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Collaborators: Ancu, Lucian Stefan; Bell, William; Benhar Noccioli, Eleonora; Bilbao De Mendizabal, Javier; Calace, Noemi; Clark, Allan Geoffrey; Coccaro, Andrea; Delitzsch, Chris Malena; Della Volpe, Domenico; Ferrere, Didier; Gadomski, Szymon; Golling, Tobias Gonzalez Sevilla, Sergio [**and 14 more**]

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Combination of searches for WW , WZ , and ZZ resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration ^{*}

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ABSTRACT

The ATLAS experiment at the CERN Large Hadron Collider has performed searches for new, heavy bosons decaying to WW , WZ and ZZ final states in multiple decay channels using 20.3 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV. In the current study, the results of these searches are combined to provide a more stringent test of models predicting heavy resonances with couplings to vector bosons. Direct searches for a charged diboson resonance decaying to WZ in the $\ell\nu\ell'\ell'$ ($\ell = \mu, e$), $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and fully hadronic final states are combined and upper limits on the rate of production times branching ratio to the WZ bosons are compared with predictions of an extended gauge model with a heavy W' boson. In addition, direct searches for a neutral diboson resonance decaying to WW and ZZ in the $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and fully hadronic final states are combined and upper limits on the rate of production times branching ratio to the WW and ZZ bosons are compared with predictions for a heavy, spin-2 graviton in an extended Randall–Sundrum model where the Standard Model fields are allowed to propagate in the bulk of the extra dimension.

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1. Introduction

The naturalness argument associated with the small mass of the recently discovered Higgs boson [1–4] suggests that the Standard Model (SM) is conceivably to be extended by a theory that includes additional particles and interactions at the TeV scale. Many such extensions of the SM, such as extended gauge models [5–7], models of warped extra dimensions [8–10], technicolour [11–14], and more generic composite Higgs models [15,16], predict the existence of massive resonances decaying to pairs of W and Z bosons.

In the extended gauge model (EGM) [5] a new, charged vector boson (W') couples to the SM particles. The coupling between the W' and the SM fermions is the same as the coupling between the W boson and the SM fermions. The $W'WZ$ coupling has the same structure as the WWZ coupling in the SM, but is scaled by a factor $c \times (m_W/m_{W'})^2$, where c is a scaling constant, m_W is the W boson mass, and $m_{W'}$ is the W' boson mass. The scaling of the coupling allows the width of the W' boson to increase approximately linearly with $m_{W'}$ at $m_{W'} \gg m_W$ and to remain narrow for $c \sim 1$. For $c = 1$ and $m_{W'} > 0.5$ TeV the W' width is approximately 3.6% of its mass and the branching ratio of the $W' \rightarrow WZ$ ranges from 1.6% to 1.2% depending on $m_{W'}$. Production cross sec-

tions in pp collisions at $\sqrt{s} = 8$ TeV for the W' boson as well as the W' width and branching ratios of $W' \rightarrow WZ$ for a selection of W' boson masses in the EGM with scale factor $c = 1$ are given in Table 1.

Searches for a W' boson decaying to $\ell\nu$ have set strong bounds on the mass of the W' when assuming the sequential standard model (SSM) [17,18], which differs from the EGM in that the $W'WZ$ coupling is set to zero. For $c \sim 1$ the effect of this coupling on the production cross section of the W' boson at the LHC is very small, thus the production cross section of the W' boson in the SSM and the EGM is very similar. Moreover, due to the small branching ratio of the $W' \rightarrow WZ$ in the EGM with the scale factor $c \sim 1$, the branching ratios of the W' boson to fermions are approximately the same as in the SSM. Nevertheless, models with narrow vector resonances with suppressed fermionic couplings remain viable extensions to the SM, and thus the EGM provides a useful and simple benchmark in searches for narrow vector resonances decaying to WZ .

The ATLAS and CMS Collaborations have set exclusion bounds on the production and decay of the EGM W' boson. In searches using the $\ell\nu\ell'\ell'$ ($\ell \equiv e, \mu$) channel, the ATLAS [19] and CMS [20] Collaborations have excluded, at the 95% confidence level (CL), EGM ($c = 1$) W' bosons decaying to WZ for W' masses below 1.52 TeV and 1.55 TeV, respectively. In addition the ATLAS Collaboration has excluded EGM ($c = 1$) W' bosons for masses below

^{*} E-mail address: atlas_publications@cern.ch.

1.59 TeV using the $\ell\ell q\bar{q}$ [21] channel, and below 1.49 TeV using the $\ell\nu q\bar{q}$ [22] channel. These have also been excluded with masses between 1.3 and 1.5 TeV and below 1.7 TeV by the ATLAS [23] and CMS [24] Collaborations, respectively, using the fully hadronic final state.

Diboson resonances are also predicted in an extension of the original Randall–Sundrum (RS) [8–10] model with a warped extra dimension. In this extension to the RS model [25–27], the SM fields are allowed to propagate in the bulk of the extra dimension, avoiding constraints on the original RS model from flavour-changing neutral currents and from electroweak precision measurements. This so-called bulk-RS model is characterised by a dimensionless coupling constant $k/\bar{M}_{\text{Pl}} \sim 1$, where k is the curvature of the warped extra dimension, and $\bar{M}_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8\pi}$ is the reduced Planck mass. In this model a Kaluza–Klein excitation of the spin-2 graviton, G^* , can decay to pairs of W or Z bosons. For bulk RS models with $k/\bar{M}_{\text{Pl}} = 1$ and for G^* masses between 0.5 and 2.5 TeV, the branching ratio of G^* to WW ranges from 34% to 16% and the branching ratio to ZZ ranges from 18% to 8%. The G^* width ranges from 3.7% to 6.2% depending on the G^* mass. Table 1 lists widths, branching ratio to WW and ZZ for G^* , and production cross sections in pp collisions at 8 TeV in these bulk RS models.

The ATLAS Collaboration has excluded, at the 95% CL, bulk $G^* \rightarrow ZZ$ with masses below 740 GeV, using the $\ell\ell q\bar{q}$ channel [21], as well as bulk $G^* \rightarrow WW$ with masses below 760 GeV, using the $\ell\nu q\bar{q}$ channel assuming $k/\bar{M}_{\text{Pl}} = 1$ [22]. The CMS Collaboration has also excluded at the 95% CL the G^* of the original RS model, decaying to WW and ZZ with masses below 1.2 TeV using the fully hadronic final state [24] and has set limits on the production and decay of generic diboson resonances using a combination of $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and fully hadronic final states [28].

To improve the sensitivity to new diboson resonances, this article presents a combination of four statistically independent searches for diboson resonances previously published by the ATLAS Collaboration [19,21–23]. The searches are combined while considering the correlations between systematic uncertainties in the different channels. The first search, sensitive to charged resonances decaying to WZ , uses the $\ell\nu\ell'\ell'$ [19] final state. The second search, sensitive to charged resonances decaying to WZ and neutral resonances decaying to ZZ , uses the $\ell\ell q\bar{q}$ final state [21]. The third search, sensitive to charged resonances decaying to WZ and neutral resonances decaying to WW , uses the $\ell\nu q\bar{q}$ final state [22]. Finally, the fourth search, sensitive to charged resonances decaying to WZ and to neutral resonances decaying to either WW or ZZ , uses the fully hadronic final state [23]. Due to the large momenta of the bosons from the resonance decay, the resonance in this channel is reconstructed with two large-radius jets, and the fully hadronic channel is hereafter referred to as the JJ channel.

To search for a charged diboson resonance decaying to WZ the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels are combined. The result of this combination is interpreted using the EGM W' model with $c = 1$ as a benchmark.

To search for neutral diboson resonances decaying to WW and ZZ the $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels are combined, and the result is interpreted using the bulk G^* , assuming $k/\bar{M}_{\text{Pl}} = 1$, as a benchmark.

The ATLAS Collaboration has performed additional searches in which new diboson resonances could manifest themselves as excesses over the background expectation. In the analysis presented in Ref. [29] the $\ell\ell\ell'\ell'$, $\ell\nu\nu$, $\ell\ell q\bar{q}$ and $q\bar{q}\nu\nu$ final states have been explored in the context of the search for a new, heavy Higgs boson. Also, in the context of searches for dark matter a final state of a hadronically decaying boson and missing transverse momentum [30], and a final state of a leptonically decaying Z boson and

missing transverse momentum have been explored [31]. These additional searches are not included in this combination. They are not expected to contribute significantly to the sensitivity of the combined search due to the lower branching ratio in case of the leptonic channels, and the use of only narrow jets in case of the $q\bar{q}\nu\nu$ final state.

2. ATLAS detector and data sample

The ATLAS detector is described in detail in Ref. [32]. It covers nearly the entire solid angle¹ around the interaction point and has an approximately cylindrical geometry. It consists of an inner tracking detector (ID) placed within a 2 T axial magnetic field surrounded by electromagnetic and hadronic calorimeters and followed by a muon spectrometer (MS) with a magnetic field provided by a system of superconducting toroids.

The results presented in this article use the dataset collected in 2012 by ATLAS from the LHC pp collisions at $\sqrt{s} = 8$ TeV, using a single-lepton (electron or muon) trigger [33] with a p_{T} threshold of 24 GeV, or a single large-radius jet trigger with a p_{T} threshold of 360 GeV. The integrated luminosity of this dataset after requiring data quality criteria to ensure that all detector components have been operational during data taking is 20.3 fb^{-1} . The uncertainty on the integrated luminosity is $\pm 2.8\%$. It is derived following the methodology detailed in Ref. [34].

3. Signal and background samples

The acceptance and the reconstructed mass spectra for narrow resonances are estimated with signal samples generated with resonance masses between 200 and 2500 GeV, in 100 GeV steps. The bulk G^* signal events are produced by CALCHEP 3.4 [35] with $k/\bar{M}_{\text{Pl}} = 1.0$, and the W' signal samples are generated with PYTHIA 8.170 [36], setting the coupling scale factor $c = 1$. The factorisation and renormalisation scales are set to the generated resonance mass. The hadronisation and fragmentation are modelled with PYTHIA 8 in both cases, and the CTEQ6L1 [37] (MSTW2008LO [38]) parton distribution functions (PDFs) are used for the G^* (W') signal. The leading-order cross sections and branching ratios for the W' and bulk G^* signal samples for selected mass points and assumed values of the coupling parameters are provided in Table 1.

The backgrounds in the different decay channels are modelled with simulated event samples. The W + jets and Z + jets backgrounds are generated using SHERPA 1.4.1 [39] with CT10 PDFs [40]. A separate sample is generated using ALPGEN 2.14 [41] to estimate systematic effects, using CTEQ6L1 PDFs and PYTHIA 6 [36] for fragmentation and hadronisation.

The W + jets and Z + jets production cross sections are scaled to next-to-next-to-leading-order (NNLO) calculations [42]. The top quark pair, s -channel single-top quark and Wt processes are modelled by the MC@NLO 4.03 generator [43,44] with CT10 PDFs, interfaced to HERWIG [45] for fragmentation and hadronisation and JIMMY [46] for modelling of the underlying event. The top quark pair sample is scaled to the production cross section calculated at NNLO in QCD including resummation of next-to-next-to-leading logarithmic soft gluon terms with Top++2.0 [47–52]. The

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$, and the distance in (ϕ, η) space as $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$.

Table 1

Leading-order cross sections, widths, and branching ratios for the W' boson in the EGM with scale factor $c = 1$ and for the G^* in the bulk RS model with $k/M_{\text{Pl}} = 1$ in pp collisions at $\sqrt{s} = 8$ TeV for a variety of mass points.

m [TeV]	$\Gamma_{W'}$ [GeV]	$\sigma(W')$ [fb]	BR($W' \rightarrow WZ$) [%]	Γ_{G^*} [GeV]	$\sigma(G^*)$ [fb]	BR($G^* \rightarrow WW$) [%]	BR($G^* \rightarrow ZZ$) [%]
0.5	18.0	2.00×10^5	1.6	18.4	3.11×10^3	34	18
1.0	36.0	1.17×10^4	1.3	55.4	5.60×10^1	19	10
1.5	54.0	1.44×10^3	1.3	89.5	3.14×10^0	17	8
2.0	73.3	2.42×10^2	1.2	122.5	2.90×10^{-1}	16	8
2.5	90.7	5.31×10^1	1.2	155.0	3.20×10^{-2}	16	8

t -channel single-top events are generated by AcerMC [53] with CTEQ6L1 PDFs and PYTHIA 6 for hadronisation. The diboson events are produced with the HERWIG generator and CTEQ6L1 PDFs, except for the $\ell\nu\ell'\ell'$ channel which uses POWHEG [54,55] interfaced to PYTHIA 6. The diboson production cross sections are normalised to next-to-leading-order predictions [56]. Additional diboson samples for the $\ell\nu q\bar{q}$ channel are produced with the SHERPA generator. QCD multijet samples are simulated with PYTHIA 6, HERWIG, and POWHEG interfaced to PYTHIA 6.

Generated events are processed with the ATLAS detector simulation program [57] based on the GEANT4 package [58]. Signal and background samples simulated or interfaced with PYTHIA use an ATLAS specific tune of PYTHIA [59]. Effects from additional inelastic pp interactions (pile-up) occurring in the same and neighbouring bunch crossings are taken into account by overlaying minimum-bias events simulated by PYTHIA 8.

4. Object reconstruction and selection

The search channels included in the combination presented in this article use reconstructed electrons, muons, jets and the measurement of the missing transverse momentum.

Electron candidates are selected from energy clusters in the electromagnetic calorimeter within $|\eta| < 2.47$, excluding the transition region between the barrel and the endcap calorimeters ($1.37 < |\eta| < 1.52$), that match a track reconstructed in the ID. Electrons satisfying ‘tight’ identification criteria are used to reconstruct $W \rightarrow e\nu$ candidates, while $Z \rightarrow ee$ are reconstructed from electrons that satisfy ‘medium’ identification criteria. These criteria are described in Ref. [60]. Muon candidates are reconstructed within the range $|\eta| < 2.5$ by combining tracks with compatible momentum in the ID and the MS [61]. Only leptons with $p_T > 25$ GeV are considered.

Backgrounds due to misidentified leptons and non-prompt leptons are suppressed by requiring leptons to be isolated from other activity in the event and also to be consistent with originating from the primary vertex of the event.² Upper bounds on calorimeter and track isolation discriminants are used to ensure that the leptons are isolated.

Details of the lepton isolation criteria are given in the publications for the $\ell\nu\ell'\ell'$ [19], $\ell\ell q\bar{q}$ [21], and $\ell\nu q\bar{q}$ [22] channels.

Jets are formed by combining topological clusters reconstructed in the calorimeter system [62], which are calibrated in energy with the local calibration weighting scheme [63] and are considered massless. The measured energies are corrected for losses in passive material, the non-compensating response of the calorimeters and pile-up [64].

Hadronically decaying vector bosons with low p_T ($\lesssim 450$ GeV) are reconstructed using a pair of jets. The jets are formed with the anti- k_t algorithm [65] with a radius parameter $R = 0.4$. These

jets are hereafter referred to as small- R jets. Only small- R jets with $|\eta| < 2.8$ (2.1) and $p_T > 30$ GeV are considered for the $\ell\nu q\bar{q}$ ($\ell\ell q\bar{q}$) channel. For small- R jets with $p_T < 50$ GeV it is required that the summed scalar p_T of the tracks matched to the primary vertex accounts for at least 50% of the scalar summed p_T of all tracks matched to the jet. Jets containing hadrons from b -quarks are identified using a multivariate b -tagging algorithm as described in Ref. [66].

Hadronically decaying vector bosons with high p_T ($\gtrsim 400$ GeV) can be reconstructed as a single jet with a large radius parameter, or large- R jet, due to the collimated nature of their decay products. These large- R jets, hereafter denoted by J , are first formed with the Cambridge–Aachen (C/A) algorithm [67,68] with a radius parameter $R = 1.2$. After the jet formation a set of criteria is applied to identify the jet as originating from a hadronically decaying boson (boson tagging). A grooming algorithm is applied to the jets to reduce the effect of pile-up and underlying event activity and to identify a pair of subjets associated with the quarks emerging from the vector boson decay. The grooming algorithm, a variant of the mass-drop filtering technique [69], is described in detail in Ref. [23]. The grooming procedure provides a small degree of discriminating power between jets from hadronically decaying bosons and those originating from background processes.

Jet discrimination is further improved by imposing additional requirements on the large- R jet properties. First, in all of the channels using large- R jets, a requirement on the subjet momentum-balance found at the stopping point of the grooming algorithm, $\sqrt{y} > 0.45$,³ is applied to the jet. Second, jets are required to have the groomed jet mass within a selection window. Due to the different backgrounds affecting each of the search channels, different mass windows are used for each channel. In the single lepton and dilepton channels, mass windows of $65 < m_J < 105$ GeV and $70 < m_J < 110$ GeV, where m_J represents the jet mass, are used for selecting W and Z bosons. In the fully hadronic channel, mass windows of $69.4 < m_J < 95.4$ GeV and $79.8 < m_J < 105.8$ GeV, which are ± 13 GeV around the expected W or Z reconstructed mass peak, are used for selecting W or Z boson candidates respectively.

The high- p_T jets in background events are expected to have a larger charged-particle track multiplicity than the jets emerging from boson decays. This is due to the higher energy scale involved in the fragmentation process of background jets and also due to the larger colour charge of gluons in comparison to quarks. Hence, to improve the sensitivity of the search in the fully hadronic channel, a requirement on the charged-particle track multiplicity matched to the large- R jet prior to the grooming, $n_{\text{trk}} < 30$, is used to discriminate between jets originating from boson decays

² The primary vertex of the event is defined as the reconstructed primary vertex with highest $\sum p_T^2$ where the sum is over the tracks associated with this vertex.

³ $\sqrt{y} \equiv \min(p_{T_{j_1}}, p_{T_{j_2}}) \frac{\Delta R_{(j_1, j_2)}}{m_0}$, where m_0 is the mass of the groomed jet at the stopping point of the splitting stage of the grooming algorithm, $p_{T_{j_1}}$ and $p_{T_{j_2}}$ are the transverse momenta of the subjets at the stopping point of the splitting stage of the grooming algorithm and $\Delta R_{(j_1, j_2)}$ is the distance in (ϕ, η) space between these subjets.

Table 2
Dominant background to the individual channels and their estimation methods.

Channel	Dominant background	Estimation method
$\ell\nu\ell'\ell'$	WZ production	MC (POWHEG)
$\ell\ell q\bar{q}$	Z + jets	MC (SHERPA), normalisation and shape correction data driven
$\ell\nu q\bar{q}$	W/Z + jets	MC (SHERPA), normalisation and shape correction data driven
JJ	QCD jets	Data driven

and jets from background processes. Charged-particle tracks re-constructed with the ID and consistent with particles originating from the primary vertex and with $p_T \geq 500$ MeV are matched to a large- R jet by representing each track by a “ghost” constituent that is collinear with the track at the perigee with negligible energy during jet formation [70].

The missing transverse momentum E_T^{miss} is calculated from the negative vector sum of the transverse momenta of all reconstructed objects, including electrons, muons, photons and jets, as well as calibrated energy deposits in the calorimeter that are not associated to these objects, as described in Ref. [71].

5. Analysis channels

The selections in the four analysis channels $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ are mutually exclusive and therefore the channels are statistically independent. This independence is enforced by the required lepton multiplicity of the events at a pre-selection stage, with lepton selection criteria looser than those finally applied in the individual channels. The searches in the individual channels are described in detail in their corresponding publications [19,21–23]. Table 2 summarises the dominant backgrounds affecting each of

the individual channels and the methods used to estimate these backgrounds. Summaries of the event selection and classification criteria are given in Tables 3 and 4.

The $\ell\nu\ell'\ell'$ analysis channel is described in detail in Ref. [19]. For the purpose of combination the binning of the diboson candidates’ invariant mass distribution is adjusted. The $\ell\nu\ell'\ell'$ channel requires exactly three leptons with $p_T > 25$ GeV, of which at least one must be geometrically matched to a lepton reconstructed by a trigger algorithm. Events with additional leptons with $p_T > 20$ GeV are vetoed. At least one pair of oppositely-charged, same-flavour leptons is required to have an invariant mass within the Z mass window $|m_{\ell\ell} - m_Z| < 20$ GeV. If there are two acceptable combinations satisfying this requirement the combination with the mass value closer to the Z boson mass is chosen as the Z candidate. The event is required to have $E_T^{\text{miss}} > 25$ GeV. The W candidate is reconstructed from the third lepton, assuming the neutrino is the only source of E_T^{miss} and constraining the $(\ell^{3\text{rd}}, E_T^{\text{miss}})$ system to have the pole mass of the W. This constraint results in a quadratic equation with two solutions for the longitudinal momentum of the neutrino. If the solutions are real, the one with the smaller absolute value is used. If the solutions are complex, the real part is used. To enhance the signal sensitivity, the rapidity difference must satisfy $\Delta y(W, Z) < 1.5$ and requirements are placed on the azimuthal angle difference $\Delta\phi(\ell^{3\text{rd}}, E_T^{\text{miss}})$. Exclusive *high-mass* and *low-mass* regions are defined with $\Delta\phi(\ell^{3\text{rd}}, E_T^{\text{miss}}) < 1.5$ for boosted W bosons and $\Delta\phi(\ell^{3\text{rd}}, E_T^{\text{miss}}) > 1.5$ for W bosons at low p_T , respectively. The main background sources in the $\ell\nu\ell'\ell'$ channel are SM WZ and ZZ processes with leptonic decays of the W and Z bosons, and are estimated from simulation. Other background sources are W/Z + jets, top quark and multijet production, where one or several jets are mis-reconstructed as leptons. To estimate these backgrounds the mis-reconstruction rate of jets as

Table 3
Summary of the event selection requirements in the different search channels. The selected events are further classified into different kinematic categories as listed in Table 4.

Channel	Leptons	Jets	E_T^{miss}	Boson identification
$\ell\nu\ell'\ell'$	3 leptons $p_T > 25$ GeV	–	$E_T^{\text{miss}} > 25$ GeV	$ m_{\ell\ell} - m_Z < 20$ GeV
$\ell\ell q\bar{q}$	2 leptons $p_T > 25$ GeV	2 small- R jets or 1 large- R jet $p_T > 30$ GeV	–	$ m_{\ell\ell} - m_Z < 25$ GeV $70 \text{ GeV} < m_{jj} < 110 \text{ GeV}$ $70 \text{ GeV} < m_j < 110 \text{ GeV}, \sqrt{y} > 0.45$
$\ell\nu q\bar{q}$	1 lepton $p_T > 25$ GeV	2 small- R jets or 1 large- R jet $p_T > 30$ GeV No b -jet with $\Delta R(b, W/Z) > 0.8$	$E_T^{\text{miss}} > 30$ GeV	$65 \text{ GeV} < m_{jj} < 105 \text{ GeV}$ $65 \text{ GeV} < m_j < 105 \text{ GeV}, \sqrt{y} > 0.45$
JJ	Lepton veto	2 large- R jets, $ \eta < 2.0$, $p_T > 540$ GeV	$E_T^{\text{miss}} < 350$ GeV	$ m_{W/Z} - m_j < 13 \text{ GeV}$ $\sqrt{y} > 0.45, n_{\text{trk}} < 30$

Table 4
Summary of the event classification requirements in the different search channels. The classifications are mutually exclusive, applying the requirements in sequence beginning with the high- p_T merged, followed by the high- p_T resolved and finally with the low- p_T resolved classification.

Channel	High- p_T merged	High- p_T resolved (high mass)	Low- p_T resolved (low mass)
$\ell\nu\ell'\ell'$	–	$\Delta\phi(\ell^{3\text{rd}}, E_T^{\text{miss}}) < 1.5$	$\Delta y(W, Z) < 1.5$ $\Delta\phi(\ell^{3\text{rd}}, E_T^{\text{miss}}) > 1.5$
$\ell\ell q\bar{q}$	$p_T(\ell\ell) > 400$ GeV $p_T(j) > 400$ GeV	$p_T(\ell\ell) > 250$ GeV $p_T(jj) > 250$ GeV	$p_T(\ell\ell) > 100$ GeV $p_T(jj) > 100$ GeV
$\ell\nu q\bar{q}$	1 large- R jet, $p_T > 400$ GeV $p_T(\ell\nu) > 400$ GeV	2 small- R jets, $p_T > 80$ GeV $p_T(jj) > 300$ GeV $p_T(\ell\nu) > 300$ GeV $\Delta\phi(E_T^{\text{miss}}, j) > 1$ (electron channel)	2 small- R jets, $p_T > 30$ GeV $p_T(jj) > 100$ GeV $p_T(\ell\nu) > 100$ GeV
JJ	$ \Delta y_{12} < 1.2$ $m(JJ) > 1.05$ TeV	–	

leptons is determined with data-driven methods, and applied to control data samples with leptons and one or more jets.

The $\ell\ell q\bar{q}$ analysis channel is described in detail in Ref. [21]. The $\ell\ell q\bar{q}$ channel requires exactly two leptons, having the same flavour and with $p_T > 25$ GeV. Muon pairs are required to have opposite charge. At least one lepton is required to be matched to a lepton reconstructed by a trigger algorithm. The invariant mass of the lepton pair must be within 25 GeV of the Z mass. Three regions (*merged*, *high- p_T resolved* and *low- p_T resolved*) are defined to optimise the selection for different mass ranges. The merged region requirements are $p_T(\ell\ell) > 400$ GeV and a groomed large- R jet described in Section 4 with $p_T(J) > 400$ GeV and satisfying the boson-tagging criteria. The high- p_T resolved region is defined by $p_T(\ell\ell) > 250$ GeV, $p_T(jj) > 250$ GeV, and the low- p_T resolved region requires $p_T(\ell\ell) > 100$ GeV, $p_T(jj) > 100$ GeV. The invariant mass requirement on the jet system is $70 \text{ GeV} < m_{jj/J} < 110 \text{ GeV}$. The three regions are made exclusive by applying the above selections in sequence, starting with the merged region, and progressing with the high- p_T and then the low- p_T resolved regions. The main background sources in the $\ell\ell q\bar{q}$ channel are Z + jets, followed by top-quark pair and non-resonant vector-boson pair production. Background estimates are based on simulation. Additionally, for the main background source, Z + jets, the shape of the invariant mass distribution is modelled with simulation, while the normalisation and a linear shape correction are determined from data in a control region, defined as the side-bands of the $q\bar{q}$ invariant mass distribution outside the signal region.

The $\ell\nu q\bar{q}$ analysis channel is described in detail in Ref. [22]. In the $\ell\nu q\bar{q}$ channel exactly one lepton with $p_T > 25$ GeV and matched to a lepton reconstructed by the trigger is required. The missing transverse momentum in the event is required to be $E_T^{\text{miss}} > 30$ GeV. Similar to the $\ell\ell q\bar{q}$ channel the event selection contains three different mass regions of the signal, referred to as *merged*, *high- p_T resolved* and *low- p_T resolved* regions. In the merged region where the hadronic decay products merge into a single jet, a groomed large- R jet with $p_T > 400$ GeV and $65 \text{ GeV} < m_J < 105 \text{ GeV}$ is required. The leptonically decaying W candidate is reconstructed using the same W mass constraint technique used in the $\ell\nu\ell'\ell'$ channel. The leptonically decaying $W \rightarrow \ell\nu$ must have $p_T(\ell\nu) > 400$ GeV, where $p_T(\ell\nu)$ is reconstructed from the sum of the charged-lepton momentum vector and the E_T^{miss} vector. To suppress the background from top-quark production, events with an identified b -jet separated by $\Delta R > 0.8$ from the large- R jet are rejected. Additionally, in the electron channel the leading large- R jet and E_T^{miss} are required to be separated by $\Delta\phi(E_T^{\text{miss}}, J) > 1$ to reject multi-jet background. If the event does not satisfy the criteria of the merged region, the resolved region selection criteria are applied. In the high- p_T resolved region, two small- R jets with $p_T > 80$ GeV are required to form the hadronically decaying W/Z candidate with a transverse momentum of $p_T(jj) > 300$ GeV and an invariant mass of $65 \text{ GeV} < m_{jj} < 105 \text{ GeV}$. The leptonically decaying $W \rightarrow \ell\nu$ must have $p_T(\ell\nu) > 300$ GeV. The event is rejected if a b -jet is identified in addition to the two leading jets. In the electron channel the leading small- R jet and E_T^{miss} are required to be separated by $\Delta\phi(E_T^{\text{miss}}, j) > 1$. If the event does not pass the selection requirements of the high- p_T resolved region the selection of the low- p_T resolved region is used, where $p_T(jj) > 100$ GeV and $p_T(\ell\nu) > 100$ GeV are applied. The dominant background in the $\ell\nu q\bar{q}$ channel is W/Z + jets production, followed by top quark production, and multijet and diboson processes. The shape of the invariant mass distribution for the W/Z + jets background is modelled by simulation, while the normalisation is determined from data in a control region, defined as the side-bands of the $q\bar{q}$ invariant mass distribution outside the signal region. The $p_T(W)$ distribution of the W + jets simulation is corrected using data to

improve the modelling. The sub-dominant background processes are estimated using simulation only (diboson), or simulation and data-driven techniques (multijet, top quark).

The JJ analysis channel is described in detail in Ref. [23]. For the combined G^* search the analysis is extended, combining the WW and ZZ selections into a single inclusive analysis of both decay modes. The analysis of the fully hadronic decay mode selects events that pass a large- R jet trigger⁴ with a nominal threshold of 360 GeV in transverse momentum and have at least two large- R jets within $|\eta| < 2.0$, a rapidity difference between the two jets of $|\Delta y_{12}| < 1.2$, and an invariant mass of the two jets of $m(JJ) > 1.05 \text{ TeV}$. Events that contain one or more leptons with $p_T > 20$ GeV or missing transverse momentum in excess of 350 GeV are vetoed. The large- R jets must satisfy the boson-tagging criteria described in Section 4. Furthermore, the dijet p_T asymmetry defined as $A = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$ must be less than 0.15 to avoid mis-measured jets. In the search for the EGM W' decaying to WZ , events are selected by requiring one W boson candidate and one Z boson candidate in each event by applying the selections described in Section 4. In the search for the bulk G^* decaying to WW and ZZ , events are selected by requiring two W boson or two Z boson candidates by applying the selections described in Section 4. Due to the overlapping jet mass windows applied to select W and Z candidates, the selection for the EGM W' and the bulk G^* are not exclusive and about 20% of the inclusive event sample is shared. In the fully hadronic channel the dominant background is dijet production. The dijet background is estimated by a parametric fit with a smoothly falling function to the observed dijet mass spectrum in the data. Only diboson resonances with mass values $> 1.3 \text{ TeV}$ are considered as signal for this analysis channel.

The selections described above have a combined acceptance times efficiency of up to 17% for $G^* \rightarrow WW$, up to 11% for $G^* \rightarrow ZZ$, and up to 17% for $W' \rightarrow WZ$. The acceptance times efficiency includes the W and Z branching ratios. Figs. 1(a) and 1(b) summarise the acceptance times efficiency for the different analyses as a function of the W' mass and of the G^* mass, considering only decays of the resonance into VV , where V denotes a W or a Z boson.

6. Statistical procedure

The combination of the individual channels proceeds with a simultaneous analysis of the invariant mass distributions of the diboson candidates in the different channels. For each hypothesis being tested, only the channels sensitive to that hypothesis are included in the combination. The signal strength, μ , defined as a scale factor on the cross section times branching ratio predicted by the signal hypothesis, is the parameter of interest. The analysis follows the Frequentist approach with a test statistic based on the profile-likelihood ratio [72]. The test statistic extracts information on the signal strength from a binned maximum-likelihood fit of the signal-plus-background model to the data. The effect of a systematic uncertainty k on the likelihood is modelled with a nuisance parameter, θ_k , constrained with a corresponding probability density function $f_k(\theta_k)$, as explained in the publications corresponding to the individual channels [19,21–23]. In this manner, correlated effects across the different channels are modelled by the use of a common nuisance parameter and its corresponding probability density function. The likelihood model, $\mathcal{L}$, is given by:

$$\mathcal{L} = \prod_c \prod_i \text{Pois} \left(n_{ic}^{\text{obs}} \middle| n_{ic}^{\text{sig}}(\mu, \theta_k) + n_{ic}^{\text{bkg}}(\theta_k) \right) \prod_k f_k(\theta_k) \quad (1)$$

⁴ The trigger uses anti- k_t jets with $R = 1.0$.

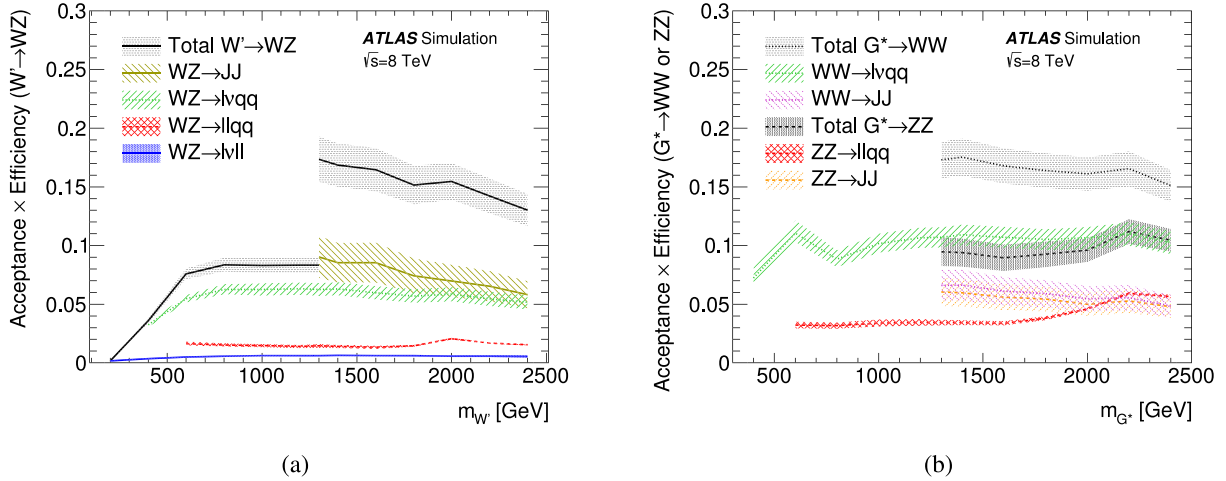


Fig. 1. Signal acceptance times efficiency for the different analyses entering the combination for (a) the EGM W' model and (b) the bulk G^* model. The branching ratio of the new resonance to dibosons is included in the denominator. The error bands represent the combined statistical and systematic uncertainties.

where the index c represents the analysis channel, and i represents the bin in the invariant mass distribution, n^{obs} , the observed number of events, n^{sig} the number of expected signal events, and n^{bkg} the expected number of background events.

The compatibility between the observations of different channels with a common signal strength of a particular resonance model and mass is quantified using a profile-likelihood-ratio test. The corresponding profile-likelihood ratio is

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(\hat{\mu}_A, \hat{\mu}_B, \hat{\theta})}, \quad (2)$$

where μ is the common signal strength, $\hat{\mu}_A$ and $\hat{\mu}_B$ are the unconditional maximum likelihood (ML) estimators of the independent signal strengths in the channels being compared, $\hat{\theta}$ are the unconditional ML estimators for the nuisance parameters, and $\hat{\theta}(\mu)$ are the conditional ML estimators of θ for a given value of μ . The compatibility between the observations is tested by the probability of observing $\lambda(\hat{\mu})$, where $\hat{\mu}$ is the ML estimator for the common signal strength for the model in question. If the two channels being compared have a common signal strength, i.e. $\mu = \mu_A = \mu_B$, then in the asymptotic limit $-2 \log(\lambda(\hat{\mu}))$ is expected to be χ^2 distributed with one degree of freedom.

The significance of observed excesses over the background-only prediction is quantified using the local p -value (p_0), defined as the probability of the background-only model to produce a signal-like fluctuation at least as large as observed in the data. Upper limits on μ for W' in the EGM and G^* in the bulk RS model at the simulated resonance masses are evaluated at the 95% CL following the CL_s prescription [73]. Lower mass limits at the 95% CL for new diboson resonances in these models are obtained by finding the maximum resonance mass where the 95% CL upper limit on μ is less or equal to 1. This mass is found by interpolating between the limits on μ at the simulated signal masses. The interpolation assumes monotonic and smooth behaviour of the efficiencies for the signal and background processes, and that the impact of the variation of signal mass distributions between adjacent test masses is negligible.

In the combined analysis to search for W' resonances, all four individual channels are used. For the charge-neutral bulk G^* , only the $\ell\nu q\bar{q}$, $\ell\ell q\bar{q}$, and the JJ channels contribute to the combination, and in the case of the fully hadronic channel, a merged signal region resulting from the union of the WW and ZZ signal regions

Table 5

Channels and signal regions contributing to the combination for the EGM W' and bulk G^* .

Channel	Signal region	W' mass range [TeV]	G^* mass range [TeV]
$\ell\nu\ell'\ell'$	Low-mass	0.2–1.9	–
	High-mass	0.2–2.5	–
$\ell\ell q\bar{q}$	Low- p_T resolved	0.3–0.9	0.2–0.9
	High- p_T resolved	0.6–2.5	0.6–0.9
	Merged	0.9–2.5	0.9–2.5
$\ell\nu q\bar{q}$	Low- p_T resolved	0.3–0.8	0.2–0.7
	High- p_T resolved	0.6–1.1	0.6–0.9
	Merged	0.8–2.5	0.8–2.5
JJ	WZ selection	1.3–2.5	–
	$WW + ZZ$ selection	–	1.3–2.5

is used in the analysis. The background to this merged signal region is estimated using the same technique as for the individual signal regions. Table 5 summarises the channels and signal regions combined in the analysis for the EGM W' and bulk G^* .

7. Systematic uncertainties

The sources of systematic uncertainty along with their effects on the expected signal and background yields for each of the individual channels used in this combination are described in detail in their corresponding publications [19,21–23]. Although the results from the different search channels in this combination are statistically independent, commonalities between the different search channels, such as the objects used, the signal and background simulation, and the integrated luminosity estimation, introduce correlated effects in the signal and background expectations. Whenever an effect due to an uncertainty in the triggering, identification, or reconstruction of leptons is considered for a channel, it is treated as fully correlated with the effects due to this uncertainty in other channels.

In the same manner, the effects of each uncertainty related to the small- R jet energy scale and resolution are treated as fully correlated in all channels using small- R jets or E_T^{miss} . For the search channels using large- R jets, uncertainties in the large- R jet energy scale, energy resolution, mass scale, mass resolution, or in the modelling of the boson-tagging discriminant $\sqrt{y}$ are taken as fully correlated. Uncertainties in the data-driven background estimates are treated as uncorrelated. The effects of uncertainty in the

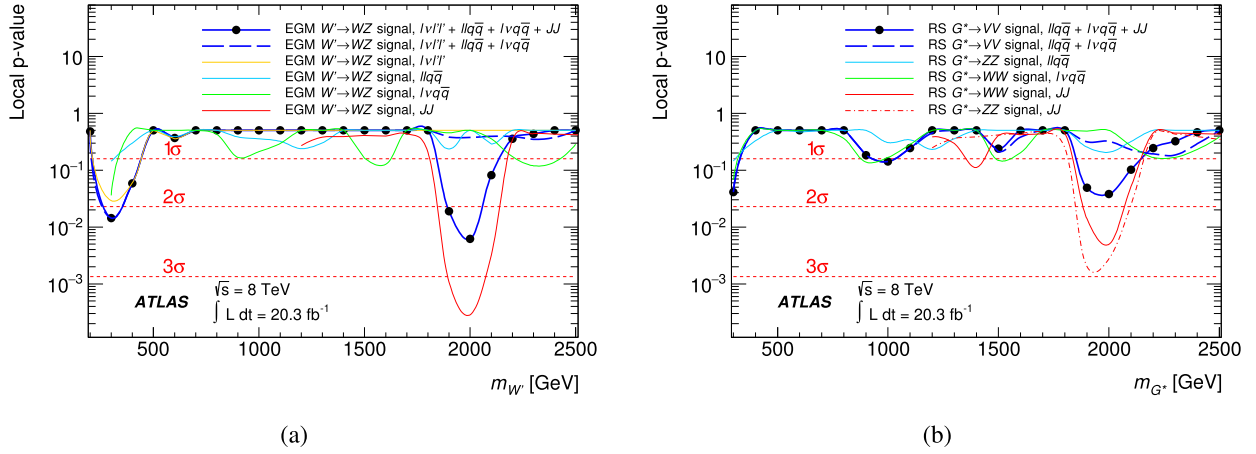


Fig. 2. The p_0 -value for the individual and combined channels for (a) the EGM W' search in the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ channels and (b) the bulk G^* search in the $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ channels.

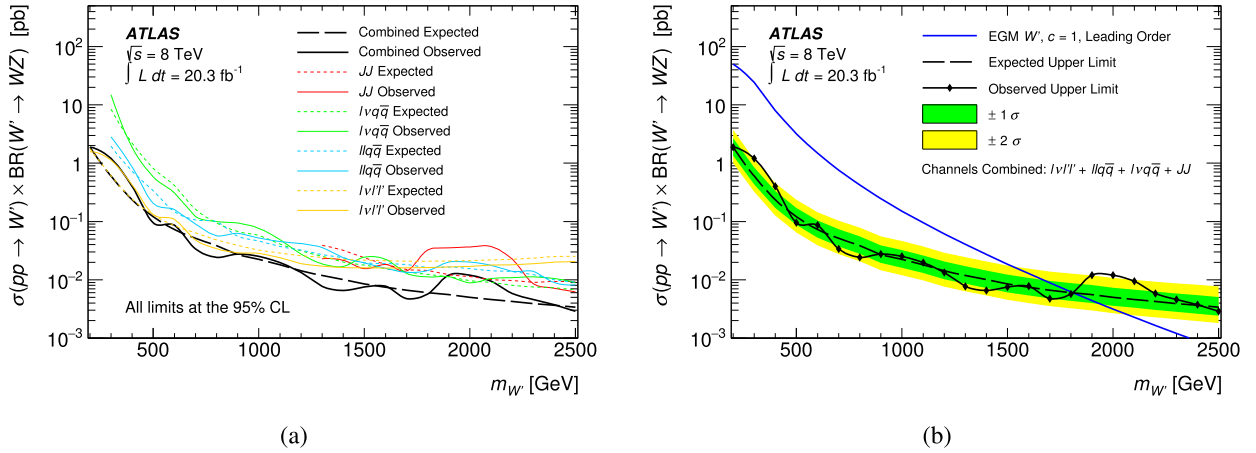


Fig. 3. The 95% CL limits on (a) the EGM W' using the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels and their combination, and (b) the combined 95% CL limit with the green (yellow) bands representing the 1σ (2σ) intervals of the expected limit including statistical and systematic uncertainties. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

initial- and final-state radiation (ISR and FSR) modelling and in the PDFs are each treated as fully correlated across all search channels.

The effect of a single source of systematic uncertainty on the combined limit can be ranked by the loss in sensitivity caused by its inclusion. To quantify the loss of sensitivity at a given mass point the value computed with all systematic uncertainties included is compared to the value obtained excluding the single systematic uncertainty. In the low mass region at $\lesssim 0.5$ TeV the leading uncertainty is the modelling of the SM diboson background in the dominant $\ell\nu\ell'\ell'$ channel with an impact of 35% sensitivity degradation in the combined limit for EGM W' . The leading source of uncertainty in case of the G^* limit is the modelling of the Z + jets background in the $\ell\nu q\bar{q}$ channel with a degradation of 25%. In the intermediate mass region up to $\lesssim 1.5$ TeV the uncertainty on the normalisation of the W + jets background in the $\ell\nu q\bar{q}$ channel is dominating with 20% to 30% degradation of the EGM W' limit and 25% to 55% degradation of the G^* limit depending on the mass point, while in the high mass region up to 2 TeV the shape uncertainty on the W + jets background dominates with a degradation of around 25% for the EGM W' limit and 35% for the G^* limit.

8. Results

Fig. 2 shows the p_0 -value obtained in the search for the EGM W' and G^* as a function of the resonance mass for the $\ell\nu\ell'\ell'$,

$\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ channels combined and for the individual channels. For the full combination the largest deviation from the background-only expectation is found in the EGM W' search at around 2.0 TeV with a p_0 -value corresponding to 2.5 standard deviations (σ). This is smaller than the p_0 -value of 3.4σ observed in the JJ channel alone because the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, and $\ell\nu q\bar{q}$ channels are more consistent with the background-only hypothesis.

The compatibility of the individual channels is quantified with the test described in Section 6. In the mass region around 2 TeV the JJ channel presents an excess while the other channels are in good agreement with the background-only expectation. For the EGM W' benchmark the compatibility of the combined $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, and $\ell\nu q\bar{q}$ channels with the JJ channel is at the level of 2.9σ . When accounting for the probability for any of the four channels to fluctuate the compatibility is found to be at the level of 2.6σ . In comparison the corresponding test for the bulk G^* interpretation shows better compatibility.

Fig. 3 shows the combined upper limit on the EGM W' production cross section times its branching ratio to WZ at the 95% CL in the mass range from 300 GeV to 2.5 TeV. In Fig. 3(a) the observed and expected limits of the individual and combined channels are shown. In Fig. 3(b) the observed and expected combined limits are compared with the theoretical EGM W' prediction. The resulting combined lower limit on the EGM W' mass using a LO cross-section calculation is observed to be 1.81 TeV, with an expected

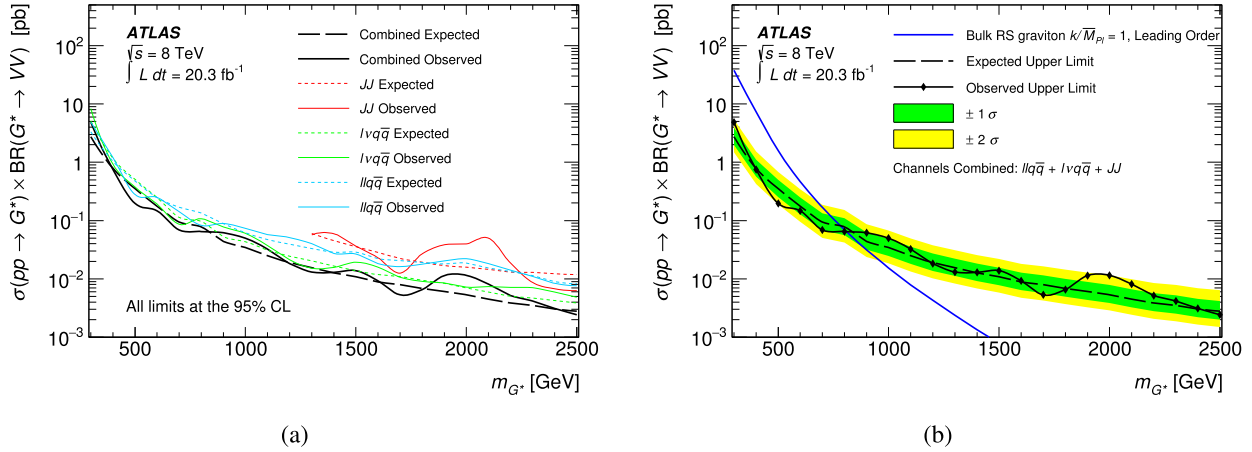


Fig. 4. The 95% CL limits on (a) the bulk G^* using the $llqq$, $lvqq$, and JJ channels and their combination, and (b) the combined 95% CL limit with the green (yellow) bands representing the 1σ (2σ) intervals of the expected limit including statistical and systematic uncertainties. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

limit of 1.81 TeV. The most stringent observed mass limit from an individual channel is 1.59 TeV at NNLO in the $lvqq$ analysis.

In Fig. 4 the observed and expected upper limits at the 95% CL on the bulk G^* production cross section times its branching ratio to WW and ZZ are shown in the mass range from 200 GeV to 2.5 TeV. In Fig. 4(b) the observed and expected limits of the individual and combined channels are shown and compared with the theoretical bulk G^* prediction for $k/\bar{M}_{Pl} = 1$. The combined, lower mass limit for the bulk G^* , assuming $k/\bar{M}_{Pl} = 1$, is 810 GeV, with an expected limit of 790 GeV. The most stringent lower mass limit from the individual $llqq$, $lvqq$ and JJ channels is 760 GeV from the $lvqq$ channel.

9. Conclusion

A combination of individual searches in all-leptonic, semileptonic, and all-hadronic final states to search for new heavy bosons decaying to WW , WZ and ZZ is presented. The searches use 20.3 fb^{-1} of 8 TeV pp collision data collected by the ATLAS detector at the LHC. Within the combined result, no significant excess over the background-only expectation in the invariant mass distribution of the diboson candidates is observed. Upper limits on the production cross section times branching ratio to dibosons at the 95% CL are evaluated within the context of an extended gauge model with a heavy W' boson and a bulk Randall–Sundrum model with a heavy spin-2 graviton. The combination significantly improves both the cross-section limits and the mass limits for EGM W' and bulk G^* production over the most stringent limits of the individual analyses. The observed lower limit on the EGM W' mass is found to be 1.81 TeV and for the bulk G^* mass, assuming $k/\bar{M}_{Pl} = 1$, the observed limit is 810 GeV.

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G. Aad⁸⁵, B. Abbott¹¹³, J. Abdallah¹⁵¹, O. Abdinov¹¹, R. Aben¹⁰⁷, M. Abolins⁹⁰, O.S. AbouZeid¹⁵⁸, H. Abramowicz¹⁵³, H. Abreu¹⁵², R. Abreu¹¹⁶, Y. Abulaiti^{146a,146b}, B.S. Acharya^{164a,164b,a}, L. Adamczyk^{38a}, D.L. Adams²⁵, J. Adelman¹⁰⁸, S. Adomeit¹⁰⁰, T. Adye¹³¹, A.A. Affolder⁷⁴, T. Agatonovic-Jovin¹³, J. Agricola⁵⁴, J.A. Aguilar-Saavedra^{126a,126f}, S.P. Ahlen²², F. Ahmadov^{65,b}, G. Aielli^{133a,133b}, H. Akerstedt^{146a,146b}, T.P.A. Åkesson⁸¹, A.V. Akimov⁹⁶, G.L. Alberghi^{20a,20b}, J. Albert¹⁶⁹, S. Albrand⁵⁵, M.J. Alconada Verzini⁷¹, M. Aleksa³⁰, I.N. Aleksandrov⁶⁵, C. Alexa^{26b}, G. Alexander¹⁵³, T. Alexopoulos¹⁰, M. Alhroob¹¹³, G. Alimonti^{91a}, L. Alio⁸⁵, J. Alison³¹, S.P. Alkire³⁵, B.M.M. Allbrooke¹⁴⁹, P.P. Allport¹⁸, A. Aloisio^{104a,104b}, A. Alonso³⁶, F. Alonso⁷¹, C. Alpigiani¹³⁸, A. Althamer³⁵, B. Alvarez Gonzalez³⁰, D. Álvarez Piqueras¹⁶⁷, M.G. Alviggi^{104a,104b}, B.T. Amadio¹⁵, K. Amako⁶⁶, Y. Amaral Coutinho^{24a}, C. Amelung²³, D. Amidei⁸⁹, S.P. Amor Dos Santos^{126a,126c}, A. Amorim^{126a,126b}, S. Amoroso⁴⁸, N. Amram¹⁵³, G. Amundsen²³, C. Anastopoulos¹³⁹, L.S. Ancu⁴⁹, N. Andari¹⁰⁸, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders³⁰, J.K. Anders⁷⁴, K.J. Anderson³¹, A. Andreazza^{91a,91b}, V. Andrei^{58a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁷, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A.V. Anisenkov^{109,c}, N. Anjos¹², A. Annovi^{124a,124b}, M. Antonelli⁴⁷, A. Antonov⁹⁸, J. Antos^{144b}, F. Anulli^{132a}, M. Aoki⁶⁶, L. Aperio Bella¹⁸, G. Arabidze⁹⁰, Y. Arai⁶⁶, J.P. Araque^{126a}, A.T.H. Arce⁴⁵, F.A. Arduh⁷¹, J.-F. Arguin⁹⁵, S. Argyropoulos⁶³, M. Arik^{19a}, A.J. Armbruster³⁰, O. Arnaez³⁰, H. Arnold⁴⁸, M. Arratia²⁸, O. Arslan²¹, A. Artamonov⁹⁷, G. Artoni²³, S. Artz⁸³, S. Asai¹⁵⁵, N. Asbah⁴², A. Ashkenazi¹⁵³, B. Åsman^{146a,146b}, L. Asquith¹⁴⁹, K. Assamagan²⁵, R. Astalos^{144a}, M. Atkinson¹⁶⁵, N.B. Atlay¹⁴¹, K. Augsten¹²⁸, M. Auresseau^{145b}, G. Avolio³⁰, B. Axen¹⁵, M.K. Ayoub¹¹⁷, G. Azuelos^{95,d}, M.A. Baak³⁰, A.E. Baas^{58a}, M.J. Baca¹⁸, C. Bacci^{134a,134b}, H. Bachacou¹³⁶, K. Bachas¹⁵⁴, M. Backes³⁰, M. Backhaus³⁰, P. Bagiacchi^{132a,132b}, P. Bagnaia^{132a,132b}, Y. Bai^{33a}, T. Bain³⁵, J.T. Baines¹³¹, O.K. Baker¹⁷⁶, E.M. Baldin^{109,c}, P. Balek¹²⁹, T. Balestri¹⁴⁸, F. Balli⁸⁴, W.K. Balunas¹²², E. Banas³⁹, Sw. Banerjee^{173,e}, A.A.E. Bannoura¹⁷⁵, L. Barak³⁰, E.L. Barberio⁸⁸, D. Barberis^{50a,50b}, M. Barbero⁸⁵, T. Barillari¹⁰¹, M. Barisonzi^{164a,164b}, T. Barklow¹⁴³, N. Barlow²⁸, S.L. Barnes⁸⁴, B.M. Barnett¹³¹, R.M. Barnett¹⁵, Z. Barnovska⁵, A. Baroncelli^{134a}, G. Barone²³, A.J. Barr¹²⁰, F. Barreiro⁸², J. Barreiro Guimarães da Costa^{33a}, R. Bartoldus¹⁴³, A.E. Barton⁷², P. Bartos^{144a}, A. Basalae¹²³, A. Bassalat¹¹⁷, A. Basye¹⁶⁵, R.L. Bates⁵³, S.J. Batista¹⁵⁸, J.R. Batley²⁸, M. Battaglia¹³⁷, M. Bauce^{132a,132b}, F. Bauer¹³⁶, H.S. Bawa^{143,f}, J.B. Beacham¹¹¹, M.D. Beattie⁷², T. Beau⁸⁰, P.H. Beauchemin¹⁶¹, R. Beccherle^{124a,124b}, P. Bechtel²¹, H.P. Beck^{17,g}, K. Becker¹²⁰, M. Becker⁸³, M. Beckingham¹⁷⁰, C. Becot¹¹⁷, A.J. Beddall^{19b}, A. Beddall^{19b}, V.A. Bednyakov⁶⁵, C.P. Bee¹⁴⁸, L.J. Beemster¹⁰⁷, T.A. Beermann³⁰, M. Begel²⁵, J.K. Behr¹²⁰, C. Belanger-Champagne⁸⁷, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{20a}, A. Bellerive²⁹, M. Bellomo⁸⁶, K. Belotskiy⁹⁸, O. Beltramello³⁰, O. Benary¹⁵³, D. Bencheikroun^{135a}, M. Bender¹⁰⁰, K. Bendtz^{146a,146b}, N. Benekos¹⁰, Y. Benhammou¹⁵³, E. Benhar Noccioli⁴⁹, J.A. Benitez Garcia^{159b}, D.P. Benjamin⁴⁵, J.R. Bensinger²³, S. Bentvelsen¹⁰⁷, L. Beresford¹²⁰, M. Beretta⁴⁷, D. Berge¹⁰⁷, E. Bergeas Kuutmann¹⁶⁶, N. Berger⁵, F. Berghaus¹⁶⁹, J. Beringer¹⁵, C. Bernard²², N.R. Bernard⁸⁶, C. Bernius¹¹⁰, F.U. Bernlochner²¹, T. Berry⁷⁷, P. Berta¹²⁹, C. Bertella⁸³, G. Bertoli^{146a,146b}, F. Bertolucci^{124a,124b}, C. Bertsche¹¹³, D. Bertsche¹¹³, M.I. Besana^{91a}, G.J. Besjes³⁶, O. Bessidskaia Bylund^{146a,146b}, M. Bessner⁴², N. Besson¹³⁶, C. Betancourt⁴⁸, S. Bethke¹⁰¹, A.J. Bevan⁷⁶, W. Bhimji¹⁵, R.M. Bianchi¹²⁵, L. Bianchini²³, M. Bianco³⁰, O. Biebel¹⁰⁰, D. Biedermann¹⁶, N.V. Biesuz^{124a,124b}, M. Biglietti^{134a}, J. Bilbao De Mendizabal⁴⁹, H. Bilokon⁴⁷, M. Bindi⁵⁴, S. Binet¹¹⁷, A. Bingul^{19b}, C. Bini^{132a,132b}, S. Biondi^{20a,20b}, D.M. Bjergaard⁴⁵, C.W. Black¹⁵⁰, J.E. Black¹⁴³, K.M. Black²², D. Blackburn¹³⁸, R.E. Blair⁶, J.-B. Blanchard¹³⁶, J.E. Blanco⁷⁷, T. Blazek^{144a}, I. Bloch⁴², C. Blocker²³, W. Blum^{83,*}, U. Blumenschein⁵⁴, S. Blunier^{32a}, G.J. Bobbink¹⁰⁷, V.S. Bobrovnikov^{109,c}, S.S. Bocchetta⁸¹, A. Bocci⁴⁵, C. Bock¹⁰⁰, M. Boehler⁴⁸, J.A. Bogaerts³⁰, D. Bogavac¹³, A.G. Bogdanchikov¹⁰⁹, C. Bohm^{146a}, V. Boisvert⁷⁷, T. Bold^{38a}, V. Boldea^{26b}, A.S. Boldyrev⁹⁹, M. Bomben⁸⁰, M. Bona⁷⁶, M. Boonekamp¹³⁶, A. Borisov¹³⁰, G. Borissov⁷², S. Borroni⁴², J. Bortfeldt¹⁰⁰, V. Bortolotto^{60a,60b,60c}, K. Bos¹⁰⁷, D. Boscherini^{20a}, M. Bosman¹², J. Boudreau¹²⁵, J. Bouffard²,

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Butt³, C.M. Buttar⁵³, J.M. Butterworth⁷⁸, P. Butti¹⁰⁷, W. Buttinger²⁵, A. Buzatu⁵³, A.R. Buzykaev^{109,c}, S. Cabrera Urbán¹⁶⁷, D. Caforio¹²⁸, V.M. Cairo^{37a,37b}, O. Cakir^{4a}, N. Calace⁴⁹, P. Calafiura¹⁵, A. Calandri¹³⁶, G. Calderini⁸⁰, P. Calfayan¹⁰⁰, L.P. Caloba^{24a}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro³¹, S. Camarda⁴², P. Camarri^{133a,133b}, D. Cameron¹¹⁹, R. Caminal Armadans¹⁶⁵, S. Campana³⁰, M. Campanelli⁷⁸, A. Campoverde¹⁴⁸, V. Canale^{104a,104b}, A. Canepa^{159a}, M. Cano Bret^{33e}, J. Cantero⁸², R. Cantrill^{126a}, T. Cao⁴⁰, M.D.M. Capeans Garrido³⁰, I. Caprini^{26b}, M. Caprini^{26b}, M. Capua^{37a,37b}, R. Caputo⁸³, R.M. Carbone³⁵, R. Cardarelli^{133a}, F. Cardillo⁴⁸, T. Carli³⁰, G. Carlino^{104a}, L. Carminati^{91a,91b}, S. Caron¹⁰⁶, E. Carquin^{32a}, G.D. Carrillo-Montoya³⁰, J.R. Carter²⁸, J. Carvalho^{126a,126c}, D. Casadei⁷⁸, M.P. Casado¹², M. Casolino¹², D.W. Casper¹⁶³, E. Castaneda-Miranda^{145a}, A. Castelli¹⁰⁷, V. Castillo Gimenez¹⁶⁷, N.F. Castro^{126a,h}, P. Catastini⁵⁷, A. Catinaccio³⁰, J.R. Catmore¹¹⁹, A. Cattai³⁰, J. Caudron⁸³, V. Cavaliere¹⁶⁵, D. Cavalli^{91a}, M. Cavalli-Sforza¹², V. Cavasinni^{124a,124b}, F. Ceradini^{134a,134b}, L. Cerda Alberich¹⁶⁷, B.C. Cerio⁴⁵, K. Cerny¹²⁹, A.S. Cerqueira^{24b}, A. Cerri¹⁴⁹, L. Cerrito⁷⁶, F. Cerutti¹⁵, M. Cerv³⁰, A. Cervelli¹⁷, S.A. Cetin^{19c}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁸, I. Chalupkova¹²⁹, Y.L. Chan^{60a}, P. Chang¹⁶⁵, J.D. Chapman²⁸, D.G. Charlton¹⁸, C.C. Chau¹⁵⁸, C.A. Chavez Barajas¹⁴⁹, S. Cheatham¹⁵², A. Chegwidan⁹⁰, S. Chekanov⁶, S.V. Chekulaev^{159a}, G.A. Chelkov^{65,i}, M.A. Chelstowska⁸⁹, C. Chen⁶⁴, H. Chen²⁵, K. Chen¹⁴⁸, L. Chen^{33d,j}, S. Chen^{33c}, S. Chen¹⁵⁵, X. Chen^{33f}, Y. Chen⁶⁷, H.C. Cheng⁸⁹, Y. Cheng³¹, A. Cheplakov⁶⁵, E. Cheremushkina¹³⁰, R. Cherkaoui El Moursli^{135e}, V. Chernyatin^{25,*}, E. Cheu⁷, L. Chevalier¹³⁶, V. Chiarella⁴⁷, G. Chiarelli^{124a,124b}, G. Chiodini^{73a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁸, A. Chitan^{26b}, M.V. Chizhov⁶⁵, K. Choi⁶¹, S. Chouridou⁹, B.K.B. Chow¹⁰⁰, V. Christodoulou⁷⁸, D. Chromek-Burckhart³⁰, J. Chudoba¹²⁷, A.J. Chuinard⁸⁷, J.J. Chwastowski³⁹, L. Chytka¹¹⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{4a}, D. Cinca⁵³, V. Cindro⁷⁵, I.A. Cioara²¹, A. Ciocio¹⁵, F. Ciotto^{104a,104b}, Z.H. Citron¹⁷², M. Ciubancan^{26b}, A. Clark⁴⁹, B.L. Clark⁵⁷, P.J. Clark⁴⁶, R.N. Clarke¹⁵, C. Clement^{146a,146b}, Y. Coadou⁸⁵, M. Cobal^{164a,164c}, A. Coccaro⁴⁹, J. Cochran⁶⁴, L. Coffey²³, J.G. Cogan¹⁴³, L. Colasurdo¹⁰⁶, B. Cole³⁵, S. Cole¹⁰⁸, A.P. Colijn¹⁰⁷, J. Collot⁵⁵, T. Colombo^{58c}, G. Compostella¹⁰¹, P. Conde Muiño^{126a,126b}, E. Coniavitis⁴⁸, S.H. Connell^{145b}, I.A. Connolly⁷⁷, V. Consorti⁴⁸, S. Constantinescu^{26b}, C. Conta^{121a,121b}, G. Conti³⁰, F. Conventi^{104a,k}, M. Cooke¹⁵, B.D. Cooper⁷⁸, A.M. Cooper-Sarkar¹²⁰, T. Cornelissen¹⁷⁵, M. Corradi^{132a,132b}, F. Corriveau^{87,l}, A. Corso-Radu¹⁶³, A. Cortes-Gonzalez¹², G. Cortiana¹⁰¹, G. Costa^{91a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, D. Côté⁸, G. Cottin²⁸, G. Cowan⁷⁷, B.E. Cox⁸⁴, K. Cranmer¹¹⁰, G. Cree²⁹, S. Crépe-Renaudin⁵⁵, F. Crescioli⁸⁰, W.A. Cribbs^{146a,146b}, M. Crispin Ortuzar¹²⁰, M. Cristinziani²¹, V. Croft¹⁰⁶, G. Crosetti^{37a,37b}, T. Cuhadar Donszelmann¹³⁹, J. Cummings¹⁷⁶, M. Curatolo⁴⁷, J. Cúth⁸³, C. Cuthbert¹⁵⁰, H. Czirr¹⁴¹, P. Czodrowski³, S. D'Auria⁵³, M. D'Onofrio⁷⁴, M.J. Da Cunha Sargedas De Sousa^{126a,126b}, C. Da Via⁸⁴, W. Dabrowski^{38a}, A. Dafinca¹²⁰, T. Dai⁸⁹, O. Dale¹⁴, F. Dallaire⁹⁵, C. Dallapiccola⁸⁶, M. Dam³⁶, J.R. Dandoy³¹, N.P. Dang⁴⁸, A.C. Daniells¹⁸, M. Danninger¹⁶⁸, M. Dano Hoffmann¹³⁶, V. Dao⁴⁸, G. Darbo^{50a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta⁶¹, W. Davey²¹, C. David¹⁶⁹, T. Davidek¹²⁹, E. Davies^{120,m}, M. Davies¹⁵³, P. Davison⁷⁸, Y. Davygora^{58a}, E. Dawe⁸⁸, I. Dawson¹³⁹, R.K. Daya-Ishmukhametova⁸⁶, K. De⁸, R. de Asmundis^{104a}, A. De Benedetti¹¹³, S. De Castro^{20a,20b}, S. De Cecco⁸⁰, N. De Groot¹⁰⁶, P. de Jong¹⁰⁷, H. De la Torre⁸², F. De Lorenzi⁶⁴, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis¹⁴⁹, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁷, W.J. Dearnaley⁷², R. Debbe²⁵, C. Debenedetti¹³⁷, D.V. Dedovich⁶⁵, I. Deigaard¹⁰⁷, J. Del Peso⁸², T. Del Prete^{124a,124b}, D. Delgove¹¹⁷, F. Deliot¹³⁶, C.M. Delitzsch⁴⁹, M. Deliyergiyev⁷⁵, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Dell'Orso^{124a,124b}, M. Della Pietra^{104a,k},

D. della Volpe⁴⁹, M. Delmastro⁵, P.A. Delsart⁵⁵, C. Deluca¹⁰⁷, D.A. DeMarco¹⁵⁸, S. Demers¹⁷⁶, M. Demichev⁶⁵, A. Demilly⁸⁰, S.P. Denisov¹³⁰, D. Derendarz³⁹, J.E. Derkaoui^{135d}, F. Derue⁸⁰, P. Dervan⁷⁴, K. Desch²¹, C. Deterre⁴², K. Dette⁴³, P.O. Deviveiros³⁰, A. Dewhurst¹³¹, S. Dhaliwal²³, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵, A. Di Domenico^{132a,132b}, C. Di Donato^{132a,132b}, A. Di Girolamo³⁰, B. Di Girolamo³⁰, A. Di Mattia¹⁵², B. Di Micco^{134a,134b}, R. Di Nardo⁴⁷, A. Di Simone⁴⁸, R. Di Sipio¹⁵⁸, D. Di Valentino²⁹, C. Diaconu⁸⁵, M. Diamond¹⁵⁸, F.A. Dias⁴⁶, M.A. Diaz^{32a}, E.B. Diehl⁸⁹, J. Dietrich¹⁶, S. Diglio⁸⁵, A. Dimitrievska¹³, J. Dingfelder²¹, P. Dita^{26b}, S. Dita^{26b}, F. Dittus³⁰, F. Djama⁸⁵, T. Djobava^{51b}, J.I. Djuvsland^{58a}, M.A.B. do Vale^{24c}, D. Dobos³⁰, M. Dobre^{26b}, C. Doglioni⁸¹, T. Dohmae¹⁵⁵, J. Dolejsi¹²⁹, Z. Dolezal¹²⁹, B.A. Dolgoshein^{98,*}, M. Donadelli^{24d}, S. Donati^{124a,124b}, P. Dondero^{121a,121b}, J. Donini³⁴, J. Dopke¹³¹, A. Doria^{104a}, M.T. Dova⁷¹, A.T. Doyle⁵³, E. Drechsler⁵⁴, M. Dris¹⁰, Y. Du^{33d}, E. Dubreuil³⁴, E. Duchovni¹⁷², G. Duckeck¹⁰⁰, O.A. Ducu^{26b,85}, D. Duda¹⁰⁷, A. Dudarev³⁰, L. Dufлот¹¹⁷, L. Duguid⁷⁷, M. Dührssen³⁰, M. Dunford^{58a}, H. Duran Yildiz^{4a}, M. Düren⁵², A. Durglishvili^{51b}, D. Duschinger⁴⁴, B. Dutta⁴², M. Dyndal^{38a}, C. Eckardt⁴², K.M. Ecker¹⁰¹, R.C. Edgar⁸⁹, W. Edson², N.C. Edwards⁴⁶, W. Ehrenfeld²¹, T. Eifert³⁰, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁶, M. El Kacimi^{135c}, M. Ellert¹⁶⁶, S. Elles⁵, F. Ellinghaus¹⁷⁵, A.A. Elliot¹⁶⁹, N. Ellis³⁰, J. Elmsheuser¹⁰⁰, M. Elsing³⁰, D. Emelianov¹³¹, Y. Enari¹⁵⁵, O.C. Endner⁸³, M. Endo¹¹⁸, J. Erdmann⁴³, A. Ereditato¹⁷, G. Ernis¹⁷⁵, J. Ernst², M. Ernst²⁵, S. Errede¹⁶⁵, E. Ertel⁸³, M. Escalier¹¹⁷, H. Esch⁴³, C. Escobar¹²⁵, B. Esposito⁴⁷, A.I. Etiennevre¹³⁶, E. Etzion¹⁵³, H. Evans⁶¹, A. Ezhilov¹²³, L. Fabbri^{20a,20b}, G. Facini³¹, R.M. Fakhruddinov¹³⁰, S. Falciano^{132a}, R.J. Falla⁷⁸, J. Faltova¹²⁹, Y. Fang^{33a}, M. Fanti^{91a,91b}, A. Farbin⁸, A. Farilla^{134a}, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁷⁰, P. Farthouat³⁰, F. Fassi^{135e}, P. Fassnacht³⁰, D. Fassouliotis⁹, M. Faucci Giannelli⁷⁷, A. Favareto^{50a,50b}, L. Fayard¹¹⁷, O.L. Fedin^{123,n}, W. Fedorko¹⁶⁸, S. Feigl³⁰, L. Feligioni⁸⁵, C. Feng^{33d}, E.J. Feng³⁰, H. Feng⁸⁹, A.B. Fenyuk¹³⁰, L. Feremenga⁸, P. Fernandez Martinez¹⁶⁷, S. Fernandez Perez³⁰, J. Ferrando⁵³, A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁷, R. Ferrari^{121a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁹, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³¹, F. Fiedler⁸³, A. Filipčič⁷⁵, M. Filipuzzi⁴², F. Filthaut¹⁰⁶, M. Fincke-Keeler¹⁶⁹, K.D. Finelli¹⁵⁰, M.C.N. Fiolhais^{126a,126c}, L. Fiorini¹⁶⁷, A. Firan⁴⁰, A. Fischer², C. Fischer¹², J. Fischer¹⁷⁵, W.C. Fisher⁹⁰, N. Flaschel⁴², I. Fleck¹⁴¹, P. Fleischmann⁸⁹, G.T. Fletcher¹³⁹, G. Fletcher⁷⁶, R.R.M. Fletcher¹²², T. Flick¹⁷⁵, A. Floderus⁸¹, L.R. Flores Castillo^{60a}, M.J. Flowerdew¹⁰¹, A. Formica¹³⁶, A. Forti⁸⁴, D. Fournier¹¹⁷, H. Fox⁷², S. Fracchia¹², P. Francavilla⁸⁰, M. Franchini^{20a,20b}, D. Francis³⁰, L. Franconi¹¹⁹, M. Franklin⁵⁷, M. Frate¹⁶³, M. Fraternali^{121a,121b}, D. Freeborn⁷⁸, S.T. French²⁸, S.M. Fressard-Batraneanu³⁰, F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost¹²⁰, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa⁸³, B.G. Fulsom¹⁴³, T. Fusayasu¹⁰², J. Fuster¹⁶⁷, C. Gabaldon⁵⁵, O. Gabizon¹⁷⁵, A. Gabrielli^{20a,20b}, A. Gabrielli¹⁵, G.P. Gach¹⁸, S. Gadatsch³⁰, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶¹, C. Galea¹⁰⁶, B. Galhardo^{126a,126c}, E.J. Gallas¹²⁰, B.J. Gallop¹³¹, P. Gallus¹²⁸, G. Galster³⁶, K.K. Gan¹¹¹, J. Gao^{33b,85}, Y. Gao⁴⁶, Y.S. Gao^{143,f}, F.M. Garay Walls⁴⁶, F. Garbersson¹⁷⁶, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷, M. Garcia-Sciveres¹⁵, R.W. Gardner³¹, N. Garelli¹⁴³, V. Garonne¹¹⁹, C. Gatti⁴⁷, A. Gaudiello^{50a,50b}, G. Gaudio^{121a}, B. Gaur¹⁴¹, L. Gauthier⁹⁵, P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁶, C. Gay¹⁶⁸, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gecse¹⁶⁸, C.N.P. Gee¹³¹, Ch. Geich-Gimbel²¹, M.P. Geisler^{58a}, C. Gemme^{50a}, M.H. Genest⁵⁵, C. Geng^{33b,o}, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁷, D. Gerbaudo¹⁶³, A. Gershon¹⁵³, S. Ghasemi¹⁴¹, H. Ghazlane^{135b}, B. Giacobbe^{20a}, S. Giagu^{132a,132b}, V. Giangiobbe¹², P. Giannetti^{124a,124b}, B. Gibbard²⁵, S.M. Gibson⁷⁷, M. Gignac¹⁶⁸, M. Gilchriese¹⁵, T.P.S. Gillam²⁸, D. Gillberg³⁰, G. Gilles³⁴, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{164a,164c}, F.M. Giorgi^{20a}, F.M. Giorgi¹⁶, P.F. Giraud¹³⁶, P. Giromini⁴⁷, D. Giugni^{91a}, C. Giuliani¹⁰¹, M. Giulini^{58b}, B.K. Gjelsten¹¹⁹, S. Gkaitatzis¹⁵⁴, I. Gkialas¹⁵⁴, E.L. Gkoukousis¹¹⁷, L.K. Gladilin⁹⁹, C. Glasman⁸², J. Glatzer³⁰, P.C.F. Glaysher⁴⁶, A. Glazov⁴², M. Goblirsch-Kolb¹⁰¹, J.R. Goddard⁷⁶, J. Godlewski³⁹, S. Goldfarb⁸⁹, T. Golling⁴⁹, D. Golubkov¹³⁰, A. Gomes^{126a,126b,126d}, R. Gonçalo^{126a}, J. Goncalves Pinto Firmino Da Costa¹³⁶, L. Gonella²¹, S. González de la Hoz¹⁶⁷, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁴⁹, L. Goossens³⁰, P.A. Gorbounov⁹⁷, H.A. Gordon²⁵, I. Gorelov¹⁰⁵, B. Gorini³⁰, E. Gorini^{73a,73b}, A. Gorišek⁷⁵, E. Gornicki³⁹, A.T. Goshaw⁴⁵, C. Gössling⁴³, M.I. Gostkin⁶⁵, D. Goujdami^{135c}, A.G. Goussiou¹³⁸, N. Govender^{145b}, E. Gozani¹⁵², H.M.X. Grabas¹³⁷, L. Graber⁵⁴, I. Grabowska-Bold^{38a}, P.O.J. Gradin¹⁶⁶, P. Grafström^{20a,20b}, J. Gramling⁴⁹, E. Gramstad¹¹⁹, S. Grancagnolo¹⁶, V. Gratchev¹²³, H.M. Gray³⁰, E. Graziani^{134a}, Z.D. Greenwood^{79,p}, C. Grefe²¹,

K. Gregersen⁷⁸, I.M. Gregor⁴², P. Grenier¹⁴³, J. Griffiths⁸, A.A. Grillo¹³⁷, K. Grimm⁷², S. Grinstein^{12,q}, Ph. Gris³⁴, J.-F. Grivaz¹¹⁷, S. Groh⁸³, J.P. Grohs⁴⁴, A. Grohsjean⁴², E. Gross¹⁷², J. Grosse-Knetter⁵⁴, G.C. Grossi⁷⁹, Z.J. Grout¹⁴⁹, L. Guan⁸⁹, J. Guenther¹²⁸, F. Guescini⁴⁹, D. Guest¹⁶³, O. Gueta¹⁵³, E. Guido^{50a,50b}, T. Guillemain¹¹⁷, S. Guindon², U. Gul⁵³, C. Gumpert³⁰, J. Guo^{33e}, Y. Guo^{33b,o}, S. Gupta¹²⁰, G. Gustavino^{132a,132b}, P. Gutierrez¹¹³, N.G. Gutierrez Ortiz⁷⁸, C. Gutsche⁴⁴, C. Guyot¹³⁶, C. Gwenlan¹²⁰, C.B. Gwilliam⁷⁴, A. Haas¹¹⁰, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{135e}, P. Haefner²¹, S. Hageböck²¹, Z. Hajduk³⁹, H. Hakobyan¹⁷⁷, M. Haleem⁴², J. Haley¹¹⁴, D. Hall¹²⁰, G. Halladjian⁹⁰, G.D. Hallowell⁸⁵, K. Hamacher¹⁷⁵, P. Hamal¹¹⁵, K. Hamano¹⁶⁹, A. Hamilton^{145a}, G.N. Hamity¹³⁹, P.G. Hamnett⁴², L. Han^{33b}, K. Hanagaki^{66,r}, K. Hanawa¹⁵⁵, M. Hance¹³⁷, B. Haney¹²², P. Hanke^{58a}, R. Hanna¹³⁶, J.B. Hansen³⁶, J.D. Hansen³⁶, M.C. Hansen²¹, P.H. Hansen³⁶, K. Hara¹⁶⁰, A.S. Hard¹⁷³, T. Harenberg¹⁷⁵, F. Hariri¹¹⁷, S. Harkusha⁹², R.D. Harrington⁴⁶, P.F. Harrison¹⁷⁰, F. Hartjes¹⁰⁷, M. Hasegawa⁶⁷, Y. Hasegawa¹⁴⁰, A. Hasib¹¹³, S. Hassani¹³⁶, S. Haug¹⁷, R. Hauser⁹⁰, L. Hauswald⁴⁴, M. Havranek¹²⁷, C.M. Hawkes¹⁸, R.J. Hawking³⁰, A.D. Hawkins⁸¹, T. Hayashi¹⁶⁰, D. Hayden⁹⁰, C.P. Hays¹²⁰, J.M. Hays⁷⁶, H.S. Hayward⁷⁴, S.J. Haywood¹³¹, S.J. Head¹⁸, T. Heck⁸³, V. Hedberg⁸¹, L. Heelan⁸, S. Heim¹²², T. Heim¹⁷⁵, B. Heinemann¹⁵, L. Heinrich¹¹⁰, J. Hejbal¹²⁷, L. Helary²², S. Hellman^{146a,146b}, C. Helsens³⁰, J. Henderson¹²⁰, R.C.W. Henderson⁷², Y. Heng¹⁷³, C. Hengler⁴², S. Henkelmann¹⁶⁸, A. Henrichs¹⁷⁶, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁷, G.H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁷, G. Herten⁴⁸, R. Hertenberger¹⁰⁰, L. Hervas³⁰, G.G. Hesketh⁷⁸, N.P. Hessey¹⁰⁷, J.W. Hetherly⁴⁰, R. Hickling⁷⁶, E. Higón-Rodríguez¹⁶⁷, E. Hill¹⁶⁹, J.C. Hill²⁸, K.H. Hiller⁴², S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²², R.R. Hinman¹⁵, M. Hirose¹⁵⁷, D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁸, N. Hod¹⁰⁷, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker³⁰, M.R. Hoferkamp¹⁰⁵, F. Hoenig¹⁰⁰, M. Hohlfield⁸³, D. Hohn²¹, T.R. Holmes¹⁵, M. Homann⁴³, T.M. Hong¹²⁵, W.H. Hopkins¹¹⁶, Y. Horii¹⁰³, A.J. Horton¹⁴², J.-Y. Hostachy⁵⁵, S. Hou¹⁵¹, A. Hoummada^{135a}, J. Howard¹²⁰, J. Howarth⁴², M. Hrabovsky¹¹⁵, I. Hristova¹⁶, J. Hrivnac¹¹⁷, T. Hryn'ova⁵, A. Hrynevich⁹³, C. Hsu^{145c}, P.J. Hsu^{151,s}, S.-C. Hsu¹³⁸, D. Hu³⁵, Q. Hu^{33b}, X. Hu⁸⁹, Y. Huang⁴², Z. Hubacek¹²⁸, F. Hubaut⁸⁵, F. Huegging²¹, T.B. Huffman¹²⁰, E.W. Hughes³⁵, G. Hughes⁷², M. Huhtinen³⁰, T.A. Hülsing⁸³, N. Huseynov^{65,b}, J. Huston⁹⁰, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis²⁵, I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁷, E. Ideal¹⁷⁶, Z. Idrissi^{135e}, P. Iengo³⁰, O. Igonkina¹⁰⁷, T. Iizawa¹⁷¹, Y. Ikegami⁶⁶, K. Ikematsu¹⁴¹, M. Ikeno⁶⁶, Y. Ilchenko^{31,t}, D. Iliadis¹⁵⁴, N. Ilic¹⁴³, T. Ince¹⁰¹, G. Introzzi^{121a,121b}, P. Ioannou⁹, M. Iodice^{134a}, K. Iordanidou³⁵, V. Ippolito⁵⁷, A. Irles Quiles¹⁶⁷, C. Isaksson¹⁶⁶, M. Ishino⁶⁸, M. Ishitsuka¹⁵⁷, R. Ishmukhametov¹¹¹, C. Issever¹²⁰, S. Istin^{19a}, J.M. Iturbe Ponce⁸⁴, R. Iuppa^{133a,133b}, J. Ivarsson⁸¹, W. Iwanski³⁹, H. Iwasaki⁶⁶, J.M. Izen⁴¹, V. Izzo^{104a}, S. Jabbar³, B. Jackson¹²², M. Jackson⁷⁴, P. Jackson¹, M.R. Jaekel³⁰, V. Jain², K.B. Jakobi⁸³, K. Jakobs⁴⁸, S. Jakobsen³⁰, T. Jakoubek¹²⁷, J. Jakubek¹²⁸, D.O. Jamin¹¹⁴, D.K. Jana⁷⁹, E. Jansen⁷⁸, R. Jansky⁶², J. Janssen²¹, M. Janus⁵⁴, G. Jarlskog⁸¹, N. Javadov^{65,b}, T. Javůrek⁴⁸, L. Jeanty¹⁵, J. Jejelava^{51a,u}, G.-Y. Jeng¹⁵⁰, D. Jennens⁸⁸, P. Jenni^{48,v}, J. Jentzsch⁴³, C. Jeske¹⁷⁰, S. Jézéquel⁵, H. Ji¹⁷³, J. Jia¹⁴⁸, Y. Jiang^{33b}, S. Jiggins⁷⁸, J. Jimenez Pena¹⁶⁷, S. Jin^{33a}, A. Jinaru^{26b}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁶, P. Johansson¹³⁹, K.A. Johns⁷, W.J. Johnson¹³⁸, K. Jon-And^{146a,146b}, G. Jones¹⁷⁰, R.W.L. Jones⁷², T.J. Jones⁷⁴, J. Jongmanns^{58a}, P.M. Jorge^{126a,126b}, K.D. Joshi⁸⁴, J. Jovicevic^{159a}, X. Ju¹⁷³, A. Juste Rozas^{12,q}, M. Kaci¹⁶⁷, A. Kaczmarska³⁹, M. Kado¹¹⁷, H. Kagan¹¹¹, M. Kagan¹⁴³, S.J. Kahn⁸⁵, E. Kajomovitz⁴⁵, C.W. Kalderon¹²⁰, A. Kaluza⁸³, S. Kama⁴⁰, A. Kamenshchikov¹³⁰, N. Kanaya¹⁵⁵, S. Kaneti²⁸, V.A. Kantserov⁹⁸, J. Kanzaki⁶⁶, B. Kaplan¹¹⁰, L.S. Kaplan¹⁷³, A. Kapliy³¹, D. Kar^{145c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis^{10,107}, M.J. Kareem⁵⁴, E. Karentzos¹⁰, M. Karnevskiy⁸³, S.N. Karpov⁶⁵, Z.M. Karpova⁶⁵, K. Karthik¹¹⁰, V. Kartvelishvili⁷², A.N. Karyukhin¹³⁰, K. Kasahara¹⁶⁰, L. Kashif¹⁷³, R.D. Kass¹¹¹, A. Kastanas¹⁴, Y. Kataoka¹⁵⁵, C. Kato¹⁵⁵, A. Katre⁴⁹, J. Katzy⁴², K. Kawade¹⁰³, K. Kawagoe⁷⁰, T. Kawamoto¹⁵⁵, G. Kawamura⁵⁴, S. Kazama¹⁵⁵, V.F. Kazanin^{109,c}, R. Keeler¹⁶⁹, R. Kehoe⁴⁰, J.S. Keller⁴², J.J. Kempster⁷⁷, H. Keoshkerian⁸⁴, O. Kepka¹²⁷, B.P. Kerševan⁷⁵, S. Kersten¹⁷⁵, R.A. Keyes⁸⁷, F. Khalil-zada¹¹, H. Khandanyan^{146a,146b}, A. Khanov¹¹⁴, A.G. Kharlamov^{109,c}, T.J. Khoo²⁸, V. Khovanskii⁹⁷, E. Khramov⁶⁵, J. Khubua^{51b,w}, S. Kido⁶⁷, H.Y. Kim⁸, S.H. Kim¹⁶⁰, Y.K. Kim³¹, N. Kimura¹⁵⁴, O.M. Kind¹⁶, B.T. King⁷⁴, M. King¹⁶⁷, S.B. King¹⁶⁸, J. Kirk¹³¹, A.E. Kiryunin¹⁰¹, T. Kishimoto⁶⁷, D. Kisielewska^{38a}, F. Kiss⁴⁸, K. Kiuchi¹⁶⁰, O. Kivernyk¹³⁶, E. Kladiva^{144b}, M.H. Klein³⁵, M. Klein⁷⁴, U. Klein⁷⁴, K. Kleinknecht⁸³, P. Klimek^{146a,146b}, A. Klimontov²⁵, R. Klingenberg⁴³, J.A. Klinger¹³⁹, T. Klioutchnikova³⁰, E.-E. Kluge^{58a}, P. Kluit¹⁰⁷, S. Kluth¹⁰¹, J. Knapik³⁹, E. Kneringer⁶²,

E.B.F.G. Knoops⁸⁵, A. Knue⁵³, A. Kobayashi¹⁵⁵, D. Kobayashi¹⁵⁷, T. Kobayashi¹⁵⁵, M. Kobel⁴⁴, M. Kocian¹⁴³, P. Kodys¹²⁹, T. Koffas²⁹, E. Koffeman¹⁰⁷, L.A. Kogan¹²⁰, S. Kohlmann¹⁷⁵, Z. Kohout¹²⁸, T. Kohriki⁶⁶, T. Koi¹⁴³, H. Kolanoski¹⁶, M. Kolb^{58b}, I. Koletsou⁵, A.A. Komar^{96,*}, Y. Komori¹⁵⁵, T. Kondo⁶⁶, N. Kondrashova⁴², K. Köneke⁴⁸, A.C. König¹⁰⁶, T. Kono⁶⁶, R. Konoplich^{110,x}, N. Konstantinidis⁷⁸, R. Kopeliansky¹⁵², S. Koperny^{38a}, L. Köpke⁸³, A.K. Kopp⁴⁸, K. Korcyl³⁹, K. Kordas¹⁵⁴, A. Korn⁷⁸, A.A. Korol^{109,c}, I. Korolkov¹², E.V. Korolkova¹³⁹, O. Kortner¹⁰¹, S. Kortner¹⁰¹, T. Kosek¹²⁹, V.V. Kostyukhin²¹, V.M. Kotov⁶⁵, A. Kotwal⁴⁵, A. Kourkoumeli-Charalampidi¹⁵⁴, C. Kourkoumelis⁹, V. Kouskoura²⁵, A. Koutsman^{159a}, R. Kowalewski¹⁶⁹, T.Z. Kowalski^{38a}, W. Kozanecki¹³⁶, A.S. Kozhin¹³⁰, V.A. Kramarenko⁹⁹, G. Kramberger⁷⁵, D. Krasnopevtsev⁹⁸, M.W. Krasny⁸⁰, A. Krasznahorkay³⁰, J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹¹⁰, M. Kretz^{58c}, J. Kretzschmar⁷⁴, K. Kreutzfeldt⁵², P. Krieger¹⁵⁸, K. Krizka³¹, K. Kroeninger⁴³, H. Kroha¹⁰¹, J. Kroll¹²², J. Kroseberg²¹, J. Krstic¹³, U. Kruchonak⁶⁵, H. Krüger²¹, N. Krumnack⁶⁴, A. Kruse¹⁷³, M.C. Kruse⁴⁵, M. Kruskal²², T. Kubota⁸⁸, H. Kucuk⁷⁸, S. Kuday^{4b}, S. Kuehn⁴⁸, A. Kugel^{58c}, F. Kuger¹⁷⁴, A. Kuhl¹³⁷, T. Kuhl⁴², V. Kukhtin⁶⁵, R. Kukla¹³⁶, Y. Kulchitsky⁹², S. Kuleshov^{32b}, M. Kuna^{132a,132b}, T. Kunigo⁶⁸, A. Kupco¹²⁷, H. Kurashige⁶⁷, Y.A. Kurochkin⁹², V. Kus¹²⁷, E.S. Kuwertz¹⁶⁹, M. Kuze¹⁵⁷, J. Kvita¹¹⁵, T. Kwan¹⁶⁹, D. Kyriazopoulos¹³⁹, A. La Rosa¹³⁷, J.L. La Rosa Navarro^{24d}, L. La Rotonda^{37a,37b}, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁸⁰, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁵, R. Lafaye⁵, B. Laforge⁸⁰, T. Lagouri¹⁷⁶, S. Lai⁵⁴, L. Lambourne⁷⁸, S. Lammers⁶¹, C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁶, V.S. Lang^{58a}, J.C. Lange¹², A.J. Lankford¹⁶³, F. Lanni²⁵, K. Lantzscheid²¹, A. Lanza^{121a}, S. Laplace⁸⁰, C. Lapoire³⁰, J.F. Laporte¹³⁶, T. Lari^{91a}, F. Lasagni Manghi^{20a,20b}, M. Lassnig³⁰, P. Laurelli⁴⁷, W. Lavrijsen¹⁵, A.T. Law¹³⁷, P. Laycock⁷⁴, T. Lazovich⁵⁷, O. Le Dortz⁸⁰, E. Le Guirriec⁸⁵, E. Le Menedeu¹², M. LeBlanc¹⁶⁹, T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, C.A. Lee^{145a}, S.C. Lee¹⁵¹, L. Lee¹, G. Lefebvre⁸⁰, M. Lefebvre¹⁶⁹, F. Legger¹⁰⁰, C. Leggett¹⁵, A. Lehan⁷⁴, G. Lehmann Miotto³⁰, X. Lei⁷, W.A. Leight²⁹, A. Leisos^{154,y}, A.G. Leister¹⁷⁶, M.A.L. Leite^{24d}, R. Leitner¹²⁹, D. Lellouch¹⁷², B. Lemmer⁵⁴, K.J.C. Leney⁷⁸, T. Lenz²¹, B. Lenzi³⁰, R. Leone⁷, S. Leone^{124a,124b}, C. Leonidopoulos⁴⁶, S. Leontsinis¹⁰, C. Leroy⁹⁵, C.G. Lester²⁸, M. Levchenko¹²³, J. Levêque⁵, D. Levin⁸⁹, L.J. Levinson¹⁷², M. Levy¹⁸, A. Lewis¹²⁰, A.M. Leyko²¹, M. Leyton⁴¹, B. Li^{33b,z}, H. Li¹⁴⁸, H.L. Li³¹, L. Li⁴⁵, L. Li^{33e}, S. Li⁴⁵, X. Li⁸⁴, Y. Li^{33c,aa}, Z. Liang¹³⁷, H. Liao³⁴, B. Liberti^{133a}, A. Liblong¹⁵⁸, P. Lichard³⁰, K. Lie¹⁶⁵, J. Liebal²¹, W. Liebig¹⁴, C. Limbach²¹, A. Limosani¹⁵⁰, S.C. Lin^{151,ab}, T.H. Lin⁸³, F. Linde¹⁰⁷, B.E. Lindquist¹⁴⁸, J.T. Linnemann⁹⁰, E. Lipeles¹²², A. Lipniacka¹⁴, M. Lisovsky^{58b}, T.M. Liss¹⁶⁵, D. Lissauer²⁵, A. Lister¹⁶⁸, A.M. Litke¹³⁷, B. Liu^{151,ac}, D. Liu¹⁵¹, H. Liu⁸⁹, J. Liu⁸⁵, J.B. Liu^{33b}, K. Liu⁸⁵, L. Liu¹⁶⁵, M. Liu⁴⁵, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{121a,121b}, A. Lleres⁵⁵, J. Llorente Merino⁸², S.L. Lloyd⁷⁶, F. Lo Sterzo¹⁵¹, E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁷, F.K. Loebinger⁸⁴, A.E. Loevschall-Jensen³⁶, K.M. Loew²³, A. Loginov¹⁷⁶, T. Lohse¹⁶, K. Lohwasser⁴², M. Lokajicek¹²⁷, B.A. Long²², J.D. Long¹⁶⁵, R.E. Long⁷², K.A. Looper¹¹¹, L. Lopes^{126a}, D. Lopez Mateos⁵⁷, B. Lopez Paredes¹³⁹, I. Lopez Paz¹², J. Lorenz¹⁰⁰, N. Lorenzo Martinez⁶¹, M. Losada¹⁶², P.J. Lösel¹⁰⁰, X. Lou^{33a}, A. Lounis¹¹⁷, J. Love⁶, P.A. Love⁷², H. Lu^{60a}, N. Lu⁸⁹, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, C. Luedtke⁴⁸, F. Luehring⁶¹, W. Lukas⁶², L. Luminari^{132a}, O. Lundberg^{146a,146b}, B. Lund-Jensen¹⁴⁷, D. Lynn²⁵, R. Lysak¹²⁷, E. Lytken⁸¹, H. Ma²⁵, L.L. Ma^{33d}, G. Maccarrone⁴⁷, A. Macchiolo¹⁰¹, C.M. Macdonald¹³⁹, B. Maček⁷⁵, J. Machado Miguens^{122,126b}, D. Macina³⁰, D. Madaffari⁸⁵, R. Madar³⁴, H.J. Maddocks⁷², W.F. Mader⁴⁴, A. Madsen⁴², J. Maeda⁶⁷, S. Maeland¹⁴, T. Maeno²⁵, A. Maevskiy⁹⁹, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁷, C. Maiani¹³⁶, C. Maidantchik^{24a}, A.A. Maier¹⁰¹, T. Maier¹⁰⁰, A. Maio^{126a,126b,126d}, S. Majewski¹¹⁶, Y. Makida⁶⁶, N. Makovec¹¹⁷, B. Malaescu⁸⁰, Pa. Malecki³⁹, V.P. Maleev¹²³, F. Malek⁵⁵, U. Mallik⁶³, D. Malon⁶, C. Malone¹⁴³, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁹, S. Malyukov³⁰, J. Mamuzic⁴², G. Mancini⁴⁷, B. Mandelli³⁰, L. Mandelli^{91a}, I. Mandić⁷⁵, R. Mandrysch⁶³, J. Maneira^{126a,126b}, L. Manhaes de Andrade Filho^{24b}, J. Manjarres Ramos^{159b}, A. Mann¹⁰⁰, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁶, R. Mantifel⁸⁷, M. Mantoani⁵⁴, L. Mapelli³⁰, L. March^{145c}, G. Marchiori⁸⁰, M. Marcisovsky¹²⁷, C.P. Marino¹⁶⁹, M. Marjanovic¹³, D.E. Marley⁸⁹, F. Marroquim^{24a}, S.P. Marsden⁸⁴, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁷, B. Martin⁹⁰, T.A. Martin¹⁷⁰, V.J. Martin⁴⁶, B. Martin dit Latour¹⁴, M. Martinez^{12,q}, S. Martin-Haugh¹³¹, V.S. Martoiu^{26b}, A.C. Martyniuk⁷⁸, M. Marx¹³⁸, F. Marzano^{132a}, A. Marzin³⁰, L. Masetti⁸³, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁶, J. Masik⁸⁴,

A.L. Maslennikov^{109,c}, I. Massa^{20a,20b}, L. Massa^{20a,20b}, P. Mastrandrea⁵, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁵, P. Mättig¹⁷⁵, J. Mattmann⁸³, J. Maurer^{26b}, S.J. Maxfield⁷⁴, D.A. Maximov^{109,c}, R. Mazini¹⁵¹, S.M. Mazza^{91a,91b}, G. Mc Goldrick¹⁵⁸, S.P. Mc Kee⁸⁹, A. McCarn⁸⁹, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁹, N.A. McCubbin¹³¹, K.W. McFarlane^{56,*}, J.A. Mcfayden⁷⁸, G. Mchedlidze⁵⁴, S.J. McMahon¹³¹, R.A. McPherson^{169,l}, M. Medinnis⁴², S. Meehan¹³⁸, S. Mehlhase¹⁰⁰, A. Mehta⁷⁴, K. Meier^{58a}, C. Meineck¹⁰⁰, B. Meirose⁴¹, B.R. Mellado Garcia^{145c}, F. Meloni¹⁷, A. Mengarelli^{20a,20b}, S. Menke¹⁰¹, E. Meoni¹⁶¹, K.M. Mercurio⁵⁷, S. Mergelmeyer²¹, P. Mermod⁴⁹, L. Merola^{104a,104b}, C. Meroni^{91a}, F.S. Merritt³¹, A. Messina^{132a,132b}, J. Metcalfe⁶, A.S. Mete¹⁶³, C. Meyer⁸³, C. Meyer¹²², J.-P. Meyer¹³⁶, J. Meyer¹⁰⁷, H. Meyer Zu Theenhausen^{58a}, R.P. Middleton¹³¹, S. Miglioranza^{164a,164c}, L. Mijović²¹, G. Mikenberg¹⁷², M. Mikestikova¹²⁷, M. Mikuž⁷⁵, M. Milesi⁸⁸, A. Milic³⁰, D.W. Miller³¹, C. Mills⁴⁶, A. Milov¹⁷², D.A. Milstead^{146a,146b}, A.A. Minaenko¹³⁰, Y. Minami¹⁵⁵, I.A. Minashvili⁶⁵, A.I. Mincer¹¹⁰, B. Mindur^{38a}, M. Mineev⁶⁵, Y. Ming¹⁷³, L.M. Mir¹², K.P. Mistry¹²², T. Mitani¹⁷¹, J. Mitrevski¹⁰⁰, V.A. Mitsou¹⁶⁷, A. Miucci⁴⁹, P.S. Miyagawa¹³⁹, J.U. Mjörnmark⁸¹, T. Moa^{146a,146b}, K. Mochizuki⁸⁵, S. Mohapatra³⁵, W. Mohr⁴⁸, S. Molander^{146a,146b}, R. Moles-Valls²¹, R. Monden⁶⁸, M.C. Mondragon⁹⁰, K. Mönig⁴², C. Monini⁵⁵, J. Monk³⁶, E. Monnier⁸⁵, A. Montalbano¹⁴⁸, J. Montejo Berlingen³⁰, F. Monticelli⁷¹, S. Monzani^{132a,132b}, R.W. Moore³, N. Morange¹¹⁷, D. Moreno¹⁶², M. Moreno Llácer⁵⁴, P. Morettini^{50a}, D. Mori¹⁴², T. Mori¹⁵⁵, M. Morii⁵⁷, M. Morinaga¹⁵⁵, V. Morisbak¹¹⁹, S. Moritz⁸³, A.K. Morley¹⁵⁰, G. Mornacchi³⁰, J.D. Morris⁷⁶, S.S. Mortensen³⁶, A. Morton⁵³, L. Morvaj¹⁰³, M. Mosidze^{51b}, J. Moss¹⁴³, K. Motohashi¹⁵⁷, R. Mount¹⁴³, E. Mountricha²⁵, S.V. Mouraviev^{96,*}, E.J.W. Moyse⁸⁶, S. Muanza⁸⁵, R.D. Mudd¹⁸, F. Mueller¹⁰¹, J. Mueller¹²⁵, R.S.P. Mueller¹⁰⁰, T. Mueller²⁸, D. Muenstermann⁴⁹, P. Mullen⁵³, G.A. Mullier¹⁷, F.J. Munoz Sanchez⁸⁴, J.A. Murillo Quijada¹⁸, W.J. Murray^{170,131}, H. Musheghyan⁵⁴, E. Musto¹⁵², A.G. Myagkov^{130,ad}, M. Myska¹²⁸, B.P. Nachman¹⁴³, O. Nackenhorst⁵⁴, J. Nadal⁵⁴, K. Nagai¹²⁰, R. Nagai¹⁵⁷, Y. Nagai⁸⁵, K. Nagano⁶⁶, A. Nagarkar¹¹¹, Y. Nagasaka⁵⁹, K. Nagata¹⁶⁰, M. Nagel¹⁰¹, E. Nagy⁸⁵, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura⁶⁶, T. Nakamura¹⁵⁵, I. Nakano¹¹², H. Namasivayam⁴¹, R.F. Naranjo Garcia⁴², R. Narayan³¹, D.I. Narrias Villar^{58a}, T. Naumann⁴², G. Navarro¹⁶², R. Nayyar⁷, H.A. Neal⁸⁹, P.Yu. Nechaeva⁹⁶, T.J. Neep⁸⁴, P.D. Nef¹⁴³, A. Negri^{121a,121b}, M. Negrini^{20a}, S. Nektarijevic¹⁰⁶, C. Nellist¹¹⁷, A. Nelson¹⁶³, S. Nemecek¹²⁷, P. Nemethy¹¹⁰, A.A. Nepomuceno^{24a}, M. Nessi^{30,ae}, M.S. Neubauer¹⁶⁵, M. Neumann¹⁷⁵, R.M. Neves¹¹⁰, P. Nevski²⁵, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹²⁰, R. Nicolaidou¹³⁶, B. Nicquevert³⁰, J. Nielsen¹³⁷, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko^{130,ad}, I. Nikolic-Audit⁸⁰, K. Nikolopoulos¹⁸, J.K. Nilsen¹¹⁹, P. Nilsson²⁵, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, R. Nisius¹⁰¹, T. Nobe¹⁵⁵, M. Nomachi¹¹⁸, I. Nomidis²⁹, T. Nooney⁷⁶, S. Norberg¹¹³, M. Nordberg³⁰, O. Novgorodova⁴⁴, S. Nowak¹⁰¹, M. Nozaki⁶⁶, L. Nozka¹¹⁵, K. Ntekas¹⁰, G. Nunes Hanninger⁸⁸, T. Nunnemann¹⁰⁰, E. Nurse⁷⁸, F. Nuti⁸⁸, F. O'grady⁷, D.C. O'Neil¹⁴², V. O'Shea⁵³, F.G. Oakham^{29,d}, H. Oberlack¹⁰¹, T. Obermann²¹, J. Ocariz⁸⁰, A. Ochi⁶⁷, I. Ochoa³⁵, J.P. Ochoa-Ricoux^{32a}, S. Oda⁷⁰, S. Odaka⁶⁶, H. Ogren⁶¹, A. Oh⁸⁴, S.H. Oh⁴⁵, C.C. Ohm¹⁵, H. Ohman¹⁶⁶, H. Oide³⁰, W. Okamura¹¹⁸, H. Okawa¹⁶⁰, Y. Okumura³¹, T. Okuyama⁶⁶, A. Olariu^{26b}, S.A. Olivares Pino⁴⁶, D. Oliveira Damazio²⁵, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{126a,126e}, K. Onogi¹⁰³, P.U.E. Onyisi^{31,t}, C.J. Oram^{159a}, M.J. Oreglia³¹, Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando¹⁵⁴, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov⁸⁴, G. Otero y Garzon²⁷, H. Otono⁷⁰, M. Ouchrif^{135d}, F. Ould-Saada¹¹⁹, A. Ouraou¹³⁶, K.P. Oussoren¹⁰⁷, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁵³, R.E. Owen¹⁸, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹⁴², A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁸, S. Pagan Griso¹⁵, E. Paganis¹³⁹, F. Paige²⁵, P. Pais⁸⁶, K. Pajchel¹¹⁹, G. Palacino^{159b}, S. Palestini³⁰, M. Palka^{38b}, D. Pallin³⁴, A. Palma^{126a,126b}, Y.B. Pan¹⁷³, E.St. Panagiotopoulou¹⁰, C.E. Pandini⁸⁰, J.G. Panduro Vazquez⁷⁷, P. Pani^{146a,146b}, S. Panitkin²⁵, D. Pantea^{26b}, L. Paolozzi⁴⁹, Th.D. Papadopoulou¹⁰, K. Papageorgiou¹⁵⁴, A. Paramonov⁶, D. Paredes Hernandez¹⁵⁴, M.A. Parker²⁸, K.A. Parker¹³⁹, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, E. Pasqualucci^{132a}, S. Passaggio^{50a}, F. Pastore^{134a,134b,*}, Fr. Pastore⁷⁷, G. Pásztor²⁹, S. Patariaia¹⁷⁵, N.D. Patel¹⁵⁰, J.R. Pater⁸⁴, T. Pauly³⁰, J. Pearce¹⁶⁹, B. Pearson¹¹³, L.E. Pedersen³⁶, M. Pedersen¹¹⁹, S. Pedraza Lopez¹⁶⁷, R. Pedro^{126a,126b}, S.V. Peleganchuk^{109,c}, D. Pelikan¹⁶⁶, O. Penc¹²⁷, C. Peng^{33a}, H. Peng^{33b}, B. Penning³¹, J. Penwell⁶¹, D.V. Perepelitsa²⁵, E. Perez Codina^{159a}, M.T. Pérez García-Estañ¹⁶⁷, L. Perini^{91a,91b}, H. Pernegger³⁰, S. Perrella^{104a,104b}, R. Peschke⁴², V.D. Peshekhonov⁶⁵, K. Peters³⁰, R.F.Y. Peters⁸⁴, B.A. Petersen³⁰,

T.C. Petersen³⁶, E. Petit⁴², A. Petridis¹, C. Petridou¹⁵⁴, P. Petroff¹¹⁷, E. Petrolo^{132a}, F. Petrucci^{134a,134b}, N.E. Pettersson¹⁵⁷, R. Pezoa^{32b}, P.W. Phillips¹³¹, G. Piacquadio¹⁴³, E. Pianori¹⁷⁰, A. Picazio⁴⁹, E. Piccaro⁷⁶, M. Piccinini^{20a,20b}, M.A. Pickering¹²⁰, R. Piegai²⁷, D.T. Pignotti¹¹¹, J.E. Pilcher³¹, A.D. Pilkington⁸⁴, A.W.J. Pin⁸⁴, J. Pina^{126a,126b,126d}, M. Pinamonti^{164a,164c,af}, J.L. Pinfold³, A. Pingel³⁶, S. Pires⁸⁰, H. Pirumov⁴², M. Pitt¹⁷², C. Pizio^{91a,91b}, L. Plazak^{144a}, M.-A. Pleier²⁵, V. Pleskot¹²⁹, E. Plotnikova⁶⁵, P. Plucinski^{146a,146b}, D. Pluth⁶⁴, R. Poettgen^{146a,146b}, L. Poggioli¹¹⁷, D. Pohl²¹, G. Polesello^{121a}, A. Poley⁴², A. Policicchio^{37a,37b}, R. Polifka¹⁵⁸, A. Polini^{20a}, C.S. Pollard⁵³, V. Polychronakos²⁵, K. Pommès³⁰, L. Pontecorvo^{132a}, B.G. Pope⁹⁰, G.A. Popeneciu^{26c}, D.S. Popovic¹³, A. Poppleton³⁰, S. Pospisil¹²⁸, K. Potamianos¹⁵, I.N. Potrap⁶⁵, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁶, G. Poulard³⁰, J. Poveda³⁰, V. Pozdnyakov⁶⁵, M.E. Pozo Astigarraga³⁰, P. Pralavorio⁸⁵, A. Pranko¹⁵, S. Prasad³⁰, S. Prell⁶⁴, D. Price⁸⁴, L.E. Price⁶, M. Primavera^{73a}, S. Prince⁸⁷, M. Proissl⁴⁶, K. Prokofiev^{60c}, F. Prokoshin^{32b}, E. Protopapadaki¹³⁶, S. Protopopescu²⁵, J. Proudfoot⁶, M. Przybycien^{38a}, E. Ptacek¹¹⁶, D. Puddu^{134a,134b}, E. Pueschel⁸⁶, D. Pulton¹⁴⁸, M. Purohit^{25,ag}, P. Puzo¹¹⁷, J. Qian⁸⁹, G. Qin⁵³, Y. Qin⁸⁴, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle^{164a,164b}, M. Queitsch-Maitland⁸⁴, D. Quilty⁵³, S. Raddum¹¹⁹, V. Radeka²⁵, V. Radescu⁴², S.K. Radhakrishnan¹⁴⁸, P. Radloff¹¹⁶, P. Rados⁸⁸, F. Ragusa^{91a,91b}, G. Rahal¹⁷⁸, S. Rajagopalan²⁵, M. Rammensee³⁰, C. Rangel-Smith¹⁶⁶, F. Rauscher¹⁰⁰, S. Rave⁸³, T. Ravenscroft⁵³, M. Raymond³⁰, A.L. Read¹¹⁹, N.P. Readioff⁷⁴, D.M. Rebuzzi^{121a,121b}, A. Redelbach¹⁷⁴, G. Redlinger²⁵, R. Reece¹³⁷, K. Reeves⁴¹, L. Rehnisch¹⁶, J. Reichert¹²², H. Reisin²⁷, C. Rembser³⁰, H. Ren^{33a}, A. Renaud¹¹⁷, M. Rescigno^{132a}, S. Resconi^{91a}, O.L. Rezanova^{109,c}, P. Reznicek¹²⁹, R. Rezvani⁹⁵, R. Richter¹⁰¹, S. Richter⁷⁸, E. Richter-Was^{38b}, O. Ricken²¹, M. Ridel⁸⁰, P. Rieck¹⁶, C.J. Riegel¹⁷⁵, J. Rieger⁵⁴, O. Rifki¹¹³, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{121a,121b}, L. Rinaldi^{20a}, B. Ristić⁴⁹, E. Ritsch³⁰, I. Riu¹², F. Rizatdinova¹¹⁴, E. Rizvi⁷⁶, S.H. Robertson^{87,l}, A. Robichaud-Veronneau⁸⁷, D. Robinson²⁸, J.E.M. Robinson⁴², A. Robson⁵³, C. Roda^{124a,124b}, S. Roe³⁰, O. Røhne¹¹⁹, A. Romaniouk⁹⁸, M. Romano^{20a,20b}, S.M. Romano Saez³⁴, E. Romero Adam¹⁶⁷, N. Rompotis¹³⁸, M. Ronzani⁴⁸, L. Roos⁸⁰, E. Ros¹⁶⁷, S. Rosati^{132a}, K. Rosbach⁴⁸, P. Rose¹³⁷, O. Rosenthal¹⁴¹, V. Rossetti^{146a,146b}, E. Rossi^{104a,104b}, L.P. Rossi^{50a}, J.H.N. Rosten²⁸, R. Rosten¹³⁸, M. Rotaru^{26b}, I. Roth¹⁷², J. Rothberg¹³⁸, D. Rousseau¹¹⁷, C.R. Royon¹³⁶, A. Rozanov⁸⁵, Y. Rozen¹⁵², X. Ruan^{145c}, F. Rubbo¹⁴³, I. Rubinskiy⁴², V.I. Rud⁹⁹, C. Rudolph⁴⁴, M.S. Rudolph¹⁵⁸, F. Rühr⁴⁸, A. Ruiz-Martinez³⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁵, A. Ruschke¹⁰⁰, H.L. Russell¹³⁸, J.P. Rutherford⁷, N. Ruthmann³⁰, Y.F. Ryabov¹²³, M. Rybar¹⁶⁵, G. Rybkin¹¹⁷, N.C. Ryder¹²⁰, A. Ryzhov¹³⁰, A.F. Saavedra¹⁵⁰, G. Sabato¹⁰⁷, S. Sacerdoti²⁷, A. Saddique³, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁵, F. Safai Tehrani^{132a}, P. Saha¹⁰⁸, M. Sahinsoy^{58a}, M. Saimpert¹³⁶, T. Saito¹⁵⁵, H. Sakamoto¹⁵⁵, Y. Sakurai¹⁷¹, G. Salamanna^{134a,134b}, A. Salamon^{133a}, J.E. Salazar Loyola^{32b}, M. Saleem¹¹³, D. Salek¹⁰⁷, P.H. Sales De Bruin¹³⁸, D. Salihagic¹⁰¹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, D. Salvatore^{37a,37b}, F. Salvatore¹⁴⁹, A. Salvucci^{60a}, A. Salzburger³⁰, D. Sammel⁴⁸, D. Sampsonidis¹⁵⁴, A. Sanchez^{104a,104b}, J. Sánchez¹⁶⁷, V. Sanchez Martinez¹⁶⁷, H. Sandaker¹¹⁹, R.L. Sandbach⁷⁶, H.G. Sander⁸³, M.P. Sanders¹⁰⁰, M. Sandhoff¹⁷⁵, C. Sandoval¹⁶², R. Sandstroem¹⁰¹, D.P.C. Sankey¹³¹, M. Sannino^{50a,50b}, A. Sansoni⁴⁷, C. Santoni³⁴, R. Santonico^{133a,133b}, H. Santos^{126a}, I. Santoyo Castillo¹⁴⁹, K. Sapp¹²⁵, A. Saponov⁶⁵, J.G. Saraiva^{126a,126d}, B. Sarrazin²¹, O. Sasaki⁶⁶, Y. Sasaki¹⁵⁵, K. Sato¹⁶⁰, G. Sauvage^{5,*}, E. Sauvan⁵, G. Savage⁷⁷, P. Savard^{158,d}, C. Sawyer¹³¹, L. Sawyer^{79,p}, J. Saxon³¹, C. Sbarra^{20a}, A. Sbrizzi^{20a,20b}, T. Scanlon⁷⁸, D.A. Scannicchio¹⁶³, M. Scarcella¹⁵⁰, V. Scarfone^{37a,37b}, J. Schaarschmidt¹⁷², P. Schacht¹⁰¹, D. Schaefer³⁰, R. Schaefer⁴², J. Schaeffer⁸³, S. Schaepe²¹, S. Schaetzel^{58b}, U. Schäfer⁸³, A.C. Schaffer¹¹⁷, D. Schaile¹⁰⁰, R.D. Schamberger¹⁴⁸, V. Scharf^{58a}, V.A. Schegelsky¹²³, D. Scheirich¹²⁹, M. Schernau¹⁶³, C. Schiavi^{50a,50b}, C. Schillo⁴⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, K. Schmieden³⁰, C. Schmitt⁸³, S. Schmitt^{58b}, S. Schmitt⁴², S. Schmitz⁸³, B. Schneider^{159a}, Y.J. Schnellbach⁷⁴, U. Schnoor⁴⁴, L. Schoeffel¹³⁶, A. Schoening^{58b}, B.D. Schoenrock⁹⁰, E. Schopf²¹, A.L.S. Schorlemmer⁵⁴, M. Schott⁸³, D. Schouten^{159a}, J. Schovancova⁸, S. Schramm⁴⁹, M. Schreyer¹⁷⁴, N. Schuh⁸³, M.J. Schultens²¹, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸⁴, A. Schwartzman¹⁴³, T.A. Schwarz⁸⁹, Ph. Schwegler¹⁰¹, H. Schweiger⁸⁴, Ph. Schwemling¹³⁶, R. Schwienhorst⁹⁰, J. Schwindling¹³⁶, T. Schwindt²¹, E. Scifo¹¹⁷, G. Sciolla²³, F. Scuri^{124a,124b}, F. Scutti²¹, J. Searcy⁸⁹, G. Sedov⁴², E. Sedykh¹²³, P. Seema²¹, S.C. Seidel¹⁰⁵, A. Seiden¹³⁷, F. Seifert¹²⁸, J.M. Seixas^{24a}, G. Sekhniaidze^{104a}, K. Sekhon⁸⁹, S.J. Sekula⁴⁰, D.M. Seliverstov^{123,*}, N. Semprini-Cesari^{20a,20b}, C. Serfon³⁰, L. Serin¹¹⁷,

L. Serkin ^{164a,164b}, T. Serre ⁸⁵, M. Sessa ^{134a,134b}, R. Seuster ^{159a}, H. Severini ¹¹³, T. Sfiligoi ⁷⁵, F. Sforza ³⁰, A. Sfyrla ³⁰, E. Shabalina ⁵⁴, M. Shamim ¹¹⁶, L.Y. Shan ^{33a}, R. Shang ¹⁶⁵, J.T. Shank ²², M. Shapiro ¹⁵, P.B. Shatalov ⁹⁷, K. Shaw ^{164a,164b}, S.M. Shaw ⁸⁴, A. Shcherbakova ^{146a,146b}, C.Y. Shehu ¹⁴⁹, P. Sherwood ⁷⁸, L. Shi ^{151,ah}, S. Shimizu ⁶⁷, C.O. Shimmin ¹⁶³, M. Shimojima ¹⁰², M. Shiyakova ⁶⁵, A. Shmeleva ⁹⁶, D. Shoaleh Saadi ⁹⁵, M.J. Shochet ³¹, S. Shojaii ^{91a,91b}, S. Shrestha ¹¹¹, E. Shulga ⁹⁸, M.A. Shupe ⁷, P. Sicho ¹²⁷, P.E. Sidebo ¹⁴⁷, O. Sidiropoulou ¹⁷⁴, D. Sidorov ¹¹⁴, A. Sidoti ^{20a,20b}, F. Siegert ⁴⁴, Dj. Sijacki ¹³, J. Silva ^{126a,126d}, Y. Silver ¹⁵³, S.B. Silverstein ^{146a}, V. Simak ¹²⁸, O. Simard ⁵, Lj. Simic ¹³, S. Simion ¹¹⁷, E. Simioni ⁸³, B. Simmons ⁷⁸, D. Simon ³⁴, M. Simon ⁸³, P. Sinervo ¹⁵⁸, N.B. Sinev ¹¹⁶, M. Sioli ^{20a,20b}, G. Siragusa ¹⁷⁴, A.N. Sisakyan ^{65,*}, S.Yu. Sivoklokov ⁹⁹, J. Sjölin ^{146a,146b}, T.B. Sjursen ¹⁴, M.B. Skinner ⁷², H.P. Skottowe ⁵⁷, P. Skubic ¹¹³, M. Slater ¹⁸, T. Slavicek ¹²⁸, M. Slawinska ¹⁰⁷, K. Sliwa ¹⁶¹, V. Smakhtin ¹⁷², B.H. Smart ⁴⁶, L. Smestad ¹⁴, S.Yu. Smirnov ⁹⁸, Y. Smirnov ⁹⁸, L.N. Smirnova ^{99,ai}, O. Smirnova ⁸¹, M.N.K. Smith ³⁵, R.W. Smith ³⁵, M. Smizanska ⁷², K. Smolek ¹²⁸, A.A. Snesarev ⁹⁶, G. Snidero ⁷⁶, S. Snyder ²⁵, R. Sobie ^{169,l}, F. Socher ⁴⁴, A. Soffer ¹⁵³, D.A. Soh ^{151,ah}, G. Sokhrannyi ⁷⁵, C.A. Solans ³⁰, M. Solar ¹²⁸, J. Solc ¹²⁸, E.Yu. Soldatov ⁹⁸, U. Soldevila ¹⁶⁷, A.A. Solodkov ¹³⁰, A. Soloshenko ⁶⁵, O.V. Solovyanov ¹³⁰, V. Solovyev ¹²³, P. Sommer ⁴⁸, H.Y. Song ^{33b,z}, N. Soni ¹, A. Sood ¹⁵, A. Sopczak ¹²⁸, B. Sopko ¹²⁸, V. Sopko ¹²⁸, V. Sorin ¹², D. Sosa ^{58b}, M. Sosebee ⁸, C.L. Sotiropoulou ^{124a,124b}, R. Soualah ^{164a,164c}, A.M. Soukharev ^{109,c}, D. South ⁴², B.C. Sowden ⁷⁷, S. Spagnolo ^{73a,73b}, M. Spalla ^{124a,124b}, M. Spangenberg ¹⁷⁰, F. Spanò ⁷⁷, W.R. Spearman ⁵⁷, D. Sperlich ¹⁶, F. Spettel ¹⁰¹, R. Spighi ^{20a}, G. Spigo ³⁰, L.A. Spiller ⁸⁸, M. Spousta ¹²⁹, R.D. St. Denis ^{53,*}, A. Stabile ^{91a}, S. Staerz ³⁰, J. Stahlman ¹²², R. Stamen ^{58a}, S. Stamm ¹⁶, E. Stanecka ³⁹, C. Stanescu ^{134a}, M. Stanescu-Bellu ⁴², M.M. Stanitzki ⁴², S. Stapnes ¹¹⁹, E.A. Starchenko ¹³⁰, J. Stark ⁵⁵, P. Staroba ¹²⁷, P. Starovoitov ^{58a}, R. Staszewski ³⁹, P. Steinberg ²⁵, B. Stelzer ¹⁴², H.J. Stelzer ³⁰, O. Stelzer-Chilton ^{159a}, H. Stenzel ⁵², G.A. Stewart ⁵³, J.A. Stillings ²¹, M.C. Stockton ⁸⁷, M. Stoebe ⁸⁷, G. Stoica ^{26b}, P. Stolte ⁵⁴, S. Stonjek ¹⁰¹, A.R. Stradling ⁸, A. Straessner ⁴⁴, M.E. Stramaglia ¹⁷, J. Strandberg ¹⁴⁷, S. Strandberg ^{146a,146b}, A. Strandlie ¹¹⁹, E. Strauss ¹⁴³, M. Strauss ¹¹³, P. Strizenec ^{144b}, R. Ströhmer ¹⁷⁴, D.M. Strom ¹¹⁶, R. Stroynowski ⁴⁰, A. Strubig ¹⁰⁶, S.A. Stucci ¹⁷, B. Stugu ¹⁴, N.A. Styles ⁴², D. Su ¹⁴³, J. Su ¹²⁵, R. Subramaniam ⁷⁹, A. Succurro ¹², S. Suchek ^{58a}, Y. Sugaya ¹¹⁸, M. Suk ¹²⁸, V.V. Sulin ⁹⁶, S. Sultansoy ^{4c}, T. Sumida ⁶⁸, S. Sun ⁵⁷, X. Sun ^{33a}, J.E. Sundermann ⁴⁸, K. Suruliz ¹⁴⁹, G. Susinno ^{37a,37b}, M.R. Sutton ¹⁴⁹, S. Suzuki ⁶⁶, M. Svatos ¹²⁷, M. Swiatlowski ³¹, I. Sykora ^{144a}, T. Sykora ¹²⁹, D. Ta ⁴⁸, C. Taccini ^{134a,134b}, K. Tackmann ⁴², J. Taenzer ¹⁵⁸, A. Taffard ¹⁶³, R. Tafirout ^{159a}, N. Taiblum ¹⁵³, H. Takai ²⁵, R. Takashima ⁶⁹, H. Takeda ⁶⁷, T. Takeshita ¹⁴⁰, Y. Takubo ⁶⁶, M. Talby ⁸⁵, A.A. Talyshev ^{109,c}, J.Y.C. Tam ¹⁷⁴, K.G. Tan ⁸⁸, J. Tanaka ¹⁵⁵, R. Tanaka ¹¹⁷, S. Tanaka ⁶⁶, B.B. Tannenwald ¹¹¹, S. Tapia Araya ^{32b}, S. Tapprogge ⁸³, S. Tarem ¹⁵², F. Tarrade ²⁹, G.F. Tartarelli ^{91a}, P. Tas ¹²⁹, M. Tasevsky ¹²⁷, T. Tashiro ⁶⁸, E. Tassi ^{37a,37b}, A. Tavares Delgado ^{126a,126b}, Y. Tayalati ^{135d}, A.C. Taylor ¹⁰⁵, F.E. Taylor ⁹⁴, G.N. Taylor ⁸⁸, P.T.E. Taylor ⁸⁸, W. Taylor ^{159b}, F.A. Teischinger ³⁰, M. Teixeira Dias Castanheira ⁷⁶, P. Teixeira-Dias ⁷⁷, K.K. Temming ⁴⁸, D. Temple ¹⁴², H. Ten Kate ³⁰, P.K. Teng ¹⁵¹, J.J. Teoh ¹¹⁸, F. Tepel ¹⁷⁵, S. Terada ⁶⁶, K. Terashi ¹⁵⁵, J. Terron ⁸², S. Terzo ¹⁰¹, M. Testa ⁴⁷, R.J. Teuscher ^{158,l}, T. Theveneaux-Pelzer ³⁴, J.P. Thomas ¹⁸, J. Thomas-Wilsker ⁷⁷, E.N. Thompson ³⁵, P.D. Thompson ¹⁸, R.J. Thompson ⁸⁴, A.S. Thompson ⁵³, L.A. Thomsen ¹⁷⁶, E. Thomson ¹²², M. Thomson ²⁸, R.P. Thun ^{89,*}, M.J. Tibbetts ¹⁵, R.E. Ticse Torres ⁸⁵, V.O. Tikhomirov ^{96,aj}, Yu.A. Tikhonov ^{109,c}, S. Timoshenko ⁹⁸, E. Tiouchichine ⁸⁵, P. Tipton ¹⁷⁶, S. Tisserant ⁸⁵, K. Todome ¹⁵⁷, T. Todorov ^{5,*}, S. Todorova-Nova ¹²⁹, J. Tojo ⁷⁰, S. Tokár ^{144a}, K. Tokushuku ⁶⁶, K. Tollefson ⁹⁰, E. Tolley ⁵⁷, L. Tomlinson ⁸⁴, M. Tomoto ¹⁰³, L. Tompkins ^{143,ak}, K. Toms ¹⁰⁵, E. Torrence ¹¹⁶, H. Torres ¹⁴², E. Torró Pastor ¹³⁸, J. Toth ^{85,al}, F. Touchard ⁸⁵, D.R. Tovey ¹³⁹, T. Trefzger ¹⁷⁴, L. Tremblet ³⁰, A. Tricoli ³⁰, I.M. Trigger ^{159a}, S. Trincaz-Duvold ⁸⁰, M.F. Tripiana ¹², W. Trischuk ¹⁵⁸, B. Trocmé ⁵⁵, C. Troncon ^{91a}, M. Trotter-McDonald ¹⁵, M. Trovatelli ¹⁶⁹, L. Truong ^{164a,164c}, M. Trzebinski ³⁹, A. Trzupek ³⁹, C. Tsarouchas ³⁰, J.C.-L. Tseng ¹²⁰, P.V. Tsiarehsha ⁹², D. Tsionou ¹⁵⁴, G. Tsipolitis ¹⁰, N. Tsirintanis ⁹, S. Tsiskaridze ¹², V. Tsiskaridze ⁴⁸, E.G. Tskhadadze ^{51a}, K.M. Tsui ^{60a}, I.I. Tsukerman ⁹⁷, V. Tsulaia ¹⁵, S. Tsuno ⁶⁶, D. Tsybychev ¹⁴⁸, A. Tudorache ^{26b}, V. Tudorache ^{26b}, A.N. Tuna ⁵⁷, S.A. Tupputi ^{20a,20b}, S. Turchikhin ^{99,ai}, D. Turecek ¹²⁸, R. Turra ^{91a,91b}, A.J. Turvey ⁴⁰, P.M. Tuts ³⁵, A. Tykhonov ⁴⁹, M. Tylmad ^{146a,146b}, M. Tyndel ¹³¹, I. Ueda ¹⁵⁵, R. Ueno ²⁹, M. Ughetto ^{146a,146b}, F. Ukegawa ¹⁶⁰, G. Unal ³⁰, A. Undrus ²⁵, G. Unel ¹⁶³, F.C. Ungaro ⁸⁸, Y. Unno ⁶⁶, C. Unverdorben ¹⁰⁰, J. Urban ^{144b}, P. Urquijo ⁸⁸, P. Urrejola ⁸³, G. Usai ⁸, A. Usanova ⁶², L. Vacavant ⁸⁵,

V. Vacek¹²⁸, B. Vachon⁸⁷, C. Valderanis⁸³, N. Valencic¹⁰⁷, S. Valentinetti^{20a,20b}, A. Valero¹⁶⁷,
 L. Valery¹², S. Valkar¹²⁹, S. Vallecorsa⁴⁹, J.A. Valls Ferrer¹⁶⁷, W. Van Den Wollenberg¹⁰⁷,
 P.C. Van Der Deijl¹⁰⁷, R. van der Geer¹⁰⁷, H. van der Graaf¹⁰⁷, N. van Eldik¹⁵², P. van Gemmeren⁶,
 J. Van Nieuwkoop¹⁴², I. van Vulpen¹⁰⁷, M.C. van Woerden³⁰, M. Vanadia^{132a,132b}, W. Vandelli³⁰,
 R. Vanguri¹²², A. Vaniachine⁶, F. Vannucci⁸⁰, G. Vardanyan¹⁷⁷, R. Vari^{132a}, E.W. Varnes⁷, T. Varol⁴⁰,
 D. Varouchas⁸⁰, A. Vartapetian⁸, K.E. Varvell¹⁵⁰, F. Vazeille³⁴, T. Vazquez Schroeder⁸⁷, J. Veatch⁷,
 L.M. Veloce¹⁵⁸, F. Veloso^{126a,126c}, T. Velz²¹, S. Veneziano^{132a}, A. Ventura^{73a,73b}, D. Ventura⁸⁶,
 M. Venturi¹⁶⁹, N. Venturi¹⁵⁸, A. Venturini²³, V. Vercesi^{121a}, M. Verducci^{132a,132b}, W. Verkerke¹⁰⁷,
 J.C. Vermeulen¹⁰⁷, A. Vest⁴⁴, M.C. Vetterli^{142,d}, O. Viazlo⁸¹, I. Vichou¹⁶⁵, T. Vickey¹³⁹,
 O.E. Vickey Boeriu¹³⁹, G.H.A. Viehhauser¹²⁰, S. Viel¹⁵, R. Vigne⁶², M. Villa^{20a,20b},
 M. Villaplana Perez^{91a,91b}, E. Vilucchi⁴⁷, M.G. Vincker²⁹, V.B. Vinogradov⁶⁵, I. Vivarelli¹⁴⁹, S. Vlachos¹⁰,
 D. Vladoiu¹⁰⁰, M. Vlasak¹²⁸, M. Vogel^{32a}, P. Vokac¹²⁸, G. Volpi^{124a,124b}, M. Volpi⁸⁸,
 H. von der Schmitt¹⁰¹, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁹, K. Vorobev⁹⁸, M. Vos¹⁶⁷,
 R. Voss³⁰, J.H. Vossebeld⁷⁴, N. Vranjes¹³, M. Vranjes Milosavljevic¹³, V. Vrba¹²⁷, M. Vreeswijk¹⁰⁷,
 R. Vuillermet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁸, P. Wagner²¹, W. Wagner¹⁷⁵, H. Wahlberg⁷¹,
 S. Wahrmond⁴⁴, J. Wakabayashi¹⁰³, J. Walder⁷², R. Walker¹⁰⁰, W. Walkowiak¹⁴¹, C. Wang¹⁵¹,
 F. Wang¹⁷³, H. Wang¹⁵, H. Wang⁴⁰, J. Wang⁴², J. Wang¹⁵⁰, K. Wang⁸⁷, R. Wang⁶, S.M. Wang¹⁵¹,
 T. Wang²¹, T. Wang³⁵, X. Wang¹⁷⁶, C. Wanotayaroj¹¹⁶, A. Warburton⁸⁷, C.P. Ward²⁸, D.R. Wardrope⁷⁸,
 A. Washbrook⁴⁶, C. Wasicki⁴², P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵⁰, M.F. Watson¹⁸,
 G. Watts¹³⁸, S. Watts⁸⁴, B.M. Waugh⁷⁸, S. Webb⁸⁴, M.S. Weber¹⁷, S.W. Weber¹⁷⁴, J.S. Webster⁶,
 A.R. Weidberg¹²⁰, B. Weinert⁶¹, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Weits¹⁰⁷, P.S. Wells³⁰, T. Wenaus²⁵,
 T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Wessels^{58a}, J. Wetter¹⁶¹,
 K. Whalen¹¹⁶, A.M. Wharton⁷², A. White⁸, M.J. White¹, R. White^{32b}, S. White^{124a,124b}, D. Whiteson¹⁶³,
 F.J. Wickens¹³¹, W. Wiedenmann¹⁷³, M. Wielers¹³¹, P. Wienemann²¹, C. Wiglesworth³⁶,
 L.A.M. Wiik-Fuchs²¹, A. Wildauer¹⁰¹, H.G. Wilkens³⁰, H.H. Williams¹²², S. Williams¹⁰⁷, C. Willis⁹⁰,
 S. Willocq⁸⁶, A. Wilson⁸⁹, J.A. Wilson¹⁸, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁶, B.T. Winter²¹,
 M. Wittgen¹⁴³, J. Wittkowski¹⁰⁰, S.J. Wollstadt⁸³, M.W. Wolter³⁹, H. Wolters^{126a,126c}, B.K. Wosiek³⁹,
 J. Wotschack³⁰, M.J. Woudstra⁸⁴, K.W. Wozniak³⁹, M. Wu⁵⁵, M. Wu³¹, S.L. Wu¹⁷³, X. Wu⁴⁹, Y. Wu⁸⁹,
 T.R. Wyatt⁸⁴, B.M. Wynne⁴⁶, S. Xella³⁶, D. Xu^{33a}, L. Xu²⁵, B. Yabsley¹⁵⁰, S. Yacoob^{145a}, R. Yakabe⁶⁷,
 M. Yamada⁶⁶, D. Yamaguchi¹⁵⁷, Y. Yamaguchi¹¹⁸, A. Yamamoto⁶⁶, S. Yamamoto¹⁵⁵, T. Yamanaka¹⁵⁵,
 K. Yamauchi¹⁰³, Y. Yamazaki⁶⁷, Z. Yan²², H. Yang^{33e}, H. Yang¹⁷³, Y. Yang¹⁵¹, W.-M. Yao¹⁵, Y.C. Yap⁸⁰,
 Y. Yasu⁶⁶, E. Yatsenko⁵, K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵, I. Yeletskikh⁶⁵, A.L. Yen⁵⁷, E. Yildirim⁴²,
 K. Yorita¹⁷¹, R. Yoshida⁶, K. Yoshihara¹²², C. Young¹⁴³, C.J.S. Young³⁰, S. Youssef²², D.R. Yu¹⁵, J. Yu⁸,
 J.M. Yu⁸⁹, J. Yu¹¹⁴, L. Yuan⁶⁷, S.P.Y. Yuen²¹, A. Yurkewicz¹⁰⁸, I. Yusuff^{28,am}, B. Zabinski³⁹, R. Zaidan⁶³,
 A.M. Zaitsev^{130,ad}, J. Zalieckas¹⁴, A. Zaman¹⁴⁸, S. Zambito⁵⁷, L. Zanello^{132a,132b}, D. Zanzi⁸⁸,
 C. Zeitnitz¹⁷⁵, M. Zeman¹²⁸, A. Zemla^{38a}, J.C. Zeng¹⁶⁵, Q. Zeng¹⁴³, K. Zengel²³, O. Zenin¹³⁰,
 T. Ženiš^{144a}, D. Zerwas¹¹⁷, D. Zhang⁸⁹, F. Zhang¹⁷³, G. Zhang^{33b}, H. Zhang^{33c}, J. Zhang⁶, L. Zhang⁴⁸,
 R. Zhang^{33b,j}, X. Zhang^{33d}, Z. Zhang¹¹⁷, X. Zhao⁴⁰, Y. Zhao^{33d,117}, Z. Zhao^{33b}, A. Zhemchugov⁶⁵,
 J. Zhong¹²⁰, B. Zhou⁸⁹, C. Zhou⁴⁵, L. Zhou³⁵, L. Zhou⁴⁰, M. Zhou¹⁴⁸, N. Zhou^{33f}, C.G. Zhu^{33d}, H. Zhu^{33a},
 J. Zhu⁸⁹, Y. Zhu^{33b}, X. Zhuang^{33a}, K. Zhukov⁹⁶, A. Zibell¹⁷⁴, D. Zieminska⁶¹, N.I. Zimine⁶⁵,
 C. Zimmermann⁸³, S. Zimmermann⁴⁸, Z. Zinonos⁵⁴, M. Zinser⁸³, M. Ziolkowski¹⁴¹, L. Živković¹³,
 G. Zobernig¹⁷³, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, G. Zurzolo^{104a,104b}, L. Zwalinski³⁰

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany, NY, United States

³ Department of Physics, University of Alberta, Edmonton, AB, Canada

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

⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

⁷ Department of Physics, University of Arizona, Tucson, AZ, United States

⁸ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

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, Barcelona, Spain

¹³ Institute of Physics, 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, CA, United States

- 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
- ¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Dogus University, Istanbul, Turkey
- ²⁰ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- ²¹ Physikalisches Institut, University of Bonn, Bonn, Germany
- ²² Department of Physics, Boston University, Boston, MA, United States
- ²³ Department of Physics, Brandeis University, Waltham, MA, United States
- ²⁴ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁵ Physics Department, Brookhaven National Laboratory, Upton, NY, United States
- ²⁶ (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
- ²⁷ Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ²⁹ Department of Physics, Carleton University, Ottawa, ON, Canada
- ³⁰ CERN, Geneva, Switzerland
- ³¹ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
- ³² (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³³ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
- ³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵ Nevis Laboratory, Columbia University, Irvington, NY, United States
- ³⁶ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ³⁷ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸ (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ³⁹ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas, TX, United States
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson, TX, United States
- ⁴² DESY, Hamburg and Zeuthen, Germany
- ⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁵ Department of Physics, Duke University, Durham, NC, United States
- ⁴⁶ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ (a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton, VA, United States
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- ⁵⁸ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰ (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶¹ Department of Physics, Indiana University, Bloomington, IN, United States
- ⁶² Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶³ University of Iowa, Iowa City, IA, United States
- ⁶⁴ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- ⁶⁵ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁶ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁷ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁸ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁹ Kyoto University of Education, Kyoto, Japan
- ⁷⁰ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷¹ Instituto de Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷² Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷³ (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁴ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁵ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁶ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁷ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁸ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁹ Louisiana Tech University, Ruston, LA, United States
- ⁸⁰ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸¹ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸² Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
- ⁸³ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁴ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁵ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁶ Department of Physics, University of Massachusetts, Amherst, MA, United States

- ⁸⁷ Department of Physics, McGill University, Montreal, QC, Canada
- ⁸⁸ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁹ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁹⁰ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁹¹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹² B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹³ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹⁴ Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- ⁹⁵ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁶ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁷ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁸ National Research Nuclear University MEPhI, Moscow, Russia
- ⁹⁹ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹⁰⁰ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰¹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰² Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰³ Graduate School of Science and Kobayashi–Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁴ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁵ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁶ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁷ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁸ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹⁰⁹ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹⁰ Department of Physics, New York University, New York, NY, United States
- ¹¹¹ Ohio State University, Columbus, OH, United States
- ¹¹² Faculty of Science, Okayama University, Okayama, Japan
- ¹¹³ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- ¹¹⁴ Department of Physics, Oklahoma State University, Stillwater, OK, United States
- ¹¹⁵ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁶ Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- ¹¹⁷ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁸ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁹ Department of Physics, University of Oslo, Oslo, Norway
- ¹²⁰ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²¹ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²² Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- ¹²³ National Research Centre “Kurchatov Institute” B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ¹²⁴ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁵ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- ¹²⁶ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁷ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁸ Czech Technical University in Prague, Praha, Czech Republic
- ¹²⁹ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹³⁰ State Research Center Institute for High Energy Physics (Protvino), NRC KI, Moscow, Russia
- ¹³¹ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³² ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹³³ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁴ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹³⁵ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V, 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, CA, United States
- ¹³⁸ Department of Physics, University of Washington, Seattle, WA, United States
- 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, BC, Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford, CA, United States
- ¹⁴⁴ ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ¹⁴⁵ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁶ ^(a) Department of Physics, Stockholm University; ^(b) 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, NY, United States
- 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, ON, Canada
- ¹⁵⁹ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada

- ¹⁶⁰ Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- ¹⁶¹ Department of Physics and Astronomy, Tufts University, Medford, MA, United States
- ¹⁶² Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ¹⁶³ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
- ¹⁶⁴ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁵ Department of Physics, University of Illinois, Urbana, IL, United States
- 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, BC, Canada
- ¹⁶⁹ Department of Physics and Astronomy, University of Victoria, Victoria, BC, 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, WI, United States
- 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, CT, United States
- 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

^a Also at Department of Physics, King's College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^c Also at Novosibirsk State University, Novosibirsk, Russia.

^d Also at TRIUMF, Vancouver, BC, Canada.

^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States.

^f Also at Department of Physics, California State University, Fresno, CA, United States.

^g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

^h Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

ⁱ Also at Tomsk State University, Tomsk, Russia.

^j Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^k Also at Università di Napoli Parthenope, Napoli, Italy.

^l Also at Institute of Particle Physics (IPP), Canada.

^m Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

ⁿ Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^o Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

^p Also at Louisiana Tech University, Ruston, LA, United States.

^q Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

^r Also at Graduate School of Science, Osaka University, Osaka, Japan.

^s Also at Department of Physics, National Tsing Hua University, Taiwan.

^t Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.

^u Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^v Also at CERN, Geneva, Switzerland.

^w Also at Georgian Technical University (GTU), Tbilisi, Georgia.

^x Also at Manhattan College, New York, NY, United States.

^y Also at Hellenic Open University, Patras, Greece.

^z Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{aa} Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

^{ab} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{ac} Also at School of Physics, Shandong University, Shandong, China.

^{ad} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^{ae} Also at Section de Physique, Université de Genève, Geneva, Switzerland.

^{af} Also at International School for Advanced Studies (SISSA), Trieste, Italy.

^{ag} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

^{ah} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

^{ai} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

^{aj} Also at National Research Nuclear University MEPhI, Moscow, Russia.

^{ak} Also at Department of Physics, Stanford University, Stanford, CA, United States.

^{al} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

^{am} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

* Deceased.