collected in 2011, corresponds to an integrated luminosity of 4.7 fb^{-1} [50,51] after applying data-quality requirements [52]. MC events must satisfy the same trigger selection requirements.

All triggered events must have at least one reconstructed vertex formed by the intersection of at least three tracks with $p_T > 400$ MeV [53]. From the list of all vertices satisfying this requirement, the vertex with the largest sum of squared p_T of the associated tracks is assumed to be the primary hard-scatter vertex (PV).

Electrons are reconstructed from energy clusters in the calorimeter with an electromagnetic shower profile consistent with that expected for an electron, and must have a matching ID track. Electron candidates must have $E_T > 30$ GeV and be found within the fiducial region defined by $|\eta| < 2.47$, excluding the region $1.37 < |\eta| < 1.52$ which corresponds to the poorly instrumented transition between the barrel and endcap calorimeters. The longitudinal impact parameter of the electron track with respect to the PV ($|z_0|$) must be less than 1 mm, and the significance of its transverse impact parameter with respect to the PV ($|d_0|/\sigma_{d_0}$) must be less than 10.

Electron candidates must also be isolated from other activity in the calorimeter, such that the sum of calorimeter transverse energy in a cone of radius

$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the electron, corrected for pileup contributions and the electron energy, is less than 6 GeV. The energy scale and resolution for electrons in MC events are corrected to match that in $Z \rightarrow e^+e^-$ events [54] measured in data.

Muons are reconstructed from the combination of tracks formed from hits in the MS and the ID [55,56]. The combined muon track must have $p_T > 30$ GeV and $|\eta| < 2.4$. The muon track must have $|z_0| < 10$ mm and $|d_0|/\sigma_{d_0} < 10$. The difference in $|z_0|$ requirements between the electron and muon tracks results from the higher fraction of misreconstructed electrons due to QCD multijet events.

Furthermore, muon candidates must be isolated from other tracks and calorimeter activity: the sum of track transverse momenta surrounding the muon track in a cone of radius $\Delta R = 0.3$ must be less than 15% of the muon p_T ; the calorimeter transverse energy, corrected for pileup contributions, in a cone of radius $\Delta R = 0.3$ must be less than 14% of the muon p_T . The muon p_T scale and resolution in MC events are adjusted to match that in $Z \rightarrow \mu^+\mu^-$ events measured in data [57].

Jets are reconstructed using the anti- k_r sequential recombination clustering algorithm [58,59], with radius set to 0.4. The inputs to the reconstruction algorithm are topological energy clusters [60] calibrated at the EM energy scale, appropriate for the energy deposited by electrons or photons [60]. These jets are then calibrated to the hadronic energy scale, using p_T - and η -dependent correction factors obtained from simulation. The uncertainty on these correction factors is determined from control samples in data. Jets originating from the PV are selected by requiring that at least 75% of the p_T sum of tracks matched to the jet belongs to tracks originating from the PV. If a reconstructed electron and jet candidate overlap within $\Delta R = 0.3$, the jet is rejected. Finally, jets must have $p_T > 40$ GeV and $|\eta| < 2.8$.

Jets originating from b -quarks are identified by exploiting the long lifetimes of bottom hadrons, which lead to observable decay lengths in the detector. The SV0 secondary vertex b -tagger [61,62] is used at an operating point yielding an average b -jet-tagging efficiency of 50% in simulated $t\bar{t}$ events and an average light-quark jet rejection factor of 200.

The missing transverse momentum (E_T^{miss}) is defined as the negative vector sum of transverse energies or momenta of all objects in the event. The ATLAS E_T^{miss} algorithm [63] combines the p_T of muons reconstructed in the MS with the transverse energies measured in calorimeter cells associated either to physics objects (such as jets or leptons) or to topological clusters not associated with physics objects. Calorimeter cells used in the E_T^{miss} calculation are calibrated individually according to the physics object to which they are associated. Cells in topological energy clusters that are not associated with any reconstructed high- p_T object are calibrated separately using the local hadronic calibration scheme [64].

In the initial selection, events must contain exactly one electron or muon, and must have $E_T^{\text{miss}} > 40$ GeV.

Events are also required to contain at least two jets, with the requirement that the highest- p_T jet has $p_T > 100$ GeV. In the following, events with an electron are labeled $e\nu jj$ and muon events are labeled $\mu\nu jj$. To reduce the QCD multijet background, two triangular veto regions are constructed in the plane defined by the E_T^{miss} and $\Delta\phi(\ell, E_T^{\text{miss}})$, the difference in azimuthal angle between the lepton and E_T^{miss} directions. The first region, defined by $|\Delta\phi| < 1.5 - 1.5 \times (E_T^{\text{miss}}/75 \text{ GeV})$, corresponds to events where the lepton and E_T^{miss} directions are aligned. Back-to-back event topologies populate the second region defined by $|\Delta\phi| > 2.0 + (\pi - 2) \times (E_T^{\text{miss}}/75 \text{ GeV})$. Events falling in either of these two regions are rejected. The selection cuts described above define the preselection criteria.

V. BACKGROUND ESTIMATION

Background sources are classified into two categories based on the origin of the charged lepton in the event. The first category includes backgrounds where the charged lepton is produced in the decay of a W or Z boson. The second category corresponds to all other sources, including both events with a misidentified lepton, e.g. where a jet with a large electromagnetic energy fraction passes the electron selection requirements, and events with a true lepton produced in a hadron decay.

Backgrounds from the first category, which include $W/Z + \text{jets}$, $t\bar{t}$, single top quark, and diboson production, are modeled with MC events and are normalized to the product of the production cross section for that background and the total integrated luminosity of the data set. The normalization of the $W + \text{jets}$ and $t\bar{t}$ backgrounds is further tested using data as described in Sec. VI.

Backgrounds in the second category are modeled with independent samples of collision data based on the following prescriptions. In the $e\nu jj$ channel, the sample is selected by inverting the calorimeter isolation requirement for electron candidates that satisfy all other selection criteria. This selects events that are likely to originate from multijet production but have kinematic properties that are very similar to those multijet events that pass the isolation

TABLE II. The number of data and estimated background events after applying the preselection cuts. The associated errors are the quadrature sum of the systematic and statistical uncertainties.

Process	$e\nu jj$ channel [10^3 events]	$\mu\nu jj$ channel [10^3 events]
$W + \text{jets}$	38.0 ± 4.1	46.0 ± 4.8
$Z + \text{jets}$	1.3 ± 0.1	1.8 ± 0.2
Top	15.0 ± 1.4	16.0 ± 1.5
Diboson	0.5 ± 0.1	0.5 ± 0.1
Fake lepton	0.9 ± 0.2	0.5 ± 0.2
Total background	56.0 ± 4.3	65.0 ± 5.1
Data	55.2	64.2

requirement. In the $\mu\nu jj$ channel, the primary source of these backgrounds are semileptonic decays of hadrons within a jet. Events with muons that satisfy all selection criteria except the transverse impact parameter significance cut are used to model this background. Kinematic variable templates are derived from these samples after subtracting the contributions from backgrounds in the first category.

The data-driven backgrounds in the second category, henceforth labeled “fake” lepton backgrounds, are then normalized together with the $W + \text{jets}$ background through a likelihood fit to the data in a region with negligible signal contamination. This is done separately for the $e\nu jj$ and $\mu\nu jj$ channels using the lepton transverse mass distribution, $m_T \equiv \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\Delta\phi))}$, which distinguishes events with charged leptons from a W boson decay from events with a fake lepton. The normalization of all other backgrounds, from the first category, remains fixed in the fit.

The distributions of the lepton p_T , E_T^{miss} and the leading jet p_T in data and for the predicted backgrounds, after applying the event preselection criteria, are shown in Fig. 1. In this figure, the associated errors are a combination of the systematic and statistical uncertainties. Table II shows the yields for each background and for the data. The total estimated background and the data agree within the expected total uncertainty at this stage of the selection.

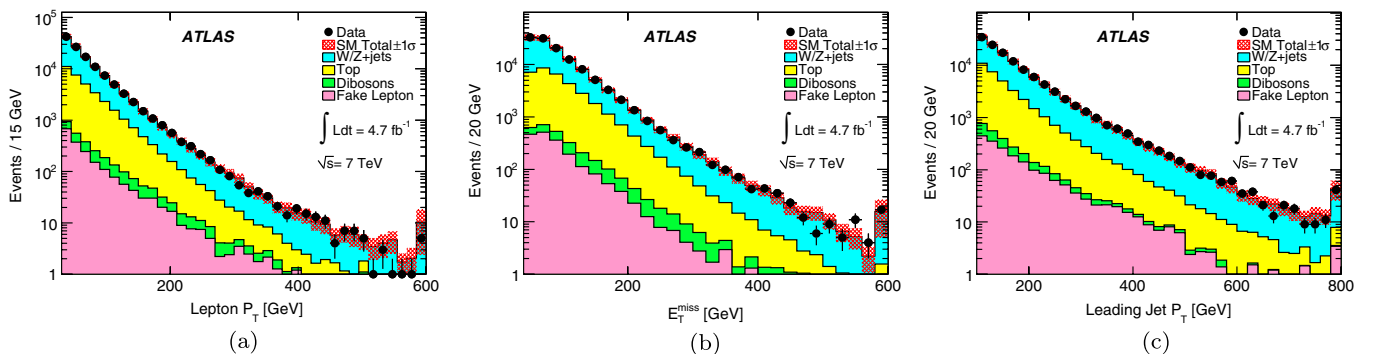


FIG. 1 (color online). Data and background predictions for (a) the lepton p_T , (b) E_T^{miss} , and (c) leading jet p_T for preselected events. Electron and muon events are combined in all plots. The rightmost bin contains overflow events.

VI. SELECTION OF SIGNAL AND CONTROL REGIONS

The WW or WZ mass, $m_{\ell\nu jj}$, is calculated as the invariant mass of the $\ell\nu jj$ system. To reconstruct this quantity, the x and y components of the neutrino momentum vector, p_x and p_y , are set equal to $E_T^{\text{miss}} \cos(\phi_{\text{miss}})$ and $E_T^{\text{miss}} \sin(\phi_{\text{miss}})$, respectively, with ϕ_{miss} corresponding to the direction of the E_T^{miss} vector in the transverse plane. The neutrino p_z is obtained by imposing the W boson mass constraint in the momentum conservation equation. It is defined as either the real component of the complex p_z solution or the minimum of the two real solutions. In events with three or more jets, the two jets with the highest transverse momenta are considered.

In signal events, the p_T of each boson peaks near half of the resonance mass, and the dijet mass distribution, m_{jj} , is characterized by a peak close to the W or Z boson mass. Since this analysis searches for resonant masses larger than 500 GeV, the signal region is defined by requiring the reconstructed p_T of the dijet system and of the lepton- E_T^{miss} system to be greater than 200 GeV and the reconstructed dijet mass to be within the window $65 < m_{jj} < 115$ GeV. Figure 2 compares the m_{jj} distribution observed in data with those predicted for the backgrounds and an enhanced EGM W' signal after the requirements on the reconstructed dijet and lepton- E_T^{miss} p_T values but without the dijet mass window requirement.

Two control regions are created to test the $W + \text{jets}$ and $t\bar{t}$ background modeling of the $m_{\ell\nu jj}$ distribution. The $W + \text{jets}$ control region is identical to the signal region, except for the m_{jj} requirement, which is inverted. Two independent sidebands are formed, $m_{jj} < 65$ GeV and $m_{jj} > 115$ GeV. A scale factor, defined as the number of data events divided by the total background prediction, is computed in each sideband and parametrized as a function of

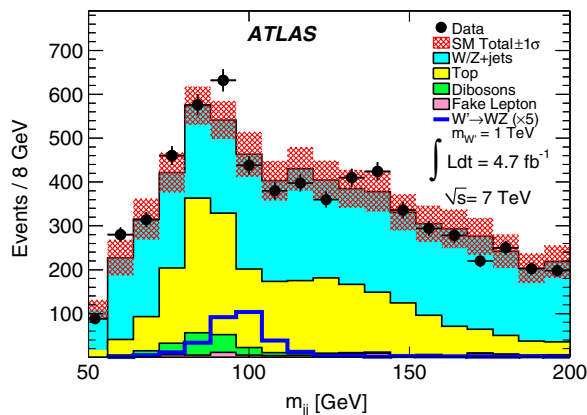


FIG. 2 (color online). Observed and predicted m_{jj} distribution in all events satisfying the p_T selection requirements of the reconstructed W/Z bosons. Predictions for an EGM W' boson, with the signal cross section enhanced by a factor of 5, are shown for a resonance mass of 1 TeV.

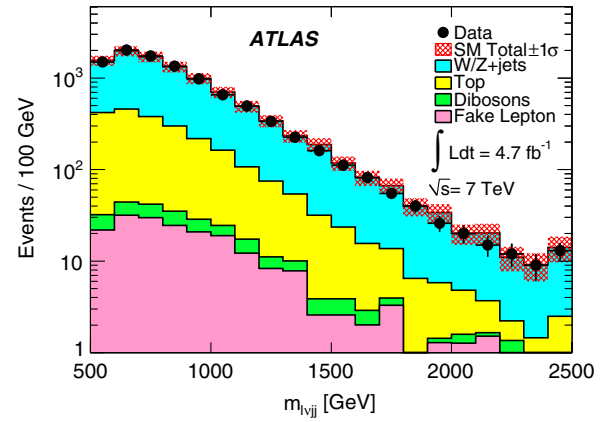


FIG. 3 (color online). The $m_{\ell\nu jj}$ distribution for the data and the background predictions for events in the $W + \text{jets}$ background control region. The rightmost bin contains overflow events.

$m_{\ell\nu jj}$. The weighted average of the scale factors, found in the $m_{jj} < 65$ GeV and $m_{jj} > 115$ GeV sidebands, has a value of 1.012 and is used to normalize the $W + \text{jets}$ background prediction in the signal region. The difference between the individual scale factors is used as the uncertainty on this normalization. The two sidebands are combined in Fig. 3, which shows the $m_{\ell\nu jj}$ distribution for the $W + \text{jets}$ control region after applying the $W + \text{jets}$ scale factors. Good agreement between the data and MC is observed.

The $t\bar{t}$ control region is created by selecting events with at least two b -tagged jets. The reconstructed p_T of the dijet system is required to be greater than 200 GeV, and events are required to have $m_{jj} < 65$ GeV or $m_{jj} > 115$ GeV to avoid overlap with the signal region. Figure 4 shows $m_{\ell\nu jj}$ for all events in the $t\bar{t}$ control region. In this control region, 587 ± 87 $t\bar{t}$ events and 42 ± 6 events from other backgrounds are expected and 602 data events are observed. Given the agreement observed in the $t\bar{t}$ control region, no normalization correction is applied to the $t\bar{t}$ background prediction in the signal region.

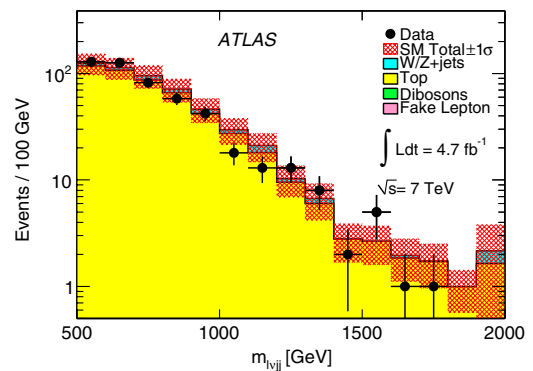


FIG. 4 (color online). The $m_{\ell\nu jj}$ distribution in data events and the estimated backgrounds for the $t\bar{t}$ background control region. The rightmost bin contains overflow events.

VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties that affect the predicted signal acceptance and background rate are grouped into three independent categories: uncertainties due to the limited precision of theoretical calculations, experimental uncertainties on the event reconstruction efficiencies and resolutions, and the determination of the integrated luminosity. Uncertainties from the first and third categories impact the signal and all of the backgrounds except $W + \text{jets}$ and fake lepton backgrounds which are estimated from data. The integrated luminosity uncertainty is 3.9% [50,51].

Several sources of theoretical uncertainty on the $t\bar{t}$ background rate are considered. The largest of these is the ${}_{-10}^{+7}\%$ [39,40] uncertainty on the production cross section. Additionally, the magnitudes of the following systematic uncertainties affecting the $t\bar{t}$ background distribution vary with $m_{\ell\nu jj}$. The largest deviation from the $t\bar{t}$ prediction for all $m_{\ell\nu jj}$ values is presented below. The nominal MC@NLO model for $t\bar{t}$ production differs from the POWHEG model by at most 3%. A 1%–2% variation is measured when the top quark mass is varied by ± 2.5 GeV using MC@NLO MC samples. The difference between the nominal HERWIG parton shower model and the PYTHIA model in POWHEG generated events is at most 2%. Finally, the uncertainty due to the initial-state radiation (ISR) and final-state radiation (FSR) model in PYTHIA is estimated to be at most 3% for all $m_{\ell\nu jj}$ values.

For the remaining, smaller backgrounds modeled with MC simulation, only theoretical uncertainties due to limited knowledge of their production cross sections are considered. The production rate of WW and ZZ dibosons is known to 5% accuracy, while that for WZ production is known to within 7% [44]. The uncertainty on the $Z + \text{jets}$ production rate is estimated to be 5%, primarily due to limited knowledge of the u - and d -quark PDFs [20]. The production of s -channel single top quarks (tb) is known to 6% [41] while t -channel (tqb) and tW production are known to ${}_{-4}^{+5}\%$ and 9% [42], respectively.

For the signals, the PDF uncertainty is estimated by comparing signal events generated with MRST2007LO* and CTEQ6L PDFs and a maximum difference of 5% is measured in the acceptance. The ISR and FSR uncertainty is determined to be 5% using the same procedure as that for $t\bar{t}$ events.

The largest experimental uncertainties come from the determination of the jet energy scale (JES) [60] and resolution (JER) [65]. The JES uncertainty includes effects due to uncertainties in jet flavor composition, overlapping jets, and pileup effects. The overall JES uncertainty on each background process as well as the signal is determined by varying all jet energies within their uncertainties. The impact of this uncertainty varies with $m_{\ell\nu jj}$, and the largest deviation from the nominal prediction is presented. For the background samples, this ranges from 8% for single top quark events to 13% for diboson events. For the signal

events samples, the largest deviation from the nominal prediction for all $m_{\ell\nu jj}$ values is 4%. An equivalent procedure is applied to evaluate the JER uncertainty, and the largest deviation from the nominal prediction is found to be between 1% and 3% for all signal and background samples.

Additional uncertainties arise from the differences between data and MC simulation in the reconstruction efficiencies and energy or momentum resolution for electrons, muons, and E_T^{miss} . The electron energy scale and resolution uncertainties are derived by comparing $Z \rightarrow e^+e^-$ events in data and MC samples. The combined uncertainty is 2%–3% depending on $m_{\ell\nu jj}$. The corresponding uncertainty for muons is at most 2% for any $m_{\ell\nu jj}$ value. The primary contribution to the E_T^{miss} scale uncertainty is pileup, but the impact on the $m_{\ell\nu jj}$ distribution above 500 GeV is less than 1% for all backgrounds. The combined uncertainty on the signal acceptance ranges from 7% at low $m_{\ell\nu jj}$ to 20% at high $m_{\ell\nu jj}$.

The distributions from the fake lepton and $W + \text{jets}$ backgrounds are normalized to the number of events in data control regions, and are therefore not affected by systematic uncertainties in the relative reconstruction efficiency in data and MC events, nor uncertainties in their respective production cross sections. The fake lepton background normalization uncertainty is estimated by using the distributions of E_T^{miss} and the scalar sum of the lepton p_T and E_T^{miss} to determine the fake lepton normalization, and quoting the maximum deviation from the m_T -fitted value. This results in an 80 (100)% uncertainty on events with electrons (muons). The $W + \text{jets}$ normalization uncertainty is defined as the difference between the low- m_{jj} and high- m_{jj} control region scale factors, resulting in an uncertainty of 9%.

VIII. RESULTS AND INTERPRETATION

The numbers of expected and observed events after the final signal selection are reported in Table III. A total of 1453 $e\nu jj$ and 1328 $\mu\nu jj$ events are observed with

TABLE III. Estimated background yields, number of data events, and predicted signal yield after applying the signal selection criteria. Quoted uncertainties are statistical plus systematic as described in text.

Process	$e\nu jj$	$\mu\nu jj$
$W + \text{jets}$	700 ± 65	590 ± 60
$Z + \text{jets}$	15 ± 2	15 ± 2
Top	615 ± 70	515 ± 65
Diboson	75 ± 9	60 ± 8
Fake lepton	20 ± 16	15 ± 15
Total backgrounds	1425 ± 100	1195 ± 85
Data	1453	1328
RS1 $G^*(m_{G^*} = 1 \text{ TeV})$	22 ± 2	18 ± 2
Bulk $G^*(m_{G^*} = 1 \text{ TeV})$	4 ± 0.4	3.5 ± 0.3
EGM $W'(m_{W'} = 1 \text{ TeV})$	29 ± 2	24 ± 2

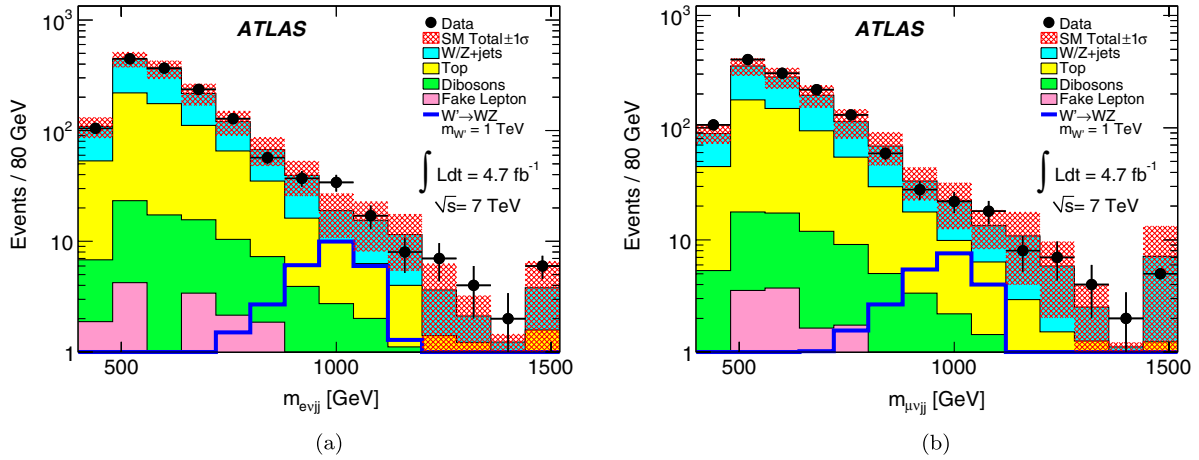


FIG. 5 (color online). Observed and predicted $m_{\ell\nu jj}$ distributions shown for all (a) $e\nu jj$ and (b) $\mu\nu jj$ events satisfying the signal selection requirements. Predictions for an EGM W' boson are shown for a resonance mass of 1 TeV. The rightmost bin contains overflow events.

background predictions of 1425 ± 100 and 1195 ± 85 events, respectively. The $m_{\ell\nu jj}$ distributions for data, predicted background samples, and an EGM W' boson signal with mass $m_{W'} = 1$ TeV are shown in Fig. 5.

These distributions are used to construct a log-likelihood ratio (LLR) test statistic to compute the statistical significance of any excess over expectation using a modified frequentist approach. Pseudoexperiments that treat all

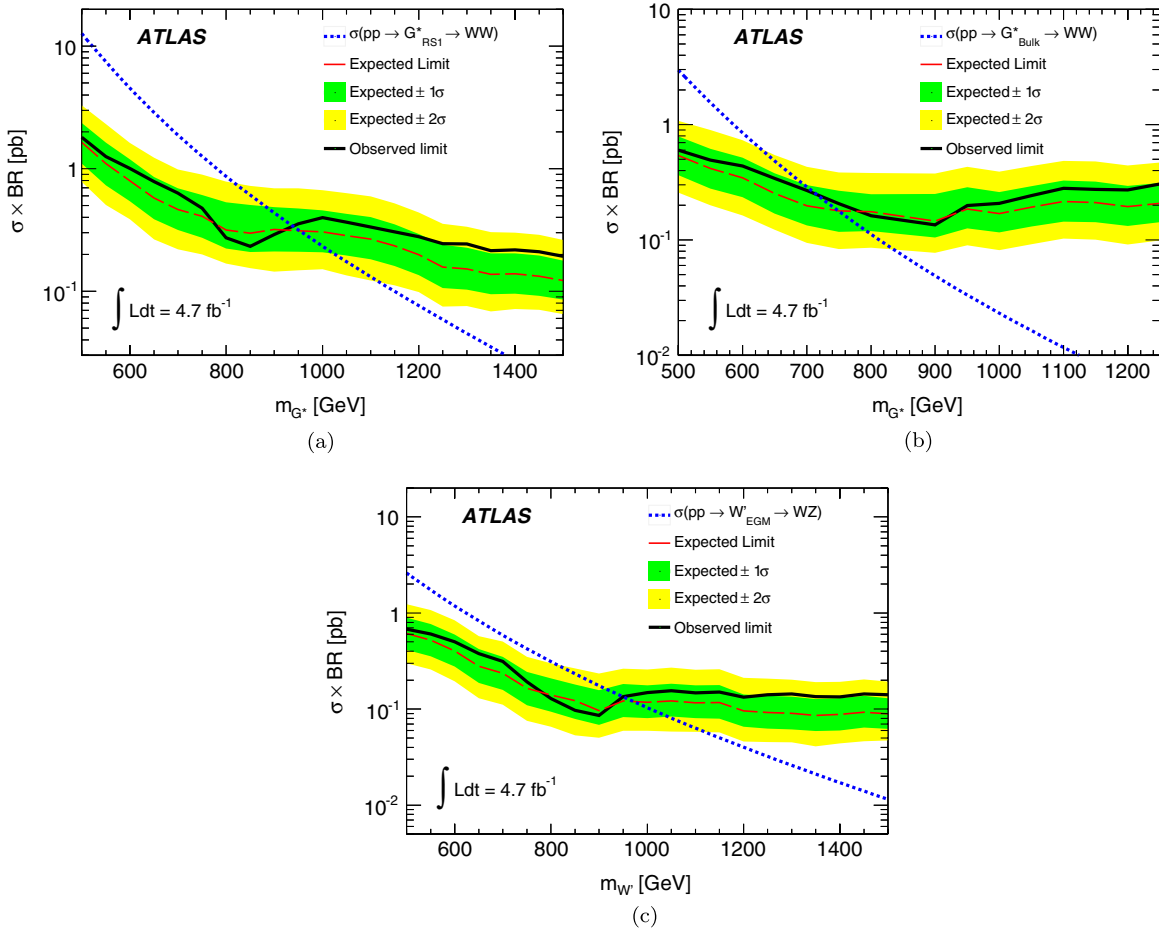


FIG. 6 (color online). Observed and expected 95% C.L. upper limits on $\sigma(pp \rightarrow G^*) \times BR(G^* \rightarrow WW)$ for (a) an RS1 G^* and (b) a bulk RS G^* , and on $\sigma(pp \rightarrow W') \times BR(W' \rightarrow WZ)$ for (c) an EGM W' boson.

TABLE IV. Expected and observed 95% C.L. lower mass limits (GeV) for the RS1 G^* , bulk RS G^* , and the EGM W' boson using $evjj$ events, $\mu\nu jj$ events and the combined channels.

Process	$evjj$	$\mu\nu jj$	$\ell\nu jj$
Expected Limits [GeV]			
RS1 G^*	930	900	950
Bulk RS G^*	740	710	750
EGM W'	950	930	970
Observed limits [GeV]			
RS1 G^*	910	920	940
Bulk RS G^*	760	650	710
EGM W'	930	930	950

systematic uncertainties as Gaussian-sampled nuisance parameters are used to generate the distribution of possible LLR values for the background-only (b) and signal-plus-background (s + b) hypotheses. Confidence levels (C.L.) for each hypothesis are defined as the fraction of experiments with LLR greater than or equal to the LLR evaluated on the data.

The statistical significance of an observed signal is quantified by giving, for each mass point, the p value ($p \equiv 1 - \text{CL}_b$) of the background-only hypothesis. The greatest deviations from the background prediction occur at $m_{\ell\nu jj} = 1300$ and 1500 GeV with $p = 0.12$ and 0.11 , respectively.

Lacking evidence for new phenomena, limits on the signal rate are determined using the CL_s method [66,67]. This method uses a ratio of the p values of the signal-plus-background and background-only hypotheses called CL_s . For a 95% C.L. exclusion, the signal production cross section ($\sigma^{95\%}$) is adjusted until $\text{CL}_s = 0.05$, and the resonance mass limit ($m^{95\%}$) is defined by the mass for which

$\sigma(m^{95\%}) = \sigma^{95\%}$. The excluded production cross sections times the branching ratios to the WW or WZ final state are shown in Fig. 6, with the $evjj$ and $\mu\nu jj$ channels combined, for the three signal hypotheses. The expected and observed limits on the resonances are shown in Table IV for the $evjj$ and $\mu\nu jj$ channels separately, as well as their combination.

Limits are also set on the EGM W' boson coupling strength scaling factor c_{EGM} within the EGM framework. The EGM W' boson limits shown in Fig. 6 correspond to $c_{\text{EGM}} = 1$. For $c_{\text{EGM}} > 10$, the resonance width exceeds the experimental resolution, thus only values less than 10 are considered. Limits on c_{EGM} are derived as a function of $m_{W'}$ as shown in Fig. 7.

IX. CONCLUSION

We report the results of a search for resonant WW and WZ production in the $\ell\nu jj$ decay channels using an integrated luminosity of 4.7 fb^{-1} of pp -collision data at $\sqrt{s} = 7$ TeV collected in 2011 by the ATLAS detector at the Large Hadron Collider. A set of event selections for the RS1 G^* , the bulk RS G^* , and the EGM W' boson signals are derived using simulated events. No evidence for resonant diboson production is observed and 95% C.L. upper bounds on the two graviton and EGM W' boson production cross sections are determined. Resonance masses below 940, 710, and 950 GeV are excluded at 95% C.L. for the spin-2 RS1 graviton, the spin-2 bulk RS graviton and the spin-1 EGM W' boson, respectively.

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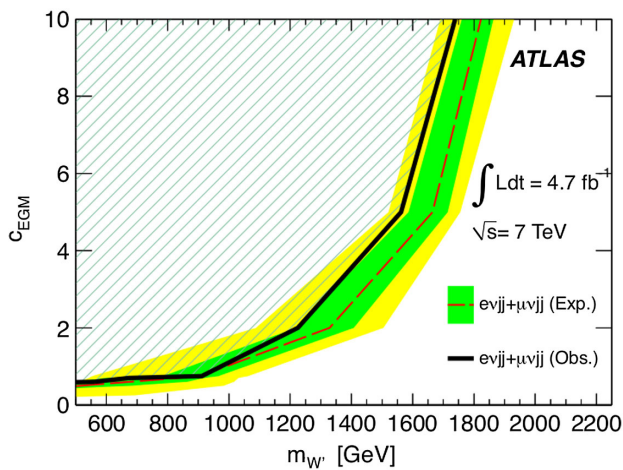


FIG. 7 (color online). The 95% C.L. observed and expected excluded regions of the EGM coupling strength scaling factor c_{EGM} as a function of $m_{W'}$. The green and yellow band correspond to the ± 1 and $\pm 2\sigma$ intervals, respectively.

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- A. Bogouch,^{90,a} C. Bohm,^{146a} J. Bohm,¹²⁵ V. Boisvert,⁷⁶ T. Bold,³⁸ V. Boldea,^{26a} N. M. Bolnet,¹³⁶ M. Bomben,⁷⁸ M. Bona,⁷⁵ M. Boonekamp,¹³⁶ S. Bordini,⁷⁸ C. Borer,¹⁷ A. Borisov,¹²⁸ G. Borissoy,⁷¹ I. Borjanovic,^{13a} M. Borri,⁸² S. Borroni,⁸⁷ J. Bortfeldt,⁹⁸ V. Bortolotto,^{134a,134b} K. Bos,¹⁰⁵ D. Boscherini,^{20a} M. Bosman,¹² H. Boterenbrood,¹⁰⁵ J. Bouchami,⁹³ J. Boudreau,¹²³ E. V. Bouhova-Thacker,⁷¹ D. Boumediene,³⁴ C. Bourdarios,¹¹⁵ N. Bousson,⁸³ A. Boveia,³¹ J. Boyd,³⁰ I. R. Boyko,⁶⁴ I. Bozovic-Jelisavcic,^{13b} J. Bracinik,¹⁸ P. Branchini,^{134a} A. Brandt,⁸ G. Brandt,¹¹⁸ O. Brandt,⁵⁴ U. Bratzler,¹⁵⁶ B. Brau,⁸⁴ J. E. Brau,¹¹⁴ H. M. Braun,^{175,a} S. F. Brazzale,^{164a,164c} B. Brelrier,¹⁵⁸ J. Bremer,³⁰ K. Brendlinger,¹²⁰ R. Brenner,¹⁶⁶ S. Bressler,¹⁷² D. Britton,⁵³ F. M. Brochu,²⁸ I. Brock,²¹ R. Brock,⁸⁸ F. Broggi,^{89a} C. Bromberg,⁸⁸ J. Bronner,⁹⁹ G. Brooijmans,³⁵ T. Brooks,⁷⁶ W. K. Brooks,^{32b} G. Brown,⁸² H. Brown,⁸ P. A. Bruckman de Renstrom,³⁹ D. Bruncko,^{144b} R. Bruneliere,⁴⁸ S. Brunet,⁶⁰ A. Bruni,^{20a} G. Bruni,^{20a} M. Bruschi,^{20a} T. Buanes,¹⁴ Q. Buat,⁵⁵ F. Bucci,⁴⁹ J. Buchanan,¹¹⁸ P. Buchholz,¹⁴¹ R. M. Buckingham,¹¹⁸ A. G. Buckley,⁴⁶ S. I. Buda,^{26a} I. A. Budagov,⁶⁴ B. Budick,¹⁰⁸ L. Bugge,¹¹⁷ O. Bulekov,⁹⁶ A. C. Bundock,⁷³ M. Bunse,⁴³ T. Buran,^{117,a} H. Burckhart,³⁰ S. Burdin,⁷³ T. Burgess,¹⁴ S. Burke,¹²⁹ E. Busato,³⁴ V. Büscher,⁸¹ P. Bussey,⁵³ C. P. Buszello,¹⁶⁶ B. Butler,¹⁴³ J. M. Butler,²² C. M. Buttar,⁵³ J. M. Butterworth,⁷⁷ W. Buttinger,²⁸ M. Byszewski,³⁰ S. Cabrera Urbán,¹⁶⁷ D. Caforio,^{20a,20b} O. Cakir,^{4a} P. Calafiura,¹⁵ G. Calderini,⁷⁸ P. Calfayan,⁹⁸ R. Calkins,¹⁰⁶ L. P. Caloba,^{24a} R. Caloi,^{132a,132b} D. Calvet,³⁴ S. Calvet,³⁴ R. Camacho Toro,³⁴ P. Camarri,^{133a,133b} D. Cameron,¹¹⁷ L. M. Caminada,¹⁵ R. Caminal Armadans,¹² S. Campana,³⁰ M. Campanelli,⁷⁷ V. Canale,^{102a,102b} F. Canelli,³¹ A. Canepa,^{159a} J. Cantero,⁸⁰ R. Cantrill,⁷⁶ L. Capasso,^{102a,102b} M. D. M. Capeans Garrido,³⁰ I. Caprini,^{26a} M. Caprini,^{26a} D. Capriotti,⁹⁹ M. Capua,^{37a,37b} R. Caputo,⁸¹ R. Cardarelli,^{133a} T. Carli,³⁰ G. Carlino,^{102a} L. Carminati,^{89a,89b} B. Caron,⁸⁵ S. Caron,¹⁰⁴ E. Carquin,^{32b} G. D. Carrillo-Montoya,¹⁷³ A. A. Carter,⁷⁵ J. R. Carter,²⁸ J. Carvalho,^{124a,i} D. Casadei,¹⁰⁸ M. P. Casado,¹² M. Cascella,^{122a,122b} C. Caso,^{50a,50b,a} A. M. Castaneda Hernandez,^{173,j} E. Castaneda-Miranda,¹⁷³ V. Castillo Gimenez,¹⁶⁷ N. F. Castro,^{124a} G. Cataldi,^{72a} P. Catastini,⁵⁷ A. Catinaccio,³⁰ J. R. Catmore,³⁰ A. Cattai,³⁰ G. Cattani,^{133a,133b} S. Caughron,⁸⁸ V. Cavaliere,¹⁶⁵ P. Cavalleri,⁷⁸ D. Cavalli,^{89a} M. Cavalli-Sforza,¹² V. Cavasinni,^{122a,122b} F. Ceradini,^{134a,134b} A. S. Cerqueira,^{24b} A. Cerri,³⁰ L. Cerrito,⁷⁵ F. Cerutti,⁴⁷ S. A. Cetin,^{19b} A. Chafaq,^{135a} D. Chakraborty,¹⁰⁶ I. Chalupkova,¹²⁷ K. Chan,³ P. Chang,¹⁶⁵ B. Chapleau,⁸⁵ J. D. Chapman,²⁸ J. W. Chapman,⁸⁷ E. Chareyre,⁷⁸ D. G. Charlton,¹⁸ V. Chavda,⁸² C. A. Chavez Barajas,³⁰ S. Cheatham,⁸⁵ S. Chekanov,⁶ S. V. Chekulaev,^{159a} G. A. Chelkov,⁶⁴ M. A. Chelstowska,¹⁰⁴ C. Chen,⁶³ H. Chen,²⁵ S. Chen,^{33c} X. Chen,¹⁷³ Y. Chen,³⁵ Y. Cheng,³¹ A. Cheplakov,⁶⁴ R. Cherkaoui El Moursli,^{135e} V. Chernyatin,²⁵ E. Cheu,⁷ S. L. Cheung,¹⁵⁸ L. Chevalier,¹³⁶ G. Chiefari,^{102a,102b} L. Chikovani,^{51a,a} J. T. Childers,³⁰ A. Chilingarov,⁷¹ G. Chiodini,^{72a} A. S. Chisholm,¹⁸ R. T. Chislett,⁷⁷ A. Chitan,^{26a} M. V. Chizhov,⁶⁴ G. Choudalakis,³¹ S. Chouridou,¹³⁷ I. A. Christidi,⁷⁷ A. Christov,⁴⁸ D. Chromek-Burckhart,³⁰ M. L. Chu,¹⁵¹ J. Chudoba,¹²⁵ G. Ciapetti,^{132a,132b} A. K. Ciftci,^{4a} R. Ciftci,^{4a} D. Cinca,³⁴ V. Cindro,⁷⁴ A. Ciocio,¹⁵ M. Cirilli,⁸⁷ P. Cirkovic,^{13b} Z. H. Citron,¹⁷² M. Citterio,^{89a} M. Ciubancan,^{26a} A. Clark,⁴⁹ P. J. Clark,⁴⁶ R. N. Clarke,¹⁵ W. Cleland,¹²³ J. C. Clemens,⁸³ B. Clement,⁵⁵ C. Clement,^{146a,146b} Y. Coadou,⁸³ M. Cobal,^{164a,164c} A. Coccaro,¹³⁸ J. Cochran,⁶³ L. Coffey,²³ J. G. Cogan,¹⁴³ J. Coggeshall,¹⁶⁵ E. Cogneras,¹⁷⁸ J. Colas,⁵ S. Cole,¹⁰⁶ A. P. Colijn,¹⁰⁵ N. J. Collins,¹⁸ C. Collins-Tooth,⁵³ J. Collot,⁵⁵ T. Colombo,^{119a,119b} G. Colon,⁸⁴ G. Compostella,⁹⁹ P. Conde Muiño,^{124a} E. Coniavitis,¹⁶⁶ M. C. Conidi,¹² S. M. Consonni,^{89a,89b} V. Consorti,⁴⁸ S. Constantinescu,^{26a} C. Conta,^{119a,119b} G. Conti,⁵⁷ F. Conventi,^{102a,k} M. Cooke,¹⁵ B. D. Cooper,⁷⁷ A. M. Cooper-Sarkar,¹¹⁸ K. Copic,¹⁵ T. Cornelissen,¹⁷⁵ M. Corradi,^{20a} F. Corriveau,^{85,l} A. Corso-Radu,¹⁶³ A. Cortes-Gonzalez,¹⁶⁵ G. Cortiana,⁹⁹ G. Costa,^{89a} M. J. Costa,¹⁶⁷ D. Costanzo,¹³⁹ D. Côté,³⁰ L. Courneyea,¹⁶⁹ G. Cowan,⁷⁶ C. Cowden,²⁸ B. E. Cox,⁸² K. Cranmer,¹⁰⁸ S. Crépe-Renaudin,⁵⁵ F. Crescioli,⁷⁸ M. Cristinziani,²¹ G. Crosetti,^{37a,37b} C.-M. Cuciuc,^{26a} C. Cuenca Almenar,¹⁷⁶ T. Cuhadar Donszelmann,¹³⁹ J. Cummings,¹⁷⁶ M. Curatolo,⁴⁷ C. J. Curtis,¹⁸ C. Cuthbert,¹⁵⁰ P. Cwetanski,⁶⁰ H. Czirr,¹⁴¹ P. Czodrowski,⁴⁴ Z. Czcycula,¹⁷⁶ S. D'Auria,⁵³ M. D'Onofrio,⁷³ A. D'Orazio,^{132a,132b} M. J. Da Cunha Sargedas De Sousa,^{124a} C. Da Via,⁸² W. Dabrowski,³⁸ A. Dafinca,¹¹⁸ T. Dai,⁸⁷ C. Dallapiccola,⁸⁴ M. Dam,³⁶ M. Dameri,^{50a,50b} D. S. Damiani,¹³⁷ H. O. Danielsson,³⁰ V. Dao,⁴⁹ G. Darbo,^{50a} G. L. Darlea,^{26b} J. A. Dassoulas,⁴² W. Davey,²¹ T. Davidek,¹²⁷ N. Davidson,⁸⁶ R. Davidson,⁷¹ E. Davies,^{118,e} M. Davies,⁹³ O. Davignon,⁷⁸ A. R. Davison,⁷⁷ Y. Davygora,^{58a} E. Dawe,¹⁴² I. Dawson,¹³⁹ R. K. Daya-Ishmukhametova,²³ K. De,⁸ R. de Asmundis,^{102a} S. De Castro,^{20a,20b} S. De Cecco,⁷⁸ J. de Graat,⁹⁸ N. De Groot,¹⁰⁴ P. de Jong,¹⁰⁵ C. De La Taille,¹¹⁵ H. De la Torre,⁸⁰ F. De Lorenzi,⁶³ L. de Mora,⁷¹ L. De Nooij,¹⁰⁵ D. De Pedis,^{132a} A. De Salvo,^{132a} U. De Sanctis,^{164a,164c} A. De Santo,¹⁴⁹ J. B. De Vivie De Regie,¹¹⁵ G. De Zorzi,^{132a,132b} W. J. Dearnaley,⁷¹ R. Debbe,²⁵ C. Debenedetti,⁴⁶ B. Dechenaux,⁵⁵ D. V. Dedovich,⁶⁴ J. Degenhardt,¹²⁰ C. Del Papa,^{164a,164c} J. Del Peso,⁸⁰ T. Del Prete,^{122a,122b} T. Delemontex,⁵⁵ M. Deliyergiyev,⁷⁴ A. Dell'Acqua,³⁰ L. Dell'Asta,²²

- M. Della Pietra,^{102a,k} D. della Volpe,^{102a,102b} M. Delmastro,⁵ P. A. Delsart,⁵⁵ C. Deluca,¹⁰⁵ S. Demers,¹⁷⁶
M. Demichev,⁶⁴ B. Demirkoz,^{12,m} J. Deng,¹⁶³ S. P. Denisov,¹²⁸ D. Derendarz,³⁹ J. E. Derkaoui,^{135d} F. Derue,⁷⁸
P. Dervan,⁷³ K. Desch,²¹ E. Devetak,¹⁴⁸ P. O. Deviveiros,¹⁰⁵ A. Dewhurst,¹²⁹ B. DeWilde,¹⁴⁸ S. Dhaliwal,¹⁵⁸
R. Dhullipudi,^{25,n} A. Di Ciaccio,^{133a,133b} L. Di Ciaccio,⁵ C. Di Donato,^{102a,102b} A. Di Girolamo,³⁰ B. Di Girolamo,³⁰
S. Di Luise,^{134a,134b} A. Di Mattia,¹⁷³ B. Di Micco,³⁰ R. Di Nardo,⁴⁷ A. Di Simone,^{133a,133b} R. Di Sipio,^{20a,20b}
M. A. Diaz,^{32a} E. B. Diehl,⁸⁷ J. Dietrich,⁴² T. A. Dietzsch,^{58a} S. Diglio,⁸⁶ K. Dindar Yagci,⁴⁰ J. Dingfelder,²¹
F. Dinut,^{26a} C. Dionisi,^{132a,132b} P. Dita,^{26a} S. Dita,^{26a} F. Dittus,³⁰ F. Djama,⁸³ T. Djobava,^{51b} M. A. B. do Vale,^{24c}
A. Do Valle Wemans,^{124a,o} T. K. O. Doan,⁵ M. Dobbs,⁸⁵ D. Dobos,³⁰ E. Dobson,^{30,p} J. Dodd,³⁵ C. Doglioni,⁴⁹
T. Doherty,⁵³ T. Dohmae,¹⁵⁵ Y. Doi,^{65,a} J. Dolejsi,¹²⁷ I. Dolenc,⁷⁴ Z. Dolezal,¹²⁷ B. A. Dolgoshein,^{96,a}
M. Donadelli,^{24d} J. Donini,³⁴ J. Dopke,³⁰ A. Doria,^{102a} A. Dos Anjos,¹⁷³ A. Dotti,^{122a,122b} M. T. Dova,⁷⁰
A. D. Doxiadis,¹⁰⁵ A. T. Doyle,⁵³ N. Dressnandt,¹²⁰ M. Dris,¹⁰ J. Dubbert,⁹⁹ S. Dube,¹⁵ E. Duchovni,¹⁷²
G. Duckeck,⁹⁸ D. Duda,¹⁷⁵ A. Dudarev,³⁰ F. Dudziak,⁶³ I. P. Duerdoth,⁸² L. Dufлот,¹¹⁵ M-A. Dufour,⁸⁵ L. Duguid,⁷⁶
M. Dührssen,³⁰ M. Dunford,^{58a} H. Duran Yildiz,^{4a} M. Düren,⁵² R. Duxfield,¹³⁹ M. Dwuznik,³⁸ F. Dydak,³⁰
W. L. Ebenstein,⁴⁵ J. Ebke,⁹⁸ S. Eckweiler,⁸¹ K. Edmonds,⁸¹ W. Edson,² C. A. Edwards,⁷⁶ N. C. Edwards,⁵³
W. Ehrenfeld,⁴² T. Eifert,¹⁴³ G. Eigen,¹⁴ K. Einsweiler,⁵⁴ E. Eisenhandler,⁷⁵ T. Ekelof,¹⁶⁶ M. El Kacimi,^{135c}
M. Ellert,¹⁶⁶ S. Elles,⁵ F. Ellinghaus,⁸¹ K. Ellis,⁷⁵ N. Ellis,³⁰ J. Elmsheuser,⁹⁸ M. Elsing,³⁰ D. Emelianov,¹²⁹
R. Engelmann,¹⁴⁸ A. Engl,⁹⁸ B. Epp,⁶¹ J. Erdmann,⁵⁴ A. Ereditato,¹⁷ D. Eriksson,^{146a} J. Ernst,² M. Ernst,²⁵
J. Ernwein,¹³⁶ D. Errede,¹⁶⁵ S. Errede,¹⁶⁵ E. Ertel,⁸¹ M. Escalier,¹¹⁵ H. Esch,⁴³ C. Escobar,¹²³ X. Espinal Curull,¹²
B. Esposito,⁴⁷ F. Etienne,⁸³ A. I. Etiennevire,¹³⁶ E. Etzion,¹⁵³ D. Evangelakou,⁵⁴ H. Evans,⁶⁰ L. Fabbri,^{20a,20b} C. Fabre,³⁰
R. M. Fakhruddinov,¹²⁸ S. Falciano,^{132a} Y. Fang,¹⁷³ M. Fanti,^{89a,89b} A. Farbin,⁸ A. Farilla,^{134a} J. Farley,¹⁴⁸
T. Farooque,¹⁵⁸ S. Farrell,¹⁶³ S. M. Farrington,¹⁷⁰ P. Farthouat,³⁰ F. Fassi,¹⁶⁷ P. Fassnacht,³⁰ D. Fassouliotis,⁹
B. Fatholahzadeh,¹⁵⁸ A. Favareto,^{89a,89b} L. Fayard,¹¹⁵ S. Fazio,^{37a,37b} R. Febbraro,³⁴ P. Federic,^{144a} O. L. Fedin,¹²¹
W. Fedorko,⁸⁸ M. Fehling-Kaschek,⁴⁸ L. Feligioni,⁸³ D. Fellmann,⁶ C. Feng,^{33d} E. J. Feng,⁶ A. B. Fenyuk,¹²⁸
J. Ferencei,^{144b} W. Fernando,⁶ S. Ferrag,⁵³ J. Ferrando,⁵³ V. Ferrara,⁴² A. Ferrari,¹⁶⁶ P. Ferrari,¹⁰⁵ R. Ferrari,^{119a}
D. E. Ferreira de Lima,⁵³ A. Ferrer,¹⁶⁷ D. Ferrere,⁴⁹ C. Ferretti,⁸⁷ A. Ferretto Parodi,^{50a,50b} M. Fiassaric,³¹
F. Fiedler,⁸¹ A. Filipčić,⁷⁴ F. Filthaut,¹⁰⁴ M. Fincke-Keeler,¹⁶⁹ M. C. N. Fiolhais,^{124a,i} L. Fiorini,¹⁶⁷ A. Firan,⁴⁰
G. Fischer,⁴² M. J. Fisher,¹⁰⁹ M. Flechl,⁴⁸ I. Fleck,¹⁴¹ J. Fleckner,⁸¹ P. Fleischmann,¹⁷⁴ S. Fleischmann,¹⁷⁵ T. Flick,¹⁷⁵
A. Floderus,⁷⁹ L. R. Flores Castillo,¹⁷³ M. J. Flowerdew,⁹⁹ T. Fonseca Martin,¹⁷ A. Formica,¹³⁶ A. Forti,⁸²
D. Fortin,^{159a} D. Fournier,¹¹⁵ A. J. Fowler,⁴⁵ H. Fox,⁷¹ P. Francavilla,¹² M. Franchini,^{20a,20b} S. Franchino,^{119a,119b}
D. Francis,³⁰ T. Frank,¹⁷² M. Franklin,⁵⁷ S. Franz,³⁰ M. Fraternali,^{119a,119b} S. Fratina,¹²⁰ S. T. French,²⁸
C. Friedrich,⁴² F. Friedrich,⁴⁴ R. Froeschl,³⁰ D. Froidevaux,³⁰ J. A. Frost,²⁸ C. Fukunaga,¹⁵⁶ E. Fullana Torregrosa,³⁰
B. G. Fulson,¹⁴³ J. Fuster,¹⁶⁷ C. Gabaldon,³⁰ O. Gabizon,¹⁷² T. Gadfort,²⁵ S. Gadomski,⁴⁹ G. Gagliardi,^{50a,50b}
P. Gagnon,⁶⁰ C. Galea,⁹⁸ B. Galhardo,^{124a} E. J. Gallas,¹¹⁸ V. Gallo,¹⁷ B. J. Gallop,¹²⁹ P. Gallus,¹²⁵ K. K. Gan,¹⁰⁹
Y. S. Gao,^{143,g} A. Gaponenko,¹⁵ F. Garbersen,¹⁷⁶ C. García,¹⁶⁷ J. E. García Navarro,¹⁶⁷ M. Garcia-Sciveres,¹⁵
R. W. Gardner,³¹ N. Garelli,³⁰ H. Garitaonandia,¹⁰⁵ V. Garonne,³⁰ C. Gatti,⁴⁷ G. Gaudio,^{119a} B. Gaur,¹⁴¹
L. Gauthier,¹³⁶ P. Gauzzi,^{132a,132b} I. L. Gavrilenko,⁹⁴ C. Gay,¹⁶⁸ G. Gaycken,²¹ E. N. Gazis,¹⁰ P. Ge,^{33d,q} Z. Geese,¹⁶⁸
C. N. P. Gee,¹²⁹ D. A. A. Geerts,¹⁰⁵ Ch. Geich-Gimbel,²¹ K. Gellerstedt,^{146a,146b} C. Gemme,^{50a} A. Gemmell,⁵³
M. H. Genest,⁵⁵ S. Gentile,^{132a,132b} M. George,⁵⁴ S. George,⁷⁶ A. Gershon,¹⁵³ C. Geweniger,^{58a} H. Ghazlane,^{135b}
N. Ghodbane,³⁴ B. Giacobbe,^{20a} S. Giagu,^{132a,132b} V. Giakoumopoulou,⁹ V. Giangiobbe,¹² F. Gianotti,³⁰
B. Gibbard,²⁵ A. Gibson,¹⁵⁸ S. M. Gibson,³⁰ M. Gilchriese,¹⁵ D. Gillberg,²⁹ A. R. Gillman,¹²⁹ D. M. Gingrich,^{3,f}
N. Giokaris,⁹ M. P. Giordani,^{164c} R. Giordano,^{102a,102b} F. M. Giorgi,¹⁶ P. Giovannini,⁹⁹ P. F. Giraud,¹³⁶ D. Giugni,^{89a}
M. Giunta,⁹³ P. Giusti,^{20a} B. K. Gjelsten,¹¹⁷ L. K. Gladilin,⁹⁷ C. Glasman,⁸⁰ J. Glatzer,²¹ A. Glazov,⁴² K. W. Glitza,¹⁷⁵
G. L. Glonti,⁶⁴ J. R. Goddard,⁷⁵ J. Godfrey,¹⁴² J. Godlewski,³⁰ M. Goebel,⁴² C. Goeringer,⁸¹ S. Goldfarb,⁸⁷
T. Golling,¹⁷⁶ A. Gomes,^{124a,d} L. S. Gomez Fajardo,⁴² R. Gonçalo,⁷⁶ J. Goncalves Pinto Firmino Da Costa,⁴²
L. Gonella,²¹ S. González de la Hoz,¹⁶⁷ G. Gonzalez Parra,¹² M. L. Gonzalez Silva,²⁷ S. Gonzalez-Sevilla,⁴⁹
J. J. Goodson,¹⁴⁸ L. Goossens,³⁰ T. Göpfert,⁴⁴ P. A. Gorbounov,⁹⁵ H. A. Gordon,²⁵ I. Gorelov,¹⁰³ G. Gorfine,¹⁷⁵
B. Gorini,³⁰ E. Gorini,^{72a,72b} A. Gorišek,⁷⁴ E. Gornicki,³⁹ B. Gosdzik,⁴² A. T. Goshaw,⁶ M. Gosselink,¹⁰⁵
C. Gössling,⁴³ M. I. Gostkin,⁶⁴ I. Gough Eschrich,¹⁶³ M. Gouighri,^{135a} D. Goujdami,^{135c} M. P. Goulette,⁴⁹
A. G. Goussiou,¹³⁸ C. Goy,⁵ S. Gozpinar,²³ I. Grabowska-Bold,³⁸ P. Grafström,^{20a,20b} K-J. Grahm,⁴² E. Gramstad,¹¹⁷
F. Grancagnolo,^{72a} S. Grancagnolo,¹⁶ V. Grassi,¹⁴⁸ V. Gratchev,¹²¹ N. Grau,³⁵ H. M. Gray,³⁰ J. A. Gray,¹⁴⁸
E. Graziani,^{134a} O. G. Grebenyuk,¹²¹ T. Greenshaw,⁷³ Z. D. Greenwood,^{25,n} K. Gregersen,³⁶ I. M. Gregor,⁴²

- P. Grenier,¹⁴³ J. Griffiths,⁸ N. Grigalashvili,⁶⁴ A. A. Grillo,¹³⁷ S. Grinstein,¹² Ph. Gris,³⁴ Y. V. Grishkevich,⁹⁷ J.-F. Grivaz,¹¹⁵ E. Gross,¹⁷² J. Grosse-Knetter,⁵⁴ J. Groth-Jensen,¹⁷² K. Grybel,¹⁴¹ D. Guest,¹⁷⁶ C. Guicheney,³⁴ S. Guindon,⁵⁴ U. Gul,⁵³ J. Gunther,¹²⁵ B. Guo,¹⁵⁸ J. Guo,³⁵ P. Gutierrez,¹¹¹ N. Guttman,¹⁵³ O. Gutzwiller,¹⁷³ C. Guyot,¹³⁶ C. Gwenlan,¹¹⁸ C. B. Gwilliam,⁷³ A. Haas,¹⁰⁸ S. Haas,³⁰ C. Haber,¹⁵ H. K. Hadavand,⁸ D. R. Hadley,¹⁸ P. Haefner,²¹ F. Hahn,³⁰ S. Haider,³⁰ Z. Hajduk,³⁹ H. Hakobyan,¹⁷⁷ D. Hall,¹¹⁸ K. Hamacher,¹⁷⁵ P. Hamal,¹¹³ K. Hamano,⁸⁶ M. Hamer,⁵⁴ A. Hamilton,^{145b,r} S. Hamilton,¹⁶¹ L. Han,^{33b} K. Hanagaki,¹¹⁶ K. Hanawa,¹⁶⁰ M. Hance,¹⁵ C. Handel,⁸¹ P. Hanke,^{58a} J. R. Hansen,³⁶ J. B. Hansen,³⁶ J. D. Hansen,³⁶ P. H. Hansen,³⁶ P. Hansson,¹⁴³ K. Hara,¹⁶⁰ G. A. Hare,¹³⁷ T. Harenberg,¹⁷⁵ S. Harkusha,⁹⁰ D. Harper,⁸⁷ R. D. Harrington,⁴⁶ O. M. Harris,¹³⁸ J. Hartert,⁴⁸ F. Hartjes,¹⁰⁵ T. Haruyama,⁶⁵ A. Harvey,⁵⁶ S. Hasegawa,¹⁰¹ Y. Hasegawa,¹⁴⁰ S. Hassani,¹³⁶ S. Haug,¹⁷ M. Hauschild,³⁰ R. Hauser,⁸⁸ M. Havranek,²¹ C. M. Hawkes,¹⁸ R. J. Hawkings,³⁰ A. D. Hawkins,⁷⁹ T. Hayakawa,⁶⁶ T. Hayashi,¹⁶⁰ D. Hayden,⁷⁶ C. P. Hays,¹¹⁸ H. S. Hayward,⁷³ S. J. Haywood,¹²⁹ S. J. Head,¹⁸ V. Hedberg,⁷⁹ L. Heelan,⁸ S. Heim,¹²⁰ B. Heinemann,¹⁵ S. Heisterkamp,³⁶ L. Helary,²² C. Heller,⁹⁸ M. Heller,³⁰ S. Hellman,^{146a,146b} D. Hellmich,²¹ C. Helsens,¹² R. C. W. Henderson,⁷¹ M. Henke,^{58a} A. Henrichs,¹⁷⁶ A. M. Henriques Correia,³⁰ S. Henrot-Versille,¹¹⁵ C. Hensel,⁵⁴ T. Henß,¹⁷⁵ C. M. Hernandez,⁸ Y. Hernández Jiménez,¹⁶⁷ R. Herrberg,¹⁶ G. Herten,⁴⁸ R. Hertenberger,⁹⁸ L. Hervas,³⁰ G. G. Hesketh,⁷⁷ N. P. Hessey,¹⁰⁵ E. Higón-Rodríguez,¹⁶⁷ J. C. Hill,²⁸ K. H. Hiller,⁴² S. Hillert,²¹ S. J. Hillier,¹⁸ I. Hinchliffe,¹⁵ E. Hines,¹²⁰ M. Hirose,¹¹⁶ F. Hirsch,⁴³ D. Hirschbuehl,¹⁷⁵ J. Hobbs,¹⁴⁸ N. Hod,¹⁵³ M. C. Hodgkinson,¹³⁹ P. Hodgson,¹³⁹ A. Hoecker,³⁰ M. R. Hoferkamp,¹⁰³ J. Hoffman,⁴⁰ D. Hoffmann,⁸³ M. Hohlfeld,⁸¹ M. Holder,¹⁴¹ S. O. Holmgren,^{146a} T. Holy,¹²⁶ J. L. Holzbauer,⁸⁸ T. M. Hong,¹²⁰ L. Hooft van Huysduynen,¹⁰⁸ S. Horner,⁴⁸ J.-Y. Hostachy,⁵⁵ S. Hou,¹⁵¹ A. Hoummada,^{135a} J. Howard,¹¹⁸ J. Howarth,⁸² I. Hristova,¹⁶ J. Hrivnac,¹¹⁵ T. Hryn'ova,⁵ P. J. Hsu,⁸¹ S.-C. Hsu,¹⁵ D. Hu,³⁵ Z. Hubacek,¹²⁶ F. Hubaut,⁸³ F. Huegging,²¹ A. Huettmann,⁴² T. B. Huffman,¹¹⁸ E. W. Hughes,³⁵ G. Hughes,⁷¹ M. Huhtinen,³⁰ M. Hurwitz,¹⁵ N. Huseynov,^{64,s} J. Huston,⁸⁸ J. Huth,⁵⁷ G. Iacobucci,⁴⁹ G. Iakovidis,¹⁰ M. Ibbotson,⁸² I. Ibragimov,¹⁴¹ L. Iconomidou-Fayard,¹¹⁵ J. Idarraga,¹¹⁵ P. Iengo,^{102a} O. Igonkina,¹⁰⁵ Y. Ikegami,⁶⁵ M. Ikeno,⁶⁵ D. Iliadis,¹⁵⁴ N. Ilic,¹⁵⁸ T. Ince,⁹⁹ J. Inigo-Golfin,³⁰ P. Ioannou,⁹ M. Iodice,^{134a} K. Iordanidou,⁹ V. Ippolito,^{132a,132b} A. Irls Quiles,¹⁶⁷ C. Isaksson,¹⁶⁶ M. Ishino,⁶⁷ M. Ishitsuka,¹⁵⁷ R. Ishmukhametov,¹⁰⁹ C. Issever,¹¹⁸ S. Istin,^{19a} A. V. Ivashin,¹²⁸ W. Iwanski,³⁹ H. Iwasaki,⁶⁵ J. M. Izen,⁴¹ V. Izzo,^{102a} B. Jackson,¹²⁰ J. N. Jackson,⁷³ P. Jackson,¹ M. R. Jaekel,³⁰ V. Jain,⁶⁰ K. Jakobs,⁴⁸ S. Jakobsen,³⁶ T. Jakoubek,¹²⁵ J. Jakubek,¹²⁶ D. O. Jamin,¹⁵¹ D. K. Jana,¹¹¹ E. Jansen,⁷⁷ H. Jansen,³⁰ A. Jantsch,⁹⁹ M. Janus,⁴⁸ R. C. Jared,¹⁷³ G. Jarlskog,⁷⁹ L. Jeanty,⁵⁷ I. Jen-La Plante,³¹ D. Jennens,⁸⁶ P. Jenni,³⁰ P. Jež,³⁶ S. Jézéquel,⁵ M. K. Jha,^{20a} H. Ji,⁸¹ W. Ji,⁸¹ J. Jia,¹⁴⁸ Y. Jiang,^{33b} M. Jimenez Belenguer,⁴² S. Jin,^{33a} O. Jinnouchi,¹⁵⁷ M. D. Joergensen,³⁶ D. Joffe,⁴⁰ M. Johansen,^{146a,146b} K. E. Johansson,^{146a} P. Johansson,¹³⁹ S. Johnert,⁴² K. A. Johns,⁷ K. Jon-And,^{146a,146b} G. Jones,¹⁷⁰ R. W. L. Jones,⁷¹ T. J. Jones,⁷³ C. Joram,³⁰ P. M. Jorge,^{124a} K. D. Joshi,⁸² J. Jovicevic,¹⁴⁷ T. Jovin,^{13b} X. Ju,¹⁷³ C. A. Jung,⁴³ R. M. Jungst,³⁰ V. Juranek,¹²⁵ P. Jussel,⁶¹ A. Juste Rozas,¹² S. Kabana,¹⁷ M. Kaci,¹⁶⁷ A. Kaczmarska,³⁹ P. Kadlecik,³⁶ M. Kado,¹¹⁵ H. Kagan,¹⁰⁹ M. Kagan,⁵⁷ E. Kajomovitz,¹⁵² S. Kalinin,¹⁷⁵ L. V. Kalinovskaya,⁶⁴ S. Kama,⁴⁰ N. Kanaya,¹⁵⁵ M. Kaneda,³⁰ S. Kaneti,²⁸ T. Kanno,¹⁵⁷ V. A. Kantserov,⁹⁶ J. Kanzaki,⁶⁵ B. Kaplan,¹⁰⁸ A. Kapliy,³¹ J. Kaplon,³⁰ D. Kar,⁵³ M. Karagounis,²¹ K. Karakostas,¹⁰ M. Karnevskiy,⁴² V. Kartvelishvili,⁷¹ A. N. Karyukhin,¹²⁸ L. Kashif,¹⁷³ G. Kasieczka,^{58b} R. D. Kass,¹⁰⁹ A. Kastanas,¹⁴ Y. Kataoka,¹⁵⁵ E. Katsoufis,¹⁰ J. Katzy,⁴² V. Kaushik,⁷ K. Kawagoe,⁶⁹ T. Kawamoto,¹⁵⁵ G. Kawamura,⁸¹ M. S. Kayl,¹⁰⁵ S. Kazama,¹⁵⁵ V. F. Kazanin,¹⁰⁷ M. Y. Kazarinov,⁶⁴ R. Keeler,¹⁶⁹ P. T. Keener,¹²⁰ R. Kehoe,⁴⁰ M. Keil,⁵⁴ G. D. Kekelidze,⁶⁴ J. S. Keller,¹³⁸ M. Kenyon,⁵³ O. Kepka,¹²⁵ N. Kerschen,³⁰ B. P. Kerševan,⁷⁴ S. Kersten,¹⁷⁵ K. Kessoku,¹⁵⁵ J. Keung,¹⁵⁸ F. Khalil-zada,¹¹ H. Khandanyan,^{146a,146b} A. Khanov,¹¹² D. Kharchenko,⁶⁴ A. Khodinov,⁹⁶ A. Khomich,^{58a} T. J. Khoo,²⁸ G. Khoriauli,²¹ A. Khoroshilov,¹⁷⁵ V. Khovanskiy,⁹⁵ E. Khranov,⁶⁴ J. Khubua,^{51b} H. Kim,^{146a,146b} S. H. Kim,¹⁶⁰ N. Kimura,¹⁷¹ O. Kind,¹⁶ B. T. King,⁷³ M. King,⁶⁶ R. S. B. King,¹¹⁸ J. Kirk,¹²⁹ A. E. Kiryunin,⁹⁹ T. Kishimoto,⁶⁶ D. Kisiielewska,³⁸ T. Kitamura,⁶⁶ T. Kittelmann,¹²³ K. Kiuchi,¹⁶⁰ E. Kladiva,^{144b} M. Klein,⁷³ U. Klein,⁷³ K. Kleinknecht,⁸¹ M. Klemetti,⁸⁵ A. Klier,¹⁷² P. Klimek,^{146a,146b} A. Klimentov,²⁵ R. Klingenberg,⁴³ J. A. Klinger,⁸² E. B. Klinkby,³⁶ T. Klioutchnikova,³⁰ P. F. Klok,¹⁰⁴ S. Klous,¹⁰⁵ E.-E. Kluge,^{58a} T. Kluge,⁷³ P. Kluit,¹⁰⁵ S. Kluth,⁹⁹ E. Kneringer,⁶¹ E. B. F. G. Knoops,⁸³ A. Knue,⁵⁴ B. R. Ko,⁴⁵ T. Kobayashi,¹⁵⁵ M. Kobel,⁴⁴ M. Kocian,¹⁴³ P. Kodys,¹²⁷ S. Koenig,⁸¹ F. Koetsveld,¹⁰⁴ P. Koesvarki,²¹ T. Koffas,²⁹ E. Koffeman,¹⁰⁵ L. A. Kogan,¹¹⁸ S. Kohlmann,¹⁷⁵ F. Kohn,⁵⁴ Z. Kohout,¹²⁶ T. Kohriki,⁶⁵ T. Koi,¹⁴³ G. M. Kolachev,^{107,a} H. Kolanoski,¹⁶ V. Kolesnikov,⁶⁴ I. Koletsou,^{89a} J. Koll,⁸⁸ A. A. Komar,⁹⁴ Y. Komori,¹⁵⁵ T. Kondo,⁶⁵ K. Köneke,³⁰ A. C. König,¹⁰⁴ T. Kono,^{42,t} A. I. Kononov,⁴⁸ R. Konoplich,^{108,u} N. Konstantinidis,⁷⁷

R. Kopeliansky,¹⁵² S. Koperny,³⁸ L. Köpke,⁸¹ K. Korcyl,³⁹ K. Kordas,¹⁵⁴ A. Korn,¹¹⁸ A. Korol,¹⁰⁷ I. Korolkov,¹² E. V. Korolkova,¹³⁹ V. A. Korotkov,¹²⁸ O. Kortner,⁹⁹ S. Kortner,⁹⁹ V. V. Kostyukhin,²¹ S. Kotov,⁹⁹ V. M. Kotov,⁶⁴ A. Kotwal,⁴⁵ C. Kourkouvelis,⁹ V. Kouskoura,¹⁵⁴ A. Koutsman,^{159a} R. Kowalewski,¹⁶⁹ T. Z. Kowalski,³⁸ W. Kozanecki,¹³⁶ A. S. Kozhin,¹²⁸ V. Kral,¹²⁶ V. A. Kramarenko,⁹⁷ G. Kramberger,⁷⁴ M. W. Krasny,⁷⁸ A. Krasznahorkay,¹⁰⁸ J. K. Kraus,²¹ S. Kreiss,¹⁰⁸ F. Krejci,¹²⁶ J. Kretzschmar,⁷³ N. Krieger,⁵⁴ P. Krieger,¹⁵⁸ K. Kroeninger,⁵⁴ H. Kroha,⁹⁹ J. Kroll,¹²⁰ J. Kroseberg,²¹ J. Krstic,^{13a} U. Kruchonak,⁶⁴ H. Krüger,²¹ T. Kruker,¹⁷ N. Krumnack,⁶³ Z. V. Krumshteyn,⁶⁴ T. Kubota,⁸⁶ S. Kuday,^{4a} S. Kuehn,⁴⁸ A. Kugel,^{58c} T. Kuhl,⁴² D. Kuhn,⁶¹ V. Kukhtin,⁶⁴ Y. Kulchitsky,⁹⁰ S. Kuleshov,^{32b} C. Kummer,⁹⁸ M. Kuna,⁷⁸ J. Kunkle,¹²⁰ A. Kupco,¹²⁵ H. Kurashige,⁶⁶ M. Kurata,¹⁶⁰ Y. A. Kurochkin,⁹⁰ V. Kus,¹²⁵ E. S. Kuwertz,¹⁴⁷ M. Kuze,¹⁵⁷ J. Kvita,¹⁴² R. Kwee,¹⁶ A. La Rosa,⁴⁹ L. La Rotonda,^{37a,37b} L. Labarga,⁸⁰ J. Labbe,⁵ S. Lablak,^{135a} C. Lacasta,¹⁶⁷ F. Lacava,^{132a,132b} J. Lacey,²⁹ H. Lacker,¹⁶ D. Lacour,⁷⁸ V. R. Lacuesta,¹⁶⁷ E. Ladygin,⁶⁴ R. Lafaye,⁵ B. Laforge,⁷⁸ T. Lagouri,¹⁷⁶ S. Lai,⁴⁸ E. Laisne,⁵⁵ M. Lamanna,³⁰ L. Lambourne,⁷⁷ C. L. Lampen,⁷ W. Lampl,⁷ E. Lançon,¹³⁶ U. Landgraf,⁴⁸ M. P. J. Landon,⁷⁵ V. S. Lang,^{58a} C. Lange,⁴² A. J. Lankford,¹⁶³ F. Lanni,²⁵ K. Lantzsch,³⁰ A. Lanza,^{119a} S. Laplace,⁷⁸ C. Lapoire,²¹ J. F. Laporte,¹³⁶ T. Lari,^{89a} A. Lerner,¹¹⁸ M. Lassnig,³⁰ P. Laurelli,⁴⁷ V. Lavorini,^{37a,37b} W. Lavrijsen,¹⁵ P. Laycock,⁷³ O. Le Dortz,⁷⁸ E. Le Guirriec,⁸³ E. Le Menedeu,¹² T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁵ H. Lee,¹⁰⁵ J. S. H. Lee,¹¹⁶ S. C. Lee,¹⁵¹ L. Lee,¹⁷⁶ M. Lefebvre,¹⁶⁹ M. Legendre,¹³⁶ F. Legger,⁹⁸ C. Leggett,¹⁵ M. Lehmacher,²¹ G. Lehmann Miotto,³⁰ M. A. L. Leite,^{24d} R. Leitner,¹²⁷ D. Lellouch,¹⁷² B. Lemmer,⁵⁴ V. Lendermann,^{58a} K. J. C. Leney,^{145b} T. Lenz,¹⁰⁵ G. Lenzen,¹⁷⁵ B. Lenzi,³⁰ K. Leonhardt,⁴⁴ S. Leontsinis,¹⁰ F. Lepold,^{58a} C. Leroy,⁹³ J-R. Lessard,¹⁶⁹ C. G. Lester,²⁸ C. M. Lester,¹²⁰ J. Levêque,⁵ D. Levin,⁸⁷ L. J. Levinson,¹⁷² A. Lewis,¹¹⁸ G. H. Lewis,¹⁰⁸ A. M. Leyko,²¹ M. Leyton,¹⁶ B. Li,⁸³ H. Li,¹⁴⁸ H. L. Li,³¹ S. Li,^{33b,v} X. Li,⁸⁷ Z. Liang,^{118,w} H. Liao,³⁴ B. Liberti,^{133a} P. Lichard,³⁰ M. Lichtnecker,⁹⁸ K. Lie,¹⁶⁵ W. Liebig,¹⁴ C. Limbach,²¹ A. Limosani,⁸⁶ M. Limper,⁶² S. C. Lin,^{151,x} F. Linde,¹⁰⁵ J. T. Linnemann,⁸⁸ E. Lipeles,¹²⁰ A. Lipniacka,¹⁴ T. M. Liss,¹⁶⁵ D. Lissauer,²⁵ A. Lister,⁴⁹ A. M. Litke,¹³⁷ C. Liu,²⁹ D. Liu,¹⁵¹ H. Liu,⁸⁷ J. B. Liu,⁸⁷ L. Liu,⁸⁷ M. Liu,^{33b} Y. Liu,^{33b} M. Livan,^{119a,119b} S. S. A. Livermore,¹¹⁸ A. Lleres,⁵⁵ J. Llorente Merino,⁸⁰ S. L. Lloyd,⁷⁵ F. Lo Sterzo,^{132a,132b} E. Lobodzinska,⁴² P. Loch,⁷ W. S. Lockman,¹³⁷ T. Loddenkoetter,²¹ F. K. Loebinger,⁸² A. E. Loevschall-Jensen,³⁶ A. Loginov,¹⁷⁶ C. W. Loh,¹⁶⁸ T. Lohse,¹⁶ K. Lohwasser,⁴⁸ M. Lokajicek,¹²⁵ V. P. Lombardo,⁵ R. E. Long,⁷¹ L. Lopes,^{124a} D. Lopez Mateos,⁵⁷ J. Lorenz,⁹⁸ N. Lorenzo Martinez,¹¹⁵ M. Losada,¹⁶² P. Loscutoff,¹⁵ M. J. Losty,^{159a,a} X. Lou,⁴¹ A. Lounis,¹¹⁵ K. F. Loureiro,¹⁶² J. Love,⁶ P. A. Love,⁷¹ A. J. Lowe,^{143,g} F. Lu,^{33a} H. J. Lubatti,¹³⁸ C. Luci,^{132a,132b} A. Lucotte,⁵⁵ A. Ludwig,⁴⁴ D. Ludwig,⁴² I. Ludwig,⁴⁸ J. Ludwig,⁴⁸ F. Luehring,⁶⁰ G. Luijckx,¹⁰⁵ W. Lukas,⁶¹ L. Luminari,^{132a} E. Lund,¹¹⁷ B. Lundberg,⁷⁹ J. Lundberg,^{146a,146b} O. Lundberg,^{146a,146b} B. Lund-Jensen,¹⁴⁷ J. Lundquist,³⁶ M. Lungwitz,⁸¹ D. Lynn,²⁵ E. Lytken,⁷⁹ H. Ma,²⁵ L. L. Ma,¹⁷³ G. Maccarrone,⁴⁷ A. Macchiolo,⁹⁹ B. Maček,⁷⁴ J. Machado Miguens,^{124a} R. Mackeprang,³⁶ R. J. Madaras,¹⁵ H. J. Maddocks,⁷¹ W. F. Mader,⁴⁴ R. Maenner,^{58c} M. Maeno,⁵ T. Maeno,²⁵ L. Magnoni,¹⁶³ E. Magradze,⁵⁴ K. Mahboubi,⁴⁸ J. Mahlstedt,¹⁰⁵ S. Mahmoud,⁷³ G. Mahout,¹⁸ C. Maiani,¹³⁶ C. Maidantchik,^{24a} A. Maio,^{124a,d} S. Majewski,²⁵ Y. Makida,⁶⁵ N. Makovec,¹¹⁵ P. Mal,^{136,y} B. Malaescu,³⁰ Pa. Malecki,³⁹ P. Malecki,³⁹ V. P. Maleev,¹²¹ F. Malek,⁵⁵ U. Mallik,⁶² D. Malon,⁶ C. Malone,¹⁴³ S. Maltezos,¹⁰ V. Malyshev,¹⁰⁷ S. Malyukov,³⁰ R. Mameghani,⁹⁸ J. Mamuzic,^{13b} L. Mandelli,^{89a} I. Mandić,⁷⁴ R. Mandrysch,¹⁶ J. Maneira,^{124a} A. Manfredini,⁹⁹ P. S. Mangeard,⁸⁸ L. Manhaes de Andrade Filho,^{24b} J. A. Manjarres Ramos,¹³⁶ A. Mann,⁵⁴ P. M. Manning,¹³⁷ A. Manousakis-Katsikakis,⁹ B. Mansoulie,¹³⁶ A. Mapelli,³⁰ L. Mapelli,³⁰ L. March,¹⁶⁷ J. F. Marchand,²⁹ F. Marchese,^{133a,133b} G. Marchiori,⁷⁸ M. Marcisovsky,¹²⁵ C. P. Marino,¹⁶⁹ F. Marroquim,^{24a} Z. Marshall,³⁰ F. K. Martens,¹⁵⁸ L. F. Marti,¹⁷ S. Marti-Garcia,¹⁶⁷ B. Martin,³⁰ B. Martin,⁸⁸ J. P. Martin,⁹³ T. A. Martin,¹⁸ V. J. Martin,⁴⁶ B. Martin dit Latour,⁴⁹ M. Martinez,¹² V. Martinez Outschoorn,⁵⁷ S. Martin-Haugh,¹⁴⁹ A. C. Martyniuk,¹⁶⁹ M. Marx,⁸² F. Marzano,^{132a} A. Marzin,¹¹¹ L. Masetti,⁸¹ T. Mashimo,¹⁵⁵ R. Mashinistov,⁹⁴ J. Masik,⁸² A. L. Maslennikov,¹⁰⁷ I. Massa,^{20a,20b} G. Massaro,¹⁰⁵ N. Massol,⁵ P. Mastrandrea,¹⁴⁸ A. Mastroberardino,^{37a,37b} T. Masubuchi,¹⁵⁵ P. Matricon,¹¹⁵ H. Matsunaga,¹⁵⁵ T. Matsushita,⁶⁶ P. Mättig,¹⁷⁵ S. Mättig,⁸¹ C. Mattraversi,^{118,e} J. Maurer,⁸³ S. J. Maxfield,⁷³ D. A. Maximov,^{107,h} A. Mayne,¹³⁹ R. Mazini,¹⁵¹ M. Mazur,²¹ L. Mazzaferro,^{133a,133b} M. Mazzanti,^{89a} J. Mc Donald,⁸⁵ S. P. Mc Kee,⁸⁷ A. McCarn,¹⁶⁵ R. L. McCarthy,¹⁴⁸ T. G. McCarthy,²⁹ N. A. McCubbin,¹²⁹ K. W. McFarlane,^{56,a} J. A. McFayden,¹³⁹ G. Mchedlidze,^{51b} T. McLaughlan,¹⁸ S. J. McMahon,¹²⁹ R. A. McPherson,^{169,i} A. Meade,⁸⁴ J. Mechnich,¹⁰⁵ M. Mechtel,¹⁷⁵ M. Medinnis,⁴² R. Meera-Lebbai,¹¹¹ T. Meguro,¹¹⁶ S. Mehlhase,³⁶ A. Mehta,⁷³ K. Meier,^{58a} B. Meirose,⁷⁹ C. Melachrinou,³¹ B. R. Mellado Garcia,¹⁷³ F. Meloni,^{89a,89b} L. Mendoza Navas,¹⁶² Z. Meng,^{151,z}

- A. Mengarelli,^{20a,20b} S. Menke,⁹⁹ E. Meoni,¹⁶¹ K. M. Mercurio,⁵⁷ P. Mermod,⁴⁹ L. Merola,^{102a,102b} C. Meroni,^{89a} F. S. Merritt,³¹ H. Merritt,¹⁰⁹ A. Messina,^{30,aa} J. Metcalfe,²⁵ A. S. Mete,¹⁶³ C. Meyer,⁸¹ C. Meyer,³¹ J.-P. Meyer,¹³⁶ J. Meyer,¹⁷⁴ J. Meyer,⁵⁴ T. C. Meyer,³⁰ S. Michal,³⁰ R. P. Middleton,¹²⁹ S. Migas,⁷³ L. Mijović,¹³⁶ G. Mikenberg,¹⁷² M. Mikestikova,¹²⁵ M. Mikuz,⁷⁴ D. W. Miller,³¹ R. J. Miller,⁸⁸ W. J. Mills,¹⁶⁸ C. Mills,⁵⁷ A. Milov,¹⁷² D. A. Milstead,^{146a,146b} D. Milstein,¹⁷² A. A. Minaenko,¹²⁸ M. Miñano Moya,¹⁶⁷ I. A. Minashvili,⁶⁴ A. I. Mincer,¹⁰⁸ B. Mindur,³⁸ M. Mineev,⁶⁴ Y. Ming,¹⁷³ L. M. Mir,¹² G. Mirabelli,^{132a} J. Mitrevski,¹³⁷ V. A. Mitsou,¹⁶⁷ S. Mitsui,⁶⁵ P. S. Miyagawa,¹³⁹ J. U. Mjörnmark,⁷⁹ T. Moa,^{146a,146b} V. Moeller,²⁸ S. Mohapatra,¹⁴⁸ W. Mohr,⁴⁸ R. Moles-Valls,¹⁶⁷ A. Molfetas,³⁰ K. Mönig,⁴² J. Monk,⁷⁷ E. Monnier,⁸³ J. Montejo Berlingen,¹² F. Monticelli,⁷⁰ S. Monzani,^{20a,20b} R. W. Moore,³ G. F. Moorhead,⁸⁶ C. Mora Herrera,⁴⁹ A. Moraes,⁵³ N. Morange,¹³⁶ J. Morel,⁵⁴ G. Morello,^{37a,37b} D. Moreno,⁸¹ M. Moreno Llácer,¹⁶⁷ P. Morettini,^{50a} M. Morgenstern,⁴⁴ M. Morii,⁵⁷ A. K. Morley,³⁰ G. Mornacchi,³⁰ J. D. Morris,⁷⁵ L. Morvaj,¹⁰¹ N. Möser,²¹ H. G. Moser,⁹⁹ M. Mosidze,^{51b} J. Moss,¹⁰⁹ R. Mount,¹⁴³ E. Mountricha,^{10,bb} S. V. Mouraviev,^{94,a} E. J. W. Moyses,⁸⁴ F. Mueller,^{58a} J. Mueller,¹²³ K. Mueller,²¹ T. Mueller,⁸¹ D. Muenstermann,³⁰ T. A. Müller,⁹⁸ Y. Munwes,¹⁵³ W. J. Murray,¹²⁹ I. Mussche,¹⁰⁵ E. Musto,^{102a,102b} A. G. Myagkov,¹²⁸ M. Myska,¹²⁵ O. Nackenhorst,⁵⁴ J. Nadal,¹² K. Nagai,¹⁶⁰ R. Nagai,¹⁵⁷ K. Nagano,⁶⁵ A. Nagarkar,¹⁰⁹ Y. Nagasaka,⁵⁹ M. Nagel,⁹⁹ A. M. Nairz,³⁰ Y. Nakahama,³⁰ K. Nakamura,¹⁵⁵ T. Nakamura,¹⁵⁵ I. Nakano,¹¹⁰ G. Nanava,²¹ A. Napier,¹⁶¹ R. Narayan,^{58b} M. Nash,^{77,e} T. Nattermann,²¹ T. Naumann,⁴² G. Navarro,¹⁶² H. A. Neal,⁸⁷ P. Yu. Nechaeva,⁹⁴ T. J. Neep,⁸² A. Negri,^{119a,119b} G. Negri,³⁰ M. Negrini,^{20a} S. Nektarijevic,⁴⁹ A. Nelson,¹⁶³ T. K. Nelson,¹⁴³ S. Nemecek,¹²⁵ P. Nemethy,¹⁰⁸ A. A. Nepomuceno,^{24a} M. Nessi,^{30,cc} M. S. Neubauer,¹⁶⁵ M. Neumann,¹⁷⁵ A. Neusiedl,⁸¹ R. M. Neves,¹⁰⁸ P. Nevski,²⁵ F. M. Newcomer,¹²⁰ P. R. Newman,¹⁸ V. Nguyen Thi Hong,¹³⁶ R. B. Nickerson,¹¹⁸ R. Nicolaidou,¹³⁶ B. Nicquevert,³⁰ F. Niedercorn,¹¹⁵ J. Nielsen,¹³⁷ N. Nikiforou,³⁵ A. Nikiforov,¹⁶ V. Nikolaenko,¹²⁸ I. Nikolic-Audit,⁷⁸ K. Nikolics,⁴⁹ K. Nikolopoulos,¹⁸ H. Nilsen,⁴⁸ P. Nilsson,⁸ Y. Ninomiya,¹⁵⁵ A. Nisati,^{132a} R. Nisius,⁹⁹ T. Nobe,¹⁵⁷ L. Nodulman,⁶ M. Nomachi,¹¹⁶ I. Nomidis,¹⁵⁴ S. Norberg,¹¹¹ M. Nordberg,³⁰ P. R. Norton,¹²⁹ J. Novakova,¹²⁷ M. Nozaki,⁶⁵ L. Nozka,¹¹³ I. M. Nugent,^{159a} A.-E. Nuncio-Quiroz,²¹ G. Nunes Hanninger,⁸⁶ T. Nunnemann,⁹⁸ E. Nurse,⁷⁷ B. J. O'Brien,⁴⁶ D. C. O'Neil,¹⁴² V. O'Shea,⁵³ L. B. Oakes,⁹⁸ F. G. Oakham,^{29,f} H. Oberlack,⁹⁹ J. Ocariz,⁷⁸ A. Ochi,⁶⁶ S. Oda,⁶⁹ S. Odaka,⁶⁵ J. Odier,⁸³ H. Ogren,⁶⁰ A. Oh,⁸² S. H. Oh,⁴⁵ C. C. Ohm,³⁰ T. Ohshima,¹⁰¹ W. Okamura,¹¹⁶ H. Okawa,²⁵ Y. Okumura,³¹ T. Okuyama,¹⁵⁵ A. Olariu,^{26a} A. G. Olchevski,⁶⁴ S. A. Olivares Pino,^{32a} M. Oliveira,^{124a,i} D. Oliveira Damazio,²⁵ E. Oliver Garcia,¹⁶⁷ D. Olivito,¹²⁰ A. Olszewski,³⁹ J. Olszowska,³⁹ A. Onofre,^{124a,dd} P. U. E. Onyisi,³¹ C. J. Oram,^{159a} M. J. Oreglia,³¹ Y. Oren,¹⁵³ D. Orestano,^{134a,134b} N. Orlando,^{72a,72b} I. Orlov,¹⁰⁷ C. Oropeza Barrera,⁵³ R. S. Orr,¹⁵⁸ B. Osculati,^{50a,50b} R. Ospanov,¹²⁰ C. Osuna,¹² G. Otero y Garzon,²⁷ J. P. Ottersbach,¹⁰⁵ M. Ouchrif,^{135d} E. A. Ouellette,¹⁶⁹ F. Ould-Saada,¹¹⁷ A. Ouraou,¹³⁶ Q. Ouyang,^{33a} A. Ovcharova,¹⁵ M. Owen,⁸² S. Owen,¹³⁹ V. E. Ozcan,^{19a} N. Ozturk,⁸ A. Pacheco Pages,¹² C. Padilla Aranda,¹² S. Pagan Griso,¹⁵ E. Paganis,¹³⁹ C. Pahl,⁹⁹ F. Paige,²⁵ P. Pais,⁸⁴ K. Pajchel,¹¹⁷ G. Palacino,^{159b} C. P. Paleari,⁷ S. Palestini,³⁰ D. Pallin,³⁴ A. Palma,^{124a} J. D. Palmer,¹⁸ Y. B. Pan,¹⁷³ E. Panagiotopoulou,¹⁰ J. G. Panduro Vazquez,⁷⁶ P. Pani,¹⁰⁵ N. Panikashvili,⁸⁷ S. Panitkin,²⁵ D. Pantea,^{26a} A. Papadelis,^{146a} Th. D. Papadopoulou,¹⁰ A. Paramonov,⁶ D. Paredes Hernandez,³⁴ W. Park,^{25,ee} M. A. Parker,²⁸ F. Parodi,^{50a,50b} J. A. Parsons,³⁵ U. Parzefall,⁴⁸ S. Pashapour,⁵⁴ E. Pasqualucci,^{132a} S. Passaggio,^{50a} A. Passeri,^{134a} F. Pastore,^{134a,134b,a} Fr. Pastore,⁷⁶ G. Pásztor,^{49,ff} S. Pataraya,¹⁷⁵ N. D. Patel,¹⁵⁰ J. R. Pater,⁸² S. Patricelli,^{102a,102b} T. Pauly,³⁰ M. Pecsny,^{144a} S. Pedraza Lopez,¹⁶⁷ M. I. Pedraza Morales,¹⁷³ S. V. Peleganchuk,¹⁰⁷ D. Pelikan,¹⁶⁶ H. Peng,^{33b} B. Penning,³¹ A. Penson,³⁵ J. Penwell,⁶⁰ M. Perantoni,^{24a} K. Perez,^{35,gg} T. Perez Cavalcanti,⁴² E. Perez Codina,^{159a} M. T. Pérez García-Estañ,¹⁶⁷ V. Perez Reale,³⁵ L. Perini,^{89a,89b} H. Pernegger,³⁰ R. Perrino,^{72a} P. Perrodo,⁵ V. D. Peshekhonov,⁶⁴ K. Peters,³⁰ B. A. Petersen,³⁰ J. Petersen,³⁰ T. C. Petersen,³⁶ E. Petit,⁵ A. Petridis,¹⁵⁴ C. Petridou,¹⁵⁴ E. Petrolo,^{132a} F. Petrucci,^{134a,134b} D. Petschull,⁴² M. Petteni,¹⁴² R. Pezoa,^{32b} A. Phan,⁸⁶ P. W. Phillips,¹²⁹ G. Piacquadio,³⁰ A. Picazio,⁴⁹ E. Piccaro,⁷⁵ M. Piccinini,^{20a,20b} S. M. Piec,⁴² R. Piegai,²⁷ D. T. Pignotti,¹⁰⁹ J. E. Pilcher,³¹ A. D. Pilkington,⁸² J. Pina,^{124a,d} M. Pinamonti,^{164a,164c,hh} A. Pinder,¹¹⁸ J. L. Pinfold,³ B. Pinto,^{124a} C. Pizio,^{89a,89b} M. Plamondon,¹⁶⁹ M.-A. Pleier,²⁵ E. Plotnikova,⁶⁴ A. Poblaguev,²⁵ S. Poddar,^{58a} F. Podlyski,³⁴ L. Poggioli,¹¹⁵ D. Pohl,²¹ M. Pohl,⁴⁹ G. Polesello,^{119a} A. Policicchio,^{37a,37b} A. Polini,^{20a} J. Poll,⁷⁵ V. Polychronakos,²⁵ D. Pomeroy,²³ K. Pommès,³⁰ L. Pontecorvo,^{132a} B. G. Pope,⁸⁸ G. A. Popeneciu,^{26a} D. S. Popovic,^{13a} A. Poppleton,³⁰ X. Portell Bueso,³⁰ G. E. Pospelov,⁹⁹ S. Pospisil,¹²⁶ I. N. Potrap,⁹⁹ C. J. Potter,¹⁴⁹ C. T. Potter,¹¹⁴ G. Poulard,³⁰ J. Poveda,⁶⁰ V. Pozdnyakov,⁶⁴ R. Prabhu,⁷⁷ P. Pralavorio,⁸³ A. Pranko,¹⁵ S. Prasad,³⁰ R. Pravahan,²⁵ S. Prell,⁶³ K. Pretzl,¹⁷ D. Price,⁶⁰ J. Price,⁷³ L. E. Price,⁶ D. Prieur,¹²³ M. Primavera,^{72a} K. Prokofiev,¹⁰⁸ F. Prokoshin,^{32b} S. Protopopescu,²⁵ J. Proudfoot,⁶ X. Prudent,⁴⁴ M. Przybycien,³⁸ H. Przysieznik,⁵

S. Psoroulas,²¹ E. Ptacek,¹¹⁴ E. Pueschel,⁸⁴ J. Purdham,⁸⁷ M. Purohit,^{25,ee} P. Puzo,¹¹⁵ Y. Pylypchenko,⁶² J. Qian,⁸⁷ A. Quadt,⁵⁴ D. R. Quarrie,¹⁵ W. B. Quayle,¹⁷³ F. Quinonez,^{32a} M. Raas,¹⁰⁴ V. Radeka,²⁵ V. Radescu,⁴² P. Radloff,¹¹⁴ T. Rador,^{19a} F. Ragusa,^{89a,89b} G. Rahal,¹⁷⁸ A. M. Rahimi,¹⁰⁹ D. Rahm,²⁵ S. Rajagopalan,²⁵ M. Rammensee,⁴⁸ M. Rammes,¹⁴¹ A. S. Randle-Conde,⁴⁰ K. Randrianarivony,²⁹ F. Rauscher,⁹⁸ T. C. Rave,⁴⁸ M. Raymond,³⁰ A. L. Read,¹¹⁷ D. M. Rebuffi,^{119a,119b} A. Redelbach,¹⁷⁴ G. Redlinger,²⁵ R. Reece,¹²⁰ K. Reeves,⁴¹ E. Reinherz-Aronis,¹⁵³ A. Reinsch,¹¹⁴ I. Reisinger,⁴³ C. Rembser,³⁰ Z. L. Ren,¹⁵¹ A. Renaud,¹¹⁵ M. Rescigno,^{132a} S. Resconi,^{89a} B. Resende,¹³⁶ P. Reznicek,⁹⁸ R. Rezvani,¹⁵⁸ R. Richter,⁹⁹ E. Richter-Was,⁵ M. Ridel,⁷⁸ M. Rijpstra,¹⁰⁵ M. Rijssenbeek,¹⁴⁸ A. Rimoldi,^{119a,119b} L. Rinaldi,^{20a} R. R. Rios,⁴⁰ I. Riu,¹² G. Rivoltella,^{89a,89b} F. Rizatdinova,¹¹² E. Rizvi,⁷⁵ S. H. Robertson,^{85,1} A. Robichaud-Veronneau,¹¹⁸ D. Robinson,²⁸ J. E. M. Robinson,⁸² A. Robson,⁵³ J. G. Rocha de Lima,¹⁰⁶ C. Roda,^{122a,122b} D. Roda Dos Santos,³⁰ A. Roe,⁵⁴ S. Roe,³⁰ O. Røhne,¹¹⁷ S. Rolli,¹⁶¹ A. Romaniouk,⁹⁶ M. Romano,^{20a,20b} G. Romeo,²⁷ E. Romero Adam,¹⁶⁷ N. Rompotis,¹³⁸ L. Roos,⁷⁸ E. Ros,¹⁶⁷ S. Rosati,^{132a} K. Rosbach,⁴⁹ A. Rose,¹⁴⁹ M. Rose,⁷⁶ G. A. Rosenbaum,¹⁵⁸ E. I. Rosenberg,⁶³ P. L. Rosendahl,¹⁴ O. Rosenthal,¹⁴¹ L. Rosselet,⁴⁹ V. Rossetti,¹² E. Rossi,^{132a,132b} L. P. Rossi,^{50a} M. Rotaru,^{26a} I. Roth,¹⁷² J. Rothberg,¹³⁸ D. Rousseau,¹¹⁵ C. R. Royon,¹³⁶ A. Rozanov,⁸³ Y. Rozen,¹⁵² X. Ruan,^{33a,ii} F. Rubbo,¹² I. Rubinskiy,⁴² N. Ruckstuhl,¹⁰⁵ V. I. Rud,⁹⁷ C. Rudolph,⁴⁴ G. Rudolph,⁶¹ F. Rühr,⁷ A. Ruiz-Martinez,⁶³ L. Rummyantsev,⁶⁴ Z. Rurikova,⁴⁸ N. A. Rusakovich,⁶⁴ A. Ruschke,⁹⁸ J. P. Rutherford,⁷ P. Ruzicka,¹²⁵ Y. F. Ryabov,¹²¹ M. Rybar,¹²⁷ G. Rybkin,¹¹⁵ N. C. Ryder,¹¹⁸ A. F. Saavedra,¹⁵⁰ I. Sadeh,¹⁵³ H. F.-W. Sadrozinski,¹³⁷ R. Sadykov,⁶⁴ F. Safai Tehrani,^{132a} H. Sakamoto,¹⁵⁵ G. Salamanna,⁷⁵ A. Salamon,^{133a} M. Saleem,¹¹¹ D. Salek,³⁰ D. Salihagic,⁹⁹ A. Salnikov,¹⁴³ J. Salt,¹⁶⁷ B. M. Salvachua Ferrando,⁶ D. Salvatore,^{37a,37b} F. Salvatore,¹⁴⁹ A. Salvucci,¹⁰⁴ A. Salzburger,³⁰ D. Sampsonidis,¹⁵⁴ B. H. Samset,¹¹⁷ A. Sanchez,^{102a,102b} J. Sánchez,¹⁶⁷ V. Sanchez Martinez,¹⁶⁷ H. Sandaker,¹⁴ H. G. Sander,⁸¹ M. P. Sanders,⁹⁸ M. Sandhoff,¹⁷⁵ T. Sandoval,²⁸ C. Sandoval,¹⁶² R. Sandstroem,⁹⁹ D. P. C. Sankey,¹²⁹ A. Sansoni,⁴⁷ C. Santoni,³⁴ R. Santonico,^{133a,133b} H. Santos,^{124a} J. G. Saraiva,^{124a} T. Sarangi,¹⁷³ E. Sarkisyan-Grinbaum,⁸ F. Sarri,^{122a,122b} G. Sartisohn,¹⁷⁵ O. Sasaki,⁶⁵ Y. Sasaki,¹⁵⁵ N. Sasao,⁶⁷ I. Satsounkevitch,⁹⁰ G. Sauvage,^{5,a} E. Sauvan,⁵ J. B. Sauvan,¹¹⁵ P. Savard,^{158,f} V. Savinov,¹²³ D. O. Savu,³⁰ L. Sawyer,^{25,n} D. H. Saxon,⁵³ J. Saxon,¹²⁰ C. Sbarra,^{20a} A. Sbrizzi,^{20a,20b} D. A. Scannicchio,¹⁶³ M. Scarcella,¹⁵⁰ J. Schaarschmidt,¹¹⁵ P. Schacht,⁹⁹ D. Schaefer,¹²⁰ A. Schaelicke,⁴⁶ S. Schaepe,²¹ S. Schaezel,^{58b} U. Schäfer,⁸¹ A. C. Schaffer,¹¹⁵ D. Schaile,⁹⁸ R. D. Schamberger,¹⁴⁸ A. G. Schamov,¹⁰⁷ V. Scharf,^{58a} V. A. Schegelsky,¹²¹ D. Scheirich,⁸⁷ M. Schernau,¹⁶³ M. I. Scherzer,³⁵ C. Schiavi,^{50a,50b} J. Schieck,⁹⁸ M. Schioppa,^{37a,37b} S. Schlenker,³⁰ E. Schmidt,⁴⁸ K. Schmieden,²¹ C. Schmitt,⁸¹ S. Schmitt,^{58b} M. Schmitz,²¹ B. Schneider,¹⁷ U. Schnoor,⁴⁴ L. Schoeffel,¹³⁶ A. Schoening,^{58b} A. L. S. Schorlemmer,⁵⁴ M. Schott,³⁰ D. Schouten,^{159a} J. Schovancova,¹²⁵ M. Schram,⁸⁵ C. Schroeder,⁸¹ N. Schroer,^{58c} M. J. Schultens,²¹ H.-C. Schultz-Coulon,^{58a} H. Schulz,¹⁶ M. Schumacher,⁴⁸ B. A. Schumm,¹³⁷ Ph. Schune,¹³⁶ A. Schwartzman,¹⁴³ Ph. Schwegler,⁹⁹ Ph. Schwemling,⁷⁸ R. Schwienhorst,⁸⁸ R. Schwierz,⁴⁴ J. Schwindling,¹³⁶ T. Schwindt,²¹ M. Schwoerer,⁵ G. Sciolla,²³ W. G. Scott,¹²⁹ J. Searcy,¹¹⁴ G. Sedov,⁴² E. Sedykh,¹²¹ S. C. Seidel,¹⁰³ A. Seiden,¹³⁷ F. Seifert,⁴⁴ J. M. Seixas,^{24a} G. Sekhniaidze,^{102a} S. J. Sekula,⁴⁰ K. E. Selbach,⁴⁶ D. M. Seliverstov,¹²¹ G. Sellers,⁷³ M. Seman,^{144b} N. Semprini-Cesari,^{20a,20b} C. Serfon,⁹⁸ L. Serin,¹¹⁵ L. Serkin,⁵⁴ R. Seuster,^{159a} H. Severini,¹¹¹ A. Sfyrila,³⁰ E. Shabalina,⁵⁴ M. Shamim,¹¹⁴ L. Y. Shan,^{33a} J. T. Shank,²² Q. T. Shao,⁸⁶ M. Shapiro,¹⁵ P. B. Shatalov,⁹⁵ K. Shaw,^{164a,164c} D. Sherman,¹⁷⁶ P. Sherwood,⁷⁷ S. Shimizu,¹⁰¹ M. Shimojima,¹⁰⁰ T. Shin,⁵⁶ M. Shiyakova,⁶⁴ A. Shmeleva,⁹⁴ M. J. Shochet,³¹ D. Short,¹¹⁸ S. Shrestha,⁶³ E. Shulga,⁹⁶ M. A. Shupe,⁷ P. Sicho,¹²⁵ A. Sidoti,^{132a} F. Siegert,⁴⁸ Dj. Sijacki,^{13a} O. Silbert,¹⁷² J. Silva,^{124a} Y. Silver,¹⁵³ D. Silverstein,¹⁴³ S. B. Silverstein,^{146a} V. Simak,¹²⁶ O. Simard,¹³⁶ Lj. Simic,^{13a} S. Simion,¹¹⁵ E. Simioni,⁸¹ B. Simmons,⁷⁷ R. Simoniello,^{89a,89b} M. Simonyan,³⁶ P. Sinervo,¹⁵⁸ N. B. Sinev,¹¹⁴ V. Sipica,¹⁴¹ G. Siragusa,¹⁷⁴ A. Sircar,²⁵ A. N. Sisakyan,^{64,a} S. Yu. Sivoklov,⁹⁷ J. Sjölin,^{146a,146b} T. B. Sjurson,¹⁴ L. A. Skinnari,¹⁵ H. P. Skottowe,⁵⁷ K. Skovpen,¹⁰⁷ P. Skubic,¹¹¹ M. Slater,¹⁸ T. Slavicek,¹²⁶ K. Sliwa,¹⁶¹ V. Smakhtin,¹⁷² B. H. Smart,⁴⁶ L. Smestad,¹¹⁷ S. Yu. Smirnov,⁹⁶ Y. Smirnov,⁹⁶ L. N. Smirnova,^{97,ij} O. Smirnova,⁷⁹ B. C. Smith,⁵⁷ D. Smith,¹⁴³ K. M. Smith,⁵³ M. Smizanska,⁷¹ K. Smolek,¹²⁶ A. A. Snesarev,⁹⁴ J. Snow,¹¹¹ S. Snyder,²⁵ R. Sobie,^{169,1} J. Sodomka,¹²⁶ A. Soffer,¹⁵³ D. A. Soh,^{151,w} C. A. Solans,¹⁶⁷ M. Solar,¹²⁶ J. Solc,¹²⁶ E. Yu. Soldatov,⁹⁶ U. Soldevila,¹⁶⁷ E. Solfaroli Camillocci,^{132a,132b} A. A. Solodkov,¹²⁸ O. V. Solovyanov,¹²⁸ V. Solovyev,¹²¹ N. Soni,¹ V. Sopko,¹²⁶ B. Sopko,¹²⁶ M. Sosebee,⁸ R. Soualah,^{164a,164c} A. Soukharev,¹⁰⁷ S. Spagnolo,^{72a,72b} F. Spanò,⁷⁶ R. Spighi,^{20a} G. Spigo,³⁰ R. Spiwoks,³⁰ M. Spousta,^{127,kk} T. Spreitzer,¹⁵⁸ B. Spurlock,⁸ R. D. St. Denis,⁵³ J. Stahlman,¹²⁰ R. Stamen,^{58a} E. Stanecka,³⁹ R. W. Stanek,⁶ C. Stanescu,^{134a} M. Stanescu-Bellu,⁴² M. M. Stanitzki,⁴² S. Stapnes,¹¹⁷ E. A. Starchenko,¹²⁸ J. Stark,⁵⁵ P. Staroba,¹²⁵ P. Starovoitov,⁴² R. Staszewski,³⁹ A. Staude,⁹⁸

P. Stavina,^{144a,a} G. Steele,⁵³ P. Steinbach,⁴⁴ P. Steinberg,²⁵ I. Stekl,¹²⁶ B. Stelzer,¹⁴² H. J. Stelzer,⁸⁸
O. Stelzer-Chilton,^{159a} H. Stenzel,⁵² S. Stern,⁹⁹ G. A. Stewart,³⁰ J. A. Stillings,²¹ M. C. Stockton,⁸⁵ K. Stoerig,⁴⁸
G. Stoica,^{26a} S. Stonjek,⁹⁹ P. Strachota,¹²⁷ A. R. Stradling,⁸ A. Straessner,⁴⁴ J. Strandberg,¹⁴⁷ S. Strandberg,^{146a,146b}
A. Strandlie,¹¹⁷ M. Strang,¹⁰⁹ E. Strauss,¹⁴³ M. Strauss,¹¹¹ P. Strizenec,^{144b} R. Ströhmer,¹⁷⁴ D. M. Strom,¹¹⁴
J. A. Strong,^{76,a} R. Stroynowski,⁴⁰ B. Stugu,¹⁴ I. Stumer,^{25,a} J. Stupak,¹⁴⁸ P. Sturm,¹⁷⁵ N. A. Styles,⁴² D. Su,¹⁴³
HS. Subramania,³ R. Subramaniam,²⁵ A. Succurro,¹² Y. Sugaya,¹¹⁶ C. Suhr,¹⁰⁶ M. Suk,¹²⁷ V. V. Sulin,⁹⁴
S. Sultansoy,^{4d} T. Sumida,⁶⁷ X. Sun,⁵⁵ J. E. Sundermann,⁴⁸ K. Suruliz,¹³⁹ G. Susinno,^{37a,37b} M. R. Sutton,¹⁴⁹
Y. Suzuki,⁶⁵ Y. Suzuki,⁶⁶ M. Svatos,¹²⁵ S. Swedish,¹⁶⁸ I. Sykora,^{144a} T. Sykora,¹²⁷ D. Ta,¹⁰⁵ K. Tackmann,⁴²
A. Taffard,¹⁶³ R. Tafirout,^{159a} N. Taiblum,¹⁵³ Y. Takahashi,¹⁰¹ H. Takai,²⁵ R. Takashima,⁶⁸ H. Takeda,⁶⁶
T. Takeshita,¹⁴⁰ Y. Takubo,⁶⁵ M. Talby,⁸³ A. Talyshv,^{107,h} M. C. Tamsett,²⁵ K. G. Tan,⁸⁶ J. Tanaka,¹⁵⁵ R. Tanaka,¹¹⁵
S. Tanaka,¹³¹ S. Tanaka,⁶⁵ A. J. Tanasijczuk,¹⁴² K. Tani,⁶⁶ N. Tannoury,⁸³ S. Tapprogge,⁸¹ D. Tardif,¹⁵⁸ S. Tarem,¹⁵²
F. Tarrade,²⁹ G. F. Tartarelli,^{89a} P. Tas,¹²⁷ M. Tasevsky,¹²⁵ E. Tassi,^{37a,37b} M. Tatarkhanov,¹⁵ Y. Tayalati,^{135d}
C. Taylor,⁷⁷ F. E. Taylor,⁹² G. N. Taylor,⁸⁶ W. Taylor,^{159b} M. Teinturier,¹¹⁵ F. A. Teischinger,³⁰
M. Teixeira Dias Castanheira,⁷⁵ P. Teixeira-Dias,⁷⁶ K. K. Temming,⁴⁸ H. Ten Kate,³⁰ P. K. Teng,¹⁵¹ S. Terada,⁶⁵
K. Terashi,¹⁵⁵ J. Terron,⁸⁰ M. Testa,⁴⁷ R. J. Teuscher,^{158,l} J. Therhaag,²¹ T. Thevenaux-Pelzer,⁷⁸ S. Thoma,⁴⁸
J. P. Thomas,¹⁸ E. N. Thompson,³⁵ P. D. Thompson,¹⁸ P. D. Thompson,¹⁵⁸ A. S. Thompson,⁵³ L. A. Thomsen,³⁶
E. Thomson,¹²⁰ M. Thomson,²⁸ W. M. Thong,⁸⁶ R. P. Thun,⁸⁷ F. Tian,³⁵ M. J. Tibbetts,¹⁵ T. Tic,¹²⁵
V. O. Tikhomirov,⁹⁴ Y. A. Tikhonov,^{107,h} S. Timoshenko,⁹⁶ E. Tiouchichine,⁸³ P. Tipton,¹⁷⁶ S. Tisserant,⁸³
T. Todorov,⁵ S. Todorova-Nova,¹⁶¹ B. Toggerson,¹⁶³ J. Tojo,⁶⁹ S. Tokár,^{144a} K. Tokushuku,⁶⁵ K. Tollefson,⁸⁸
M. Tomoto,¹⁰¹ L. Tompkins,³¹ K. Toms,¹⁰³ A. Tonoyan,¹⁴ C. Topfel,¹⁷ N. D. Topilin,⁶⁴ I. Torchiani,³⁰ E. Torrence,¹¹⁴
H. Torres,⁷⁸ E. Torró Pastor,¹⁶⁷ J. Toth,^{83,ff} F. Touchard,⁸³ D. R. Tovey,¹³⁹ T. Trefzger,¹⁷⁴ L. Tremblet,³⁰ A. Tricoli,³⁰
I. M. Trigger,^{159a} S. Trincaz-Duvoid,⁷⁸ M. F. Tripiana,⁷⁰ N. Triplett,²⁵ W. Trischuk,¹⁵⁸ B. Trocmé,⁵⁵ C. Troncon,^{89a}
M. Trotter-McDonald,¹⁴² P. True,⁸⁸ M. Trzebinski,³⁹ A. Trzupek,³⁹ C. Tsarouchas,³⁰ J. C.-L. Tseng,¹¹⁸
M. Tsiakiris,¹⁰⁵ P. V. Tsiareshka,⁹⁰ D. Tsiou, ^{5,II} G. Tsipolitis,¹⁰ S. Tsiskaridze,¹² V. Tsiskaridze,⁴⁸
E. G. Tskhadadze,^{51a} I. I. Tsukerman,⁹⁵ V. Tsulaia,¹⁵ J.-W. Tsung,²¹ S. Tsuno,⁶⁵ D. Tsybychev,¹⁴⁸ A. Tua,¹³⁹
A. Tudorache,^{26a} V. Tudorache,^{26a} J. M. Tuggle,³¹ M. Turala,³⁹ D. Turecek,¹²⁶ I. Turk Cakir,^{4e} E. Turlay,¹⁰⁵
R. Turra,^{89a,89b} P. M. Tuts,³⁵ A. Tykhonov,⁷⁴ M. Tylmad,^{146a,146b} M. Tyndel,¹²⁹ G. Tzanakos,⁹ K. Uchida,²¹
I. Ueda,¹⁵⁵ R. Ueno,²⁹ M. Ugland,¹⁴ M. Uhlenbrock,²¹ M. Uhrmacher,⁵⁴ F. Ukegawa,¹⁶⁰ G. Unal,³⁰ A. Undrus,²⁵
G. Unel,¹⁶³ Y. Unno,⁶⁵ D. Urbaniec,³⁵ P. Urquijo,²¹ G. Usai,⁸ M. Uslenghi,^{119a,119b} L. Vacavant,⁸³ V. Vacek,¹²⁶
B. Vachon,⁸⁵ S. Vahsen,¹⁵ J. Valenta,¹²⁵ S. Valentinetti,^{20a,20b} A. Valero,¹⁶⁷ S. Valkar,¹²⁷ E. Valladolid Gallego,¹⁶⁷
S. Vallecora,¹⁵² J. A. Valls Ferrer,¹⁶⁷ R. Van Berg,¹²⁰ P. C. Van Der Deijl,¹⁰⁵ R. van der Geer,¹⁰⁵ H. van der Graaf,¹⁰⁵
R. Van Der Leeuw,¹⁰⁵ E. van der Poel,¹⁰⁵ D. van der Ster,³⁰ N. van Eldik,³⁰ P. van Gemmeren,⁶ I. van Vulpen,¹⁰⁵
M. Vanadia,⁹⁹ W. Vandelli,³⁰ A. Vaniachine,⁶ P. Vankov,⁴² F. Vannucci,⁷⁸ R. Vari,^{132a} E. W. Varnes,⁷ T. Varol,⁸⁴
D. Varouchas,¹⁵ A. Vartapetian,⁸ K. E. Varvell,¹⁵⁰ V. I. Vassilakopoulos,⁵⁶ F. Vazeille,³⁴ T. Vazquez Schroeder,⁵⁴
G. Vegni,^{89a,89b} J. J. Veillet,¹¹⁵ F. Veloso,^{124a} R. Veness,³⁰ S. Veneziano,^{132a} A. Ventura,^{72a,72b} D. Ventura,⁸⁴
M. Venturi,⁴⁸ N. Venturi,¹⁵⁸ V. Vercesi,^{119a} M. Verducci,¹³⁸ W. Verkerke,¹⁰⁵ J. C. Vermeulen,¹⁰⁵ A. Vest,⁴⁴
M. C. Vetterli,^{142,f} I. Vichou,¹⁶⁵ T. Vickey,^{145b,mm} O. E. Vickey Boeriu,^{145b} G. H. A. Viehhauser,¹¹⁸ S. Viel,¹⁶⁸
M. Villa,^{20a,20b} M. Villaplana Perez,¹⁶⁷ E. Vilucchi,⁴⁷ M. G. Vincter,²⁹ E. Vinek,³⁰ V. B. Vinogradov,⁶⁴
M. Virchaux,^{136,a} J. Virzi,¹⁵ O. Vitells,¹⁷² M. Viti,⁴² I. Vivarelli,⁴⁸ F. Vives Vaque,³ S. Vlachos,¹⁰ D. Vladoiu,⁹⁸
M. Vlasak,¹²⁶ A. Vogel,²¹ P. Vokac,¹²⁶ G. Volpi,⁴⁷ M. Volpi,⁸⁶ G. Volpini,^{89a} H. von der Schmitt,⁹⁹
H. von Radziewski,⁴⁸ E. von Toerne,²¹ V. Vorobel,¹²⁷ V. Vorwerk,¹² M. Vos,¹⁶⁷ R. Voss,³⁰ J. H. Vosseveld,⁷³
N. Vranjes,¹³⁶ M. Vranjes Milosavljevic,¹⁰⁵ V. Vrba,¹²⁵ M. Vreeswijk,¹⁰⁵ T. Vu Anh,⁴⁸ R. Vuillermet,³⁰ I. Vukotic,³¹
W. Wagner,¹⁷⁵ P. Wagner,¹²⁰ S. Wahrenmund,⁴⁴ J. Wakabayashi,¹⁰¹ S. Walch,⁸⁷ J. Walder,⁷¹ R. Walker,⁹⁸
W. Walkowiak,¹⁴¹ R. Wall,¹⁷⁶ P. Waller,⁷³ B. Walsh,¹⁷⁶ C. Wang,⁴⁵ H. Wang,¹⁷³ H. Wang,^{33b,nn} J. Wang,¹⁵¹
J. Wang,⁵⁵ R. Wang,¹⁰³ S. M. Wang,¹⁵¹ T. Wang,²¹ A. Warburton,⁸⁵ C. P. Ward,²⁸ D. R. Wardrope,⁷⁷ M. Warsinsky,⁴⁸
A. Washbrook,⁴⁶ C. Wasicki,⁴² I. Watanabe,⁶⁶ P. M. Watkins,¹⁸ A. T. Watson,¹⁸ I. J. Watson,¹⁵⁰ M. F. Watson,¹⁸
G. Watts,¹³⁸ S. Watts,⁸² A. T. Waugh,¹⁵⁰ B. M. Waugh,⁷⁷ M. S. Weber,¹⁷ P. Weber,⁵⁴ J. S. Webster,³¹
A. R. Weidberg,¹¹⁸ P. Weigell,⁹⁹ J. Weingarten,⁵⁴ C. Weiser,⁴⁸ P. S. Wells,³⁰ T. Wenaus,²⁵ D. Wendland,¹⁶
Z. Weng,^{151,w} T. Wengler,³⁰ S. Wenig,³⁰ N. Wermes,²¹ M. Werner,⁴⁸ P. Werner,³⁰ M. Werth,¹⁶³ M. Wessels,^{58a}
J. Wetter,¹⁶¹ C. Weydert,⁵⁵ K. Whalen,²⁹ A. White,⁸ M. J. White,⁸⁶ S. White,^{122a,122b} S. R. Whitehead,¹¹⁸
D. Whiteson,¹⁶³ D. Whittington,⁶⁰ F. Wicke,¹¹⁵ D. Wicke,¹⁷⁵ F. J. Wickens,¹²⁹ W. Wiedenmann,¹⁷³ M. Wielers,¹²⁹

P. Wienemann,²¹ C. Wiglesworth,⁷⁵ L. A. M. Wiik-Fuchs,²¹ P. A. Wijeratne,⁷⁷ A. Wildauer,⁹⁹ M. A. Wildt,^{42,t}
 I. Wilhelm,¹²⁷ H. G. Wilkens,³⁰ J. Z. Will,⁹⁸ E. Williams,³⁵ H. H. Williams,¹²⁰ W. Willis,³⁵ S. Willocq,⁸⁴
 J. A. Wilson,¹⁸ M. G. Wilson,¹⁴³ A. Wilson,⁸⁷ I. Wingerter-Seez,⁵ S. Winkelmann,⁴⁸ F. Winklmeier,³⁰ M. Wittgen,¹⁴³
 S. J. Wollstadt,⁸¹ M. W. Wolter,³⁹ H. Wolters,^{124a,i} W. C. Wong,⁴¹ G. Wooden,⁸⁷ B. K. Wosiek,³⁹ J. Wotschack,³⁰
 M. J. Woudstra,⁸² K. W. Wozniak,³⁹ K. Wraight,⁵³ M. Wright,⁵³ B. Wrona,⁷³ S. L. Wu,¹⁷³ X. Wu,⁴⁹ Y. Wu,^{33b,oo}
 E. Wulf,³⁵ B. M. Wynne,⁴⁶ S. Xella,³⁶ M. Xiao,¹³⁶ S. Xie,⁴⁸ C. Xu,^{33b,bb} D. Xu,¹³⁹ B. Yabsley,¹⁵⁰ S. Yacoob,^{145a,pp}
 M. Yamada,⁶⁵ H. Yamaguchi,¹⁵⁵ A. Yamamoto,⁶⁵ K. Yamamoto,⁶³ S. Yamamoto,¹⁵⁵ T. Yamamura,¹⁵⁵
 T. Yamanaka,¹⁵⁵ T. Yamazaki,¹⁵⁵ Y. Yamazaki,⁶⁶ Z. Yan,²² H. Yang,⁸⁷ U. K. Yang,⁸² Y. Yang,¹⁰⁹ Z. Yang,^{146a,146b}
 S. Yanush,⁹¹ L. Yao,^{33a} Y. Yao,¹⁵ Y. Yasu,⁶⁵ G. V. Ybeles Smit,¹³⁰ J. Ye,⁴⁰ S. Ye,²⁵ M. Yilmaz,^{4c} R. Yoosoofmiya,¹²³
 K. Yorita,¹⁷¹ R. Yoshida,⁶ K. Yoshihara,¹⁵⁵ C. Young,¹⁴³ C. J. S. Young,¹¹⁸ S. Youssef,²² D. Yu,²⁵ J. Yu,⁸ J. Yu,¹¹²
 L. Yuan,⁶⁶ A. Yurkewicz,¹⁰⁶ B. Zabinski,³⁹ R. Zaidan,⁶² A. M. Zaitsev,¹²⁸ Z. Zajacova,³⁰ L. Zanello,^{132a,132b}
 D. Zanzi,⁹⁹ A. Zaytsev,²⁵ C. Zeitnitz,¹⁷⁵ M. Zeman,¹²⁶ A. Zemla,³⁹ C. Zender,²¹ O. Zenin,¹²⁸ T. Ženiš,^{144a} S. Zenz,¹⁵
 D. Zerwas,¹¹⁵ G. Zevi della Porta,⁵⁷ D. Zhang,^{33b,nn} H. Zhang,⁸⁸ J. Zhang,⁶ X. Zhang,^{33d} Z. Zhang,¹¹⁵ L. Zhao,¹⁰⁸
 Z. Zhao,^{33b} A. Zhemchugov,⁶⁴ J. Zhong,¹¹⁸ B. Zhou,⁸⁷ N. Zhou,¹⁶³ Y. Zhou,¹⁵¹ C. G. Zhu,^{33d} H. Zhu,⁴² J. Zhu,⁸⁷
 Y. Zhu,^{33b} X. Zhuang,⁹⁸ V. Zhuravlov,⁹⁹ A. Zibell,⁹⁸ D. Zieminska,⁶⁰ N. I. Zimin,⁶⁴ R. Zimmermann,²¹
 S. Zimmermann,²¹ S. Zimmermann,⁴⁸ Z. Zinonos,^{122a,122b} M. Ziolkowski,¹⁴¹ R. Zitoun,⁵ L. Živković,³⁵
 V. V. Zmouchko,^{128,a} G. Zoernig,¹⁷³ A. Zoccoli,^{20a,20b} M. zur Nedden,¹⁶ V. Zutshi,¹⁰⁶ and L. Zwalinski³⁰

(ATLAS Collaboration)

¹*School of Chemistry and Physics, University of Adelaide, Adelaide, Australia*²*Physics Department, SUNY Albany, Albany, New York, USA*³*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*^{4a}*Department of Physics, Ankara University, Ankara, Turkey*^{4b}*Department of Physics, Dumlupinar University, Kutahya, Turkey*^{4c}*Department of Physics, Gazi University, Ankara, Turkey*^{4d}*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*^{4e}*Turkish Atomic Energy Authority, Ankara, Turkey*⁵*LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*⁶*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*⁷*Department of Physics, University of Arizona, Tucson, Arizona, USA*⁸*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*⁹*Physics Department, University of Athens, Athens, Greece*¹⁰*Physics Department, National Technical University of Athens, Zografou, Greece*¹¹*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*¹²*Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain*^{13a}*Institute of Physics, University of Belgrade, Belgrade, Serbia*^{13b}*Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*¹⁴*Department for Physics and Technology, University of Bergen, Bergen, Norway*¹⁵*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*¹⁶*Department of Physics, Humboldt University, Berlin, Germany*¹⁷*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*¹⁸*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*^{19a}*Department of Physics, Bogazici University, Istanbul, Turkey*^{19b}*Division of Physics, Dogus University, Istanbul, Turkey*^{19c}*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*^{19d}*Department of Physics, Istanbul Technical University, Istanbul, Turkey*^{20a}*INFN Sezione di Bologna, Italy*^{20b}*Dipartimento di Fisica, Università di Bologna, Bologna, Italy*²¹*Physikalisches Institut, University of Bonn, Bonn, Germany*²²*Department of Physics, Boston University, Boston, Massachusetts, USA*²³*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*^{24a}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*^{24b}*Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*^{24c}*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*^{24d}*Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil*

- ²⁵Physics Department, Brookhaven National Laboratory, Upton, New York, USA
- ^{26a}National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- ^{26b}University Politehnica Bucharest, Bucharest, Romania
- ^{26c}West University in Timisoara, Timisoara, Romania
- ²⁷Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁸Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ²⁹Department of Physics, Carleton University, Ottawa, Ontario, Canada
- ³⁰CERN, Geneva, Switzerland
- ³¹Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
- ^{32a}Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- ^{32b}Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ^{33a}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
- ^{33b}Department of Modern Physics, University of Science and Technology of China, Anhui, China
- ^{33c}Department of Physics, Nanjing University, Jiangsu, China
- ^{33d}School of Physics, Shandong University, Shandong, China
- ³⁴Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵Nevis Laboratory, Columbia University, Irvington, New York, USA
- ³⁶Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ^{37a}INFN Gruppo Collegato di Cosenza, Italy
- ^{37b}Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ³⁹The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰Physics Department, Southern Methodist University, Dallas, Texas, USA
- ⁴¹Physics Department, University of Texas at Dallas, Richardson, Texas, USA
- ⁴²DESY, Hamburg and Zeuthen, Germany
- ⁴³Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁵Department of Physics, Duke University, Durham, North Carolina, USA
- ⁴⁶SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁴⁹Section de Physique, Université de Genève, Genève, Switzerland
- ^{50a}INFN Sezione di Genova, Italy
- ^{50b}Dipartimento di Fisica, Università di Genova, Genova, Italy
- ^{51a}E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
- ^{51b}High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵²II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶Department of Physics, Hampton University, Hampton, Virginia, USA
- ⁵⁷Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
- ^{58a}Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{58b}Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{58c}ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰Department of Physics, Indiana University, Bloomington, Indiana, USA
- ⁶¹Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶²University of Iowa, Iowa City, Iowa, USA
- ⁶³Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
- ⁶⁴Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸Kyoto University of Education, Kyoto, Japan
- ⁶⁹Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹Physics Department, Lancaster University, Lancaster, United Kingdom
- ^{72a}INFN Sezione di Lecce, Italy

- ^{72b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ⁷³*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁷⁴*Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
- ⁷⁵*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- ⁷⁶*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
- ⁷⁷*Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁷⁸*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
- ⁷⁹*Fysiska institutionen, Lunds Universitet, Lund, Sweden*
- ⁸⁰*Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain*
- ⁸¹*Institut für Physik, Universität Mainz, Mainz, Germany*
- ⁸²*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁸³*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
- ⁸⁴*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- ⁸⁵*Department of Physics, McGill University, Montreal, Quebec City, Canada*
- ⁸⁶*School of Physics, University of Melbourne, Victoria, Australia*
- ⁸⁷*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
- ⁸⁸*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ^{89a}*INFN Sezione di Milano, Italy*
- ^{89b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ⁹⁰*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
- ⁹¹*National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus*
- ⁹²*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ⁹³*Group of Particle Physics, University of Montreal, Montreal, Quebec City, Canada*
- ⁹⁴*P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
- ⁹⁵*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ⁹⁶*Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
- ⁹⁷*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- ⁹⁸*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ⁹⁹*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹⁰⁰*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹⁰¹*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ^{102a}*INFN Sezione di Napoli, Italy*
- ^{102b}*Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
- ¹⁰³*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹⁰⁴*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹⁰⁵*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹⁰⁶*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ¹⁰⁷*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
- ¹⁰⁸*Department of Physics, New York University, New York, New York, USA*
- ¹⁰⁹*Ohio State University, Columbus, Ohio, USA*
- ¹¹⁰*Faculty of Science, Okayama University, Okayama, Japan*
- ¹¹¹*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹¹²*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹¹³*Palacký University, RCPTM, Olomouc, Czech Republic*
- ¹¹⁴*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹¹⁵*LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France*
- ¹¹⁶*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹¹⁷*Department of Physics, University of Oslo, Oslo, Norway*
- ¹¹⁸*Department of Physics, Oxford University, Oxford, United Kingdom*
- ^{119a}*INFN Sezione di Pavia, Italy*
- ^{119b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ¹²⁰*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹²¹*Petersburg Nuclear Physics Institute, Gatchina, Russia*
- ^{122a}*INFN Sezione di Pisa, Italy*
- ^{122b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ¹²³*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania*
- ^{124a}*Laboratório de Instrumentação e Física Experimental de Partículas-LIP, Lisboa, Portugal*
- ^{124b}*Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
- ¹²⁵*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
- ¹²⁶*Czech Technical University in Prague, Praha, Czech Republic*
- ¹²⁷*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*

- ¹²⁸*State Research Center Institute for High Energy Physics, Protvino, Russia*
- ¹²⁹*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹³⁰*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
- ¹³¹*Ritsumeikan University, Kusatsu, Shiga, Japan*
- ^{132a}*INFN Sezione di Roma I, Italy*
- ^{132b}*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
- ^{133a}*INFN Sezione di Roma Tor Vergata, Italy*
- ^{133b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{134a}*INFN Sezione di Roma Tre, Italy*
- ^{134b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ^{135a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco*
- ^{135b}*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
- ^{135c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- ^{135d}*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
- ^{135e}*Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco*
- ¹³⁶*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France*
- ¹³⁷*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ¹³⁸*Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹³⁹*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴⁰*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴¹*Fachbereich Physik, Universität Siegen, Siegen, Germany*
- ¹⁴²*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
- ¹⁴³*SLAC National Accelerator Laboratory, Stanford California*
- ^{144a}*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{144b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ^{145a}*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
- ^{145b}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ^{146a}*Department of Physics, Stockholm University, Sweden*
- ^{146b}*The Oskar Klein Centre, Stockholm, Sweden*
- ¹⁴⁷*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁴⁸*Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA*
- ¹⁴⁹*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁵⁰*School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵¹*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ¹⁵²*Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
- ¹⁵³*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵⁴*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵⁵*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
- ¹⁵⁶*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁵⁷*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁵⁸*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
- ^{159a}*TRIUMF, Vancouver, British Columbia, Canada*
- ^{159b}*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
- ¹⁶⁰*Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
- ¹⁶¹*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
- ¹⁶²*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
- ¹⁶³*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- ^{164a}*INFN Gruppo Collegato di Udine, Italy*
- ^{164b}*ICTP, Trieste, Italy*
- ^{164c}*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
- ¹⁶⁵*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- ¹⁶⁶*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁷*Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*
- ¹⁶⁸*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
- ¹⁶⁹*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*

¹⁷⁰*Department of Physics, University of Warwick, Coventry, United Kingdom*¹⁷¹*Waseda University, Tokyo, Japan*¹⁷²*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*¹⁷³*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*¹⁷⁴*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*¹⁷⁵*Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*¹⁷⁶*Department of Physics, Yale University, New Haven, Connecticut, USA*¹⁷⁷*Yerevan Physics Institute, Yerevan, Armenia*¹⁷⁸*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3),**Villeurbanne, France*^aDeceased.^bAlso at Department of Physics, King's College London, London, United Kingdom.^cAlso at Laboratório de Instrumentação e Física Experimental de Partículas-LIP, Lisboa, Portugal.^dAlso at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.^eAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.^fAlso at TRIUMF, Vancouver, British Columbia, Canada.^gAlso at Department of Physics, California State University, Fresno, CA, USA.^hAlso at Novosibirsk State University, Novosibirsk, Russia.ⁱAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.^jAlso at Department of Physics, UASLP, San Luis Potosi, Mexico.^kAlso at Università di Napoli Parthenope, Napoli, Italy.^lAlso at Institute of Particle Physics (IPP), Canada.^mAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.ⁿAlso at Louisiana Tech University, Ruston, LA, USA.^oAlso at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.^pAlso at Department of Physics and Astronomy, University College London, London, United Kingdom.^qAlso at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA.^rAlso at Department of Physics, University of Cape Town, Cape Town, South Africa.^sAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.^tAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.^uAlso at Manhattan College, New York, NY, USA.^vAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.^wAlso at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.^xAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.^yAlso at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.^zAlso at School of Physics, Shandong University, Shandong, China.^{aa}Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.^{bb}Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France.^{cc}Also at Section de Physique, Université de Genève, Geneva, Switzerland.^{dd}Also at Departamento de Física, Universidade de Minho, Braga, Portugal.^{ee}Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.^{ff}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.^{gg}Also at California Institute of Technology, Pasadena, CA, USA.^{hh}Also at International School for Advanced Studies (SISSA), Trieste, Italy.ⁱⁱAlso at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.^{jj}Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.^{kk}Also at Nevis Laboratory, Columbia University, Irvington, NY, USA.^{ll}Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.^{mm}Also at Department of Physics, Oxford University, Oxford, United Kingdom.ⁿⁿAlso at Institute of Physics, Academia Sinica, Taipei, Taiwan.^{oo}Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.^{pp}Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.