

Search for Gluinos in Events with Two Same-Sign Leptons, Jets, and Missing Transverse Momentum with the ATLAS Detector in pp Collisions at $\sqrt{s} = 7$ TeV

G. Aad *et al.**

(ATLAS Collaboration)

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A search is presented for gluinos decaying via the supersymmetric partner of the top quark using events with two same-sign leptons, jets, and missing transverse momentum. The analysis is performed with 2.05 fb^{-1} of integrated luminosity from pp collisions at $\sqrt{s} = 7$ TeV collected by the ATLAS detector at the LHC. No excess beyond the standard model expectation is observed, and exclusion limits are derived for simplified models where the gluino decays via the supersymmetric partner of the top quark and in the minimal supergravity and constrained minimal supersymmetric standard model framework. In those scenarios, gluino masses below 550 GeV are excluded at 95% C.L. within the parameter space considered, significantly extending the coverage with respect to existing limits. Depending on the model parameters, gluino masses up to 750 GeV can also be excluded at 95% C.L.

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Supersymmetry (SUSY) [1–7] is a theory beyond the standard model (SM) which predicts new bosonic partners for the existing fermions and fermionic partners for the known bosons. In the framework of a generic R -parity conserving minimal supersymmetric extension of the SM, SUSY particles are produced in pairs [8,9] and the lightest supersymmetric particle is stable, providing a possible candidate for dark matter.

In SUSY models, the gluino is a strongly interacting Majorana fermion. Pair-produced gluinos therefore have an equal probability to produce a pair of leptons that have the same charge [same-sign (SS)] and the opposite charge from their decays. The supersymmetric partner of the top quark (top squark) has two mass eigenstates with \tilde{t}_1 being the lightest. Top quarks and \tilde{t}_1 squarks can be produced in the decay of the gluino via $\tilde{g} \tilde{g} \rightarrow t\tilde{t}_1\tilde{t}_1^*$, $t\tilde{t}_1^*\tilde{t}_1$, $\tilde{t}_1\tilde{t}_1\tilde{t}_1$ [10–14]. The \tilde{t}_1 squark can further decay to the lightest chargino ($\tilde{\chi}_1^\pm$) or lightest neutralino ($\tilde{\chi}_1^0$) via $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ or $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ producing isolated leptons in the semileptonic top-quark decay or in the leptonic $\tilde{\chi}_1^\pm$ decay and enriching the signal events with two or more leptons, jets, and missing transverse momentum (E_T^{miss}) from the undetected neutralinos. This analysis considers events with a pair of isolated SS leptons, multiple high- p_T jets, and large E_T^{miss} . The requirement of SS leptons in the event suppresses the contribution from SM processes and thus enhances the potential signal significance even for final state topologies with relatively soft jet kinematics. This Letter presents the first search for gluino-mediated top squark production using the SS

signature, although other searches with SS leptons have been performed [15–18]. The analysis presented here complements the results of the ATLAS search based on a single lepton plus b jets [19], enhancing the sensitivity in the experimentally difficult region near the kinematic limit for the production of two top quarks and a neutralino and for the region with low top squark masses.

ATLAS is a general-purpose detector [20] at the LHC. This search uses pp collision data recorded from March to August 2011 at a center-of-mass energy of 7 TeV. The data set corresponds to a total integrated luminosity of $2.05 \pm 0.08 \text{ fb}^{-1}$ [21,22] after the application of data quality requirements. Events are selected by using single lepton and dilepton triggers that have constant efficiency as a function of lepton p_T above the offline p_T cuts used in the analysis.

Jets are reconstructed from three-dimensional calorimeter energy clusters by using the anti- k_r jet algorithm [23,24] with a radius parameter of 0.4. The measured jet energy is corrected for inhomogeneities in, and for the noncompensating nature of, the calorimeter by using p_T - and η -dependent correction factors [25]. Only jet candidates with $p_T > 20$ GeV within $|\eta| < 2.8$ are retained. Events with any jet that fails the jet quality criteria designed to remove noise and noncollision backgrounds [25] are rejected.

Electron candidates are required to have $p_T > 20$ GeV, $|\eta| < 2.47$ and satisfy the “tight” selection criteria defined in Ref. [26]. They are also required to be isolated: The scalar sum of p_T of tracks within a cone in the $\eta - \phi$ plane of radius $\Delta R = 0.2$ around the candidate excluding its own track, Σ_{p_T} , must be less than 10% of the electron p_T . Muon candidates are required to have $p_T > 20$ GeV, $|\eta| < 2.4$ and are identified by matching an extrapolated inner detector track and one or more track segments in the muon spectrometer [27]. They must have longitudinal and

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

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transverse impact parameters within 1 and 0.2 mm of the primary vertex [28], respectively, and $\sum p_T < 1.8$ GeV.

The calculation of E_T^{miss} [29] is based on the vectorial sum of the p_T of the reconstructed jets (with $p_T > 20$ GeV and $|\eta| < 4.5$), leptons, and the calorimeter energy clusters not belonging to reconstructed objects.

During part of the data-taking period, a localized electronics failure in the electromagnetic calorimeter created a dead region ($\Delta\eta \times \Delta\phi \simeq 1.4 \times 0.2$). For jets in this region, a correction to their energy is made by using the energy depositions in the neighboring cells and is propagated to E_T^{miss} . If this correction projected onto the direction of the E_T^{miss} is larger than 10 GeV or 10% of the E_T^{miss} , the event is discarded [30]. Events with reconstructed electrons in the calorimeter dead region are also rejected.

Events in which the two highest- p_T leptons ($\ell = e, \mu$) have the same charge and with at least four jets with $p_T > 50$ GeV are selected. In addition, two signal regions are considered: SR1, which requires $E_T^{\text{miss}} > 150$ GeV, and SR2, which in addition requires $m_T > 100$ GeV, where m_T is the transverse mass of the E_T^{miss} and the highest- p_T lepton defined as $m_T^2 = 2p_T^\ell E_T^{\text{miss}} \{1 - \cos[\Delta\phi(\ell, E_T^{\text{miss}})]\}$. This final m_T cut helps reduce the $t\bar{t}$ background. The signal regions are optimized based on several models where SS dileptons are produced in gluino decays. In signals such as the MSUGRA-CMSSM (minimal supergravity or constrained minimal supersymmetric standard model) [31,32], the directions of the lepton and $\tilde{\chi}_1^0$ are strongly correlated, as they originate from the decay of a common parent particle (usually $\tilde{\chi}_1^\pm$ or the next-to-lightest neutralino $\tilde{\chi}_2^0$). This leads to a softer m_T spectrum than that found in gluino-mediated top squark signal models, where the lepton and the $\tilde{\chi}_1^0$ originate from different parent particles and are thus uncorrelated.

Simulated Monte Carlo (MC) event samples are used to aid in the description of the background and to model the SUSY signal. Top-quark pair and single-top production are simulated with MC@NLO [33], fixing the top-quark mass at 172.5 GeV and using the next-to-leading-order (NLO) parton density function (PDF) set CTEQ6.6 [34]. Samples of W + jets and Z + jets with both light- and heavy-flavor jets are generated with ALPGEN [35] and PDF set CTEQ6L1 [36]. The fragmentation and hadronization for the ALPGEN and MC@NLO samples are performed with HERWIG [37], using JIMMY [38] for the underlying event. Samples of $t\bar{t}Z$, $t\bar{t}W$, and $t\bar{t}WW$ (referred to as $t\bar{t} + X$) are generated with MADGRAPH [39] interfaced to PYTHIA [40]. The total LO cross section for these samples is 0.39 pb and is normalized to NLO by using a K factor of 1.3 [41]. Diboson samples are generated with HERWIG for $W^\pm W^\mp$, WZ , and ZZ processes and with MADGRAPH for $W^\pm W^\pm qq$ processes. The total NLO cross section for the diboson background is 71 pb [42,43]. SUSY signal processes are simulated for various models by using HERWIG++ [37] v2.4.2. The SUSY sample yields are normalized to the results of NLO

calculations, as obtained by using PROSPINO [44] v2.1. The CTEQ6.6M [45] parameterization of the PDFs is used. The tunings of the MC parameters of Ref. [46] are used in the production of the MC samples, which are processed through a detector simulation [47] based on GEANT4 [48]. Effects of multiple proton-proton interactions per bunch crossing are included in the simulation.

The SM backgrounds are evaluated by using a combination of MC simulation and data-driven techniques. SM processes that generate events containing jets which are misidentified as leptons or where a lepton from a b - or c -hadron decay is selected are collectively referred to as “fake-lepton” background. It generally consists of semi-leptonic $t\bar{t}$, single-top, W + jets, and strong light- and heavy-flavor jet production. The contribution from the fake-lepton background is estimated from data with a method similar to that described in Refs. [49,50] by loosening the lepton identification and isolation criteria. For electrons the “medium” criteria are used instead of the “tight” criteria [26], and for both electrons and muons the isolation criterion is relaxed. The method counts the number of observed events containing loose-loose, loose-tight, tight-loose, and tight-tight lepton pairs. The probability of loose real leptons passing the tight selection criteria is obtained by using a $Z \rightarrow \ell^+ \ell^-$ sample. The probability of loose fake leptons to pass the tight selection criteria is determined as a function of the lepton p_T by using multijet control samples obtained by requiring two SS leptons and low E_T^{miss} . By using these probabilities, relations are obtained for the observed event counts in the signal regions as functions of the numbers of events containing fake-fake, fake-real, real-fake, and real-real lepton pairs. These can be solved simultaneously to estimate the number of background events [49,50]. The results of the estimations have been validated with data in control regions obtained by reversing the E_T^{miss} or jet multiplicity cuts used in the signal regions.

Background events from charge misidentification (dominated by electrons which have undergone hard bremsstrahlung with subsequent photon conversion) are estimated by using a partially data-driven technique [16]. The probability of charge misidentification is calculated from MC simulations and corrected by consideration of the number of events in the data with SS electron pairs and invariant mass within 15 GeV of the Z -boson mass. This probability is applied to $t\bar{t}$ MC events producing $e^\pm \ell^\mp$ pairs to evaluate the number of SS events from incorrect charge assignment in each signal region. The probability of misidentifying the charge of a muon and the contributions in the signal regions from charge misidentification of $Z/\gamma^* + \text{jets}$ and other SM backgrounds are negligible.

Contributions from other SM background sources (diboson and $t\bar{t} + X$) are evaluated by using the MC samples described above. In these processes, real SS lepton pairs are produced, and their contribution to the signal regions can be described with MC simulations. In particular, the

contribution from the experimentally unmeasured $t\bar{t} + X$ processes has been studied by using several MC generators. The background from cosmic rays is evaluated with data by using the method in Ref. [16], and its contribution is negligible in the signal regions.

Systematic uncertainties are estimated in the signal regions for the background and the SUSY signal processes. The primary sources of systematic uncertainties in the background are the jet energy scale calibration (35%), the jet energy resolution (10%), uncertainties on lepton and jet reconstruction and identification (5%), and MC modeling and theoretical cross section uncertainties (40%–70%). In particular, the theoretical uncertainties on the cross section of the $t\bar{t} + X$ processes are found to be between 35% and 55% by varying factorization and renormalization scales and 25% due to PDF uncertainties. In addition, a 50% uncertainty is assigned on the K factor used to obtain the NLO cross section [41]. In the fake-lepton background estimation, systematic uncertainties are assigned to the probabilities for loose fake leptons to pass the tight selection. This accounts for potentially different compositions of the signal and control regions. These uncertainties vary in the 10%–80% range depending on the lepton p_T and are evaluated by using data samples with jets of different energies. The absolute uncertainty for each background source is given in Table I. Systematic uncertainties on the signal expectations are evaluated through variations of the factorization and renormalization scales between half and twice their default values and by including the uncertainty on α_s and on the PDF provided by CTEQ6. Uncertainties are calculated for individual SUSY processes. The total uncertainty varies in the 20%–40% range for the considered MC signals. Any correlations of the systematic uncertainties in signals and background are taken into account.

Figure 1 shows the distribution of the number of jets with $p_T > 50$ GeV for events with 2 SS leptons and the

TABLE I. Number of expected SM background events together with the number of observed events in the data. The errors are a combination of the uncertainties due to MC statistics, statistical uncertainties in control regions, and systematic uncertainties. Observed and expected upper limits at 95% confidence level on $\sigma_{\text{vis}} = \sigma \times \epsilon \times A$, together with the $\pm 1\sigma$ errors on the expected limits, are also shown.

	SR1	SR2
$t\bar{t} + X$	0.37 ± 0.26	0.21 ± 0.16
Diboson	0.05 ± 0.02	0.02 ± 0.01
Fake-lepton	0.34 ± 0.20	<0.17
Charge mis-ID	0.08 ± 0.01	0.039 ± 0.007
Total SM	0.84 ± 0.33	0.27 ± 0.24
Observed	0	0
$\sigma_{\text{vis}}^{\text{obs}}$ [fb]	<1.6	<1.5
$\sigma_{\text{vis}}^{\text{exp}}$ [fb]	$<1.7^{+0.5}_{-0.1}$	$<1.6^{+0.2}_{-0.1}$

E_T^{miss} distribution for events with 2 SS leptons and at least four jets with $p_T > 50$ GeV. The contributions from all the SM backgrounds are shown together with their total statistical and systematic uncertainties. For illustration, the distribution for a signal obtained with the decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ in $\tilde{g}\tilde{g}$ pair-produced events with $m_{\tilde{g}} = 650$ GeV and $m_{\tilde{\chi}_1^0} = 150$ GeV is also shown. The data are in agreement with the SM background expectation, and once four jets of $p_T > 50$ GeV are required no event is observed with $E_T^{\text{miss}} > 150$ GeV.

Table I shows the number of expected events in the signal regions for each background source together with the observed number of events. The expectation from the SM is estimated to be less than one event for each signal region with no events observed in the data. Limits at 95% confidence level (C.L.) are derived on the visible cross section $\sigma_{\text{vis}} = \sigma \times \epsilon \times A$, where σ is the total production cross section for any new signal producing SS dileptons, A is the acceptance defined by the fraction of events passing

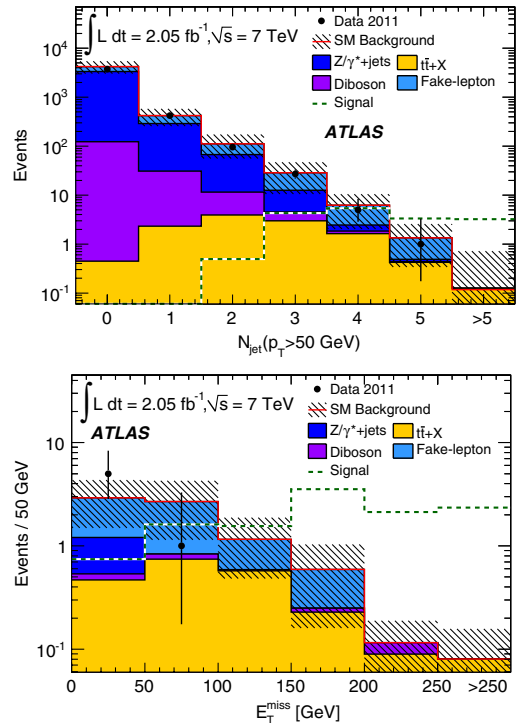


FIG. 1 (color online). Number of jets with $p_T > 50$ GeV for events with 2 SS leptons (top) and the E_T^{miss} distribution for events with 2 SS leptons and at least 4 jets with $p_T > 50$ GeV (bottom). Errors on data points are statistical, while the error band on the SM background represents the total uncertainty. The component labeled “Fake-lepton” is evaluated by using data as described in the text. The component labeled “ $Z/\gamma^* + \text{jets}$ ” is estimated from MC simulations. No estimation of the charge mis-ID is included in the distribution. The component labeled “Signal” corresponds to a signal obtained with the decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ via off mass-shell \tilde{t} ($m_{\tilde{t}} = 1.2$ TeV) in $\tilde{g}\tilde{g}$ pair-produced events with $m_{\tilde{g}} = 650$ GeV and $m_{\tilde{\chi}_1^0} = 150$ GeV.

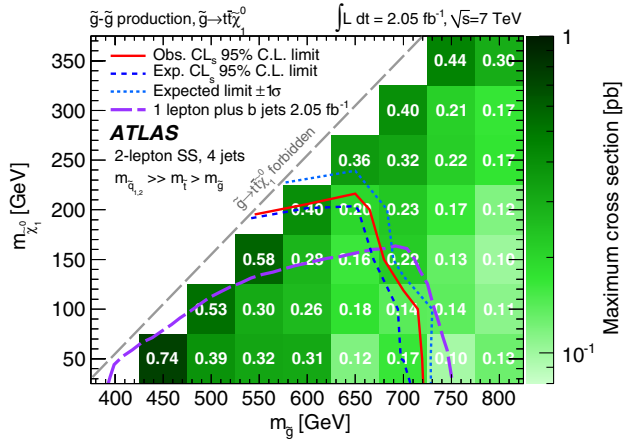


FIG. 2 (color online). Expected and observed 95% C.L. exclusion limits in the $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (via off mass-shell \tilde{t} , $m_{\tilde{t}} = 1.2$ TeV) simplified model as a function of the gluino and neutralino masses, together with existing limits [19]. The -1σ limit lies outside the range of the figure. The production cross section upper limits at 95% C.L. are also shown.

geometric and kinematic cuts at particle level, and ϵ is the detector reconstruction, identification, and trigger efficiency. For the signal shown in Fig. 1, the acceptance and efficiency are 1.5% and 55%, respectively. Limits are set by using the CL_s prescription, as described in Ref. [51]. The results are given in Table I.

The results obtained in SR2 are interpreted in a simplified model where gluinos are produced only in pairs, the top squark ($m_{\tilde{t}} = 1.2$ TeV) is heavier than the gluino, and only the gluino three-body decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ via an off-shell top squark is allowed. Figure 2 shows the limit in the gluino-neutralino mass plane. For a gluino mass of 650 GeV, neutralino masses below 215 GeV are excluded at 95% C.L. For a neutralino mass of 100 GeV, gluino masses below 715 GeV are similarly excluded. The -1σ uncertainty limit on the expected limit lies outside the range of the figure as a consequence of the low number of expected signal events and a total signal uncertainty that reaches close to 50%. The results can be generalized in terms of production cross section upper limits at 95% C.L. for $\tilde{g}\tilde{g}$ pair production processes with the produced particles decaying into $t\bar{t}\tilde{\chi}_1^0$ final states, as also shown in Fig. 2.

The results in SR2 are also interpreted by considering gluino pair production followed by the $\tilde{g} \rightarrow \tilde{t}_1 t$ decay. Only top squark decays via $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ are considered with $m_{\tilde{\chi}_1^\pm} \approx 2m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_1^0} = 60$ GeV. Figure 3 shows the exclusion limit as a function of gluino and top squark masses, where gluino masses below 660 GeV are excluded at 95% C.L. for top squark masses below 460 GeV.

The results in SR1 are interpreted within the MSUGRA-CMSSM framework in terms of limits on the universal scalar and gaugino mass parameters m_0 and $m_{1/2}$, as shown in Fig. 4. These are presented for fixed values of the universal trilinear coupling parameter $A_0 = 0$, ratio of

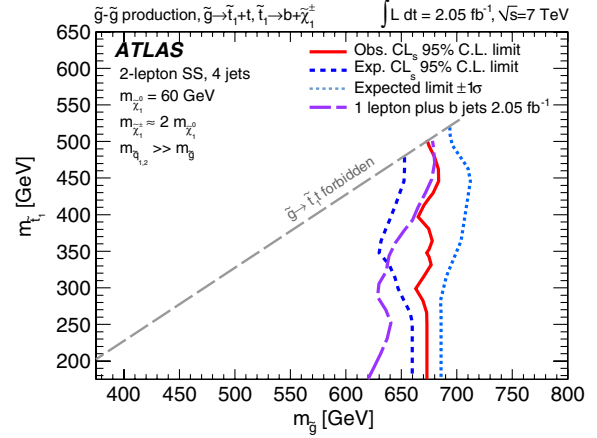


FIG. 3 (color online). Expected and observed 95% C.L. exclusion limits in the $\tilde{g} \rightarrow \tilde{t}_1 t$ with $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ model as a function of the gluino and top squark masses assuming that $m_{\tilde{\chi}_1^\pm} \approx 2m_{\tilde{\chi}_1^0}$. The -1σ band lies outside the range of the figure.

the vacuum expectation values of the two Higgs doublets $\tan\beta = 10$, and Higgs mixing parameter $\mu > 0$. In this model, values of $m_{1/2}$ below 300 GeV are excluded at 95% C.L. for m_0 values below 750 GeV, and $m_{1/2}$ values below 180 GeV are excluded over the entire m_0 region considered. These are equivalent to the exclusion of gluino masses below ~ 550 GeV independent of the squark mass (and gluino masses below ~ 750 GeV for squark masses below 1 TeV).

In summary, a search for SUSY with two SS leptons, jets, and missing transverse momentum has been performed by using 2.05 fb^{-1} of ATLAS data. With no events observed in the signal regions, limits have been derived in the context of models where top quarks are produced in gluino decays and MSUGRA-CMSSM scenarios. In all these signal models, gluino masses below ~ 550 GeV are

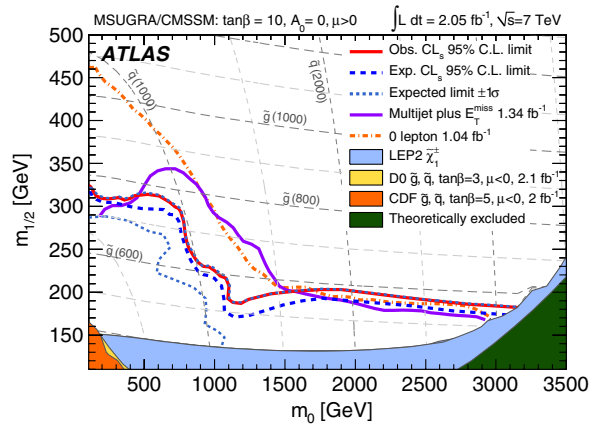


FIG. 4 (color online). Expected and observed 95% C.L. exclusion limits in the MSUGRA-CMSSM (m_0 , $m_{1/2}$) plane for $\tan\beta = 10$, $A_0 = 0$, and $\mu > 0$, compared to existing limits [52–56].

excluded at 95% C.L. within the parameter space considered, and gluino masses up to ~ 750 GeV are excluded at 95% C.L., depending on the model parameters. The results of this analysis are complementary to and extend the current exclusion limits on the gluino mass beyond those from other ATLAS searches [19,52].

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G. Aad,⁴⁷ B. Abbott,¹⁰⁹ J. Abdallah,¹¹ S. Abdel Khalek,¹¹³ A. A. Abdelalim,⁴⁸ A. Abdesselam,¹¹⁶ O. Abdinov,¹⁰ B. Abi,¹¹⁰ M. Abolins,⁸⁶ O. S. AbouZeid,¹⁵⁶ H. Abramowicz,¹⁵¹ H. Abreu,¹¹³ E. Acerbi,^{87a,87b} B. S. Acharya,^{162a,162b} L. Adamczyk,³⁷ D. L. Adams,²⁴ T. N. Addy,⁵⁵ J. Adelman,¹⁷³ M. Aderholz,⁹⁷ S. Adomeit,⁹⁶ P. Adragna,⁷³ T. Adye,¹²⁷ S. Aefsky,²² J. A. Aguilar-Saavedra,^{122b,b} M. Aharrouche,⁷⁹ S. P. Ahlen,²¹ F. Ahles,⁴⁷ A. Ahmad,¹⁴⁶ M. Ahsan,⁴⁰ G. Aielli,^{131a,131b} T. Akdogan,^{18a} T. P. A. Åkesson,⁷⁷ G. Akimoto,¹⁵³ A. V. Akimov,⁹² A. Akiyama,⁶⁵ M. S. Alam,¹ M. A. Alam,⁷⁴ J. Albert,¹⁶⁷ S. Albrand,⁵⁴ M. Aleksa,²⁹ I. N. Aleksandrov,⁶³ F. Alessandria,^{87a} C. Alexa,^{25a} G. Alexander,¹⁵¹ G. Alexandre,⁴⁸ T. Alexopoulos,⁹ M. Alhroob,²⁰ M. Aliev,¹⁵ G. Alimonti,^{87a} J. Alison,¹¹⁸ M. Aliyev,¹⁰ B. M. M. Allbrooke,¹⁷ P. P. Allport,⁷¹ S. E. Allwood-Spiers,⁵² J. Almond,⁸⁰ A. Aloisio,^{100a,100b} R. Alon,¹⁶⁹ A. Alonso,⁷⁷ B. Alvarez Gonzalez,⁸⁶ M. G. Alvigi,^{100a,100b} K. Amako,⁶⁴ P. Amaral,²⁹ C. Amelung,²² V. V. Ammosov,¹²⁶ A. Amorim,^{122a,c} G. Amorós,¹⁶⁵ N. Amram,¹⁵¹ C. Anastopoulos,²⁹ L. S. Ancu,¹⁶ N. Andari,¹¹³ T. Andeen,³⁴ C. F. Anders,²⁰ G. Anders,^{57a} K. J. Anderson,³⁰ A. Andreazza,^{87a,87b} V. Andrei,^{57a} M.-L. Andrieux,⁵⁴ X. S. Anduaga,⁶⁸ A. Angerami,³⁴ F. Anghinolfi,²⁹ A. Anisenkov,¹⁰⁵ N. Anjos,^{122a} A. Annovi,⁴⁶ A. Antonaki,⁸ M. Antonelli,⁴⁶ A. Antonov,⁹⁴ J. Antos,^{142b} F. Anulli,^{130a} S. Aoun,⁸¹ L. Aperio Bella,⁴ R. Apolle,^{116,d} G. Arabidze,⁸⁶ I. Aracena,¹⁴¹ Y. Arai,⁶⁴ A. T. H. Arce,⁴⁴ S. Arfaoui,¹⁴⁶ J.-F. Arguin,¹⁴ E. Arik,^{18a,a} M. Arik,^{18a} A. J. Armbruster,⁸⁵ O. Arnaez,⁷⁹ V. Arnal,⁷⁸ C. Arnault,¹¹³ A. Artamonov,⁹³ G. Artoni,^{130a,130b} D. Arutinov,²⁰ S. Asai,¹⁵³ R. Asfandiyarov,¹⁷⁰ S. Ask,²⁷ B. Åsman,^{144a,144b} L. Asquith,⁵ K. Assamagan,²⁴ A. Astbury,¹⁶⁷ A. Astvatsatourov,⁵¹ B. Aubert,⁴ E. Auge,¹¹³ K. Augsten,¹²⁵ M. Aurousseau,^{143a} G. Avolio,¹⁶¹ R. Avramidou,⁹ D. Axen,¹⁶⁶ C. Ay,⁵³ G. Azuelos,^{91,e} Y. Azuma,¹⁵³ M. A. Baak,²⁹ G. Baccaglioni,^{87a} C. Bacci,^{132a,132b} A. M. Bach,¹⁴ H. Bachacou,¹³⁴ K. Bachas,²⁹ M. Backes,⁴⁸ M. Backhaus,²⁰ E. Badescu,^{25a} P. Bagnaia,^{130a,130b} S. Bahinipati,² Y. Bai,^{32a} D. C. Bailey,¹⁵⁶ T. Bain,¹⁵⁶ J. T. Baines,¹²⁷ O. K. Baker,¹⁷³ M. D. Baker,²⁴ S. Baker,⁷⁵ E. Banas,³⁸ P. Banerjee,⁹¹ Sw. Banerjee,¹⁷⁰ D. Banfi,²⁹ A. Bangert,¹⁴⁸ V. Bansal,¹⁶⁷ H. S. Bansil,¹⁷ L. Barak,¹⁶⁹ S. P. Baranov,⁹² A. Barashkou,⁶³ A. Barbaro Galtieri,¹⁴ T. Barber,⁴⁷ E. L. Barberio,⁸⁴ D. Barberis,^{49a,49b} M. Barbero,²⁰ D. Y. Bardin,⁶³ T. Barillari,⁹⁷ M. Barisonzi,¹⁷² T. Barklow,¹⁴¹ N. Barlow,²⁷ B. M. Barnett,¹²⁷ R. M. Barnett,¹⁴ A. Baroncelli,^{132a} G. Barone,⁴⁸ A. J. Barr,¹¹⁶ F. Barreiro,⁷⁸ J. Barreiro Guimarães da Costa,⁵⁶ P. Barrillon,¹¹³ R. Bartoldus,¹⁴¹ A. E. Barton,⁶⁹ V. Bartsch,¹⁴⁷ R. L. Bates,⁵² L. Batkova,^{142a} J. R. Batley,²⁷ A. Battaglia,¹⁶ M. Battistin,²⁹ F. Bauer,¹³⁴ H. S. Bawa,^{141,f} S. Beale,⁹⁶ T. Beau,⁷⁶ P. H. Beauchemin,¹⁵⁹ R. Beccherle,^{49a} P. Bechtel,²⁰ H. P. Beck,¹⁶ S. Becker,⁹⁶ M. Beckingham,¹³⁶ K. H. Becks,¹⁷² A. J. Beddall,^{18c} A. Beddall,^{18c} S. Bedikian,¹⁷³ V. A. Bednyakov,⁶³ C. P. Bee,⁸¹ M. Begel,²⁴ S. Behar Harpaz,¹⁵⁰ P. K. Behera,⁶¹ M. Beimforde,⁹⁷ C. Belanger-Champagne,⁸³ P. J. Bell,⁴⁸ W. H. Bell,⁴⁸ G. Bella,¹⁵¹ L. Bellagamba,^{19a} F. Bellina,²⁹ M. Bellomo,²⁹ A. Belloni,⁵⁶ O. Beloborodova,^{105,g} K. Belotskiy,⁹⁴ O. Beltramello,²⁹ O. Benary,¹⁵¹ D. Benckroun,^{133a} M. Bendel,⁷⁹ N. Benekos,¹⁶³ Y. Benhammou,¹⁵¹ E. Benhar Noccioli,⁴⁸ J. A. Benitez Garcia,^{157b} D. P. Benjamin,⁴⁴ M. Benoit,¹¹³ J. R. Bensinger,²² K. Benslama,¹²⁸ S. Bentvelsen,¹⁰³ D. Berge,²⁹ E. Bergeas Kuutmann,⁴¹ N. Berger,⁴ F. Berghaus,¹⁶⁷ E. Berglund,¹⁰³ J. Beringer,¹⁴ P. Bernat,⁷⁵ R. Bernhard,⁴⁷ C. Bernius,²⁴ T. Berry,⁷⁴ C. Bertella,⁸¹ A. Bertin,^{19a,19b} F. Bertinelli,²⁹ F. Bertolucci,^{120a,120b} M. I. Besana,^{87a,87b} N. Besson,¹³⁴ S. Bethke,⁹⁷ W. Bhimji,⁴⁵ R. M. Bianchi,²⁹ M. Bianco,^{70a,70b} O. Biebel,⁹⁶ S. P. Bieniek,⁷⁵ K. Bierwagen,⁵³ J. Biesiada,¹⁴ M. Biglietti,^{132a} H. Bilokon,⁴⁶ M. Bindi,^{19a,19b} S. Binet,¹¹³ A. Bingul,^{18c} C. Bini,^{130a,130b} C. Biscarat,¹⁷⁵ U. Bitenc,⁴⁷ K. M. Black,²¹ R. E. Blair,⁵ J.-B. Blanchard,¹³⁴ G. Blanchot,²⁹ T. Blazek,^{142a} C. Blocker,²² J. Blocki,³⁸ A. Blondel,⁴⁸ W. Blum,⁷⁹ U. Blumenschein,⁵³ G. J. Bobbink,¹⁰³ V. B. Bobrovnikov,¹⁰⁵ S. S. Bocchetta,⁷⁷ A. Bocci,⁴⁴ C. R. Boddy,¹¹⁶ M. Boehler,⁴¹ J. Boek,¹⁷² N. Boelaert,³⁵

J. A. Bogaerts,²⁹ A. Bogdanchikov,¹⁰⁵ A. Bogouch,^{88,a} C. Bohm,^{144a} J. Bohm,¹²³ V. Boisvert,⁷⁴ T. Bold,³⁷
V. Boldea,^{25a} N. M. Bolnet,¹³⁴ M. Bomben,⁷⁶ M. Bona,⁷³ V. G. Bondarenko,⁹⁴ M. Bondioli,¹⁶¹ M. Boonekamp,¹³⁴
C. N. Booth,¹³⁷ S. Bordini,⁷⁶ C. Borer,¹⁶ A. Borisov,¹²⁶ G. Borisso,⁶⁹ I. Borjanovic,^{12a} M. Borri,⁸⁰ S. Borroni,⁸⁵
V. Bortolotto,^{132a,132b} K. Bos,¹⁰³ D. Boscherini,^{19a} M. Bosman,¹¹ H. Boterenbrood,¹⁰³ D. Botterill,¹²⁷ J. Bouchami,⁹¹
J. Boudreau,¹²¹ E. V. Bouhova-Thacker,⁶⁹ D. Boumediene,³³ C. Bourdarios,¹¹³ N. Bousson,⁸¹ A. Boveia,³⁰ J. Boyd,²⁹
I. R. Boyko,⁶³ N. I. Bozhko,¹²⁶ I. Bozovic-Jelisavcic,^{12b} J. Bracinik,¹⁷ A. Braem,²⁹ P. Branchini,^{132a}
G. W. Brandenburg,⁵⁶ A. Brandt,⁷ G. Brandt,¹¹⁶ O. Brandt,⁵³ U. Bratzler,¹⁵⁴ B. Brau,⁸² J. E. Brau,¹¹² H. M. Braun,¹⁷²
B. Brelrier,¹⁵⁶ J. Bremer,²⁹ K. Brendlinger,¹¹⁸ R. Brenner,¹⁶⁴ S. Bressler,¹⁶⁹ D. Britton,⁵² F. M. Brochu,²⁷ I. Brock,²⁰
R. Brock,⁸⁶ T. J. Brodbeck,⁶⁹ E. Brodet,¹⁵¹ F. Broggi,^{87a} C. Bromberg,⁸⁶ J. Bronner,⁹⁷ G. Brooijmans,³⁴
W. K. Brooks,^{31b} G. Brown,⁸⁰ H. Brown,⁷ P. A. Bruckman de Renstrom,³⁸ D. Bruncko,^{142b} R. Bruneliere,⁴⁷
S. Brunet,⁵⁹ A. Bruni,^{19a} G. Bruni,^{19a} M. Bruschi,^{19a} T. Buanes,¹³ Q. Buat,⁵⁴ F. Bucci,⁴⁸ J. Buchanan,¹¹⁶
N. J. Buchanan,² P. Buchholz,¹³⁹ R. M. Buckingham,¹¹⁶ A. G. Buckley,⁴⁵ S. I. Buda,^{25a} I. A. Budagov,⁶³
B. Budick,¹⁰⁶ V. Büscher,⁷⁹ L. Bugge,¹¹⁵ O. Bulekov,⁹⁴ M. Bunse,⁴² T. Buran,¹¹⁵ H. Burckhart,²⁹ S. Burdin,⁷¹
T. Burgess,¹³ S. Burke,¹²⁷ E. Busato,³³ P. Bussey,⁵² C. P. Buszello,¹⁶⁴ F. Butin,²⁹ B. Butler,¹⁴¹ J. M. Butler,²¹
C. M. Buttar,⁵² J. M. Butterworth,⁷⁵ W. Buttinger,²⁷ S. Cabrera Urbán,¹⁶⁵ D. Caforio,^{19a,19b} O. Cakir,^{3a} P. Calafiura,¹⁴
G. Calderini,⁷⁶ P. Calfayan,⁹⁶ R. Calkins,¹⁰⁴ L. P. Caloba,^{23a} R. Caloi,^{130a,130b} D. Calvet,³³ S. Calvet,³³
R. Camacho Toro,³³ P. Camarri,^{131a,131b} M. Cambiaghi,^{117a,117b} D. Cameron,¹¹⁵ L. M. Caminada,¹⁴ S. Campana,²⁹
M. Campanelli,⁷⁵ V. Canale,^{100a,100b} F. Canelli,^{30,h} A. Canepa,^{157a} J. Cantero,⁷⁸ L. Capasso,^{100a,100b}
M. D. M. Capeans Garrido,²⁹ I. Caprini,^{25a} M. Caprini,^{25a} D. Capriotti,⁹⁷ M. Capua,^{36a,36b} R. Caputo,⁷⁹
R. Cardarelli,^{131a} T. Carli,²⁹ G. Carlino,^{100a} L. Carminati,^{87a,87b} B. Caron,⁸³ S. Caron,¹⁰² E. Carquin,^{31b}
G. D. Carrillo Montoya,¹⁷⁰ A. A. Carter,⁷³ J. R. Carter,²⁷ J. Carvalho,^{122a,i} D. Casadei,¹⁰⁶ M. P. Casado,¹¹
M. Cascella,^{120a,120b} C. Caso,^{49a,49b,a} A. M. Castaneda Hernandez,¹⁷⁰ E. Castaneda-Miranda,¹⁷⁰
V. Castillo Gimenez,¹⁶⁵ N. F. Castro,^{122a} G. Cataldi,^{70a} A. Catinaccio,²⁹ J. R. Catmore,²⁹ A. Cattai,²⁹
G. Cattani,^{131a,131b} S. Caughron,⁸⁶ D. Cauz,^{162a,162c} P. Cavalleri,⁷⁶ D. Cavalli,^{87a} M. Cavalli-Sforza,¹¹
V. Cavasinni,^{120a,120b} F. Ceradini,^{132a,132b} A. S. Cerqueira,^{23b} A. Cerri,²⁹ L. Cerrito,⁷³ F. Cerutti,⁴⁶ S. A. Cetin,^{18b}
F. Cevenini,^{100a,100b} A. Chafaq,^{133a} D. Chakraborty,¹⁰⁴ K. Chan,² B. Chapleau,⁸³ J. D. Chapman,²⁷ J. W. Chapman,⁸⁵
E. Chareyre,⁷⁶ D. G. Charlton,¹⁷ V. Chavda,⁸⁰ C. A. Chavez Barajas,²⁹ S. Cheatham,⁸³ S. Chekanov,⁵
S. V. Chekulaev,^{157a} G. A. Chelkov,⁶³ M. A. Chelstowska,¹⁰² C. Chen,⁶² H. Chen,²⁴ S. Chen,^{32c} T. Chen,^{32c}
X. Chen,¹⁷⁰ S. Cheng,^{32a} A. Cheplakov,⁶³ V. F. Chepurinov,⁶³ R. Cherkaoui El Moursli,^{133e} V. Chernyatin,²⁴ E. Cheu,⁶
S. L. Cheung,¹⁵⁶ L. Chevalier,¹³⁴ G. Chiefari,^{100a,100b} L. Chikovani,^{50a} J. T. Childers,²⁹ A. Chilingarov,⁶⁹
G. Chiodini,^{70a} A. S. Chisholm,¹⁷ R. T. Chislett,⁷⁵ M. V. Chizhov,⁶³ G. Choudalakis,³⁰ S. Chouridou,¹³⁵
I. A. Christidi,⁷⁵ A. Christov,⁴⁷ D. Chromek-Burckhart,²⁹ M. L. Chu,¹⁴⁹ J. Chudoba,¹²³ G. Ciapetti,^{130a,130b}
A. K. Ciftci,^{3a} R. Ciftci,^{3a} D. Cinca,³³ V. Cindro,⁷² M. D. Ciobotaru,¹⁶¹ C. Ciocca,^{19a} A. Ciocio,¹⁴ M. Cirilli,⁸⁵
M. Citterio,^{87a} M. Ciubancan,^{25a} A. Clark,⁴⁸ P. J. Clark,⁴⁵ W. Cleland,¹²¹ J. C. Clemens,⁸¹ B. Clement,⁵⁴
C. Clement,^{144a,144b} R. W. Clift,¹²⁷ Y. Coadou,⁸¹ M. Cobal,^{162a,162c} A. Coccaro,¹⁷⁰ J. Cochran,⁶² P. Coe,¹¹⁶
J. G. Cogan,¹⁴¹ J. Coggeshall,¹⁶³ E. Cogneras,¹⁷⁵ J. Colas,⁴ A. P. Colijn,¹⁰³ N. J. Collins,¹⁷ C. Collins-Tooth,⁵²
J. Collot,⁵⁴ G. Colon,⁸² P. Conde Muño,^{122a} E. Coniavitis,¹¹⁶ M. C. Conidi,¹¹ M. Consonni,¹⁰² S. M. Consonni,^{87a,87b}
V. Consorti,⁴⁷ S. Constantinescu,^{25a} C. Conta,^{117a,117b} G. Conti,⁵⁶ F. Conventi,^{100a,j} J. Cook,²⁹ M. Cooke,¹⁴
B. D. Cooper,⁷⁵ A. M. Cooper-Sarkar,¹¹⁶ K. Copic,¹⁴ T. Cornelissen,¹⁷² M. Corradi,^{19a} F. Corriveau,^{83,k}
A. Cortes-Gonzalez,¹⁶³ G. Cortiana,⁹⁷ G. Costa,^{87a} M. J. Costa,¹⁶⁵ D. Costanzo,¹³⁷ T. Costin,³⁰ D. Côté,²⁹
R. Coura Torres,^{23a} L. Courneyea,¹⁶⁷ G. Cowan,⁷⁴ C. Cowden,²⁷ B. E. Cox,⁸⁰ K. Cranmer,¹⁰⁶ F. Crescioli,^{120a,120b}
M. Cristinziani,²⁰ G. Crosetti,^{36a,36b} R. Crupi,^{70a,70b} S. Crépe-Renaudin,⁵⁴ C.-M. Cuciuc,^{25a} C. Cuenca Almenar,¹⁷³
T. Cuhadar Donszelmann,¹³⁷ M. Curatolo,⁴⁶ C. J. Curtis,¹⁷ C. Cuthbert,¹⁴⁸ P. Cwetanski,⁵⁹ H. Czirr,¹³⁹
P. Czodrowski,⁴³ Z. Czyczula,¹⁷³ S. D'Auria,⁵² M. D'Onofrio,⁷¹ A. D'Orazio,^{130a,130b} P. V. M. Da Silva,^{23a}
C. Da Via,⁸⁰ W. Dabrowski,³⁷ A. Dafinca,¹¹⁶ T. Dai,⁸⁵ C. Dallapiccola,⁸² M. Dam,³⁵ M. Dameri,^{49a,49b}
D. S. Damiani,¹³⁵ H. O. Danielsson,²⁹ D. Dannheim,⁹⁷ V. Dao,⁴⁸ G. Darbo,^{49a} G. L. Darlea,^{25b} W. Davey,²⁰
T. Davidek,¹²⁴ N. Davidson,⁸⁴ R. Davidson,⁶⁹ E. Davies,^{116,d} M. Davies,⁹¹ A. R. Davison,⁷⁵ Y. Davygora,^{57a}
E. Dawe,¹⁴⁰ I. Dawson,¹³⁷ J. W. Dawson,^{5a} R. K. Daya-Ishmukhametova,²² K. De,⁷ R. de Asmundis,^{100a}
S. De Castro,^{19a,19b} P. E. De Castro Faria Salgado,²⁴ S. De Cecco,⁷⁶ J. de Graat,⁹⁶ N. De Groot,¹⁰² P. de Jong,¹⁰³
C. De La Taille,¹¹³ H. De la Torre,⁷⁸ B. De Lotto,^{162a,162c} L. de Mora,⁶⁹ L. De Nooij,¹⁰³ D. De Pedis,^{130a}
A. De Salvo,^{130a} U. De Sanctis,^{162a,162c} A. De Santo,¹⁴⁷ J. B. De Vivie De Regie,¹¹³ G. De Zorzi,^{130a,130b} S. Dean,⁷⁵

W. J. Dearnaley,⁶⁹ R. Debbe,²⁴ C. Debenedetti,⁴⁵ B. Dechenaux,⁵⁴ D. V. Dedovich,⁶³ J. Degenhardt,¹¹⁸
M. Dehchar,¹¹⁶ C. Del Papa,^{162a,162c} J. Del Peso,⁷⁸ T. Del Prete,^{120a,120b} T. Delemontex,⁵⁴ M. Deliyergiyev,⁷²
A. Dell'Acqua,²⁹ L. Dell'Asta,²¹ M. Della Pietra,^{100a,j} D. della Volpe,^{100a,100b} M. Delmastro,⁴ N. Delruelle,²⁹
P. A. Delsart,⁵⁴ C. Deluca,¹⁴⁶ S. Demers,¹⁷³ M. Demichev,⁶³ B. Demirkoz,^{11,l} J. Deng,¹⁶¹ S. P. Denisov,¹²⁶
D. Derendarz,³⁸ J. E. Derkaoui,^{133d} F. Derue,⁷⁶ P. Dervan,⁷¹ K. Desch,²⁰ E. Devetak,¹⁴⁶ P. O. Deviveiros,¹⁰³
A. Dewhurst,¹²⁷ B. DeWilde,¹⁴⁶ S. Dhaliwal,¹⁵⁶ R. Dhullipudi,^{24,m} A. Di Ciaccio,^{131a,131b} L. Di Ciaccio,⁴
A. Di Girolamo,²⁹ B. Di Girolamo,²⁹ S. Di Luise,^{132a,132b} A. Di Mattia,¹⁷⁰ B. Di Micco,²⁹ R. Di Nardo,⁴⁶
A. Di Simone,^{131a,131b} R. Di Sipio,^{19a,19b} M. A. Diaz,^{31a} F. Diblen,^{18c} E. B. Diehl,⁸⁵ J. Dietrich,⁴¹ T. A. Dietzsch,^{57a}
S. Diglio,⁸⁴ K. Dindar Yagci,³⁹ J. Dingfelder,²⁰ C. Dionisi,^{130a,130b} P. Dita,^{25a} S. Dita,^{25a} F. Dittus,²⁹ F. Djama,⁸¹
T. Djobava,^{50b} M. A. B. do Vale,^{23c} A. Do Valle Wemans,^{122a} T. K. O. Doan,⁴ M. Dobbs,⁸³ R. Dobinson,^{29,a}
D. Dobos,²⁹ E. Dobson,^{29,n} J. Dodd,³⁴ C. Doglioni,⁴⁸ T. Doherty,⁵² Y. Doi,^{64,a} J. Dolejsi,¹²⁴ I. Dolenc,⁷²
Z. Dolezal,¹²⁴ B. A. Dolgoshein,^{94,a} T. Dohmae,¹⁵³ M. Donadelli,^{23d} M. Donega,¹¹⁸ J. Donini,³³ J. Dopke,²⁹
A. Doria,^{100a} A. Dos Anjos,¹⁷⁰ M. Dosil,¹¹ A. Dotti,^{120a,120b} M. T. Dova,⁶⁸ A. D. Doxiadis,¹⁰³ A. T. Doyle,⁵²
Z. Drasal,¹²⁴ J. Drees,¹⁷² N. Dressnandt,¹¹⁸ H. Drevermann,²⁹ C. Driouichi,³⁵ M. Dris,⁹ J. Dubbert,⁹⁷ S. Dube,¹⁴
E. Duchovni,¹⁶⁹ G. Duckeck,⁹⁶ A. Dudarev,²⁹ F. Dudziak,⁶² M. Dührssen,²⁹ I. P. Duerdoth,⁸⁰ L. Duflot,¹¹³
M-A. Dufour,⁸³ M. Dunford,²⁹ H. Duran Yildiz,^{3a} R. Duxfield,¹³⁷ M. Dwuznik,³⁷ F. Dydak,²⁹ M. Düren,⁵¹
W. L. Ebenstein,⁴⁴ J. Ebke,⁹⁶ S. Eckweiler,⁷⁹ K. Edmonds,⁷⁹ C. A. Edwards,⁷⁴ N. C. Edwards,⁵² W. Ehrenfeld,⁴¹
T. Ehrich,⁹⁷ T. Eifert,¹⁴¹ G. Eigen,¹³ K. Einsweiler,¹⁴ E. Eisenhandler,⁷³ T. Ekelof,¹⁶⁴ M. El Kacimi,^{133c} M. Ellert,¹⁶⁴
S. Elles,⁴ F. Ellinghaus,⁷⁹ K. Ellis,⁷³ N. Ellis,²⁹ J. Elmsheuser,⁹⁶ M. Elsing,²⁹ D. Emelianov,¹²⁷ R. Engelmann,¹⁴⁶
A. Engl,⁹⁶ B. Epp,⁶⁰ A. Eppig,⁸⁵ J. Erdmann,⁵³ A. Ereditato,¹⁶ D. Eriksson,^{144a} J. Ernst,¹ M. Ernst,²⁴ J. Ernwein,¹³⁴
D. Errede,¹⁶³ S. Errede,¹⁶³ E. Ertel,⁷⁹ M. Escalier,¹¹³ C. Escobar,¹²¹ X. Espinal Curull,¹¹ B. Esposito,⁴⁶ F. Etienne,⁸¹
A. I. Etienvre,¹³⁴ E. Etzion,¹⁵¹ D. Evangelakou,⁵³ H. Evans,⁵⁹ L. Fabbri,^{19a,19b} C. Fabre,²⁹ R. M. Fakhruddinov,¹²⁶
S. Falciano,^{130a} Y. Fang,¹⁷⁰ M. Fanti,^{87a,87b} A. Farbin,⁷ A. Farilla,^{132a} J. Farley,¹⁴⁶ T. Faroouque,¹⁵⁶ S. Farrell,¹⁶¹
S. M. Farrington,¹¹⁶ P. Farthouat,²⁹ P. Fassnacht,²⁹ D. Fassouliotis,⁸ B. Fatholahzadeh,¹⁵⁶ A. Favareto,^{87a,87b}
L. Fayard,¹¹³ S. Fazio,^{36a,36b} R. Febbraro,³³ P. Federic,^{142a} O. L. Fedin,¹¹⁹ W. Fedorko,⁸⁶ M. Fehling-Kaschek,⁴⁷
L. Felgioni,⁸¹ D. Fellmann,⁵ C. Feng,^{32d} E. J. Feng,³⁰ A. B. Fenyuk,¹²⁶ J. Ferencei,^{142b} J. Ferland,⁹¹ W. Fernando,¹⁰⁷
S. Ferrag,⁵² J. Ferrando,⁵² V. Ferrara,⁴¹ A. Ferrari,¹⁶⁴ P. Ferrari,¹⁰³ R. Ferrari,^{117a} D. E. Ferreira de Lima,⁵²
A. Ferrer,¹⁶⁵ M. L. Ferrer,⁴⁶ D. Ferrere,⁴⁸ C. Ferretti,⁸⁵ A. Ferretto Parodi,^{49a,49b} M. Fiassaric,³⁰ F. Fiedler,⁷⁹
A. Filipčič,⁷² A. Filippas,⁹ F. Filthaut,¹⁰² M. Fincke-Keeler,¹⁶⁷ M. C. N. Fiolhais,^{122a,i} L. Fiorini,¹⁶⁵ A. Firan,³⁹
G. Fischer,⁴¹ P. Fischer,²⁰ M. J. Fisher,¹⁰⁷ M. Flechl,⁴⁷ I. Fleck,¹³⁹ J. Fleckner,⁷⁹ P. Fleischmann,¹⁷¹
S. Fleischmann,¹⁷² T. Flick,¹⁷² A. Floderus,⁷⁷ L. R. Flores Castillo,¹⁷⁰ M. J. Flowerdew,⁹⁷ M. Fokitis,⁹
T. Fonseca Martin,¹⁶ D. A. Forbush,¹³⁶ A. Formica,¹³⁴ A. Forti,⁸⁰ D. Fortin,^{157a} J. M. Foster,⁸⁰ D. Fournier,¹¹³
A. Foussat,²⁹ A. J. Fowler,⁴⁴ K. Fowler,¹³⁵ H. Fox,⁶⁹ P. Francavilla,¹¹ S. Franchino,^{117a,117b} D. Francis,²⁹ T. Frank,¹⁶⁹
M. Franklin,⁵⁶ S. Franz,²⁹ M. Fraternali,^{117a,117b} S. Fratina,¹¹⁸ S. T. French,²⁷ F. Friedrich,⁴³ R. Froeschl,²⁹
D. Froidevaux,²⁹ J. A. Frost,²⁷ C. Fukunaga,¹⁵⁴ E. Fullana Torregrosa,²⁹ J. Fuster,¹⁶⁵ C. Gabaldon,²⁹ O. Gabizon,¹⁶⁹
T. Gadfort,²⁴ S. Gadomski,⁴⁸ G. Gagliardi,^{49a,49b} P. Gagnon,⁵⁹ C. Galea,⁹⁶ E. J. Gallas,¹¹⁶ V. Gallo,¹⁶ B. J. Gallop,¹²⁷
P. Gallus,¹²³ K. K. Gan,¹⁰⁷ Y. S. Gao,^{141,f} V. A. Gapienko,¹²⁶ A. Gaponenko,¹⁴ F. Garberson,¹⁷³ M. Garcia-Sciveres,¹⁴
C. García,¹⁶⁵ J. E. García Navarro,¹⁶⁵ R. W. Gardner,³⁰ N. Garelli,²⁹ H. Garitaonandia,¹⁰³ V. Garonne,²⁹ J. Garvey,¹⁷
C. Gatti,⁴⁶ G. Gaudio,^{117a} B. Gaur,¹³⁹ L. Gauthier,¹³⁴ P. Gauzzi,^{130a,130b} I. L. Gavrilenko,⁹² C. Gay,¹⁶⁶ G. Gaycken,²⁰
J-C. Gayde,²⁹ E. N. Gazis,⁹ P. Ge,^{32d} C. N. P. Gee,¹²⁷ D. A. A. Geerts,¹⁰³ Ch. Geich-Gimbel,²⁰ K. Gellerstedt,^{144a,144b}
C. Gemme,^{49a} A. Gemmell,⁵² M. H. Genest,⁵⁴ S. Gentile,^{130a,130b} M. George,⁵³ S. George,⁷⁴ P. Gerlach,¹⁷²
A. Gershon,¹⁵¹ C. Geweniger,^{57a} H. Ghazlane,^{133b} N. Ghodbane,³³ B. Giacobbe,^{19a} S. Giagu,^{130a,130b}
V. Giakoumopoulou,⁸ V. Giangiobbe,¹¹ F. Gianotti,²⁹ B. Gibbard,²⁴ A. Gibson,¹⁵⁶ S. M. Gibson,²⁹ L. M. Gilbert,¹¹⁶
V. Gilevsky,⁸⁹ D. Gillberg,²⁸ A. R. Gillman,¹²⁷ D. M. Gingrich,^{2,e} J. Ginzburg,¹⁵¹ N. Giokaris,⁸ M. P. Giordani,^{162c}
R. Giordano,^{100a,100b} F. M. Giorgi,¹⁵ P. Giovannini,⁹⁷ P. F. Giraud,¹³⁴ D. Giugni,^{87a} M. Giunta,⁹¹ P. Giusti,^{19a}
B. K. Gjelsten,¹¹⁵ L. K. Gladilin,⁹⁵ C. Glasman,⁷⁸ J. Glatzer,⁴⁷ A. Glazov,⁴¹ K. W. Glitza,¹⁷² G. L. Glonti,⁶³
J. R. Goddard,⁷³ J. Godfrey,¹⁴⁰ J. Godlewski,²⁹ M. Goebel,⁴¹ T. Göpfert,⁴³ C. Goeringer,⁷⁹ C. Gössling,⁴²
T. Göttfert,⁹⁷ S. Goldfarb,⁸⁵ T. Golling,¹⁷³ A. Gomes,^{122a,c} L. S. Gomez Fajardo,⁴¹ R. Gonçalves,⁷⁴
J. Goncalves Pinto Firmino Da Costa,⁴¹ L. Gonella,²⁰ A. Gonidec,²⁹ S. Gonzalez,¹⁷⁰ S. González de la Hoz,¹⁶⁵
G. Gonzalez Parra,¹¹ M. L. Gonzalez Silva,²⁶ S. Gonzalez-Sevilla,⁴⁸ J. J. Goodson,¹⁴⁶ L. Goossens,²⁹
P. A. Gorbounov,⁹³ H. A. Gordon,²⁴ I. Gorelov,¹⁰¹ G. Gorfine,¹⁷² B. Gorini,²⁹ E. Gorini,^{70a,70b} A. Gorišek,⁷²

E. Gornicki,³⁸ V. N. Goryachev,¹²⁶ B. Gosdzik,⁴¹ A. T. Goshaw,⁵ M. Gosselink,¹⁰³ M. I. Gostkin,⁶³
 I. Gough Eschrich,¹⁶¹ M. Gouighri,^{133a} D. Goujdami,^{133c} M. P. Goulette,⁴⁸ A. G. Goussiou,¹³⁶ C. Goy,⁴
 S. Gozpinar,²² I. Grabowska-Bold,³⁷ P. Grafström,²⁹ K.-J. Grahm,⁴¹ F. Grancagnolo,^{70a} S. Grancagnolo,¹⁵
 V. Grassi,¹⁴⁶ V. Gratchev,¹¹⁹ N. Grau,³⁴ H. M. Gray,²⁹ J. A. Gray,¹⁴⁶ E. Graziani,^{132a} O. G. Grebenyuk,¹¹⁹
 T. Greenshaw,⁷¹ Z. D. Greenwood,^{24,m} K. Gregersen,³⁵ I. M. Gregor,⁴¹ P. Grenier,¹⁴¹ J. Griffiths,¹³⁶
 N. Grigalashvili,⁶³ A. A. Grillo,¹³⁵ S. Grinstein,¹¹ Y. V. Grishkevich,⁹⁵ J.-F. Grivaz,¹¹³ M. Groh,⁹⁷ E. Gross,¹⁶⁹
 J. Grosse-Knetter,⁵³ J. Groth-Jensen,¹⁶⁹ K. Grybel,¹³⁹ V. J. Guarino,⁵ D. Guest,¹⁷³ C. Guichenev,³³ A. Guida,^{70a,70b}
 S. Guindon,⁵³ H. Guler,^{83,o} J. Gunther,¹²³ B. Guo,¹⁵⁶ J. Guo,³⁴ A. Gupta,³⁰ Y. Gusakov,⁶³ V. N. Gushchin,¹²⁶
 P. Gutierrez,¹⁰⁹ N. Guttman,¹⁵¹ O. Gutzwiller,¹⁷⁰ C. Guyot,¹³⁴ C. Gwenlan,¹¹⁶ C. B. Gwilliam,⁷¹ A. Haas,¹⁴¹
 S. Haas,²⁹ C. Haber,¹⁴ H. K. Hadavand,³⁹ D. R. Hadley,¹⁷ P. Haefner,⁹⁷ F. Hahn,²⁹ S. Haider,²⁹ Z. Hajduk,³⁸
 H. Hakobyan,¹⁷⁴ D. Hall,¹¹⁶ J. Haller,⁵³ K. Hamacher,¹⁷² P. Hamal,¹¹¹ M. Hamer,⁵³ A. Hamilton,^{143b,p}
 S. Hamilton,¹⁵⁹ H. Han,^{32a} L. Han,^{32b} K. Hanagaki,¹¹⁴ K. Hanawa,¹⁵⁸ M. Hance,¹⁴ C. Handel,⁷⁹ P. Hanke,^{57a}
 J. R. Hansen,³⁵ J. B. Hansen,³⁵ J. D. Hansen,³⁵ P. H. Hansen,³⁵ P. Hansson,¹⁴¹ K. Hara,¹⁵⁸ G. A. Hare,¹³⁵
 T. Harenberg,¹⁷² S. Harkusha,⁸⁸ D. Harper,⁸⁵ R. D. Harrington,⁴⁵ O. M. Harris,¹³⁶ K. Harrison,¹⁷ J. Hartert,⁴⁷
 F. Hartjes,¹⁰³ T. Haruyama,⁶⁴ A. Harvey,⁵⁵ S. Hasegawa,⁹⁹ Y. Hasegawa,¹³⁸ S. Hassani,¹³⁴ M. Hatch,²⁹ D. Hauff,⁹⁷
 S. Haug,¹⁶ M. Hauschild,²⁹ R. Hauser,⁸⁶ M. Havranek,²⁰ B. M. Hawes,¹¹⁶ C. M. Hawkes,¹⁷ R. J. Hawkings,²⁹
 A. D. Hawkins,⁷⁷ D. Hawkins,¹⁶¹ T. Hayakawa,⁶⁵ T. Hayashi,¹⁵⁸ D. Hayden,⁷⁴ H. S. Hayward,⁷¹ S. J. Haywood,¹²⁷
 E. Hazen,²¹ M. He,^{32d} S. J. Head,¹⁷ V. Hedberg,⁷⁷ L. Heelan,⁷ S. Heim,⁸⁶ B. Heinemann,¹⁴ S. Heisterkamp,³⁵
 L. Helary,⁴ C. Heller,⁹⁶ M. Heller,²⁹ S. Hellman,^{144a,144b} D. Hellmich,²⁰ C. Helsen,¹¹ R. C. W. Henderson,⁶⁹
 M. Henke,^{57a} A. Henrichs,⁵³ A. M. Henriques Correia,²⁹ S. Henrot-Versille,¹¹³ F. Henry-Couannier,⁸¹ C. Hensel,⁵³
 T. Henß,¹⁷² C. M. Hernandez,⁷ Y. Hernández Jiménez,¹⁶⁵ R. Herrberg,¹⁵ A. D. Hershenhorn,¹⁵⁰ G. Herten,⁴⁷
 R. Hertenberger,⁹⁶ L. Hervas,²⁹ G. G. Hesketh,⁷⁵ N. P. Hessey,¹⁰³ E. Higón-Rodríguez,¹⁶⁵ D. Hill,^{5,a} J. C. Hill,²⁷
 N. Hill,⁵ K. H. Hiller,⁴¹ S. Hillert,²⁰ S. J. Hillier,¹⁷ I. Hinchliffe,¹⁴ E. Hines,¹¹⁸ M. Hirose,¹¹⁴ F. Hirsch,⁴²
 D. Hirschbuehl,¹⁷² J. Hobbs,¹⁴⁶ N. Hod,¹⁵¹ M. C. Hodgkinson,¹³⁷ P. Hodgson,¹³⁷ A. Hoecker,²⁹
 M. R. Hoferkamp,¹⁰¹ J. Hoffman,³⁹ D. Hoffmann,⁸¹ M. Hohlfeld,⁷⁹ M. Holder,¹³⁹ S. O. Holmgren,^{144a} T. Holy,¹²⁵
 J. L. Holzbauer,⁸⁶ Y. Homma,⁶⁵ T. M. Hong,¹¹⁸ L. Hooft van Huysduynen,¹⁰⁶ T. Horazdovsky,¹²⁵ C. Horn,¹⁴¹
 S. Horner,⁴⁷ J.-Y. Hostachy,⁵⁴ S. Hou,¹⁴⁹ M. A. Houlden,⁷¹ A. Hoummada,^{133a} J. Howarth,⁸⁰ D. F. Howell,¹¹⁶
 I. Hristova,¹⁵ J. Hrivnac,¹¹³ I. Hruska,¹²³ T. Hryn'ova,⁴ P. J. Hsu,⁷⁹ S.-C. Hsu,¹⁴ G. S. Huang,¹⁰⁹ Z. Hubacek,¹²⁵
 F. Hubaut,⁸¹ F. Huegging,²⁰ A. Huettmann,⁴¹ T. B. Huffman,¹¹⁶ E. W. Hughes,³⁴ G. Hughes,⁶⁹ R. E. Hughes-Jones,⁸⁰
 M. Huhtinen,²⁹ P. Hurst,⁵⁶ M. Hurwitz,¹⁴ U. Husemann,⁴¹ N. Huseynov,^{63,q} J. Huston,⁸⁶ J. Huth,⁵⁶ G. Iacobucci,⁴⁸
 G. Iakovidis,⁹ M. Ibbotson,⁸⁰ I. Ibragimov,¹³⁹ R. Ichimiya,⁶⁵ L. Iconomidou-Fayard,¹¹³ J. Idarraga,¹¹³ P. Iengo,^{100a}
 O. Igonkina,¹⁰³ Y. Ikegami,⁶⁴ M. Ikeno,⁶⁴ Y. Ilchenko,³⁹ D. Iliadis,¹⁵² N. Ilic,¹⁵⁶ M. Imori,¹⁵³ T. Ince,²⁰
 J. Inigo-Golfin,²⁹ P. Ioannou,⁸ M. Iodice,^{132a} V. Ippolito,^{130a,130b} A. Irles Quiles,¹⁶⁵ C. Isaksson,¹⁶⁴ A. Ishikawa,⁶⁵
 M. Ishino,⁶⁶ R. Ishmukhametov,³⁹ C. Issever,¹¹⁶ S. Istin,^{18a} A. V. Ivashin,¹²⁶ W. Iwanski,³⁸ H. Iwasaki,⁶⁴ J. M. Izen,⁴⁰
 V. Izzo,^{100a} B. Jackson,¹¹⁸ J. N. Jackson,⁷¹ P. Jackson,¹⁴¹ M. R. Jaekel,²⁹ V. Jain,⁵⁹ K. Jakobs,⁴⁷ S. Jakobsen,³⁵
 J. Jakubek,¹²⁵ D. K. Jana,¹⁰⁹ E. Jansen,⁷⁵ H. Jansen,²⁹ A. Jantsch,⁹⁷ M. Janus,⁴⁷ G. Jarlskog,⁷⁷ L. Jeanty,⁵⁶ K. Jelen,³⁷
 I. Jen-La Plante,³⁰ P. Jenni,²⁹ A. Jeremie,⁴ P. Jež,³⁵ S. Jézéquel,⁴ M. K. Jha,^{19a} H. Ji,¹⁷⁰ W. Ji,⁷⁹ J. Jia,¹⁴⁶ Y. Jiang,^{32b}
 M. Jimenez Belenguier,⁴¹ G. Jin,^{32b} S. Jin,^{32a} O. Jinnouchi,¹⁵⁵ M. D. Joergensen,³⁵ D. Joffe,³⁹ L. G. Johansen,¹³
 M. Johansen,^{144a,144b} K. E. Johansson,^{144a} P. Johansson,¹³⁷ S. Johnert,⁴¹ K. A. Johns,⁶ K. Jon-And,^{144a,144b}
 G. Jones,¹¹⁶ R. W. L. Jones,⁶⁹ T. W. Jones,⁷⁵ T. J. Jones,⁷¹ O. Jonsson,²⁹ C. Joram,²⁹ P. M. Jorge,^{122a} J. Joseph,¹⁴
 K. D. Joshi,⁸⁰ J. Jovicevic,¹⁴⁵ T. Jovin,^{12b} X. Ju,¹⁷⁰ C. A. Jung,⁴² R. M. Jungst,²⁹ V. Juranek,¹²³ P. Jussel,⁶⁰
 A. Juste Rozas,¹¹ V. V. Kabachenko,¹²⁶ S. Kabana,¹⁶ M. Kaci,¹⁶⁵ A. Kaczmarska,³⁸ P. Kadlecik,³⁵ M. Kado,¹¹³
 H. Kagan,¹⁰⁷ M. Kagan,⁵⁶ S. Kaiser,⁹⁷ E. Kajomovitz,¹⁵⁰ S. Kalinin,¹⁷² L. V. Kalinovskaya,⁶³ S. Kama,³⁹
 N. Kanaya,¹⁵³ M. Kaneda,²⁹ S. Kaneti,²⁷ T. Kanno,¹⁵⁵ V. A. Kantserov,⁹⁴ J. Kanzaki,⁶⁴ B. Kaplan,¹⁷³ A. Kapliy,³⁰
 J. Kaplon,²⁹ D. Kar,⁴³ M. Karagounis,²⁰ M. Karagoz,¹¹⁶ M. Karnevskiy,⁴¹ V. Kartvelishvili,⁶⁹ A. N. Karyukhin,¹²⁶
 L. Kashif,¹⁷⁰ G. Kasieczka,^{57b} R. D. Kass,¹⁰⁷ A. Kastanas,¹³ M. Kataoka,⁴ Y. Kataoka,¹⁵³ E. Katsoufis,⁹ J. Katzy,⁴¹
 V. Kaushik,⁶ K. Kawagoe,⁶⁵ T. Kawamoto,¹⁵³ G. Kawamura,⁷⁹ M. S. Kayl,¹⁰³ V. A. Kazanin,¹⁰⁵ M. Y. Kazarinov,⁶³
 R. Keeler,¹⁶⁷ R. Kehoe,³⁹ M. Keil,⁵³ G. D. Kekelidze,⁶³ J. S. Keller,¹³⁶ J. Kennedy,⁹⁶ M. Kenyon,⁵² O. Kepka,¹²³
 N. Kerschen,²⁹ B. P. Kerševan,⁷² S. Kersten,¹⁷² K. Kessoku,¹⁵³ J. Keung,¹⁵⁶ F. Khalil-zada,¹⁰ H. Khandanyan,¹⁶³
 A. Khanov,¹¹⁰ D. Kharchenko,⁶³ A. Khodinov,⁹⁴ A. G. Kholodenko,¹²⁶ A. Khomich,^{57a} T. J. Khoo,²⁷ G. Khoriali,²⁰
 A. Khoroshilov,¹⁷² N. Khovanskiy,⁶³ V. Khovanskiy,⁹³ E. Khramov,⁶³ J. Khubua,^{50b} H. Kim,^{144a,144b} M. S. Kim,²

S. H. Kim,¹⁵⁸ N. Kimura,¹⁶⁸ O. Kind,¹⁵ B. T. King,⁷¹ M. King,⁶⁵ R. S. B. King,¹¹⁶ J. Kirk,¹²⁷ L. E. Kirsch,²²
A. E. Kiryunin,⁹⁷ T. Kishimoto,⁶⁵ D. Kisielewska,³⁷ T. Kittelmann,¹²¹ A. M. Kiver,¹²⁶ E. Kladiva,^{142b} M. Klein,⁷¹
U. Klein,⁷¹ K. Kleinknecht,⁷⁹ M. Klemetti,⁸³ A. Klier,¹⁶⁹ P. Klimek,^{144a,144b} A. Klimentov,²⁴ R. Klingenberg,⁴²
J. A. Klinger,⁸⁰ E. B. Klinkby,³⁵ T. Klioutchnikova,²⁹ P. F. Klok,¹⁰² S. Klous,¹⁰³ E.-E. Kluge,^{57a} T. Kluge,⁷¹
P. Kluit,¹⁰³ S. Kluth,⁹⁷ N. S. Knecht,¹⁵⁶ E. Kneringer,⁶⁰ J. Knobloch,²⁹ E. B. F. G. Knoops,⁸¹ A. Knue,⁵³ B. R. Ko,⁴⁴
T. Kobayashi,¹⁵³ M. Kobel,⁴³ M. Kocian,¹⁴¹ P. Kodys,¹²⁴ K. Köneke,²⁹ A. C. König,¹⁰² S. Koenig,⁷⁹ L. Köpke,⁷⁹
F. Koetsveld,¹⁰² P. Koevesarki,²⁰ T. Koffas,²⁸ E. Koffeman,¹⁰³ L. A. Kogan,¹¹⁶ F. Kohn,⁵³ Z. Kohout,¹²⁵ T. Kohriki,⁶⁴
T. Koi,¹⁴¹ T. Kokott,²⁰ G. M. Kolachev,¹⁰⁵ H. Kolanoski,¹⁵ V. Kolesnikov,⁶³ I. Koletsou,^{87a} J. Koll,⁸⁶ M. Kollefrath,⁴⁷
S. D. Kolya,⁸⁰ A. A. Komar,⁹² Y. Komori,¹⁵³ T. Kondo,⁶⁴ T. Kono,^{41,r} A. I. Kononov,⁴⁷ R. Konoplich,^{106,s}
N. Konstantinidis,⁷⁵ A. Kootz,¹⁷² S. Koperny,³⁷ K. Korcyl,³⁸ K. Kordas,¹⁵² V. Koreshev,¹²⁶ A. Korn,¹¹⁶ A. Korol,¹⁰⁵
I. Korolkov,¹¹ E. V. Korolkova,¹³⁷ V. A. Korotkov,¹²⁶ O. Kortner,⁹⁷ S. Kortner,⁹⁷ V. V. Kostyukhin,²⁰
M. J. Kotamäki,²⁹ S. Kotov,⁹⁷ V. M. Kotov,⁶³ A. Kotwal,⁴⁴ C. Kourkoumelis,⁸ V. Kouskoura,¹⁵² A. Koutsman,^{157a}
R. Kowalewski,¹⁶⁷ T. Z. Kowalski,³⁷ W. Kozanecki,¹³⁴ A. S. Kozhin,¹²⁶ V. Kral,¹²⁵ V. A. Kramarenko,⁹⁵
G. Kramberger,⁷² M. W. Krasny,⁷⁶ A. Krasznahorkay,¹⁰⁶ J. Kraus,⁸⁶ J. K. Kraus,²⁰ A. Kreisel,¹⁵¹ F. Krejci,¹²⁵
J. Kretzschmar,⁷¹ N. Krieger,⁵³ P. Krieger,¹⁵⁶ K. Kroeninger,⁵³ H. Kroha,⁹⁷ J. Kroll,¹¹⁸ J. Kroseberg,²⁰ J. Krstic,^{12a}
U. Kruchonak,⁶³ H. Krüger,²⁰ T. Kruker,¹⁶ N. Krumnack,⁶² Z. V. Krumshiteyn,⁶³ A. Kruth,²⁰ T. Kubota,⁸⁴ S. Kuday,^{3a}
S. Kuehn,⁴⁷ A. Kugel,^{57c} T. Kuhl,⁴¹ D. Kuhn,⁶⁰ V. Kukhtin,⁶³ Y. Kulchitsky,⁸⁸ S. Kuleshov,^{31b} C. Kummer,⁹⁶
M. Kuna,⁷⁶ N. Kundu,¹¹⁶ J. Kunkle,¹¹⁸ A. Kupco,¹²³ H. Kurashige,⁶⁵ M. Kurata,¹⁵⁸ Y. A. Kurochkin,⁸⁸ V. Kus,¹²³
E. S. Kuwertz,¹⁴⁵ M. Kuze,¹⁵⁵ J. Kvita,¹⁴⁰ R. Kwee,¹⁵ A. La Rosa,⁴⁸ L. La Rotonda,^{36a,36b} L. Labarga,⁷⁸ J. Labbe,⁴
S. Lablak,^{133a} C. Lacasta,¹⁶⁵ F. Lacava,^{130a,130b} H. Lacker,¹⁵ D. Lacour,⁷⁶ V. R. Lacuesta,¹⁶⁵ E. Ladygin,⁶³
R. Lafaye,⁴ B. Laforge,⁷⁶ T. Lagouri,⁷⁸ S. Lai,⁴⁷ E. Laisne,⁵⁴ M. Lamanna,²⁹ L. Lambourne,⁷⁵ C. L. Lampen,⁶
W. Lampl,⁶ E. Lancon,¹³⁴ U. Landgraf,⁴⁷ M. P. J. Landon,⁷³ J. L. Lane,⁸⁰ C. Lange,⁴¹ A. J. Lankford,¹⁶¹ F. Lanni,²⁴
K. Lantzsch,¹⁷² S. Laplace,⁷⁶ C. Lapoire,²⁰ J. F. Laporte,¹³⁴ T. Lari,^{87a} A. V. Larionov,¹²⁶ A. Larner,¹¹⁶ C. Lasseur,²⁹
M. Lassnig,²⁹ P. Laurelli,⁴⁶ V. Lavorini,^{36a,36b} W. Lavrijsen,¹⁴ P. Laycock,⁷¹ A. B. Lazarev,⁶³ O. Le Dortz,⁷⁶
E. Le Guirriec,⁸¹ C. Le Maner,¹⁵⁶ E. Le Menedeu,¹¹ C. Lebel,⁹¹ T. LeCompte,⁵ F. Ledroit-Guillon,⁵⁴ H. Lee,¹⁰³
J. S. H. Lee,¹¹⁴ S. C. Lee,¹⁴⁹ L. Lee,¹⁷³ M. Lefebvre,¹⁶⁷ M. Legendre,¹³⁴ A. Leger,⁴⁸ B. C. LeGeyt,¹¹⁸ F. Legger,⁹⁶
C. Leggett,¹⁴ M. Lehmacher,²⁰ G. Lehmann Miotto,²⁹ X. Lei,⁶ M. A. L. Leite,^{23d} R. Leitner,¹²⁴ D. Lellouch,¹⁶⁹
M. Leltchouk,³⁴ B. Lemmer,⁵³ V. Lendermann,^{57a} K. J. C. Leney,^{143b} T. Lenz,¹⁰³ G. Lenzen,¹⁷² B. Lenzi,²⁹
K. Leonhardt,⁴³ S. Leontsinis,⁹ C. Leroy,⁹¹ J.-R. Lessard,¹⁶⁷ J. Lesser,^{144a} C. G. Lester,²⁷ A. Leung Fook Cheong,¹⁷⁰
J. Levêque,⁴ D. Levin,⁸⁵ L. J. Levinson,¹⁶⁹ M. S. Levitski,¹²⁶ A. Lewis,¹¹⁶ G. H. Lewis,¹⁰⁶ A. M. Leyko,²⁰
M. Leyton,¹⁵ B. Li,⁸¹ H. Li,^{170,t} S. Li,^{32b,u} X. Li,⁸⁵ Z. Liang,^{116,v} H. Liao,³³ B. Liberti,^{131a} P. Lichard,²⁹
M. Lichtnecker,⁹⁶ K. Lie,¹⁶³ W. Liebig,¹³ C. Limbach,²⁰ A. Limosani,⁸⁴ M. Limper,⁶¹ S. C. Lin,^{149,w} F. Linde,¹⁰³
J. T. Linnemann,⁸⁶ E. Lipeles,¹¹⁸ L. Lipinsky,¹²³ A. Lipniacka,¹³ T. M. Liss,¹⁶³ D. Lissauer,²⁴ A. Lister,⁴⁸
A. M. Litke,¹³⁵ C. Liu,²⁸ D. Liu,¹⁴⁹ H. Liu,⁸⁵ J. B. Liu,⁸⁵ M. Liu,^{32b} Y. Liu,^{32b} M. Livan,^{117a,117b}
S. S. A. Livermore,¹¹⁶ A. Lleres,⁵⁴ J. Llorente Merino,⁷⁸ S. L. Lloyd,⁷³ E. Lobodzinska,⁴¹ P. Loch,⁶
W. S. Lockman,¹³⁵ T. Loddenkoetter,²⁰ F. K. Loebinger,⁸⁰ A. Loginov,¹⁷³ C. W. Loh,¹⁶⁶ T. Lohse,¹⁵ K. Lohwasser,⁴⁷
M. Lokajicek,¹²³ J. Loken,¹¹⁶ V. P. Lombardo,⁴ R. E. Long,⁶⁹ L. Lopes,^{122a} D. Lopez Mateos,⁵⁶ J. Lorenz,⁹⁶
N. Lorenzo Martinez,¹¹³ M. Losada,¹⁶⁰ P. Loscutoff,¹⁴ F. Lo Sterzo,^{130a,130b} M. J. Losty,^{157a} X. Lou,⁴⁰ A. Lounis,¹¹³
K. F. Loureiro,¹⁶⁰ J. Love,²¹ P. A. Love,⁶⁹ A. J. Lowe,^{141,f} F. Lu,^{32a} H. J. Lubatti,¹³⁶ C. Luci,^{130a,130b} A. Lucotte,⁵⁴
A. Ludwig,⁴³ D. Ludwig,⁴¹ I. Ludwig,⁴⁷ J. Ludwig,⁴⁷ F. Luehring,⁵⁹ G. Luijckx,¹⁰³ W. Lukas,⁶⁰ D. Lumb,⁴⁷
L. Luminari,^{130a} E. Lund,¹¹⁵ B. Lund-Jensen,¹⁴⁵ B. Lundberg,⁷⁷ J. Lundberg,^{144a,144b} J. Lundquist,³⁵ M. Lungwitz,⁷⁹
G. Lutz,⁹⁷ D. Lynn,²⁴ J. Lys,¹⁴ E. Lytken,⁷⁷ H. Ma,²⁴ L. L. Ma,¹⁷⁰ J. A. Macana Goia,⁹¹ G. Maccarrone,⁴⁶
A. Macchiolo,⁹⁷ B. Maček,⁷² J. Machado Miguens,^{122a} R. Mackeprang,³⁵ R. J. Madaras,¹⁴ W. F. Mader,⁴³
R. Maenner,^{57c} T. Maeno,²⁴ P. Mättig,¹⁷² S. Mättig,⁴¹ L. Magnoni,²⁹ E. Magradze,⁵³ Y. Mahalalal,¹⁵¹ K. Mahboubi,⁴⁷
S. Mahmoud,⁷¹ G. Mahout,¹⁷ C. Maiani,^{130a,130b} C. Maidantchik,^{23a} A. Maio,^{122a,c} S. Majewski,²⁴ Y. Makida,⁶⁴
N. Makovec,¹¹³ P. Mal,¹³⁴ B. Malaescu,²⁹ Pa. Malecki,³⁸ P. Malecki,³⁸ V. P. Maleev,¹¹⁹ F. Malek,⁵⁴ U. Mallik,⁶¹
D. Malon,⁵ C. Malone,¹⁴¹ S. Maltezos,⁹ V. Malyshev,¹⁰⁵ S. Malyukov,²⁹ R. Mameghani,⁹⁶ J. Mamuzic,^{12b}
A. Manabe,⁶⁴ L. Mandelli,^{87a} I. Mandić,⁷² R. Mandrysch,¹⁵ J. Maneira,^{122a} P. S. Mangeard,⁸⁶
L. Manhaes de Andrade Filho,^{23a} I. D. Manjavidze,⁶³ A. Mann,⁵³ P. M. Manning,¹³⁵ A. Manousakis-Katsikakis,⁸
B. Mansoulie,¹³⁴ A. Manz,⁹⁷ A. Mapelli,²⁹ L. Mapelli,²⁹ L. March,⁷⁸ J. F. Marchand,²⁸ F. Marchese,^{131a,131b}
G. Marchiori,⁷⁶ M. Marcisovsky,¹²³ C. P. Marino,¹⁶⁷ F. Marroquim,^{23a} R. Marshall,⁸⁰ Z. Marshall,²⁹ F. K. Martens,¹⁵⁶

S. Marti-Garcia,¹⁶⁵ A. J. Martin,¹⁷³ B. Martin,²⁹ B. Martin,⁸⁶ F. F. Martin,¹¹⁸ J. P. Martin,⁹¹ Ph. Martin,⁵⁴
T. A. Martin,¹⁷ V. J. Martin,⁴⁵ B. Martin dit Latour,⁴⁸ S. Martin-Haugh,¹⁴⁷ M. Martinez,¹¹ V. Martinez Outschoorn,⁵⁶
A. C. Martyniuk,¹⁶⁷ M. Marx,⁸⁰ F. Marzano,^{130a} A. Marzin,¹⁰⁹ L. Masetti,⁷⁹ T. Mashimo,¹⁵³ R. Mashinistov,⁹²
J. Masik,⁸⁰ A. L. Maslennikov,¹⁰⁵ I. Massa,^{19a,19b} G. Massaro,¹⁰³ N. Massol,⁴ P. Mastrandrea,^{130a,130b}
A. Mastroberardino,^{36a,36b} T. Masubuchi,¹⁵³ P. Matricon,¹¹³ H. Matsumoto,¹⁵³ H. Matsunaga,¹⁵³ T. Matsushita,⁶⁵
C. Mattravers,^{116,d} J. M. Maugain,²⁹ J. Maurer,⁸¹ S. J. Maxfield,⁷¹ D. A. Maximov,^{105,g} E. N. May,⁵ A. Mayne,¹³⁷
R. Mazini,¹⁴⁹ M. Mazur,²⁰ M. Mazzanti,^{87a} S. P. Mc Kee,⁸⁵ A. McCarn,¹⁶³ R. L. McCarthy,¹⁴⁶ T. G. McCarthy,²⁸
N. A. McCubbin,¹²⁷ K. W. McFarlane,⁵⁵ J. A. MCFayden,¹³⁷ H. McGlone,⁵² G. Mchedlidze,^{50b} R. A. McLaren,²⁹
T. McLaughlan,¹⁷ S. J. McMahon,¹²⁷ R. A. McPherson,^{167,k} A. Meade,⁸² J. Mechnich,¹⁰³ M. Mechtel,¹⁷²
M. Medinnis,⁴¹ R. Meera-Lebbai,¹⁰⁹ T. Meguro,¹¹⁴ R. Mehdiyev,⁹¹ S. Mehlhase,³⁵ A. Mehta,⁷¹ K. Meier,^{57a}
B. Meirose,⁷⁷ C. Melachrinou,³⁰ B. R. Mellado Garcia,¹⁷⁰ L. Mendoza Navas,¹⁶⁰ Z. Meng,^{149,t} A. Mengarelli,^{19a,19b}
S. Menke,⁹⁷ C. Menot,²⁹ E. Meoni,¹¹ K. M. Mercurio,⁵⁶ P. Mermod,⁴⁸ L. Merola,^{100a,100b} C. Meroni,^{87a}
F. S. Merritt,³⁰ H. Merritt,¹⁰⁷ A. Messina,²⁹ J. Metcalfe,¹⁰¹ A. S. Mete,⁶² C. Meyer,⁷⁹ C. Meyer,³⁰ J-P. Meyer,¹³⁴
J. Meyer,¹⁷¹ J. Meyer,⁵³ T. C. Meyer,²⁹ W. T. Meyer,⁶² J. Miao,^{32d} S. Michal,²⁹ L. Micu,^{25a} R. P. Middleton,¹²⁷
S. Migas,⁷¹ L. Mijović,⁴¹ G. Mikenberg,¹⁶⁹ M. Mikestikova,¹²³ M. Mikuž,⁷² D. W. Miller,³⁰ R. J. Miller,⁸⁶
W. J. Mills,¹⁶⁶ C. Mills,⁵⁶ A. Milov,¹⁶⁹ D. A. Milstead,^{144a,144b} D. Milstein,¹⁶⁹ A. A. Minaenko,¹²⁶
M. Miñano Moya,¹⁶⁵ I. A. Minashvili,⁶³ A. I. Mincer,¹⁰⁶ B. Mindur,³⁷ M. Mineev,⁶³ Y. Ming,¹⁷⁰ L. M. Mir,¹¹
G. Mirabelli,^{130a} L. Miralles Verge,¹¹ A. Misiejuk,⁷⁴ J. Mitrevski,¹³⁵ G. Y. Mitrofanov,¹²⁶ V. A. Mitsou,¹⁶⁵
S. Mitsui,⁶⁴ P. S. Miyagawa,¹³⁷ K. Miyazaki,⁶⁵ J. U. Mjörnmark,⁷⁷ T. Moa,^{144a,144b} P. Mockett,¹³⁶ S. Moed,⁵⁶
V. Moeller,²⁷ K. Mönig,⁴¹ N. Möser,²⁰ S. Mohapatra,¹⁴⁶ W. Mohr,⁴⁷ S. Mohrdieck-Möck,⁹⁷ R. Moles-Valls,¹⁶⁵
J. Molina-Perez,²⁹ J. Monk,⁷⁵ E. Monnier,⁸¹ S. Montesano,^{87a,87b} F. Monticelli,⁶⁸ S. Monzani,^{19a,19b} R. W. Moore,²
G. F. Moorhead,⁸⁴ C. Mora Herrera,⁴⁸ A. Moraes,⁵² N. Morange,¹³⁴ J. Morel,⁵³ G. Morello,^{36a,36b} D. Moreno,⁷⁹
M. Moreno Llácer,¹⁶⁵ P. Moretini,^{49a} M. Morgenstern,⁴³ M. Morii,⁵⁶ J. Morin,⁷³ A. K. Morley,²⁹ G. Mornacchi,²⁹
S. V. Morozov,⁹⁴ J. D. Morris,⁷³ L. Morvaj,⁹⁹ H. G. Moser,⁹⁷ M. Mosidze,^{50b} J. Moss,¹⁰⁷ R. Mount,¹⁴¹
E. Mountricha,^{9,x} S. V. Mouraviev,⁹² E. J. W. Moyse,⁸² M. Mudrinic,^{12b} F. Mueller,^{57a} J. Mueller,¹²¹ K. Mueller,²⁰
T. A. Müller,⁹⁶ T. Mueller,⁷⁹ D. Muenstermann,²⁹ A. Muir,¹⁶⁶ Y. Munwes,¹⁵¹ W. J. Murray,¹²⁷ I. Mussche,¹⁰³
E. Musto,^{100a,100b} A. G. Myagkov,¹²⁶ M. Myska,¹²³ J. Nadal,¹¹ K. Nagai,¹⁵⁸ K. Nagano,⁶⁴ A. Nagarkar,¹⁰⁷
Y. Nagasaka,⁵⁸ M. Nagel,⁹⁷ A. M. Nairz,²⁹ Y. Nakahama,²⁹ K. Nakamura,¹⁵³ T. Nakamura,¹⁵³ I. Nakano,¹⁰⁸
G. Nanava,²⁰ A. Napier,¹⁵⁹ R. Narayan,^{57b} M. Nash,^{75,d} N. R. Nation,²¹ T. Nattermann,²⁰ T. Naumann,⁴¹
G. Navarro,¹⁶⁰ H. A. Neal,⁸⁵ E. Nebot,⁷⁸ P. Yu. Nechaeva,⁹² T. J. Neep,⁸⁰ A. Negri,^{117a,117b} G. Negri,²⁹
S. Nektarijevic,⁴⁸ A. Nelson,¹⁶¹ T. K. Nelson,¹⁴¹ S. Nemecek,¹²³ P. Nemethy,¹⁰⁶ A. A. Nepomuceno,^{23a} M. Nessi,^{29,y}
M. S. Neubauer,¹⁶³ A. Neusiedl,⁷⁹ R. M. Neves,¹⁰⁶ P. Nevski,²⁴ P. R. Newman,¹⁷ V. Nguyen Thi Hong,¹³⁴
R. B. Nickerson,¹¹⁶ R. Nicolaidou,¹³⁴ L. Nicolas,¹³⁷ B. Nicquevert,²⁹ F. Niedercorn,¹¹³ J. Nielsen,¹³⁵ T. Niinikoski,²⁹
N. Nikiforou,³⁴ A. Nikiforov,¹⁵ V. Nikolaenko,¹²⁶ K. Nikolaev,⁶³ I. Nikolic-Audit,⁷⁶ K. Nikolics,⁴⁸
K. Nikolopoulos,²⁴ H. Nilsen,⁴⁷ P. Nilsson,⁷ Y. Ninomiya,¹⁵³ A. Nisati,^{130a} T. Nishiyama,⁶⁵ R. Nisius,⁹⁷
L. Nodulman,⁵ M. Nomachi,¹¹⁴ I. Nomidis,¹⁵² M. Nordberg,²⁹ P. R. Norton,¹²⁷ J. Novakova,¹²⁴ M. Nozaki,⁶⁴
L. Nozka,¹¹¹ I. M. Nugent,^{157a} A.-E. Nuncio-Quiroz,²⁰ G. Nunes Hanninger,⁸⁴ T. Nunnemann,⁹⁶ E. Nurse,⁷⁵
B. J. O'Brien,⁴⁵ S. W. O'Neale,^{17,a} D. C. O'Neil,¹⁴⁰ V. O'Shea,⁵² L. B. Oakes,⁹⁶ F. G. Oakham,^{28,e} H. Oberlack,⁹⁷
J. Ocariz,⁷⁶ A. Ochi,⁶⁵ S. Oda,¹⁵³ S. Odaka,⁶⁴ J. Odier,⁸¹ H. Ogren,⁵⁹ A. Oh,⁸⁰ S. H. Oh,⁴⁴ C. C. Ohm,^{144a,144b}
T. Ohshima,⁹⁹ H. Ohshita,¹³⁸ S. Okada,⁶⁵ H. Okawa,¹⁶¹ Y. Okumura,⁹⁹ T. Okuyama,¹⁵³ A. Olariu,^{25a} M. Olcese,^{49a}
A. G. Olchevski,⁶³ S. A. Olivares Pino,^{31a} M. Oliveira,^{122a,1} D. Oliveira Damazio,²⁴ E. Oliver Garcia,¹⁶⁵ D. Olivito,¹¹⁸
A. Olszewski,³⁸ J. Olszowska,³⁸ C. Omachi,⁶⁵ A. Onofre,^{122a,z} P. U. E. Onyisi,³⁰ C. J. Oram,^{157a} M. J. Oreglia,³⁰
Y. Oren,¹⁵¹ D. Orestano,^{132a,132b} N. Orlando,^{70a,70b} I. Orlov,¹⁰⁵ C. Oropeza Barrera,⁵² R. S. Orr,¹⁵⁶ B. Osculati,^{49a,49b}
R. Ospanov,¹¹⁸ C. Osuna,¹¹ G. Otero y Garzon,²⁶ J. P. Ottersbach,¹⁰³ M. Ouchrif,^{133d} E. A. Ouellette,¹⁶⁷
F. Ould-Saada,¹¹⁵ A. Ouraou,¹³⁴ Q. Ouyang,^{32a} A. Ovcharova,¹⁴ M. Owen,⁸⁰ S. Owen,¹³⁷ V. E. Ozcan,^{18a} N. Ozturk,⁷
A. Pacheco Pages,¹¹ C. Padilla Aranda,¹¹ S. Pagan Griso,¹⁴ E. Paganis,¹³⁷ F. Paige,²⁴ P. Pais,⁸² K. Pajchel,¹¹⁵
G. Palacino,^{157b} C. P. Paleari,⁶ S. Palestini,²⁹ D. Pallin,³³ A. Palma,^{122a} J. D. Palmer,¹⁷ Y. B. Pan,¹⁷⁰
E. Panagiotopoulou,⁹ B. Panes,^{31a} N. Panikashvili,⁸⁵ S. Panitkin,²⁴ D. Pantea,^{25a} M. Panuskova,¹²³ V. Paolone,¹²¹
A. Papadelis,^{144a} Th. D. Papadopoulou,⁹ A. Paramonov,⁵ D. Paredes Hernandez,³³ W. Park,^{24,aa} M. A. Parker,²⁷
F. Parodi,^{49a,49b} J. A. Parsons,³⁴ U. Parzefall,⁴⁷ S. Pashapour,⁵³ E. Pasqualucci,^{130a} S. Passaggio,^{49a} A. Passeri,^{132a}
F. Pastore,^{132a,132b} Fr. Pastore,⁷⁴ G. Pásztor,^{48,bb} S. Patariaia,¹⁷² N. Patel,¹⁴⁸ J. R. Pater,⁸⁰ S. Patricelli,^{100a,100b}

T. Pauly,²⁹ M. Pecsý,^{142a} M. I. Pedraza Morales,¹⁷⁰ S. V. Peleganchuk,¹⁰⁵ H. Peng,^{32b} B. Penning,³⁰ A. Penson,³⁴ J. Penwell,⁵⁹ M. Perantoni,^{23a} K. Perez,^{34,cc} T. Perez Cavalcanti,⁴¹ E. Perez Codina,^{157a} M. T. Pérez García-Estañ,¹⁶⁵ V. Perez Reale,³⁴ L. Perini,^{87a,87b} H. Pernegger,²⁹ R. Perrino,^{70a} P. Perrodo,⁴ S. Perseme,^{3a} V. D. Peshekhonov,⁶³ K. Peters,²⁹ B. A. Petersen,²⁹ J. Petersen,²⁹ T. C. Petersen,³⁵ E. Petit,⁴ A. Petridis,¹⁵² C. Petridou,¹⁵² E. Petrolo,^{130a} F. Petrucci,^{132a,132b} D. Petschull,⁴¹ M. Petteni,¹⁴⁰ R. Pezoa,^{31b} A. Phan,⁸⁴ P. W. Phillips,¹²⁷ G. Piacquadio,²⁹ A. Picazio,⁴⁸ E. Piccaro,⁷³ M. Piccinini,^{19a,19b} S. M. Piec,⁴¹ R. Piegaiia,²⁶ D. T. Pignotti,¹⁰⁷ J. E. Pilcher,³⁰ A. D. Pilkington,⁸⁰ J. Pina,^{122a,c} M. Pinamonti,^{162a,162c} A. Pinder,¹¹⁶ J. L. Pinfeld,² J. Ping,^{32c} B. Pinto,^{122a} O. Pirotte,²⁹ C. Pizio,^{87a,87b} M. Plamondon,¹⁶⁷ M.-A. Pleier,²⁴ A. V. Pleskach,¹²⁶ E. Plotnikova,⁶³ A. Poblaguev,²⁴ S. Poddar,^{57a} F. Podlyski,³³ L. Poggioli,¹¹³ T. Poghosyan,²⁰ M. Pohl,⁴⁸ F. Polci,⁵⁴ G. Polesello,^{117a} A. Policicchio,^{36a,36b} A. Polini,^{19a} J. Poll,⁷³ V. Polychronakos,²⁴ D. M. Pomarede,¹³⁴ D. Pomeroy,²² K. Pommès,²⁹ L. Pontecorvo,^{130a} B. G. Pope,⁸⁶ G. A. Popeneciu,^{25a} D. S. Popovic,^{12a} A. Poppleton,²⁹ X. Portell Bueso,²⁹ C. Posch,²¹ G. E. Pospelov,⁹⁷ S. Pospisil,¹²⁵ I. N. Potrap,⁹⁷ C. J. Potter,¹⁴⁷ C. T. Potter,¹¹² G. Poulard,²⁹ J. Poveda,¹⁷⁰ V. Pozdnyakov,⁶³ R. Prabhu,⁷⁵ P. Pralavorio,⁸¹ A. Pranko,¹⁴ S. Prasad,²⁹ R. Pravahan,⁷ S. Prell,⁶² K. Pretzl,¹⁶ L. Pribyl,²⁹ D. Price,⁵⁹ J. Price,⁷¹ L. E. Price,⁵ M. J. Price,²⁹ D. Prieur,¹²¹ M. Primavera,^{70a} K. Prokofiev,¹⁰⁶ F. Prokoshin,^{31b} S. Protopopescu,²⁴ J. Proudfoot,⁵ X. Prudent,⁴³ M. Przybycien,³⁷ H. Przysieszniak,⁴ S. Psoroulas,²⁰ E. Ptacek,¹¹² E. Pueschel,⁸² J. Purdham,⁸⁵ M. Purohit,^{24,aa} P. Puzo,¹¹³ Y. Pylypchenko,⁶¹ J. Qian,⁸⁵ Z. Qian,⁸¹ Z. Qin,⁴¹ A. Quadt,⁵³ D. R. Quarrie,¹⁴ W. B. Quayle,¹⁷⁰ F. Quinonez,^{31a} M. Raas,¹⁰² V. Radescu,⁴¹ B. Radics,²⁰ P. Radloff,¹¹² T. Rador,^{18a} F. Ragusa,^{87a,87b} G. Rahal,¹⁷⁵ A. M. Rahimi,¹⁰⁷ D. Rahm,²⁴ S. Rajagopalan,²⁴ M. Rammensee,⁴⁷ M. Rammes,¹³⁹ A. S. Randle-Conde,³⁹ K. Randrianarivony,²⁸ P. N. Ratoff,⁶⁹ F. Rauscher,⁹⁶ T. C. Rave,⁴⁷ M. Raymond,²⁹ A. L. Read,¹¹⁵ D. M. Rebuffi,^{117a,117b} A. Redelbach,¹⁷¹ G. Redlinger,²⁴ R. Reece,¹¹⁸ K. Reeves,⁴⁰ A. Reichold,¹⁰³ E. Reinherz-Aronis,¹⁵¹ A. Reinsch,¹¹² I. Reisinger,⁴² C. Rembser,²⁹ Z. L. Ren,¹⁴⁹ A. Renaud,¹¹³ M. Rescigno,^{130a} S. Resconi,^{87a} B. Resende,¹³⁴ P. Reznicek,⁹⁶ R. Rezvani,¹⁵⁶ A. Richards,⁷⁵ R. Richter,⁹⁷ E. Richter-Was,^{4,dd} M. Ridel,⁷⁶ M. Rijpstra,¹⁰³ M. Rijssenbeek,¹⁴⁶ A. Rimoldi,^{117a,117b} L. Rinaldi,^{19a} R. R. Rios,³⁹ I. Riu,¹¹ G. Rivoltella,^{87a,87b} F. Rizatdinova,¹¹⁰ E. Rizvi,⁷³ S. H. Robertson,^{83,k} A. Robichaud-Veronneau,¹¹⁶ D. Robinson,²⁷ J. E. M. Robinson,⁷⁵ A. Robson,⁵² J. G. Rocha de Lima,¹⁰⁴ C. Roda,^{120a,120b} D. Roda Dos Santos,²⁹ D. Rodriguez,¹⁶⁰ A. Roe,⁵³ S. Roe,²⁹ O. Røhne,¹¹⁵ V. Rojo,¹ S. Rolli,¹⁵⁹ A. Romaniouk,⁹⁴ M. Romano,^{19a,19b} V. M. Romanov,⁶³ G. Romeo,²⁶ E. Romero Adam,¹⁶⁵ L. Roos,⁷⁶ E. Ros,¹⁶⁵ S. Rosati,^{130a} K. Rosbach,⁴⁸ A. Rose,¹⁴⁷ M. Rose,⁷⁴ G. A. Rosenbaum,¹⁵⁶ E. I. Rosenberg,⁶² P. L. Rosendahl,¹³ O. Rosenthal,¹³⁹ L. Rosselet,⁴⁸ V. Rossetti,¹¹ E. Rossi,^{130a,130b} L. P. Rossi,^{49a} M. Rotaru,^{25a} I. Roth,¹⁶⁹ J. Rothberg,¹³⁶ D. Rousseau,¹¹³ C. R. Royon,¹³⁴ A. Rozanov,⁸¹ Y. Rozen,¹⁵⁰ X. Ruan,^{32a,ee} F. Rubbo,¹¹ I. Rubinskiy,⁴¹ B. Ruckert,⁹⁶ N. Ruckstuhl,¹⁰³ V. I. Rud,⁹⁵ C. Rudolph,⁴³ G. Rudolph,⁶⁰ F. Rühr,⁶ F. Ruggieri,^{132a,132b} A. Ruiz-Martinez,⁶² V. Rumiantsev,^{89,a} L. Rummyantsev,⁶³ K. Runge,⁴⁷ Z. Rurikova,⁴⁷ N. A. Rusakovich,⁶³ J. P. Rutherford,⁶ C. Ruwiedel,¹⁴ P. Ruzicka,¹²³ Y. F. Ryabov,¹¹⁹ V. Ryadovikov,¹²⁶ P. Ryan,⁸⁶ M. Rybar,¹²⁴ G. Rybkin,¹¹³ N. C. Ryder,¹¹⁶ S. Rzaeva,¹⁰ A. F. Saavedra,¹⁴⁸ I. Sadeh,¹⁵¹ H. F. W. Sadrozinski,¹³⁵ R. Sadykov,⁶³ F. Safai Tehrani,^{130a} H. Sakamoto,¹⁵³ G. Salamanna,⁷³ A. 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Schaezel,^{57b} A. C. Schaffer,¹¹³ D. Schaile,⁹⁶ R. D. Schamberger,¹⁴⁶ A. G. Schamov,¹⁰⁵ V. Scharf,^{57a} V. A. Schegelsky,¹¹⁹ D. Scheirich,⁸⁵ M. Schernau,¹⁶¹ M. I. Scherzer,³⁴ C. Schiavi,^{49a,49b} J. Schieck,⁹⁶ M. Schioppa,^{36a,36b} S. Schlenker,²⁹ J. L. Schlereth,⁵ E. Schmidt,⁴⁷ K. Schmieden,²⁰ C. Schmitt,⁷⁹ S. Schmitt,^{57b} M. Schmitz,²⁰ A. Schöning,^{57b} M. Schott,²⁹ D. Schouten,^{157a} J. Schovancova,¹²³ M. Schram,⁸³ C. Schroeder,⁷⁹ N. Schroer,^{57c} G. Schuler,²⁹ M. J. Schultens,²⁰ J. Schultes,¹⁷² H.-C. Schultz-Coulon,^{57a} H. Schulz,¹⁵ J. W. Schumacher,²⁰ M. Schumacher,⁴⁷ B. A. Schumm,¹³⁵ Ph. Schune,¹³⁴ C. Schwanenberger,⁸⁰ A. Schwartzman,¹⁴¹ Ph. Schwemling,⁷⁶ R. Schwienhorst,⁸⁶ R. Schwierz,⁴³ J. Schwindling,¹³⁴ T. Schwindt,²⁰ M. Schwoerer,⁴ G. Sciolla,²² W. G. Scott,¹²⁷ J. Searcy,¹¹² G. Sedov,⁴¹ E. Sedykh,¹¹⁹ E. Segura,¹¹ S. C. Seidel,¹⁰¹ A. Seiden,¹³⁵ F. Seifert,⁴³

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Sivoklov,⁹⁵ J. Sjölin,^{144a,144b} T. B. Sjursen,¹³ L. A. Skinnari,¹⁴ H. P. Skottowe,⁵⁶ K. Skovpen,¹⁰⁵ P. Skubic,¹⁰⁹ N. Skvorodnev,²² M. Slater,¹⁷ T. Slavicek,¹²⁵ K. Sliwa,¹⁵⁹ J. Sloper,²⁹ V. Smakhtin,¹⁶⁹ B. H. Smart,⁴⁵ S. Yu. Smirnov,⁹⁴ Y. Smirnov,⁹⁴ L. N. Smirnova,⁹⁵ O. Smirnova,⁷⁷ B. C. Smith,⁵⁶ D. Smith,¹⁴¹ K. M. Smith,⁵² M. Smizanska,⁶⁹ K. Smolek,¹²⁵ A. A. Snesarev,⁹² S. W. Snow,⁸⁰ J. Snow,¹⁰⁹ J. Snuverink,¹⁰³ S. Snyder,²⁴ M. Soares,^{122a} R. Sobie,^{167,k} J. Sodomka,¹²⁵ A. Soffer,¹⁵¹ C. A. Solans,¹⁶⁵ M. Solar,¹²⁵ J. Solc,¹²⁵ E. Soldatov,⁹⁴ U. Soldevila,¹⁶⁵ E. Solfaroli Camillocci,^{130a,130b} A. A. Solodkov,¹²⁶ O. V. Solovyanov,¹²⁶ N. Soni,² V. Sopko,¹²⁵ B. Sopko,¹²⁵ M. Sosebee,⁷ R. Soualah,^{162a,162c} A. Soukharev,¹⁰⁵ S. Spagnolo,^{70a,70b} F. Spanò,⁷⁴ R. Spighi,^{19a} G. Spigo,²⁹ F. Spila,^{130a,130b} R. Spiwoks,²⁹ M. Spousta,¹²⁴ T. Spreitzer,¹⁵⁶ B. Spurlock,⁷ R. D. St. Denis,⁵² J. Stahlman,¹¹⁸ R. Stamen,^{57a} E. Stanecka,³⁸ R. W. Stanek,⁵ C. Stanescu,^{132a} M. 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Suzuki,⁶⁴ Y. Suzuki,⁶⁵ M. Svatos,¹²³ Yu. M. Sviridov,¹²⁶ S. Swedish,¹⁶⁶ I. Sykora,^{142a} T. Sykora,¹²⁴ B. Szeless,²⁹ J. Sánchez,¹⁶⁵ D. Ta,¹⁰³ K. Tackmann,⁴¹ A. Taffard,¹⁶¹ R. Tafirout,^{157a} N. Taiblum,¹⁵¹ Y. Takahashi,⁹⁹ H. Takai,²⁴ R. Takashima,⁶⁷ H. Takeda,⁶⁵ T. Takeshita,¹³⁸ Y. Takubo,⁶⁴ M. Talby,⁸¹ A. Talyshev,^{105,g} M. C. Tamssett,²⁴ J. Tanaka,¹⁵³ R. Tanaka,¹¹³ S. Tanaka,¹²⁹ S. Tanaka,⁶⁴ Y. Tanaka,⁹⁸ A. J. Tanasijczuk,¹⁴⁰ K. Tani,⁶⁵ N. Tannoury,⁸¹ G. P. Tappern,²⁹ S. Tapprogge,⁷⁹ D. Tardif,¹⁵⁶ S. Tarem,¹⁵⁰ F. Tarrade,²⁸ G. F. Tartarelli,^{87a} P. Tas,¹²⁴ M. Tasevsky,¹²³ E. Tassi,^{36a,36b} M. Tatarkhanov,¹⁴ Y. Tayalati,^{133d} C. Taylor,⁷⁵ F. E. Taylor,⁹⁰ G. N. Taylor,⁸⁴ W. Taylor,^{157b} M. Teinturier,¹¹³ M. Teixeira Dias Castanheira,⁷³ P. Teixeira-Dias,⁷⁴ K. K. Temming,⁴⁷ H. Ten Kate,²⁹ P. K. Teng,¹⁴⁹ S. Terada,⁶⁴ K. Terashi,¹⁵³ J. Terron,⁷⁸ M. Testa,⁴⁶ R. J. Teuscher,^{156,k} J. Thadome,¹⁷² J. Therhaag,²⁰ T. Thevenaux-Pelzer,⁷⁶ M. Thioye,¹⁷³ S. Thoma,⁴⁷ J. P. Thomas,¹⁷ E. N. Thompson,³⁴ P. D. Thompson,¹⁷ P. D. Thompson,¹⁵⁶ A. S. Thompson,⁵² L. A. Thomsen,³⁵ E. Thomson,¹¹⁸ M. Thomson,²⁷ R. P. Thun,⁸⁵ F. Tian,³⁴ M. J. Tibbetts,¹⁴ T. Tic,¹²³ V. O. Tikhomirov,⁹² Y. A. Tikhonov,^{105,g} S. Timoshenko,⁹⁴ P. Tipton,¹⁷³ F. J. Tique Aires Viegas,²⁹ S. Tisserant,⁸¹ B. Toczek,³⁷ T. Todorov,⁴ S. Todorova-Nova,¹⁵⁹ B. Toggerson,¹⁶¹ J. Tojo,⁶⁴ S. Tokár,^{142a} K. Tokunaga,⁶⁵ K. Tokushuku,⁶⁴ K. Tollefson,⁸⁶ M. Tomoto,⁹⁹ L. Tompkins,³⁰ K. Toms,¹⁰¹ G. Tong,^{32a} A. Tonoyan,¹³ C. Topfel,¹⁶ N. D. Topilin,⁶³ I. Torchiani,²⁹ E. Torrence,¹¹² H. Torres,⁷⁶ E. Torró Pastor,¹⁶⁵ J. Toth,^{81,bb} F. Touchard,⁸¹ D. R. Tovey,¹³⁷ T. Trefzger,¹⁷¹ L. Tremblet,²⁹ A. Tricoli,²⁹ I. M. Trigger,^{157a} S. Trincaz-Duvoid,⁷⁶ T. N. Trinh,⁷⁶ M. F. Tripijana,⁶⁸ W. Trischuk,¹⁵⁶ A. Trivedi,^{24,aa} B. Trocmé,⁵⁴ C. Troncon,^{87a} M. Trotter-McDonald,¹⁴⁰ M. Trzebinski,³⁸ A. Trzupek,³⁸ C. Tsarouchas,²⁹ J. C-L. Tseng,¹¹⁶ M. Tsiakiris,¹⁰³ P. V. Tsiarehshka,⁸⁸ D. Tsiouou,^{4,ff} G. Tsiopolitis,⁹ V. Tsiskaridze,⁴⁷ E. G. Tskhadadze,^{50a} I. I. Tsukerman,⁹³ V. Tsulaia,¹⁴ J.-W. Tsung,²⁰ S. Tsuno,⁶⁴ D. Tsybychev,¹⁴⁶ A. Tua,¹³⁷ A. Tudorache,^{25a} V. Tudorache,^{25a} J. M. Tuggle,³⁰ M. Turala,³⁸ D. Turecek,¹²⁵ I. Turk Cakir,^{3e} E. Turlay,¹⁰³ R. Turra,^{87a,87b} P. M. Tuts,³⁴ A. Tykhonov,⁷² M. Tylmad,^{144a,144b} M. Tyndel,¹²⁷ G. Tzanakos,⁸ K. Uchida,²⁰ I. Ueda,¹⁵³ R. Ueno,²⁸ M. Ugland,¹³ M. Uhlenbrock,²⁰ M. Uhrmacher,⁵³ F. Ukegawa,¹⁵⁸ G. Unal,²⁹ D. G. Underwood,⁵ A. Undrus,²⁴ G. Unel,¹⁶¹ Y. Unno,⁶⁴ D. Urbaniec,³⁴ G. Usai,⁷ M. Uslenghi,^{117a,117b} L. Vacavant,⁸¹ V. Vacek,¹²⁵ B. Vachon,⁸³ S. Vahsen,¹⁴ J. Valenta,¹²³ P. Valente,^{130a} S. Valentini,^{19a,19b} S. Valkar,¹²⁴ E. Valladolid Gallego,¹⁶⁵ S. Vallecorsa,¹⁵⁰ J. A. Valls Ferrer,¹⁶⁵ H. van der Graaf,¹⁰³ E. van der Kraaij,¹⁰³ R. Van Der Leeuw,¹⁰³ E. van der Poel,¹⁰³ D. van der Ster,²⁹ N. van Eldik,⁸² P. van Gemmeren,⁵ Z. van Kesteren,¹⁰³

I. van Vulpen,¹⁰³ M. Vanadia,⁹⁷ W. Vandelli,²⁹ G. Vandoni,²⁹ A. Vaniachine,⁵ P. Vankov,⁴¹ F. Vannucci,⁷⁶
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 K. W. Wozniak,³⁸ K. Wraight,⁵² C. Wright,⁵² M. Wright,⁵² B. Wrona,⁷¹ S. L. Wu,¹⁷⁰ X. Wu,⁴⁸ Y. Wu,^{32b,ii} E. Wulf,³⁴
 R. Wunstorf,⁴² B. M. Wynne,⁴⁵ S. Xella,³⁵ M. Xiao,¹³⁴ S. Xie,⁴⁷ Y. Xie,^{32a} C. Xu,^{32b,x} D. Xu,¹³⁷ G. Xu,^{32a}
 B. Yabsley,¹⁴⁸ S. Yacoub,^{143b} M. Yamada,⁶⁴ H. Yamaguchi,¹⁵³ A. Yamamoto,⁶⁴ K. Yamamoto,⁶² S. Yamamoto,¹⁵³
 T. Yamamura,¹⁵³ T. Yamanaka,¹⁵³ J. Yamaoka,⁴⁴ T. Yamazaki,¹⁵³ Y. Yamazaki,⁶⁵ Z. Yan,²¹ H. Yang,⁸⁵ U. K. Yang,⁸⁰
 Y. Yang,⁵⁹ Y. Yang,^{32a} Z. Yang,^{144a,144b} S. Yanush,⁸⁹ Y. Yao,¹⁴ Y. Yasu,⁶⁴ G. V. Ybeles Smit,¹²⁸ J. Ye,³⁹ S. Ye,²⁴
 M. Yilmaz,^{3c} R. Yoosofmiya,¹²¹ K. Yorita,¹⁶⁸ R. Yoshida,⁵ C. Young,¹⁴¹ S. Youssef,²¹ D. Yu,²⁴ J. Yu,⁷ J. Yu,¹¹⁰
 L. Yuan,^{32a,ji} A. Yurkewicz,¹⁰⁴ B. Zabinski,³⁸ V. G. Zaets,¹²⁶ R. Zaidan,⁶¹ A. M. Zaitsev,¹²⁶ Z. Zajacova,²⁹
 L. Zanello,^{130a,130b} A. Zaytsev,¹⁰⁵ C. Zeitnitz,¹⁷² M. Zeller,¹⁷³ M. Zeman,¹²³ A. Zemla,³⁸ C. Zender,²⁰ O. Zenin,¹²⁶
 T. Ženiš,^{142a} Z. Zinonos,^{120a,120b} S. Zenz,¹⁴ D. Zerwas,¹¹³ G. Zevi della Porta,⁵⁶ Z. Zhan,^{32d} D. Zhang,^{32b,hh}
 H. Zhang,⁸⁶ J. Zhang,⁵ X. Zhang,^{32d} Z. Zhang,¹¹³ L. Zhao,¹⁰⁶ T. Zhao,¹³⁶ Z. Zhao,^{32b} A. Zhemchugov,⁶³ S. Zheng,^{32a}
 J. Zhong,¹¹⁶ B. Zhou,⁸⁵ N. Zhou,¹⁶¹ Y. Zhou,¹⁴⁹ C. G. Zhu,^{32d} H. Zhu,⁴¹ J. Zhu,⁸⁵ Y. Zhu,^{32b} X. Zhuang,⁹⁶
 V. Zhuravlov,⁹⁷ D. Zieminska,⁵⁹ R. Zimmermann,²⁰ S. Zimmermann,²⁰ S. Zimmermann,⁴⁷ M. Ziolkowski,¹³⁹
 R. Zitoun,⁴ L. Živković,³⁴ V. V. Zmouchko,^{126,a} G. Zobernig,¹⁷⁰ A. Zoccoli,^{19a,19b} A. Zsenei,²⁹ M. zur Nedden,¹⁵
 V. Zutshi,¹⁰⁴ and L. Zwalinski²⁹

(ATLAS Collaboration)

¹University at Albany, Albany, New York, USA²Department of Physics, University of Alberta, Edmonton, Alberta, Canada^{3a}Department of Physics, Ankara University, Ankara, Turkey^{3b}Department of Physics, Dumlupinar University, Kutahya, Turkey^{3c}Department of Physics, Gazi University, Ankara, Turkey^{3d}Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey^{3e}Turkish Atomic Energy Authority, Ankara, Turkey⁴LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France⁵High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA⁶Department of Physics, University of Arizona, Tucson, Arizona, USA⁷Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA⁸Physics Department, University of Athens, Athens, Greece

- ⁹Physics Department, National Technical University of Athens, Zografou, Greece
- ¹⁰Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹¹Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
- ^{12a}Institute of Physics, University of Belgrade, Belgrade, Serbia
- ^{12b}Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
- ¹³Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁴Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
- ¹⁵Department of Physics, Humboldt University, Berlin, Germany
- ¹⁶Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁷School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ^{18a}Department of Physics, Bogazici University, Istanbul, Turkey
- ^{18b}Division of Physics, Dogus University, Istanbul, Turkey
- ^{18c}Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- ^{18d}Department of Physics, Istanbul Technical University, Istanbul, Turkey
- ^{19a}INFN Sezione di Bologna, Italy
- ^{19b}Dipartimento di Fisica, Università di Bologna, Bologna, Italy
- ²⁰Physikalisches Institut, University of Bonn, Bonn, Germany
- ²¹Department of Physics, Boston University, Boston, Massachusetts, USA
- ²²Department of Physics, Brandeis University, Waltham, Massachusetts, USA
- ^{23a}Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
- ^{23b}Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
- ^{23c}Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
- ^{23d}Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁴Physics Department, Brookhaven National Laboratory, Upton, New York, USA
- ^{25a}National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- ^{25b}University Politehnica Bucharest, Bucharest, Romania
- ^{25c}West University in Timisoara, Timisoara, Romania
- ²⁶Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁷Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ²⁸Department of Physics, Carleton University, Ottawa, Ontario, Canada
- ²⁹CERN, Geneva, Switzerland
- ³⁰Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
- ^{31a}Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- ^{31b}Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ^{32a}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
- ^{32b}Department of Modern Physics, University of Science and Technology of China, Anhui, China
- ^{32c}Department of Physics, Nanjing University, Jiangsu, China
- ^{32d}School of Physics, Shandong University, Shandong, China
- ³³Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
- ³⁴Nevis Laboratory, Columbia University, Irvington, New York, USA
- ³⁵Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ^{36a}INFN Gruppo Collegato di Cosenza, Italy
- ^{36b}Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
- ³⁷AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ³⁸The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ³⁹Physics Department, Southern Methodist University, Dallas, Texas, USA
- ⁴⁰Physics Department, University of Texas at Dallas, Richardson, Texas, USA
- ⁴¹DESY, Hamburg and Zeuthen, Germany
- ⁴²Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴³Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁴Department of Physics, Duke University, Durham, North Carolina, USA
- ⁴⁵SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁶INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁷Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- ⁴⁸Section de Physique, Université de Genève, Geneva, Switzerland
- ^{49a}INFN Sezione di Genova, Italy
- ^{49b}Dipartimento di Fisica, Università di Genova, Genova, Italy
- ^{50a}E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi, Georgia
- ^{50b}High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

- ⁵¹*II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵²*SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵³*II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
- ⁵⁴*Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France*
- ⁵⁵*Department of Physics, Hampton University, Hampton, Virginia, USA*
- ⁵⁶*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- ^{57a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{57b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{57c}*ZITI Institut für Technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany*
- ⁵⁸*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ⁵⁹*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- ⁶⁰*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- ⁶¹*University of Iowa, Iowa City, Iowa, USA*
- ⁶²*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
- ⁶³*Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
- ⁶⁴*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- ⁶⁵*Graduate School of Science, Kobe University, Kobe, Japan*
- ⁶⁶*Faculty of Science, Kyoto University, Kyoto, Japan*
- ⁶⁷*Kyoto University of Education, Kyoto, Japan*
- ⁶⁸*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- ⁶⁹*Physics Department, Lancaster University, Lancaster, United Kingdom*
- ^{70a}*INFN Sezione di Lecce, Italy*
- ^{70b}*Dipartimento di Fisica, Università del Salento, Lecce, Italy*
- ⁷¹*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁷²*Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
- ⁷³*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- ⁷⁴*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
- ⁷⁵*Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁷⁶*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
- ⁷⁷*Fysiska Institutionen, Lunds Universitet, Lund, Sweden*
- ⁷⁸*Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain*
- ⁷⁹*Institut für Physik, Universität Mainz, Mainz, Germany*
- ⁸⁰*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁸¹*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
- ⁸²*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- ⁸³*Department of Physics, McGill University, Montreal, Quebec, Canada*
- ⁸⁴*School of Physics, University of Melbourne, Victoria, Australia*
- ⁸⁵*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
- ⁸⁶*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ^{87a}*INFN Sezione di Milano, Italy*
- ^{87b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ⁸⁸*B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
- ⁸⁹*National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus*
- ⁹⁰*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ⁹¹*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
- ⁹²*P. N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
- ⁹³*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ⁹⁴*Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
- ⁹⁵*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
- ⁹⁶*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ⁹⁷*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ⁹⁸*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ⁹⁹*Graduate School of Science, Nagoya University, Nagoya, Japan*
- ^{100a}*INFN Sezione di Napoli, Italy*
- ^{100b}*Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
- ¹⁰¹*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹⁰²*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands*
- ¹⁰³*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands*
- ¹⁰⁴*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ¹⁰⁵*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*

- ¹⁰⁶*Department of Physics, New York University, New York, New York, USA*
¹⁰⁷*Ohio State University, Columbus, Ohio, USA*
¹⁰⁸*Faculty of Science, Okayama University, Okayama, Japan*
¹⁰⁹*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
¹¹⁰*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
¹¹¹*Palacký University, RCPTM, Olomouc, Czech Republic*
¹¹²*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
¹¹³*LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France*
¹¹⁴*Graduate School of Science, Osaka University, Osaka, Japan*
¹¹⁵*Department of Physics, University of Oslo, Oslo, Norway*
¹¹⁶*Department of Physics, Oxford University, Oxford, United Kingdom*
^{117a}*INFN Sezione di Pavia, Italy*
^{117b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
¹¹⁸*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
¹¹⁹*Petersburg Nuclear Physics Institute, Gatchina, Russia*
^{120a}*INFN Sezione di Pisa, Italy*
^{120b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
¹²¹*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
^{122a}*Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal*
^{122b}*Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
¹²³*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
¹²⁴*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
¹²⁵*Czech Technical University in Prague, Praha, Czech Republic*
¹²⁶*State Research Center Institute for High Energy Physics, Protvino, Russia*
¹²⁷*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
¹²⁸*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
¹²⁹*Ritsumeikan University, Kusatsu, Shiga, Japan*
^{130a}*INFN Sezione di Roma I, Italy*
^{130b}*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
^{131a}*INFN Sezione di Roma Tor Vergata, Italy*
^{131b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
^{132a}*INFN Sezione di Roma Tre, Italy*
^{132b}*Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
^{133a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco*
^{133b}*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
^{133c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
^{133d}*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
^{133e}*Faculté des Sciences, Université Mohammed V- Agdal, Rabat, Morocco*
¹³⁴*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France*
¹³⁵*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
¹³⁶*Department of Physics, University of Washington, Seattle, Washington, USA*
¹³⁷*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
¹³⁸*Department of Physics, Shinshu University, Nagano, Japan*
¹³⁹*Fachbereich Physik, Universität Siegen, Siegen, Germany*
¹⁴⁰*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
¹⁴¹*SLAC National Accelerator Laboratory, Stanford, California, USA*
^{142a}*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
^{142b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
^{143a}*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
^{143b}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
^{144a}*Department of Physics, Stockholm University, Sweden*
^{144b}*The Oskar Klein Centre, Stockholm, Sweden*
¹⁴⁵*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
¹⁴⁶*Departments of Physics and Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA*
¹⁴⁷*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
¹⁴⁸*School of Physics, University of Sydney, Sydney, Australia*
¹⁴⁹*Institute of Physics, Academia Sinica, Taipei, Taiwan*
¹⁵⁰*Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
¹⁵¹*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*

- ¹⁵²*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵³*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
- ¹⁵⁴*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁵⁵*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁵⁶*Department 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*
- ¹⁵⁸*Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan*
- ¹⁵⁹*Science and Technology Center, Tufts University, Medford, Massachusetts, USA*
- ¹⁶⁰*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
- ¹⁶¹*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- ^{162a}*INFN Gruppo Collegato di Udine, Italy*
- ^{162b}*ICTP, Trieste, Italy*
- ^{162c}*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
- ¹⁶³*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- ¹⁶⁴*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁵*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*
- ¹⁶⁶*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
- ¹⁶⁷*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
- ¹⁶⁸*Waseda University, Tokyo, Japan*
- ¹⁶⁹*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷⁰*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
- ¹⁷¹*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
- ¹⁷²*Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- ¹⁷³*Department of Physics, Yale University, New Haven, Connecticut, USA*
- ¹⁷⁴*Yerevan Physics Institute, Yerevan, Armenia*
- ¹⁷⁵*Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France*

^aDeceased.

^bAlso at Laboratório de Instrumentação e Física Experimental de Partículas-LIP, Lisboa, Portugal.

^cAlso at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

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

^eAlso at TRIUMF, Vancouver, BC, Canada.

^fAlso at Department of Physics, California State University, Fresno, CA, USA.

^gAlso at Novosibirsk State University, Novosibirsk, Russia.

^hAlso at Fermilab, Batavia, IL, USA.

ⁱAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.

^jAlso at Università di Napoli Parthenope, Napoli, Italy.

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

^lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.

^mAlso at Louisiana Tech University, Ruston, LA, USA.

ⁿAlso at Department of Physics and Astronomy, University College London, London, United Kingdom.

^oAlso at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.

^pAlso at Department of Physics, University of Cape Town, Cape Town, South Africa.

^qAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^rAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

^sAlso at Manhattan College, New York, NY, USA.

^tAlso at School of Physics, Shandong University, Shandong, China.

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

^vAlso at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.

^wAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

^xAlso at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Énergie Atomique), Gif-sur-Yvette, France.

^yAlso at Section de Physique, Université de Genève, Geneva, Switzerland.

^zAlso at Departamento de Física, Universidade de Minho, Braga, Portugal.

^{aa}Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

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

^{cc}Also at California Institute of Technology, Pasadena, CA, USA.

^{dd}Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

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

^{ff}Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

^{gg}Also at Department of Physics, Oxford University, Oxford, United Kingdom.

^{hh}Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

ⁱⁱAlso at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.

^{jj}Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.