

Search for a new Z' gauge boson via the $pp \rightarrow W^{\pm(*)} \rightarrow Z'\mu^{\pm}\nu \rightarrow \mu^{\pm}\mu^{\mp}\mu^{\pm}\nu$ process in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

G. Aad *et al.*^{*}
(ATLAS Collaboration)



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A search for a new Z' gauge boson predicted by $L_\mu - L_\tau$ models, based on charged-current Drell–Yan production, $pp \rightarrow W^{\pm(*)} \rightarrow Z'\mu^{\pm}\nu \rightarrow \mu^{\pm}\mu^{\mp}\mu^{\pm}\nu$, is presented. The data sample used corresponds to an integrated luminosity of 140 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. The search examines a final state of 3μ plus large missing transverse momentum. Upper limits are set on the Z' production cross section times branching ratio in the mass range of 5–81 GeV. After combining with the previous Z' search using the neutral-current Drell–Yan production with a 4μ final state, the most stringent exclusion limits to date are achieved in the parameter space of the Z' coupling strength and mass.

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I. INTRODUCTION

Various extensions of the Standard Model (SM) feature an extra $U(1)$ gauge symmetry and predict a new massive gauge boson, generally referred to as Z' [1,2]. Typical benchmark models include the sequential Standard Model [3], grand unified theories based on the E_6 gauge group [4], and left (L)–right (R) symmetric extensions of the SM based on the $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge group [5–7], where $B - L$ denotes the difference between baryon and lepton numbers. For Z' boson that significantly couples to light quarks, the constraint on its mass from LHC is up to 5 TeV [8,9]. Alternatively, $U(1)$ gauge symmetries based on the difference between lepton family numbers are less constrained and are anomaly free [10]. The model based on gauging the difference between μ -lepton number and τ -lepton number, $L_\mu - L_\tau$, is particularly interesting since it is the least constrained experimentally, because the $L_\mu - L_\tau$ Z' boson only couples to the second and third generations of leptons. In recent years, this model has attracted interest in both theoretical and experimental communities [11–13] because it could address some of the reported anomalies, such as the measured muon anomalous magnetic moment [14,15] and lepton flavor anomalies [16–20]. In addition, these models also provide a viable solution to dark matter and neutrino mass [2,21,22].

The interaction between the Z' boson and the second- and third-generation leptons can be described with the following Lagrangian:

$$L_{Z'} = -\frac{1}{4}F_{\alpha\beta}F^{\alpha\beta} + \frac{1}{2}m_{Z'}^2Z'^\alpha Z'_\alpha - g_{Z'}Z'_\alpha(\bar{\ell}_2\gamma^\alpha\ell_2 + \mu_L\gamma^\alpha\mu_R - \bar{\ell}_3\gamma^\alpha\ell_3 - \tau_L\gamma^\alpha\tau_R),$$

where $F_{\alpha\beta} = \partial_\alpha Z'_\beta - \partial_\beta Z'_\alpha$ is the Z' field strength tensor; $\ell_i = (\nu_i, e_i)^T$ ($i = 2, 3$, denoting the second and the third generation left-handed lepton doublets); and $g_{Z'}$ (from hereon referred to as g) is the coupling constant of the interaction between the Z' boson and the SM leptons. The Z' -boson mass, $m_{Z'}$, and g are the free parameters of the model. In proton–proton (pp) collisions at the Large Hadron Collider (LHC), the Z' boson could be produced by final state radiation from μ , ν_μ , τ and ν_τ leptons originating from other physics processes.

This paper presents the first search for a $L_\mu - L_\tau$ Z' boson produced from leptons arising from charged-current Drell–Yan (DY) process, $pp \rightarrow W^{\pm(*)} \rightarrow Z'\mu^{\pm}\nu \rightarrow \mu^{\pm}\mu^{\mp}\mu^{\pm}\nu$ (see Fig. 1), giving a final state of 3μ plus large missing transverse momentum. This novel search complements previous analyses by the ATLAS and CMS Collaborations using the neutral-current DY process with a 4μ final state, $pp \rightarrow Z^{(*)} \rightarrow Z'\mu^+\mu^- \rightarrow \mu^+\mu^-$, and has a much higher cross section by a factor of 3–6. The CMS Collaboration searched for the Z' boson in the mass range of 5–70 GeV using 77.3 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV [23]. The ATLAS Collaboration searched for the Z' boson with a mass up to 81 GeV using 139 fb^{-1} of data at $\sqrt{s} = 13$ TeV [24].

^{*}Full author list given at the end of the article.

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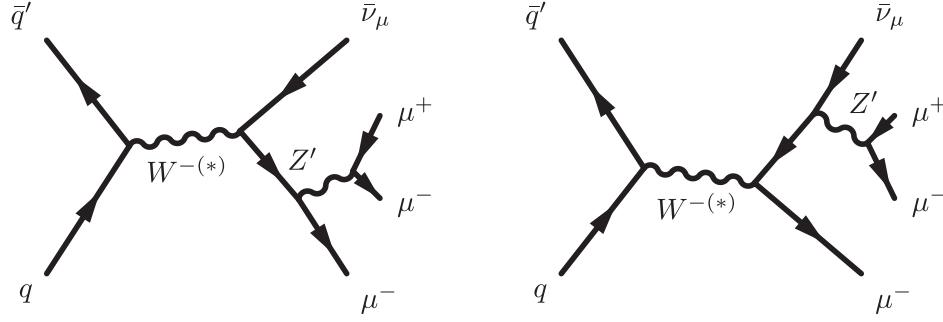


FIG. 1. Representative Feynman diagrams of a Z' boson via radiation off a lepton in charged-current Drell–Yan production giving a $\mu^-\mu^+\mu^-\bar{\nu}_\mu$ final state.

II. DATASET AND MONTE CARLO SIMULATION

The ATLAS experiment at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle [25–27].¹ The pp collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment during 2015–2018 are used. The corresponding integrated luminosity is 140 fb^{-1} after applying data quality requirements [28]. A combination of single-lepton and multilepton triggers [29,30] is used, with transverse momentum (p_T) thresholds varying from 20 to 26 GeV for single-muon triggers, 10 to 14 GeV for dimuon triggers, and 6 GeV for trimuon triggers. The overall trigger efficiency is greater than 96% for events passing the offline event selection. An extensive software suite [31] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

Monte Carlo (MC) signal samples are simulated using MADGRAPH5_AMC@NLO2.9.5 [32], with matrix elements (ME) calculated at leading order (LO) in perturbative quantum chromodynamics (QCD) and with the NNPDF3.0NLO [33] parton distribution function (PDF) set. The events were interfaced to PYTHIA 8.245 [34] to model the parton shower, hadronization, and underlying event, with parameter values set according to the A14 parton-shower tune [35] and using the NNPDF2.3LO [36] set of PDFs. The appropriate next-to-next-to-leading-order to LO K factor of 1.3 is used to correct the MC LO signal cross sections [37,38]. Benchmark signal samples are generated in the mass range of 5–81 GeV following the

previous 4μ search [24] and to ensure a negligible Z' width compared with the detector resolution. The contribution from $pp \rightarrow Z'\tau\bar{\nu}_\tau$ to this search is found to be negligible and thus is not included in the MC signal samples.

The dominant SM background processes, $q\bar{q} \rightarrow W(Z/\gamma^*) \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$ ($\ell = e, \mu, \tau$; $\nu = \nu_e, \nu_\mu, \nu_\tau$; referred to as $q\bar{q} \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$) and $q\bar{q} \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ (referred to as $q\bar{q} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$), are simulated with the SHERPA 2.2.2 event generator [39]. Matrix elements are calculated at next-to-leading-order (NLO) accuracy in QCD for up to one additional parton and at LO accuracy for two and three additional parton emissions. The ME calculations are matched and merged with the SHERPA parton shower based on Catani–Seymour dipole factorization [40,41], using the MEPS@NLO prescription [42–45]. SHERPA 2.2.2 is also used for the $gg \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ process, with LO precision for zero- and one-jet final states, where a constant K factor of 1.7 [46] is applied to account for NLO effects on the cross section. The events with nonprompt leptons arising from $Z + \text{jets}$ and $t\bar{t}$ processes are modeled using SHERPA 2.2.1 and POWHEG BOX v2 generators [47–50], respectively. Samples for other subdominant processes, such as the resonant $H \rightarrow ZZ^* \rightarrow 4\ell$ process, triboson processes (VVV , $V = W, Z$) and W/Z bosons produced along with a $t\bar{t}$ pair ($t\bar{t}V$), are also simulated as described in Ref. [24], and their contribution is found to be negligible and thus ignored.

Except for the signal, all samples are produced with a detailed simulation of the ATLAS detector [51] based on GEANT4 [52] to produce predictions that can be compared with the data. The signal samples are processed through a faster simulation where the full GEANT4 simulation of the calorimeter response is replaced by a parametrization of the shower shapes [51]. Furthermore, simulated inelastic minimum-bias events are overlaid to model additional pp collisions in the same and neighboring bunch crossings (pileup) [53]. Simulated events are reweighted to match the pileup conditions in the data. All simulated events were processed using the same reconstruction algorithms as used for data.

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

III. EVENT RECONSTRUCTION AND SELECTION

Interaction vertices from the pp collisions are reconstructed from at least two tracks with $p_T > 500$ MeV that are consistent with originating from the beam collision region in the x - y plane. If more than one primary vertex candidate is found in the event, the candidate for which the associated tracks form the largest sum of squared p_T is selected as the hard-scatter primary vertex.

Muon candidates are reconstructed by combining the information from both the muon spectrometer and the inner detector (ID). Muons are required to satisfy the “Medium” identification criterion [54] and have $p_T > 3$ GeV and $|\eta| < 2.5$. Electrons and jets are used to select control samples for the background estimate. Electrons are reconstructed from energy clusters in the electromagnetic calorimeter matched to ID tracks. Candidate electrons must satisfy the “Tight” likelihood identification criterion [55] and have $p_T > 4.5$ GeV and $|\eta| < 2.47$, excluding the transition region between the barrel and endcaps in the calorimeter ($1.37 < |\eta| < 1.52$). All muons and electrons must be isolated from other particles based on a particle-flow algorithm and satisfy the “PflowLoose” and “PflowTight” isolation criteria [54,55], respectively. Furthermore, muons (electrons) are required to have matched tracks satisfying $|d_0|/\sigma_{d_0} < 3(5)$ and $|z_0 \sin(\theta)| < 0.5$ mm, where d_0 is the transverse impact parameter relative to the beam line, σ_{d_0} is its uncertainty, and z_0 is the longitudinal impact parameter relative to the primary vertex.

Jet candidates are reconstructed from particle flow objects [56] using the anti- k_t algorithm with a radius parameter of $R = 0.4$ [57,58]. They are calibrated using simulation with corrections obtained from *in situ* techniques in data [59]. A jet vertex tagger algorithm [60] is applied to suppress pileup jets. All jets must have $p_T > 30$ GeV and $|\eta| < 4.5$. Jets containing b -hadrons, referred to as b -jets, are identified using a deep-learning neural network, DL1 τ [61]. The chosen working point has an efficiency of 85% for selecting b -jets with $p_T > 20$ GeV and $|\eta| < 2.5$ and a rejection factor of about 3 and 40 for charm jets and light-flavor jets, respectively [61].

The missing transverse momentum, $\vec{p}_T^{\text{miss}}$ (with magnitude E_T^{miss}), is defined as the negative vector sum of the p_T of all selected and calibrated objects in the event, including a term to account for the momentum from soft particles in the event that are not associated with any of the selected objects [62].

Events are required to contain exactly three muon candidates satisfying the selection criteria previously described. Events with a fourth muon candidate satisfying a looser selection criterion as defined in the 4μ channel [24] are rejected to ensure the two search regions are disjoint. Candidate events are required to have a total charge from the muons equal to ± 1 . The three p_T -ordered muons are required to satisfy p_T thresholds of 20, 10, and 7 GeV,

respectively. The muons firing triggers are also required to satisfy the corresponding trigger p_T thresholds. Events are required to have $E_T^{\text{miss}} > 15$ GeV. To suppress the background contribution from top-quark production, events containing b -jets are rejected. Two opposite-sign muon pairs ($\mu^+\mu^-$) are selected from the three muons in each event. Each $\mu^+\mu^-$ pair must have an invariant mass greater than 4 GeV to suppress the background contribution from low-mass resonances. The $\mu^+\mu^-$ pair with the largest mass is referred to as the leading pair Z_1 , and the other pair is referred to as the subleading pair Z_2 . Events are required to satisfy $m_{Z_1} < 85$ GeV to suppress the background from Z -boson production. These selection requirements define the signal region (SR).

IV. BACKGROUND ESTIMATION

Background sources are classified into two categories: the irreducible background with events containing prompt muons, and the reducible background with events containing at least one nonprompt muon from hadron decays or misidentification of jets.

The irreducible background, which mainly originates from diboson production of $q\bar{q}' \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$ and $q\bar{q} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$, is estimated by using simulation. The contribution from $t\bar{t}V$, VVV and Higgs boson production processes is found to be negligible. The background event yield of the dominant contribution from $q\bar{q}' \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$ production is normalized to the data with the help of a control region (CR) enriched in $\ell^\pm \nu \ell^\pm \ell^\mp$ events, referred to as $\text{CR}_{3\ell}$. The $\text{CR}_{3\ell}$ sample is defined by selecting events with three leptons, where the lowest- p_T lepton must be a muon, satisfying the p_T requirements of 25, 20, and 20 GeV, respectively, and with $E_T^{\text{miss}} > 25$ GeV. The same selection of lepton pairs used for the SR is implemented in the $\text{CR}_{3\ell}$, and the leading lepton pair forming the Z -boson candidate must have an invariant mass in the range of 85–100 GeV.

The reducible background, with contributions from $Z + \text{jets}$, $Z + \gamma$, and $t\bar{t}$ production processes, is estimated by using a fake-factor method as described in Refs. [63,64]. The fake factor is defined as the ratio of numbers of nonprompt muons $N_{\text{fake}}^{\text{tight}}/N_{\text{fake}}^{\text{loose}}$, where “tight” or “loose” indicates whether those muons satisfy the impact parameter and isolation requirements, or fail to meet at least one of the requirements. The fake factor is measured in $Z + \text{jets}$ events, considering an additional muon candidate that does not originate from the Z -boson decay. The measurement is performed in bins of p_T of the additional muon and E_T^{miss} . The nonprompt muon background is then estimated by applying the fake factor as a weight to events satisfying the same selection as the SR, but with at least one loose-not-tight muon required. The modeling of the estimated reducible background is studied in a validation

region (VR), which is disjoint to both the SR and the $\text{CR}_{3\ell}$. The VR is defined using the same selections used for the SR but with two opposite-sign electrons with $p_T > 20$ GeV and a muon that satisfies the “tight” identification criteria. The nonprompt muon background in this VR is also estimated with the fake-factor method. The sum of the estimated nonprompt background yield and the MC prediction is consistent with data within the statistical uncertainties.

V. EVENT CLASSIFICATION WITH A PARAMETRIZED DEEP NEURAL NETWORK

The signal and background have different distributions for the various kinematic variables. A *parametrized deep neural network* (pDNN) [65] is used to combine several discriminating variables into a single final discriminant. The pDNN architecture allows the training of a single classifier for multiple signal mass hypotheses in the search range by adding a mass parameter together with other inputs. The mass parameter is equal to the value of the nominal generated Z' mass for the signal component, while a random value is drawn from the same distribution for the background mass parameter. In the evaluation process, when applying the training results to real data, the mass parameter takes the value of the investigated signal mass. The algorithm was implemented in the PyTorch [66] framework. Two classifiers are trained for low (high) Z' mass searches using mass parameters less than (greater than or equal to) 40 GeV. A set of kinematic distributions was used for pDNN training input features: the p_T of each muon, the invariant mass of the Z_1 , Z_2 and three-muon system, $\Delta\phi$ of each muon pair that forms the Z_1 and Z_2 , E_T^{miss} , H_T , which is the scalar sum of E_T^{miss} and the p_T of all muons, $V_T = \sqrt{H_{T,x}^2 + H_{T,y}^2}$, and $M_T = \sqrt{H_T^2 - V_T^2}$, where $H_{T,x}(H_{T,y})$ is the scalar sum of E_T^{miss} and the p_T of all muons along the direction of the $x(y)$ axis.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties due to imperfect modeling of the detector in the simulation or the underlying physics of each process are also considered for the prediction of signal and background processes.

Experimental uncertainties originate mainly from E_T^{miss} resolution and scale, measurements of muon momentum resolutions and scales, muon reconstruction and identification

efficiencies, jet energy scale and resolution, and b -tagging efficiency. Uncertainties due to the trigger selection efficiency and pileup correction are also considered. In addition, the uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [28], obtained using the LUCID-2 detector [67] for the primary luminosity measurements. Overall, the total experimental uncertainty in the predicted yields is 5% (7%) for the signal (background with prompt muons).

The theoretical uncertainties in the signal, and the major prompt background due to the diboson processes, include the uncertainties in PDFs, QCD scales, and α_s . The PDF uncertainty is estimated following the PDF4LHC [68] procedure. The α_s uncertainty is estimated by varying the nominal $\alpha_s = 0.118$ by its uncertainty of ± 0.001 . The QCD scale uncertainty is estimated by varying the renormalization and factorization scales, following the procedure described in Ref. [69]. The parton showering uncertainty is estimated by comparing events with different parton shower parameters in the Sherpa MC samples. The total theoretical uncertainties in the reconstructed event yields for the signal and the $q\bar{q}' \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$ background processes are estimated to be 15% and 13%, respectively, dominated by the QCD scale uncertainty. The interference effect between the signal and SM DY background is about 2%, and this effect is accounted as an uncertainty affecting the signal.

Systematic uncertainties assigned to the reducible background, about 11% in total, mainly account for the measurement of the fake factors, the differences between the composition of the events with fake leptons between Z + jets events and the events in the SR, and data statistical uncertainties in the dedicated region where fake factors are applied. The overall impact of systematic uncertainties in the search sensitivity is a degradation on the expected cross section limits up to 14% in the mass range considered.

VII. RESULTS

A simultaneous profile binned maximum-likelihood fit [70–72] to the distribution of pDNN score in the SR and the event yield of the $\text{CR}_{3\ell}$ is performed to constrain uncertainties and obtain information about a possible signal. The normalizations of both the signal and the $q\bar{q}' \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$ background are allowed to vary freely in the fit. The systematic uncertainties are modeled as nuisance

TABLE I. Summary of observed and expected background yields in the SR after the likelihood fit under the background-only hypothesis. The “Nonprompt” represents the contribution from nonprompt muons. The uncertainty in the total background yield can be smaller than the quadrature sum of the contributions because of correlations resulting from the fit. The expected signal yield obtained using the theoretical cross section for a benchmark point ($m_{Z'} = 19$ GeV, $g_{Z'} = 0.0085$) is also shown with its prefit uncertainty.

Data	Total background	$q\bar{q}' \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$	$q\bar{q}/gg \rightarrow \ell^+ \ell^- \ell^+ \ell^-$	Nonprompt	Signal
3089	3080 ± 54	1125 ± 75	396 ± 51	1559 ± 86	36.5 ± 0.5

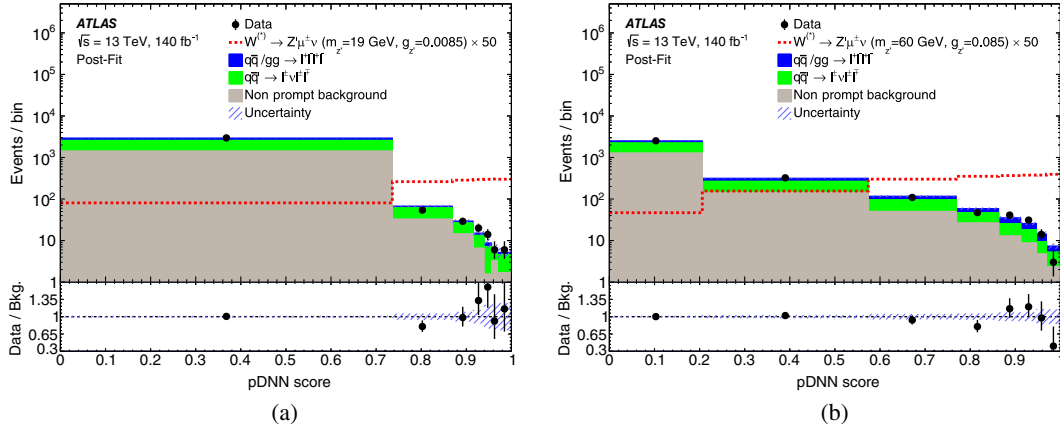


FIG. 2. The distributions of the pDNN score corresponding to (a) $m_{Z'} = 19$ GeV and (b) $m_{Z'} = 60$ GeV in the SR for the data and postfit background contributions. Signals are overlaid, with the predicted yield scaled up by a factor of 50. The error bands include experimental and theoretical systematic uncertainties. The ratio of the data to the background (“Bkg”) prediction is shown in the lower panel.

parameters subject to Gaussian constraints in the likelihood fit. The expected signal yields and pDNN scores are interpolated across the MC generated signal samples and are used in the fitting process. The fit is independently performed for each signal mass point since the pDNN score depends on the value of $m_{Z'}$ under test. The binning of the pDNN distribution varies with each signal mass point to limit the size of the MC statistical uncertainties to at most 20% per bin and also to maximize the expected signal sensitivity.

Table I shows the expected background and observed event yields in the SR after the background-only fit. The normalization factor of the $q\bar{q} \rightarrow \ell^\pm \nu \ell^\pm \ell^\mp$ background

is determined to be 0.92 ± 0.08 and 0.91 ± 0.09 when the pDNN score is obtained with $m_{Z'} = 19$ GeV and $m_{Z'} = 60$ GeV, respectively. The corresponding distributions of the pDNN score are presented in Fig. 2. Examples of kinematic distributions after the background-only fit are presented in Appendix.

No significant deviation from the SM background hypothesis is observed, and the largest excess of events is found for $m_{Z'}$ around 18.3 GeV, with a local significance of 2.4σ and global significance of 0.8σ . Exclusion limits are set using the CL_s method [73]. Upper limits at 95% confidence level (CL) on the cross section times branching fraction of the process $pp \rightarrow W^{\pm(*)} \rightarrow Z'\mu^\pm \nu \rightarrow \mu^\pm \mu^\mp \mu^\pm \nu$ are shown in Fig. 3 as a function of $m_{Z'}$.

A statistical combination with the ATLAS search for Z' in the 4μ channel [24] is performed to improve the overall sensitivity. The coupling parameter g is used as a common parameter of interest for the 3μ and 4μ channels. The contribution of the signal process $pp \rightarrow Z'^{(*)} \rightarrow Z'\mu^+ \mu^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ in the SR of the 3μ channel is also considered. Common experimental uncertainties and theoretical modeling uncertainties are fully correlated. The uncertainties relevant to backgrounds are uncorrelated due to a different background estimate in the 4μ channel. Upper limits at 95% CL on the coupling parameter g as a function of $m_{Z'}$ are shown in Fig. 4(a). The combined exclusion limits are significantly improved relative to the 4μ channel. The improvement is up to 40% in the high-mass region, where the 3μ channel dominates the sensitivity. In Fig. 4(b), the results are also compared with the exclusion regions inferred from a measurement of neutrino tridents by the CCFR Collaboration [74] and the B_s mixing measurements by a global analysis performed in Ref. [21]. The large region in the parameter space up to 81 GeV allowed by the neutrino trident and B_s measurements is now largely excluded.

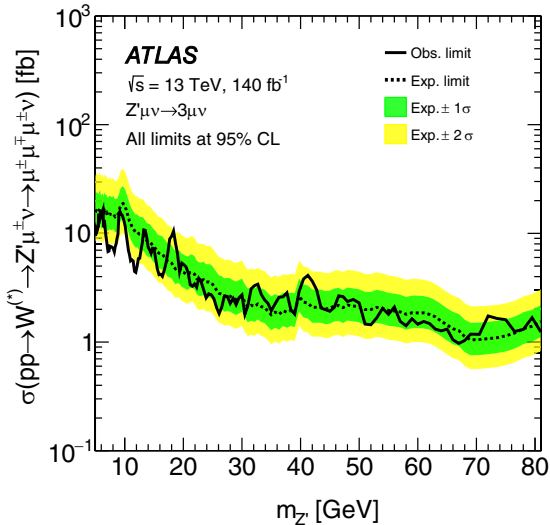


FIG. 3. Observed (solid line) and expected (dashed line) upper limits at 95% CL on the production cross section times branching fraction of the process $pp \rightarrow W^{\pm(*)} \rightarrow Z'\mu^\pm \nu \rightarrow \mu^\pm \mu^\mp \mu^\pm \nu$ as a function of $m_{Z'}$. The surrounding shaded bands correspond to ± 1 and ± 2 standard deviations around the expected limit.

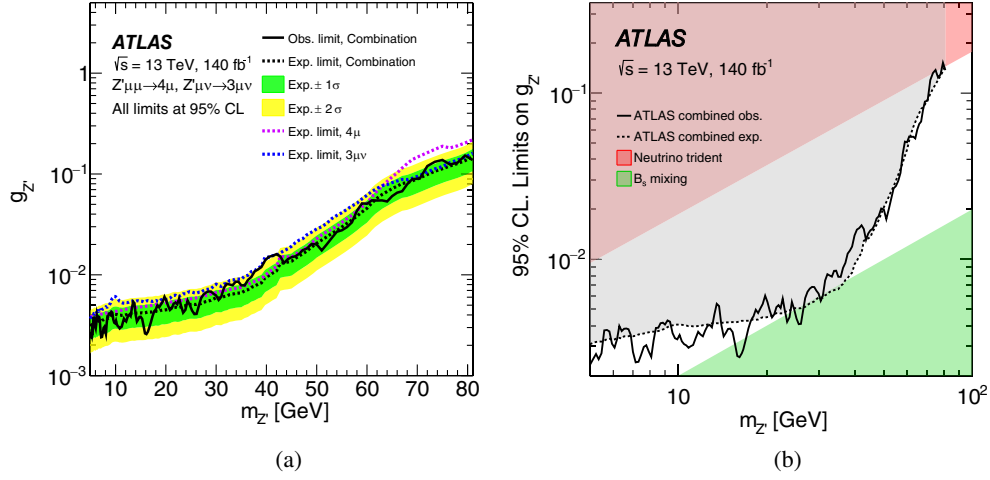


FIG. 4. Results from the statistical combination of the 3μ and 4μ channels: (a) observed and expected 95% CL upper limits on g as a function of $m_{Z'}$, (b) exclusion contour of g compared with the limits inferred from the neutrino-trident (red) and the B_s mixing (green) experimental results [21].

In conclusion, the search for a $L_\mu - L_\tau$ gauge boson Z' using charged-current Drell–Yan production is reported for the first time at the LHC, with a final state of 3μ plus large missing transverse momentum, using 140 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton–proton collision data collected with the ATLAS detector. This search benefits from the considerably higher Z' production cross section compared with previous searches using the neutral-current Drell–Yan production, and has better sensitivity for $m_{Z'} > 60 \text{ GeV}$.

No significant excess of events over the expected SM background is observed. Upper limits are set on the Z' production cross section times the decay branching fraction of the $pp \rightarrow W^{\pm(*)} \rightarrow Z'\mu^\pm\nu \rightarrow \mu^\pm\mu^\mp\mu^\pm\nu$ process in a Z' mass range of 5–81 GeV. The search is further statistically combined with the Z' search using neutral-current Drell–Yan production with a 4μ final state [24]. The most stringent exclusion limits to date are set in the allowed parameter space of the Z' coupling strength and $m_{Z'}$.

APPENDIX

The Z' mass resonance can be reconstructed either from m_{Z_1} or m_{Z_2} as shown in Fig. 5, depending on the value of $m_{Z'}$.

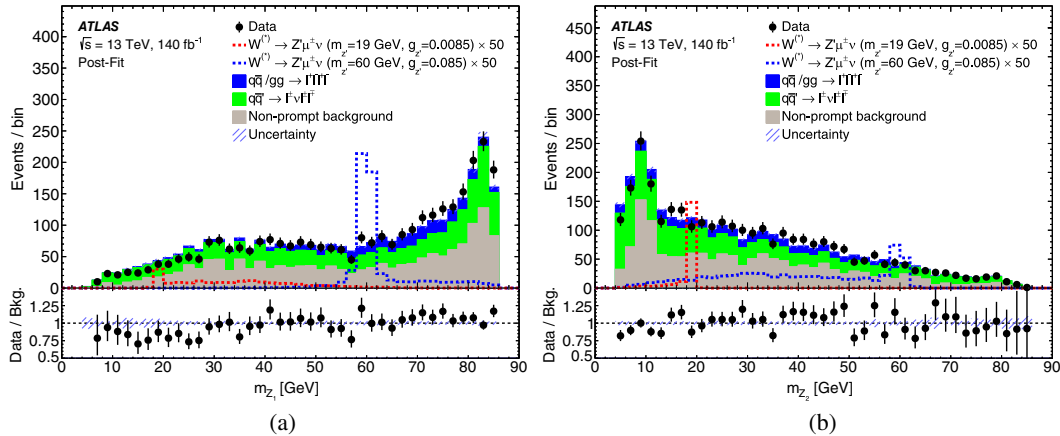


FIG. 5. Comparison of data and postfit SM prediction for (a) the invariant mass of the leading $\mu^+\mu^-$ pair, m_{Z_1} , (b) the invariant mass of the subleading $\mu^+\mu^-$ pair, m_{Z_2} , in the SR. Two representative signals with masses of 19 GeV and 60 GeV are also overlaid, with the predicted yield scaled up by a factor of 50. The error bands include experimental and theoretical systematic uncertainties. The ratio of the data to the background (“Bkg”) prediction is shown in the lower panel.

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Y. C. Cekmecelioglu,⁴⁸ E. Celebi,^{21a} F. Celli,¹²⁷ M. S. Centonze,^{70a,70b} V. Cepaitis,⁵⁶ K. Cerny,¹²³ A. S. Cerqueira,^{83a}
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R. Cherkaoui El Moursli,^{35e} E. Cheu,⁷ K. Cheung,⁶⁵ L. Chevalier,¹³⁶ V. Chiarella,⁵³ G. Chiarelli,^{74a} N. Chiedde,¹⁰³
G. Chiodini,^{70a} A. S. Chisholm,²⁰ A. Chitan,^{27b} M. Chitishvili,¹⁶⁴ M. V. Chizhov,^{38,t} K. Choi,¹¹ Y. Chou,¹³⁹ E. Y. S. Chow,¹¹⁴
K. L. Chu,¹⁷⁰ M. C. Chu,^{64a} X. Chu,^{14a,14e} J. Chudoba,¹³² J. J. Chwastowski,⁸⁷ D. Cieri,¹¹¹ K. M. Ciesla,^{86a} V. Cindro,⁹⁴
A. Ciocio,^{17a} F. Ciotto,^{72a,72b} Z. H. Citron,^{170,1} M. Citterio,^{71a} D. A. Ciubotaru,^{27b} A. Clark,⁵⁶ P. J. Clark,⁵² C. Clarry,¹⁵⁶
J. M. Clavijo Columbie,⁴⁸ S. E. Clawson,⁴⁸ C. Clement,^{47a,47b} J. Clercx,⁴⁸ Y. Coadou,¹⁰³ M. Cobal,^{69a,69c} A. Coccoaro,^{57b}
R. F. Coelho Barrue,^{131a} R. Coelho Lopes De Sa,¹⁰⁴ S. Coelli,^{71a} B. Cole,⁴¹ J. Collot,⁶⁰ P. Conde Muno,^{131a,131g}
M. P. Connell,^{33c} S. H. Connell,^{33c} E. I. Conroy,¹²⁷ F. Conventi,^{72a,ai} H. G. Cooke,²⁰ A. M. Cooper-Sarkar,¹²⁷
A. Cordeiro Oudot Choi,¹²⁸ L. D. Corpe,⁴⁰ M. Corradi,^{75a,75b} F. Corriveau,^{105,z} A. Cortes-Gonzalez,¹⁸ M. J. Costa,¹⁶⁴
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F. Crescioli,¹²⁸ M. Cristinziani,¹⁴² M. Cristoforetti,^{78a,78b} V. Croft,¹¹⁵ J. E. Crosby,¹²² G. Crosetti,^{43b,43a} A. Cueto,¹⁰⁰
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T. Dado,⁴⁹ S. Dahbi,¹⁴⁹ T. Dai,¹⁰⁷ D. Dal Santo,¹⁹ C. Dallapiccola,¹⁰⁴ M. Dam,⁴² G. D'amen,²⁹ V. D'Amico,¹¹⁰ J. Damp,¹⁰¹
J. R. Dandoy,³⁴ M. Danninger,¹⁴³ V. Dao,³⁶ G. Darbo,^{57b} S. Darmora,⁶ S. J. Das,^{29,aj} S. D'Auria,^{71a,71b} A. D'Avanzo,^{131a}
C. David,^{33a} T. Davidek,¹³⁴ B. Davis-Purcell,³⁴ I. Dawson,⁹⁵ H. A. Day-hall,¹³³ K. De,⁸ R. De Asmundis,^{72a} N. De Biase,⁴⁸
S. De Castro,^{23b,23a} N. De Groot,¹¹⁴ P. de Jong,¹¹⁵ H. De la Torre,¹¹⁶ A. De Maria,^{14c} A. De Salvo,^{75a} U. De Sanctis,^{76a,76b}
F. De Santis,^{70a,70b} A. De Santo,¹⁴⁷ J. B. De Vivie De Regie,⁶⁰ D. V. Dedovich,³⁸ J. Degens,¹¹⁵ A. M. Deiana,⁴⁴
F. Del Corso,^{23b,23a} J. Del Peso,¹⁰⁰ F. Del Rio,^{63a} L. Delagr nge,¹²⁸ F. Deliot,¹³⁶ C. M. Delitzsch,⁴⁹ M. Della Pietra,^{72a,72b}
D. Della Volpe,⁵⁶ A. Dell'Acqua,³⁶ L. Dell'Asta,^{71a,71b} M. Delmastro,⁴ P. A. Delsart,⁶⁰ S. Demers,¹⁷³ M. Demichev,³⁸
S. P. Denisov,³⁷ L. D'Eramo,⁴⁰ D. Derendarz,⁸⁷ F. Derue,¹²⁸ P. Dervan,⁹³ K. Desch,²⁴ C. Deutsch,²⁴ F. A. Di Bello,^{57b,57a}
A. Di Ciaccio,^{76a,76b} L. Di Ciaccio,⁴ A. Di Domenico,^{75a,75b} C. Di Donato,^{72a,72b} A. Di Girolamo,³⁶ G. Di Gregorio,³⁶
A. Di Luca,^{78a,78b} B. Di Micco,^{77a,77b} R. Di Nardo,^{77a,77b} M. Diamantopoulou,³⁴ F. A. Dias,¹¹⁵ T. Dias Do Vale,¹⁴³
M. A. Diaz,^{138a,138b} F. G. Diaz Capriles,²⁴ M. Didenko,¹⁶⁴ E. B. Diehl,¹⁰⁷ S. D  ez Cornell,⁴⁸ C. Diez Pardos,¹⁴²
C. Dimitriadi,^{162,24} A. Dimitrievska,^{17a} J. Dingfelder,²⁴ I.-M. Dinu,^{27b} S. J. Dittmeier,^{63b} F. Dittus,³⁶ F. Djama,¹⁰³
T. Djobava,^{150b} C. Doglioni,^{102,99} A. Dohnalova,^{28a} J. Dolejsi,¹³⁴ Z. Dolezal,¹³⁴ K. M. Dona,³⁹ M. Donadelli,^{83c} B. Dong,¹⁰⁸
J. Donini,⁴⁰ A. D'Onofrio,^{72a,72b} M. D'Onofrio,⁹³ J. Dopke,¹³⁵ A. Doria,^{72a} N. Dos Santos Fernandes,^{131a} P. Dougan,¹⁰²
M. T. Dova,⁹¹ A. T. Doyle,⁵⁹ M. A. Dragnet,¹²⁷ E. Dreyer,¹⁷⁰ I. Drivas-koulouris,¹⁰ M. Drnevich,¹¹⁸ M. Drozdova,⁵⁶
D. Du,^{62a} T. A. du Pree,¹¹⁵ F. Dubinin,³⁷ M. Dubovsky,^{28a} E. Duchovni,¹⁷⁰ G. Duckeck,¹¹⁰ O. A. Ducu,^{27b} D. Duda,⁵²
A. Dudarev,³⁶ E. R. Duden,²⁶ M. D'uffizi,¹⁰² L. Duflot,⁶⁶ M. D  hrssen,³⁶ A. E. Dumitriu,^{27b} M. Dunford,^{63a} S. Dungs,⁴⁹
K. Dunne,^{47a,47b} A. Duperrin,¹⁰³ H. Duran Yildiz,^{3a} M. D  ren,⁵⁸ A. Durglishvili,^{150b} B. L. Dwyer,¹¹⁶ G. I. Dyckes,^{17a}
M. Dyndal,^{86a} B. S. Dziedzic,⁸⁷ Z. O. Earnshaw,¹⁴⁷ G. H. Eberwein,¹²⁷ B. Eckerova,^{28a} S. Eggebrecht,⁵⁵
E. Egidio Purcino De Souza,¹²⁸ L. F. Ehrke,⁵⁶ G. Eigen,¹⁶ K. Einsweiler,^{17a} T. Ekelof,¹⁶² P. A. Ekman,⁹⁹ S. El Farkh,^{35b}
Y. El Ghazali,^{35b} H. El Jarrari,³⁶ A. El Moussaouy,¹⁰⁹ V. Ellajosyula,¹⁶² M. Ellert,¹⁶² F. Ellinghaus,¹⁷² N. Ellis,³⁶
J. Elmsheuser,²⁹ M. Elsing,³⁶ D. Emelianov,¹³⁵ Y. Enari,¹⁵⁴ I. Ene,^{17a} S. Epari,¹³ P. A. Erland,⁸⁷ M. Errenst,¹⁷² M. Escalier,⁶⁶
C. Escobar,¹⁶⁴ E. Etzion,¹⁵² G. Evans,^{131a} H. Evans,⁶⁸ L. S. Evans,⁹⁶ A. Ezhilov,³⁷ S. Ezzarqtouni,^{35a} F. Fabbri,^{23b,23a}
L. Fabbri,^{23b,23a} G. Facini,⁹⁷ V. Fadeyev,¹³⁷ R. M. Fakhrutdinov,³⁷ D. Fakoudis,¹⁰¹ S. Falciano,^{75a}
L. F. Falda Ulhoa Coelho,³⁶ P. J. Falke,²⁴ J. Faltova,¹³⁴ C. Fan,¹⁶³ Y. Fan,^{14a} Y. Fang,^{14a,14e} M. Fanti,^{71a,71b} M. Faraj,^{69a,69b}
Z. Farazpay,⁹⁸ A. Farbin,⁸ A. Farilla,^{77a} T. Farooque,¹⁰⁸ S. M. Farrington,⁵² F. Fassi,^{35e} D. Fassouliotis,⁹
M. Fauci Giannelli,^{76a,76b} W. J. Fawcett,³² L. Fayard,⁶⁶ P. Federic,¹³⁴ P. Federicova,¹³² O. L. Fedin,^{37,b} M. Feickert,¹⁷¹
L. Feligioni,¹⁰³ D. E. Fellers,¹²⁴ C. Feng,^{62b} M. Feng,^{14b} Z. Feng,¹¹⁵ M. J. Fenton,¹⁶⁰ L. Ferencz,⁴⁸ R. A. M. Ferguson,⁹²
S. I. Fernandez Luengo,^{138f} P. Fernandez Martinez,¹³ M. J. V. Fernoux,¹⁰³ J. Ferrando,⁹² A. Ferrari,¹⁶² P. Ferrari,^{115,114}
R. Ferrari,^{73a} D. Ferrere,⁵⁶ C. Ferretti,¹⁰⁷ F. Fiedler,¹⁰¹ P. Fiedler,¹³³ A. Filip  i  ,⁹⁴ E. K. Filmer,¹ F. Filthaut,¹¹⁴

- M. C. N. Fiolhais,^{131a,131c,d} L. Fiorini,¹⁶⁴ W. C. Fisher,¹⁰⁸ T. Fitschen,¹⁰² P. M. Fitzhugh,¹³⁶ I. Fleck,¹⁴² P. Fleischmann,¹⁰⁷ T. Flick,¹⁷² M. Flores,^{33d,ae} L. R. Flores Castillo,^{64a} L. Flores Sanz De Acedo,³⁶ F. M. Follega,^{78a,78b} N. Fomin,¹⁶ J. H. Foo,¹⁵⁶ A. Formica,¹³⁶ A. C. Forti,¹⁰² E. Fortin,³⁶ A. W. Fortman,^{17a} M. G. Foti,^{17a} L. Fountas,^{9,k} D. Fournier,⁶⁶ H. Fox,⁹² P. Francavilla,^{74a,74b} S. Francescato,⁶¹ S. Franchellucci,⁵⁶ M. Franchini,^{23b,23a} S. Franchino,^{63a} D. Francis,³⁶ L. Franco,¹¹⁴ V. Franco Lima,³⁶ L. Franconi,⁴⁸ M. Franklin,⁶¹ G. Frattari,²⁶ W. S. Freund,^{83b} Y. Y. Frid,¹⁵² J. Friend,⁵⁹ N. Fritzsche,⁵⁰ A. Froch,⁵⁴ D. Froidevaux,³⁶ J. A. Frost,¹²⁷ Y. Fu,^{62a} S. Fuenzalida Garrido,^{138f} M. Fujimoto,¹⁰³ K. Y. Fung,^{64a} E. Furtado De Simas Filho,^{83b} M. Furukawa,¹⁵⁴ J. Fuster,¹⁶⁴ A. Gabrielli,^{23b,23a} A. Gabrielli,¹⁵⁶ P. Gadow,³⁶ G. Gagliardi,^{57b,57a} L. G. Gagnon,^{17a} S. Galantzan,¹⁵² E. J. Gallas,¹²⁷ B. J. Gallop,¹³⁵ K. K. Gan,¹²⁰ S. Ganguly,¹⁵⁴ Y. Gao,⁵² F. M. Garay Walls,^{138a,138b} B. Garcia,²⁹ C. García,¹⁶⁴ A. Garcia Alonso,¹¹⁵ A. G. Garcia Caffaro,¹⁷³ J. E. García Navarro,¹⁶⁴ M. Garcia-Sciveres,^{17a} G. L. Gardner,¹²⁹ R. W. Gardner,³⁹ N. Garelli,¹⁵⁹ D. Garg,⁸⁰ R. B. Garg,^{144,o} J. M. Gargan,⁵² C. A. Garner,¹⁵⁶ C. M. Garvey,^{33a} P. Gaspar,^{83b} V. K. Gassmann,¹⁵⁹ G. Gaudio,^{73a} V. Gautam,¹³ P. Gauzzi,^{75a,75b} I. L. Gavrilenko,³⁷ A. Gavriluk,³⁷ C. Gay,¹⁶⁵ G. Gaycken,⁴⁸ E. N. Gazis,¹⁰ A. A. Geanta,^{27b} C. M. Gee,¹³⁷ A. Gekow,¹²⁰ C. Gemme,^{57b} M. H. Genest,⁶⁰ A. D. Gentry,¹¹³ S. George,⁹⁶ W. F. George,²⁰ T. Gerialis,⁴⁶ P. Gessinger-Befurt,³⁶ M. E. Geyik,¹⁷² M. Ghani,¹⁶⁸ M. Ghneimat,¹⁴² K. Ghorbanian,⁹⁵ A. Ghosal,¹⁴² A. Ghosh,¹⁶⁰ A. Ghosh,⁷ B. Giacobbe,^{23b} S. Giagu,^{75a,75b} T. Giani,¹¹⁵ P. Giannetti,^{74a} A. Giannini,^{62a} S. M. Gibson,⁹⁶ M. Gignac,¹³⁷ D. T. Gil,^{86b} A. K. Gilbert,^{86a} B. J. Gilbert,⁴¹ D. Gillberg,³⁴ G. Gilles,¹¹⁵ L. Ginabat,¹²⁸ D. M. Gingrich,^{2,ah} M. P. Giordani,^{69a,69c} P. F. Giraud,¹³⁶ G. Giugliarelli,^{69a,69c} D. Giugni,^{71a} F. Giuli,³⁶ I. Gkialas,^{9,k} L. K. Gladilin,³⁷ C. Glasman,¹⁰⁰ G. R. Gledhill,¹²⁴ G. Glemža,⁴⁸ M. Glisic,¹²⁴ I. Gnesi,^{43b,g} Y. Go,²⁹ M. Goblirsch-Kolb,³⁶ B. Gocke,⁴⁹ D. Godin,¹⁰⁹ B. Gokturk,^{21a} S. Goldfarb,¹⁰⁶ T. Golling,⁵⁶ M. G. D. Gololo,^{33g} D. Golubkov,³⁷ J. P. Gombas,¹⁰⁸ A. Gomes,^{131a,131b} G. Gomes Da Silva,¹⁴² A. J. Gomez Delegido,¹⁶⁴ R. Gonçalves,^{131a,131c} L. Gonella,²⁰ A. Gongadze,^{150c} F. Gonnella,²⁰ J. L. Gonski,¹⁴⁴ R. Y. González Andana,⁵² S. González de la Hoz,¹⁶⁴ R. Gonzalez Lopez,⁹³ C. Gonzalez Renteria,^{17a} M. V. Gonzalez Rodrigues,⁴⁸ R. Gonzalez Suarez,¹⁶² S. Gonzalez-Sevilla,⁵⁶ G. R. Gonzalvo Rodriguez,¹⁶⁴ L. Goossens,³⁶ B. Gorini,³⁶ E. Gorini,^{70a,70b} A. Gorišek,⁹⁴ T. C. Gosart,¹²⁹ A. T. Goshaw,⁵¹ M. I. Gostkin,³⁸ S. Goswami,¹²² C. A. Gottardo,³⁶ S. A. Gotz,¹¹⁰ M. Gouighri,^{35b} V. Goumarre,⁴⁸ A. G. Goussiou,¹³⁹ N. Govender,^{33c} I. Grabowska-Bold,^{86a} K. Graham,³⁴ E. Gramstad,¹²⁶ S. Grancagnolo,^{70a,70b} C. M. Grant,^{1,136} P. M. Gravila,^{27f} F. G. Gravili,^{70a,70b} H. M. Gray,^{17a} M. Greco,^{70a,70b} C. Grefe,²⁴ I. M. Gregor,⁴⁸ P. Grenier,¹⁴⁴ S. G. Grewe,¹¹¹ A. A. Grillo,¹³⁷ K. Grimm,³¹ S. Grinstein,^{13,v} J.-F. Grivaz,⁶⁶ E. Gross,¹⁷⁰ J. Grosse-Knetter,⁵⁵ J. C. Grundy,¹²⁷ L. Guan,¹⁰⁷ C. Gubbels,¹⁶⁵ J. G. R. Guerrero Rojas,¹⁶⁴ G. Guerrieri,^{69a,69c} F. Guescini,¹¹¹ R. Gugel,¹⁰¹ J. A. M. Guhit,¹⁰⁷ A. Guida,¹⁸ E. Guilloton,¹⁶⁸ S. Guindon,³⁶ F. Guo,^{14a,14e} J. Guo,^{62c} L. Guo,⁴⁸ Y. Guo,¹⁰⁷ R. Gupta,⁴⁸ R. Gupta,¹³⁰ S. Gurbuz,²⁴ S. S. Gurdasani,⁵⁴ G. Gustavino,³⁶ M. Guth,⁵⁶ P. Gutierrez,¹²¹ L. F. Gutierrez Zagazeta,¹²⁹ M. Gutsche,⁵⁰ C. Gutschow,⁹⁷ C. Gwenlan,¹²⁷ C. B. Gwilliam,⁹³ E. S. Haaland,¹²⁶ A. Haas,¹¹⁸ M. Habedank,⁴⁸ C. Haber,^{17a} H. K. Hadavand,⁸ A. Hadeef,⁵⁰ S. Hadzic,¹¹¹ A. I. Hagan,⁹² J. J. Hahn,¹⁴² E. H. Haines,⁹⁷ M. Haleem,¹⁶⁷ J. Haley,¹²² J. J. Hall,¹⁴⁰ G. D. Hallewell,¹⁰³ L. Halser,¹⁹ K. Hamano,¹⁶⁶ M. Hamer,²⁴ G. N. Hamity,⁵² E. J. Hampshire,⁹⁶ J. Han,^{62b} K. Han,^{62a} L. Han,^{14c} L. Han,^{62a} S. Han,^{17a} Y. F. Han,¹⁵⁶ K. Hanagaki,⁸⁴ M. Hance,¹³⁷ D. A. Hangal,⁴¹ H. Hanif,¹⁴³ M. D. Hank,¹²⁹ J. B. Hansen,⁴² P. H. Hansen,⁴² K. Hara,¹⁵⁸ D. Harada,⁵⁶ T. Harenberg,¹⁷² S. Harkusha,³⁷ M. L. Harris,¹⁰⁴ Y. T. Harris,¹²⁷ J. Harrison,¹³ N. M. Harrison,¹²⁰ P. F. Harrison,¹⁶⁸ N. M. Hartman,¹¹¹ N. M. Hartmann,¹¹⁰ Y. Hasegawa,¹⁴¹ R. Hauser,¹⁰⁸ C. M. Hawkes,²⁰ R. J. Hawkings,³⁶ Y. Hayashi,¹⁵⁴ S. Hayashida,¹¹² D. Hayden,¹⁰⁸ C. Hayes,¹⁰⁷ R. L. Hayes,¹¹⁵ C. P. Hays,¹²⁷ J. M. Hays,⁹⁵ H. S. Hayward,⁹³ F. He,^{62a} M. He,^{14a,14e} Y. He,¹⁵⁵ Y. He,⁴⁸ Y. He,⁹⁷ N. B. Heatley,⁹⁵ V. Hedberg,⁹⁹ A. L. Heggelund,¹²⁶ N. D. Hehir,^{95,a} C. Heidegger,⁵⁴ K. K. Heidegger,⁵⁴ W. D. Heidorn,⁸¹ J. Heilman,³⁴ S. Heim,⁴⁸ T. Heim,^{17a} J. G. Heinlein,¹²⁹ J. J. Heinrich,¹²⁴ L. Heinrich,^{111,af} J. Hejbal,¹³² A. Held,¹⁷¹ S. Hellesund,¹⁶ C. M. Helling,¹⁶⁵ S. Hellman,^{47a,47b} R. C. W. Henderson,⁹² L. Henkelmann,³² A. M. Henriques Correia,³⁶ H. Herde,⁹⁹ Y. Hernández Jiménez,¹⁴⁶ L. M. Herrmann,²⁴ T. Herrmann,⁵⁰ G. Herten,⁵⁴ R. Hertenberger,¹¹⁰ L. Hervas,³⁶ M. E. Hespington,¹⁰¹ N. P. Hessey,^{157a} E. Hill,¹⁵⁶ S. J. Hillier,²⁰ J. R. Hinds,¹⁰⁸ F. Hinterkeuser,²⁴ M. Hirose,¹²⁵ S. Hirose,¹⁵⁸ D. Hirschbuehl,¹⁷² T. G. Hitchings,¹⁰² B. Hiti,⁹⁴ J. Hobbs,¹⁴⁶ R. Hobincu,^{27e} N. Hod,¹⁷⁰ M. C. Hodgkinson,¹⁴⁰ B. H. Hodgkinson,¹²⁷ A. Hoecker,³⁶ D. D. Hofer,¹⁰⁷ J. Hofer,⁴⁸ T. Holm,²⁴ M. Holzbock,¹¹¹ L. B. A. H. Hommels,³² B. P. Honan,¹⁰² J. Hong,^{62c} T. M. Hong,¹³⁰ B. H. Hooberman,¹⁶³ W. H. Hopkins,⁶ Y. Horii,¹¹² S. Hou,¹⁴⁹ A. S. Howard,⁹⁴ J. Howarth,⁵⁹ J. Hoya,⁶ M. Hrabovsky,¹²³ A. Hrynevich,⁴⁸ T. Hryn'ova,⁴ P. J. Hsu,⁶⁵ S.-C. Hsu,¹³⁹ Q. Hu,^{62a} S. Huang,^{64b} X. Huang,^{14c} X. Huang,^{14a,14e} Y. Huang,¹⁴⁰ Y. Huang,^{14a} Z. Huang,¹⁰² Z. Hubacek,¹³³ M. Huebner,²⁴ F. Huegging,²⁴ T. B. Huffman,¹²⁷ C. A. Hugli,⁴⁸ M. Huhtinen,³⁶ S. K. Huiberts,¹⁶ R. Hulsken,¹⁰⁵ N. Huseynov,¹² J. Huston,¹⁰⁸ J. Huth,⁶¹ R. Hyneman,¹⁴⁴ G. Iacobucci,⁵⁶ G. Iakovidis,²⁹ I. Ibragimov,¹⁴²

L. Iconomidou-Fayard,⁶⁶ J. P. Iddon,³⁶ P. Iengo,^{72a,72b} R. Iguchi,¹⁵⁴ T. Iizawa,¹²⁷ Y. Ikegami,⁸⁴ N. Ilic,¹⁵⁶ H. Imam,^{35a} M. Ince Lezki,⁵⁶ T. Ingebretsen Carlson,^{47a,47b} G. Introzzi,^{73a,73b} M. Iodice,^{77a} V. Ippolito,^{75a,75b} R. K. Irwin,⁹³ M. Ishino,¹⁵⁴ W. Islam,¹⁷¹ C. Issever,^{18,48} S. Istin,^{21a,al} H. Ito,¹⁶⁹ R. Iuppa,^{78a,78b} A. Ivina,¹⁷⁰ J. M. Izen,⁴⁵ V. Izzo,^{72a} P. Jacka,^{132,133} P. Jackson,¹ B. P. Jaeger,¹⁴³ C. S. Jagfeld,¹¹⁰ G. Jain,^{157a} P. Jain,⁵⁴ K. Jakobs,⁵⁴ T. Jakoubek,¹⁷⁰ J. Jamieson,⁵⁹ K. W. Janas,^{86a} M. Javurkova,¹⁰⁴ L. Jeanty,¹²⁴ J. Jejelava,^{150a,ac} P. Jenni,^{54,h} C. E. Jessiman,³⁴ C. Jia,^{62b} J. Jia,¹⁴⁶ X. Jia,⁶¹ X. Jia,^{14a,14e} Z. Jia,^{14c} S. Jiggins,⁴⁸ J. Jimenez Pena,¹³ S. Jin,^{14c} A. Jinaru,^{27b} O. Jinnouchi,¹⁵⁵ P. Johansson,¹⁴⁰ K. A. Johns,⁷ J. W. Johnson,¹³⁷ D. M. Jones,³² E. Jones,⁴⁸ P. Jones,³² R. W. L. Jones,⁹² T. J. Jones,⁹³ H. L. Joos,^{55,36} R. Joshi,¹²⁰ J. Jovicevic,¹⁵ X. Ju,^{17a} J. J. Junggeburth,¹⁰⁴ T. Junkermann,^{63a} A. Juste Rozas,^{13,v} M. K. Juzek,⁸⁷ S. Kabana,^{138e} A. Kaczmarzka,⁸⁷ M. Kado,¹¹¹ H. Kagan,¹²⁰ M. Kagan,¹⁴⁴ A. Kahn,⁴¹ A. Kahn,¹²⁹ C. Kahra,¹⁰¹ T. Kaji,¹⁵⁴ E. Kajomovitz,¹⁵¹ N. Kakati,¹⁷⁰ I. Kalaitzidou,⁵⁴ C. W. Kalderon,²⁹ N. J. Kang,¹³⁷ D. Kar,^{33g} K. Karava,¹²⁷ M. J. Kareem,^{157b} E. Karentzos,⁵⁴ I. Karkanas,¹⁵³ O. Karkout,¹¹⁵ S. N. Karpov,³⁸ Z. M. Karpova,³⁸ V. Kartvelishvili,⁹² A. N. Karyukhin,³⁷ E. Kasimi,¹⁵³ J. Katzy,⁴⁸ S. Kaur,³⁴ K. Kawade,¹⁴¹ M. P. Kawale,¹²¹ C. Kawamoto,⁸⁸ T. Kawamoto,^{62a} E. F. Kay,³⁶ F. I. Kaya,¹⁵⁹ S. Kazakos,¹⁰⁸ V. F. Kazanin,³⁷ Y. Ke,¹⁴⁶ J. M. Keaveney,^{33a} R. Keeler,¹⁶⁶ G. V. Kehris,⁶¹ J. S. Keller,³⁴ A. S. Kelly,⁹⁷ J. J. Kempster,¹⁴⁷ P. D. Kennedy,¹⁰¹ O. Kepka,¹³² B. P. Kerridge,¹³⁵ S. Kersten,¹⁷² B. P. Kerševan,⁹⁴ S. Keshri,⁶⁶ L. Keszeghova,^{28a} S. Ketabchi Haghighat,¹⁵⁶ R. A. Khan,¹³⁰ A. Khanov,¹²² A. G. Kharlamov,³⁷ T. Kharlamova,³⁷ E. E. Khoda,¹³⁹ M. Kholodenko,³⁷ T. J. Khoo,¹⁸ G. Khoriali,¹⁶⁷ J. Khubua,^{150b,a} Y. A. R. Khwaira,⁶⁶ B. Kibirige,^{33g} A. Kilgallon,¹²⁴ D. W. Kim,^{47a,47b} Y. K. Kim,³⁹ N. Kimura,⁹⁷ M. K. Kingston,⁵⁵ A. Kirchhoff,⁵⁵ C. Kirfel,²⁴ F. Kirfel,²⁴ J. Kirk,¹³⁵ A. E. Kiryunin,¹¹¹ C. Kitsaki,¹⁰ O. Kivernyk,²⁴ M. Klassen,^{63a} C. Klein,³⁴ L. Klein,¹⁶⁷ M. H. Klein,⁴⁴ S. B. Klein,⁵⁶ U. Klein,⁹³ P. Klimek,³⁶ A. Klimentov,²⁹ T. Klioutchnikova,³⁶ P. Kluit,¹¹⁵ S. Kluth,¹¹¹ E. Kneringer,⁷⁹ T. M. Knight,¹⁵⁶ A. Knue,⁴⁹ R. Kobayashi,⁸⁸ D. Kobylanski,¹⁷⁰ S. F. Koch,¹²⁷ M. Kocian,¹⁴⁴ P. Kodyš,¹³⁴ D. M. Koeck,¹²⁴ P. T. Koenig,²⁴ T. Koffas,³⁴ O. Kolay,⁵⁰ I. Koletsou,⁴ T. Komarek,¹²³ K. Köneke,⁵⁴ A. X. Y. Kong,¹ T. Kono,¹¹⁹ N. Konstantinidis,⁹⁷ P. Kontaxakis,⁵⁶ B. Konya,⁹⁹ R. Kopeliansky,⁶⁸ S. Koperny,^{86a} K. Korcyl,⁸⁷ K. Kordas,^{153,f} A. Korn,⁹⁷ S. Korn,⁵⁵ I. Korolkov,¹³ N. Korotkova,³⁷ B. Kortman,¹¹⁵ O. Kortner,¹¹¹ S. Kortner,¹¹¹ W. H. Kostecka,¹¹⁶ V. V. Kostyukhin,¹⁴² A. Kotskechagia,¹³⁶ A. Kotwal,⁵¹ A. Koulouris,³⁶ A. Kourkoumeli-Charalampidi,^{73a,73b} C. Kourkoumelis,⁹ E. Kourlitis,^{111,af} O. Kovanda,¹²⁴ R. Kowalewski,¹⁶⁶ W. Kozański,¹³⁶ A. S. Kozhin,³⁷ V. A. Kramarenko,³⁷ G. Kramberger,⁹⁴ P. Kramer,¹⁰¹ M. W. Krasny,¹²⁸ A. Krasznahorkay,³⁶ J. W. Kraus,¹⁷² J. A. Kremer,⁴⁸ T. Kresse,⁵⁰ J. Kretschmar,⁹³ K. Kreul,¹⁸ P. Krieger,¹⁵⁶ S. Krishnamurthy,¹⁰⁴ M. Krivos,¹³⁴ K. Krizka,²⁰ K. Kroeninger,⁴⁹ H. Kroha,¹¹¹ J. Kroll,¹³² J. Kroll,¹²⁹ K. S. Krowpman,¹⁰⁸ U. Kruchonak,³⁸ H. Krüger,²⁴ N. Krumnack,⁸¹ M. C. Kruse,⁵¹ O. Kuchinskaia,³⁷ S. Kудay,^{3a} S. Kuehn,³⁶ R. Kuesters,⁵⁴ T. Kuhl,⁴⁸ V. Kukhtin,³⁸ Y. Kulchitsky,^{37,b} S. Kuleshov,^{138d,138b} M. Kumar,^{33g} N. Kumari,⁴⁸ P. Kumari,^{157b} A. Kupco,¹³² T. Kupfer,⁴⁹ A. Kupich,³⁷ O. Kuprash,⁵⁴ H. Kurashige,⁸⁵ L. L. Kurchaninov,^{157a} O. Kurdysh,⁶⁶ Y. A. Kurochkin,³⁷ A. Kurova,³⁷ M. Kuze,¹⁵⁵ A. K. Kvam,¹⁰⁴ J. Kvita,¹²³ T. Kwan,¹⁰⁵ N. G. Kyriacou,¹⁰⁷ L. A. O. Laatu,¹⁰³ C. Lacasta,¹⁶⁴ F. Lacava,^{75a,75b} H. Lacker,¹⁸ D. Lacour,¹²⁸ N. N. Lad,⁹⁷ E. Ladygin,³⁸ B. Laforge,¹²⁸ T. Lagouri,^{27b} F. Z. Lahbabi,^{35a} S. Lai,⁵⁵ N. Lalloue,⁶⁰ J. E. Lambert,¹⁶⁶ S. Lammers,⁶⁸ W. Lampl,⁷ C. Lampoudis,^{153,f} G. Lamprinoudis,¹⁰¹ A. N. Lancaster,¹¹⁶ E. Lançon,²⁹ U. Landgraf,⁵⁴ M. P. J. Landon,⁹⁵ V. S. Lang,⁵⁴ O. K. B. Langrekken,¹²⁶ A. J. Lankford,¹⁶⁰ F. Lanni,³⁶ K. Lantzsche,²⁴ A. Lanza,^{73a} A. Lapertosa,^{57b,57a} J. F. Laporte,¹³⁶ T. Lari,^{71a} F. Lasagni Manghi,^{23b} M. Lassnig,³⁶ V. Latonova,¹³² A. Laudrain,¹⁰¹ A. Laurier,¹⁵¹ S. D. Lawlor,¹⁴⁰ Z. Lawrence,¹⁰² R. Lazaridou,¹⁶⁸ M. Lazzaroni,^{71a,71b} B. Le,¹⁰² E. M. Le Boulicaut,⁵¹ B. Leban,⁹⁴ A. Lebedev,⁸¹ M. LeBlanc,¹⁰² F. Ledroit-Guillon,⁶⁰ A. C. A. Lee,⁹⁷ S. C. Lee,¹⁴⁹ S. Lee,^{47a,47b} T. F. Lee,⁹³ L. L. Leeuw,^{33c} H. P. Lefebvre,⁹⁶ M. Lefebvre,¹⁶⁶ C. Leggett,^{17a} G. Lehmann Miotto,³⁶ M. Leigh,⁵⁶ W. A. Leight,¹⁰⁴ W. Leinonen,¹¹⁴ A. Leisos,^{153,u} M. A. L. Leite,^{83c} C. E. Leitgeb,¹⁸ R. Leitner,¹³⁴ K. J. C. Leney,⁴⁴ T. Lenz,²⁴ S. Leone,^{74a} C. Leonidopoulos,⁵² A. Leopold,¹⁴⁵ C. Leroy,¹⁰⁹ R. Les,¹⁰⁸ C. G. Lester,³² M. Levchenko,³⁷ J. Levêque,⁴ L. J. Levinson,¹⁷⁰ G. Levirini,^{23b,23a} M. P. Lewicki,⁸⁷ D. J. Lewis,⁴ A. Li,⁵ B. Li,^{62b} C. Li,^{62a} C-Q. Li,¹¹¹ H. Li,^{62a} H. Li,^{62b} H. Li,^{14c} H. Li,^{14b} H. Li,^{62b} J. Li,^{62c} K. Li,¹³⁹ L. Li,^{62c} M. Li,^{14a,14e} Q. Y. Li,^{62a} S. Li,^{14a,14e} S. Li,^{62d,62c,e} T. Li,⁵ X. Li,¹⁰⁵ Z. Li,¹²⁷ Z. Li,¹⁰⁵ Z. Li,^{14a,14e} S. Liang,^{14a,14e} Z. Liang,^{14a} M. Liberatore,¹³⁶ B. Liberti,^{76a} K. Lie,^{64c} J. Lieber Marin,^{83b} H. Lien,⁶⁸ K. Lin,¹⁰⁸ R. E. Lindley,⁷ J. H. Lindon,² E. Lipeles,¹²⁹ A. Lipniacka,¹⁶ A. Lister,¹⁶⁵ J. D. Little,⁴ B. Liu,^{14a} B. X. Liu,¹⁴³ D. Liu,^{62d,62c} E. H. L. Liu,²⁰ J. B. Liu,^{62a} J. K. K. Liu,³² K. Liu,^{62d} K. Liu,^{62d,62c} M. Liu,^{62a} M. Y. Liu,^{62a} P. Liu,^{14a} Q. Liu,^{62d,139,62c} X. Liu,^{62a} X. Liu,^{62b} Y. Liu,^{14d,14e} Y. L. Liu,^{62b} Y. W. Liu,^{62a} J. Llorente Merino,¹⁴³ S. L. Lloyd,⁹⁵ E. M. Lobodzinska,⁴⁸ P. Loch,⁷ T. Lohse,¹⁸ K. Lohwasser,¹⁴⁰ E. Loiacono,⁴⁸ M. Lokajicek,^{132,a} J. D. Lomas,²⁰ J. D. Long,¹⁶³ I. Longarini,¹⁶⁰ L. Longo,^{70a,70b} R. Longo,¹⁶³ I. Lopez Paz,⁶⁷ A. Lopez Solis,⁴⁸ N. Lorenzo Martinez,⁴ A. M. Lory,¹¹⁰ G. Löschcke Centeno,¹⁴⁷ O. Loseva,³⁷ X. Lou,^{47a,47b} X. Lou,^{14a,14e}

- A. Lounis,⁶⁶ P. A. Love,⁹² G. Lu,^{14a,14e} M. Lu,⁸⁰ S. Lu,¹²⁹ Y. J. Lu,⁶⁵ H. J. Lubatti,¹³⁹ C. Luci,^{75a,75b} F. L. Lucio Alves,^{14c} F. Luehring,⁶⁸ I. Luise,¹⁴⁶ O. Lukianchuk,⁶⁶ O. Lundberg,¹⁴⁵ B. Lund-Jensen,^{145,a} N. A. Luongo,⁶ M. S. Lutz,³⁶ A. B. Lux,²⁵ D. Lynn,²⁹ R. Lysak,¹³² E. Lytken,⁹⁹ V. Lyubushkin,³⁸ T. Lyubushkina,³⁸ M. M. Lyukova,¹⁴⁶ H. Ma,²⁹ K. Ma,^{62a} L. L. Ma,^{62b} W. Ma,^{62a} Y. Ma,¹²² D. M. Mac Donell,¹⁶⁶ G. Maccarrone,⁵³ J. C. MacDonald,¹⁰¹ P. C. Machado De Abreu Farias,^{83b} R. Madar,⁴⁰ W. F. Mader,⁵⁰ T. Madula,⁹⁷ J. Maeda,⁸⁵ T. Maeno,²⁹ H. Maguire,¹⁴⁰ V. Maiboroda,¹³⁶ A. Maio,^{131a,131b,131d} K. Maj,^{86a} O. Majersky,⁴⁸ S. Majewski,¹²⁴ N. Makovec,⁶⁶ V. Maksimovic,¹⁵ B. Malaescu,¹²⁸ Pa. Malecki,⁸⁷ V. P. Maleev,³⁷ F. Malek,^{60,p} M. Mali,⁹⁴ D. Malito,⁹⁶ U. Mallik,⁸⁰ S. Maltezos,¹⁰ S. Malyukov,³⁸ J. Mamuzic,¹³ G. Mancini,⁵³ M. N. Mancini,²⁶ G. Manco,^{73a,73b} J. P. Mandalia,⁹⁵ I. Mandić,⁹⁴ L. Manhaes de Andrade Filho,^{83a} I. M. Maniatis,¹⁷⁰ J. Manjarres Ramos,⁹⁰ D. C. Mankad,¹⁷⁰ A. Mann,¹¹⁰ S. Manzoni,³⁶ L. Mao,^{62c} X. Maepkula,^{33c} A. Marantis,^{153,u} G. Marchiori,⁵ M. Marcisovsky,¹³² C. Marcon,^{71a} M. Marinescu,²⁰ S. Marium,⁴⁸ M. Marjanovic,¹²¹ M. Markovitch,⁶⁶ E. J. Marshall,⁹² Z. Marshall,^{17a} S. Marti-Garcia,¹⁶⁴ T. A. Martin,¹⁶⁸ V. J. Martin,⁵² B. Martin dit Latour,¹⁶ L. Martinelli,^{75a,75b} M. Martinez,^{13,v} P. Martinez Agullo,¹⁶⁴ V. I. Martinez Outschoorn,¹⁰⁴ P. Martinez Suarez,¹³ S. Martin-Haugh,¹³⁵ G. Martinovicova,¹³⁴ V. S. Martoiu,^{27b} A. C. Martyniuk,⁹⁷ A. Marzin,³⁶ D. Mascione,^{78a,78b} L. Masetti,¹⁰¹ T. Mashimo,¹⁵⁴ J. Masik,¹⁰² A. L. Maslennikov,³⁷ P. Massarotti,^{72a,72b} P. Mastrandrea,^{74a,74b} A. Mastroberardino,^{43b,43a} T. Masubuchi,¹⁵⁴ T. Mathisen,¹⁶² J. Matousek,¹³⁴ N. Matsuzawa,¹⁵⁴ J. Maurer,^{27b} A. J. Maury,⁶⁶ B. Maček,⁹⁴ D. A. Maximov,³⁷ R. Mazini,¹⁴⁹ I. Maznas,¹¹⁶ M. Mazza,¹⁰⁸ S. M. Mazza,¹³⁷ E. Mazzeo,^{71a,71b} C. Mc Ginn,²⁹ J. P. Mc Gowan,¹⁰⁵ S. P. Mc Kee,¹⁰⁷ C. C. McCracken,¹⁶⁵ E. F. McDonald,¹⁰⁶ A. E. McDougall,¹¹⁵ J. A. Mcfayden,¹⁴⁷ R. P. McGovern,¹²⁹ G. Mchedlidze,^{150b} R. P. McKenzie,^{33g} T. C. McLachlan,⁴⁸ D. J. McLaughlin,⁹⁷ S. J. McMahon,¹³⁵ C. M. Mcpartland,⁹³ R. A. McPherson,^{166,z} S. Mehlhase,¹¹⁰ A. Mehta,⁹³ D. Melini,¹⁶⁴ B. R. Mellado Garcia,^{33g} A. H. Melo,⁵⁵ F. Meloni,⁴⁸ A. M. Mendes Jacques Da Costa,¹⁰² H. Y. Meng,¹⁵⁶ L. Meng,⁹² S. Menke,¹¹¹ M. Mentink,³⁶ E. Meoni,^{43b,43a} G. Mercado,¹¹⁶ C. Merlassino,^{69a,69c} L. Merola,^{72a,72b} C. Meroni,^{71a,71b} J. Metcalfe,⁶ A. S. Mete,⁶ C. Meyer,⁶⁸ J-P. Meyer,¹³⁶ R. P. Middleton,¹³⁵ L. Mijović,⁵² G. Mikenberg,¹⁷⁰ M. Mikestikova,¹³² M. Mikuž,⁹⁴ H. Mildner,¹⁰¹ A. Milic,³⁶ D. W. Miller,³⁹ E. H. Miller,¹⁴⁴ L. S. Miller,³⁴ A. Milov,¹⁷⁰ D. A. Milstead,^{47a,47b} T. Min,^{14c} A. A. Minaenko,³⁷ I. A. Minashvili,^{150b} L. Mince,⁵⁹ A. I. Mincer,¹¹⁸ B. Mindur,^{86a} M. Mineev,³⁸ Y. Mino,⁸⁸ L. M. Mir,¹³ M. Miralles Lopez,⁵⁹ M. Mironova,^{17a} A. Mishima,¹⁵⁴ M. C. Missio,¹¹⁴ A. Mitra,¹⁶⁸ V. A. Mitsou,¹⁶⁴ Y. Mitsumori,¹¹² O. Miu,¹⁵⁶ P. S. Miyagawa,⁹⁵ T. Mkrtchyan,^{63a} M. Mlinarevic,⁹⁷ T. Mlinarevic,⁹⁷ M. Mlynarikova,³⁶ S. Mobius,¹⁹ P. Mogg,¹¹⁰ M. H. Mohamed Farook,¹¹³ A. F. Mohammed,^{14a,14e} S. Mohapatra,⁴¹ G. Mokgatitswane,^{33g} L. Moleri,¹⁷⁰ B. Mondal,¹⁴² S. Mondal,¹³³ K. Mönig,⁴⁸ E. Monnier,¹⁰³ L. Monsonis Romero,¹⁶⁴ J. Montejo Berlingen,¹³ M. Montella,¹²⁰ F. Montecelli,^{77a,77b} F. Monticelli,⁹¹ S. Monzani,^{69a,69c} N. Morange,⁶⁶ A. L. Moreira De Carvalho,^{131a} M. Moreno Llácer,¹⁶⁴ C. Moreno Martinez,⁵⁶ P. Morettini,^{57b} S. Morgenstern,³⁶ M. Morii,⁶¹ M. Morinaga,¹⁵⁴ F. Morodei,^{75a,75b} L. Morvaj,³⁶ P. Moschovakos,³⁶ B. Moser,³⁶ M. Mosidze,^{150b} T. Moskalets,⁵⁴ P. Moskvitina,¹¹⁴ J. Moss,^{31,m} A. Moussa,^{35d} E. J. W. Moyse,¹⁰⁴ O. Mtintsilana,^{33g} S. Muanza,¹⁰³ J. Mueller,¹³⁰ D. Muenstermann,⁹² R. Müller,¹⁹ G. A. Mullier,¹⁶² A. J. Mullin,³² J. J. Mullin,¹²⁹ D. P. Mungo,¹⁵⁶ D. Munoz Perez,¹⁶⁴ F. J. Munoz Sanchez,¹⁰² M. Murin,¹⁰² W. J. Murray,^{168,135} M. Muškinja,⁹⁴ C. Mwewa,²⁹ A. G. Myagkov,^{37,b} A. J. Myers,⁸ G. Myers,¹⁰⁷ M. Myska,¹³³ B. P. Nachman,^{17a} O. Nackenhorst,⁴⁹ K. Nagai,¹²⁷ K. Nagano,⁸⁴ J. L. Nagle,^{29,aj} E. Nagy,¹⁰³ A. M. Nairz,³⁶ Y. Nakahama,⁸⁴ K. Nakamura,⁸⁴ K. Nakkalil,⁵ H. Nanjo,¹²⁵ R. Narayan,⁴⁴ E. A. Narayanan,¹¹³ I. Naryshkin,³⁷ M. Naseri,³⁴ S. Nasri,^{117b} C. Nass,²⁴ G. Navarro,^{22a} J. Navarro-Gonzalez,¹⁶⁴ R. Nayak,¹⁵² A. Nayaz,¹⁸ P. Y. Nechaeva,³⁷ F. Nechansky,⁴⁸ L. Nedic,¹²⁷ T. J. Neepe,²⁰ A. Negri,^{73a,73b} M. Negrini,^{23b} C. Nellist,¹¹⁵ C. Nelson,¹⁰⁵ K. Nelson,¹⁰⁷ S. Nemecek,¹³² M. Nessi,^{36,i} M. S. Neubauer,¹⁶³ F. Neuhaus,¹⁰¹ J. Neundorff,⁴⁸ R. Newhouse,¹⁶⁵ P. R. Newman,²⁰ C. W. Ng,¹³⁰ Y. W. Y. Ng,⁴⁸ B. Ngair,^{117a} H. D. N. Nguyen,¹⁰⁹ R. B. Nickerson,¹²⁷ R. Nicolaidou,¹³⁶ J. Nielsen,¹³⁷ M. Niemeyer,⁵⁵ J. Niermann,⁵⁵ N. Nikiforou,³⁶ V. Nikolaenko,^{37,b} I. Nikolic-Audit,¹²⁸ K. Nikolopoulos,²⁰ P. Nilsson,²⁹ I. Nincta,⁴⁸ H. R. Nindhito,⁵⁶ G. Ninio,¹⁵² A. Nisati,^{75a} N. Nishu,² R. Nisius,¹¹¹ J-E. Nitschke,⁵⁰ E. K. Nkadimeng,^{33g} T. Nobe,¹⁵⁴ D. L. Noel,³² T. Nommensen,¹⁴⁸ M. B. Norfolk,¹⁴⁰ R. R. B. Norisam,⁹⁷ B. J. Norman,³⁴ M. Noury,^{35a} J. Novak,⁹⁴ T. Novak,⁴⁸ L. Novotny,¹³³ R. Novotny,¹¹³ L. Nozka,¹²³ K. Ntekas,¹⁶⁰ N. M. J. Nunes De Moura Junior,^{83b} J. Ocariz,¹²⁸ A. Ochi,⁸⁵ I. Ochoa,^{131a} S. Oerdek,^{48,w} J. T. Offermann,³⁹ A. Ogrodnik,¹³⁴ A. Oh,¹⁰² C. C. Ohm,¹⁴⁵ H. Oide,⁸⁴ R. Oishi,¹⁵⁴ M. L. Ojeda,⁴⁸ Y. Okumura,¹⁵⁴ L. F. Oleiro Seabra,^{131a} S. A. Olivares Pino,^{138d} D. Oliveira Damazio,²⁹ D. Oliveira Goncalves,^{83a} J. L. Oliver,¹⁶⁰ Ö. O. Öncel,⁵⁴ A. P. O'Neill,¹⁹ A. Onofre,^{131a,131e} P. U. E. Onyisi,¹¹ M. J. Oreglia,³⁹ G. E. Orellana,⁹¹ D. Orestano,^{77a,77b} N. Orlando,¹³ R. S. Orr,¹⁵⁶ V. O'Shea,⁵⁹ L. M. Osojnak,¹²⁹ R. Ospanov,^{62a} G. Otero y Garzon,³⁰ H. Otono,⁸⁹ P. S. Ott,^{63a} G. J. Ottino,^{17a} M. Ouchrif,^{35d} F. Ould-Saada,¹²⁶ T. Ovsianikova,¹³⁹ M. Owen,⁵⁹ R. E. Owen,¹³⁵ K. Y. Oyulmaz,^{21a}

V. E. Ozcan,^{21a} F. Ozturk,⁸⁷ N. Ozturk,⁸ S. Ozturk,⁸² H. A. Pacey,¹²⁷ A. Pacheco Pages,¹³ C. Padilla Aranda,¹³ G. Padovano,^{75a,75b} S. Pagan Griso,^{17a} G. Palacino,⁶⁸ A. Palazzo,^{70a,70b} J. Pampel,²⁴ J. Pan,¹⁷³ T. Pan,^{64a} D. K. Panchal,¹¹ C. E. Pandini,¹¹⁵ J. G. Panduro Vazquez,⁹⁶ H. D. Pandya,¹ H. Pang,^{14b} P. Pani,⁴⁸ G. Panizzo,^{69a,69c} L. Panwar,¹²⁸ L. Paolozzi,⁵⁶ S. Parajuli,¹⁶³ A. Paramonov,⁶ C. Paraskevopoulos,⁵³ D. Paredes Hernandez,^{64b} A. Pareti,^{73a,73b} K. R. Park,⁴¹ T. H. Park,¹⁵⁶ M. A. Parker,³² F. Parodi,^{57b,57a} E. W. Parrish,¹¹⁶ V. A. Parrish,⁵² J. A. Parsons,⁴¹ U. Parzefall,⁵⁴ B. Pascual Dias,¹⁰⁹ L. Pascual Dominguez,¹⁵² E. Pasqualucci,^{75a} S. Passaggio,^{57b} F. Pastore,⁹⁶ P. Patel,⁸⁷ U. M. Patel,⁵¹ J. R. Pater,¹⁰² T. Pauly,³⁶ C. I. Pazos,¹⁵⁹ J. Pearkes,¹⁴⁴ M. Pedersen,¹²⁶ R. Pedro,^{131a} S. V. Peleganchuk,³⁷ O. Penc,³⁶ E. A. Pender,⁵² G. D. Penn,¹⁷³ K. E. Penski,¹¹⁰ M. Penzin,³⁷ B. S. Peralva,^{83d} A. P. Pereira Peixoto,¹³⁹ L. Pereira Sanchez,¹⁴⁴ D. V. Perepelitsa,^{29,aj} E. Perez Codina,^{157a} M. Perganti,¹⁰ H. Pernegger,³⁶ O. Perrin,⁴⁰ K. Peters,⁴⁸ R. F. Y. Peters,¹⁰² B. A. Petersen,³⁶ T. C. Petersen,⁴² E. Petit,¹⁰³ V. Petousis,¹³³ C. Petridou,^{153,f} T. Petru,¹³⁴ A. Petrukhin,¹⁴² M. Pettee,^{17a} N. E. Pettersson,³⁶ A. Petukhov,³⁷ K. Petukhova,¹³⁴ R. Pezoa,^{138f} L. Pezzotti,³⁶ G. Pezzullo,¹⁷³ T. M. Pham,¹⁷¹ T. Pham,¹⁰⁶ P. W. Phillips,¹³⁵ G. Piacquadio,¹⁴⁶ E. Pianori,^{17a} F. Piazza,¹²⁴ R. Piegaia,³⁰ D. Pietreanu,^{27b} A. D. Pilkington,¹⁰² M. Pinamonti,^{69a,69c} J. L. Pinfold,² B. C. Pinheiro Pereira,^{131a} A. E. Pinto Pinoargote,^{101,136} L. Pintucci,^{69a,69c} K. M. Piper,¹⁴⁷ A. Pirttikoski,⁵⁶ D. A. Pizzi,³⁴ L. Pizzimento,^{64b} A. Pizzini,¹¹⁵ M.-A. Pleier,²⁹ V. Plesanovs,⁵⁴ V. Pleskot,¹³⁴ E. Plotnikova,³⁸ G. Poddar,⁹⁵ R. Poettgen,⁹⁹ L. Poggioli,¹²⁸ I. Pokharel,⁵⁵ S. Polacek,¹³⁴ G. Polesello,^{73a} A. Poley,^{143,157a} A. Polini,^{23b} C. S. Pollard,¹⁶⁸ Z. B. Pollock,¹²⁰ E. Pompa Pacchi,^{75a,75b} D. Ponomarenko,¹¹⁴ L. Pontecorvo,³⁶ S. Popa,^{27a} G. A. Popeneciu,^{27d} A. Poreba,³⁶ D. M. Portillo Quintero,^{157a} S. Pospisil,¹³³ M. A. Postill,¹⁴⁰ P. Postolache,^{27c} K. Potamianos,¹⁶⁸ P. A. Potepa,^{86a} I. N. Potrap,³⁸ C. J. Potter,³² H. Potti,¹ T. Poulsen,⁴⁸ J. Poveda,¹⁶⁴ M. E. Pozo Astigarraga,³⁶ A. Prades Ibanez,¹⁶⁴ J. Pretel,⁵⁴ D. Price,¹⁰² M. Primavera,^{70a} M. A. Principe Martin,¹⁰⁰ R. Privara,¹²³ T. Procter,⁵⁹ M. L. Proffitt,¹³⁹ N. Proklova,¹²⁹ K. Prokofiev,^{64c} G. Proto,¹¹¹ J. Proudfoot,⁶ M. Przybycien,^{86a} W. W. Przygoda,^{86b} A. Psallidas,⁴⁶ J. E. Puddefoot,¹⁴⁰ D. Pudzha,³⁷ D. Pyatiizbyantseva,³⁷ J. Qian,¹⁰⁷ D. Qichen,¹⁰² Y. Qin,¹³ T. Qiu,⁵² A. Quadt,⁵⁵ M. Queitsch-Maitland,¹⁰² G. Quetant,⁵⁶ R. P. Quinn,¹⁶⁵ G. Rabanal Bolanos,⁶¹ D. Rafanoharana,⁵⁴ F. Ragusa,^{71a,71b} J. L. Rainbolt,³⁹ J. A. Raine,⁵⁶ S. Rajagopalan,²⁹ E. Ramakoti,³⁷ I. A. Ramirez-Berend,³⁴ K. Ran,^{48,14e} N. P. Rapheeha,^{33g} H. Rasheed,^{27b} V. Raskina,¹²⁸ D. F. Rassloff,^{63a} A. Rastogi,^{17a} S. Rave,¹⁰¹ B. Ravina,⁵⁵ I. Ravinovich,¹⁷⁰ M. Raymond,³⁶ A. L. Read,¹²⁶ N. P. Readioff,¹⁴⁰ D. M. Rebuzzi,^{73a,73b} G. Redlinger,²⁹ A. S. Reed,¹¹¹ K. Reeves,²⁶ J. A. Reidelsturz,¹⁷² D. Reikher,¹⁵² A. Rej,⁴⁹ C. Rembser,³⁶ M. Renda,^{27b} M. B. Rendel,¹¹¹ F. Renner,⁴⁸ A. G. Rennie,¹⁶⁰ A. L. Rescia,⁴⁸ S. Resconi,^{71a} M. Ressegotti,^{57b,57a} S. Rettie,³⁶ J. G. Reyes Rivera,¹⁰⁸ E. Reynolds,^{17a} O. L. Rezanova,³⁷ P. Reznicek,¹³⁴ H. Riani,^{35d} N. Ribaric,⁹² E. Ricci,^{78a,78b} R. Richter,¹¹¹ S. Richter,^{47a,47b} E. Richter-Was,^{86b} M. Ridel,¹²⁸ S. Ridouani,^{35d} P. Rieck,¹¹⁸ P. Riedler,³⁶ E. M. Riefel,^{47a,47b} J. O. Rieger,¹¹⁵ M. Rijssenbeek,¹⁴⁶ M. Rimoldi,³⁶ L. Rinaldi,^{23b,23a} T. T. Rinn,²⁹ M. P. Rinnagel,¹¹⁰ G. Ripellino,¹⁶² I. Riu,¹³ J. C. Rivera Vergara,¹⁶⁶ F. Rizatdinova,¹²² E. Rizvi,⁹⁵ B. R. Roberts,^{17a} S. H. Robertson,^{105,z} D. Robinson,³² C. M. Robles Gajardo,^{138f} M. Robles Manzano,¹⁰¹ A. Robson,⁵⁹ A. Rocchi,^{76a,76b} C. Roda,^{74a,74b} S. Rodriguez Bosca,³⁶ Y. Rodriguez Garcia,^{22a} A. Rodriguez Rodriguez,⁵⁴ A. M. Rodríguez Vera,^{157b} S. Roe,³⁶ J. T. Roemer,¹⁶⁰ A. R. Roepe-Gier,¹³⁷ J. Roggel,¹⁷² O. Röhne,¹²⁶ R. A. Rojas,¹⁰⁴ C. P. A. Roland,¹²⁸ J. Roloff,²⁹ A. Romaniouk,³⁷ E. Romano,^{73a,73b} M. Romano,^{23b} A. C. Romero Hernandez,¹⁶³ N. Rompotis,⁹³ L. Roos,¹²⁸ S. Rosati,^{75a} B. J. Rosser,³⁹ E. Rossi,¹²⁷ E. Rossi,^{72a,72b} L. P. Rossi,⁶¹ L. Rossini,⁵⁴ R. Rosten,¹²⁰ M. Rotaru,^{27b} B. Rottler,⁵⁴ C. Rougier,⁹⁰ D. Rousseau,⁶⁶ D. Rousso,³² A. Roy,¹⁶³ S. Roy-Garand,¹⁵⁶ A. Rozanov,¹⁰³ Z. M. A. Rozario,⁵⁹ Y. Rozen,¹⁵¹ A. Rubio Jimenez,¹⁶⁴ A. J. Ruby,⁹³ V. H. Ruelas Rivera,¹⁸ T. A. Ruggeri,¹ A. Ruggiero,¹²⁷ A. Ruiz-Martinez,¹⁶⁴ A. Rummmler,³⁶ Z. Rurikova,⁵⁴ N. A. Rusakovich,³⁸ H. L. Russell,¹⁶⁶ G. Russo,^{75a,75b} J. P. Rutherford,⁷ S. Rutherford Colmenares,³² K. Rybacki,⁹² M. Rybar,¹³⁴ E. B. Rye,¹²⁶ A. Ryzhov,⁴⁴ J. A. Sabater Iglesias,⁵⁶ P. Sabatini,¹⁶⁴ H. F.-W. Sadrozinski,¹³⁷ F. Safai Tehrani,^{75a} B. Safarzadeh Samani,¹³⁵ M. Safdari,¹⁴⁴ S. Saha,¹ M. Sahinsoy,¹¹¹ A. Saibel,¹⁶⁴ M. Saimpert,¹³⁶ M. Saito,¹⁵⁴ T. Saito,¹⁵⁴ D. Salamani,³⁶ A. Salnikov,¹⁴⁴ J. Salt,¹⁶⁴ A. Salvador Salas,¹⁵² D. Salvatore,^{43b,43a} F. Salvatore,¹⁴⁷ A. Salzburger,³⁶ D. Sammel,⁵⁴ E. Sampson,⁹² D. Sampsonidis,^{153,f} D. Sampsonidou,¹²⁴ J. Sánchez,¹⁶⁴ V. Sanchez Sebastian,¹⁶⁴ H. Sandaker,¹²⁶ C. O. Sander,⁴⁸ J. A. Sandesara,¹⁰⁴ M. Sandhoff,¹⁷² C. Sandoval,^{22b} D. P. C. Sankey,¹³⁵ T. Sano,⁸⁸ A. Sansoni,⁵³ L. Santi,^{75a,75b} C. Santoni,⁴⁰ H. Santos,^{131a,131b} A. Santra,¹⁷⁰ K. A. Saoucha,¹⁶¹ J. G. Saraiva,^{131a,131d} J. Sardain,⁷ O. Sasaki,⁸⁴ K. Sato,¹⁵⁸ C. Sauer,^{63b} F. Sauerburger,⁵⁴ E. Sauvan,⁴ P. Savard,^{156,ah} R. Sawada,¹⁵⁴ C. Sawyer,¹³⁵ L. Sawyer,⁹⁸ I. Sayago Galvan,¹⁶⁴ C. Sbarra,^{23b} A. Sbrizzi,^{23b,23a} T. Scanlon,⁹⁷ J. Schaarschmidt,¹³⁹ U. Schäfer,¹⁰¹ A. C. Schaffer,^{66,44} D. Schaile,¹¹⁰ R. D. Schamberger,¹⁴⁶ C. Scharf,¹⁸ M. M. Schefer,¹⁹ V. A. Schegelsky,³⁷ D. Scheirich,¹³⁴ F. Schenck,¹⁸ M. Schernau,¹⁶⁰ C. Scheulen,⁵⁵ C. Schiavi,^{57b,57a} M. Schioppa,^{43b,43a} B. Schlag,^{144,o} K. E. Schleicher,⁵⁴ S. Schlenker,³⁶ J. Schmeing,¹⁷² M. A. Schmidt,¹⁷² K. Schmieden,¹⁰¹ C. Schmitt,¹⁰¹

- N. Schmitt,¹⁰¹ S. Schmitt,⁴⁸ L. Schoeffel,¹³⁶ A. Schoening,^{63b} P. G. Scholer,³⁴ E. Schopf,¹²⁷ M. Schott,¹⁰¹ J. Schovancova,³⁶ S. Schramm,⁵⁶ T. Schroer,⁵⁶ H-C. Schultz-Coulon,^{63a} M. Schumacher,⁵⁴ B. A. Schumm,¹³⁷ Ph. Schune,¹³⁶ A. J. Schuy,¹³⁹ H. R. Schwartz,¹³⁷ A. Schwartzman,¹⁴⁴ T. A. Schwarz,¹⁰⁷ Ph. Schwemling,¹³⁶ R. Schwienhorst,¹⁰⁸ A. Sciandra,¹³⁷ G. Sciolla,²⁶ F. Scuri,^{74a} C. D. Sebastiani,⁹³ K. Sedlaczek,¹¹⁶ P. Seema,¹⁸ S. C. Seidel,¹¹³ A. Seiden,¹³⁷ B. D. Seidlitz,⁴¹ C. Seitz,⁴⁸ J. M. Seixas,^{83b} G. Sekhniaidze,^{72a} L. Selem,⁶⁰ N. Semprini-Cesari,^{23b,23a} D. Sengupta,⁵⁶ V. Senthilkumar,¹⁶⁴ L. Serin,⁶⁶ L. Serkin,^{69a,69b} M. Sessa,^{76a,76b} H. Severini,¹²¹ F. Sforza,^{57b,57a} A. Sfyrila,⁵⁶ Q. Sha,^{14a} E. Shabalina,⁵⁵ R. Shaheen,¹⁴⁵ J. D. Shahinian,¹²⁹ D. Shaked Renous,¹⁷⁰ L. Y. Shan,^{14a} M. Shapiro,^{17a} A. Sharma,³⁶ A. S. Sharma,¹⁶⁵ P. Sharma,⁸⁰ P. B. Shatalov,³⁷ K. Shaw,¹⁴⁷ S. M. Shaw,¹⁰² A. Shcherbakova,³⁷ Q. Shen,^{62c,5} D. J. Sheppard,¹⁴³ P. Sherwood,⁹⁷ L. Shi,⁹⁷ X. Shi,^{14a} C. O. Shimmin,¹⁷³ J. D. Shinner,⁹⁶ I. P. J. Shipsey,¹²⁷ S. Shirabe,⁸⁹ M. Shiyakova,^{38,x} J. Shlomi,¹⁷⁰ M. J. Shochet,³⁹ J. Shojaii,¹⁰⁶ D. R. Shope,¹²⁶ B. Shrestha,¹²¹ S. Shrestha,^{120,ak} E. M. Shrif,^{33g} M. J. Shroff,¹⁶⁶ P. Sicho,¹³² A. M. Sickles,¹⁶³ E. Sideras Haddad,^{33g} A. Sidoti,^{23b} F. Siegert,⁵⁰ Dj. Sijacki,¹⁵ F. Sili,⁹¹ J. M. Silva,⁵² M. V. Silva Oliveira,²⁹ S. B. Silverstein,^{47a} S. Simion,⁶⁶ R. Simoniello,³⁶ E. L. Simpson,⁵⁹ H. Simpson,¹⁴⁷ L. R. Simpson,¹⁰⁷ N. D. Simpson,⁹⁹ S. Simsek,⁸² S. Sindhu,⁵⁵ P. Sinervo,¹⁵⁶ S. Singh,¹⁵⁶ S. Sinha,⁴⁸ S. Sinha,¹⁰² M. Sioli,^{23b,23a} I. Siral,³⁶ E. Sitnikova,⁴⁸ J. Sjölin,^{47a,47b} A. Skaf,⁵⁵ E. Skorda,²⁰ P. Skubic,¹²¹ M. Slawinska,⁸⁷ V. Smakhtin,¹⁷⁰ B. H. Smart,¹³⁵ S. Yu. Smirnov,³⁷ Y. Smirnov,³⁷ L. N. Smirnova,^{37,b} O. Smirnova,⁹⁹ A. C. Smith,⁴¹ E. A. Smith,³⁹ H. A. Smith,¹²⁷ J. L. Smith,⁹³ R. Smith,¹⁴⁴ M. Smizanska,⁹² K. Smolek,¹³³ A. A. Snesarev,³⁷ S. R. Snider,¹⁵⁶ H. L. Snoek,¹¹⁵ S. Snyder,²⁹ R. Sobie,^{166,z} A. Soffer,¹⁵² C. A. Solans Sanchez,³⁶ E. Yu. Soldatov,³⁷ U. Soldevila,¹⁶⁴ A. A. Solodkov,³⁷ S. Solomon,²⁶ A. Soloshenko,³⁸ K. Solovieva,⁵⁴ O. V. Solovyanov,⁴⁰ V. Solovyev,³⁷ P. Sommer,³⁶ A. Sonay,¹³ W. Y. Song,^{157b} A. Sopczak,¹³³ A. L. Soppio,⁹⁷ F. Sopkova,^{28b} J. D. Sorenson,¹¹³ I. R. Sotarriva Alvarez,¹⁵⁵ V. Sothilingam,^{63a} O. J. Soto Sandoval,^{138c,138b} S. Sottocornola,⁶⁸ R. Soualah,¹⁶¹ Z. Soumami,^{35e} D. South,⁴⁸ N. Soybelman,¹⁷⁰ S. Spagnolo,^{70a,70b} M. Spalla,¹¹¹ D. Sperlich,⁵⁴ G. Spigo,³⁶ S. Spinali,⁹² D. P. Spiteri,⁵⁹ M. Spousta,¹³⁴ E. J. Staats,³⁴ R. Stamen,^{63a} A. Stampekis,²⁰ M. Standke,²⁴ E. Stanecka,⁸⁷ M. V. Stange,⁵⁰ B. Stanislaus,^{17a} M. M. Stanitzki,⁴⁸ B. Stapf,⁴⁸ E. A. Starchenko,³⁷ G. H. Stark,¹³⁷ J. Stark,⁹⁰ P. Staroba,¹³² P. Starovoitov,^{63a} S. Stärz,¹⁰⁵ R. Staszewski,⁸⁷ G. Stavropoulos,⁴⁶ J. Steentoft,¹⁶² P. Steinberg,²⁹ B. Stelzer,^{143,157a} H. J. Stelzer,¹³⁰ O. Stelzer-Chilton,^{157a} H. Stenzel,⁵⁸ T. J. Stevenson,¹⁴⁷ G. A. Stewart,³⁶ J. R. Stewart,¹²² M. C. Stockton,³⁶ G. Stoicea,^{27b} M. Stolarski,^{131a} S. Stonjek,¹¹¹ A. Straessner,⁵⁰ J. Strandberg,¹⁴⁵ S. Strandberg,^{47a,47b} M. Stratmann,¹⁷² M. Strauss,¹²¹ T. Strebler,¹⁰³ P. Strizenec,^{28b} R. Ströhmer,¹⁶⁷ D. M. Strom,¹²⁴ R. Stroynowski,⁴⁴ A. Strubig,^{47a,47b} S. A. Stucci,²⁹ B. Stugu,¹⁶ J. Stupak,¹²¹ N. A. Styles,⁴⁸ D. Su,¹⁴⁴ S. Su,^{62a} W. Su,^{62d} X. Su,^{62a} D. Suchy,^{28a} K. Sugizaki,¹⁵⁴ V. V. Sulin,³⁷ M. J. Sullivan,⁹³ D. M. S. Sultan,¹²⁷ L. Sultanaliev,³⁷ S. Sultansoy,^{3b} T. Sumida,⁸⁸ S. Sun,¹⁰⁷ S. Sun,¹⁷¹ O. Sunneborn Gudnadottir,¹⁶² N. Sur,¹⁰³ M. R. Sutton,¹⁴⁷ H. Suzuki,¹⁵⁸ M. Svatos,¹³² M. Swiatlowski,^{157a} T. Swirski,¹⁶⁷ I. Sykora,^{28a} M. Sykora,¹³⁴ T. Sykora,¹³⁴ D. Ta,¹⁰¹ K. Tackmann,^{48,w} A. Taffard,¹⁶⁰ R. Tafirout,^{157a} J. S. Tafoya Vargas,⁶⁶ Y. Takubo,⁸⁴ M. Talby,¹⁰³ A. A. Talyshev,³⁷ K. C. Tam,^{64b} N. M. Tamir,¹⁵² A. Tanaka,¹⁵⁴ J. Tanaka,¹⁵⁴ R. Tanaka,⁶⁶ M. Tanasini,^{57b,57a} Z. Tao,¹⁶⁵ S. Tapia Araya,^{138f} S. Tapprogge,¹⁰¹ A. Tarek Abouelfadl Mohamed,¹⁰⁸ S. Tarem,¹⁵¹ K. Tariq,^{14a} G. Tarna,^{103,27b} G. F. Tartarelli,^{71a} P. Tas,¹³⁴ M. Tasevsky,¹³² E. Tassi,^{43b,43a} A. C. Tate,¹⁶³ G. Tateno,¹⁵⁴ Y. Tayalati,^{35e,y} G. N. Taylor,¹⁰⁶ W. Taylor,^{157b} A. S. Tee,¹⁷¹ R. Teixeira De Lima,¹⁴⁴ P. Teixeira-Dias,⁹⁶ J. J. Teoh,¹⁵⁶ K. Terashi,¹⁵⁴ J. Terron,¹⁰⁰ S. Terzo,¹³ M. Testa,⁵³ R. J. Teuscher,^{156,z} A. Thaler,⁷⁹ O. Theiner,⁵⁶ N. Themistokleous,⁵² T. Thevenaux-Pelzer,¹⁰³ O. Thielmann,¹⁷² D. W. Thomas,⁹⁶ J. P. Thomas,²⁰ E. A. Thompson,^{17a} P. D. Thompson,²⁰ E. Thomson,¹²⁹ R. E. Thornberry,⁴⁴ Y. Tian,⁵⁵ V. Tikhomirov,^{37,b} Yu. A. Tikhonov,³⁷ S. Timoshenko,³⁷ D. Timoshyn,¹³⁴ E. X. L. Ting,¹ P. Tipton,¹⁷³ S. H. Tlou,^{33g} A. Tnourji,⁴⁰ K. Todome,¹⁵⁵ S. Todorova-Nova,¹³⁴ S. Todt,⁵⁰ M. Togawa,⁸⁴ J. Tojo,⁸⁹ S. Tokár,^{28a} K. Tokushuku,⁸⁴ O. Toldaiev,⁶⁸ R. Tombs,³² M. Tomoto,^{84,112} L. Tompkins,^{144,o} K. W. Topolnicki,^{86b} E. Torrence,¹²⁴ H. Torres,⁹⁰ E. Torró Pastor,¹⁶⁴ M. Toscani,³⁰ C. Toscirri,³⁹ M. Tost,¹¹ D. R. Tovey,¹⁴⁰ A. Traet,¹⁶ I. S. Trandafir,^{27b} T. Trefzger,¹⁶⁷ A. Tricoli,²⁹ I. M. Trigger,^{157a} S. Trincas-Duvold,¹²⁸ D. A. Trischuk,²⁶ B. Trocmé,⁶⁰ L. Truong,^{33c} M. Trzebinski,⁸⁷ A. Trzupek,⁸⁷ F. Tsai,¹⁴⁶ M. Tsai,¹⁰⁷ A. Tsiamis,^{153,f} P. V. Tsiarehska,³⁷ S. Tsigaridas,^{157a} A. Tsirigotis,^{153,u} V. Tsiskaridze,¹⁵⁶ E. G. Tskhadadze,^{150a} M. Tsopoulou,¹⁵³ Y. Tsujikawa,⁸⁸ I. I. Tsukerman,³⁷ V. Tsulaia,^{17a} S. Tsuno,⁸⁴ K. Tsuru,¹¹⁹ D. Tsybychev,¹⁴⁶ Y. Tu,^{64b} A. Tudorache,^{27b} V. Tudorache,^{27b} A. N. Tuna,⁶¹ S. Turchikhin,^{57b,57a} I. Turk Cakir,^{3a} R. Turra,^{71a} T. Turtuvshin,^{38,aa} P. M. Tuts,⁴¹ S. Tzamarias,^{153,f} P. Tzanis,¹⁰ E. Tzovara,¹⁰¹ F. Ukegawa,¹⁵⁸ P. A. Ulloa Poblete,^{138c,138b} E. N. Umaka,²⁹ G. Unal,³⁶ M. Unal,¹¹ A. Undrus,²⁹ G. Unel,¹⁶⁰ J. Urban,^{28b} P. Urquijo,¹⁰⁶ P. Urrejola,^{138a} G. Usai,⁸ R. Ushioda,¹⁵⁵ M. Usman,¹⁰⁹ Z. Uysal,⁸² V. Vacek,¹³³ B. Vachon,¹⁰⁵ K. O. H. Vadla,¹²⁶ T. Vafeiadis,³⁶ A. Vaitkus,⁹⁷ C. Valderanis,¹¹⁰ E. Valdes Santurio,^{47a,47b} M. Valente,^{157a} S. Valentinetti,^{23b,23a} A. Valero,¹⁶⁴ E. Valiente Moreno,¹⁶⁴

A. Vallier,⁹⁰ J. A. Valls Ferrer,¹⁶⁴ D. R. Van Arman,¹¹⁵ T. R. Van Daalen,¹³⁹ A. Van Der Graaf,⁴⁹ P. Van Gemmeren,⁶ M. Van Rijnbach,¹²⁶ S. Van Stroud,⁹⁷ I. Van Vulpen,¹¹⁵ P. Vana,¹³⁴ M. Vanadia,^{76a,76b} W. Vandelli,³⁶ E. R. Vandewall,¹²² D. Vannicola,¹⁵² L. Vannoli,^{57b,57a} R. Vari,^{75a} E. W. Varnes,⁷ C. Varni,^{17b} T. Varol,¹⁴⁹ D. Varouchas,⁶⁶ L. Varriale,¹⁶⁴ K. E. Varvell,¹⁴⁸ M. E. Vasile,^{27b} L. Vaslin,⁸⁴ G. A. Vazquez,¹⁶⁶ A. Vasyukov,³⁸ R. Vavricka,¹⁰¹ F. Vazeille,⁴⁰ T. Vazquez Schroeder,³⁶ J. Veatch,³¹ V. Vecchio,¹⁰² M. J. Veen,¹⁰⁴ I. Veliscek,²⁹ L. M. Veloce,¹⁵⁶ F. Veloso,^{131a,131c} S. Veneziano,^{75a} A. Ventura,^{70a,70b} S. Ventura Gonzalez,¹³⁶ A. Verbytskyi,¹¹¹ M. Verducci,^{74a,74b} C. Vergis,²⁴ M. Verissimo De Araujo,^{83b} W. Verkerke,¹¹⁵ J. C. Vermeulen,¹¹⁵ C. Vernieri,¹⁴⁴ M. Vessella,¹⁰⁴ M. C. Vetterli,^{143,ah} A. Vgenopoulos,^{153,f} N. Viaux Maira,^{138f} T. Vickey,¹⁴⁰ O. E. Vickey Boeriu,¹⁴⁰ G. H. A. Viehhauser,¹²⁷ L. Vigani,^{63b} M. Villa,^{23b,23a} M. Villaplana Perez,¹⁶⁴ E. M. Villhauer,⁵² E. Vilucchi,⁵³ M. G. Vinciter,³⁴ G. S. Virdee,²⁰ A. Vishwakarma,⁵² A. Visibile,¹¹⁵ C. Vittori,³⁶ I. Vivarelli,^{23b,23a} E. Voevodina,¹¹¹ F. Vogel,¹¹⁰ J. C. Voigt,⁵⁰ P. Vokac,¹³³ Yu. Volkotrub,^{86a} J. Von Ahnen,⁴⁸ E. Von Toerne,²⁴ B. Vormwald,³⁶ V. Vorobel,¹³⁴ K. Vorobev,³⁷ M. Vos,¹⁶⁴ K. Voss,¹⁴² M. Vozak,¹¹⁵ L. Vozdecky,¹²¹ N. Vranjes,¹⁵ M. Vranjes Milosavljevic,¹⁵ M. Vreeswijk,¹¹⁵ N. K. Vu,^{62d,62c} R. Vuillermet,³⁶ O. Vujanovic,¹⁰¹ I. Vukotic,³⁹ S. Wada,¹⁵⁸ C. Wagner,¹⁰⁴ J. M. Wagner,^{17a} W. Wagner,¹⁷² S. Wahdan,¹⁷² H. Wahlberg,⁹¹ M. Wakida,¹¹² J. Walder,¹³⁵ R. Walker,¹¹⁰ W. Walkowiak,¹⁴² A. Wall,¹²⁹ E. J. Wallin,⁹⁹ T. Wamorkar,⁶ A. Z. Wang,¹³⁷ C. Wang,¹⁰¹ C. Wang,¹¹ H. Wang,^{17a} J. Wang,^{64c} R.-J. Wang,¹⁰¹ R. Wang,⁶¹ R. Wang,⁶ S. M. Wang,¹⁴⁹ S. Wang,^{62b} T. Wang,^{62a} W. T. Wang,⁸⁰ W. Wang,^{14a} X. Wang,^{14c} X. Wang,¹⁶³ X. Wang,^{62c} Y. Wang,^{62d} Y. Wang,^{14c} Z. Wang,¹⁰⁷ Z. Wang,^{62d,51,62c} Z. Wang,¹⁰⁷ A. Warburton,¹⁰⁵ R. J. Ward,²⁰ N. Warrack,⁵⁹ S. Waterhouse,⁹⁶ A. T. Watson,²⁰ H. Watson,⁵⁹ M. F. Watson,²⁰ E. Watton,^{59,135} G. Watts,¹³⁹ B. M. Waugh,⁹⁷ C. Weber,²⁹ H. A. Weber,¹⁸ M. S. Weber,¹⁹ S. M. Weber,^{63a} C. Wei,^{62a} Y. Wei,¹²⁷ A. R. Weidberg,¹²⁷ E. J. Weik,¹¹⁸ J. Weingarten,⁴⁹ M. Weirich,¹⁰¹ C. Weiser,⁵⁴ C. J. Wells,⁴⁸ T. Wenaus,²⁹ B. Wendland,⁴⁹ T. Wengler,³⁶ N. S. Wenke,¹¹¹ N. Wermes,²⁴ M. Wessels,^{63a} A. M. Wharton,⁹² A. S. White,⁶¹ A. White,⁸ M. J. White,¹ D. Whiteson,¹⁶⁰ L. Wickremasinghe,¹²⁵ W. Wiedenmann,¹⁷¹ M. WIELERS,¹³⁵ C. Wigglesworth,⁴² D. J. Wilbern,¹²¹ H. G. Wilkens,³⁶ D. M. Williams,⁴¹ H. H. Williams,¹²⁹ S. Williams,³² S. Willocq,¹⁰⁴ B. J. Wilson,¹⁰² P. J. Windischhofer,³⁹ F. I. Winkel,³⁰ F. Winklmeier,¹²⁴ B. T. Winter,⁵⁴ J. K. Winter,¹⁰² M. Wittgen,¹⁴⁴ M. Wobisch,⁹⁸ Z. Wolfs,¹¹⁵ J. Wollrath,¹⁶⁰ M. W. Wolter,⁸⁷ H. Wolters,^{131a,131c} M. C. Wong,¹³⁷ E. L. Woodward,⁴¹ S. D. Worm,⁴⁸ B. K. Wosiek,⁸⁷ K. W. Woźniak,⁸⁷ S. Wozniowski,⁵⁵ K. Wraight,⁵⁹ C. Wu,²⁰ M. Wu,^{14d} M. Wu,¹¹⁴ S. L. Wu,¹⁷¹ X. Wu,⁵⁶ Y. Wu,^{62a} Z. Wu,¹³⁶ J. Wuerzinger,^{111,af} T. R. Wyatt,¹⁰² B. M. Wynne,⁵² S. Xella,⁴² L. Xia,^{14c} M. Xia,^{14b} J. Xiang,^{64c} M. Xie,^{62a} X. Xie,^{62a} S. Xin,^{14a,14e} A. Xiong,¹²⁴ J. Xiong,^{17a} D. Xu,^{14a} H. Xu,^{62a} L. Xu,^{62a} R. Xu,¹²⁹ T. Xu,¹⁰⁷ Y. Xu,^{14b} Z. Xu,⁵² Z. Xu,^{14c} B. Yabsley,¹⁴⁸ S. Yacoub,^{33a} Y. Yamaguchi,¹⁵⁵ E. Yamashita,¹⁵⁴ H. Yamauchi,¹⁵⁸ T. Yamazaki,^{17a} Y. Yamazaki,⁸⁵ J. Yan,^{62c} S. Yan,⁵⁹ Z. Yan,¹⁰⁴ H. J. Yang,^{62c,62d} H. T. Yang,^{62a} S. Yang,^{62a} T. Yang,^{64c} X. Yang,³⁶ X. Yang,^{14a} Y. Yang,⁴⁴ Y. Yang,^{62a} Z. Yang,^{62a} W.-M. Yao,^{17a} H. Ye,^{14c} H. Ye,⁵⁵ J. Ye,^{14a} S. Ye,²⁹ X. Ye,^{62a} Y. Yeh,⁹⁷ I. Yeletsikh,³⁸ B. Yeo,^{17b} M. R. Yexley,⁹⁷ P. Yin,⁴¹ K. Yorita,¹⁶⁹ S. Younas,^{27b} C. J. S. Young,³⁶ C. Young,¹⁴⁴ C. Yu,^{14a,14e} Y. Yu,^{62a} M. Yuan,¹⁰⁷ R. Yuan,^{62b} L. Yue,⁹⁷ M. Zaazoua,^{62a} B. Zabinski,⁸⁷ E. Zaid,⁵² Z. K. Zak,⁸⁷ T. Zakareishvili,¹⁶⁴ N. Zakharuk,³⁴ S. Zambito,⁵⁶ J. A. Zamora Saa,^{138d,138b} J. Zang,¹⁵⁴ D. Zanzi,⁵⁴ O. Zaplatilek,¹³³ C. Zeitnitz,¹⁷² H. Zeng,^{14a} J. C. Zeng,¹⁶³ D. T. Zenger Jr.,²⁶ O. Zenin,³⁷ T. Ženiš,^{28a} S. Zenz,⁹⁵ S. Zerradi,^{35a} D. Zerwas,⁶⁶ M. Zhai,^{14a,14e} D. F. Zhang,¹⁴⁰ J. Zhang,^{62b} J. Zhang,⁶ K. Zhang,^{14a,14e} L. Zhang,^{14c} P. Zhang,^{14a,14e} R. Zhang,¹⁷¹ S. Zhang,¹⁰⁷ S. Zhang,⁴⁴ T. Zhang,¹⁵⁴ X. Zhang,^{62c} X. Zhang,^{62b} Y. Zhang,^{62c,5} Y. Zhang,⁹⁷ Y. Zhang,^{14c} Z. Zhang,^{17a} Z. Zhang,⁶⁶ H. Zhao,¹³⁹ T. Zhao,^{62b} Y. Zhao,¹³⁷ Z. Zhao,^{62a} A. Zhemchugov,³⁸ J. Zheng,^{14c} K. Zheng,¹⁶³ X. Zheng,^{62a} Z. Zheng,¹⁴⁴ D. Zhong,¹⁶³ B. Zhou,¹⁰⁷ H. Zhou,⁷ N. Zhou,^{62c} Y. Zhou,^{14c} Y. Zhou,⁷ C. G. Zhu,^{62b} J. Zhu,¹⁰⁷ Y. Zhu,^{62c} Y. Zhu,^{62a} X. Zhuang,^{14a} K. Zhukov,³⁷ N. I. Zimine,³⁸ J. Zinsser,^{63b} M. Ziolkowski,¹⁴² L. Živković,¹⁵ A. Zoccoli,^{23b,23a} K. Zoch,⁶¹ T. G. Zorbass,¹⁴⁰ O. Zormpa,⁴⁶ W. Zou,⁴¹ and L. Zwalinski³⁶

(ATLAS Collaboration)

¹Department of Physics, University of Adelaide, Adelaide, Australia²Department of Physics, University of Alberta, Edmonton, Alberta, Canada^{3a}Department of Physics, Ankara University, Ankara, Türkiye^{3b}Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye⁴LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France⁵APC, Université Paris Cité, CNRS/IN2P3, Paris, France⁶High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA⁷Department of Physics, University of Arizona, Tucson, Arizona, USA⁸Department of Physics, University of Texas at Arlington, Arlington, Texas, USA

- ⁹*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
- ¹⁰*Physics Department, National Technical University of Athens, Zografou, Greece*
- ¹¹*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
- ¹²*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
- ¹³*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
- ^{14a}*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
- ^{14b}*Physics Department, Tsinghua University, Beijing, China*
- ^{14c}*Department of Physics, Nanjing University, Nanjing, China*
- ^{14d}*School of Science, Shenzhen Campus of Sun Yat-sen University, Beijing, China*
- ^{14e}*University of Chinese Academy of Science (UCAS), Beijing, China*
- ¹⁵*Institute of Physics, University of Belgrade, Belgrade, Serbia*
- ¹⁶*Department for Physics and Technology, University of Bergen, Bergen, Norway*
- ^{17a}*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
- ^{17b}*University of California, Berkeley, California, USA*
- ¹⁸*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
- ¹⁹*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- ²⁰*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- ^{21a}*Department of Physics, Bogazici University, Istanbul, Türkiye*
- ^{21b}*Department of Physics Engineering, Gaziantep University, Gaziantep, Istanbul, Türkiye*
- ^{21c}*Department of Physics, Istanbul University, Istanbul, Türkiye*
- ^{22a}*Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia*
- ^{22b}*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
- ^{23a}*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy*
- ^{23b}*INFN Sezione di Bologna, Bologna, Italy*
- ²⁴*Physikalisches Institut, Universität Bonn, Bonn, Germany*
- ²⁵*Department of Physics, Boston University, Boston, Massachusetts, USA*
- ²⁶*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
- ^{27a}*Transilvania University of Brasov, Brasov, Romania*
- ^{27b}*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
- ^{27c}*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
- ^{27d}*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
- ^{27e}*National University of Science and Technology Politehnica, Bucharest, Romania*
- ^{27f}*West University in Timisoara, Timisoara, Romania*
- ^{27g}*Faculty of Physics, University of Bucharest, Bucharest, Romania*
- ^{28a}*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{28b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ²⁹*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
- ³⁰*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
- ³¹*California State University, Fresno, California, USA*
- ³²*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ^{33a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
- ^{33b}*iThemba Labs, Western Cape, South Africa*
- ^{33c}*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
- ^{33d}*National Institute of Physics, University of the Philippines Diliman, Philippines*
- ^{33e}*University of South Africa, Department of Physics, Pretoria, South Africa*
- ^{33f}*University of Zululand, KwaDlangezwa, South Africa*
- ^{33g}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ³⁴*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
- ^{35a}*Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Casablanca, Morocco*
- ^{35b}*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
- ^{35c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- ^{35d}*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
- ^{35e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ^{35f}*Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*

- ³⁶CERN, Geneva, Switzerland
- ³⁷Affiliated with an institute covered by a cooperation agreement with CERN
- ³⁸Affiliated with an international laboratory covered by a cooperation agreement with CERN
- ³⁹Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
- ⁴⁰LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- ⁴¹Nevis Laboratory, Columbia University, Irvington, New York, USA
- ⁴²Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ^{43a}Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ^{43b}INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- ⁴⁴Physics Department, Southern Methodist University, Dallas, Texas, USA
- ⁴⁵Physics Department, University of Texas at Dallas, Richardson, Texas, USA
- ⁴⁶National Centre for Scientific Research “Demokritos,” Agia Paraskevi, Greece
- ^{47a}Department of Physics, Stockholm University, Stockholm, Sweden
- ^{47b}Oskar Klein Centre, Stockholm, Sweden
- ⁴⁸Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- ⁴⁹Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
- ⁵⁰Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁵¹Department of Physics, Duke University, Durham, North Carolina, USA
- ⁵²SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁵³INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- ⁵⁴Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- ⁵⁵II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- ⁵⁶Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- ^{57a}Dipartimento di Fisica, Università di Genova, Genova, Italy
- ^{57b}INFN Sezione di Genova, Genova, Italy
- ⁵⁸II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵⁹SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁶⁰LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- ⁶¹Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
- ^{62a}Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
- ^{62b}Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
- ^{62c}School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
- ^{62d}Tsung-Dao Lee Institute, Shanghai, China
- ^{62e}School of Physics and Microelectronics, Zhengzhou University, China
- ^{63a}Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{63b}Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{64a}Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
- ^{64b}Department of Physics, University of Hong Kong, Hong Kong, China
- ^{64c}Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶⁵Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- ⁶⁶IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
- ⁶⁷Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain
- ⁶⁸Department of Physics, Indiana University, Bloomington, Indiana, USA
- ^{69a}INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
- ^{69b}ICTP, Trieste, Italy
- ^{69c}Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
- ^{70a}INFN Sezione di Lecce, Lecce, Italy
- ^{70b}Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ^{71a}INFN Sezione di Milano, Milano, Italy
- ^{71b}Dipartimento di Fisica, Università di Milano, Milano, Italy
- ^{72a}INFN Sezione di Napoli, Napoli, Italy
- ^{72b}Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ^{73a}INFN Sezione di Pavia, Pavia, Italy
- ^{73b}Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ^{74a}INFN Sezione di Pisa, Pisa, Italy
- ^{74b}Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

- ^{75a}*INFN Sezione di Roma, Roma, Italy*
^{75b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
^{76a}*INFN Sezione di Roma Tor Vergata, Roma, Italy*
^{76b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
^{77a}*INFN Sezione di Roma Tre, Roma, Italy*
^{77b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
^{78a}*INFN-TIFPA, Trento, Italy*
^{78b}*Università degli Studi di Trento, Trento, Italy*
⁷⁹*Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
⁸⁰*University of Iowa, Iowa City, Iowa, USA*
⁸¹*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
⁸²*Istinye University, Sariyer, Istanbul, Türkiye*
^{83a}*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
^{83b}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
^{83c}*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
^{83d}*Rio de Janeiro State University, Rio de Janeiro, Brazil*
^{83e}*Federal University of Bahia, Bahia, Brazil*
⁸⁴*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
⁸⁵*Graduate School of Science, Kobe University, Kobe, Japan*
^{86a}*AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland*
^{86b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
⁸⁷*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
⁸⁸*Faculty of Science, Kyoto University, Kyoto, Japan*
⁸⁹*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
⁹⁰*L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France*
⁹¹*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
⁹²*Physics Department, Lancaster University, Lancaster, United Kingdom*
⁹³*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
⁹⁴*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
⁹⁵*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
⁹⁶*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
⁹⁷*Department of Physics and Astronomy, University College London, London, United Kingdom*
⁹⁸*Louisiana Tech University, Ruston, Louisiana, USA*
⁹⁹*Fysiska institutionen, Lunds universitet, Lund, Sweden*
¹⁰⁰*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
¹⁰¹*Institut für Physik, Universität Mainz, Mainz, Germany*
¹⁰²*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
¹⁰³*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
¹⁰⁴*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
¹⁰⁵*Department of Physics, McGill University, Montreal, Quebec, Canada*
¹⁰⁶*School of Physics, University of Melbourne, Victoria, Australia*
¹⁰⁷*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
¹⁰⁸*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
¹⁰⁹*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
¹¹⁰*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
¹¹¹*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
¹¹²*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
¹¹³*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
¹¹⁴*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
¹¹⁵*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
¹¹⁶*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
^{117a}*New York University Abu Dhabi, Abu Dhabi, Al Ain, United Arab Emirates*
^{117b}*United Arab Emirates University, Al Ain, United Arab Emirates*
¹¹⁸*Department of Physics, New York University, New York, New York, USA*
¹¹⁹*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
¹²⁰*The Ohio State University, Columbus, Ohio, USA*

- ¹²¹Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
- ¹²²Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
- ¹²³Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
- ¹²⁴Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
- ¹²⁵Graduate School of Science, Osaka University, Osaka, Japan
- ¹²⁶Department of Physics, University of Oslo, Oslo, Norway
- ¹²⁷Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²⁸LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
- ¹²⁹Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
- ¹³⁰Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
- ^{131a}Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
- ^{131b}Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
- ^{131c}Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
- ^{131d}Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
- ^{131e}Departamento de Física, Universidade do Minho, Braga, Portugal
- ^{131f}Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain
- ^{131g}Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
- ¹³²Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
- ¹³³Czech Technical University in Prague, Prague, Czech Republic
- ¹³⁴Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- ¹³⁵Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³⁶IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ¹³⁷Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
- ^{138a}Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- ^{138b}Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
- ^{138c}Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, La Serena, Chile
- ^{138d}Universidad Andres Bello, Department of Physics, Santiago, Chile
- ^{138e}Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
- ^{138f}Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ¹³⁹Department of Physics, University of Washington, Seattle, Washington, USA
- ¹⁴⁰Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴¹Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴²Department Physik, Universität Siegen, Siegen, Germany
- ¹⁴³Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
- ¹⁴⁴SLAC National Accelerator Laboratory, Stanford, California, USA
- ¹⁴⁵Department of Physics, Royal Institute of Technology, Stockholm, Sweden
- ¹⁴⁶Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
- ¹⁴⁷Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁴⁸School of Physics, University of Sydney, Sydney, Australia
- ¹⁴⁹Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^{150a}E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
- ^{150b}High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ^{150c}University of Georgia, Tbilisi, Georgia
- ¹⁵¹Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
- ¹⁵²Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵³Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁴International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
- ¹⁵⁵Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁶Department of Physics, University of Toronto, Toronto, Ontario, Canada
- ^{157a}TRIUMF, Vancouver, British Columbia, Canada
- ^{157b}Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
- ¹⁵⁸Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- ¹⁵⁹Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
- ¹⁶⁰Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
- ¹⁶¹University of Sharjah, Sharjah, United Arab Emirates

¹⁶²*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*¹⁶³*Department of Physics, University of Illinois, Urbana, Illinois, USA*¹⁶⁴*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*¹⁶⁵*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*¹⁶⁶*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*¹⁶⁷*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*¹⁶⁸*Department of Physics, University of Warwick, Coventry, United Kingdom*¹⁶⁹*Waseda University, Tokyo, Japan*¹⁷⁰*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*¹⁷¹*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*¹⁷²*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik,**Bergische Universität Wuppertal, Wuppertal, Germany*¹⁷³*Department of Physics, Yale University, New Haven, Connecticut, USA*^aDeceased.^bAlso Affiliated with an institute covered by a cooperation agreement with CERN.^cAlso at An-Najah National University, Nablus, Palestine.^dAlso at Borough of Manhattan Community College, City University of New York, New York, New York, USA.^eAlso at Center for High Energy Physics, Peking University, Beijing, China.^fAlso at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.^gAlso at Centro Studi e Ricerche Enrico Fermi, Roma, Italy.^hAlso at CERN, Geneva, Switzerland.ⁱAlso at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.^jAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.^kAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.^lAlso at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.^mAlso at Department of Physics, California State University, Sacramento, California, USA.ⁿAlso at Department of Physics, King's College London, London, United Kingdom.^oAlso at Department of Physics, Stanford University, Stanford, California, USA.^pAlso at Department of Physics, Stellenbosch University, South Africa.^qAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.^rAlso at Department of Physics, University of Thessaly, Greece.^sAlso at Department of Physics, Westmont College, Santa Barbara, California, USA.^tAlso at Faculty of Physics, Sofia University, "St. Kliment Ohridski," Sofia, Bulgaria.^uAlso at Hellenic Open University, Patras, Greece.^vAlso at Institutio Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.^wAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.^xAlso at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.^yAlso at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.^zAlso at Institute of Particle Physics (IPP), Victoria, BC, Canada.^{aa}Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.^{ab}Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.^{ac}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.^{ad}Also at Lawrence Livermore National Laboratory, Livermore, California, USA.^{ae}Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines.^{af}Also at Technical University of Munich, Munich, Germany.^{ag}Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.^{ah}Also at TRIUMF, Vancouver, British Columbia, Canada.^{ai}Also at Università di Napoli Parthenope, Napoli, Italy.^{aj}Also at University of Colorado Boulder, Department of Physics, Colorado, Boulder, USA.^{ak}Also at Washington College, Chestertown, Maryland, USA.^{al}Also at Yeditepe University, Physics Department, Istanbul, Türkiye.