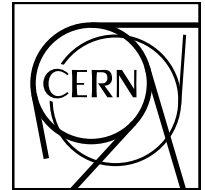
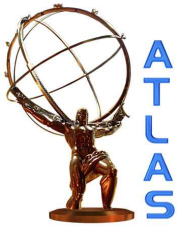


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Measurement of the $t\bar{t}$ production cross section in the tau+jets channel using the ATLAS detector

The ATLAS Collaboration

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¹CERN, 1211 Geneva 23, Switzerland

March 25, 2013

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1 Introduction

Top quark pairs ($t\bar{t}$) are produced in abundance at the Large Hadron Collider (LHC) due to the high centre-of-mass energy of 7 TeV. The large sample of $t\bar{t}$ events collected with the ATLAS detector makes it possible to study experimentally challenging decay channels and topologies. This letter describes a measurement of the $t\bar{t}$ production cross section. The final state studied here consists of a hadronically decaying tau lepton (τ_{had}) and jets, corresponding to the $t\bar{t} \rightarrow [b\tau_{\text{had}}\nu_\tau][bq\bar{q}]$ decay, where b and q are used to denote b -quarks and lighter quarks, respectively. Such an event topology with a hadronically decaying tau lepton corresponds to approximately 10% of all $t\bar{t}$ decays [1].

A $t\bar{t}$ cross-section measurement in the final state with tau leptons makes it possible to probe flavour-dependent effects in top quark decays. It is also relevant to searches for processes beyond the Standard Model, where $t\bar{t}$ events with tau leptons in the final state are a dominant background. This measurement is particularly important for hypothetical charged Higgs boson production [2–5] in top quark decays, where the existence of a charged Higgs boson would lead to an

enhancement in the cross section for the considered $t\bar{t}$ final state. The measurement presented here is complementary to the previously published tau + lepton (electron or muon) channel measurement [6]. The most recent cross-section measurements of the tau + jets decay channel have been performed by the CDF and D0 collaborations in proton–antiproton collisions at $\sqrt{s} = 1.96 \text{ TeV}$ [7, 8]. This is the first measurement reported in this specific channel at the LHC.

In this analysis, events with at least five jets are selected, where two of the jets are identified as having originated from b -quarks. After identifying the two jets likely to come from the hadronic decay of one of the top quarks, one of the remaining jets is selected as the τ_{had} candidate from the other top quark. The τ_{had} contribution is separated from quark- or gluon-initiated jets with a one-dimensional fit to the distribution of the number of tracks associated with the τ_{had} candidate. Since the τ_{had} decays preferentially to one or three charged particles (and other neutral decay products), this variable provides good separation between hadronically decaying tau leptons and jets, as the latter typically produce a large number of charged particles. The main backgrounds to the $t\bar{t}$ signal are multijet events, $t\bar{t}$ events with a different final state or signal events where the wrong jet is chosen as the τ_{had} candidate. A small contribution from single-top and W +jets events is also present. The distributions for the backgrounds used in the fit are obtained with data-driven methods.

2 The ATLAS detector

The ATLAS detector [9] is a multipurpose particle physics detector with a forward-backward symmetric cylin-

drical geometry and a near- 4π coverage in solid angle¹. The inner tracking system covers the pseudorapidity range $|\eta| < 2.5$, and consists of a silicon pixel detector, a silicon microstrip detector (SCT), and, for $|\eta| < 2.0$, a transition radiation tracker. The inner detector is surrounded by a thin superconducting solenoid providing a 2 T magnetic field along the beam direction. A high-granularity liquid-argon sampling electromagnetic calorimeter covers the region $|\eta| < 3.2$. An iron/scintillator tile hadronic calorimeter provides coverage in the range $|\eta| < 1.7$. The end-cap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer surrounds the calorimeters. It consists of three large air-core superconducting toroid systems and separate trigger and high-precision tracking chambers providing accurate muon tracking for $|\eta| < 2.7$.

3 Data and simulation samples

The data used in this analysis were collected during the first half of the 2011 data-taking period and correspond to a total integrated luminosity of $\mathcal{L} = 1.67 \text{ fb}^{-1}$. The data sample was selected with a b -jet trigger that required at least four jets identified with $|\eta| < 3.2$ and a transverse energy (E_T) above 10 GeV. Two of these jets were required to be identified as b -jets using a dedicated high-level-trigger b -tagging algorithm [10]. This trigger was enabled for only part of the 2011 data-taking period and is therefore the limiting factor in determining the integrated luminosity of the dataset used.

The selection efficiency for the $t\bar{t} \rightarrow \tau_{\text{had}} + \text{jets}$ signal is derived from Monte Carlo (MC) simulations. The MC@NLO v4.01 [11] generator, with the parton distribution function (PDF) set CT10 [12], is used for the $t\bar{t}$ signal. The theoretical prediction of the $t\bar{t}$ cross section for proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$ is $\sigma_{t\bar{t}} = 167_{-18}^{+17} \text{ pb}$ for a top quark mass of 172.5 GeV. It has been calculated at approximate next-to-next-to-leading order (NNLO) in QCD with HATHOR 1.2 [13] using the MSTW2008 90% confidence level NNLO PDF sets [14], incorporating PDF

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

and α_S uncertainties according to the MSTW prescription [15], and cross-checked with the next-to-leading-order + next-to-next-to-leading-log calculation of Cacciari et al. [16] as implemented in TOP++ 1.0 [17]. Tau lepton decays are modelled with TAUOLA [18]. Samples of simulated events are also used to estimate the small contributions from W +jets, Z +jets, single-top-quark and diboson events, as described in Ref. [19]. The generated events were processed through the full ATLAS detector simulation using GEANT4 [20, 21], followed by the trigger and offline reconstruction. The distribution of the number of pile-up events (i.e. collisions in the same, or nearby, bunch crossing as the hard-scattering event) is adjusted to match the scattering multiplicity measured in the data.

4 Event selection

Jets are reconstructed from clusters of calorimeter cells [22] using the anti- k_t algorithm [23, 24] with a radius parameter $R = 0.4$. The jets are calibrated using transverse momentum- and η -dependent corrections obtained from simulation and validated with collision data [25]. Candidate events are required to contain at least five jets with a transverse momentum (p_T) larger than 20 GeV and $|\eta| < 2.5$.

The identification of jets originating from b -quarks is performed using algorithms that combine secondary vertex properties and track impact parameters [26]. The algorithm identifies b -jets with an average efficiency of 60% and provides a light-quark jet rejection factor of about 340 in $t\bar{t}$ topologies. The likelihood of misidentifying a τ_{had} as a b -jet in a $t\bar{t}$ event is approximately 5%. The two jets with the highest b -tag probability are chosen as the event b -candidates; events with fewer than two b -jets are rejected.

The magnitude of the missing transverse energy (E_T^{miss}) is reconstructed from energy clusters in the calorimeters. The calibration of each cluster depends on the type of physical object associated with the cluster. The transverse momentum of muons in the event is also taken into account. The E_T^{miss} significance ($S_{E_T^{\text{miss}}}$) is defined as $E_T^{\text{miss}} / (0.5 [\sqrt{\text{GeV}}] \cdot \sqrt{\Sigma E_T})$, where ΣE_T is the scalar sum of the transverse momentum of all objects. Using a $S_{E_T^{\text{miss}}}$ requirement instead of a direct E_T^{miss} requirement allows the rejection of multijet events where the E_T^{miss} arises from energy resolution effects, while still retaining high efficiency for signal events with E_T^{miss} coming from particles which do not interact with the detector [27]. Candidate events are required to have $S_{E_T^{\text{miss}}} > 8$.

Events containing a reconstructed electron or muon [28, 29] with $p_T > 15$ GeV and $|\eta| < 2.5$ are vetoed to reduce the background due to events containing W bosons that decay to electrons or muons and to avoid overlap with other $t\bar{t}$ cross-section measurements.

In each event, a single τ_{had} candidate is selected from the reconstructed jets using the following procedure. First, the reconstruction of the hadronically decaying top quark is attempted by selecting the three jets (including exactly one of the two b -candidates) which, when their four-momenta are added vectorially, give the highest p_T sum. The remaining jet with the highest p_T , excluding the remaining b -candidate, is selected as the τ_{had} candidate. Events where the τ_{had} candidate p_T is below 40 GeV are rejected.

The main contributions to the selected τ_{had} candidates in the signal region come from the signal (τ_{had} from $t\bar{t}$ events), electrons from $t\bar{t}$ events and misidentified jets from $t\bar{t}$, single-top-quark production, W +jets and multijet events. The contributions from Z/γ^* +jets and diboson processes are negligible.

5 Data analysis

The majority of τ_{had} decays are characterised by the presence of one or three charged hadrons in the final state, which can be reconstructed as charged particle tracks in the inner detector. The number of tracks (n_{track}) originating from the interaction point associated with a τ_{had} candidate is used to separate the τ_{had} contribution from the misidentified jet background.

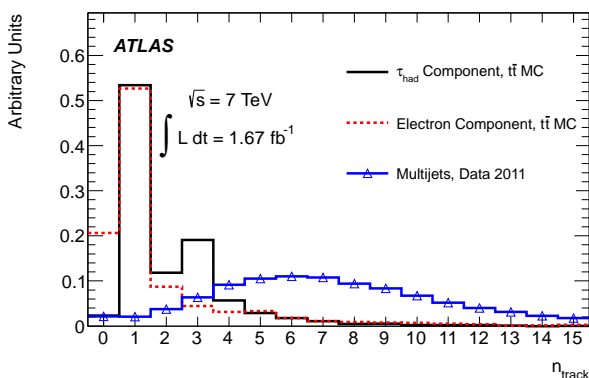


Fig. 1 Distribution of n_{track} for τ_{had} from MC $t\bar{t}$ events (solid black line), electrons from MC $t\bar{t}$ events (dashed red line), and for jets from multijet events from data (blue triangles). The multijet event selection uses a $S_{E_T^{\text{miss}}}$ sideband region as described in Sect. 5. All distributions are normalised to unity.

All selected tracks with $p_T > 1$ GeV located in a core region spanning $\Delta R < 0.2$ around the jet axis are

counted. To increase the discriminating power, tracks in the outer cone $0.2 < \Delta R < 0.6$ are also counted, using a variable p_T requirement that is dependent on both the ΔR of the outer track and the p_T of the core tracks. This variable p_T requirement is designed to reduce the contribution from pile-up and underlying event tracks, and is explained in Ref. [30]. The separation power of the n_{track} variable is illustrated in Fig. 1 where a comparison of the n_{track} distribution is shown for τ_{had} , electrons and misidentified jets from multijet events.

To extract the signal from the n_{track} distribution, the data sample is fitted with three probability density functions (templates): a *tau/electron* template, a *gluon-jet* template and a *quark-jet* template. The τ_{had} component from $t\bar{t}$ events constitutes the signal in the event sample. Real electrons from $t\bar{t}$ events (either prompt or from leptonic tau decays) which failed to be rejected by the electron veto also contribute significantly to the event sample. The electron and τ_{had} templates are combined into a single *tau/electron* template to ensure a stable fit, using MC predictions to determine their relative contributions. The *tau/electron* template is obtained from simulated $t\bar{t}$ events. The small expected contributions to the real *tau/electron* component of the fit from single-top-quark and W +jets events do not change the shape of the template.

The remaining significant contributions come from misidentified jets, and are separated into two templates. The *gluon-jet* template describes the QCD multijet processes which are dominated by gluon-initiated jets, and the *quark-jet* template describes the remaining processes ($t\bar{t}$, single-top quark and W +jets) that are enriched in quark-initiated jets.

The *gluon-jet* template is determined using a sideband region where the $S_{E_T^{\text{miss}}}$ requirement is changed to $3 < S_{E_T^{\text{miss}}} < 4$. This selection greatly enhances the contribution from multijet events, reducing other contributions (e.g. from $t\bar{t}$ events) to less than 1%. The regions defined by the selection $2 < S_{E_T^{\text{miss}}} < 3$ and $4 < S_{E_T^{\text{miss}}} < 5$ are also used to study any correlations between the $S_{E_T^{\text{miss}}}$ criteria and the n_{track} distribution.

The *quark-jet* template is obtained from a $t\bar{t}$ control sample where the τ_{had} candidate is replaced by a muon candidate. The reconstructed muon [29] is required to have $p_T > 20$ GeV, $|\eta| < 2.5$ and no jet within a distance $\Delta R = 0.4$. The requirement on the number of non- b -tagged jets is changed from three to two as the jet corresponding to the τ_{had} is now replaced by a muon. The other selection requirements are the same as for the signal region. This isolates $t\bar{t}$ events with very high purity; the contribution from backgrounds is estimated from MC predictions to be at the 5% level, and consists mainly of single-top-quark and W +jets events. The two

highest- p_T jets that are not identified as b -jet candidates are selected as τ_{had} candidates. The template is corrected using MC simulations for differences in the transverse momentum distribution between the signal region and the control sample, and for the expected contribution to the control sample from $t\bar{t}$ dilepton events ($t\bar{t} \rightarrow \mu + \tau_{\text{had}} + X$, $t\bar{t} \rightarrow \mu + e + X$).

6 Results

An extended binned-likelihood fit is used to extract the different contributions from the n_{track} distribution. To improve the fit stability, a soft constraint is applied to the ratio of *quark-jet* events to *tau/electron* events, which are dominated by the same process ($t\bar{t}$ events). The constraint, based on MC predictions, is a Gaussian with a width of 19% of its central value. This width was estimated based on studies of the associated systematic uncertainties using the same methodology as described in Sect. 7. The statistical uncertainties on the fit parameters are calculated using the shape of the fit likelihood. The systematic uncertainties on the shapes of the templates are propagated using a pseudo-experiment approach, taking into account the bin-by-bin correlations. This yields a final number of *tau/electron* events of 270 ± 24 (stat.) ± 11 (syst.).

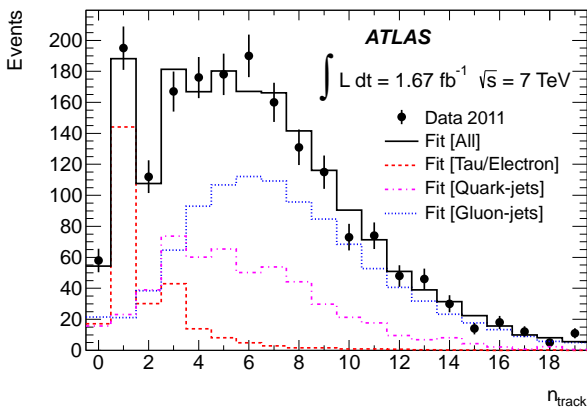


Fig. 2 The n_{track} distribution for τ_{had} candidates after all selection cuts. The black points correspond to data, while the solid black line is the result of the fit. The red (dashed), blue (dotted) and magenta (dash-dotted) histograms show the fitted contributions from the *tau/electron* signal, and the *gluon-jet* and *quark-jet* backgrounds, respectively.

The fit results are shown in Fig. 2. A comparison between the fit results, and the expected event yields from the MC predictions is presented in Table 1. The numbers are in good agreement.

To extract the number of signal events, predictions from simulation are used to subtract the backgrounds

Source	Number of events
<i>tau/electron</i>	
$t\bar{t}$ (τ_{had})	170 ± 40
$t\bar{t}$ (electrons)	47 ± 11
Single top	12 ± 2
W +jets	9 ± 5
Total expected	240 ± 50
Fit result	270 ± 24 (stat.) ± 11 (syst.)
<i>quark-jet</i>	
$t\bar{t}$ (jets)	540 ± 160
Single top	24 ± 4
W +jets	21 ± 12
Total expected	580 ± 160
Fit result	520 ± 97 (stat.) ± 78 (syst.)
<i>gluon-jet</i>	
Fit result	960 ± 77 (stat.) ± 74 (syst.)

Table 1 Comparison of the numbers of events from MC expectations and from the results of the fit to the data for the three templates. The uncertainties on the MC expectations include the systematic uncertainties of the selection efficiency described in Sect. 7. No MC predictions are available for the *gluon-jet* contribution.

from W +jets and single-top events (9 ± 5 and 12 ± 2 , respectively) from the fitted number of *tau/electron* events. The number is then scaled by the expected ratio, $N_{\tau}/(N_{\tau} + N_e)$, of τ_{had} and electrons passing the selection in the $t\bar{t}$ sample. This ratio is estimated from MC simulation to be 0.78 ± 0.03 (stat.) ± 0.03 (syst.). This yields a final number of observed signal events of $N_{\tau} = 194 \pm 18$ (stat.) ± 11 (syst.).

The cross section is obtained using $\sigma_{t\bar{t}} = N_{\tau}/(\mathcal{L} \cdot \varepsilon)$. The efficiency (ε) is estimated from MC simulation to be $(6.0 \pm 1.4) \times 10^{-4}$. It includes the branching fractions for the various $t\bar{t}$ decays and the acceptance, and assumes $\text{Br}(t\bar{t} \rightarrow \tau_{\text{had}} + \text{jets})$ to be 0.098 ± 0.002 [1]. The efficiency is corrected for a 13% difference between MC simulation and data in the trigger and b -tagging efficiencies [26]. The method used for obtaining the uncertainty on the cross section is detailed in Sect. 7.

The cross section is measured to be $\sigma_{t\bar{t}} = 194 \pm 18$ (stat.) ± 46 (syst.) pb.

7 Systematic uncertainties

A summary of all systematic uncertainties on the cross section is given in Table 2.

The uncertainty on the selection efficiency due to the choice of the configuration for the MC simulation is estimated by using alternative MC samples and reweighting procedures. The difference in the efficiency obtained from various configurations is taken as the uncertainty.

Source of uncertainty	Relative uncertainty
ISR/FSR	15%
Event generator	11%
Hadronisation model	6%
PDFs	2%
Pile-up	1%
b -jet tagging efficiency	9%
Jet energy scale	5%
E_T^{miss} significance mismodelling	5%
b -jet trigger efficiency	3%
Jet energy resolution	2%
Fit systematic uncertainties	4%
Luminosity	4%
Total uncertainty	24%

Table 2 Systematic uncertainties on the $t\bar{t}$ cross section.

The uncertainty on the modeling of the ISR/FSR is taken into account by using ACERMC [31] samples with specific tunes aimed at conservatively varying the amount of parton showering [32]. The uncertainty due to the choice of the matrix element event generator is estimated by comparing $t\bar{t}$ samples generated using MC@NLO, POWHEG [33–35], and ALPGEN [36]. To study the impact of different hadronization models, events generated using POWHEG are processed with two different hadronization programs: HERWIG and PYTHIA. The uncertainty of the choice of PDFs is estimated using a number of current PDF sets [37].

Uncertainties on the simulation of the detector response are taken into account using dedicated studies of the reconstructed physics objects (electrons, muons, jets, E_T^{miss}). The uncertainties considered are associated with the jet energy scale, jet energy resolution, b -tagging efficiency, trigger efficiency and the E_T^{miss} calculation [25, 26]. The uncertainty due to mismodelling of the lepton veto is estimated using the uncertainties on the muon and electron reconstruction efficiencies determined from independent data samples, and is found to be negligible.

To obtain the uncertainty on the fit results, variations are applied to the templates to describe various systematic effects. As the τ / e template is taken directly from MC-simulated $t\bar{t}$ events, the systematic uncertainties on this template are taken from estimates of the mismodelling of the simulation. The dominant contributions come from variations in the amount of ISR/FSR in the simulation (1%), the modelling of the pile-up (1%), and the statistical uncertainties (1%). Uncertainties on the track reconstruction efficiency, jet energy scale, and the ratio of τ_{had} to electrons are found to be negligible. The $quark$ -jet template is obtained from a μ + jets control sample of $t\bar{t}$ events in data. The dom-

inant contributions to the uncertainty come from the statistical uncertainties (4%), the difference in shape between the μ + jets template and the expected $quark$ -jet distribution, estimated from MC samples (2%), and the MC-based subtraction of the dilepton contribution (1%). The uncertainty on the MC-based kinematic correction is found to be negligible. The $gluon$ -jet template is derived from a background-dominated sideband region with small values of $S_{E_T^{\text{miss}}}$. The two sources of uncertainties are the dependence of the template on the $S_{E_T^{\text{miss}}}$ criterion of the control region, obtained by varying the $S_{E_T^{\text{miss}}}$ requirement (1%), and the statistical uncertainty of the control region (1%). The total systematic uncertainty on the fit is found to be 4%.

The uncertainty on the luminosity is calculated to be 3.7% as described in Ref. [38]. The total systematic uncertainty on the cross section is 24%.

8 Conclusions

This letter presents a measurement of the top quark pair production cross section in the final state corresponding to the $t\bar{t} \rightarrow [b\tau_{\text{had}}\nu_\tau][bqq]$ decay. The measurement uses a dataset corresponding to an integrated luminosity of 1.67 fb^{-1} of proton–proton collision data at a centre-of-mass energy of 7 TeV recorded by the ATLAS experiment at the LHC. The signal has been extracted by fitting the number of tracks associated with tau lepton candidates using templates derived from simulation for the $t\bar{t}$ signal and from the data for the backgrounds.

The $t\bar{t}$ production cross section is measured to be $\sigma_{t\bar{t}} = 194 \pm 18 \text{ (stat.)} \pm 46 \text{ (syst.) pb}$. This result is compatible with the highest precision ATLAS measurements [39, 40], and with the result of $186 \pm 13 \text{ (stat.)} \pm 20 \text{ (syst.)} \pm 7 \text{ (lum.) pb}$ obtained in the complementary tau + lepton (electron or muon) channel [6]. It is also in good agreement with the theoretical prediction of $167_{-18}^{+17} \text{ pb}$.

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G. Aad⁴⁸, T. Abajyan²¹, B. Abbott¹¹¹, J. Abdallah¹², S. Abdel Khalek¹¹⁵, A.A. Abdelalim⁴⁹, O. Abdinov¹¹, R. Aben¹⁰⁵, B. Abi¹¹², M. Abolins⁸⁸, O.S. AbouZeid¹⁵⁸, H. Abramowicz¹⁵³, H. Abreu¹³⁶, B.S. Acharya^{164a,164b,a}, L. Adamczyk³⁸, D.L. Adams²⁵, T.N. Addy⁵⁶, J. Adelman¹⁷⁶, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²³, J.A. Aguilar-Saavedra^{124b,b}, M. Agustoni¹⁷, M. Aharrouche⁸¹, S.P. Ahlen²², F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴¹, G. Aielli^{133a,133b}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, M.A. Alam⁷⁶, J. Albert¹⁶⁹, S. Albrand⁵⁵, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, F. Alessandria^{89a}, C. Alexa^{26a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos¹⁰, M. Alhroob^{164a,164c}, M. Aliev¹⁶, G. Alimonti^{89a}, J. Alison¹²⁰, B.M.M. Allbrooke¹⁸, L.J. Allison⁷¹, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷², A. Alonso⁷⁹, F. Alonso⁷⁰, A. Altheimer³⁵, B. Alvarez Gonzalez⁸⁸, M.G. Alviggi^{102a,102b}, K. Amako⁶⁵, C. Amelung²³, V.V. Ammosov^{128,*}, S.P. Amor Dos Santos^{124a}, A. Amorim^{124a,c}, N. Amram¹⁵³, C. Anastopoulos³⁰, L.S. Ancu¹⁷, N. Andari¹¹⁵, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders^{58a}, K.J. Anderson³¹, A. Andreazza^{89a,89b}, V. Andrei^{58a}, M-L. Andrieux⁵⁵, X.S. Anduaga⁷⁰, S. Angelidakis⁹, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A. Anisenkov¹⁰⁷, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁶, J. Antos^{144b}, F. Anulli^{132a}, M. Aoki¹⁰¹, S. Aoun⁸³, L. Aperio Bella⁵, R. Apolle^{118,d}, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁵, A.T.H. Arce⁴⁵, S. Arfaoui¹⁴⁸, J-F. Arguin⁹³, S. Argyropoulos⁴², E. Arik^{19a,*}, M. Arik^{19a}, A.J. Armbruster⁸⁷, O. Arnæz⁸¹, V. Arnal⁸⁰, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²¹, S. Asai¹⁵⁵, S. Ask²⁸, B. Åsman^{146a,146b}, L. Asquith⁶, K. Assamagan^{25,e}, A. Astbury¹⁶⁹, M. Atkinson¹⁶⁵, B. Aubert⁵, E. Auge¹¹⁵, K. Augsten¹²⁶, M. Auresseau^{145a}, G. Avolio³⁰, D. Axen¹⁶⁸, G. Azuelos^{93,f}, Y. Azuma¹⁵⁵, M.A. Baak³⁰, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁵, H. Bachacou¹³⁶, K. Bachas¹⁵⁴, M. Backes⁴⁹, M. Backhaus²¹, J. Backus Mayes¹⁴³, E. Badescu^{26a}, P. Bagnaia^{132a,132b}, S. Bahinipati³, Y. Bai^{33a}, D.C. Bailey¹⁵⁸, T. Bain³⁵, J.T. Baines¹²⁹, O.K. Baker¹⁷⁶, M.D. Baker²⁵, S. Baker⁷⁷, P. Balek¹²⁷, E. Banas³⁹, P. Banerjee⁹³, Sw. Banerjee¹⁷³, D. Banfi³⁰, A. Bangert¹⁵⁰, V. Bansal¹⁶⁹, H.S. Bansil¹⁸, L. Barak¹⁷², S.P. Baranov⁹⁴, T. Barber⁴⁸, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²¹, D.Y. Bardin⁶⁴, T. Barillari⁹⁹, M. Barisonzi¹⁷⁵, T. Barklow¹⁴³, N. Barlow²⁸, B.M. Barnett¹²⁹, R.M. Barnett¹⁵, A. Baroncelli^{134a}, G. Barone⁴⁹, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, R. Bartoldus¹⁴³, A.E. Barton⁷¹, V. Bartsch¹⁴⁹, A. Basye¹⁶⁵, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁸, A. Battaglia¹⁷, M. Battistin³⁰, F. Bauer¹³⁶, H.S. Bawa^{143,g}, S. Beale⁹⁸, T. Beau⁷⁸, P.H. Beauchemin¹⁶¹, R. Beccherle^{50a}, P. Bechtel²¹, H.P. Beck¹⁷, K. Becker¹⁷⁵, S. Becker⁹⁸, M. Beckingham¹³⁸, K.H. Becks¹⁷⁵, A.J. Beddall^{19c}, A. Beddall^{19c}, S. Bedikian¹⁷⁶, V.A. Bednyakov⁶⁴, C.P. Bee⁸³, L.J. Beemster¹⁰⁵, M. Begel²⁵, S. Behar Harpaz¹⁵², P.K. Behera⁶², M. Beimforde⁹⁹, C. Belanger-Champagne⁸⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{20a}, M. Bellomo³⁰, A. Belloni⁵⁷, O. Beloborodova^{107,h}, K. Belotskiy⁹⁶, O. Beltramello³⁰, O. Benary¹⁵³, D. Benchekroun^{135a}, K. Bendtz^{146a,146b}, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, E. Benhar Nocchioli⁴⁹, J.A. Benitez Garcia^{159b}, D.P. Benjamin⁴⁵, M. Benoit¹¹⁵, J.R. Bensinger²³, K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge³⁰, E. Bergeas Kuutmann⁴², N. Berger⁵, F. Berghaus¹⁶⁹, E. Berglund¹⁰⁵, J. Beringer¹⁵, P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius²⁵, T. Berry⁷⁶, C. Bertella⁸³, A. Bertin^{20a,20b}, F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, G.J. Besjes¹⁰⁴, N. Besson¹³⁶, S. Bethke⁹⁹, W. Bhimji⁴⁶, R.M. Bianchi³⁰, L. Bianchini²³, M. Bianco^{72a,72b}, O. Biebel⁹⁸, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁵, M. Biglietti^{134a}, H. Bilokon⁴⁷, M. Bindi^{20a,20b}, S. Binet¹¹⁵, A. Bingul^{19c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁸, B. Bittner⁹⁹, C.W. Black¹⁵⁰, K.M. Black²², R.E. Blair⁶, J.-B. Blanchard¹³⁶, T. Blazek^{144a}, I. Bloch⁴², C. Blocker²³, J. Blocki³⁹, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵, V.S. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁵, C.R. Boddy¹¹⁸, M. Boehler⁴⁸, J. Boek¹⁷⁵, T.T. Boek¹⁷⁵, N. Boelaert³⁶, J.A. Bogaerts³⁰, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Bohm^{146a}, J. Bohm¹²⁵, V. Boisvert⁷⁶, T. Bold³⁸, V. Boldea^{26a}, N.M. Bolnet¹³⁶, M. Bomben⁷⁸, M. Bona⁷⁵, M. Boonekamp¹³⁶, S. Bordini⁷⁸, C. Borer¹⁷, A. Borisov¹²⁸, G. Borissov⁷¹, I. Borjanovic^{13a}, M. Borri⁸², S. Borroni⁸⁷, J. Bortfeldt⁹⁸, V. Bortolotto^{134a,134b}, K. Bos¹⁰⁵, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁵, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³¹, J. Boyd³⁰, I.R. Boyko⁶⁴, I. Bozovic-Jelisavcic^{13b}, J. Bracinik¹⁸, P. Branchini^{134a}, A. Brandt⁸, G. Brandt¹¹⁸, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun^{175,*}, S.F. Brazzale^{164a,164c}, B. Brelier¹⁵⁸, J. Bremer³⁰, K. Brendlinger¹²⁰, R. Brenner¹⁶⁶, S. Bressler¹⁷², T.M. Bristow^{145b}, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁸⁸, F. Broggi^{89a}, C. Bromberg⁸⁸, J. Bronner⁹⁹, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, G. Brown⁸², P.A. Bruckman de Renstrom³⁹, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a},

M. Bruschi^{20a}, L. Bryngemark⁷⁹, T. Buanes¹⁴, Q. Buat⁵⁵, F. Bucci⁴⁹, J. Buchanan¹¹⁸, P. Buchholz¹⁴¹,
R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁶, S.I. Buda^{26a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷,
O. Bulekov⁹⁶, A.C. Bundock⁷³, M. Bunse⁴³, T. Buran¹¹⁷, H. Burckhart³⁰, S. Burdin⁷³, T. Burgess¹⁴, S. Burke¹²⁹,
E. Busato³⁴, P. Bussey⁵³, C.P. Buszello¹⁶⁶, B. Butler¹⁴³, J.M. Butler²², C.M. Buttar⁵³, J.M. Butterworth⁷⁷,
W. Buttinger²⁸, M. Byszewski³⁰, S. Cabrera Urbán¹⁶⁷, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafura¹⁵,
G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{24a}, R. Caloi^{132a,132b}, D. Calvet³⁴, S. Calvet³⁴,
R. Camacho Toro³⁴, P. Camarri^{133a,133b}, D. Cameron¹¹⁷, L.M. Caminada¹⁵, R. Caminal Armadans¹²,
S. Campana³⁰, M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli³¹, A. Canepa^{159a}, J. Cantero⁸⁰, R. Cantrill⁷⁶,
M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}, D. Capriotti⁹⁹, M. Capua^{37a,37b}, R. Caputo⁸¹,
R. Cardarelli^{133a}, T. Carli³⁰, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron⁸⁵, S. Caron¹⁰⁴, E. Carquin^{32b},
G.D. Carrillo-Montoya^{145b}, A.A. Carter⁷⁵, J.R. Carter²⁸, J. Carvalho^{124a,i}, D. Casadei¹⁰⁸, M.P. Casado¹²,
M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez^{173,j}, E. Castaneda-Miranda¹⁷³,
V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124a}, G. Cataldi^{72a}, P. Catastini⁵⁷, A. Catinaccio³⁰, J.R. Catmore³⁰,
A. Cattai³⁰, G. Cattani^{133a,133b}, S. Caughron⁸⁸, V. Cavaliere¹⁶⁵, P. Cavalleri⁷⁸, D. Cavalli^{89a},
M. Cavalli-Sforza¹², V. Cavasinni^{122a,122b}, F. Ceradini^{134a,134b}, A.S. Cerqueira^{24b}, A. Cerri¹⁵, L. Cerrito⁷⁵,
F. Cerutti¹⁵, S.A. Cetin^{19b}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁶, I. Chalupkova¹²⁷, K. Chan³, P. Chang¹⁶⁵,
B. Chapleau⁸⁵, J.D. Chapman²⁸, J.W. Chapman⁸⁷, D.G. Charlton¹⁸, V. Chavda⁸², C.A. Chavez Barajas³⁰,
S. Cheatham⁸⁵, S. Chekanov⁶, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰⁴, C. Chen⁶³, H. Chen²⁵,
S. Chen^{33c}, X. Chen¹⁷³, Y. Chen³⁵, Y. Cheng³¹, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁵,
E. Cheu⁷, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani^{51a,*}, J.T. Childers³⁰,
A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷, A. Chitan^{26a}, M.V. Chizhov⁶⁴,
G. Choudalakis³¹, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart³⁰, M.L. Chu¹⁵¹,
J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca³⁴, V. Cindro⁷⁴, A. Ciocio¹⁵, M. Cirilli⁸⁷,
P. Cirkovic^{13b}, Z.H. Citron¹⁷², M. Citterio^{89a}, M. Ciubancan^{26a}, A. Clark⁴⁹, P.J. Clark⁴⁶, R.N. Clarke¹⁵,
W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, Y. Coadou⁸³, M. Cobal^{164a,164c},
A. Coccaro¹³⁸, J. Cochran⁶³, L. Coffey²³, J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, J. Colas⁵, S. Cole¹⁰⁶, A.P. Colijn¹⁰⁵,
N.J. Collins¹⁸, C. Collins-Tooth⁵³, J. Collot⁵⁵, T. Colombo^{119a,119b}, G. Colon⁸⁴, G. Compostella⁹⁹,
P. Conde Muiño^{124a}, E. Coniavitis¹⁶⁶, M.C. Conidi¹², S.M. Consonni^{89a,89b}, V. Consorti⁴⁸, S. Constantinescu^{26a},
C. Conta^{119a,119b}, G. Conti⁵⁷, F. Conventi^{102a,k}, M. Cooke¹⁵, B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁸,
K. Copic¹⁵, T. Cornelissen¹⁷⁵, M. Corradi^{20a}, F. Corriveau^{85,l}, A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹,
G. Costa^{89a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, D. Côté³⁰, L. Courneyea¹⁶⁹, G. Cowan⁷⁶, B.E. Cox⁸²,
K. Cranmer¹⁰⁸, F. Crescioli⁷⁸, M. Cristinziani²¹, G. Crosetti^{37a,37b}, S. Crépe-Renaudin⁵⁵, C.-M. Cuciuc^{26a},
C. Cuenca Almenar¹⁷⁶, T. Cuhadar Donszelmann¹³⁹, J. Cummings¹⁷⁶, M. Curatolo⁴⁷, C.J. Curtis¹⁸,
C. Cuthbert¹⁵⁰, P. Cwetanski⁶⁰, H. Czirr¹⁴¹, P. Czodrowski⁴⁴, Z. Czyczula¹⁷⁶, S. D'Auria⁵³, M. D'Onofrio⁷³,
A. D'Orazio^{132a,132b}, M.J. Da Cunha Sargedas De Sousa^{124a}, C. Da Via⁸², W. Dabrowski³⁸, A. Dafinca¹¹⁸,
T. Dai⁸⁷, F. Dallaire⁹³, C. Dallapiccola⁸⁴, M. Dam³⁶, M. Dameri^{50a,50b}, D.S. Damiani¹³⁷, H.O. Danielsson³⁰,
V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{26b}, J.A. Dassoulas⁴², W. Davey²¹, T. Davidek¹²⁷, N. Davidson⁸⁶,
R. Davidson⁷¹, E. Davies^{118,d}, M. Davies⁹³, O. Davignon⁷⁸, A.R. Davison⁷⁷, Y. Davygora^{58a}, E. Dawe¹⁴²,
I. Dawson¹³⁹, R.K. Daya-Ishmukhametova²³, K. De⁸, R. de Asmundis^{102a}, S. De Castro^{20a,20b}, S. De Cecco⁷⁸,
J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, C. De La Taille¹¹⁵, H. De la Torre⁸⁰, F. De Lorenzi⁶³,
L. de Mora⁷¹, L. De Nooij¹⁰⁵, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹,
J.B. De Vivie De Regie¹¹⁵, G. De Zorzi^{132a,132b}, W.J. Dearnaley⁷¹, R. Debbé²⁵, C. Debenedetti⁴⁶,
B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹²⁰, J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, T. Delemontex⁵⁵,
M. Deliyergiyev⁷⁴, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Della Pietra^{102a,k}, D. della Volpe^{102a,102b}, M. Delmastro⁵,
P.A. Delsart⁵⁵, C. Deluca¹⁰⁵, S. Demers¹⁷⁶, M. Demichev⁶⁴, B. Demirköz^{12,m}, S.P. Denisov¹²⁸, D. Derendarz³⁹,
J.E. Derkaoui^{135d}, F. Derue⁷⁸, P. Dervan⁷³, K. Desch²¹, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁰⁵, A. Dewhurst¹²⁹,
B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸, R. Dhullipudi^{25,n}, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵, C. Di Donato^{102a,102b},
A. Di Girolamo³⁰, B. Di Girolamo³⁰, S. Di Luise^{134a,134b}, A. Di Mattia¹⁵², B. Di Micco³⁰, R. Di Nardo⁴⁷,
A. Di Simone^{133a,133b}, R. Di Sipio^{20a,20b}, M.A. Diaz^{32a}, E.B. Diehl⁸⁷, J. Dietrich⁴², T.A. Dietzsch^{58a}, S. Diglio⁸⁶,
K. Dindar Yagci⁴⁰, J. Dingfelder²¹, F. Dinut^{26a}, C. Dionisi^{132a,132b}, P. Dita^{26a}, S. Dita^{26a}, F. Dittus³⁰,
F. Djama⁸³, T. Djobava^{51b}, M.A.B. do Vale^{24c}, A. Do Valle Wemans^{124a,o}, T.K.O. Doan⁵, M. Dobbs⁸⁵,
D. Dobos³⁰, E. Dobson^{30,p}, J. Dodd³⁵, C. Doglioni⁴⁹, T. Doherty⁵³, Y. Doi^{65,*}, J. Dolejsi¹²⁷, Z. Dolezal¹²⁷,
B.A. Dolgoshein^{96,*}, T. Dohmae¹⁵⁵, M. Donadelli^{24d}, J. Donini³⁴, J. Dopke³⁰, A. Doria^{102a}, A. Dos Anjos¹⁷³,

A. Dotti^{122a,122b}, M.T. Dova⁷⁰, A.D. Doxiadis¹⁰⁵, A.T. Doyle⁵³, N. Dressnandt¹²⁰, M. Dris¹⁰, J. Dubbert⁹⁹,
 S. Dube¹⁵, E. Duchovni¹⁷², G. Duckeck⁹⁸, D. Duda¹⁷⁵, A. Dudarev³⁰, F. Dudziak⁶³, M. Dührssen³⁰,
 I.P. Duerdoth⁸², L. Duflot¹¹⁵, M-A. Dufour⁸⁵, L. Duguid⁷⁶, M. Dunford^{58a}, H. Duran Yildiz^{4a}, R. Duxfield¹³⁹,
 M. Dwuznik³⁸, M. Düren⁵², W.L. Ebenstein⁴⁵, J. Ebke⁹⁸, S. Eckweiler⁸¹, W. Edson², C.A. Edwards⁷⁶,
 N.C. Edwards⁵³, W. Ehrenfeld⁴², T. Eifert¹⁴³, G. Eigen¹⁴, K. Einsweiler¹⁵, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶,
 M. El Kacimi^{135c}, M. Ellert¹⁶⁶, S. Elles⁵, F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis³⁰, J. Elmsheuser⁹⁸, M. Elsing³⁰,
 D. Emeliyanov¹²⁹, R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶¹, J. Erdmann¹⁷⁶, A. Ereditato¹⁷, D. Eriksson^{146a},
 J. Ernst², M. Ernst²⁵, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, H. Esch⁴³,
 C. Escobar¹²³, X. Espinal Curull¹², B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etievre¹³⁶, E. Etzion¹⁵³,
 D. Evangelakou⁵⁴, H. Evans⁶⁰, L. Fabbri^{20a,20b}, C. Fabre³⁰, R.M. Fakhruddinov¹²⁸, S. Falciano^{132a}, Y. Fang^{33a},
 M. Fanti^{89a,89b}, A. Farbin⁸, A. Farilla^{134a}, J. Farley¹⁴⁸, T. Farooque¹⁵⁸, S. Farrell¹⁶³, S.M. Farrington¹⁷⁰,
 P. Farthouat³⁰, F. Fassi¹⁶⁷, P. Fassnacht³⁰, D. Fassouliotis⁹, B. Fatholahzadeh¹⁵⁸, A. Favareto^{89a,89b},
 L. Fayard¹¹⁵, P. Federic^{144a}, O.L. Fedin¹²¹, W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸, L. Feligioni⁸³, C. Feng^{33d},
 E.J. Feng⁶, A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, W. Fernando⁶, S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴²,
 A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷,
 A. Ferretto Parodi^{50a,50b}, M. Fiassarini³¹, F. Fiedler⁸¹, A. Filipčič⁷⁴, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹,
 M.C.N. Fiolhais^{124a,i}, L. Fiorini¹⁶⁷, A. Firan⁴⁰, G. Fischer⁴², M.J. Fisher¹⁰⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹,
 J. Fleckner⁸¹, P. Fleischmann¹⁷⁴, S. Fleischmann¹⁷⁵, T. Flick¹⁷⁵, A. Floderus⁷⁹, L.R. Flores Castillo¹⁷³,
 A.C. Florez Bustos^{159b}, M.J. Flowerdew⁹⁹, T. Fonseca Martin¹⁷, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a},
 D. Fournier¹¹⁵, A.J. Fowler⁴⁵, H. Fox⁷¹, P. Francavilla¹², M. Franchini^{20a,20b}, S. Franchino^{119a,119b}, D. Francis³⁰,
 T. Frank¹⁷², M. Franklin⁵⁷, S. Franz³⁰, M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁸, C. Friedrich⁴²,
 F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa¹²⁷, B.G. Fulsom¹⁴³,
 J. Fuster¹⁶⁷, C. Gabaldon³⁰, O. Gabizon¹⁷², T. Gadfort²⁵, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰,
 C. Galea⁹⁸, B. Galhardo^{124a}, E.J. Gallas¹¹⁸, V. Gallo¹⁷, B.J. Gallop¹²⁹, P. Gallus¹²⁵, K.K. Gan¹⁰⁹,
 Y.S. Gao^{143,g}, A. Gaponenko¹⁵, F. Garbersson¹⁷⁶, M. Garcia-Sciveres¹⁵, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷,
 R.W. Gardner³¹, N. Garelli³⁰, V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{119a}, B. Gaur¹⁴¹, L. Gauthier¹³⁶,
 P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gece¹⁶⁸,
 C.N.P. Gee¹²⁹, D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²¹, K. Gellerstedt^{146a,146b}, C. Gemme^{50a}, A. Gemmel⁵³,
 M.H. Genest⁵⁵, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁶, D. Gerbaudo¹², P. Gerlach¹⁷⁵, A. Gershon¹⁵³,
 C. Geweniger^{58a}, H. Ghazlane^{135b}, N. Ghodbane³⁴, B. Giacobbe^{20a}, S. Giagu^{132a,132b}, V. Giangiobbe¹²,
 F. Gianotti³⁰, B. Gibbard²⁵, A. Gibson¹⁵⁸, S.M. Gibson³⁰, M. Gilchriese¹⁵, D. Gillberg²⁹, A.R. Gillman¹²⁹,
 D.M. Gingrich^{3,f}, J. Ginzburg¹⁵³, N. Giokaris⁹, M.P. Giordani^{164c}, R. Giordano^{102a,102b}, F.M. Giorgi¹⁶,
 P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, M. Giunta⁹³, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰,
 J. Glatzer²¹, A. Glazov⁴², K.W. Glitza¹⁷⁵, G.L. Glonti⁶⁴, J.R. Goddard⁷⁵, J. Godfrey¹⁴², J. Godlewski³⁰,
 M. Goebel⁴², T. Göpfert⁴⁴, C. Goeringer⁸¹, C. Gössling⁴³, S. Goldfarb⁸⁷, T. Golling¹⁷⁶, D. Golubkov¹²⁸,
 A. Gomes^{124a,c}, L.S. Gomez Fajardo⁴², R. Gonçalves⁷⁶, J. Goncalves Pinto Firmino Da Costa⁴², L. Gonella²¹,
 S. González de la Hoz¹⁶⁷, G. Gonzalez Parra¹², M.L. Gonzalez Silva²⁷, S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸,
 L. Goossens³⁰, P.A. Gorbounov⁹⁵, H.A. Gordon²⁵, I. Gorelov¹⁰³, G. Gorfine¹⁷⁵, B. Gorini³⁰, E. Gorini^{72a,72b},
 A. Gorišek⁷⁴, E. Gornicki³⁹, A.T. Goshaw⁶, M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁴, I. Gough Eschrich¹⁶³,
 M. Gouighri^{135a}, D. Goujdami^{135c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸, C. Goy⁵, S. Gozpinar²³,
 I. Grabowska-Bold³⁸, P. Grafström^{20a,20b}, K-J. Grahn⁴², E. Gramstad¹¹⁷, F. Grancagnolo^{72a}, S. Grancagnolo¹⁶,
 V. Grassi¹⁴⁸, V. Gratchev¹²¹, H.M. Gray³⁰, J.A. Gray¹⁴⁸, E. Graziani^{134a}, O.G. Grebenyuk¹²¹, T. Greenshaw⁷³,
 Z.D. Greenwood^{25,n}, K. Gregersen³⁶, I.M. Gregor⁴², P. Grenier¹⁴³, J. Griffiths⁸, N. Grigalashvili⁶⁴,
 A.A. Grillo¹³⁷, K. Grimm⁷¹, S. Grinstein¹², Ph. Gris³⁴, Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, A. Grohsjean⁴²,
 E. Gross¹⁷², J. Grosse-Knetter⁵⁴, J. Groth-Jensen¹⁷², K. Grybel¹⁴¹, D. Guest¹⁷⁶, C. Guicheney³⁴,
 E. Guido^{50a,50b}, S. Guindon⁵⁴, U. Gul⁵³, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁵, P. Gutierrez¹¹¹, N. Guttman¹⁵³,
 O. Gutzwiller¹⁷³, C. Guyot¹³⁶, C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁰⁸, S. Haas³⁰, C. Haber¹⁵,
 H.K. Hadavand⁸, D.R. Hadley¹⁸, P. Haefner²¹, F. Hahn³⁰, Z. Hajduk³⁹, H. Hakobyan¹⁷⁷, D. Hall¹¹⁸,
 K. Hamacher¹⁷⁵, P. Hamal¹¹³, K. Hamano⁸⁶, M. Hamer⁵⁴, A. Hamilton^{145b,q}, S. Hamilton¹⁶¹, L. Han^{33b},
 K. Hanagaki¹¹⁶, K. Hanawa¹⁶⁰, M. Hance¹⁵, C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁶, J.B. Hansen³⁶,
 J.D. Hansen³⁶, P.H. Hansen³⁶, P. Hansson¹⁴³, K. Hara¹⁶⁰, T. Harenberg¹⁷⁵, S. Harkusha⁹⁰, D. Harper⁸⁷,
 R.D. Harrington⁴⁶, O.M. Harris¹³⁸, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁵, A. Harvey⁵⁶, S. Hasegawa¹⁰¹,
 Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁸⁸, M. Havranek²¹, C.M. Hawkes¹⁸,

R.J. Hawkings³⁰, A.D. Hawkins⁷⁹, T. Hayakawa⁶⁶, T. Hayashi¹⁶⁰, D. Hayden⁷⁶, C.P. Hays¹¹⁸, H.S. Hayward⁷³, S.J. Haywood¹²⁹, S.J. Head¹⁸, V. Hedberg⁷⁹, L. Heelan⁸, S. Heim¹²⁰, B. Heinemann¹⁵, S. Heisterkamp³⁶, L. Helary²², C. Heller⁹⁸, M. Heller³⁰, S. Hellman^{146a,146b}, D. Hellmich²¹, C. Helsens¹², R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs¹⁷⁶, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁵, C. Hensel⁵⁴, C.M. Hernandez⁸, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁶, G. Hertzen⁴⁸, R. Hertzenberger⁹⁸, L. Hervas³⁰, G.G. Hesketh⁷⁷, N.P. Hesse¹⁰⁵, E. Higón-Rodríguez¹⁶⁷, J.C. Hill²⁸, K.H. Hiller⁴², S. Hillert²¹, S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴³, D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁸, N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker³⁰, M.R. Hoferkamp¹⁰³, J. Hoffman⁴⁰, D. Hoffmann⁸³, M. Hohlfield⁸¹, M. Holder¹⁴¹, S.O. Holmgren^{146a}, T. Holy¹²⁶, J.L. Holzbauer⁸⁸, T.M. Hong¹²⁰, L. Hooft van Huysduynen¹⁰⁸, S. Horner⁴⁸, J.-Y. Hostachy⁵⁵, S. Hou¹⁵¹, A. Hoummada^{135a}, J. Howard¹¹⁸, J. Howarth⁸², I. Hristova¹⁶, J. Hrivnac¹¹⁵, T. Hryn'ova⁵, P.J. Hsu⁸¹, S.-C. Hsu¹³⁸, D. Hu³⁵, Z. Hubacek³⁰, F. Hubaut⁸³, F. Huegging²¹, A. Huettmann⁴², T.B. Huffman¹¹⁸, E.W. Hughes³⁵, G. Hughes⁷¹, M. Huhtinen³⁰, M. Hurwitz¹⁵, N. Huseynov^{64,r}, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, M. Ibbotson⁸², I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, P. Iengo^{102a}, O. Igonkina¹⁰⁵, Y. Ikegami⁶⁵, M. Ikeno⁶⁵, D. Iliadis¹⁵⁴, N. Ilic¹⁵⁸, T. Ince⁹⁹, P. Ioannou⁹, M. Iodice^{134a}, K. Iordanidou⁹, V. Ippolito^{132a,132b}, A. Irles Quiles¹⁶⁷, C. Isaksson¹⁶⁶, M. Ishino⁶⁷, M. Ishitsuka¹⁵⁷, R. Ishmukhametov¹⁰⁹, C. Issever¹¹⁸, S. Istin^{19a}, A.V. Ivashin¹²⁸, W. Iwanski³⁹, H. Iwasaki⁶⁵, J.M. Izen⁴¹, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹, M.R. Jaekel³⁰, V. Jain², K. Jakobs⁴⁸, S. Jakobsen³⁶, T. Jakoubek¹²⁵, J. Jakubek¹²⁶, D.O. Jamin¹⁵¹, D.K. Jana¹¹¹, E. Jansen⁷⁷, H. Jansen³⁰, J. Janssen²¹, A. Jantsch⁹⁹, M. Janus⁴⁸, R.C. Jared¹⁷³, G. Jarlskog⁷⁹, L. Jeanty⁵⁷, I. Jen-La Plante³¹, G.-Y. Jeng¹⁵⁰, D. Jennens⁸⁶, P. Jenni³⁰, A.E. Loevschall-Jensen³⁶, P. Jež³⁶, S. Jézéquel⁵, M.K. Jha^{20a}, H. Ji¹⁷³, W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁶, D. Joffe⁴⁰, M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴², K.A. Johns⁷, K. Jon-And^{146a,146b}, G. Jones¹⁷⁰, R.W.L. Jones⁷¹, T.J. Jones⁷³, C. Joram³⁰, P.M. Jorge^{124a}, K.D. Joshi⁸², J. Jovicevic¹⁴⁷, T. Jovin^{13b}, X. Ju¹⁷³, C.A. Jung⁴³, R.M. Jungst³⁰, V. Juraneck¹²⁵, P. Jussel⁶¹, A. Juste Rozas¹², S. Kabana¹⁷, M. Kaci¹⁶⁷, A. Kaczmarek³⁹, P. Kadlecik³⁶, M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁵, L.V. Kalinovskaya⁶⁴, S. Kama⁴⁰, N. Kanaya¹⁵⁵, M. Kaneda³⁰, S. Kaneti²⁸, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁵, B. Kaplan¹⁰⁸, A. Kapliy³¹, D. Kar⁵³, M. Karagounis²¹, K. Karakostas¹⁰, M. Karnevskiy^{58b}, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif¹⁷³, G. Kasieczka^{58b}, R.D. Kass¹⁰⁹, A. Kastanas¹⁴, M. Kataoka⁵, Y. Kataoka¹⁵⁵, J. Katzy⁴², V. Kaushik⁷, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵, S. Kazama¹⁵⁵, V.F. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁹, P.T. Keener¹²⁰, R. Kehoe⁴⁰, M. Keil⁵⁴, G.D. Kekelidze⁶⁴, J.S. Keller¹³⁸, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen³⁰, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁵, K. Kessoku¹⁵⁵, J. Keung¹⁵⁸, F. Khalil-zada¹¹, H. Khandanyan^{146a,146b}, A. Khanov¹¹², D. Kharchenko⁶⁴, A. Khodinov⁹⁶, A. Khomich^{58a}, T.J. Khoo²⁸, G. Khorauli²¹, A. Khoroshilov¹⁷⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁴, J. Khubua^{51b}, H. Kim^{146a,146b}, S.H. Kim¹⁶⁰, N. Kimura¹⁷¹, O. Kind¹⁶, B.T. King⁷³, M. King⁶⁶, R.S.B. King¹¹⁸, J. Kirk¹²⁹, A.E. Kiryunin⁹⁹, T. Kishimoto⁶⁶, D. Kisielewska³⁸, T. Kitamura⁶⁶, T. Kittelmann¹²³, K. Kiuchi¹⁶⁰, E. Kladiva^{144b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷², P. Klimek^{146a,146b}, A. Klimentov²⁵, R. Klingenberg⁴³, J.A. Klinger⁸², E.B. Klinkby³⁶, T. Klioutchnikova³⁰, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, E. Kneringer⁶¹, E.B.F.G. Knoops⁸³, A. Knue⁵⁴, B.R. Ko⁴⁵, T. Kobayashi¹⁵⁵, M. Kobel⁴⁴, M. Kocian¹⁴³, P. Kodys¹²⁷, K. Köneke³⁰, A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²¹, T. Koffas²⁹, E. Koffeman¹⁰⁵, L.A. Kogan¹¹⁸, S. Kohlmann¹⁷⁵, F. Kohn⁵⁴, Z. Kohout¹²⁶, T. Kohriki⁶⁵, T. Koi¹⁴³, G.M. Kolachev^{107,*}, H. Kolanoski¹⁶, V. Kolesnikov⁶⁴, I. Koletsou^{89a}, J. Koll⁸⁸, A.A. Komar⁹⁴, Y. Komori¹⁵⁵, T. Kondo⁶⁵, T. Kono^{42,s}, A.I. Kononov⁴⁸, R. Konoplich^{108,t}, N. Konstantinidis⁷⁷, R. Kopeliansky¹⁵², S. Koperny³⁸, K. Korcyl³⁹, K. Kordas¹⁵⁴, A. Korn¹¹⁸, A. Korol¹⁰⁷, I. Korolkov¹², E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²¹, S. Kotov⁹⁹, V.M. Kotov⁶⁴, A. Kotwal⁴⁵, C. Kourkoumelis⁹, V. Kouskoura¹⁵⁴, A. Koutsman^{159a}, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁸, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁶, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹⁰⁸, F. Krejci¹²⁶, J. Kretzschmar⁷³, K. Kreutzfeldt⁵², N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²¹, J. Krstic^{13a}, U. Kruchonak⁶⁴, H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, M.K. Kruse⁴⁵, T. Kubota⁸⁶, S. Kuday^{4a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴², D. Kuhn⁶¹, V. Kukhtin⁶⁴, Y. Kulchitsky⁹⁰, S. Kuleshov^{32b}, C. Kummer⁹⁸, M. Kuna⁷⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁶, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, E.S. Kuwertz¹⁴⁷, M. Kuze¹⁵⁷, J. Kvita¹⁴², R. Kwee¹⁶,

A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, L. Labarga⁸⁰, S. Lablak^{135a}, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, J. Lacey²⁹,
 H. Lacker¹⁶, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁴, R. Lafaye⁵, B. Laforge⁷⁸, T. Lagouri¹⁷⁶, S. Lai⁴⁸,
 E. Laisne⁵⁵, L. Lambourne⁷⁷, C.L. Lampen⁷, W. Lampl⁷, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵,
 V.S. Lang^{58a}, C. Lange⁴², A.J. Lankford¹⁶³, F. Lanni²⁵, K. Lantzsck³⁰, A. Lanza^{119a}, S. Laplace⁷⁸, C. Lapoire²¹,
 J.F. Laporte¹³⁶, T. Lari^{89a}, A. Larnier¹¹⁸, M. Lassnig³⁰, P. Laurelli⁴⁷, V. Lavorini^{37a,37b}, W. Lavrijsen¹⁵,
 P. Laycock⁷³, O. Le Dortz⁷⁸, E. Le Guirriec⁸³, E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵,
 J.S.H. Lee¹¹⁶, S.C. Lee¹⁵¹, L. Lee¹⁷⁶, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, F. Legger⁹⁸, C. Leggett¹⁵,
 M. Lehmacher²¹, G. Lehmann Miotto³⁰, A.G. Leister¹⁷⁶, M.A.L. Leite^{24d}, R. Leitner¹²⁷, D. Lellouch¹⁷²,
 B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁰⁵, G. Lenzen¹⁷⁵, B. Lenzi³⁰, K. Leonhardt⁴⁴,
 S. Leontsinis¹⁰, F. Lepold^{58a}, C. Leroy⁹³, J.-R. Lessard¹⁶⁹, C.G. Lester²⁸, C.M. Lester¹²⁰, J. Levêque⁵,
 D. Levin⁸⁷, L.J. Levinson¹⁷², A. Lewis¹¹⁸, G.H. Lewis¹⁰⁸, A.M. Leyko²¹, M. Leyton¹⁶, B. Li^{33b}, B. Li⁸³, H. Li¹⁴⁸,
 H.L. Li³¹, S. Li^{33b,u}, X. Li⁸⁷, Z. Liang^{118,v}, H. Liao³⁴, B. Liberti^{133a}, P. Lichard³⁰, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵,
 W. Liebig¹⁴, C. Limbach²¹, A. Limosani⁸⁶, M. Limper⁶², S.C. Lin^{151,w}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸,
 E. Lipeles¹²⁰, A. Lipniacka¹⁴, T.M. Liss¹⁶⁵, D. Lissauer²⁵, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁹, D. Liu¹⁵¹,
 J.B. Liu^{33b}, L. Liu⁸⁷, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵,
 J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁷, T. Loddenkoetter²¹,
 F.K. Loebinger⁸², A. Loginov¹⁷⁶, C.W. Loh¹⁶⁸, T. Lohse¹⁶, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, V.P. Lombardo⁵,
 R.E. Long⁷¹, L. Lopes^{124a}, D. Lopez Mateos⁵⁷, J. Lorenz⁹⁸, N. Lorenzo Martinez¹¹⁵, M. Losada¹⁶²,
 P. Loscutoff¹⁵, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a,*}, X. Lou⁴¹, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love⁶,
 P.A. Love⁷¹, A.J. Lowe^{143,g}, F. Lu^{33a}, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, D. Ludwig⁴², I. Ludwig⁴⁸,
 J. Ludwig⁴⁸, F. Luehring⁶⁰, G. Luijckx¹⁰⁵, W. Lukas⁶¹, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷,
 B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, O. Lundberg^{146a,146b}, J. Lundquist³⁶, M. Lungwitz⁸¹, D. Lynn²⁵,
 E. Lytken⁷⁹, H. Ma²⁵, L.L. Ma¹⁷³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a},
 D. Macina³⁰, R. Mackeprang³⁶, R.J. Madaras¹⁵, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, R. Maenner^{58c}, T. Maeno²⁵,
 P. Mättig¹⁷⁵, S. Mättig⁴², L. Magnoni¹⁶³, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁵, S. Mahmoud⁷³,
 G. Mahout¹⁸, C. Maiani¹³⁶, C. Maidantchik^{24a}, A. Maio^{124a,c}, S. Majewski²⁵, Y. Makida⁶⁵, N. Makovec¹¹⁵,
 P. Mal¹³⁶, B. Malaescu³⁰, Pa. Malecki³⁹, P. Malecki³⁹, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶,
 C. Malone¹⁴³, S. Maltezos¹⁰, V. Malyshev¹⁰⁷, S. Malyukov³⁰, J. Mamuzic^{13b}, A. Manabe⁶⁵, L. Mandelli^{89a},
 I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{124a}, A. Manfredini⁹⁹, L. Manhaes de Andrade Filho^{24b},
 J.A. Manjarres Ramos¹³⁶, A. Mann⁹⁸, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁶,
 R. Mantifel⁸⁵, A. Mapelli³⁰, L. Mapelli³⁰, L. March¹⁶⁷, J.F. Marchand²⁹, F. Marchese^{133a,133b}, G. Marchiori⁷⁸,
 M. Marcisovsky¹²⁵, C.P. Marino¹⁶⁹, F. Marroquin^{24a}, Z. Marshall³⁰, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁷,
 B. Martin³⁰, B. Martin⁸⁸, J.P. Martin⁹³, T.A. Martin¹⁸, V.J. Martin⁴⁶, B. Martin dit Latour⁴⁹,
 S. Martin-Haugh¹⁴⁹, H. Martinez¹³⁶, M. Martinez¹², V. Martinez Outschoorn⁵⁷, A.C. Martyniuk¹⁶⁹, M. Marx⁸²,
 F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷,
 I. Massa^{20a,20b}, G. Massaro¹⁰⁵, N. Massol⁵, P. Mastrandrea¹⁴⁸, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁵,
 H. Matsunaga¹⁵⁵, T. Matsushita⁶⁶, C. Mattravers^{118,d}, J. Maurer⁸³, S.J. Maxfield⁷³, D.A. Maximov^{107,h},
 A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²¹, L. Mazzaferro^{133a,133b}, M. Mazzanti^{89a}, J. Mc Donald⁸⁵, S.P. Mc Kee⁸⁷,
 A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁹, N.A. McCubbin¹²⁹, K.W. McFarlane^{56,*}, J.A. McFayden¹³⁹,
 G. Mchedlidze^{51b}, T. McLaughlan¹⁸, S.J. McMahon¹²⁹, R.A. McPherson^{169,l}, A. Meade⁸⁴, J. Mechnich¹⁰⁵,
 M. Mechtel¹⁷⁵, M. Medinnis⁴², S. Meehan³¹, R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶, S. Mehlhase³⁶, A. Mehta⁷³,
 K. Meier^{58a}, B. Meirose⁷⁹, C. Melachrinou³¹, B.R. Mellado Garcia¹⁷³, F. Meloni^{89a,89b}, L. Mendoza Navas¹⁶²,
 Z. Meng^{151,x}, A. Mengarelli^{20a,20b}, S. Menke⁹⁹, E. Meoni¹⁶¹, K.M. Mercurio⁵⁷, P. Mermod⁴⁹, L. Merola^{102a,102b},
 C. Meroni^{89a}, F.S. Merritt³¹, H. Merritt¹⁰⁹, A. Messina^{30,y}, J. Metcalfe²⁵, A.S. Mete¹⁶³, C. Meyer⁸¹, C. Meyer³¹,
 J.-P. Meyer¹³⁶, J. Meyer¹⁷⁴, J. Meyer⁵⁴, S. Michal³⁰, L. Micu^{26a}, R.P. Middleton¹²⁹, S. Migas⁷³, L. Mijović¹³⁶,
 G. Mikenberg¹⁷², M. Mikestikova¹²⁵, M. Mikuž⁷⁴, D.W. Miller³¹, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷,
 A. Milov¹⁷², D.A. Milstead^{146a,146b}, D. Milstein¹⁷², A.A. Minaenko¹²⁸, M. Miñano Moya¹⁶⁷, I.A. Minashvili⁶⁴,
 A.I. Mincer¹⁰⁸, B. Mindur³⁸, M. Mineev⁶⁴, Y. Ming¹⁷³, L.M. Mir¹², G. Mirabelli^{132a}, J. Mitrevski¹³⁷,
 V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁵, P.S. Miyagawa¹³⁹, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, V. Moeller²⁸, K. Mönig⁴²,
 N. Möser²¹, S. Mohapatra¹⁴⁸, W. Mohr⁴⁸, R. Moles-Valls¹⁶⁷, A. Molfetas³⁰, J. Monk⁷⁷, E. Monnier⁸³,
 J. Montejo Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{20a,20b}, R.W. Moore³, G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹,
 A. Moraes⁵³, N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{37a,37b}, D. Moreno⁸¹, M. Moreno Llacer¹⁶⁷, P. Morettini^{50a},
 M. Morgenstern⁴⁴, M. Morii⁵⁷, A.K. Morley³⁰, G. Mornacchi³⁰, J.D. Morris⁷⁵, L. Morvaj¹⁰¹, H.G. Moser⁹⁹,

M. Mosidze^{51b}, J. Moss¹⁰⁹, R. Mount¹⁴³, E. Mountricha^{10,z}, S.V. Mouraviev^{94,*}, E.J.W. Moyses⁸⁴, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²¹, T.A. Müller⁹⁸, T. Mueller⁸¹, D. Muenstermann³⁰, Y. Munwes¹⁵³, W.J. Murray¹²⁹, I. Mussche¹⁰⁵, E. Musto¹⁵², A.G. Myagkov¹²⁸, M. Myska¹²⁵, O. Nackenhorst⁵⁴, J. Nadal¹², K. Nagai¹⁶⁰, R. Nagai¹⁵⁷, K. Nagano⁶⁵, A. Nagarkar¹⁰⁹, Y. Nagasaka⁵⁹, M. Nagel⁹⁹, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura¹⁵⁵, T. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²¹, A. Napier¹⁶¹, R. Narayan^{58b}, M. Nash^{77,d}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶², H.A. Neal⁸⁷, P.Yu. Nechaeva⁹⁴, T.J. Neep⁸², A. Negri^{119a,119b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, A. Nelson¹⁶³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{24a}, M. Nessi^{30,aa}, M.S. Neubauer¹⁶⁵, M. Neumann¹⁷⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁵, F.M. Newcomer¹²⁰, P.R. Newman¹⁸, V. Nguyen Thi Hong¹³⁶, R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, B. Nicquevert³⁰, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko¹²⁸, I. Nikolic-Audit⁷⁸, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, H. Nilsen⁴⁸, P. Nilsson⁸, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, R. Nisius⁹⁹, T. Nobe¹⁵⁷, L. Nodulman⁶, M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, S. Norberg¹¹¹, M. Nordberg³⁰, J. Novakova¹²⁷, M. Nozaki⁶⁵, L. Nozka¹¹³, A.-E. Nuncio-Quiroz²¹, G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷, B.J. O'Brien⁴⁶, D.C. O'Neil¹⁴², V. O'Shea⁵³, L.B. Oakes⁹⁸, F.G. Oakham^{29,f}, H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁶, S. Oda⁶⁹, S. Odaka⁶⁵, J. Odier⁸³, H. Ogren⁶⁰, A. Oh⁸², S.H. Oh⁴⁵, C.C. Ohm³⁰, T. Ohshima¹⁰¹, W. Okamura¹¹⁶, H. Okawa²⁵, Y. Okumura³¹, T. Okuyama¹⁵⁵, A. Olariu^{26a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino^{32a}, M. Oliveira^{124a,i}, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{124a,ab}, P.U.E. Onyisi^{31,ac}, C.J. Oram^{159a}, M.J. Oreglia³¹, Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{72a,72b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹², G. Otero y Garzon²⁷, J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135d}, E.A. Ouellette¹⁶⁹, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸², S. Owen¹³⁹, V.E. Ozcan^{19a}, N. Ozturk⁸, A. Pacheco Pages¹², C. Padilla Aranda¹², S. Pagan Griso¹⁵, E. Paganis¹³⁹, C. Pahl⁹⁹, F. Paige²⁵, P. Pais⁸⁴, K. Pajchel¹¹⁷, G. Palacino^{159b}, C.P. Paleari⁷, S. Palestini³⁰, D. Pallin³⁴, A. Palma^{124a}, J.D. Palmer¹⁸, Y.B. Pan¹⁷³, E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁶, P. Pani¹⁰⁵, N. Panikashvili⁸⁷, S. Panitkin²⁵, D. Pantea^{26a}, A. Papadelis^{146a}, Th.D. Papadopoulou¹⁰, A. Paramonov⁶, D. Paredes Hernandez³⁴, W. Park^{25,ad}, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, S. Pashapour⁵⁴, E. Pasqualucci^{132a}, S. Passaggio^{50a}, A. Passeri^{134a}, F. Pastore^{134a,134b,*}, Fr. Pastore⁷⁶, G. Pásztor^{49,ae}, S. Patarraia¹⁷⁵, N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly³⁰, M. Pecsny^{144a}, S. Pedraza Lopez¹⁶⁷, M.I. Pedraza Morales¹⁷³, S.V. Peleganchuk¹⁰⁷, D. Pelikan¹⁶⁶, H. Peng^{33b}, B. Penning³¹, A. Penson³⁵, J. Penwell⁶⁰, M. Perantoni^{24a}, K. Perez^{35,af}, T. Perez Cavalcanti⁴², E. Perez Codina^{159a}, M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁵, L. Perini^{89a,89b}, H. Pernegger³⁰, R. Perrino^{72a}, P. Perrodó⁵, V.D. Peshekhonov⁶⁴, K. Peters³⁰, B.A. Petersen³⁰, J. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁵, A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolo^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴², M. Petteni¹⁴², R. Pezoa^{32b}, A. Phan⁸⁶, P.W. Phillips¹²⁹, G. Piacquadio³⁰, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, S.M. Piec⁴², R. Piegai²⁷, D.T. Pignotti¹⁰⁹, J.E. Pilcher³¹, A.D. Pilkington⁸², J. Pina^{124a,c}, M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{124a}, C. Pizio^{89a,89b}, M.-A. Pleier²⁵, E. Plotnikova⁶⁴, A. Poblaguev²⁵, S. Poddar^{58a}, F. Podlyski³⁴, L. Poggioli¹¹⁵, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{119a}, A. Policicchio^{37a,37b}, A. Polini^{20a}, J. Poll⁷⁵, V. Polychronakos²⁵, D. Pomeroy²³, K. Pommès³⁰, L. Pontecorvo^{132a}, B.G. Pope⁸⁸, G.A. Popeneciu^{26a}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso³⁰, G.E. Pospelov⁹⁹, S. Pospisil¹²⁶, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴, G. Poulard³⁰, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, R. Prabhu⁷⁷, P. Pralavorio⁸³, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan²⁵, S. Prell⁶³, K. Pretzl¹⁷, D. Price⁶⁰, J. Price⁷³, L.E. Price⁶, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev¹⁰⁸, F. Prokoshin^{32b}, S. Protopopescu²⁵, J. Proudfoot⁶, X. Prudent⁴⁴, M. Przybycien³⁸, H. Przysiezniak⁵, S. Psoroulas²¹, E. Ptacek¹¹⁴, E. Pueschel⁸⁴, D. Puldon¹⁴⁸, J. Purdham⁸⁷, M. Purohit^{25,ad}, P. Puzo¹¹⁵, Y. Pylypchenko⁶², J. Qian⁸⁷, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle¹⁷³, M. Raas¹⁰⁴, V. Radeka²⁵, V. Radescu⁴², P. Radloff¹¹⁴, F. Ragusa^{89a,89b}, G. Rahal¹⁷⁸, A.M. Rahimi¹⁰⁹, D. Rahm²⁵, S. Rajagopalan²⁵, M. Rammensee⁴⁸, M. Rammes¹⁴¹, A.S. Randle-Conde⁴⁰, K. Randrianarivony²⁹, K. Rao¹⁶³, F. Rauscher⁹⁸, T.C. Rave⁴⁸, M. Raymond³⁰, A.L. Read¹¹⁷, D.M. Rebuffi^{119a,119b}, A. Redelbach¹⁷⁴, G. Redlinger²⁵, R. Reece¹²⁰, K. Reeves⁴¹, A. Reinsch¹¹⁴, I. Reisinger⁴³, C. Rembser³⁰, Z.L. Ren¹⁵¹, A. Renaud¹¹⁵, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, R. Richter⁹⁹, E. Richter-Was^{5,ag}, M. Ridel⁷⁸, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{20a}, R.R. Rios⁴⁰, I. Riu¹², G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,l}, A. Robichaud-Veronneau¹¹⁸, D. Robinson²⁸, J.E.M. Robinson⁸², A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b}, D. Roda Dos Santos³⁰, A. Roe⁵⁴, S. Roe³⁰, O. Röhne¹¹⁷, S. Rolli¹⁶¹, A. Romaniouk⁹⁶, M. Romano^{20a,20b}, G. Romeo²⁷, E. Romero Adam¹⁶⁷, N. Rompotis¹³⁸, L. Roos⁷⁸, E. Ros¹⁶⁷,

S. Rosati^{132a}, K. Rosbach⁴⁹, A. Rose¹⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴¹,
 L. Rosselet⁴⁹, V. Rossetti¹², E. Rossi^{132a,132b}, L.P. Rossi^{50a}, M. Rotaru^{26a}, I. Roth¹⁷², J. Rothberg¹³⁸,
 D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan^{33a,ah}, F. Rubbo¹², I. Rubinskiy⁴²,
 N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴⁴, G. Rudolph⁶¹, F. Rühr⁷, A. Ruiz-Martinez⁶³, L. Rumyantsev⁶⁴,
 Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, A. Ruschke⁹⁸, J.P. Rutherford⁷, N. Ruthmann⁴⁸, P. Ruzicka¹²⁵,
 Y.F. Ryabov¹²¹, M. Rybar¹²⁷, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³,
 H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁴, F. Safai Tehrani^{132a}, H. Sakamoto¹⁵⁵, G. Salamanna⁷⁵, A. Salamon^{133a},
 M. Saleem¹¹¹, D. Salek³⁰, D. Salihagic⁹⁹, A. Salmikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁶,
 D. Salvatore^{37a,37b}, F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴, A. Salzburger³⁰, D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷,
 A. Sanchez^{102a,102b}, V. Sanchez Martinez¹⁶⁷, H. Sandaker¹⁴, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁵,
 T. Sandoval²⁸, C. Sandoval¹⁶², R. Sandstroem⁹⁹, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵,
 C. Santoni³⁴, R. Santonico^{133a,133b}, H. Santos^{124a}, I. Santoyo Castillo¹⁴⁹, J.G. Saraiva^{124a}, T. Sarangi¹⁷³,
 E. Sarkisyan-Grinbaum⁸, B. Sarrazin²¹, F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁵, O. Sasaki⁶⁵, Y. Sasaki¹⁵⁵, N. Sasao⁶⁷,
 I. Satsounkevitch⁹⁰, G. Sauvage^{5,*}, E. Sauvan⁵, J.B. Sauvan¹¹⁵, P. Savard^{158,f}, V. Savinov¹²³, D.O. Savu³⁰,
 L. Sawyer^{25,n}, D.H. Saxon⁵³, J. Saxon¹²⁰, C. Sbarra^{20a}, A. Sbrizzi^{20a,20b}, D.A. Scannicchio¹⁶³, M. Scarcella¹⁵⁰,
 J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹, D. Schaefer¹²⁰, U. Schäfer⁸¹, A. Schaelicke⁴⁶, S. Schaepe²¹, S. Schaezel^{58b},
 A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹,
 D. Scheirich⁸⁷, M. Schernau¹⁶³, M.I. Scherzer³⁵, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{37a,37b},
 S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden²¹, C. Schmitt⁸¹, S. Schmitt^{58b}, B. Schneider¹⁷, U. Schnoor⁴⁴,
 L. Schoeffel¹³⁶, A. Schoening^{58b}, A.L.S. Schorlemmer⁵⁴, M. Schott³⁰, D. Schouten^{159a}, J. Schovancova¹²⁵,
 M. Schram⁸⁵, C. Schroeder⁸¹, N. Schroer^{58c}, M.J. Schultens²¹, J. Schultes¹⁷⁵, H.-C. Schultz-Coulon^{58a},
 H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, A. Schwartzman¹⁴³, Ph. Schwegler⁹⁹,
 Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴⁴, J. Schwindling¹³⁶, T. Schwindt²¹, M. Schwoerer⁵,
 F.G. Sciacca¹⁷, G. Sciolla²³, W.G. Scott¹²⁹, J. Searcy¹¹⁴, G. Sedov⁴², E. Sedykh¹²¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷,
 F. Seifert⁴⁴, J.M. Seixas^{24a}, G. Sekhniaidze^{102a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov¹²¹,
 B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{20a,20b}, C. Serfon⁹⁸, L. Serin¹¹⁵, L. Serkin⁵⁴,
 R. Seuster^{159a}, H. Severini¹¹¹, A. Sfyrla³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{33a}, J.T. Shank²²,
 Q.T. Shao⁸⁶, M. Shapiro¹⁵, P.B. Shatalov⁹⁵, K. Shaw^{164a,164c}, D. Sherman¹⁷⁶, P. Sherwood⁷⁷, S. Shimizu¹⁰¹,
 M. Shimojima¹⁰⁰, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁴, M.J. Shochet³¹, D. Short¹¹⁸, S. Shrestha⁶³,
 E. Shulga⁹⁶, M.A. Shupe⁷, P. Sicho¹²⁵, A. Sidoti^{132a}, F. Siegert⁴⁸, Dj. Sijacki^{13a}, O. Silbert¹⁷², J. Silva^{124a},
 Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁶, O. Simard¹³⁶, Lj. Simic^{13a}, S. Simion¹¹⁵,
 E. Simioni⁸¹, B. Simmons⁷⁷, R. Simoniello^{89a,89b}, M. Simonyan³⁶, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹,
 G. Siragusa¹⁷⁴, A. Sircar²⁵, A.N. Sisakyan^{64,*}, S.Yu. Sivoklov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjusen¹⁴,
 L.A. Skinnari¹⁵, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, M. Slater¹⁸, T. Slavicek¹²⁶, K. Sliwa¹⁶¹,
 V. Smakhtin¹⁷², B.H. Smart⁴⁶, L. Smestad¹¹⁷, S.Yu. Smirnov⁹⁶, Y. Smirnov⁹⁶, L.N. Smirnova^{97,ai},
 O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁶, A.A. Snesarev⁹⁴,
 S.W. Snow⁸², J. Snow¹¹¹, S. Snyder²⁵, R. Sobie^{169,l}, J. Sodomka¹²⁶, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁶,
 J. Solc¹²⁶, E.Yu. Soldatov⁹⁶, U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸,
 O.V. Solovyanov¹²⁸, V. Solovyev¹²¹, N. Soni¹, A. Sood¹⁵, V. Sopko¹²⁶, B. Sopko¹²⁶, M. Sosebee⁸,
 R. Soualah^{164a,164c}, P. Soueid⁹³, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, R. Spighi^{20a}, G. Spigo³⁰,
 R. Spiwoks³⁰, M. Spousta^{127,aj}, T. Spreitzer¹⁵⁸, B. Spurlock⁸, R.D. St. Denis⁵³, J. Stahlman¹²⁰, R. Stamen^{58a},
 E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{134a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁷,
 E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁴², R. Staszewski³⁹, A. Staude⁹⁸, P. Stavina^{144a,*},
 G. Steele⁵³, P. Steinbach⁴⁴, P. Steinberg²⁵, I. Stekl¹²⁶, B. Stelzer¹⁴², H.J. Stelzer⁸⁸, O. Stelzer-Chilton^{159a},
 H. Stenzel⁵², S. Stern⁹⁹, G.A. Stewart³⁰, J.A. Stillings²¹, M.C. Stockton⁸⁵, M. Stoebe⁸⁵, K. Stoerig⁴⁸,
 G. Stoicea^{26a}, S. Stonjek⁹⁹, P. Strachota¹²⁷, A.R. Stradling⁸, A. Straessner⁴⁴, J. Strandberg¹⁴⁷,
 S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b},
 R. Ströhmer¹⁷⁴, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski⁴⁰, B. Stugu¹⁴, I. Stumer^{25,*}, J. Stupak¹⁴⁸,
 P. Sturm¹⁷⁵, N.A. Styles⁴², D.A. Soh^{151,v}, D. Su¹⁴³, HS. Subramania³, R. Subramanian²⁵, A. Succurro¹²,
 Y. Sugaya¹¹⁶, C. Suhr¹⁰⁶, M. Suk¹²⁷, V.V. Sulim⁹⁴, S. Sultansoy^{4d}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸,
 K. Suruliz¹³⁹, G. Susinno^{37a,37b}, M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶, M. Svatos¹²⁵, S. Swedish¹⁶⁸,
 I. Sykora^{144a}, T. Sykora¹²⁷, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴², A. Taffard¹⁶³, R. Tafirout^{159a},
 N. Taiblum¹⁵³, Y. Takahashi¹⁰¹, H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴⁰, Y. Takubo⁶⁵,

M. Talby⁸³, A. Talyshev^{107,h}, M.C. Tamsett²⁵, K.G. Tan⁸⁶, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴², K. Tani⁶⁶, N. Tannoury⁸³, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁹, G.F. Tartarelli^{89a}, P. Tas¹²⁷, M. Tasevsky¹²⁵, E. Tassi^{37a,37b}, Y. Tayalati^{135d}, C. Taylor⁷⁷, F.E. Taylor⁹², G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teinturier¹¹⁵, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵¹, S. Terada⁶⁵, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Testa⁴⁷, R.J. Teuscher^{158,l}, J. Therhaag²¹, T. Theveneaux-Pelzer⁷⁸, S. Thoma⁴⁸, J.P. Thomas¹⁸, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²⁰, M. Thomson²⁸, W.M. Thong⁸⁶, R.P. Thun⁸⁷, F. Tian³⁵, M.J. Tibbetts¹⁵, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴, Y.A. Tikhonov^{107,h}, S. Timoshenko⁹⁶, E. Tiouchichine⁸³, P. Tipton¹⁷⁶, S. Tisserant⁸³, T. Todorov⁵, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁹, S. Tokár^{144a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins³¹, K. Toms¹⁰³, A. Tonoyan¹⁴, C. Topfel¹⁷, N.D. Topilin⁶⁴, E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torr o Pastor¹⁶⁷, J. Toth^{83,ae}, F. Touchard⁸³, D.R. Tovey¹³⁹, T. Trefzger¹⁷⁴, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{159a}, S. Trinc az-Duvoid⁷⁸, M.F. Tripiana⁷⁰, N. Triplett²⁵, W. Trischuk¹⁵⁸, B. Trocm e⁵⁵, C. Troncon^{89a}, M. Trotter-McDonald¹⁴², P. True⁸⁸, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C.-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiarehka⁹⁰, D. Tsionou^{5,ak}, G. Tsipolitis¹⁰, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁵, J.-W. Tsung²¹, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, A. Tudorache^{26a}, V. Tudorache^{26a}, J.M. Tuggle³¹, M. Turala³⁹, D. Turecek¹²⁶, I. Turk Cakir^{4e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b}, P.M. Tuts³⁵, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, G. Tzanakos⁹, K. Uchida²¹, I. Ueda¹⁵⁵, R. Ueno²⁹, M. Ughetto⁸³, M. Ugland¹⁴, M. Uhlenbrock²¹, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶³, Y. Unno⁶⁵, D. Urbaniec³⁵, P. Urquijo²¹, G. Usai⁸, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁶, B. Vachon⁸⁵, S. Vahsen¹⁵, S. Valentinetti^{20a,20b}, A. Valero¹⁶⁷, S. Valkar¹²⁷, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, R. Van Berg¹²⁰, P.C. Van Der Deijl¹⁰⁵, R. van der Geer¹⁰⁵, H. van der Graaf¹⁰⁵, R. Van Der Leeuw¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴², I. van Vulpen¹⁰⁵, M. Vanadia⁹⁹, W. Vandelli³⁰, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁸, R. Vari^{132a}, E.W. Varnes⁷, T. Varol⁸⁴, D. Varouchas¹⁵, A. Vartapetian⁸, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, F. Veloso^{124a}, R. Veness³⁰, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura⁸⁴, M. Venturi⁴⁸, N. Venturi¹⁵⁸, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, A. Vest⁴⁴, M.C. Vetterli^{142,f}, I. Vichou¹⁶⁵, T. Vickey^{145b,al}, O.E. Vickey Boeriu^{145b}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{20a,20b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vincter²⁹, E. Vinek³⁰, V.B. Vinogradov⁶⁴, M. Virchaux^{136,*}, J. Virzi¹⁵, O. Vitells¹⁷², M. Viti⁴², I. Vivarelli⁴⁸, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁸, M. Vlasak¹²⁶, A. Vogel²¹, P. Vokac¹²⁶, G. Volpi⁴⁷, M. Volpi⁸⁶, G. Volpini^{89a}, H. von der Schmitt⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁷, V. Vorwerk¹², M. Vos¹⁶⁷, R. Voss³⁰, J.H. Vosseveld⁷³, N. Vranjes¹³⁶, M. Vranjes Milosavljevic¹⁰⁵, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, W. Wagner¹⁷⁵, P. Wagner²¹, H. Wahlen¹⁷⁵, S. Wahrenmund⁴⁴, J. Wakabayashi¹⁰¹, S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁶, P. Waller⁷³, B. Walsh¹⁷⁶, C. Wang⁴⁵, H. Wang¹⁷³, H. Wang⁴⁰, J. Wang¹⁵¹, J. Wang^{33a}, R. Wang¹⁰³, S.M. Wang¹⁵¹, T. Wang²¹, A. Warburton⁸⁵, C.P. Ward²⁸, D.R. Wardrope⁷⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², I. Watanabe⁶⁶, P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵⁰, M.F. Watson¹⁸, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, M.S. Weber¹⁷, J.S. Webster³¹, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹, J. Weingarten⁵⁴, C. Weiser⁴⁸, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{151,v}, T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Werth¹⁶³, M. Wessels^{58a}, J. Wetter¹⁶¹, C. Weydert⁵⁵, K. Whalen²⁹, A. White⁸, M.J. White⁸⁶, S. White^{122a,122b}, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶⁰, D. Wicke¹⁷⁵, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷³, M. Wielers¹²⁹, P. Wienemann²¹, C. Wiglesworth⁷⁵, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁷, A. Wildauer⁹⁹, M.A. Wildt^{42,s}, I. Wilhelm¹²⁷, H.G. Wilkens³⁰, J.Z. Will⁹⁸, E. Williams³⁵, H.H. Williams¹²⁰, S. Williams²⁸, W. Willis³⁵, S. Willocq⁸⁴, J.A. Wilson¹⁸, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁵, S. Winkelmann⁴⁸, F. Winklmeier³⁰, M. Wittgen¹⁴³, S.J. Wollstadt⁸¹, M.W. Wolter³⁹, H. Wolters^{124a,i}, W.C. Wong⁴¹, G. Wooden⁸⁷, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸², K.W. Wozniak³⁹, K. Wraight⁵³, M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷³, X. Wu⁴⁹, Y. Wu^{33b,am}, E. Wulf³⁵, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁶, S. Xie⁴⁸, C. Xu^{33b,z}, D. Xu^{33a}, L. Xu^{33b}, B. Yabsley¹⁵⁰, S. Yacoub^{145a,an}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁵, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, T. Yamanaka¹⁵⁵, K. Yamauchi¹⁰¹, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁶, Z. Yan²², H. Yang⁸⁷, U.K. Yang⁸², Y. Yang¹⁰⁹, Z. Yang^{146a,146b}, S. Yanush⁹¹, L. Yao^{33a}, Y. Yasu⁶⁵, E. Yatsenko⁴², J. Ye⁴⁰, S. Ye²⁵, A.L. Yen⁵⁷, M. Yilmaz^{4c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷¹,

R. Yoshida⁶, K. Yoshihara¹⁵⁵, C. Young¹⁴³, C.J. Young¹¹⁸, S. Youssef²², D. Yu²⁵, D.R. Yu¹⁵, J. Yu⁸, J. Yu¹¹², L. Yuan⁶⁶, A. Yurkewicz¹⁰⁶, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev¹²⁸, L. Zanello^{132a,132b}, D. Zanzi⁹⁹, A. Zaytsev²⁵, C. Zeitnitz¹⁷⁵, M. Zeman¹²⁶, A. Zemla³⁹, O. Zenin¹²⁸, T. Ženiš^{144a}, Z. Zinonos^{122a,122b}, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, D. Zhang⁸⁷, H. Zhang⁸⁸, J. Zhang⁶, X. Zhang^{33d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁸, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{33d}, H. Zhu⁴², J. Zhu⁸⁷, Y. Zhu^{33b}, X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, A. Zibell⁹⁸, D. Zieminska⁶⁰, N.I. Zimin⁶⁴, R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁵, L. Živković³⁵, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷³, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, V. Zutshi¹⁰⁶, L. Zwalinski³⁰.

¹ School of Chemistry and Physics, University of Adelaide, Adelaide, Australia

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

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

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Dumlupinar University, Kutahya; (c) Department of Physics, Gazi University, Ankara; (d) Division of Physics, TOBB University of Economics and Technology, Ankara; (e) Turkish Atomic Energy Authority, Ankara, Turkey

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

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

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

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

⁹ Physics Department, University of Athens, Athens, Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece

¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹² Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

¹³ (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

¹⁶ Department of Physics, Humboldt University, Berlin, Germany

¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey

²⁰ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy

²¹ Physikalisches Institut, University of Bonn, Bonn, Germany

²² Department of Physics, Boston University, Boston MA, United States of America

²³ Department of Physics, Brandeis University, Waltham MA, United States of America

²⁴ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁵ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

²⁶ (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania

²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

²⁹ Department of Physics, Carleton University, Ottawa ON, Canada

³⁰ CERN, Geneva, Switzerland

³¹ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

³² (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

- ³³ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Department of Modern Physics, University of Science and Technology of China, Anhui; ^(c) Department of Physics, Nanjing University, Jiangsu; ^(d) School of Physics, Shandong University, Shandong; ^(e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
- ³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵ Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ³⁶ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁷ ^(a) INFN Gruppo Collegato di Cosenza; ^(b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
- ³⁸ AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas TX, United States of America
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴² DESY, Hamburg and Zeuthen, Germany
- ⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴ Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁵ Department of Physics, Duke University, Durham NC, United States of America
- ⁴⁶ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton VA, United States of America
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- ⁵⁸ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰ Department of Physics, Indiana University, Bloomington IN, United States of America
- ⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶² University of Iowa, Iowa City IA, United States of America
- ⁶³ Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- ⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

-
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁹ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁰ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸¹ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸² School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸³ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁴ Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁸⁵ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁶ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁷ Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ⁸⁸ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ⁸⁹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹¹ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹² Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- ⁹³ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁶ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁷ D.V.Skobeltzyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ⁹⁸ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰¹ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰² ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰³ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁴ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁵ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- ¹⁰⁷ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁸ Department of Physics, New York University, New York NY, United States of America
- ¹⁰⁹ Ohio State University, Columbus OH, United States of America
- ¹¹⁰ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹¹ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹² Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹³ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁴ Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁵ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁶ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁷ Department of Physics, University of Oslo, Oslo, Norway
- ¹¹⁸ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹¹⁹ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²⁰ Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- ¹²¹ Petersburg Nuclear Physics Institute, Gatchina, Russia
- ¹²² ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²³ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

- 124 (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- 125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 126 Czech Technical University in Prague, Praha, Czech Republic
- 127 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 128 State Research Center Institute for High Energy Physics, Protvino, Russia
- 129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 130 Physics Department, University of Regina, Regina SK, Canada
- 131 Ritsumeikan University, Kusatsu, Shiga, Japan
- 132 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- 133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
- 135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- 136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- 137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- 138 Department of Physics, University of Washington, Seattle WA, United States of America
- 139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 140 Department of Physics, Shinshu University, Nagano, Japan
- 141 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
- 143 SLAC National Accelerator Laboratory, Stanford CA, United States of America
- 144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 145 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
- 147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- 149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 150 School of Physics, University of Sydney, Sydney, Australia
- 151 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- 153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 158 Department of Physics, University of Toronto, Toronto ON, Canada
- 159 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
- 160 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- 161 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- 162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

¹⁶⁴ ^(a) INFN Gruppo Collegato di Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

¹⁶⁵ Department of Physics, University of Illinois, Urbana IL, United States of America

¹⁶⁶ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

¹⁶⁷ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

¹⁶⁸ Department of Physics, University of British Columbia, Vancouver BC, Canada

¹⁶⁹ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

¹⁷⁰ Department of Physics, University of Warwick, Coventry, United Kingdom

¹⁷¹ Waseda University, Tokyo, Japan

¹⁷² Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

¹⁷³ Department of Physics, University of Wisconsin, Madison WI, United States of America

¹⁷⁴ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

¹⁷⁵ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

¹⁷⁶ Department of Physics, Yale University, New Haven CT, United States of America

¹⁷⁷ Yerevan Physics Institute, Yerevan, Armenia

¹⁷⁸ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

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

^b Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal

^c Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal

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

^e Also at Department of Physics, University of Johannesburg, Johannesburg, South Africa

^f Also at TRIUMF, Vancouver BC, Canada

^g Also at Department of Physics, California State University, Fresno CA, United States of America

^h Also at Novosibirsk State University, Novosibirsk, Russia

ⁱ Also at Department of Physics, University of Coimbra, Coimbra, Portugal

^j Also at Department of Physics, UASLP, San Luis Potosi, Mexico

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

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

^m Also at Department of Physics, Middle East Technical University, Ankara, Turkey

ⁿ Also at Louisiana Tech University, Ruston LA, United States of America

^o Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

^p Also at Department of Physics and Astronomy, University College London, London, United Kingdom

^q Also at Department of Physics, University of Cape Town, Cape Town, South Africa

^r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

^s Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

^t Also at Manhattan College, New York NY, United States of America

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

^v Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

^w Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

^x Also at School of Physics, Shandong University, Shandong, China

^y Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

^z Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Énergie Atomique et aux Énergies Alternatives), Gif-sur-Yvette, France

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

^{ab} Also at Departamento de Física, Universidade de Minho, Braga, Portugal

^{ac} Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

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

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

^{af} Also at California Institute of Technology, Pasadena CA, United States of America

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

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

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

^{aj} Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America

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

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

^{am} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

^{an} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

* Deceased