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Search for New Phenomena in $t\bar{t}$ Events with Large Missing Transverse Momentum in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad *et al.**

(ATLAS Collaboration)

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A search for new phenomena in $t\bar{t}$ events with large missing transverse momentum in proton-proton collisions at a center-of-mass energy of 7 TeV is presented. The measurement is based on 1.04 fb^{-1} of data collected with the ATLAS detector at the LHC. Contributions to this final state may arise from a number of standard model extensions. The results are interpreted in terms of a model where new top-quark partners are pair produced and each decay to an on-shell top (or antitop) quark and a long-lived undetected neutral particle. The data are found to be consistent with standard model expectations. A limit at 95% confidence level is set excluding a cross section times branching ratio of 1.1 pb for a top-partner mass of 420 GeV and a neutral particle mass less than 10 GeV. In a model of exotic fourth generation quarks, top-partner masses are excluded up to 420 GeV and neutral particle masses up to 140 GeV.

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The top quark holds great promise as a probe for new phenomena at the TeV scale. It has the strongest coupling to the standard model Higgs boson, and as a consequence it is the main contributor to the quadratic divergence in the Higgs boson mass. Thus, assuming the “naturalness” hypothesis of effective quantum field theory, light top partners (with masses below about 1 TeV) should correspond to one of the most robust predictions of solutions to the hierarchy problem.

In this Letter, a search is presented for pair-produced exotic top partners $T\bar{T}$, each decaying to a top quark and a stable, neutral weakly interacting particle A_0 , which in some models may be its own antiparticle. The final state for such a process ($T\bar{T} \rightarrow t\bar{t}A_0A_0$) is identical to $t\bar{t}$, though with a larger amount of missing transverse momentum (E_T^{miss}) from the undetected A_0 pair. In supersymmetry models with R -parity conservation, T is identified with the stop squark and A_0 with the lightest supersymmetric particle, the neutralino (χ_0) [1] or the gravitino (\tilde{G}) [2]. The $t\bar{t} + E_T^{\text{miss}}$ [3] signature appears in a general set of dark matter motivated models, as well as in other standard model (SM) extensions, such as the above-mentioned supersymmetry models, little Higgs models with T -parity conservation [4–6], models of universal extra dimensions (UED) with Kaluza-Klein parity [7], models in which baryon and lepton number conservation arises from gauge symmetries [8], or models with third-generation scalar leptiquarks. Many of these models provide a mechanism for electroweak symmetry breaking and predict dark

matter candidates, which can be identified indirectly through their large E_T^{miss} signature.

The search is performed in the $t\bar{t}$ single-lepton channel where one W boson produced by the top pair decays to a lepton-neutrino pair ($W \rightarrow \ell\nu$, including τ decays to e or μ) and the other W boson decays to a pair of quarks ($W \rightarrow q\bar{q}'$), resulting in a final state with an isolated lepton of high transverse momentum, four or more jets, and large E_T^{miss} . The observed yield in this signal region is compared with the SM expectation. In the absence of signal an upper limit on the cross-section times branching ratio $\text{BR}(T\bar{T} \rightarrow t\bar{t}A_0A_0)$ is quoted. In the model of exotic fourth generation up-type quarks [9] the $T\bar{T}$ production cross section is predicted to be approximately 6 times higher than for stop squarks with a similar mass [3], due to the multiple spin states of two T 's compared to scalar stops. For this model the cross-section limits are converted to an exclusion curve in the T vs A_0 mass parameter space. A search for these exotic top-quark partners was performed in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV by the CDF Collaboration [10]. The data were found to be consistent with SM expectations. A 95% confidence level limit was set excluding a top-partner mass of 360 GeV for a neutral particle mass less than 100 GeV. A recent update by CDF in the all-jets channel excludes top-partner masses up to 400 GeV [11].

The ATLAS detector [12] consists of an inner detector tracking system (ID) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip detectors inside a transition radiation tracker which provide tracking in the region $|\eta| < 2.5$ [13]. The electromagnetic calorimeter is a lead-liquid argon (LAr) detector in the barrel ($|\eta| < 1.475$) and end cap ($1.375 < |\eta| < 3.2$) regions. Hadron calorimetry is based on two different detector technologies.

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

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The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are composed of scintillator and steel, while the hadronic end cap calorimeters ($1.5 < |\eta| < 3.2$) are copper and LAr. The forward calorimeters ($3.1 < |\eta| < 4.9$) are instrumented with copper and LAr and tungsten and LAr, providing electromagnetic and hadronic energy measurements, respectively. The MS consists of three large superconducting toroids with 24 coils, a system of trigger chambers, and precision tracking chambers which provide muon momentum measurements up to $|\eta|$ of 2.7.

The analysis is based on data recorded by the ATLAS detector in 2011 using 1.04 fb^{-1} of integrated luminosity. The data were collected using electron and muon triggers. Requirements that ensure the quality of beam conditions, detector performance, and data are imposed. Monte Carlo (MC) event samples with full ATLAS detector simulation [14] based on the GEANT4 program [15] and corrected for all known detector effects are used to model the signal process and most of the backgrounds. The multijet background is modeled using data control samples rather than the simulation. The background sources are separated into four main categories according to their importance: dilepton $t\bar{t}$ (where both W bosons decay to a lepton-neutrino pair: $W \rightarrow \ell\nu$); single-lepton $t\bar{t}$ and W + jets; multijet production; and other electroweak processes, such as diboson production, single top, and Z + jets. The $t\bar{t}$ and single top samples are produced with MC@NLO [16], while the W + jets and Z + jets samples are generated with ALPGEN [17]. HERWIG [18] is used to simulate the parton shower and fragmentation, and JIMMY [19] is used for the underlying event simulation. The diboson background is simulated using HERWIG. The $t\bar{t}$ cross section is normalized to approximate next-to-next-to-leading order (NNLO) calculations [20], the inclusive W + jets and Z + jets cross sections are normalized to NNLO predictions [21], and the cross sections of the other backgrounds are normalized to NLO predictions [22]. Additional corrections to the MC predictions are extracted from the data, as described below.

Electron and muon candidates are selected as for other recent ATLAS top-quark studies using the single-lepton signature [23]. Jets are reconstructed using the anti- k_r [24] algorithm with the distance parameter $R = 0.4$. To take into account the differences in calorimeter response to electrons and hadrons, a p_T - and η -dependent factor, derived from simulated events and validated with data, is applied to each jet to provide an average energy scale correction [25] corresponding to the energies of the reconstructed particles.

In the calorimeter, the energy deposited by particles is reconstructed in three-dimensional clusters. These clusters are calibrated according to the associated reconstructed high- p_T object. The energy of these clusters is summed vectorially, and projections of this sum in the transverse plane correspond to the negative of the E_T^{miss} components

[26]. Clusters not associated with any high- p_T object and muons reconstructed in the MS are also included in the E_T^{miss} calculation.

Events are selected with exactly one isolated electron or muon that passes the following kinematic selection criteria. Electrons are required to satisfy $E_T > 25 \text{ GeV}$ and $|\eta| < 2.47$. Electrons in the region between the barrel and the end cap electromagnetic calorimeters ($1.37 < |\eta| < 1.52$) are removed. Muon candidates are required to satisfy $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. These selected leptons lie in the efficiency plateau of the single-lepton triggers. Only events with four or more reconstructed jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$ are selected. To reduce the single-lepton $t\bar{t}$ and W + jets background, events are required to have $E_T^{\text{miss}} > 100 \text{ GeV}$ and $m_T > 150 \text{ GeV}$, where m_T is the transverse mass of the lepton and E_T^{miss} [27]. Events with either a second lepton candidate with $p_T > 15 \text{ GeV}$ or a track with $p_T > 12 \text{ GeV}$, with no other tracks with $p_T > 3 \text{ GeV}$ within $\Delta R = 0.4$ ($\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$), are rejected in order to reduce the contribution from $t\bar{t}$ dilepton events. In particular, the isolated track veto is useful in reducing single-prong hadronic τ decays in $t\bar{t}$ dilepton events. A summary of the background estimates and a comparison with the observed number of selected events passing all selection criteria are shown in Table I. A total yield of 101 ± 16 events is expected from SM sources, and 105 events are observed in data. The background composition is similar in the electron and muon channels.

The dominant background arises from $t\bar{t}$ dilepton final states in which one of the leptons is not reconstructed, is outside the detector acceptance, or is a τ lepton. In all such cases, the $t\bar{t}$ decay products include two high- p_T neutrinos, resulting in large E_T^{miss} and m_T tails. In MC simulation, the second lepton veto removes 45% of the dilepton $t\bar{t}$ and 10% of the single-lepton $t\bar{t}$ in the signal region. The veto performance is validated in the data in several control regions both enhanced and depleted in dilepton $t\bar{t}$. Based on the data-MC agreement in these control regions a 10% uncertainty is assigned to the veto efficiencies modeled in MC simulation.

TABLE I. Summary of expected SM yields including statistical and systematic uncertainties compared with the observed number of events in the signal region.

Source	Number of events
Dilepton $t\bar{t}$	62 ± 15
Single-lepton $t\bar{t}/W$ + jets	33.1 ± 3.8
Multijet	1.2 ± 1.2
Single top	3.5 ± 0.8
Z + jets	0.9 ± 0.3
Dibosons	0.9 ± 0.2
Total	101 ± 16
Data	105

The next largest background comes from single-lepton sources, including $W + \text{jets}$ and $t\bar{t}$ with one leptonic W decay. Both the normalization and the shape of the m_T distribution for this combined background are extracted from the data. First, the yield of the single-lepton background estimated from simulation is normalized in the control region $60 \text{ GeV} < m_T < 90 \text{ GeV}$ to the data which gives a correction of $(-5 \pm 3)\%$. Next, the shape of the m_T distribution in MC is compared with data in various signal-depleted control regions, where events satisfy the signal event selection but have fewer than four jets. In these control samples events with identified b jets, based on lifetime b tagging [23], are rejected in order to reduce the dilepton $t\bar{t}$ background, such that these control samples are dominated by $W + \text{jets}$ events; the corresponding loss of single-lepton $t\bar{t}$ from this b -jet veto is accounted for in the systematic uncertainties. A comparison between data and MC in this control region shows that MC systematically underestimates the tails of the m_T distribution above 150 GeV, and a shape correction is derived that results in a $(15 \pm 10)\%$ increase of the expected yield in the signal region.

The multijet background is extracted from the data using techniques similar to those described in Ref. [23]. The techniques exploit the fact that the lepton isolation efficiency is different in signal and multijet events. In both lepton channels the contribution to the signal region is consistent with zero.

The contributions from single top, diboson production (WW , WZ , and ZZ), and $Z + \text{jets}$ are estimated using MC simulation, normalized to the theoretical cross section and total integrated luminosity.

The background yields estimated from MC simulated events are affected by systematic uncertainties related to the modeling of detector performance, reconstruction, and object identification. The largest of these uncertainties are from the jet energy scale [25] (approximately 5%–7% on the jet p_T , including a contribution from pileup effects, leading to an 11% uncertainty on the background event yield), and from the performance of the second lepton veto in dilepton $t\bar{t}$ (10%). Other uncertainties include those on the lepton momentum scales and trigger and reconstruction efficiencies. Lepton momentum scales and resolutions are determined from fits to the Z -mass peak. Trigger and reconstruction efficiencies are evaluated using tag-and-probe measurements in $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$ events. To evaluate the effect of lepton momentum and jet energy scale uncertainties, the E_T^{miss} and m_T are recalculated for each uncertainty on selected objects. Other small uncertainties affecting the E_T^{miss} calculation are due to multiple pp interactions, jets with p_T below 20 GeV, and calorimeter clusters that are not associated to a selected object [28]. Additionally, theoretical cross-section uncertainties from choice of scales and parton distribution functions are considered for these background sources, as are the effects of

using alternative MC generators, shower models, and initial- and final-state radiation tunings [23]. Finally, the 3.7% uncertainty on the integrated luminosity [29] is applied to each background source.

The systematic uncertainties applied to data-driven backgrounds are determined from the data. The dominant uncertainty for single-lepton backgrounds is due to the $(15 \pm 10)\%$ shape correction, and is derived from the variation in the measured correction in different control regions and from uncertainties in the b -tagging efficiency. The uncertainty on the single-lepton normalization of $(-5 \pm 3)\%$ includes equal contributions from limited data statistics in the W mass region and expected differences between the $W + \text{jets}$ and single-lepton $t\bar{t}$ contributions to the signal and control regions. A 100% systematic uncertainty is assigned to the small estimated multijet yield.

The expected and observed event yields are consistent within statistical and systematic uncertainties. Therefore, the results are interpreted as a limit on the possible non-SM contribution to the selected sample. A model involving pair production of heavy quarklike objects ($T\bar{T}$), each forced to decay to a top quark and a scalar neutral A_0 , is chosen to establish these limits.

MADGRAPH [30] is used to simulate the signal process with the parton distribution function set CTEQ6L1 [31], and PYTHIA [32] is used to simulate the parton shower and fragmentation. A grid of T and A_0 masses is generated with $300 \text{ GeV} \leq m(T) \leq 450 \text{ GeV}$ and $10 \text{ GeV} \leq m(A_0) \leq 150 \text{ GeV}$. Each sample is normalized to the cross section calculated at approximate NNLO in QCD using HATHOR [33], ranging from 8.0 pb for a T mass of 300 GeV to 0.66 pb for a T mass of 450 GeV. Using this grid of signal samples, the efficiency times acceptance for the $T\bar{T}$ signal model is parametrized as a function of the T and A_0 masses to generate the expected signal event yield for any pair of masses. The combined acceptance times signal selection efficiency varies between 3% and 5% for small A_0 masses and decreases to between 2% and 4% for larger A_0 masses.

All common systematic uncertainties for MC-based backgrounds are applied to this signal model. These include the uncertainties on the jet energy scale, lepton reconstruction efficiencies and scales, integrated luminosity, and the dilepton veto efficiency. Overall, the systematic uncertainty on the signal acceptance times efficiency varies between 11% and 14%, and is largest for those samples with a T - A_0 mass difference closest to the top quark mass. The theoretical uncertainties on the signal cross section vary between 10% to 15% and originate mainly from the choice of scales ($m_T/2 < \mu_R = \mu_F < 2m_T$, where μ_R and μ_F are the renormalization and factorization scale) and parton distribution functions.

The E_T^{miss} and m_T distributions for data are shown in Fig. 1 and compared with the background and signal predictions. There is no significant evidence of an excess over the SM prediction, and the kinematics are well modeled.

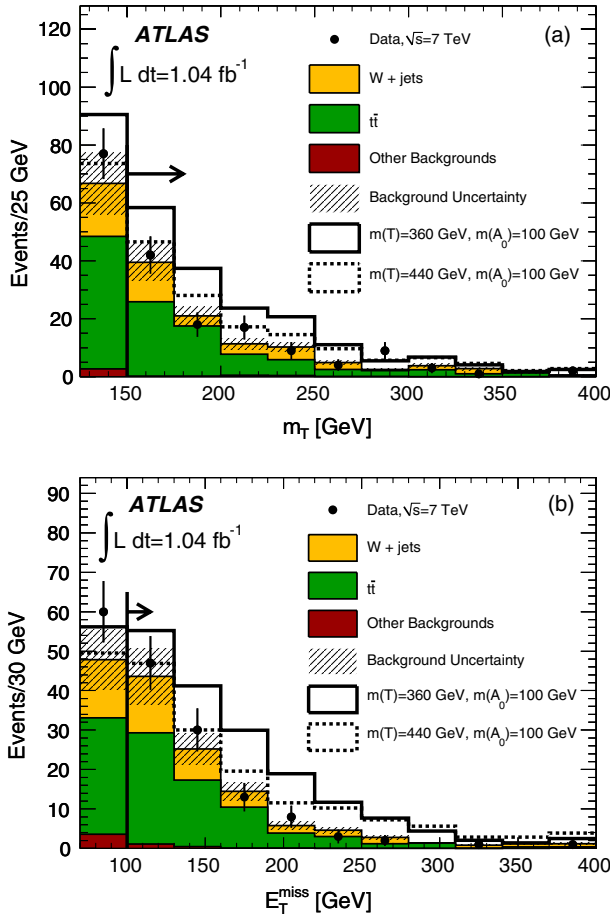


FIG. 1 (color online). (a) Transverse mass of the lepton and missing energy and (b) E_T^{miss} after applying all selection criteria except the cut on the variable shown. MC background contributions are stacked on top of each other and normalized according to the data-driven corrections discussed in the text. The lines with the arrows indicate the selection criteria that define the signal region ($m_T > 150$ GeV and $E_T^{\text{miss}} > 100$ GeV). “Other Backgrounds” includes both multijet backgrounds and Z + jets, single top, and diboson production. Expectations from two signal mass points are stacked separately on top of the SM background. The last bin includes the overflow.

From the observed event yield and the predicted signal and background event yields after all cuts, a frequentist confidence interval on the signal hypothesis is calculated for various assumed T and A_0 masses, assuming Gaussian systematic uncertainties. Correlations between signal and background uncertainties are included. Figure 2 shows the region of parameter space excluded at the 95% confidence level. As the mass difference between the T and A_0 approaches the top-quark mass, the A_0 contributes less momentum to the E_T^{miss} , and signal becomes indistinguishable from SM $t\bar{t}$. Assuming a $T\bar{T} \rightarrow t\bar{t}A_0A_0$ branching ratio of 100%, signal points with T mass up to 420 GeV are excluded at the 95% confidence level for an A_0 mass below 10 GeV, as are signal points with $330 \text{ GeV} < m(T) < 390$ GeV for an A_0 mass below 140 GeV. Figure 3 shows

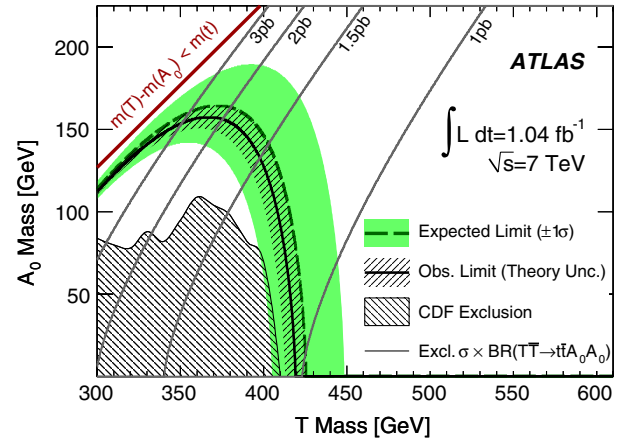


FIG. 2 (color online). Excluded region (under the curve) at the 95% confidence level as a function of T and A_0 masses, compared with the CDF exclusion [10,11]. Theoretical uncertainties on the $T\bar{T}$ cross section are not included in the limit, but the effect of these uncertainties is shown. The gray contours show the excluded cross-section times branching ratio as a function of the two masses.

the cross-section times branching ratio excluded at the 95% confidence level versus T mass, for an A_0 mass of 10 GeV. A cross-section times branching ratio of 1.1 (1.9) pb is excluded at the 95% confidence level for a T mass of 420 (370) GeV and an A_0 mass of 10 (140) GeV. The estimated acceptance times efficiency for spin- $\frac{1}{2}$ $T\bar{T}$ models is consistent within systematic uncertainties with that for scalar models, such as pair production of stop squarks (with a $t\bar{t}\chi_0\chi_0$ final state) or third-generation leptoquarks (with a $t\bar{t}\nu_\tau\bar{\nu}_\tau$ final state). The cross-section limits presented in Fig. 3 are therefore approximately valid for such models, although the predicted cross section is typically below the current sensitivity.

In summary, in 1.04 fb^{-1} of data in pp collisions at a center-of-mass energy of 7 TeV, there is no evidence of an

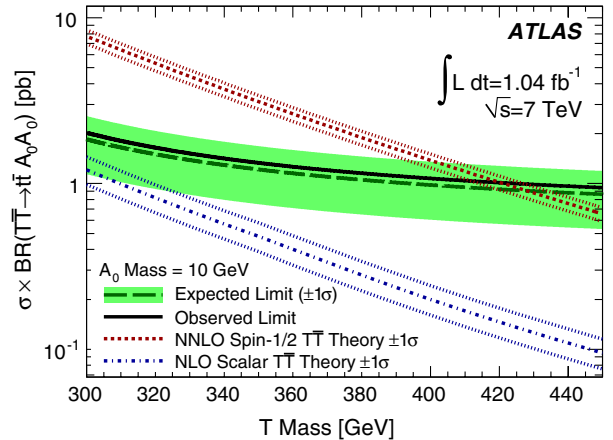


FIG. 3 (color online). Cross-section times branching ratio excluded at the 95% confidence level versus T mass for an A_0 mass of 10 GeV. Theoretical predictions for both spin- $\frac{1}{2}$ and scalar pair production are also shown.

excess of events with large E_T^{miss} in a sample dominated by $t\bar{t}$ events. Using a model of pair-produced quarklike objects decaying to a top quark and a heavy neutral particle, a limit is established excluding masses of these top partners up to 420 GeV and stable weakly interacting particle masses up to 140 GeV (see Fig. 2). In particular, a cross-section times branching ratio of 1.1 pb is excluded at the 95% confidence level for $m(T) = 420$ GeV and $m(A_0) = 10$ GeV. The cross-section limits are approximately valid for a number of models of new phenomena.

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G. Aad,⁴⁷ B. Abbott,¹¹⁰ J. Abdallah,¹¹ A. A. Abdelalim,⁴⁸ A. Abdesselam,¹¹⁷ O. Abdinov,¹⁰ B. Abi,¹¹¹ M. Abolins,⁸⁷ H. Abramowicz,¹⁵² H. Abreu,¹¹⁴ E. Acerbi,^{88a,88b} B. S. Acharya,^{163a,163b} D. L. Adams,²⁴ T. N. Addy,⁵⁵ J. Adelman,¹⁷⁴ M. Aderholz,⁹⁸ S. Adomeit,⁹⁷ P. Adragna,⁷⁴ T. Adye,¹²⁸ S. Aefsky,²² J. A. Aguilar-Saavedra,^{123b,b}

M. Aharrouche,⁸⁰ S. P. Ahlen,²¹ F. Ahles,⁴⁷ A. Ahmad,¹⁴⁷ M. Ahsan,⁴⁰ G. Aielli,^{132a,132b} T. Akdogan,^{18a}
T. P. A. Åkesson,⁷⁸ G. Akimoto,¹⁵⁴ A. V. Akimov,⁹³ A. Akiyama,⁶⁶ M. S. Alam,¹ M. A. Alam,⁷⁵ J. Albert,¹⁶⁸
S. Albrand,⁵⁴ M. Aleksa,²⁹ I. N. Aleksandrov,⁶⁴ F. Alessandria,^{88a} C. Alexa,^{25a} G. Alexander,¹⁵² G. Alexandre,⁴⁸
T. Alexopoulos,⁹ M. Alhroob,²⁰ M. Aliev,¹⁵ G. Alimonti,^{88a} J. Alison,¹¹⁹ M. Aliyev,¹⁰ P. P. Allport,⁷²
S. E. Allwood-Spiers,⁵² J. Almond,⁸¹ A. Aloisio,^{101a,101b} R. Alon,¹⁷⁰ A. Alonso,⁷⁸ M. G. Alviggi,^{101a,101b}
K. Amako,⁶⁵ P. Amaral,²⁹ C. Amelung,²² V. V. Ammosov,¹²⁷ A. Amorim,^{123a,c} G. Amorós,¹⁶⁶ N. Amram,¹⁵²
C. Anastopoulos,²⁹ L. S. Ancu,¹⁶ N. Andari,¹¹⁴ T. Andeen,³⁴ C. F. Anders,²⁰ G. Anders,^{57a} K. J. Anderson,³⁰
A. Andreazza,^{88a,88b} V. Andrei,^{57a} M-L. Andrieux,⁵⁴ X. S. Anduaga,⁶⁹ A. Angerami,³⁴ F. Anghinolfi,²⁹ N. Anjos,^{123a}
A. Annovi,⁴⁶ A. Antonaki,⁸ M. Antonelli,⁴⁶ A. Antonov,⁹⁵ J. Antos,^{143b} F. Anulli,^{131a} S. Aoun,⁸² L. Aperio Bella,⁴
R. Apolle,^{117,d} G. Arabidze,⁸⁷ I. Aracena,¹⁴² Y. Arai,⁶⁵ A. T. H. Arce,⁴⁴ J. P. Archambault,²⁸ S. Arfaoui,^{29,e}
J-F. Arguin,¹⁴ E. Arik,^{18a,a} M. Arik,^{18a} A. J. Armbruster,⁸⁶ O. Arnaez,⁸⁰ C. Arnault,¹¹⁴ A. Artamonov,⁹⁴
G. Artoni,^{131a,131b} D. Arutinov,²⁰ S. Asai,¹⁵⁴ R. Asfandiyarov,¹⁷¹ S. Ask,²⁷ B. Åsman,^{145a,145b} L. Asquith,⁵
K. Assamagan,²⁴ A. Astbury,¹⁶⁸ A. Astvatsatourov,⁵¹ G. Atoian,¹⁷⁴ B. Aubert,⁴ E. Auge,¹¹⁴ K. Augsten,¹²⁶
M. Auroousseau,^{144a} N. Austin,⁷² G. Avolio,¹⁶² R. Avramidou,⁹ D. Axen,¹⁶⁷ C. Ay,⁵³ G. Azuelos,^{92,f} Y. Azuma,¹⁵⁴
M. A. Baak,²⁹ G. Baccaglioni,^{88a} C. Bacci,^{133a,133b} A. M. Bach,¹⁴ H. Bachacou,¹³⁵ K. Bachas,²⁹ G. Bachy,²⁹
M. Backes,⁴⁸ M. Backhaus,²⁰ E. Badescu,^{25a} P. Bagnaia,^{131a,131b} S. Bahinipati,² Y. Bai,^{32a} D. C. Bailey,¹⁵⁷ T. Bain,¹⁵⁷
J. T. Baines,¹²⁸ O. K. Baker,¹⁷⁴ M. D. Baker,²⁴ S. Baker,⁷⁶ E. Banas,³⁸ P. Banerjee,⁹² Sw. Banerjee,¹⁷¹ D. Banfi,²⁹
A. Bangert,¹³⁶ V. Bansal,¹⁶⁸ H. S. Bansil,¹⁷ L. Barak,¹⁷⁰ S. P. Baranov,⁹³ A. Barashkou,⁶⁴ A. Barbaro Galtieri,¹⁴
T. Barber,²⁷ E. L. Barberio,⁸⁵ D. Barberis,^{49a,49b} M. Barbero,²⁰ D. Y. Bardin,⁶⁴ T. Barillari,⁹⁸ M. Barisonzi,¹⁷³
T. Barklow,¹⁴² N. Barlow,²⁷ B. M. Barnett,¹²⁸ R. M. Barnett,¹⁴ A. Baroncelli,^{133a} G. Barone,⁴⁸ A. J. Barr,¹¹⁷
F. Barreiro,⁷⁹ J. Barreiro Guimarães da Costa,⁵⁶ P. Barrillon,¹¹⁴ R. Bartoldus,¹⁴² A. E. Barton,⁷⁰ D. Bartsch,²⁰
V. Bartsch,¹⁴⁸ R. L. Bates,⁵² L. Batkova,^{143a} J. R. Batley,²⁷ A. Battaglia,¹⁶ M. Battistin,²⁹ G. Battistoni,^{88a}
F. Bauer,¹³⁵ H. S. Bawa,^{142,g} B. Beare,¹⁵⁷ T. Beau,⁷⁷ P. H. Beauchemin,¹¹⁷ R. Beccherle,^{49a} P. Bechtle,⁴¹ H. P. Beck,¹⁶
M. Beckingham,¹³⁷ K. H. Becks,¹⁷³ A. J. Beddall,^{18c} A. Beddall,^{18c} S. Bedikian,¹⁷⁴ V. A. Bednyakov,⁶⁴ C. P. Bee,⁸²
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K. Belotskiy,⁹⁵ O. Beltramello,²⁹ S. Ben Ami,¹⁵¹ O. Benary,¹⁵² D. Benchekroun,^{134a} C. Benchouk,⁸² M. Bendel,⁸⁰
N. Benekos,¹⁶⁴ Y. Benhammou,¹⁵² D. P. Benjamin,⁴⁴ M. Benoit,¹¹⁴ J. R. Bensinger,²² K. Benslama,¹²⁹
S. Bentvelsen,¹⁰⁴ D. Berge,²⁹ E. Bergeaas Kuutmann,⁴¹ N. Berger,⁴ F. Berghaus,¹⁶⁸ E. Berglund,⁴⁸ J. Beringer,¹⁴
K. Bernardet,⁸² P. Bernat,⁷⁶ R. Bernhard,⁴⁷ C. Bernius,²⁴ T. Berry,⁷⁵ A. Bertin,^{19a,19b} F. Bertinelli,²⁹
F. Bertolucci,^{121a,121b} M. I. Besana,^{88a,88b} N. Besson,¹³⁵ S. Bethke,⁹⁸ W. Bhimji,⁴⁵ R. M. Bianchi,²⁹ M. Bianco,^{71a,71b}
O. Biebel,⁹⁷ S. P. Bieniek,⁷⁶ K. Bierwagen,⁵³ J. Biesiada,¹⁴ M. Biglietti,^{133a,133b} H. Bilokon,⁴⁶ M. Bindi,^{19a,19b}
S. Binet,¹¹⁴ A. Bingul,^{18c} C. Bini,^{131a,131b} C. Biscarat,¹⁷⁶ U. Bitenc,⁴⁷ K. M. Black,²¹ R. E. Blair,⁵ J.-B. Blanchard,¹¹⁴
G. Blanchot,²⁹ T. Blazek,^{143a} C. Blocker,²² J. Blocki,³⁸ A. Blondel,⁴⁸ W. Blum,⁸⁰ U. Blumenschein,⁵³
G. J. Bobbink,¹⁰⁴ V. B. Bobrovnikov,¹⁰⁶ S. S. Bocchetta,⁷⁸ A. Bocci,⁴⁴ C. R. Boddy,¹¹⁷ M. Boehler,⁴¹ J. Boek,¹⁷³
N. Boelaert,³⁵ S. Böser,⁷⁶ J. A. Bogaerts,²⁹ A. Bogdanchikov,¹⁰⁶ A. Bogouch,^{89,a} C. Bohm,^{145a} V. Boisvert,⁷⁵
T. Bold,³⁷ V. Boldea,^{25a} N. M. Bolnet,¹³⁵ M. Bona,⁷⁴ V. G. Bondarenko,⁹⁵ M. Bondioli,¹⁶² M. Boonekamp,¹³⁵
G. Boorman,⁷⁵ C. N. Booth,¹³⁸ S. Bordini,⁷⁷ C. Borer,¹⁶ A. Borisov,¹²⁷ G. Borissov,⁷⁰ I. Borjanovic,^{12a} S. Borroni,⁸⁶
K. Bos,¹⁰⁴ D. Boscherini,^{19a} M. Bosman,¹¹ H. Boterenbrood,¹⁰⁴ D. Botterill,¹²⁸ J. Bouchami,⁹² J. Boudreau,¹²²
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I. Bozovic-Jelisavcic,^{12b} J. Bracinik,¹⁷ A. Braem,²⁹ P. Branchini,^{133a} G. W. Brandenburg,⁵⁶ A. Brandt,⁷ G. Brandt,¹⁵
O. Brandt,⁵³ U. Bratzler,¹⁵⁵ B. Brau,⁸³ J. E. Brau,¹¹³ H. M. Braun,¹⁷³ B. Brelier,¹⁵⁷ J. Bremer,²⁹ R. Brenner,¹⁶⁵
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F. Broggi,^{88a} C. Bromberg,⁸⁷ G. Brooijmans,³⁴ W. K. Brooks,^{31b} G. Brown,⁸¹ H. Brown,⁷
P. A. Bruckman de Renstrom,³⁸ D. Bruncko,^{143b} R. Bruneliere,⁴⁷ S. Brunet,⁶⁰ A. Bruni,^{19a} G. Bruni,^{19a}
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 B. Caron,^{158a} S. Caron,⁴⁷ G. D. Carrillo Montoya,¹⁷¹ A. A. Carter,⁷⁴ J. R. Carter,²⁷ J. Carvalho,^{123a,i} D. Casadei,¹⁰⁷
 M. P. Casado,¹¹ M. Cascella,^{121a,121b} C. Caso,^{49a,49b,a} A. M. Castaneda Hernandez,¹⁷¹ E. Castaneda-Miranda,¹⁷¹
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 G. Cattani,^{132a,132b} S. Caughron,⁸⁷ D. Cauz,^{163a,163c} P. Cavalleri,⁷⁷ D. Cavalli,^{88a} M. Cavalli-Sforza,¹¹
 V. Cavasinni,^{121a,121b} F. Ceradini,^{133a,133b} A. S. Cerqueira,^{23a} A. Cerri,²⁹ L. Cerrito,⁷⁴ F. Cerutti,⁴⁶ S. A. Cetin,^{18b}
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 E. Chareyre,⁷⁷ D. G. Charlton,¹⁷ V. Chavda,⁸¹ C. A. Chavez Barajas,²⁹ S. Cheatham,⁸⁴ S. Chekanov,⁵
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 X. Chen,¹⁷¹ S. Cheng,^{32a} A. Cheplakov,⁶⁴ V. F. Chepurinov,⁶⁴ R. Cherkaoui El Moursli,^{134e} V. Chernyatin,²⁴ E. Cheu,⁶
 S. L. Cheung,¹⁵⁷ L. Chevalier,¹³⁵ G. Chiefari,^{101a,101b} L. Chikovani,^{50a} J. T. Childers,^{57a} A. Chilingarov,⁷⁰
 G. Chiodini,^{71a} M. V. Chizhov,⁶⁴ G. Choudalakis,³⁰ S. Chouridou,¹³⁶ I. A. Christidi,⁷⁶ A. Christov,⁴⁷
 D. Chromek-Burckhart,²⁹ M. L. Chu,¹⁵⁰ J. Chudoba,¹²⁴ G. Ciapetti,^{131a,131b} K. Ciba,³⁷ A. K. Ciftci,^{3a} R. Ciftci,^{3a}
 D. Cinca,³³ V. Cindro,⁷³ M. D. Ciobotaru,¹⁶² C. Ciocca,^{19a,19b} A. Ciocio,¹⁴ M. Cirilli,⁸⁶ M. Ciubancan,^{25a} A. Clark,⁴⁸
 P. J. Clark,⁴⁵ W. Cleland,¹²² J. C. Clemens,⁸² B. Clement,⁵⁴ C. Clement,^{145a,145b} R. W. Clift,¹²⁸ Y. Coadou,⁸²
 M. Cobal,^{163a,163c} A. Coccaro,^{49a,49b} J. Cochran,⁶³ P. Coe,¹¹⁷ J. G. Cogan,¹⁴² J. Coggeshall,¹⁶⁴ E. Cogneras,¹⁷⁶
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 C. Conta,^{118a,118b} F. Conventi,^{101a,j} J. Cook,²⁹ M. Cooke,¹⁴ B. D. Cooper,⁷⁶ A. M. Cooper-Sarkar,¹¹⁷
 N. J. Cooper-Smith,⁷⁵ K. Copic,³⁴ T. Cornelissen,^{49a,49b} M. Corradi,^{19a} F. Corriveau,^{84,k} A. Cortes-Gonzalez,¹⁶⁴
 G. Cortiana,⁹⁸ G. Costa,^{88a} M. J. Costa,¹⁶⁶ D. Costanzo,¹³⁸ T. Costin,³⁰ D. Côté,²⁹ L. Courneyea,¹⁶⁸ G. Cowan,⁷⁵
 C. Cowden,²⁷ B. E. Cox,⁸¹ K. Cranmer,¹⁰⁷ F. Crescioli,^{121a,121b} M. Cristinziani,²⁰ G. Crosetti,^{36a,36b} R. Crupi,^{71a,71b}
 S. Crépe-Renaudin,⁵⁴ C.-M. Cuciuc,^{25a} C. Cuenca Almenar,¹⁷⁴ T. Cuhadar Donszelmann,¹³⁸ M. Curatolo,⁴⁶
 C. J. Curtis,¹⁷ P. Cwetanski,⁶⁰ H. Czirr,¹⁴⁰ Z. Czyczula,¹⁷⁴ S. D'Auria,⁵² M. D'Onofrio,⁷² A. D'Orazio,^{131a,131b}
 P. V. M. Da Silva,^{23a} C. Da Via,⁸¹ W. Dabrowski,³⁷ T. Dai,⁸⁶ C. Dallapiccola,⁸³ M. Dam,³⁵ M. Dameri,^{49a,49b}
 D. S. Damiani,¹³⁶ H. O. Danielsson,²⁹ D. Dannheim,⁹⁸ V. Dao,⁴⁸ G. Darbo,^{49a} G. L. Darlea,^{25b} C. Daum,¹⁰⁴
 J. P. Dauvergne,²⁹ W. Davey,⁸⁵ T. Davidek,¹²⁵ N. Davidson,⁸⁵ R. Davidson,⁷⁰ E. Davies,^{117,d} M. Davies,⁹²
 A. R. Davison,⁷⁶ Y. Davygora,^{57a} E. Dawe,¹⁴¹ I. Dawson,¹³⁸ J. W. Dawson,^{5a} R. K. Daya,³⁹ K. De,⁷
 R. de Asmundis,^{101a} S. De Castro,^{19a,19b} P. E. De Castro Faria Salgado,²⁴ S. De Cecco,⁷⁷ J. de Graat,⁹⁷
 N. De Groot,¹⁰³ P. de Jong,¹⁰⁴ C. De La Taille,¹¹⁴ H. De la Torre,⁷⁹ B. De Lotto,^{163a,163c} L. De Mora,⁷⁰
 L. De Nooij,¹⁰⁴ D. De Pedis,^{131a} A. De Salvo,^{131a} U. De Sanctis,^{163a,163c} A. De Santo,¹⁴⁸ J. B. De Vivie De Regie,¹¹⁴
 S. Dean,⁷⁶ R. Debbe,²⁴ D. V. Dedovich,⁶⁴ J. Degenhardt,¹¹⁹ M. Dehchar,¹¹⁷ C. Del Papa,^{163a,163c} J. Del Peso,⁷⁹
 T. Del Prete,^{121a,121b} M. Deliyergiyev,⁷³ A. Dell'Acqua,²⁹ L. Dell'Asta,^{88a,88b} M. Della Pietra,^{101a,j}
 D. della Volpe,^{101a,101b} M. Delmastro,²⁹ P. Delpierre,⁸² N. Delruelle,²⁹ P. A. Delsart,⁵⁴ C. Deluca,¹⁴⁷ S. Demers,¹⁷⁴
 M. Demichev,⁶⁴ B. Demirkoz,^{11,i} J. Deng,¹⁶² S. P. Denisov,¹²⁷ D. Derendarz,³⁸ J. E. Derkaoui,^{134d} F. Derue,⁷⁷
 P. Dervan,⁷² K. Desch,²⁰ E. Devetak,¹⁴⁷ P. O. Deviveiros,¹⁵⁷ A. Dewhurst,¹²⁸ B. DeWilde,¹⁴⁷ S. Dhaliwal,¹⁵⁷
 R. Dhullipudi,^{24,m} A. Di Ciaccio,^{132a,132b} L. Di Ciaccio,⁴ A. Di Girolamo,²⁹ B. Di Girolamo,²⁹ S. Di Luise,^{133a,133b}
 A. Di Mattia,⁸⁷ B. Di Micco,²⁹ R. Di Nardo,^{132a,132b} A. Di Simone,^{132a,132b} R. Di Sipio,^{19a,19b} M. A. Diaz,^{31a}
 F. Diblen,^{18c} E. B. Diehl,⁸⁶ J. Dietrich,⁴¹ T. A. Dietzsch,^{57a} S. Diglio,¹¹⁴ K. Dindar Yagci,³⁹ J. Dingfelder,²⁰
 C. Dionisi,^{131a,131b} P. Dita,^{25a} S. Dita,^{25a} F. Dittus,²⁹ F. Djama,⁸² T. Djobava,^{50b} M. A. B. do Vale,^{23a}
 A. Do Valle Wemans,^{123a} T. K. O. Doan,⁴ M. Dobbs,⁸⁴ R. Dobinson,^{29,a} D. Dobos,²⁹ E. Dobson,²⁹ M. Dobson,¹⁶²
 J. Dodd,³⁴ C. Doglioni,¹¹⁷ T. Doherty,⁵² Y. Doi,^{65,a} J. Dolejsi,¹²⁵ I. Dolenc,⁷³ Z. Dolezal,¹²⁵ B. A. Dolgoshein,^{95,a}
 T. Dohmae,¹⁵⁴ M. Donadelli,^{23d} M. Donega,¹¹⁹ J. Donini,⁵⁴ J. Dopke,²⁹ A. Doria,^{101a} A. Dos Anjos,¹⁷¹ M. Dosil,¹¹
 A. Dotti,^{121a,121b} M. T. Dova,⁶⁹ J. D. Dowell,¹⁷ A. D. Doxiadis,¹⁰⁴ A. T. Doyle,⁵² Z. Drasal,¹²⁵ J. Drees,¹⁷³
 N. Dressnandt,¹¹⁹ H. Drevermann,²⁹ C. Driouichi,³⁵ M. Dris,⁹ J. Dubbert,⁹⁸ T. Dubbs,¹³⁶ S. Dube,¹⁴ E. Duchovni,¹⁷⁰
 G. Duckeck,⁹⁷ A. Dudarev,²⁹ F. Dudziak,⁶³ M. Dührssen,²⁹ I. P. Duerdoth,⁸¹ L. Dufloc,¹¹⁴ M.-A. Dufour,⁸⁴
 M. Dunford,²⁹ H. Duran Yildiz,^{3b} R. Duxfield,¹³⁸ M. Dwuznik,³⁷ F. Dydak,²⁹ M. Düren,⁵¹ W. L. Ebenstein,⁴⁴
 J. Ebke,⁹⁷ S. Eckert,⁴⁷ S. Eckweiler,⁸⁰ K. Edmonds,⁸⁰ C. A. Edwards,⁷⁵ N. C. Edwards,⁵² W. Ehrenfeld,⁴¹ T. Ehrich,⁹⁸
 T. Eifert,²⁹ G. Eigen,¹³ K. Einsweiler,¹⁴ E. Eisenhandler,⁷⁴ T. Ekelof,¹⁶⁵ M. El Kacimi,^{134c} M. Ellert,¹⁶⁵ S. Elles,⁴

- F. Ellinghaus,⁸⁰ K. Ellis,⁷⁴ N. Ellis,²⁹ J. Elmsheuser,⁹⁷ M. Elsing,²⁹ D. Emeliyanov,¹²⁸ R. Engelmann,¹⁴⁷ A. Engl,⁹⁷
 B. Epp,⁶¹ A. Eppig,⁸⁶ J. Erdmann,⁵³ A. Ereditato,¹⁶ D. Eriksson,^{145a} J. Ernst,¹ M. Ernst,²⁴ J. Ernwein,¹³⁵
 D. Errede,¹⁶⁴ S. Errede,¹⁶⁴ E. Ertel,⁸⁰ M. Escalier,¹¹⁴ C. Escobar,¹²² X. Espinal Curull,¹¹ B. Esposito,⁴⁶ F. Etienne,⁸²
 A. I. Etievre,¹³⁵ E. Etzion,¹⁵² D. Evangelakou,⁵³ H. Evans,⁶⁰ L. Fabbri,^{19a,19b} C. Fabre,²⁹ R. M. Fakhruddinov,¹²⁷
 S. Falciano,^{131a} Y. Fang,¹⁷¹ M. Fanti,^{88a,88b} A. Farbin,⁷ A. Farilla,^{133a} J. Farley,¹⁴⁷ T. Farooque,¹⁵⁷
 S. M. Farrington,¹¹⁷ P. Farthouat,²⁹ P. Fassnacht,²⁹ D. Fassouliotis,⁸ B. Fatholahzadeh,¹⁵⁷ A. Favareto,^{88a,88b}
 L. Fayard,¹¹⁴ S. Fazio,^{36a,36b} R. Febbraro,³³ P. Federic,^{143a} O. L. Fedin,¹²⁰ W. Fedorko,⁸⁷ M. Fehling-Kaschek,⁴⁷
 L. Feligioni,⁸² C. U. Felzmann,⁸⁵ C. Feng,^{32d} E. J. Feng,³⁰ A. B. Fenyuk,¹²⁷ J. Ferencei,^{143b} J. Ferland,⁹²
 W. Fernando,¹⁰⁸ S. Ferrag,⁵² J. Ferrando,⁵² V. Ferrara,⁴¹ A. Ferrari,¹⁶⁵ P. Ferrari,¹⁰⁴ R. Ferrari,^{118a} A. Ferrer,¹⁶⁶
 M. L. Ferrer,⁴⁶ D. Ferrere,⁴⁸ C. Ferretti,⁸⁶ A. Ferretto Parodi,^{49a,49b} M. Fiascaris,³⁰ F. Fiedler,⁸⁰ A. Filipčić,⁷³
 A. Filippas,⁹ F. Filthaut,¹⁰³ M. Fincke-Keeler,¹⁶⁸ M. C. N. Fiolhais,^{123a,i} L. Fiorini,¹⁶⁶ A. Firan,³⁹ G. Fischer,⁴¹
 P. Fischer,²⁰ M. J. Fisher,¹⁰⁸ S. M. Fisher,¹²⁸ M. Flechl,⁴⁷ I. Fleck,¹⁴⁰ J. Fleckner,⁸⁰ P. Fleischmann,¹⁷²
 S. Fleischmann,¹⁷³ T. Flick,¹⁷³ L. R. Flores Castillo,¹⁷¹ M. J. Flowerdew,⁹⁸ M. Fokitis,⁹ T. Fonseca Martin,¹⁶
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 K. Fowler,¹³⁶ H. Fox,⁷⁰ P. Francavilla,^{121a,121b} S. Franchino,^{118a,118b} D. Francis,²⁹ T. Frank,¹⁷⁰ M. Franklin,⁵⁶
 S. Franz,²⁹ M. Fraternali,^{118a,118b} S. Fratina,¹¹⁹ S. T. French,²⁷ F. Friedrich,⁴³ R. Froeschl,²⁹ D. Froidevaux,²⁹
 J. A. Frost,²⁷ C. Fukunaga,¹⁵⁵ E. Fullana Torregrosa,²⁹ J. Fuster,¹⁶⁶ C. Gabaldon,²⁹ O. Gabizon,¹⁷⁰ T. Gadfort,²⁴
 S. Gadomski,⁴⁸ G. Gagliardi,^{49a,49b} P. Gagnon,⁶⁰ C. Galea,⁹⁷ E. J. Gallas,¹¹⁷ V. Gallo,¹⁶ B. J. Gallop,¹²⁸ P. Gallus,¹²⁴
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 C. Gay,¹⁶⁷ G. Gaycken,²⁰ J-C. Gayde,²⁹ E. N. Gazis,⁹ P. Ge,^{32d} C. N. P. Gee,¹²⁸ D. A. A. Geerts,¹⁰⁴
 Ch. Geich-Gimbel,²⁰ K. Gellerstedt,^{145a,145b} C. Gemme,^{49a} A. Gemmell,⁵² M. H. Genest,⁹⁷ S. Gentile,^{131a,131b}
 M. George,⁵³ S. George,⁷⁵ P. Gerlach,¹⁷³ A. Gershon,¹⁵² C. Geweniger,^{57a} H. Ghazlane,^{134b} P. Ghez,⁴
 N. Ghodbane,³³ B. Giacobbe,^{19a} S. Giagu,^{131a,131b} V. Giakoumopoulou,⁸ V. Giangiobbe,^{121a,121b} F. Gianotti,²⁹
 B. Gibbard,²⁴ A. Gibson,¹⁵⁷ S. M. Gibson,²⁹ L. M. Gilbert,¹¹⁷ M. Gilchriese,¹⁴ V. Gilewsky,⁹⁰ D. Gillberg,²⁸
 A. R. Gillman,¹²⁸ D. M. Gingrich,^{2,f} J. Ginzburg,¹⁵² N. Giokaris,⁸ M. P. Giordani,^{163c} R. Giordano,^{101a,101b}
 F. M. Giorgi,¹⁵ P. Giovannini,⁹⁸ P. F. Giraud,¹³⁵ D. Giugni,^{88a} M. Giunta,⁹² P. Giusti,^{19a} B. K. Gjelsten,¹¹⁶
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 L. Gonella,²⁰ A. Gonidec,²⁹ S. Gonzalez,¹⁷¹ S. González de la Hoz,¹⁶⁶ M. L. Gonzalez Silva,²⁶ S. Gonzalez-Sevilla,⁴⁸
 J. J. Goodson,¹⁴⁷ L. Goossens,²⁹ P. A. Gorbounov,⁹⁴ H. A. Gordon,²⁴ I. Gorelov,¹⁰² G. Gorfine,¹⁷³ B. Gorini,²⁹
 E. Gorini,^{71a,71b} A. Gorišek,⁷³ E. Gornicki,³⁸ S. A. Gorokhov,¹²⁷ V. N. Goryachev,¹²⁷ B. Gosdzik,⁴¹ M. Gosselink,¹⁰⁴
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 C. Goy,⁴ I. Grabowska-Bold,^{162,n} P. Grafström,²⁹ C. Grah,¹⁷³ K.-J. Grah,⁴¹ F. Grancagnolo,^{71a} S. Grancagnolo,¹⁵
 V. Grassi,¹⁴⁷ V. Gratchev,¹²⁰ N. Grau,³⁴ H. M. Gray,²⁹ J. A. Gray,¹⁴⁷ E. Graziani,^{133a} O. G. Grebenyuk,¹²⁰
 D. Greenfield,¹²⁸ T. Greenshaw,⁷² Z. D. Greenwood,^{24,m} K. Gregersen,³⁵ I. M. Gregor,⁴¹ P. Grenier,¹⁴² J. Griffiths,¹³⁷
 N. Grigalashvili,⁶⁴ A. A. Grillo,¹³⁶ S. Grinstein,¹¹ Y. V. Grishkevich,⁹⁶ J.-F. Grivaz,¹¹⁴ M. Groh,⁹⁸ E. Gross,¹⁷⁰
 J. Grosse-Knetter,⁵³ J. Groth-Jensen,¹⁷⁰ K. Grybel,¹⁴⁰ V. J. Guarino,⁵ D. Guest,¹⁷⁴ C. Guicheney,³³ A. Guida,^{71a,71b}
 T. Guillemin,⁴ S. Guindon,⁵³ H. Guler,^{84,o} J. Gunther,¹²⁴ B. Guo,¹⁵⁷ J. Guo,³⁴ A. Gupta,³⁰ Y. Gusakov,⁶⁴
 V. N. Gushchin,¹²⁷ A. Gutierrez,⁹² P. Gutierrez,¹¹⁰ N. Guttman,¹⁵² O. Gutzwiller,¹⁷¹ C. Guyot,¹³⁵ C. Gwenlan,¹¹⁷
 C. B. Gwilliam,⁷² A. Haas,¹⁴² S. Haas,²⁹ C. Haber,¹⁴ R. Hackenburg,²⁴ H. K. Hadavand,³⁹ D. R. Hadley,¹⁷
 P. Haefner,⁹⁸ F. Hahn,²⁹ S. Haider,²⁹ Z. Hajduk,³⁸ H. Hakobyan,¹⁷⁵ J. Haller,⁵³ K. Hamacher,¹⁷³ P. Hamal,¹¹²
 A. Hamilton,⁴⁸ S. Hamilton,¹⁶⁰ H. Han,^{32a} L. Han,^{32b} K. Hanagaki,¹¹⁵ M. Hance,¹⁴ C. Handel,⁸⁰ P. Hanke,^{57a}
 J. R. Hansen,³⁵ J. B. Hansen,³⁵ J. D. Hansen,³⁵ P. H. Hansen,³⁵ P. Hansson,¹⁴² K. Hara,¹⁵⁹ G. A. Hare,¹³⁶
 T. Harenberg,¹⁷³ S. Harkusha,⁸⁹ D. Harper,⁸⁶ R. D. Harrington,⁴⁵ O. M. Harris,¹³⁷ K. Harrison,¹⁷ J. Hartert,⁴⁷
 F. Hartjes,¹⁰⁴ T. Haruyama,⁶⁵ A. Harvey,⁵⁵ S. Hasegawa,¹⁰⁰ Y. Hasegawa,¹³⁹ S. Hassani,¹³⁵ M. Hatch,²⁹ D. Hauff,⁹⁸
 S. Haug,¹⁶ M. Hauschild,²⁹ R. Hauser,⁸⁷ M. Havranek,²⁰ B. M. Hawes,¹¹⁷ C. M. Hawkes,¹⁷ R. J. Hawkings,²⁹
 D. Hawkins,¹⁶² T. Hayakawa,⁶⁶ T. Hayashi,¹⁵⁹ D. Hayden,⁷⁵ H. S. Hayward,⁷² S. J. Haywood,¹²⁸ E. Hazen,²¹
 M. He,^{32d} S. J. Head,¹⁷ V. Hedberg,⁷⁸ L. Heelan,⁷ S. Heim,⁸⁷ B. Heinemann,¹⁴ S. Heisterkamp,³⁵ L. Helary,⁴

M. Heller,¹¹⁴ S. Hellman,^{145a,145b} D. Hellmich,²⁰ C. Helsens,¹¹ R. C. W. Henderson,⁷⁰ M. Henke,^{57a} A. Henrichs,⁵³ A. M. Henriques Correia,²⁹ S. Henrot-Versille,¹¹⁴ F. Henry-Couannier,⁸² C. Hensel,⁵³ T. Henß,¹⁷³ C. M. Hernandez,⁷ Y. Hernández Jiménez,¹⁶⁶ R. Herrberg,¹⁵ A. D. Hershenhorn,¹⁵¹ G. Herten,⁴⁷ R. Hertenberger,⁹⁷ L. Hervas,²⁹ N. P. Hessey,¹⁰⁴ A. Hidvegi,^{145a} E. Higón-Rodríguez,¹⁶⁶ 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,¹¹⁹ M. Hirose,¹¹⁵ F. Hirsch,⁴² D. Hirschbuehl,¹⁷³ J. Hobbs,¹⁴⁷ N. Hod,¹⁵² M. C. Hodgkinson,¹³⁸ P. Hodgson,¹³⁸ A. Hoecker,²⁹ M. R. Hoferkamp,¹⁰² J. Hoffman,³⁹ D. Hoffmann,⁸² M. Hohlfeld,⁸⁰ M. Holder,¹⁴⁰ S. O. Holmgren,^{145a} T. Holy,¹²⁶ J. L. Holzbauer,⁸⁷ Y. Homma,⁶⁶ T. M. Hong,¹¹⁹ L. Hoof van Huysduynen,¹⁰⁷ T. Horazdovsky,¹²⁶ C. Horn,¹⁴² S. Horner,⁴⁷ K. Horton,¹¹⁷ J.-Y. Hostachy,⁵⁴ S. Hou,¹⁵⁰ M. A. Houlden,⁷² A. Hoummada,^{134a} J. Howarth,⁸¹ D. F. Howell,¹¹⁷ I. Hristova,¹⁵ J. Hrivnac,¹¹⁴ I. Hruska,¹²⁴ T. Hryn'ova,⁴ P. J. Hsu,¹⁷⁴ S.-C. Hsu,¹⁴ G. S. Huang,¹¹⁰ Z. Hubacek,¹²⁶ F. Hubaut,⁸² F. Huegging,²⁰ T. B. Huffman,¹¹⁷ E. W. Hughes,³⁴ G. Hughes,⁷⁰ R. E. Hughes-Jones,⁸¹ M. Huhtinen,²⁹ P. Hurst,⁵⁶ M. Hurwitz,¹⁴ U. Husemann,⁴¹ N. Huseynov,^{64,p} J. Huston,⁸⁷ J. Huth,⁵⁶ G. Iacobucci,⁴⁸ G. Iakovidis,⁹ M. Ibbotson,⁸¹ I. Ibragimov,¹⁴⁰ R. Ichimiya,⁶⁶ L. Iconomidou-Fayard,¹¹⁴ J. Idarraga,¹¹⁴ P. Iengo,^{101a,101b} O. Igonkina,¹⁰⁴ Y. Ikegami,⁶⁵ M. Ikeno,⁶⁵ Y. Ilchenko,³⁹ D. Iliadis,¹⁵³ D. Imbault,⁷⁷ M. Imori,¹⁵⁴ T. Ince,²⁰ J. Inigo-Golfín,²⁹ P. Ioannou,⁸ M. Iodice,^{133a} A. Irlés Quiles,¹⁶⁶ A. Ishikawa,⁶⁶ M. Ishino,⁶⁷ R. Ishmukhametov,³⁹ C. Issever,¹¹⁷ S. Istin,^{18a} A. V. Ivashin,¹²⁷ W. Iwanski,³⁸ H. Iwasaki,⁶⁵ J. M. Izen,⁴⁰ V. Izzo,^{101a} B. Jackson,¹¹⁹ J. N. Jackson,⁷² P. Jackson,¹⁴² M. R. Jaekel,²⁹ V. Jain,⁶⁰ K. Jakobs,⁴⁷ S. Jakobsen,³⁵ J. Jakubek,¹²⁶ D. K. Jana,¹¹⁰ E. Jankowski,¹⁵⁷ E. Jansen,⁷⁶ A. Jantsch,⁹⁸ M. Janus,²⁰ G. Jarlskog,⁷⁸ 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,¹⁷¹ W. Ji,⁸⁰ J. Jia,¹⁴⁷ Y. Jiang,^{32b} M. Jimenez Belenguer,⁴¹ G. Jin,^{32b} S. Jin,^{32a} O. Jinnouchi,¹⁵⁶ M. D. Joergensen,³⁵ D. Joffe,³⁹ L. G. Johansen,¹³ M. Johansen,^{145a,145b} K. E. Johansson,^{145a} P. Johansson,¹³⁸ S. Johnert,⁴¹ K. A. Johns,⁶ K. Jon-And,^{145a,145b} G. Jones,⁸¹ R. W. L. Jones,⁷⁰ T. W. Jones,⁷⁶ T. J. Jones,⁷² O. Jonsson,²⁹ C. Joram,²⁹ P. M. Jorge,^{123a,c} J. Joseph,¹⁴ T. Jovin,^{12b} X. Ju,¹²⁹ C. A. Jung,⁴² V. Juranek,¹²⁴ P. Jussel,⁶¹ A. Juste Rozas,¹¹ V. V. Kabachenko,¹²⁷ S. Kabana,¹⁶ M. Kaci,¹⁶⁶ A. Kaczmarek,³⁸ P. Kadlecik,³⁵ M. Kado,¹¹⁴ H. Kagan,¹⁰⁸ M. Kagan,⁵⁶ S. Kaiser,⁹⁸ E. Kajomovitz,¹⁵¹ S. Kalinin,¹⁷³ L. V. Kalinovskaya,⁶⁴ S. Kama,³⁹ N. Kanaya,¹⁵⁴ M. Kaneda,²⁹ T. Kanno,¹⁵⁶ V. A. Kantserov,⁹⁵ J. Kanzaki,⁶⁵ B. Kaplan,¹⁷⁴ A. Kapliy,³⁰ J. Kaplon,²⁹ D. Kar,⁴³ M. Karagoz,¹¹⁷ M. Karnevskiy,⁴¹ K. Karr,⁵ V. Kartvelishvili,⁷⁰ A. N. Karyukhin,¹²⁷ L. Kashif,¹⁷¹ A. Kasmi,³⁹ R. D. Kass,¹⁰⁸ A. Kastanas,¹³ M. Kataoka,⁴ Y. Kataoka,¹⁵⁴ E. Katsoufis,⁹ J. Katzy,⁴¹ V. Kaushik,⁶ K. Kawagoe,⁶⁶ T. Kawamoto,¹⁵⁴ G. Kawamura,⁸⁰ M. S. Kayl,¹⁰⁴ V. A. Kazanin,¹⁰⁶ M. Y. Kazarinov,⁶⁴ J. R. Keates,⁸¹ R. Keeler,¹⁶⁸ R. Kehoe,³⁹ M. Keil,⁵³ G. D. Kekelidze,⁶⁴ M. Kelly,⁸¹ J. Kennedy,⁹⁷ C. J. Kenney,¹⁴² M. Kenyon,⁵² O. Kepka,¹²⁴ N. Kerschen,²⁹ B. P. Kerševan,⁷³ S. Kersten,¹⁷³ K. Kessoku,¹⁵⁴ C. Ketterer,⁴⁷ J. Keung,¹⁵⁷ M. Khakzad,²⁸ F. Khalil-zada,¹⁰ H. Khandanyan,¹⁶⁴ A. Khanov,¹¹¹ D. Kharchenko,⁶⁴ A. Khodinov,⁹⁵ A. G. Kholodenko,¹²⁷ A. Khomich,^{57a} T. J. Khoo,²⁷ G. Khoriauli,²⁰ A. Khoroshilov,¹⁷³ N. Khovanskiy,⁶⁴ V. Khovanskiy,⁹⁴ E. Khramov,⁶⁴ J. Khubua,^{50b} H. Kim,⁷ M. S. Kim,² P. C. Kim,¹⁴² S. H. Kim,¹⁵⁹ N. Kimura,¹⁶⁹ O. Kind,¹⁵ B. T. King,⁷² M. King,⁶⁶ R. S. B. King,¹¹⁷ J. Kirk,¹²⁸ L. E. Kirsch,²² A. E. Kiryunin,⁹⁸ T. Kishimoto,⁶⁶ D. Kisielewska,³⁷ T. Kittelmann,¹²² A. M. Kiver,¹²⁷ E. Kladiva,^{143b} J. Klaiber-Lodewigs,⁴² M. Klein,⁷² U. Klein,⁷² K. Kleinknecht,⁸⁰ M. Klemetti,⁸⁴ A. Klier,¹⁷⁰ A. Klimentov,²⁴ R. Klingenberg,⁴² E. B. Klinkby,³⁵ T. Klioutchnikova,²⁹ P. F. Klok,¹⁰³ S. Klous,¹⁰⁴ E.-E. Kluge,^{57a} T. Kluge,⁷² P. Kluit,¹⁰⁴ S. Kluth,⁹⁸ N. S. Knecht,¹⁵⁷ E. Kneringer,⁶¹ J. Knobloch,²⁹ E. B. F. G. Knoops,⁸² A. Knue,⁵³ B. R. Ko,⁴⁴ T. Kobayashi,¹⁵⁴ M. Kobel,⁴³ M. Kocian,¹⁴² A. Kocnar,¹¹² P. Kodys,¹²⁵ K. Köneke,²⁹ A. C. König,¹⁰³ S. Koenig,⁸⁰ L. Köpke,⁸⁰ F. Koetsveld,¹⁰³ P. Koevesarki,²⁰ T. Koffas,²⁸ E. Koffeman,¹⁰⁴ F. Kohn,⁵³ Z. Kohout,¹²⁶ T. Kohriki,⁶⁵ T. Koi,¹⁴² T. Kokott,²⁰ G. M. Kolachev,¹⁰⁶ H. Kolanoski,¹⁵ V. Kolesnikov,⁶⁴ I. Koletsou,^{88a} J. Koll,⁸⁷ D. Kollar,²⁹ M. Kollefrath,⁴⁷ S. D. Kolya,⁸¹ A. A. Komar,⁹³ Y. Komori,¹⁵⁴ T. Kondo,⁶⁵ T. Kono,^{41,q} A. I. Kononov,⁴⁷ R. Konoplich,^{107,r} N. Konstantinidis,⁷⁶ A. Kootz,¹⁷³ S. Koperny,³⁷ S. V. Kopikov,¹²⁷ K. Korcyl,³⁸ K. Kordas,¹⁵³ V. Koreshev,¹²⁷ A. Korn,¹¹⁷ A. Korol,¹⁰⁶ I. Korolkov,¹¹ E. V. Korolkova,¹³⁸ V. A. Korotkov,¹²⁷ O. Kortner,⁹⁸ S. Kortner,⁹⁸ V. V. Kostyukhin,²⁰ M. J. Kotamäki,²⁹ S. Kotov,⁹⁸ V. M. Kotov,⁶⁴ A. Kotwal,⁴⁴ C. Kourkoumelis,⁸ V. Kouskoura,¹⁵³ A. Koutsman,¹⁰⁴ R. Kowalewski,¹⁶⁸ T. Z. Kowalski,³⁷ W. Kozanecki,¹³⁵ A. S. Kozhin,¹²⁷ V. Kral,¹²⁶ V. A. Kramarenko,⁹⁶ G. Kramberger,⁷³ M. W. Krasny,⁷⁷ A. Krasznahorkay,¹⁰⁷ J. Kraus,⁸⁷ J. K. Kraus,²⁰ A. Kreisel,¹⁵² F. Krejci,¹²⁶ J. Kretschmar,⁷² N. Krieger,⁵³ P. Krieger,¹⁵⁷ K. Kroeninger,⁵³ H. Kroha,⁹⁸ J. Kroll,¹¹⁹ J. Kroseberg,²⁰ J. Krstic,^{12a} U. Kruchonak,⁶⁴ H. Krüger,²⁰ T. Kruker,¹⁶ Z. V. Krumshteyn,⁶⁴ A. Kruth,²⁰ T. Kubota,⁸⁵ S. Kuehn,⁴⁷ A. Kugel,^{57c} T. Kuhl,⁴¹ D. Kuhn,⁶¹ V. Kukhtin,⁶⁴ Y. Kulchitsky,⁸⁹ S. Kuleshov,^{31b} C. Kummer,⁹⁷ M. Kuna,⁷⁷ N. Kundu,¹¹⁷ J. Kunkle,¹¹⁹ A. Kupco,¹²⁴ H. Kurashige,⁶⁶ M. Kurata,¹⁵⁹ Y. A. Kurochkin,⁸⁹ V. Kus,¹²⁴ M. Kuze,¹⁵⁶

P. Kuzhir,⁹⁰ J. Kvita,²⁹ R. Kwee,¹⁵ A. La Rosa,¹⁷¹ L. La Rotonda,^{36a,36b} L. Labarga,⁷⁹ J. Labbe,⁴ S. Lablak,^{134a}
C. Lacasta,¹⁶⁶ F. Lacava,^{131a,131b} H. Lacker,¹⁵ D. Lacour,⁷⁷ V. R. Lacuesta,¹⁶⁶ E. Ladygin,⁶⁴ R. Lafaye,⁴ B. Laforge,⁷⁷
T. Lagouri,⁷⁹ S. Lai,⁴⁷ E. Laisne,⁵⁴ M. Lamanna,²⁹ C. L. Lampen,⁶ W. Lampl,⁶ E. Lancon,¹³⁵ U. Landgraf,⁴⁷
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S. Laplace,⁷⁷ C. Lapoire,²⁰ J. F. Laporte,¹³⁵ T. Lari,^{88a} A. V. Larionov,¹²⁷ A. Larner,¹¹⁷ C. Lasseur,²⁹ M. Lassnig,²⁹
P. Laurelli,⁴⁶ W. Lavrijsen,¹⁴ P. Laycock,⁷² A. B. Lazarev,⁶⁴ O. Le Dortz,⁷⁷ E. Le Guirriec,⁸² C. Le Maner,¹⁵⁷
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M. Lefebvre,¹⁶⁸ M. Legendre,¹³⁵ A. Leger,⁴⁸ B. C. LeGeyt,¹¹⁹ F. Legger,⁹⁷ C. Leggett,¹⁴ M. Lehmacher,²⁰
G. Lehmann Miotto,²⁹ X. Lei,⁶ M. A. L. Leite,^{23d} R. Leitner,¹²⁵ D. Lellouch,¹⁷⁰ M. Leltchouk,³⁴ B. Lemmer,⁵³
V. Lendermann,^{57a} K. J. C. Leney,^{144b} T. Lenz,¹⁰⁴ G. Lenzen,¹⁷³ B. Lenzi,²⁹ K. Leonhardt,⁴³ S. Leontsinis,⁹
C. Leroy,⁹² J.-R. Lessard,¹⁶⁸ J. Lesser,^{145a} C. G. Lester,²⁷ A. Leung Fook Cheong,¹⁷¹ J. Levêque,⁴ D. Levin,⁸⁶
L. J. Levinson,¹⁷⁰ M. S. Levitski,¹²⁷ M. Lewandowska,²¹ A. Lewis,¹¹⁷ G. H. Lewis,¹⁰⁷ A. M. Leyko,²⁰ M. Leyton,¹⁵
B. Li,⁸² H. Li,¹⁷¹ S. Li,^{32b,d} X. Li,⁸⁶ Z. Liang,³⁹ Z. Liang,^{117,s} H. Liao,³³ B. Liberti,^{132a} P. Lichard,²⁹
M. Lichtnecker,⁹⁷ K. Lie,¹⁶⁴ W. Liebig,¹³ R. Lifshitz,¹⁵¹ J. N. Lilley,¹⁷ C. Limbach,²⁰ A. Limosani,⁸⁵ M. Limper,⁶²
S. C. Lin,^{150,t} F. Linde,¹⁰⁴ J. T. Linnemann,⁸⁷ E. Lipeles,¹¹⁹ L. Lipinsky,¹²⁴ A. Lipniacka,¹³ T. M. Liss,¹⁶⁴
D. Lissauer,²⁴ A. Lister,⁴⁸ A. M. Litke,¹³⁶ C. Liu,²⁸ D. Liu,^{150,u} H. Liu,⁸⁶ J. B. Liu,⁸⁶ M. Liu,^{32b} S. Liu,² Y. Liu,^{32b}
M. Livan,^{118a,118b} S. S. A. Livermore,¹¹⁷ A. Lleres,⁵⁴ J. Llorente Merino,⁷⁹ S. L. Lloyd,⁷⁴ E. Lobodzinska,⁴¹ P. Loch,⁶
W. S. Lockman,¹³⁶ T. Loddenkoetter,²⁰ F. K. Loebinger,⁸¹ A. Loginov,¹⁷⁴ C. W. Loh,¹⁶⁷ T. Lohse,¹⁵ K. Lohwasser,⁴⁷
M. Lokajicek,¹²⁴ J. Loken,¹¹⁷ V. P. Lombardo,⁴ R. E. Long,⁷⁰ L. Lopes,^{123a,c} D. Lopez Mateos,⁵⁶ M. Losada,¹⁶¹
P. Loscutoff,¹⁴ F. Lo Sterzo,^{131a,131b} M. J. Losty,^{158a} X. Lou,⁴⁰ A. Lounis,¹¹⁴ K. F. Loureiro,¹⁶¹ J. Love,²¹
P. A. Love,⁷⁰ A. J. Lowe,^{142,g} F. Lu,^{32a} H. J. Lubatti,¹³⁷ C. Luci,^{131a,131b} A. Lucotte,⁵⁴ A. Ludwig,⁴³ D. Ludwig,⁴¹
I. Ludwig,⁴⁷ J. Ludwig,⁴⁷ F. Luehring,⁶⁰ G. Luijckx,¹⁰⁴ D. Lumb,⁴⁷ L. Luminari,^{131a} E. Lund,¹¹⁶ B. Lund-Jensen,¹⁴⁶
B. Lundberg,⁷⁸ J. Lundberg,^{145a,145b} J. Lundquist,³⁵ M. Lungwitz,⁸⁰ A. Lupi,^{121a,121b} G. Lutz,⁹⁸ D. Lynn,²⁴ J. Lys,¹⁴
E. Lytken,⁷⁸ H. Ma,²⁴ L. L. Ma,¹⁷¹ J. A. Macana Goia,⁹² G. Maccarrone,⁴⁶ A. Macchiolo,⁹⁸ B. Maček,⁷³
J. Machado Miguens,^{123a} R. Mackeprang,³⁵ R. J. Madaras,¹⁴ W. F. Mader,⁴³ R. Maenner,^{57c} T. Maeno,²⁴ P. Mättig,¹⁷³
S. Mättig,⁴¹ L. Magnoni,²⁹ E. Magradze,⁵³ Y. Mahalalel,¹⁵² K. Mahboubi,⁴⁷ G. Mahout,¹⁷ C. Maiani,^{131a,131b}
C. Maidantchik,^{23a} A. Maio,^{123a,c} S. Majewski,²⁴ Y. Makida,⁶⁵ N. Makovec,¹¹⁴ P. Mal,⁶ Pa. Malecki,³⁸ P. Malecki,³⁸
V. P. Maleev,¹²⁰ F. Malek,⁵⁴ U. Mallik,⁶² D. Malon,⁵ C. Malone,¹⁴² S. Maltezos,⁹ V. Malyshev,¹⁰⁶ S. Malyukov,²⁹
R. Mameghani,⁹⁷ J. Mamuzic,^{12b} A. Manabe,⁶⁵ L. Mandelli,^{88a} I. Mandić,⁷³ R. Mandrysch,¹⁵ J. Maneira,^{123a}
P. S. Mangard,⁸⁷ I. D. Manjavidze,⁶⁴ A. Mann,⁵³ P. M. Manning,¹³⁶ A. Manousakis-Katsikakis,⁸ B. Mansoulie,¹³⁵
A. Manz,⁹⁸ A. Mapelli,²⁹ L. Mapelli,²⁹ L. March,⁷⁹ J. F. Marchand,²⁹ F. Marchese,^{132a,132b} G. Marchiori,⁷⁷
M. Marcisovsky,¹²⁴ A. Marin,^{21,a} C. P. Marino,¹⁶⁸ F. Marroquim,^{23a} R. Marshall,⁸¹ Z. Marshall,²⁹ F. K. Martens,¹⁵⁷
S. Marti-Garcia,¹⁶⁶ A. J. Martin,¹⁷⁴ B. Martin,²⁹ B. Martin,⁸⁷ F. F. Martin,¹¹⁹ J. P. Martin,⁹² Ph. Martin,⁵⁴
T. A. Martin,¹⁷ V. J. Martin,⁴⁵ B. Martin dit Latour,⁴⁸ S. Martin-Haugh,¹⁴⁸ M. Martinez,¹¹ V. Martinez Outschoorn,⁵⁶
A. C. Martyniuk,⁸¹ M. Marx,⁸¹ F. Marzano,^{131a} A. Marzin,¹¹⁰ L. Masetti,⁸⁰ T. Mashimo,¹⁵⁴ R. Mashinistov,⁹³
J. Masik,⁸¹ A. L. Maslennikov,¹⁰⁶ I. Massa,^{19a,19b} G. Massaro,¹⁰⁴ N. Massol,⁴ P. Mastrandrea,^{131a,131b}
A. Mastroberardino,^{36a,36b} T. Masubuchi,¹⁵⁴ M. Mathes,²⁰ P. Matricon,¹¹⁴ H. Matsumoto,¹¹⁴ H. Matsunaga,¹⁵⁴
T. Matsushita,⁶⁶ C. Mattraversi,^{117,d} J. M. Maugein,²⁹ S. J. Maxfield,⁷² D. A. Maximov,¹⁰⁶ E. N. May,⁵ A. Mayne,¹³⁸
R. Mazini,¹⁵⁰ M. Mazur,²⁰ M. Mazzanti,^{88a} E. Mazzoni,^{121a,121b} S. P. Mc Kee,⁸⁶ A. McCarn,¹⁶⁴ R. L. McCarthy,¹⁴⁷
T. G. McCarthy,²⁸ N. A. McCubbin,¹²⁸ K. W. McFarlane,⁵⁵ J. A. McFayden,¹³⁸ H. McGlone,⁵² G. Mchedlidze,^{50b}
R. A. McLaren,²⁹ T. McLaughlan,¹⁷ S. J. McMahon,¹²⁸ R. A. McPherson,^{168,k} A. Meade,⁸³ J. Mechnich,¹⁰⁴
M. Mechtel,¹⁷³ M. Medinnis,⁴¹ R. Meera-Lebbai,¹¹⁰ T. Meguro,¹¹⁵ R. Mehdiyev,⁹² S. Mehlhase,³⁵ A. Mehta,⁷²
K. Meier,^{57a} J. Meinhardt,⁴⁷ B. Meirose,⁷⁸ C. Melachrinou,³⁰ B. R. Mellado Garcia,¹⁷¹ L. Mendoza Navas,¹⁶¹
Z. Meng,^{150,u} A. Mengarelli,^{19a,19b} S. Menke,⁹⁸ C. Menot,²⁹ E. Meoni,¹¹ K. M. Mercurio,⁵⁶ P. Mermod,¹¹⁷
L. Merola,^{101a,101b} C. Meroni,^{88a} F. S. Merritt,³⁰ A. Messina,²⁹ J. Metcalfe,¹⁰² A. S. Mete,⁶³ C. Meyer,⁸⁰
J.-P. Meyer,¹³⁵ J. Meyer,¹⁷² J. Meyer,⁵³ T. C. Meyer,²⁹ W. T. Meyer,⁶³ J. Miao,^{32d} S. Michal,²⁹ L. Micu,^{25a}
R. P. Middleton,¹²⁸ P. Miele,²⁹ S. Migas,⁷² L. Mijović,⁴¹ G. Mikenberg,¹⁷⁰ M. Mikesikova,¹²⁴ M. Mikuž,⁷³
D. W. Miller,³⁰ R. J. Miller,⁸⁷ W. J. Mills,¹⁶⁷ C. Mills,⁵⁶ A. Milov,¹⁷⁰ D. A. Milstead,^{145a,145b} D. Milstein,¹⁷⁰
A. A. Minaenko,¹²⁷ M. Miñano,¹⁶⁶ I. A. Minashvili,⁶⁴ A. I. Mincer,¹⁰⁷ B. Mindur,³⁷ M. Mineev,⁶⁴ Y. Ming,¹²⁹
L. M. Mir,¹¹ G. Mirabelli,^{131a} L. Miralles Verge,¹¹ A. Misiejuk,⁷⁵ J. Mitrevski,¹³⁶ G. Y. Mitrofanov,¹²⁷
V. A. Mitsou,¹⁶⁶ S. Mitsui,⁶⁵ P. S. Miyagawa,¹³⁸ K. Miyazaki,⁶⁶ J. U. Mjörnmark,⁷⁸ T. Moa,^{145a,145b} P. Mockett,¹³⁷

S. Moed,⁵⁶ V. Moeller,²⁷ K. Mönig,⁴¹ N. Möser,²⁰ S. Mohapatra,¹⁴⁷ W. Mohr,⁴⁷ S. Mohrdieck-Möck,⁹⁸
A. M. Moisseev,^{127,a} R. Moles-Valls,¹⁶⁶ J. Molina-Perez,²⁹ J. Monk,⁷⁶ E. Monnier,⁸² S. Montesano,^{88a,88b}
F. Monticelli,⁶⁹ S. Monzani,^{19a,19b} R. W. Moore,² G. F. Moorhead,⁸⁵ C. Mora Herrera,⁴⁸ A. Moraes,⁵² N. Morange,¹³⁵
J. Morel,⁵³ G. Morello,^{36a,36b} D. Moreno,⁸⁰ M. Moreno Llácer,¹⁶⁶ P. Morettini,^{49a} M. Morii,⁵⁶ J. Morin,⁷⁴
A. K. Morley,²⁹ G. Mornacchi,²⁹ S. V. Morozov,⁹⁵ J. D. Morris,⁷⁴ L. Morvaj,¹⁰⁰ H. G. Moser,⁹⁸ M. Mosidze,^{50b}
J. Moss,¹⁰⁸ R. Mount,¹⁴² E. Mountricha,¹³⁵ S. V. Mouraviev,⁹³ E. J. W. Moyses,⁸³ M. Mudrinic,^{12b} F. Mueller,^{57a}
J. Mueller,¹²² K. Mueller,²⁰ T. A. Müller,⁹⁷ D. Muenstermann,²⁹ A. Muir,¹⁶⁷ Y. Munwes,¹⁵² W. J. Murray,¹²⁸
I. Mussche,¹⁰⁴ E. Musto,^{101a,101b} A. G. Myagkov,¹²⁷ M. Myska,¹²⁴ J. Nadal,¹¹ K. Nagai,¹⁵⁹ K. Nagano,⁶⁵
Y. Nagasaka,⁵⁹ A. M. Nairz,²⁹ Y. Nakahama,²⁹ K. Nakamura,¹⁵⁴ T. Nakamura,¹⁵⁴ I. Nakano,¹⁰⁹ G. Nanava,²⁰
A. Napier,¹⁶⁰ M. Nash,^{76,d} N. R. Nation,²¹ T. Nattermann,²⁰ T. Naumann,⁴¹ G. Navarro,¹⁶¹ H. A. Neal,⁸⁶ E. Nebot,⁷⁹
P. Yu. Nechaeva,⁹³ A. Negri,^{118a,118b} G. Negri,²⁹ S. Nektarijevic,⁴⁸ A. Nelson,¹⁶² S. Nelson,¹⁴² T. K. Nelson,¹⁴²
S. Nemecek,¹²⁴ P. Nemethy,¹⁰⁷ A. A. Nepomuceno,^{23a} M. Nessi,^{29,v} S. Y. Nesterov,¹²⁰ M. S. Neubauer,¹⁶⁴
A. Neusiedl,⁸⁰ R. M. Neves,¹⁰⁷ P. Nevski,²⁴ P. R. Newman,¹⁷ V. Nguyen Thi Hong,¹³⁵ R. B. Nickerson,¹¹⁷
R. Nicolaidou,¹³⁵ L. Nicolas,¹³⁸ B. Nicquevert,²⁹ F. Niedercorn,¹¹⁴ J. Nielsen,¹³⁶ T. Niinikoski,²⁹ N. Nikiforou,³⁴
A. Nikiforov,¹⁵ V. Nikolaenko,¹²⁷ K. Nikolaev,⁶⁴ I. Nikolic-Audit,⁷⁷ K. Nikolics,⁴⁸ K. Nikolopoulos,²⁴ H. Nilsen,⁴⁷
P. Nilsson,⁷ Y. Ninomiya,¹⁵⁴ A. Nisati,^{131a} T. Nishiyama,⁶⁶ R. Nisius,⁹⁸ L. Nodulman,⁵ M. Nomachi,¹¹⁵
I. Nomidis,¹⁵³ M. Nordberg,²⁹ B. Nordkvist,^{145a,145b} P. R. Norton,¹²⁸ J. Novakova,¹²⁵ M. Nozaki,⁶⁵ L. Nozka,¹¹²
I. M. Nugent,^{158a} A.-E. Nuncio-Quiroz,²⁰ G. Nunes Hanninger,⁸⁵ T. Nunnemann,⁹⁷ E. Nurse,⁷⁶ T. Nyman,²⁹
B. J. O'Brien,⁴⁵ S. W. O'Neale,^{17,a} D. C. O'Neil,¹⁴¹ V. O'Shea,⁵² F. G. Oakham,^{28,f} H. Oberlack,⁹⁸ J. Ocariz,⁷⁷
A. Ochi,⁶⁶ S. Oda,¹⁵⁴ S. Odaka,⁶⁵ J. Odier,⁸² H. Ogren,⁶⁰ A. Oh,⁸¹ S. H. Oh,⁴⁴ C. C. Ohm,^{145a,145b} T. Ohshima,¹⁰⁰
H. Ohshita,¹³⁹ T. Ohsugi,⁵⁸ S. Okada,⁶⁶ H. Okawa,¹⁶² Y. Okumura,¹⁰⁰ T. Okuyama,¹⁵⁴ M. Olcese,^{49a}
A. G. Olchevski,⁶⁴ M. Oliveira,^{123a,i} D. Oliveira Damazio,²⁴ E. Oliver Garcia,¹⁶⁶ D. Olivito,¹¹⁹ A. Olszewski,³⁸
J. Olszowska,³⁸ C. Omachi,⁶⁶ A. Onofre,^{123a,w} P. U. E. Onyisi,³⁰ C. J. Oram,^{158a} M. J. Oreglia,³⁰ Y. Oren,¹⁵²
D. Orestano,^{133a,133b} I. Orlov,¹⁰⁶ C. Oropeza Barrera,⁵² R. S. Orr,¹⁵⁷ B. Osculati,^{49a,49b} R. Ospanov,¹¹⁹ C. Osuna,¹¹
G. Otero y Garzon,²⁶ J. P. Ottersbach,¹⁰⁴ M. Ouchrif,^{134d} F. Ould-Saada,¹¹⁶ A. Ouraou,¹³⁵ Q. Ouyang,^{32a} M. Owen,⁸¹
S. Owen,¹³⁸ V. E. Ozcan,^{18a} N. Ozturk,⁷ A. Pacheco Pages,¹¹ C. Padilla Aranda,¹¹ S. Pagan Griso,¹⁴ E. Paganis,¹³⁸
F. Paige,²⁴ K. Pajchel,¹¹⁶ G. Palacino,^{158b} C. P. Paleari,⁶ S. Palestini,²⁹ D. Pallin,³³ A. Palma,^{123a,c} J. D. Palmer,¹⁷
Y. B. Pan,¹⁷¹ E. Panagiotopoulou,⁹ B. Panes,^{31a} N. Panikashvili,⁸⁶ S. Panitkin,²⁴ D. Pantea,^{25a} M. Panuskova,¹²⁴
V. Paolone,¹²² A. Papadelis,^{145a} Th. D. Papadopoulou,⁹ A. Paramonov,⁵ W. Park,^{24,x} M. A. Parker,²⁷ F. Parodi,^{49a,49b}
J. A. Parsons,³⁴ U. Parzefall,⁴⁷ E. Pasqualucci,^{131a} A. Passeri,^{133a} F. Pastore,^{133a,133b} Fr. Pastore,⁷⁵ G. Pásztor,^{48,y}
S. Patarraia,¹⁷³ N. Patel,¹⁴⁹ J. R. Pater,⁸¹ S. Patricelli,^{101a,101b} T. Pauly,²⁹ M. Pecsý,^{143a} M. I. Pedraza Morales,¹⁷¹
S. V. Peleganchuk,¹⁰⁶ H. Peng,^{32b} R. Pengo,²⁹ A. Penson,³⁴ J. Penwell,⁶⁰ M. Perantoni,^{23a} K. Perez,^{34,z}
T. Perez Cavalcanti,⁴¹ E. Perez Codina,¹¹ M. T. Pérez García-Estañ,¹⁶⁶ V. Perez Reale,³⁴ L. Perini,^{88a,88b}
H. Pernegger,²⁹ R. Perrino,^{71a} P. Perrodo,⁴ S. Perseme,^{3a} V. D. Peshekhonov,⁶⁴ B. A. Petersen,²⁹ J. Petersen,²⁹
T. C. Petersen,³⁵ E. Petit,⁸² A. Petridis,¹⁵³ C. Petridou,¹⁵³ E. Petrolo,^{131a} F. Petrucci,^{133a,133b} D. Petschall,⁴¹
M. Petteni,¹⁴¹ R. Pezoa,^{31b} A. Phan,⁸⁵ A. W. Phillips,²⁷ P. W. Phillips,¹²⁸ G. Piacquadio,²⁹ E. Piccaro,⁷⁴
M. Piccinini,^{19a,19b} A. Pickford,⁵² S. M. Piec,⁴¹ R. Piegai,²⁶ J. E. Pilcher,³⁰ A. D. Pilkington,⁸¹ J. Pina,^{123a,c}
M. Pinamonti,^{163a,163c} A. Pinder,¹¹⁷ J. L. Pinfold,² J. Ping,^{32c} B. Pinto,^{123a,c} O. Pirote,²⁹ C. Pizio,^{88a,88b}
R. Placakyte,⁴¹ M. Plamondon,¹⁶⁸ M.-A. Pleier,²⁴ A. V. Pleskach,¹²⁷ A. Poblaguev,²⁴ S. Poddar,^{57a} F. Podlyski,³³
L. Poggioli,¹¹⁴ T. Poghosyan,²⁰ M. Pohl,⁴⁸ F. Polci,⁵⁴ G. Polesello,^{118a} A. Policicchio,¹³⁷ A. Polini,^{19a} J. Poll,⁷⁴
V. Polychronakos,²⁴ D. M. Pomarede,¹³⁵ D. Pomeroy,²² K. Pommès,²⁹ L. Pontecorvo,^{131a} B. G. Pope,⁸⁷
G. A. Popeneciu,^{25a} D. S. Popovic,^{12a} A. Poppleton,²⁹ X. Portell Bueso,²⁹ C. Posch,²¹ G. E. Pospelov,⁹⁸ S. Pospisil,¹²⁶
I. N. Potrap,⁹⁸ C. J. Potter,¹⁴⁸ C. T. Potter,¹¹³ G. Poulard,²⁹ J. Poveda,¹⁷¹ R. Prabhu,⁷⁶ P. Pralavorio,⁸² S. Prasad,⁵⁶
R. Pravahan,⁷ S. Prell,⁶³ K. Pretzl,¹⁶ L. Pribyl,²⁹ D. Price,⁶⁰ L. E. Price,⁵ M. J. Price,²⁹ P. M. Prichard,⁷² D. Prieur,¹²²
M. Primavera,^{71a} K. Prokofiev,¹⁰⁷ F. Prokoshin,^{31b} S. Protopopescu,²⁴ J. Proudfoot,⁵ X. Prudent,⁴³ H. Przysieznik,⁴
S. Psoroulas,²⁰ E. Ptacek,¹¹³ E. Pueschel,⁸³ J. Purdham,⁸⁶ M. Purohit,^{24,x} P. Puzo,¹¹⁴ Y. Pylypchenko,¹¹⁶ J. Qian,⁸⁶
Z. Qian,⁸² Z. Qin,⁴¹ A. Quadt,⁵³ D. R. Quarrie,¹⁴ W. B. Quayle,¹⁷¹ F. Quinonez,^{31a} M. Raas,¹⁰³ V. Radescu,^{57b}
B. Radics,²⁰ T. Rador,^{18a} F. Ragusa,^{88a,88b} G. Rahal,¹⁷⁶ A. M. Rahimi,¹⁰⁸ D. Rahm,²⁴ S. Rajagopalan,²⁴
M. Rammensee,⁴⁷ M. Rammes,¹⁴⁰ M. Ramstedt,^{145a,145b} A. S. Randle-Conde,³⁹ K. Randrianarivony,²⁸ P. N. Ratoff,⁷⁰
F. Rauscher,⁹⁷ E. Rauter,⁹⁸ M. Raymond,²⁹ A. L. Read,¹¹⁶ D. M. Rebuffi,^{118a,118b} A. Redelbach,¹⁷² G. Redlinger,²⁴
R. Reece,¹¹⁹ K. Reeves,⁴⁰ A. Reichold,¹⁰⁴ E. Reinherz-Aronis,¹⁵² A. Reinsch,¹¹³ I. Reisinger,⁴² D. Reljic,^{12a}

C. Rembser,²⁹ Z. L. Ren,¹⁵⁰ A. Renaud,¹¹⁴ P. Renkel,³⁹ M. Rescigno,^{131a} S. Resconi,^{88a} B. Resende,¹³⁵ P. Reznicek,⁹⁷
R. Rezvani,¹⁵⁷ A. Richards,⁷⁶ R. Richter,⁹⁸ E. Richter-Was,^{4,aa} M. Ridel,⁷⁷ S. Rieke,⁸⁰ M. Rijpstra,¹⁰⁴
M. Rijssenbeek,¹⁴⁷ A. Rimoldi,^{118a,118b} L. Rinaldi,^{19a} R. R. Rios,³⁹ I. Riu,¹¹ G. Rivoltella,^{88a,88b} F. Rizatdinova,¹¹¹
E. Rizvi,⁷⁴ S. H. Robertson,^{84,k} A. Robichaud-Veronneau,¹¹⁷ D. Robinson,²⁷ J. E. M. Robinson,⁷⁶ M. Robinson,¹¹³
A. Robson,⁵² J. G. Rocha de Lima,¹⁰⁵ C. Roda,^{121a,121b} D. Roda Dos Santos,²⁹ S. Rodier,⁷⁹ D. Rodriguez,¹⁶¹
A. Roe,⁵³ S. Roe,²⁹ O. Røhne,¹¹⁶ V. Rojo,¹ S. Rolli,¹⁶⁰ A. Romaniouk,⁹⁵ M. Romano,^{19a,19b} V. M. Romanov,⁶⁴
G. Romeo,²⁶ L. Roos,⁷⁷ E. Ros,¹⁶⁶ S. Rosati,^{131a,131b} K. Rosbach,⁴⁸ A. Rose,¹⁴⁸ M. Rose,⁷⁵ G. A. Rosenbaum,¹⁵⁷
E. I. Rosenberg,⁶³ P. L. Rosendahl,¹³ O. Rosenthal,¹⁴⁰ L. Rosselet,⁴⁸ V. Rossetti,¹¹ E. Rossi,^{131a,131b} L. P. Rossi,^{49a}
L. Rossi,^{88a,88b} M. Rotaru,^{25a} I. Roth,¹⁷⁰ J. Rothberg,¹³⁷ D. Rousseau,¹¹⁴ C. R. Royon,¹³⁵ A. Rozanov,⁸² Y. Rozen,¹⁵¹
X. Ruan,¹¹⁴ I. Rubinskiy,⁴¹ B. Ruckert,⁹⁷ N. Ruckstuhl,¹⁰⁴ V. I. Rud,⁹⁶ C. Rudolph,⁴³ G. Rudolph,⁶¹ F. Rühr,⁶
F. Ruggieri,^{133a,133b} A. Ruiz-Martinez,⁶³ E. Rulikowska-Zarebska,³⁷ V. Rumiantsev,^{90,a} L. Rummyantsev,⁶⁴
K. Runge,⁴⁷ O. Runolfsson,²⁰ Z. Rurikova,⁴⁷ N. A. Rusakovich,⁶⁴ D. R. Rust,⁶⁰ J. P. Rutherford,⁶ C. Ruwiedel,¹⁴
P. Ruzicka,¹²⁴ Y. F. Ryabov,¹²⁰ V. Ryadovikov,¹²⁷ P. Ryan,⁸⁷ M. Rybar,¹²⁵ G. Rybkin,¹¹⁴ N. C. Ryder,¹¹⁷ S. Rzaeva,¹⁰
A. F. Saavedra,¹⁴⁹ I. Sadeh,¹⁵² H. F. W. Sadrozinski,¹³⁶ R. Sadykov,⁶⁴ F. Safai Tehrani,^{131a,131b} H. Sakamoto,¹⁵⁴
G. Salamanna,⁷⁴ A. Salamon,^{132a} M. Saleem,¹¹⁰ D. Salihagic,⁹⁸ A. Salmikov,¹⁴² J. Salt,¹⁶⁶
B. M. Salvachua Ferrando,⁵ D. Salvatore,^{36a,36b} F. Salvatore,¹⁴⁸ A. Salvucci,¹⁰³ A. Salzburger,²⁹ D. Sampsonidis,¹⁵³
B. H. Samset,¹¹⁶ A. Sanchez,^{101a,101b} H. Sandaker,¹³ H. G. Sander,⁸⁰ M. P. Sanders,⁹⁷ M. Sandhoff,¹⁷³ T. Sandoval,²⁷
C. Sandoval,¹⁶¹ R. Sandstroem,⁹⁸ S. Sandvoss,¹⁷³ D. P. C. Sankey,¹²⁸ A. Sansoni,⁴⁶ C. Santamarina Rios,⁸⁴
C. Santoni,³³ R. Santonico,^{132a,132b} H. Santos,^{123a} J. G. Saraiva,^{123a,c} T. Sarangi,¹⁷¹ E. Sarkisyan-Grinbaum,⁷
F. Sarri,^{121a,121b} G. Sartisohn,¹⁷³ O. Sasaki,⁶⁵ T. Sasaki,⁶⁵ N. Sasao,⁶⁷ I. Satsounkevitch,⁸⁹ G. Sauvage,⁴ E. Sauvan,⁴
J. B. Sauvan,¹¹⁴ P. Savard,^{157,f} V. Savinov,¹²² D. O. Savu,²⁹ P. Savva,⁹ L. Sawyer,^{24,m} D. H. Saxon,⁵² L. P. Says,³³
C. Sbarra,^{19a,19b} A. Sbrizzi,^{19a,19b} O. Scallon,⁹² D. A. Scannicchio,¹⁶² J. Schaarschmidt,¹¹⁴ P. Schacht,⁹⁸
U. Schäfer,⁸⁰ S. Schaepe,²⁰ S. Schaezel,^{57b} A. C. Schaffer,¹¹⁴ D. Schaile,⁹⁷ R. D. Schamberger,¹⁴⁷ A. G. Schamov,¹⁰⁶
V. Scharf,^{57a} V. A. Schegelsky,¹²⁰ D. Scheirich,⁸⁶ M. Schernau,¹⁶² M. I. Scherzer,¹⁴ C. Schiavi,^{49a,49b} J. Schieck,⁹⁷
M. Schioppa,^{36a,36b} S. Schlenker,²⁹ J. L. Schlereth,⁵ E. Schmidt,⁴⁷ K. Schmieden,²⁰ C. Schmitt,⁸⁰ S. Schmitt,^{57b}
M. Schmitz,²⁰ A. Schöning,^{57b} M. Schott,²⁹ D. Schouten,^{158a} J. Schovancova,¹²⁴ M. Schram,⁸⁴ C. Schroeder,⁸⁰
N. Schroer,^{57c} S. Schuh,²⁹ G. Schuler,²⁹ J. Schultes,¹⁷³ H.-C. Schultz-Coulon,^{57a} H. Schulz,¹⁵ J. W. Schumacher,²⁰
M. Schumacher,⁴⁷ B. A. Schumm,¹³⁶ Ph. Schune,¹³⁵ C. Schwanenberger,⁸¹ A. Schwartzman,¹⁴² Ph. Schwemling,⁷⁷
R. Schwienhorst,⁸⁷ R. Schwierz,⁴³ J. Schwindling,¹³⁵ T. Schwindt,²⁰ W. G. Scott,¹²⁸ J. Searcy,¹¹³ G. Sedov,⁴¹
E. Sedykh,¹²⁰ E. Segura,¹¹ S. C. Seidel,¹⁰² A. Seiden,¹³⁶ F. Seifert,⁴³ J. M. Seixas,^{23a} G. Sekhniadze,^{101a}
D. M. Seliverstov,¹²⁰ B. Sellden,^{145a} G. Sellers,⁷² M. Seman,^{143b} N. Semprini-Cesari,^{19a,19b} C. Serfon,⁹⁷ L. Serin,¹¹⁴
R. Seuster,⁹⁸ H. Severini,¹¹⁰ M. E. Sevir,⁸⁵ A. Sfyrla,²⁹ E. Shabalina,⁵³ M. Shamim,¹¹³ L. Y. Shan,^{32a} J. T. Shank,²¹
Q. T. Shao,⁸⁵ M. Shapiro,¹⁴ P. B. Shatalov,⁹⁴ L. Shaver,⁶ K. Shaw,^{163a,163c} D. Sherman,¹⁷⁴ P. Sherwood,⁷⁶
A. Shibata,¹⁰⁷ H. Shichi,¹⁰⁰ S. Shimizu,²⁹ M. Shimojima,⁹⁹ T. Shin,⁵⁵ A. Shmeleva,⁹³ M. J. Shochet,³⁰ D. Short,¹¹⁷
M. A. Shupe,⁶ P. Sicho,¹²⁴ A. Sidoti,^{131a,131b} A. Siebel,¹⁷³ F. Siegert,⁴⁷ J. Siegrist,¹⁴ Dj. Sijacki,^{12a} O. Silbert,¹⁷⁰
J. Silva,^{123a,c} Y. Silver,¹⁵² D. Silverstein,¹⁴² S. B. Silverstein,^{145a} V. Simak,¹²⁶ O. Simard,¹³⁵ Lj. Simic,^{12a}
S. Simion,¹¹⁴ B. Simmons,⁷⁶ M. Simonyan,³⁵ P. Sinervo,¹⁵⁷ N. B. Sinev,¹¹³ V. Sipica,¹⁴⁰ G. Siragusa,¹⁷² A. Sircar,²⁴
A. N. Sisakyan,⁶⁴ S. Yu. Sivoklov,⁹⁶ J. Sjölin,^{145a,145b} T. B. Sjusren,¹³ L. A. Skinnari,¹⁴ H. P. Skottowe,⁵⁶
K. Skovpen,¹⁰⁶ P. Skubic,¹¹⁰ N. Skvorodnev,²² M. Slater,¹⁷ T. Slavicek,¹²⁶ K. Sliwa,¹⁶⁰ J. Sloper,²⁹ V. Smakhtin,¹⁷⁰
S. Yu. Smirnov,⁹⁵ L. N. Smirnova,⁹⁶ O. Smirnova,⁷⁸ B. C. Smith,⁵⁶ D. Smith,¹⁴² K. M. Smith,⁵² M. Smizanska,⁷⁰
K. Smolek,¹²⁶ A. A. Snesarev,⁹³ S. W. Snow,⁸¹ J. Snow,¹¹⁰ J. Snuverink,¹⁰⁴ S. Snyder,²⁴ M. Soares,^{123a} R. Sobie,^{168,k}
J. Sodomka,¹²⁶ A. Soffer,¹⁵² C. A. Solans,¹⁶⁶ M. Solar,¹²⁶ J. Solc,¹²⁶ E. Soldatov,⁹⁵ U. Soldevila,¹⁶⁶
E. Solfaroli Camillocci,^{131a,131b} A. A. Solodkov,¹²⁷ O. V. Solovyanov,¹²⁷ J. Sondericker,²⁴ N. Soni,² V. Sopko,¹²⁶
B. Sopko,¹²⁶ M. Sorbi,^{88a,88b} M. Sosebee,⁷ R. Soualah,^{163a,163c} A. Soukharev,¹⁰⁶ S. Spagnolo,^{71a,71b} F. Spanò,⁷⁵
R. Spighi,^{19a} G. Spigo,²⁹ F. Spila,^{131a,131b} E. Spiriti,^{133a} R. Spiwoks,²⁹ M. Spousta,¹²⁵ T. Spreitzer,¹⁵⁷ B. Spurlock,⁷
R. D. St. Denis,⁵² T. Stahl,¹⁴⁰ J. Stahlman,¹¹⁹ R. Stamen,^{57a} E. Stanecka,²⁹ R. W. Stanek,⁵ C. Stanescu,^{133a}
S. Stapnes,¹¹⁶ E. A. Starchenko,¹²⁷ J. Stark,⁵⁴ P. Staroba,¹²⁴ P. Starovoitov,⁹⁰ A. Staude,⁹⁷ P. Stavina,^{143a}
G. Stavropoulos,¹⁴ G. Steele,⁵² P. Steinbach,⁴³ P. Steinberg,²⁴ I. Stekl,¹²⁶ B. Stelzer,¹⁴¹ H. J. Stelzer,⁸⁷
O. Stelzer-Chilton,^{158a} H. Stenzel,⁵¹ K. Stevenson,⁷⁴ G. A. Stewart,²⁹ J. A. Stillings,²⁰ T. Stockmanns,²⁰
M. C. Stockton,²⁹ K. Stoerig,⁴⁷ G. Stoicea,^{25a} S. Stonjek,⁹⁸ P. Strachota,¹²⁵ A. R. Stradling,⁷ A. Straessner,⁴³
J. Strandberg,¹⁴⁶ S. Strandberg,^{145a,145b} A. Strandlie,¹¹⁶ M. Strang,¹⁰⁸ E. Strauss,¹⁴² M. Strauss,¹¹⁰ P. Strizenec,^{143b}

R. Ströhmer,¹⁷² D. M. Strom,¹¹³ J. A. Strong,^{75,a} R. Stroynowski,³⁹ J. Strube,¹²⁸ B. Stugu,¹³ I. Stumer,^{24,a} J. Stupak,¹⁴⁷ P. Sturm,¹⁷³ D. A. Soh,^{150,s} D. Su,¹⁴² HS. Subramania,² A. Succurro,¹¹ Y. Sugaya,¹¹⁵ T. Sugimoto,¹⁰⁰ C. Suhr,¹⁰⁵ K. Suita,⁶⁶ M. Suk,¹²⁵ V. V. Sulín,⁹³ S. Sultansoy,^{3d} T. Sumida,²⁹ X. Sun,⁵⁴ J. E. Sundermann,⁴⁷ K. Suruliz,¹³⁸ S. Sushkov,¹¹ G. Susinno,^{36a,36b} M. R. Sutton,¹⁴⁸ Y. Suzuki,⁶⁵ Y. Suzuki,⁶⁶ M. Svatos,¹²⁴ Yu. M. Sviridov,¹²⁷ S. Swedish,¹⁶⁷ I. Sykora,^{143a} T. Sykora,¹²⁵ B. Szeless,²⁹ J. Sánchez,¹⁶⁶ D. Ta,¹⁰⁴ K. Tackmann,⁴¹ A. Taffard,¹⁶² R. Tafirout,^{158a} N. Taiblum,¹⁵² Y. Takahashi,¹⁰⁰ H. Takai,²⁴ R. Takashima,⁶⁸ H. Takeda,⁶⁶ T. Takeshita,¹³⁹ M. Talby,⁸² A. Talyshev,¹⁰⁶ M. C. Tamsett,²⁴ J. Tanaka,¹⁵⁴ R. Tanaka,¹¹⁴ S. Tanaka,¹³⁰ S. Tanaka,⁶⁵ Y. Tanaka,⁹⁹ K. Tani,⁶⁶ N. Tannoury,⁸² G. P. Tappern,²⁹ S. Tapprogge,⁸⁰ D. Tardif,¹⁵⁷ S. Tarem,¹⁵¹ F. Tarrade,²⁸ G. F. Tartarelli,^{88a} P. Tas,¹²⁵ M. Tasevsky,¹²⁴ E. Tassi,^{36a,36b} M. Tatarkhanov,¹⁴ Y. Tayalati,^{134d} C. Taylor,⁷⁶ F. E. Taylor,⁹¹ G. N. Taylor,⁸⁵ W. Taylor,^{158b} M. Teinturier,¹¹⁴ M. Teixeira Dias Castanheira,⁷⁴ P. Teixeira-Dias,⁷⁵ K. K. Temming,⁴⁷ H. Ten Kate,²⁹ P. K. Teng,¹⁵⁰ S. Terada,⁶⁵ K. Terashi,¹⁵⁴ J. Terron,⁷⁹ M. Terwort,^{41,q} M. Testa,⁴⁶ R. J. Teuscher,^{157,k} J. Thadome,¹⁷³ J. Therhaag,²⁰ T. Thevenaux-Pelzer,⁷⁷ M. Thioye,¹⁷⁴ S. Thoma,⁴⁷ J. P. Thomas,¹⁷ E. N. Thompson,⁸³ P. D. Thompson,¹⁷ P. D. Thompson,¹⁵⁷ A. S. Thompson,⁵² E. Thomson,¹¹⁹ M. Thomson,²⁷ R. P. Thun,⁸⁶ F. Tian,³⁴ T. Tic,¹²⁴ V. O. Tikhomirov,⁹³ Y. A. Tikhonov,¹⁰⁶ C. J. W. P. Timmermans,¹⁰³ P. Tipton,¹⁷⁴ F. J. Tique Aires Viegas,²⁹ S. Tisserant,⁸² J. Tobias,⁴⁷ B. Toczek,³⁷ T. Todorov,⁴ S. Todorova-Nova,¹⁶⁰ B. Toggerson,¹⁶² J. Tojo,⁶⁵ S. Tokár,^{143a} K. Tokunaga,⁶⁶ K. Tokushuku,⁶⁵ K. Tollefson,⁸⁷ M. Tomoto,¹⁰⁰ L. Tompkins,¹⁴ K. Toms,¹⁰² G. Tong,^{32a} A. Tonoyan,¹³ C. Topfel,¹⁶ N. D. Topilin,⁶⁴ I. Torchiani,²⁹ E. Torrence,¹¹³ H. Torres,⁷⁷ E. Torró Pastor,¹⁶⁶ J. Toth,^{82,y} F. Touchard,⁸² D. R. Tovey,¹³⁸ D. Traynor,⁷⁴ T. Trefzger,¹⁷² L. Tremblet,²⁹ A. Tricoli,²⁹ I. M. Trigger,^{158a} S. Trincaz-Duvoid,⁷⁷ T. N. Trinh,⁷⁷ M. F. Tripiana,⁶⁹ W. Trischuk,¹⁵⁷ A. Trivedi,^{24,x} B. Trocmé,⁵⁴ C. Troncon,^{88a} M. Trotter-McDonald,¹⁴¹ A. Trzupek,³⁸ C. Tsarouchas,²⁹ J. C.-L. Tseng,¹¹⁷ M. Tsiakiris,¹⁰⁴ P. V. Tsiareshka,⁸⁹ D. Tsionou,⁴ G. Tsipolitis,⁹ V. Tsiskaridze,⁴⁷ E. G. Tskhadadze,^{50a} I. I. Tsukerman,⁹⁴ V. Tsulaia,¹⁴ J.-W. Tsung,²⁰ S. Tsuno,⁶⁵ D. Tsybychev,¹⁴⁷ A. Tua,¹³⁸ A. Tudorache,^{25a} V. Tudorache,^{25a} J. M. Tuggle,³⁰ M. Turala,³⁸ D. Turecek,¹²⁶ I. Turk Cakir,^{3e} E. Turlay,¹⁰⁴ R. Turra,^{88a,88b} P. M. Tuts,³⁴ A. Tykhonov,⁷³ M. Tylmad,^{145a,145b} M. Tyndel,¹²⁸ H. Tyrvaäinen,²⁹ G. Tzanakos,⁸ K. Uchida,²⁰ I. Ueda,¹⁵⁴ R. Ueno,²⁸ M. Ugland,¹³ M. Uhlenbrock,²⁰ M. Uhrmacher,⁵³ F. Ukegawa,¹⁵⁹ G. Unal,²⁹ D. G. Underwood,⁵ A. Undrus,²⁴ G. Unel,¹⁶² Y. Unno,⁶⁵ D. Urbaniec,³⁴ E. Urkovsky,¹⁵² P. Urrejola,^{31a} G. Usai,⁷ M. Uslenghi,^{118a,118b} L. Vacavant,⁸² V. Vacek,¹²⁶ B. Vachon,⁸⁴ S. Vahsen,¹⁴ J. Valenta,¹²⁴ P. Valente,^{131a} S. Valentinetti,^{19a,19b} S. Valkar,¹²⁵ E. Valladolid Gallego,¹⁶⁶ S. Vallecorsa,¹⁵¹ J. A. Valls Ferrer,¹⁶⁶ H. van der Graaf,¹⁰⁴ E. van der Kraaij,¹⁰⁴ R. Van Der Leeuw,¹⁰⁴ E. van der Poel,¹⁰⁴ D. van der Ster,²⁹ N. van Eldik,⁸³ P. van Gemmeren,⁵ Z. van Kesteren,¹⁰⁴ I. van Vulpen,¹⁰⁴ W. Vandelli,²⁹ G. Vandoni,²⁹ A. Vaniachine,⁵ P. Vankov,⁴¹ F. Vannucci,⁷⁷ F. Varela Rodriguez,²⁹ R. Vari,^{131a} D. Varouchas,¹⁴ A. Vartapetian,⁷ K. E. Varvell,¹⁴⁹ V. I. Vassilakopoulos,⁵⁵ F. Vazeille,³³ G. Vegni,^{88a,88b} J. J. Veillet,¹¹⁴ C. Vellidis,⁸ F. Veloso,^{123a} R. Veness,²⁹ S. Veneziano,^{131a} A. Ventura,^{71a,71b} D. Ventura,¹³⁷ M. Venturi,⁴⁷ N. Venturi,¹⁶ V. Vercesi,^{118a} M. Verducci,¹³⁷ W. Verkerke,¹⁰⁴ J. C. Vermeulen,¹⁰⁴ A. Vest,⁴³ M. C. Vetterli,^{141,f} I. Vichou,¹⁶⁴ T. Vickey,^{144b,bb} O. E. Vickey Boeriu,^{144b} G. H. A. Viehhauser,¹¹⁷ S. Viel,¹⁶⁷ M. Villa,^{19a,19b} M. Villaplana Perez,¹⁶⁶ E. Vilucchi,⁴⁶ M. G. Vincker,²⁸ E. Vinek,²⁹ V. B. Vinogradov,⁶⁴ M. Virchaux,^{135,a} J. Virzi,¹⁴ O. Vitells,¹⁷⁰ M. Viti,⁴¹ I. Vivarelli,⁴⁷ F. Vives Vaque,² S. Vlachos,⁹ D. Vladoiu,⁹⁷ M. Vlasak,¹²⁶ N. Vlasov,²⁰ A. Vogel,²⁰ P. Vokac,¹²⁶ G. Volpi,⁴⁶ M. Volpi,⁸⁵ G. Volpini,^{88a} H. von der Schmitt,⁹⁸ J. von Loeben,⁹⁸ H. von Radziewski,⁴⁷ E. von Toerne,²⁰ V. Vorobel,¹²⁵ A. P. Vorobiev,¹²⁷ V. Vorwerk,¹¹ M. Vos,¹⁶⁶ R. Voss,²⁹ T. T. Voss,¹⁷³ J. H. Vosseveld,⁷² N. Vranjes,^{12a} M. Vranjes Milosavljevic,¹⁰⁴ V. Vrba,¹²⁴ M. Vreeswijk,¹⁰⁴ T. Vu Anh,⁸⁰ R. Vuillemet,²⁹ I. Vukotic,¹¹⁴ W. Wagner,¹⁷³ P. Wagner,¹¹⁹ H. Wahlen,¹⁷³ J. Wakabayashi,¹⁰⁰ J. Walbersloh,⁴² S. Walch,⁸⁶ J. Walder,⁷⁰ R. Walker,⁹⁷ W. Walkowiak,¹⁴⁰ R. Wall,¹⁷⁴ P. Waller,⁷² C. Wang,⁴⁴ H. Wang,¹⁷¹ H. Wang,^{32b,cc} J. Wang,¹⁵⁰ J. Wang,^{32d} J. C. Wang,¹³⁷ R. Wang,¹⁰² S. M. Wang,¹⁵⁰ A. Warburton,⁸⁴ C. P. Ward,²⁷ M. Warsinsky,⁴⁷ P. M. Watkins,¹⁷ A. T. Watson,¹⁷ M. F. Watson,¹⁷ G. Watts,¹³⁷ S. Watts,⁸¹ A. T. Waugh,¹⁴⁹ B. M. Waugh,⁷⁶ J. Weber,⁴² M. Weber,¹²⁸ M. S. Weber,¹⁶ P. Weber,⁵³ A. R. Weidberg,¹¹⁷ P. Weigell,⁹⁸ J. Weingarten,⁵³ C. Weiser,⁴⁷ H. Wellenstein,²² P. S. Wells,²⁹ M. Wen,⁴⁶ T. Wenaus,²⁴ S. Wendler,¹²² Z. Weng,^{150,s} T. Wengler,²⁹ S. Wenig,²⁹ N. Wermes,²⁰ M. Werner,⁴⁷ P. Werner,²⁹ M. Werth,¹⁶² M. Wessels,^{57a} C. Weydert,⁵⁴ K. Whalen,²⁸ S. J. Wheeler-Ellis,¹⁶² S. P. Whitaker,²¹ A. White,⁷ M. J. White,⁸⁵ S. R. Whitehead,¹¹⁷ D. Whiteson,¹⁶² D. Whittington,⁶⁰ F. Wicke,¹¹⁴ D. Wicke,¹⁷³ F. J. Wickens,¹²⁸ W. Wiedenmann,¹⁷¹ M. Wielers,¹²⁸ P. Wienemann,²⁰ C. Wiglesworth,⁷⁴ L. A. M. Wiik,⁴⁷ P. A. Wijeratne,⁷⁶ A. Wildauer,¹⁶⁶ M. A. Wildt,^{41,q} I. Wilhelm,¹²⁵ H. G. Wilkens,²⁹ J. Z. Will,⁹⁷ E. Williams,³⁴ H. H. Williams,¹¹⁹ W. Willis,³⁴ S. Willocq,⁸³ J. A. Wilson,¹⁷ M. G. Wilson,¹⁴² A. Wilson,⁸⁶

I. Wingerter-Seez,⁴ S. Winkelmann,⁴⁷ F. Winklmeier,²⁹ M. Wittgen,¹⁴² M. W. Wolter,³⁸ H. Wolters,^{123a,i} W. C. Wong,⁴⁰ G. Wooden,⁸⁶ B. K. Wosiek,³⁸ J. Wotschack,²⁹ M. J. Woudstra,⁸³ K. Wraight,⁵² C. Wright,⁵² M. Wright,⁵² B. Wrona,⁷² S. L. Wu,¹⁷¹ X. Wu,⁴⁸ Y. Wu,^{32b,dd} E. Wulf,³⁴ R. Wunstorf,⁴² B. M. Wynne,⁴⁵ L. Xaplanteris,⁹ S. Xella,³⁵ S. Xie,⁴⁷ Y. Xie,^{32a} C. Xu,^{32b,ee} D. Xu,¹³⁸ G. Xu,^{32a} B. Yabsley,¹⁴⁹ S. Yacoob,^{144b} M. Yamada,⁶⁵ H. Yamaguchi,¹⁵⁴ A. Yamamoto,⁶⁵ K. Yamamoto,⁶³ S. Yamamoto,¹⁵⁴ T. Yamamura,¹⁵⁴ T. Yamanaka,¹⁵⁴ J. Yamaoka,⁴⁴ T. Yamazaki,¹⁵⁴ Y. Yamazaki,⁶⁶ Z. Yan,²¹ H. Yang,⁸⁶ U. K. Yang,⁸¹ Y. Yang,⁶⁰ Y. Yang,^{32a} Z. Yang,^{145a,145b} S. Yanush,⁹⁰ Y. Yao,¹⁴ Y. Yasu,⁶⁵ G. V. Ybeles Smit,¹²⁹ J. Ye,³⁹ S. Ye,²⁴ M. Yilmaz,^{3c} R. Yoosoofmiya,¹²² K. Yorita,¹⁶⁹ R. Yoshida,⁵ C. Young,¹⁴² S. Youssef,²¹ D. Yu,²⁴ J. Yu,⁷ J. Yu,¹¹¹ L. Yuan,^{32a,ff} A. Yurkewicz,¹⁴⁷ V. G. Zaets,¹²⁷ R. Zaidan,⁶² A. M. Zaitsev,¹²⁷ Z. Zajacova,²⁹ Yo. K. Zalite,¹²⁰ L. Zanello,^{131a,131b} P. Zarzhitsky,³⁹ A. Zaytsev,¹⁰⁶ C. Zeitnitz,¹⁷³ M. Zeller,¹⁷⁴ M. Zeman,¹²⁴ A. Zemla,³⁸ C. Zender,²⁰ O. Zenin,¹²⁷ T. Ženiš,^{143a} Z. Zenonos,^{121a,121b} S. Zenz,¹⁴ D. Zerwas,¹¹⁴ G. Zevi della Porta,⁵⁶ Z. Zhan,^{32d} D. Zhang,^{32b,cc} H. Zhang,⁸⁷ J. Zhang,⁵ X. Zhang,^{32d} Z. Zhang,¹¹⁴ L. Zhao,¹⁰⁷ T. Zhao,¹³⁷ Z. Zhao,^{32b} A. Zhemchugov,⁶⁴ S. Zheng,^{32a} J. Zhong,^{150,gg} B. Zhou,⁸⁶ N. Zhou,¹⁶² Y. Zhou,¹⁵⁰ C. G. Zhu,^{32d} H. Zhu,⁴¹ J. Zhu,⁸⁶ Y. Zhu,^{32b} X. Zhuang,⁹⁷ V. Zhuravlov,⁹⁸ D. Zieminska,⁶⁰ R. Zimmermann,²⁰ S. Zimmermann,²⁰ S. Zimmermann,⁴⁷ M. Ziolkowski,¹⁴⁰ R. Zitoun,⁴ L. Živković,³⁴ V. V. Zmouchko,^{127,a} G. Zobernig,¹⁷¹ A. Zoccoli,^{19a,19b} Y. Zolnierowski,⁴ A. Zsenei,²⁹ M. zur Nedden,¹⁵ V. Zutshi,¹⁰⁵ and L. Zwalinski²⁹

(ATLAS Collaboration)

¹University at Albany, Albany, New York, USA

²Department 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, Turkey

⁴LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁵High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA

⁶Department of Physics, University of Arizona, Tucson, Arizona, USA

⁷Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA

⁸Physics 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, 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, 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 Fisica, 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}High Energy Physics Group, 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
- ³⁷Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, 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, Genova, Italy
^{49b}Dipartimento di Fisica, Università di Genova, Genova, Italy
- ^{50a}E. Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia
^{50b}High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
⁵¹II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵²SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
⁵³II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁴Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
⁵⁵Department of Physics, Hampton University, Hampton, Virginia, USA
- ⁵⁶Laboratory 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
⁵⁸Faculty of Science, Hiroshima University, Hiroshima, Japan
- ⁵⁹Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
⁶⁰Department of Physics, Indiana University, Bloomington, Indiana, USA
- ⁶¹Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
⁶²University of Iowa, Iowa City, Iowa, USA
- ⁶³Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
⁶⁴Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
⁶⁶Graduate School of Science, Kobe University, Kobe, Japan
⁶⁷Faculty of Science, Kyoto University, Kyoto, Japan
⁶⁸Kyoto University of Education, Kyoto, Japan
- ⁶⁹Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
⁷⁰Physics Department, Lancaster University, Lancaster, United Kingdom
^{71a}INFN Sezione di Lecce, Lecce, Italy
^{71b}Dipartimento di Fisica, Università del Salento, Lecce, Italy
- ⁷²Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

- ⁷³*Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
- ⁷⁴*Department of Physics, Queen Mary University of London, London, United Kingdom*
- ⁷⁵*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
- ⁷⁶*Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁷⁷*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
- ⁷⁸*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁷⁹*Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain*
- ⁸⁰*Institut für Physik, Universität Mainz, Mainz, Germany*
- ⁸¹*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁸²*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
- ⁸³*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- ⁸⁴*Department of Physics, McGill University, Montreal, Quebec, Canada*
- ⁸⁵*School of Physics, University of Melbourne, Victoria, Australia*
- ⁸⁶*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
- ⁸⁷*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ^{88a}*INFN Sezione di Milano, Milano, Italy*
- ^{88b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ⁸⁹*B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
- ⁹⁰*National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus*
- ⁹¹*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ⁹²*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
- ⁹³*P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
- ⁹⁴*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ⁹⁵*Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
- ⁹⁶*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
- ⁹⁷*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ⁹⁸*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ⁹⁹*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹⁰⁰*Graduate School of Science, Nagoya University, Nagoya, Japan*
- ^{101a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{101b}*Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
- ¹⁰²*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹⁰³*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands*
- ¹⁰⁴*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands*
- ¹⁰⁵*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ¹⁰⁶*Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia*
- ¹⁰⁷*Department of Physics, New York University, New York, New York, USA*
- ¹⁰⁸*The Ohio State University, Columbus, Ohio, USA*
- ¹⁰⁹*Faculty of Science, Okayama University, Okayama, Japan*
- ¹¹⁰*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹¹¹*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹¹²*Palacký University, RCPTM, Olomouc, Czech Republic*
- ¹¹³*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹¹⁴*LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France*
- ¹¹⁵*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹¹⁶*Department of Physics, University of Oslo, Oslo, Norway*
- ¹¹⁷*Department of Physics, Oxford University, Oxford, United Kingdom*
- ^{118a}*INFN Sezione di Pavia, Pavia, Italy*
- ^{118b}*Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy*
- ¹¹⁹*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹²⁰*Petersburg Nuclear Physics Institute, Gatchina, Russia*
- ^{121a}*INFN Sezione di Pisa, Pisa, Italy*
- ^{121b}*Dipartimento di Fisica Enrico Fermi, Università di Pisa, Pisa, Italy*
- ¹²²*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- ^{123a}*Laboratorio de Instrumentacao e Fisica Experimental de Partículas-LIP, Lisboa, Portugal*
- ^{123b}*Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
- ¹²⁴*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
- ¹²⁵*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
- ¹²⁶*Czech Technical University in Prague, Praha, Czech Republic*
- ¹²⁷*State Research Center Institute for High Energy Physics, Protvino, Russia*
- ¹²⁸*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*

- ¹²⁹*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
- ¹³⁰*Ritsumeikan University, Kusatsu, Shiga, Japan*
- ^{131a}*INFN Sezione di Roma I, Roma, Italy*
- ^{131b}*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
- ^{132a}*INFN Sezione di Roma Tor Vergata, Italy*
- ^{132b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{133a}*INFN Sezione di Roma Tre, Roma, Italy*
- ^{133b}*Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
- ^{134a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco*
- ^{134b}*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
- ^{134c}*Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco*
- ^{134d}*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
- ^{134e}*Faculté des Sciences, Université Mohammed V, Rabat, Morocco*
- ¹³⁵*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France*
- ¹³⁶*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ¹³⁷*Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹³⁸*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹³⁹*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴⁰*Fachbereich Physik, Universität Siegen, Siegen, Germany*
- ¹⁴¹*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
- ¹⁴²*SLAC National Accelerator Laboratory, Stanford, California, USA*
- ^{143a}*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{143b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ^{144a}*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
- ^{144b}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ^{145a}*Department of Physics, Stockholm University, Stockholm, Sweden*
- ^{145b}*The Oskar Klein Centre, Stockholm, Sweden*
- ¹⁴⁶*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁴⁷*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
- ¹⁴⁸*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁴⁹*School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵⁰*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ¹⁵¹*Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
- ¹⁵²*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵³*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵⁴*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
- ¹⁵⁵*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁵⁶*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁵⁷*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
- ^{158a}*TRIUMF, Vancouver, British Columbia, Canada*
- ^{158b}*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
- ¹⁵⁹*Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan*
- ¹⁶⁰*Science and Technology Center, Tufts University, Medford, Massachusetts, USA*
- ¹⁶¹*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
- ¹⁶²*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- ^{163a}*INFN Gruppo Collegato di Udine, Udine, Italy*
- ^{163b}*ICTP, Trieste, Italy*
- ^{163c}*Dipartimento di Fisica, Università di Udine, Udine, Italy*
- ¹⁶⁴*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- ¹⁶⁵*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁶*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*
- ¹⁶⁷*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
- ¹⁶⁸*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
- ¹⁶⁹*Waseda University, Tokyo, Japan*
- ¹⁷⁰*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷¹*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
- ¹⁷²*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
- ¹⁷³*Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*

¹⁷⁴*Department of Physics, Yale University, New Haven, Connecticut, USA*

¹⁷⁵*Yerevan Physics Institute, Yerevan, Armenia*

¹⁷⁶*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 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^fAlso at TRIUMF, Vancouver, BC, Canada.

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

^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 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.

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

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

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

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

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

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

^uAlso at High Energy Physics Group, Shandong University, Shandong, China.

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

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

^xAlso at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

^yAlso at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

^zAlso at California Institute of Technology, Pasadena, CA, USA.

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

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

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

^{dd}Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.

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

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

^{gg}Also at Department of Physics, Nanjing University, Jiangsu, China.