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Search for Diphoton Events with Large Missing Transverse Energy in 7 TeV Proton-Proton Collisions with the ATLAS Detector

G. Aad *et al.**

(ATLAS Collaboration)

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A search for diphoton events with large missing transverse energy is presented. The data were collected with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV at the CERN Large Hadron Collider and correspond to an integrated luminosity of 3.1 pb^{-1} . No excess of such events is observed above the standard model background prediction. In the context of a specific model with one universal extra dimension with compactification radius R and gravity-induced decays, values of $1/R < 729$ GeV are excluded at 95% C. L., providing the most sensitive limit on this model to date.

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In the standard model (SM), the production in proton-proton (pp) collisions of diphoton ($\gamma\gamma$) events with large missing transverse energy (E_T^{miss}) is mainly due to $W/Z + \gamma\gamma$ processes. Taking into account the branching ratios of W/Z decays including at least one neutrino, the cross sections are only a few femtobarns for 7 TeV pp collisions. In contrast, some new physics models predict much larger $\gamma\gamma + E_T^{\text{miss}}$ rates. This Letter reports the first $\gamma\gamma + E_T^{\text{miss}}$ search with LHC data, using data recorded with the ATLAS detector. The results are interpreted in the context of a universal extra dimension (UED) model.

UED models [1] postulate the existence of additional spatial dimensions in which all SM particles can propagate, leading to the existence for each SM particle of a series of excitations, known as a Kaluza-Klein (KK) tower. This analysis considers the case of a single TeV^{-1} -sized UED, with compactification radius R . The masses of the states of successive levels in the tower are separated by $\approx 1/R$. For a given KK level, the approximate mass degeneracy of the KK excitations is broken by radiative corrections [2]. The lightest KK particle (LKP) is the KK photon of the first level, denoted γ^* . At the LHC, the main UED process would be production via the strong interaction of a pair of first-level KK quarks and/or gluons [3], which would decay via cascades involving other KK particles until reaching the LKP at the end of the decay chain. If the UED model is embedded in a larger space with N additional eV^{-1} -sized dimensions accessible only to gravity [4], the LKP could decay gravitationally via $\gamma^* \rightarrow \gamma + G$ [5], where G represents one of a tower of eV -spaced graviton states. With two decay chains per event, the final state would be $\gamma\gamma + E_T^{\text{miss}} + X$, where E_T^{miss} results from

the escaping gravitons and X represents SM particles emitted in the cascade decays.

The UED model considered is defined by specifying R and Λ , the ultraviolet cutoff used in the calculation of radiative corrections to the KK masses. This analysis treats R as a free parameter and, following the theory calculations [2], sets Λ such that $\Lambda R = 20$. For $1/R = 700$ GeV, the masses of the first-level KK photon, quark, and gluon are 700, 815, and 865 GeV, respectively [6]. The γ^* mass is insensitive to Λ , while other KK masses change by typically a few percent when varying ΛR in the range 10–30. The gravitational decay widths of the KK particles are set by N and M_D , the Planck scale in the $(4 + N)$ -dimensional theory. For the chosen values of $N = 6$ and $M_D = 5$ TeV, and provided $1/R < 1$ TeV, the LKP is the only KK particle to have an appreciable rate of gravitational decay. The same parameter values were used in the only previous study of this model, in which the D0 experiment excluded at 95% C. L. values of $1/R < 477$ GeV [7].

Monte Carlo (MC) signal samples were produced for a range of $1/R$ values using the implementation [6] of the UED model in PYTHIA [8] version 6.421, and using the MC09 parameter tune [9]. The MC samples were processed through the ATLAS detector simulation [10] based on GEANT4 [11]. In addition to the two high transverse energy (E_T) photons and large E_T^{miss} , the signal events typically include several high- E_T jets due to the cascade decays, with the E_T spectrum of the leading jet peaking at ≈ 100 GeV for $1/R = 700$ GeV.

The ATLAS detector [12] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and nearly 4π solid angle coverage. ATLAS uses a Cartesian right-handed coordinate system, with the nominal collision point at the origin. The anti-clockwise beam direction defines the positive z axis, while the positive x axis points from the collision point to the center of the LHC ring and the positive y axis points upward. The angles ϕ and θ are the azimuthal and polar angles. The pseudorapidity is defined as

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

$\eta = -\ln[\tan(\theta/2)]$. Closest to the beam line are tracking detectors which use layers of silicon-based and straw-tube detectors, located inside a thin superconducting solenoid that provides a 2 T magnetic field, to measure the trajectories of charged particles. The solenoid is surrounded by a hermetic calorimeter system. A liquid-argon (LAr) sampling calorimeter is divided into a central barrel calorimeter and two end-cap calorimeters, each housed in a separate cryostat. Fine-grained LAr electromagnetic (EM) calorimeters, with excellent energy resolution, provide coverage for $|\eta| < 3.2$. In the region $|\eta| < 2.5$, the EM calorimeters are segmented into three longitudinal layers and the second layer, in which most of the EM shower energy is deposited, is divided into cells of granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. A presampler, covering $|\eta| < 1.8$, is used to correct for energy lost upstream of the calorimeter. An iron-scintillator tile calorimeter provides hadronic coverage in the range $|\eta| < 1.7$. In the end caps ($|\eta| > 1.5$), LAr hadronic calorimeters match the outer $|\eta|$ limits of the end-cap EM calorimeters. LAr forward calorimeters provide both EM and hadronic energy measurements, and extend the coverage to $|\eta| < 4.9$. Outside the calorimeters is an extensive muon system including large superconducting toroidal magnets.

The reconstruction of photons is described in detail in Ref. [13]. To select photon candidates, EM calorimeter clusters were required to pass several quality criteria and to lie outside problematic calorimeter regions. Photon candidates were required to have $|\eta| < 1.81$ and to be outside the transition region $1.37 < |\eta| < 1.52$ between the barrel and the end-cap calorimeters. The analysis uses a “loose” photon selection, which includes cuts on the energy in the hadronic calorimeter as well as on variables that require the transverse width of the shower, measured in the second EM calorimeter layer, be consistent with the narrow width expected for an EM shower. The loose selection provides a high photon efficiency with modest rejection against the background from jets.

The reconstruction of E_T^{miss} is based on topological calorimeter clusters [14] with $|\eta| < 4.5$ that are seeded by any cell with energy higher than 4 times its noise level. In an iterative procedure, the cluster grows by including all neighboring cells with energy higher than twice the noise, plus all cells neighboring the boundary of this three-dimensional collection. Each cluster is classified as EM or hadronic, depending on its topology, and the cluster energy is calibrated to correct for the noncompensating calorimeter response, energy losses in dead material, and out-of-cluster energies. Events reconstructed with large E_T^{miss} were studied in detail with early data [15]. Rare background events with large transverse energies, unrelated to the collision and concentrated in a few cells, due mainly to discharges and noise, have been observed. Cuts were applied to eliminate such backgrounds, rejecting less than 0.05% of the selected events while having a negligible impact on the signal efficiency.

The data sample was collected during stable beam periods of 7 TeV pp collisions at the LHC, and corresponds to an integrated luminosity of 3.1 pb^{-1} . The events selected had to satisfy a trigger requiring at least one loose photon candidate with $E_T > 20 \text{ GeV}$, and had to contain at least one reconstructed primary vertex consistent with the average beam spot position and with at least three associated tracks. The trigger and vertex requirements are $\approx 99\%$ efficient for signal MC events. The presence of multiple pp collisions within the same bunch crossing, known as “pileup,” can be analyzed by examining N_{vtx} , the number of reconstructed primary vertices in each event. In this data sample, the average value of N_{vtx} was ≈ 2.1 . The MC signal samples included the simulation of pileup and were weighted to match the N_{vtx} distribution observed in data.

Events were retained if they had at least two photon candidates, each with $E_T > 25 \text{ GeV}$. In addition, a photon isolation cut was applied, wherein the E_T in a radius of 0.2 in the η - ϕ space around the center of the cluster, excluding the cells belonging to the cluster in a region corresponding to 5×7 cells in $\eta \times \phi$ in the second layer of the EM calorimeter, had to be less than 35 GeV. This requirement had a signal efficiency greater than 95% but rejected some of the background from multijet events. An event in which each of the two photon candidates satisfied the loose photon cuts was considered a $\gamma\gamma$ candidate event. An independent “misidentified jet” control sample, enriched in events with jets misidentified as photons, was defined as those events where at least one of the photon candidates did not pass the loose photon identification. After all cuts, the $\gamma\gamma$ and misidentified jet samples totaled 520 and 7323 events, respectively. Figure 1 shows the E_T spectrum of the leading photon for the $\gamma\gamma$ candidates and for UED $1/R = 700 \text{ GeV}$ MC events; the UED spectrum extends to much higher E_T values.

The background was evaluated entirely using data. Noncollision backgrounds, such as cosmic rays and beam-halo events, are reduced to a negligible level by the

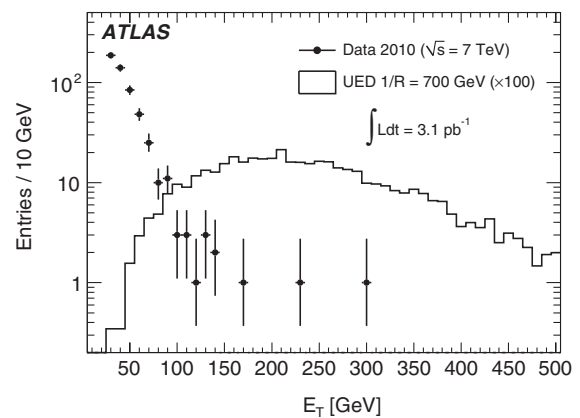


FIG. 1. E_T spectrum of the leading photon for the $\gamma\gamma$ candidate sample and for UED $1/R = 700 \text{ GeV}$ MC events (normalized to 100 times the leading order (LO) cross section).

selection cuts. The main background source, referred to hereafter as QCD background, arises from a mixture of SM processes including $\gamma\gamma$ production, and γ + jet and multi-jet events with at least one jet misidentified as a photon. With the loose photon identification, it is expected that γ + jet and multijet events dominate, with only a small $\gamma\gamma$ contribution. The misidentified jet sample provided a model of the E_T^{miss} response for events with jets faking photons. The response for $\gamma\gamma$ events was modeled using the E_T^{miss} spectrum measured in a high purity sample of $Z \rightarrow ee$ events, selected by a combination of kinematic cuts and electron identification requirements [14]. The E_T^{miss} spectrum for $Z \rightarrow ee$ events, which is dominated by the calorimeter response to two genuine EM objects, was verified in MC simulations to model the E_T^{miss} response in SM $\gamma\gamma$ processes, despite their kinematic differences. As shown in Fig. 2, $Z \rightarrow ee$ events typically have somewhat lower E_T^{miss} values than events of the misidentified jet sample, as expected since the presence of jets faking photons should result in a broader E_T^{miss} distribution. The spectrum for the $\gamma\gamma$ candidates, which for low E_T^{miss} is dominated by the QCD background with an unknown mixture of events with zero, one, and two fake photons, lies between these two samples. The E_T^{miss} spectrum of the total QCD background was modeled by a weighted sum of the spectra of the $Z \rightarrow ee$ and misidentified jet samples. The QCD background was normalized to have the same number of events as the $\gamma\gamma$ candidate sample in the region $E_T^{\text{miss}} < 20$ GeV, where any UED signal contribution can

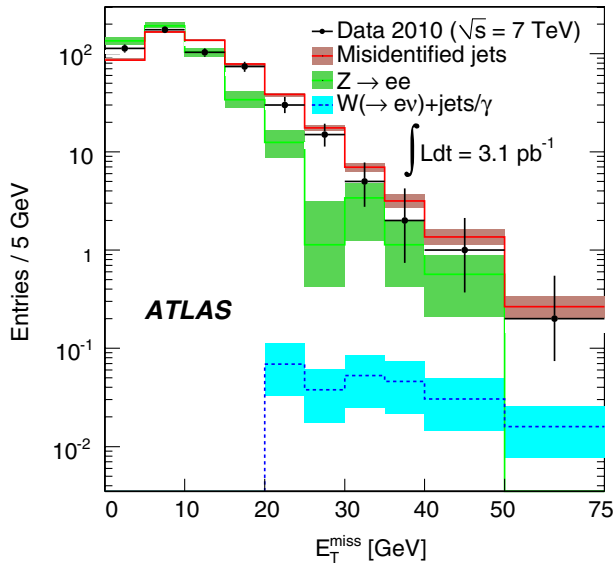


FIG. 2 (color online). E_T^{miss} spectra for the $\gamma\gamma$ candidates, for the $Z \rightarrow ee$ and misidentified jet samples used to model the QCD background (each normalized to the number of $\gamma\gamma$ candidates with $E_T^{\text{miss}} < 20$ GeV), and for the $W(\rightarrow e\nu) + \text{jets}/\gamma$ background (normalized to its expected total of ≈ 0.4 events). Variable sized bins are used, and the vertical error bars and shaded bands show the statistical errors.

be neglected. The relative contributions of the $Z \rightarrow ee$ and misidentified jet samples were determined by fitting the QCD background shape to the E_T^{miss} spectrum of the $\gamma\gamma$ candidates in this same low E_T^{miss} region. The fraction attributed to $\gamma\gamma$ production, as modeled with the $Z \rightarrow ee$ distribution, was determined to be $(36 \pm 22)\%$. The search result is not very sensitive to the exact composition of the QCD background, and the fit error was used to determine systematic uncertainties on the background prediction.

A small additional background results from $W \rightarrow e\nu$ events, which have genuine E_T^{miss} and which can pass the selection if the electron is misidentified as a photon and the second photon is either a real photon in $W\gamma$ events or a jet faking a photon in $W + \text{jets}$ events. A high purity sample of inclusive $W \rightarrow e\nu$ events was selected by a combination of kinematic and electron identification cuts [14]. Requiring in addition a loose photon with $E_T^\gamma > 25$ GeV, a “ $W + \gamma$ ” sample of only 5 events was selected. Accounting for the probability for an electron to be misidentified as a loose photon, as determined using the $Z \rightarrow ee$ sample, the total background contribution due to $W \rightarrow e\nu$ events was then estimated to be only ≈ 0.4 events. Since the number of $W\gamma$ events was too small to measure their E_T^{miss} spectrum, a sample of $W + \text{jets}$ events was used instead, requiring a jet reconstructed with an anti- k_T clustering algorithm [16] with radius parameter 0.4 and $E_T^j > 25$ GeV. The $W(\rightarrow e\nu) + \text{jets}/\gamma$ background contribution was then estimated by normalizing the $W + \text{jets}$ E_T^{miss} spectrum to the expected total of ≈ 0.4 events, as shown on Fig. 2.

Figure 3 shows the E_T^{miss} spectrum of the $\gamma\gamma$ candidates, superimposed on the total background prediction, as well

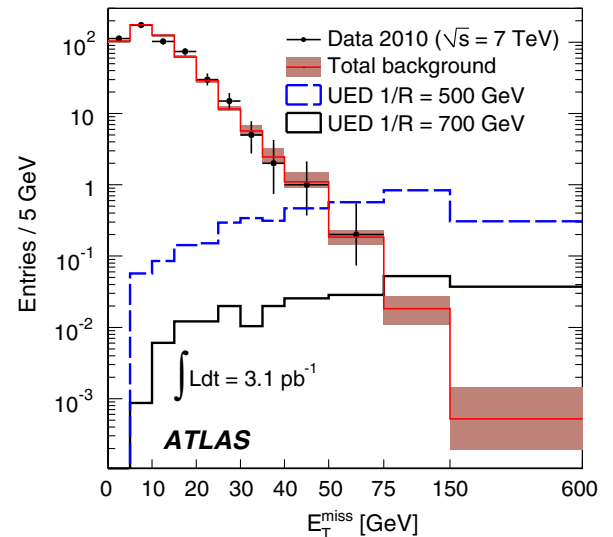


FIG. 3 (color online). E_T^{miss} spectrum for the $\gamma\gamma$ candidates, compared to the total SM background as estimated from data. Also shown are the expected UED signals for $1/R = 500$ GeV and 700 GeV. Variable sized bins are used, and the vertical error bars and shaded bands show the statistical errors.

TABLE I. The number of observed $\gamma\gamma$ candidates, as well as the SM backgrounds estimated from data and expected UED signal for $1/R$ values of 500 and 700 GeV, given in various E_T^{miss} ranges. The uncertainties are statistical only. The first row, for $E_T^{\text{miss}} < 20$ GeV, is the control region used to normalize the QCD background to the number of observed $\gamma\gamma$ candidates.

E_T^{miss} range (GeV)	Data events	Predicted background events			Expected UED signal events	
		Total	QCD	$W(\rightarrow e\nu) + \text{jets}/\gamma$	$1/R = 500$ GeV	$1/R = 700$ GeV
0–20	465	465.0 ± 9.1	465.0 ± 9.1	-	0.28 ± 0.06	0.02 ± 0.01
20–30	45	40.5 ± 2.2	40.41 ± 2.17	0.11 ± 0.07	0.45 ± 0.07	0.03 ± 0.01
30–50	9	10.3 ± 1.3	10.13 ± 1.30	0.16 ± 0.10	1.60 ± 0.12	0.08 ± 0.01
50–75	1	0.93 ± 0.23	0.85 ± 0.23	0.08 ± 0.05	2.84 ± 0.16	0.14 ± 0.01
>75	0	0.32 ± 0.16	0.28 ± 0.15	0.04 ± 0.03	40.45 ± 0.62	4.21 ± 0.06

as example UED signals. Table I summarizes the number of observed $\gamma\gamma$ candidates, as well as the expected backgrounds and example UED signal contributions, in several E_T^{miss} ranges. The QCD background dominates, and falls steeply with rising E_T^{miss} , while the $W \rightarrow e\nu$ background is very small, and flatter as a function of E_T^{miss} . The UED signals would peak at large values of E_T^{miss} . There is good agreement between the data and predicted background over the entire E_T^{miss} range, with no indication of an excess at high E_T^{miss} values.

The signal search region was chosen to be $E_T^{\text{miss}} > 75$ GeV, before looking at the data, to obtain the best sensitivity to the UED signal. In the signal region, there are zero observed events, compared to an expectation of $0.32 \pm 0.16(\text{stat})_{-0.10}^{+0.37}(\text{syst})$ background events. The systematic uncertainty was derived by studying variations of the background determination, including varying within its error the $\gamma\gamma$ fraction determined in the fit of the QCD background, varying the definition of the misidentified jet sample, and eliminating the photon isolation cut.

The UED signal efficiency, determined from MC simulations, increases smoothly from $\approx 43\%$ for $1/R = 500$ GeV to $\approx 48\%$ for $1/R = 700$ GeV, with the lower efficiencies for smaller $1/R$ due mostly to the $E_T^{\text{miss}} > 75$ GeV definition of the signal region. The various relative systematic uncertainties on the extraction of the UED signal cross section are summarized in Table II, including the dominant 11% uncertainty on the integrated luminosity [17]. Uncertainties on the efficiency for reconstructing and identifying the $\gamma\gamma$ pair arise mainly due to

TABLE II. Relative systematic uncertainties on the expected UED signal yield. For more details, see the text.

Source of uncertainty	Uncertainty
Integrated luminosity	11%
Photon reconstruction and identification	4%
Effect of pileup	2%
E_T^{miss} reconstruction and scale	1%
Signal MC statistics	1%
Total	12%

differences between MC simulations and data in the distributions of the photon identification variables, the need to extrapolate to the higher E_T values (see Fig. 1) typical of the UED photons, the impact of the photon quality cuts, varying the scale of the photon E_T cut, and uncertainties in the detailed material composition of the detector. Together these provide a systematic uncertainty of 4%. The influence of pileup, evaluated by comparing MC samples with and without pileup, gives a systematic uncertainty of 2%. Systematic effects on the E_T^{miss} reconstruction [14], including pileup, varying the cluster energies within the current uncertainties, and varying the expected E_T^{miss} resolution between the measured performance and MC expectations, combine to give a 1% uncertainty on the signal efficiency. Finally, the 1% statistical error on the signal efficiency as determined by MC simulations is treated as a systematic uncertainty on the result. Adding in quadrature, the total systematic uncertainty on the signal yield is 12%.

Given the good agreement between the measured E_T^{miss} spectrum and the expected background, a limit was set on $1/R$ in the specific UED model considered here. A Bayesian approach was used to calculate a limit based on the number of observed and expected events with $E_T^{\text{miss}} > 75$ GeV. A Poisson distribution was used as the likelihood function for the expected number of signal events, and a flat prior was used for the signal cross section. Log-normal priors were used for the various sources of uncertainty, which were treated as nuisance parameters. It was verified that the result is not very sensitive to the detailed form of the assumed priors. Figure 4 depicts the resulting 95% C.L. upper limit within the context of the UED model considered, together with the LO UED cross section as a function of $1/R$. The LO cross section was used since higher order corrections have not been calculated for the UED model. An uncertainty on the signal cross section due to parton distribution functions (PDF's) was determined by comparing the predictions using MRST2007 [18] PDF's with those from the full set of error PDF's of CTEQ6.6 [19]. The resultant uncertainty, namely $\pm 8\%$ essentially independent of $1/R$, is shown by the width of the theory curve band. The observed 95% C.L. exclusion region is $1/R < 729$ GeV. The result depends weakly on the systematic

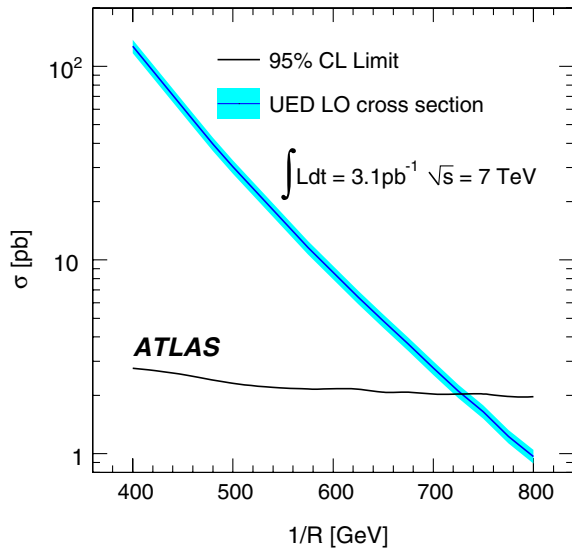


FIG. 4 (color online). 95% C.L. upper limits on the UED production cross section, and the LO theory cross section prediction, as a function of $1/R$. The shaded band shows the PDF uncertainty.

uncertainties, and would only increase to 732 GeV if they were neglected. Changing the E_T^{miss} cut to 60 or 90 GeV would change the limit by only a few GeV. A cross-check using a higher purity $\gamma\gamma$ sample, achieved by requiring that both photons pass tighter identification cuts that reject more of the background from jets, produced a consistent result.

In conclusion, a search for $\gamma\gamma$ events with large E_T^{miss} , conducted using a 3.1 pb^{-1} sample of 7 TeV pp collisions recorded with the ATLAS detector at the LHC, found no evidence of an excess above the SM prediction. The results were used to set limits on a specific model with one UED and gravity-induced LKP decays, excluding at the 95% C.L. values of $1/R < 729 \text{ GeV}$, and significantly surpassing the only existing experimental limit [7] on this model.

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- G. Aad,⁴⁸ B. Abbott,¹¹¹ J. Abdallah,¹¹ A. A. Abdelalim,⁴⁹ A. Abdesselam,¹¹⁸ O. Abdinov,¹⁰ B. Abi,¹¹² M. Abolins,⁸⁸ H. Abramowicz,¹⁵³ H. Abreu,¹¹⁵ E. Acerbi,^{89a,89b} B. S. Acharya,^{164a,164b} M. Ackers,²⁰ D. L. Adams,²⁴ T. N. Addy,⁵⁶ J. Adelman,¹⁷⁵ M. Aderholz,⁹⁹ S. Adomeit,⁹⁸ P. Adragna,⁷⁵ T. Adye,¹²⁹ S. Aefsky,²² J. A. Aguilar-Saavedra,^{124b,b} M. Aharrouche,⁸¹ S. P. Ahlen,²¹ F. Ahles,⁴⁸ A. Ahmad,¹⁴⁸ M. Ahsan,⁴⁰ G. Aielli,^{133a,133b} T. Akdogan,^{18a} T. P. A. Åkesson,⁷⁹ G. Akimoto,¹⁵⁵ A. V. Akimov,⁹⁴ M. S. Alam,¹ M. A. Alam,⁷⁶ S. Albrand,⁵⁵ M. Aleksa,²⁹ I. N. Aleksandrov,⁶⁵ M. Aleppo,^{89a,89b} F. Alessandria,^{89a} C. Alexa,^{25a} G. Alexander,¹⁵³ G. Alexandre,⁴⁹ T. Alexopoulos,⁹ M. Alhroob,²⁰ M. Aliev,¹⁵ G. Alimonti,^{89a} J. Alison,¹²⁰ M. Aliyev,¹⁰ P. P. Allport,⁷³ S. E. Allwood-Spiers,⁵³ J. Almond,⁸² A. Aloisio,^{102a,102b} R. Alon,¹⁷¹ A. Alonso,⁷⁹ J. Alonso,¹⁴ M. G. Alviggi,^{102a,102b} K. Amako,⁶⁶ P. Amaral,²⁹ C. Amelung,²² V. V. Ammosov,¹²⁸ A. Amorim,^{124a,c} G. Amorós,¹⁶⁷ N. Amram,¹⁵³ C. Anastopoulos,¹³⁹ T. Andeen,³⁴ C. F. Anders,²⁰ K. J. Anderson,³⁰ A. Andreazza,^{89a,89b} V. Andrei,^{58a} M-L. Andrieux,⁵⁵ X. S. Anduaga,⁷⁰ A. Angerami,³⁴ F. Anghinolfi,²⁹ N. Anjos,^{124a} A. Annovi,⁴⁷ A. Antonaki,⁸ M. Antonelli,⁴⁷ S. Antonelli,^{19a,19b} J. Antos,^{144b} F. Anulli,^{132a} S. Aoun,⁸³ L. Aperio Bella,⁴ R. Apolle,¹¹⁸ G. Arabidze,⁸⁸ I. Aracena,¹⁴³ Y. Arai,⁶⁶ A. T. H. Arce,⁴⁴ J. P. Archambault,²⁸ S. Arfaoui,^{29,d} J-F. Arguin,¹⁴ E. Arik,^{18a,a} M. Arik,^{18a} A. J. Armbruster,⁸⁷ K. E. Arms,¹⁰⁹ S. R. Armstrong,²⁴ O. Arnaez,⁸¹ C. Arnault,¹¹⁵ A. Artamonov,⁹⁵ G. Artoni,^{132a,132b} D. Arutinov,²⁰ S. Asai,¹⁵⁵ R. Asfandiyarov,¹⁷² S. Ask,²⁷ B. Åsman,^{146a,146b} L. Asquith,⁵ K. Assamagan,²⁴ A. Astbury,¹⁶⁹ A. Astvatsatourov,⁵² G. Atoian,¹⁷⁵ B. Aubert,⁴ B. Auerbach,¹⁷⁵ E. Auge,¹¹⁵ K. Augsten,¹²⁷ M. Aurousseau,⁴ N. Austin,⁷³ R. Avramidou,⁹ D. Axen,¹⁶⁸ C. Ay,⁵⁴ G. Azuelos,^{93,e} Y. Azuma,¹⁵⁵ M. A. Baak,²⁹ G. Baccaglioni,^{89a} C. Bacci,^{134a,134b} A. M. Bach,¹⁴ H. Bachacou,¹³⁶ K. Bachas,²⁹ G. Bachy,²⁹ M. Backes,⁴⁹ E. Badescu,^{25a} P. Bagnaia,^{132a,132b} S. Bahinipati,² Y. Bai,^{32a} D. C. Bailey,¹⁵⁸ T. Bain,¹⁵⁸ J. T. Baines,¹²⁹ O. K. Baker,¹⁷⁵ S. Baker,⁷⁷ F. Baltasar Dos Santos Pedrosa,²⁹ E. Banas,³⁸ P. Banerjee,⁹³ Sw. Banerjee,¹⁶⁹ D. Banfi,^{89a,89b} A. Bangert,¹³⁷ V. Bansal,¹⁶⁹ H. S. Bansil,¹⁷ L. Barak,¹⁷¹ S. P. Baranov,⁹⁴ A. Barashkou,⁶⁵ A. Barbaro Galtieri,¹⁴ T. Barber,²⁷ E. L. Barberio,⁸⁶ D. Barberis,^{50a,50b} M. Barbero,²⁰ D. Y. Bardin,⁶⁵ T. Barillari,⁹⁹ M. Barisonzi,¹⁷⁴ T. Barklow,¹⁴³ N. Barlow,²⁷ B. M. Barnett,¹²⁹ R. M. Barnett,¹⁴ A. Baroncelli,^{134a} A. J. Barr,¹¹⁸ F. Barreiro,⁸⁰ J. Barreiro Guimarães da Costa,⁵⁷ P. Barrillon,¹¹⁵ R. Bartoldus,¹⁴³ A. E. Barton,⁷¹ D. Bartsch,²⁰ R. L. Bates,⁵³ L. Batkova,^{144a} J. R. Batley,²⁷ A. Battaglia,¹⁶ M. Battistin,²⁹ G. Battistoni,^{89a} F. Bauer,¹³⁶ H. S. Bawa,¹⁴³ B. Beare,¹⁵⁸ T. Beau,⁷⁸ P. H. Beauchemin,¹¹⁸ R. Beccherle,^{50a} P. Bechtle,⁴¹ H. P. Beck,¹⁶ M. Beckingham,⁴⁸ K. H. Becks,¹⁷⁴ A. J. Beddall,^{18c} A. Beddall,^{18c} V. A. Bednyakov,⁶⁵ C. Bee,⁸³ M. Begel,²⁴ S. Behar Harpaz,¹⁵² P. K. Behera,⁶³ M. Beimforde,⁹⁹ C. Belanger-Champagne,¹⁶⁶ P. J. Bell,⁴⁹ W. H. Bell,⁴⁹ G. Bella,¹⁵³ L. Bellagamba,^{19a} F. Bellina,²⁹ G. Bellomo,^{89a,89b} M. Bellomo,^{119a} A. Belloni,⁵⁷ K. Belotskiy,⁹⁶ O. Beltramello,²⁹ S. Ben Ami,¹⁵² O. Benary,¹⁵³ D. Benchechroun,^{135a} C. Benchouk,⁸³ M. Bendel,⁸¹ B. H. Benedict,¹⁶³ N. Benekos,¹⁶⁵ Y. Benhammou,¹⁵³ D. P. Benjamin,⁴⁴ M. Benoit,¹¹⁵ J. R. Bensinger,²² K. Benslama,¹³⁰ S. Bentvelsen,¹⁰⁵ D. Berge,²⁹ E. Bergeas Kuutmann,⁴¹ N. Berger,⁴ F. Berghaus,¹⁶⁹ E. Berglund,⁴⁹ J. Beringer,¹⁴ K. Bernardet,⁸³ P. Bernat,¹¹⁵ R. Bernhard,⁴⁸ C. Bernius,²⁴ T. Berry,⁷⁶ A. Bertin,^{19a,19b} F. Bertinelli,²⁹ F. Bertolucci,^{122a,122b} M. I. Besana,^{89a,89b} N. Besson,¹³⁶ S. Bethke,⁹⁹ W. Bhimji,⁴⁵ R. M. Bianchi,²⁹ M. Bianco,^{72a,72b} O. Biebel,⁹⁸ J. Biesiada,¹⁴ M. Biglietti,^{132a,132b} H. Bilokon,⁴⁷ M. Bindi,^{19a,19b} A. Bingul,^{18c} C. Bini,^{132a,132b} C. Biscarat,¹⁷⁷ U. Bitenc,⁴⁸ K. M. Black,²¹ R. E. Blair,⁵ J.-B. Blanchard,¹¹⁵ G. Blanchot,²⁹ C. Blocker,²² J. Blocki,³⁸ A. Blondel,⁴⁹ W. Blum,⁸¹ U. Blumenschein,⁵⁴ G. J. Bobbink,¹⁰⁵ V. B. Bobrovnikov,¹⁰⁷ A. Bocci,⁴⁴ R. Bock,²⁹ C. R. Boddy,¹¹⁸ M. Boehler,⁴¹ J. Boek,¹⁷⁴ N. Boelaert,³⁵ S. Böser,⁷⁷ J. A. Bogaerts,²⁹ A. Bogdanchikov,¹⁰⁷ A. Bogouch,^{90,a} C. Bohm,^{146a} V. Boisvert,⁷⁶ T. Bold,^{163,f} V. Boldea,^{25a} M. Bona,⁷⁵ M. Boonekamp,¹³⁶ G. Boorman,⁷⁶ C. N. Booth,¹³⁹ P. Booth,¹³⁹ J. R. A. Booth,¹⁷ S. Bordini,⁷⁸ C. Borer,¹⁶ A. Borisov,¹²⁸ G. Borissov,⁷¹ I. Borjanovic,^{12a} S. Borroni,^{132a,132b} K. Bos,¹⁰⁵ D. Boscherini,^{19a} M. Bosman,¹¹ H. Boterenbrood,¹⁰⁵ D. Botterill,¹²⁹ J. Bouchami,⁹³ J. Boudreau,¹²³ E. V. Bouhova-Thacker,⁷¹ C. Boulahouache,¹²³ C. Bourdarios,¹¹⁵ N. Bousson,⁸³ A. Boveia,³⁰ J. Boyd,²⁹ I. R. Boyko,⁶⁵ N. I. Bozhko,¹²⁸ I. Bozovic-Jelisavcic,^{12b} J. Bracinik,¹⁷ A. Braem,²⁹ E. Brambilla,^{72a,72b} P. Branchini,^{134a} G. W. Brandenburg,⁵⁷ A. Brandt,⁷ G. Brandt,⁴¹ O. Brandt,⁵⁴ U. Bratzler,¹⁵⁶ B. Brau,⁸⁴ J. E. Brau,¹¹⁴ H. M. Braun,¹⁷⁴ B. Brelief,¹⁵⁸ J. Bremer,²⁹ R. Brenner,¹⁶⁶ S. Bressler,¹⁵² D. Breton,¹¹⁵ N. D. Brett,¹¹⁸ P. G. Bright-Thomas,¹⁷ D. Britton,⁵³ F. M. Brochu,²⁷ I. Brock,²⁰ R. Brock,⁸⁸ T. J. Brodbeck,⁷¹ E. Brodet,¹⁵³ F. Broggi,^{89a} C. Bromberg,⁸⁸ G. Brooijmans,³⁴ W. K. Brooks,^{31b} G. Brown,⁸² E. Brubaker,³⁰ P. A. Bruckman de Renstrom,³⁸ D. Bruncko,^{144b} R. Bruneliere,⁴⁸ S. Brunet,⁶¹ A. Bruni,^{19a} G. Bruni,^{19a} M. Bruschi,^{19a} T. Buanes,¹³ F. Bucci,⁴⁹ J. Buchanan,¹¹⁸ N. J. Buchanan,² P. Buchholz,¹⁴¹ R. M. Buckingham,¹¹⁸

A. G. Buckley,⁴⁵ S. I. Buda,^{25a} I. A. Budagov,⁶⁵ B. Budick,¹⁰⁸ V. Büscher,⁸¹ L. Bugge,¹¹⁷ D. Buira-Clark,¹¹⁸
 E. J. Buis,¹⁰⁵ O. Bulekov,⁹⁶ M. Bunse,⁴² T. Buran,¹¹⁷ H. Burckhart,²⁹ S. Burdin,⁷³ T. Burgess,¹³ S. Burke,¹²⁹
 E. Busato,³³ P. Bussey,⁵³ C. P. Buszello,¹⁶⁶ F. Butin,²⁹ B. Butler,¹⁴³ J. M. Butler,²¹ C. M. Buttar,⁵³
 J. M. Butterworth,⁷⁷ W. Buttinger,²⁷ T. Byatt,⁷⁷ S. Cabrera Urbán,¹⁶⁷ M. Caccia,^{89a,89b} D. Caforio,^{19a,19b} O. Cakir,^{3a}
 P. Calafiura,¹⁴ G. Calderini,⁷⁸ P. Calfayan,⁹⁸ R. Calkins,¹⁰⁶ L. P. Caloba,^{23a} R. Caloi,^{132a,132b} D. Calvet,³³ S. Calvet,³³
 A. Camard,⁷⁸ P. Camarri,^{133a,133b} M. Cambiaghi,^{119a,119b} D. Cameron,¹¹⁷ J. Cammin,²⁰ S. Campana,²⁹
 M. Campanelli,⁷⁷ V. Canale,^{102a,102b} F. Canelli,³⁰ A. Canepa,^{159a} J. Cantero,⁸⁰ L. Capasso,^{102a,102b}
 M. D. M. Capeans Garrido,²⁹ I. Caprini,^{25a} M. Caprini,^{25a} D. Capriotti,⁹⁹ M. Capua,^{36a,36b} R. Caputo,¹⁴⁸
 C. Caramarcu,^{25a} R. Cardarelli,^{133a} T. Carli,²⁹ G. Carlino,^{102a} L. Carminati,^{89a,89b} B. Caron,^{159a} S. Caron,⁴⁸
 C. Carpentieri,⁴⁸ G. D. Carrillo Montoya,¹⁷² S. Carron Montero,¹⁵⁸ A. A. Carter,⁷⁵ J. R. Carter,²⁷ J. Carvalho,^{124a,g}
 D. Casadei,¹⁰⁸ M. P. Casado,¹¹ M. Cascella,^{122a,122b} C. Caso,^{50a,50b,a} A. M. Castaneda Hernandez,¹⁷²
 E. Castaneda-Miranda,¹⁷² V. Castillo Gimenez,¹⁶⁷ N. F. Castro,^{124b,b} G. Cataldi,^{72a} F. Cataneo,²⁹ A. Catinaccio,²⁹
 J. R. Catmore,⁷¹ A. Cattai,²⁹ G. Cattani,^{133a,133b} S. Caughron,⁸⁸ A. Cavallari,^{132a,132b} P. Cavalleri,⁷⁸ D. Cavalli,^{89a}
 M. Cavalli-Sforza,¹¹ V. Cavasinni,^{122a,122b} A. Cazzato,^{72a,72b} F. Ceradini,^{134a,134b} C. Cerna,⁸³ A. S. Cerqueira,^{23a}
 A. Cerri,²⁹ L. Cerrito,⁷⁵ F. Cerutti,⁴⁷ S. A. Cetin,^{18b} F. Cevenini,^{102a,102b} A. Chafaq,^{135a} D. Chakraborty,¹⁰⁶ K. Chan,²
 B. Chapleau,⁸⁵ J. D. Chapman,²⁷ J. W. Chapman,⁸⁷ E. Chareyre,⁷⁸ D. G. Charlton,¹⁷ V. Chavda,⁸² S. Cheatham,⁷¹
 S. Chekanov,⁵ S. V. Chekulaev,^{159a} G. A. Chelkov,⁶⁵ H. Chen,²⁴ L. Chen,² S. Chen,^{32c} T. Chen,^{32c} X. Chen,¹⁷²
 S. Cheng,^{32a} A. Cheplakov,⁶⁵ V. F. Chepurinov,⁶⁵ R. Cherkaoui El Moursli,^{135d} V. Chernyatin,²⁴ E. Cheu,⁶
 S. L. Cheung,¹⁵⁸ L. Chevalier,¹³⁶ F. Chevallier,¹³⁶ G. Chiefari,^{102a,102b} L. Chikovani,⁵¹ J. T. Childers,^{58a}
 A. Chilingarov,⁷¹ G. Chiodini,^{72a} M. V. Chizhov,⁶⁵ G. Choudalakis,³⁰ S. Chouridou,¹³⁷ I. A. Christidi,⁷⁷
 A. Christov,⁴⁸ D. Chromek-Burckhart,²⁹ M. L. Chu,¹⁵¹ J. Chudoba,¹²⁵ G. Ciapetti,^{132a,132b} A. K. Ciftci,^{3a} R. Ciftci,^{3a}
 D. Cinca,³³ V. Cindro,⁷⁴ M. D. Ciobotaru,¹⁶³ C. Ciocca,^{19a,19b} A. Ciocio,¹⁴ M. Cirilli,⁸⁷ M. Ciubancan,^{25a} A. Clark,⁴⁹
 P. J. Clark,⁴⁵ W. Cleland,¹²³ J. C. Clemens,⁸³ B. Clement,⁵⁵ C. Clement,^{146a,146b} R. W. Clift,¹²⁹ Y. Coadou,⁸³
 M. Cobar,^{164a,164c} A. Coccaro,^{50a,50b} J. Cochran,⁶⁴ P. Coe,¹¹⁸ J. G. Cogan,¹⁴³ J. Coggeshall,¹⁶⁵ E. Cogneras,¹⁷⁷
 C. D. Cojocar,²⁸ J. Colas,⁴ A. P. Colijn,¹⁰⁵ C. Collard,¹¹⁵ N. J. Collins,¹⁷ C. Collins-Tooth,⁵³ J. Collot,⁵⁵ G. Colon,⁸⁴
 R. Coluccia,^{72a,72b} G. Comune,⁸⁸ P. Conde Muiño,^{124a} E. Coniavitis,¹¹⁸ M. C. Conidi,¹¹ M. Consonni,¹⁰⁴
 S. Constantinescu,^{25a} C. Conta,^{119a,119b} F. Conventi,^{102a,h} J. Cook,²⁹ M. Cooke,¹⁴ B. D. Cooper,⁷⁵
 A. M. Cooper-Sarkar,¹¹⁸ N. J. Cooper-Smith,⁷⁶ K. Copic,³⁴ T. Cornelissen,^{50a,50b} M. Corradi,^{19a} S. Correard,⁸³
 F. Corriveau,^{85,i} A. Cortes-Gonzalez,¹⁶⁵ G. Cortiana,⁹⁹ G. Costa,^{89a} M. J. Costa,¹⁶⁷ D. Costanzo,¹³⁹ T. Costin,³⁰
 D. Côté,²⁹ R. Coura Torres,^{23a} L. Courneyea,¹⁶⁹ G. Cowan,⁷⁶ C. Cowden,²⁷ B. E. Cox,⁸² K. Cranmer,¹⁰⁸
 M. Cristinziani,²⁰ G. Crosetti,^{36a,36b} R. Crupi,^{72a,72b} S. Crépe-Renaudin,⁵⁵ C. Cuenca Almenar,¹⁷⁵
 T. Cuhadar Donszelmann,¹³⁹ S. Cuneo,^{50a,50b} M. Curatolo,⁴⁷ C. J. Curtis,¹⁷ P. Cwetanski,⁶¹ H. Czirr,¹⁴¹
 Z. Czyczula,¹¹⁷ S. D'Auria,⁵³ M. D'Onofrio,⁷³ A. D'Orazio,^{132a,132b} A. Da Rocha Gesualdi Mello,^{23a}
 P. V. M. Da Silva,^{23a} C. Da Via,⁸² W. Dabrowski,³⁷ A. Dahlhoff,⁴⁸ T. Dai,⁸⁷ C. Dallapiccola,⁸⁴ S. J. Dallison,^{129,a}
 M. Dam,³⁵ M. Dameri,^{50a,50b} D. S. Damiani,¹³⁷ H. O. Danielsson,²⁹ R. Dankers,¹⁰⁵ D. Dannheim,⁹⁹ V. Dao,⁴⁹
 G. Darbo,^{50a} G. L. Darlea,^{25b} C. Daum,¹⁰⁵ J. P. Dauvergne,²⁹ W. Davey,⁸⁶ T. Davidek,¹²⁶ N. Davidson,⁸⁶
 R. Davidson,⁷¹ M. Davies,⁹³ A. R. Davison,⁷⁷ E. Dawe,¹⁴² I. Dawson,¹³⁹ J. W. Dawson,^{5a} R. K. Daya,³⁹ K. De,⁷
 R. de Asmundis,^{102a} S. De Castro,^{19a,19b} S. De Cecco,⁷⁸ J. de Graat,⁹⁸ N. De Groot,¹⁰⁴ P. de Jong,¹⁰⁵
 E. De La Cruz-Burelo,⁸⁷ C. De La Taille,¹¹⁵ B. De Lotto,^{164a,164c} L. De Mora,⁷¹ L. De Nooij,¹⁰⁵
 M. De Oliveira Branco,²⁹ D. De Pedis,^{132a} P. de Saintignon,⁵⁵ A. De Salvo,^{132a} U. De Sanctis,^{164a,164c} A. De Santo,¹⁴⁹
 J. B. De Vivie De Regie,¹¹⁵ S. Dean,⁷⁷ G. Dedes,⁹⁹ D. V. Dedovich,⁶⁵ J. Degenhardt,¹²⁰ M. Dehchar,¹¹⁸ M. Deile,⁹⁸
 C. Del Papa,^{164a,164c} J. Del Peso,⁸⁰ T. Del Prete,^{122a,122b} A. Dell'Acqua,²⁹ L. Dell'Asta,^{89a,89b} M. Della Pietra,^{102a,h}
 D. della Volpe,^{102a,102b} M. Delmastro,²⁹ P. Delpierre,⁸³ N. Delruelle,²⁹ P. A. Delsart,⁵⁵ C. Deluca,¹⁴⁸ S. Demers,¹⁷⁵
 M. Demichev,⁶⁵ B. Demirköz,¹¹ J. Deng,¹⁶³ S. P. Denisov,¹²⁸ C. Dennis,¹¹⁸ D. Derendarz,³⁸ J. E. Derkaoui,^{135c}
 F. Derue,⁷⁸ P. Dervan,⁷³ K. Desch,²⁰ E. Devetak,¹⁴⁸ P. O. Deviveiros,¹⁵⁸ A. Dewhurst,¹²⁹ B. DeWilde,¹⁴⁸
 S. Dhaliwal,¹⁵⁸ R. Dhullipudi,^{24,j} A. Di Ciaccio,^{133a,133b} L. Di Ciaccio,⁴ A. Di Girolamo,²⁹ B. Di Girolamo,²⁹
 S. Di Luise,^{134a,134b} A. Di Mattia,⁸⁸ R. Di Nardo,^{133a,133b} A. Di Simone,^{133a,133b} R. Di Sipio,^{19a,19b} M. A. Diaz,^{31a}
 F. Diblen,^{18c} E. B. Diehl,⁸⁷ H. Dietl,⁹⁹ J. Dietrich,⁴⁸ T. A. Dietzsch,^{58a} S. Diglio,¹¹⁵ K. Dindar Yagci,³⁹
 J. Dingfelder,²⁰ C. Dionisi,^{132a,132b} P. Dita,^{25a} S. Dita,^{25a} F. Dittus,²⁹ F. Djama,⁸³ R. Djilkibaev,¹⁰⁸ T. Djobava,⁵¹
 M. A. B. do Vale,^{23a} A. Do Valle Wemans,^{124a} T. K. O. Doan,⁴ M. Dobbs,⁸⁵ R. Dobinson,^{29,a} D. Dobos,⁴²
 E. Dobson,²⁹ M. Dobson,¹⁶³ J. Dodd,³⁴ O. B. Dogan,^{18a,a} C. Doglioni,¹¹⁸ T. Doherty,⁵³ Y. Doi,⁶⁶ J. Dolejsi,¹²⁶

- I. Dolenc,⁷⁴ Z. Dolezal,¹²⁶ B. A. Dolgoshein,⁹⁶ T. Dohmae,¹⁵⁵ M. Donadelli,^{23b} M. Donega,¹²⁰ J. Donini,⁵⁵
 J. Dopke,¹⁷⁴ A. Doria,^{102a} A. Dos Anjos,¹⁷² M. Dosil,¹¹ A. Dotti,^{122a,122b} M. T. Dova,⁷⁰ J. D. Dowell,¹⁷
 A. D. Doxiadis,¹⁰⁵ A. T. Doyle,⁵³ Z. Drasal,¹²⁶ J. Drees,¹⁷⁴ N. Dressnandt,¹²⁰ H. Drevermann,²⁹ C. Driouichi,³⁵
 M. Dris,⁹ J. G. Drohan,⁷⁷ J. Dubbert,⁹⁹ T. Dubbs,¹³⁷ S. Dube,¹⁴ E. Duchovni,¹⁷¹ G. Duckeck,⁹⁸ A. Dudarev,²⁹
 F. Dudziak,¹¹⁵ M. Dürrsen,²⁹ I. P. Duerdoth,⁸² L. Duflot,¹¹⁵ M-A. Dufour,⁸⁵ M. Dunford,²⁹ H. Duran Yildiz,^{3b}
 R. Duxfield,¹³⁹ M. Dwuznik,³⁷ F. Dydak,²⁹ D. Dzahini,⁵⁵ M. Düren,⁵² J. Ebke,⁹⁸ S. Eckert,⁴⁸ S. Eckweiler,⁸¹
 K. Edmonds,⁸¹ C. A. Edwards,⁷⁶ I. Efthymiopoulos,⁴⁹ W. Ehrenfeld,⁴¹ T. Ehrich,⁹⁹ T. Eifert,²⁹ G. Eigen,¹³
 K. Einsweiler,¹⁴ E. Eisenhandler,⁷⁵ T. Ekelof,¹⁶⁶ M. El Kacimi,⁴ M. Ellert,¹⁶⁶ S. Elles,⁴ F. Ellinghaus,⁸¹ K. Ellis,⁷⁵
 N. Ellis,²⁹ J. Elmsheuser,⁹⁸ M. Elsing,²⁹ R. Ely,¹⁴ D. Emelianov,¹²⁹ R. Engelmann,¹⁴⁸ A. Engl,⁹⁸ B. Epp,⁶²
 A. Eppig,⁸⁷ J. Erdmann,⁵⁴ A. Ereditato,¹⁶ D. Eriksson,^{146a} J. Ernst,¹ M. Ernst,²⁴ J. Ernwein,¹³⁶ D. Errede,¹⁶⁵
 S. Errede,¹⁶⁵ E. Ertel,⁸¹ M. Escalier,¹¹⁵ C. Escobar,¹⁶⁷ X. Espinal Curull,¹¹ B. Esposito,⁴⁷ F. Etienne,⁸³
 A. I. Etievre,¹³⁶ E. Etzion,¹⁵³ D. Evangelakou,⁵⁴ H. Evans,⁶¹ L. Fabbri,^{19a,19b} C. Fabre,²⁹ K. Facius,³⁵
 R. M. Fakhruddinov,¹²⁸ S. Falciano,^{132a} A. C. Falou,¹¹⁵ Y. Fang,¹⁷² M. Fanti,^{89a,89b} A. Farbin,⁷ A. Farilla,^{134a}
 J. Farley,¹⁴⁸ T. Farooque,¹⁵⁸ S. M. Farrington,¹¹⁸ P. Farthouat,²⁹ D. Fasching,¹⁷² P. Fassnacht,²⁹ D. Fassouliotis,⁸
 B. Fatholahzadeh,¹⁵⁸ A. Favareto,^{89a,89b} L. Fayard,¹¹⁵ S. Fazio,^{36a,36b} R. Febbraro,³³ P. Federic,^{144a} O. L. Fedin,¹²¹
 I. Fedorko,²⁹ W. Fedorko,⁸⁸ M. Fehling-Kaschek,⁴⁸ L. Feligioni,⁸³ D. Fellmann,⁵ C. U. Felzmann,⁸⁶ C. Feng,^{32d}
 E. J. Feng,³⁰ A. B. Fenyuk,¹²⁸ J. Ferencei,^{144b} D. Ferguson,¹⁷² J. Ferland,⁹³ B. Fernandes,^{124a,c} W. Fernando,¹⁰⁹
 S. Ferrag,⁵³ J. Ferrando,¹¹⁸ V. Ferrara,⁴¹ A. Ferrari,¹⁶⁶ P. Ferrari,¹⁰⁵ R. Ferrari,^{119a} A. Ferrer,¹⁶⁷ M. L. Ferrer,⁴⁷
 D. Ferrere,⁴⁹ C. Ferretti,⁸⁷ A. Ferretto Parodi,^{50a,50b} M. Fiascaris,³⁰ F. Fiedler,⁸¹ A. Filipčić,⁷⁴ A. Filippas,⁹
 F. Filthaut,¹⁰⁴ M. Fincke-Keeler,¹⁶⁹ M. C. N. Fiolhais,^{124a,g} L. Fiorini,¹¹ A. Firan,³⁹ G. Fischer,⁴¹ P. Fischer,²⁰
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 S. Fleischmann,²⁰ T. Flick,¹⁷⁴ L. R. Flores Castillo,¹⁷² M. J. Flowerdew,⁹⁹ F. Föhlich,^{58a} M. Fokitis,⁹
 T. Fonseca Martin,¹⁶ D. A. Forbush,¹³⁸ A. Formica,¹³⁶ A. Forti,⁸² D. Fortin,^{159a} J. M. Foster,⁸² D. Fournier,¹¹⁵
 A. Foussat,²⁹ A. J. Fowler,⁴⁴ K. Fowler,¹³⁷ H. Fox,⁷¹ P. Francavilla,^{122a,122b} S. Franchino,^{119a,119b} D. Francis,²⁹
 T. Frank,¹⁷¹ M. Franklin,⁵⁷ S. Franz,²⁹ M. Fraternali,^{119a,119b} S. Fratina,¹²⁰ S. T. French,²⁷ R. Froeschl,²⁹
 D. Froidevaux,²⁹ J. A. Frost,²⁷ C. Fukunaga,¹⁵⁶ E. Fullana Torregrosa,²⁹ J. Fuster,¹⁶⁷ C. Gabaldon,²⁹ O. Gabizon,¹⁷¹
 T. Gadfort,²⁴ S. Gadomski,⁴⁹ G. Gagliardi,^{50a,50b} P. Gagnon,⁶¹ C. Galea,⁹⁸ E. J. Gallas,¹¹⁸ M. V. Gallas,²⁹ V. Gallo,¹⁶
 B. J. Gallop,¹²⁹ P. Gallus,¹²⁵ E. Galyaev,⁴⁰ K. K. Gan,¹⁰⁹ Y. S. Gao,^{143,k} V. A. Gapienko,¹²⁸ A. Gaponenko,¹⁴
 F. Garberon,¹⁷⁵ M. Garcia-Sciveres,¹⁴ C. García,¹⁶⁷ J. E. García Navarro,⁴⁹ R. W. Gardner,³⁰ N. Garelli,²⁹
 H. Garitaonandia,¹⁰⁵ V. Garonne,²⁹ J. Garvey,¹⁷ C. Gatti,⁴⁷ G. Gaudio,^{119a} O. Gaumer,⁴⁹ B. Gaur,¹⁴¹ L. Gauthier,¹³⁶
 I. L. Gavrilenko,⁹⁴ C. Gay,¹⁶⁸ G. Gaycken,²⁰ J-C. Gayde,²⁹ E. N. Gazis,⁹ P. Ge,^{32d} C. N. P. Gee,¹²⁹
 Ch. Geich-Gimbel,²⁰ K. Gellerstedt,^{146a,146b} C. Gemme,^{50a} A. Gemmell,⁵³ M. H. Genest,⁹⁸ S. Gentile,^{132a,132b}
 F. Georgatos,⁹ S. George,⁷⁶ P. Gerlach,¹⁷⁴ A. Gershon,¹⁵³ C. Geweniger,^{58a} H. Ghazlane,^{135d} P. Ghez,⁴
 N. Ghodbane,³³ B. Giacobbe,^{19a} S. Giagu,^{132a,132b} V. Giakoumopoulou,⁸ V. Giangiobbe,^{122a,122b} F. Gianotti,²⁹
 B. Gibbard,²⁴ A. Gibson,¹⁵⁸ S. M. Gibson,²⁹ G. F. Gieraltowski,⁵ L. M. Gilbert,¹¹⁸ M. Gilchriese,¹⁴
 O. Gildemeister,²⁹ V. Gilevsky,⁹¹ D. Gillberg,²⁸ A. R. Gillman,¹²⁹ D. M. Gingrich,^{2,e} J. Ginzburg,¹⁵³ N. Giokaris,⁸
 R. Giordano,^{102a,102b} F. M. Giorgi,¹⁵ P. Giovannini,⁹⁹ P. F. Giraud,¹³⁶ D. Giugni,^{89a} P. Giusti,^{19a} B. K. Gjelsten,¹¹⁷
 L. K. Gladilin,⁹⁷ C. Glasman,⁸⁰ J. Glatzer,⁴⁸ A. Glazov,⁴¹ K. W. Glitza,¹⁷⁴ G. L. Glonti,⁶⁵ J. Godfrey,¹⁴²
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 T. Golling,¹⁷⁵ N. P. Gollub,²⁹ S. N. Golovnia,¹²⁸ A. Gomes,^{124a,c} L. S. Gomez Fajardo,⁴¹ R. Gonçalves,⁷⁶ L. Gonella,²⁰
 C. Gong,^{32b} A. Gonidec,²⁹ S. Gonzalez,¹⁷² S. González de la Hoz,¹⁶⁷ M. L. Gonzalez Silva,²⁶ S. Gonzalez-Sevilla,⁴⁹
 J. J. Goodson,¹⁴⁸ L. Goossens,²⁹ P. A. Gorbounov,⁹⁵ H. A. Gordon,²⁴ I. Gorelov,¹⁰³ G. Gorfine,¹⁷⁴ B. Gorini,²⁹
 E. Gorini,^{72a,72b} A. Gorišek,⁷⁴ E. Gornicki,³⁸ S. A. Gorokhov,¹²⁸ B. T. Gorski,²⁹ V. N. Goryachev,¹²⁸ B. Godzik,⁴¹
 M. Gosselink,¹⁰⁵ M. I. Gostkin,⁶⁵ M. Gouanère,⁴ I. Gough Eschrich,¹⁶³ M. Goughri,^{135a} D. Goujdami,^{135a}
 M. P. Goulette,⁴⁹ A. G. Goussiou,¹³⁸ C. Goy,⁴ I. Grabowska-Bold,^{163,f} V. Grabski,¹⁷⁶ P. Grafström,²⁹ C. Grah,¹⁷⁴
 K-J. Grahn,¹⁴⁷ F. Grancagnolo,^{72a} S. Grancagnolo,¹⁵ V. Grassi,¹⁴⁸ V. Gratchev,¹²¹ N. Grau,³⁴ H. M. Gray,^{34,1}
 J. A. Gray,¹⁴⁸ E. Graziani,^{134a} O. G. Grebenyuk,¹²¹ D. Greenfield,¹²⁹ T. Greenshaw,⁷³ Z. D. Greenwood,^{24,j}
 I. M. Gregor,⁴¹ P. Grenier,¹⁴³ E. Griesmayer,⁴⁶ J. Griffiths,¹³⁸ N. Grigalashvili,⁶⁵ A. A. Grillo,¹³⁷ K. Grimm,¹⁴⁸
 S. Grinstein,¹¹ P. L. Y. Gris,³³ Y. V. Grishkevich,⁹⁷ J.-F. Grivaz,¹¹⁵ J. Grognoz,²⁹ M. Groh,⁹⁹ E. Gross,¹⁷¹
 J. Grosse-Knetter,⁵⁴ J. Groth-Jensen,⁷⁹ M. Gruwe,²⁹ K. Grybel,¹⁴¹ V. J. Guarino,⁵ C. Guichenev,³³ A. Guida,^{72a,72b}
 T. Guillemin,⁴ S. Guindon,⁵⁴ H. Guler,^{85,m} J. Gunther,¹²⁵ B. Guo,¹⁵⁸ J. Guo,³⁴ A. Gupta,³⁰ Y. Gusakov,⁶⁵

V. N. Gushchin,¹²⁸ A. Gutierrez,⁹³ P. Gutierrez,¹¹¹ N. Guttman,¹⁵³ O. Gutzwiller,¹⁷² C. Guyot,¹³⁶ C. Gwenlan,¹¹⁸ C. B. Gwilliam,⁷³ A. Haas,¹⁴³ S. Haas,²⁹ C. Haber,¹⁴ R. Hackenburg,²⁴ H. K. Hadavand,³⁹ D. R. Hadley,¹⁷ P. Haefner,⁹⁹ F. Hahn,²⁹ S. Haider,²⁹ Z. Hajduk,³⁸ H. Hakobyan,¹⁷⁶ J. Haller,⁵⁴ K. Hamacher,¹⁷⁴ A. Hamilton,⁴⁹ S. Hamilton,¹⁶¹ H. Han,^{32a} L. Han,^{32b} K. Hanagaki,¹¹⁶ M. Hance,¹²⁰ C. Handel,⁸¹ P. Hanke,^{58a} C. J. Hansen,¹⁶⁶ J. R. Hansen,³⁵ J. B. Hansen,³⁵ J. D. Hansen,³⁵ P. H. Hansen,³⁵ P. Hansson,¹⁴³ K. Hara,¹⁶⁰ G. A. Hare,¹³⁷ T. Harenberg,¹⁷⁴ D. Harper,⁸⁷ R. D. Harrington,²¹ O. M. Harris,¹³⁸ K. Harrison,¹⁷ J. C. Hart,¹²⁹ J. Hartert,⁴⁸ F. Hartjes,¹⁰⁵ T. Haruyama,⁶⁶ A. Harvey,⁵⁶ S. Hasegawa,¹⁰¹ Y. Hasegawa,¹⁴⁰ S. Hassani,¹³⁶ M. Hatch,²⁹ D. Hauff,⁹⁹ S. Haug,¹⁶ M. Hauschild,²⁹ R. Hauser,⁸⁸ M. Havranek,¹²⁵ B. M. Hawes,¹¹⁸ C. M. Hawkes,¹⁷ R. J. Hawkings,²⁹ D. Hawkins,¹⁶³ T. Hayakawa,⁶⁷ D. Hayden,⁷⁶ H. S. Hayward,⁷³ S. J. Haywood,¹²⁹ E. Hazen,²¹ M. He,^{32d} S. J. Head,¹⁷ V. Hedberg,⁷⁹ L. Heelan,²⁸ S. Heim,⁸⁸ B. Heinemann,¹⁴ S. Heisterkamp,³⁵ L. Helary,⁴ M. Heldmann,⁴⁸ M. Heller,¹¹⁵ S. Hellman,^{146a,146b} C. Hensens,¹¹ R. C. W. Henderson,⁷¹ M. Henke,^{58a} A. Henrichs,⁵⁴ A. M. Henriques Correia,²⁹ S. Henrot-Versille,¹¹⁵ F. Henry-Couannier,⁸³ C. Hensel,⁵⁴ T. Henß,¹⁷⁴ Y. Hernández Jiménez,¹⁶⁷ R. Herrberg,¹⁵ A. D. Hershenhorn,¹⁵² G. Herten,⁴⁸ R. Hertenberger,⁹⁸ L. Hervas,²⁹ N. P. Hessey,¹⁰⁵ A. Hidvegi,^{146a} E. Higón-Rodríguez,¹⁶⁷ 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,¹²⁰ M. Hirose,¹¹⁶ F. Hirsch,⁴² D. Hirschbuehl,¹⁷⁴ J. Hobbs,¹⁴⁸ N. Hod,¹⁵³ M. C. Hodgkinson,¹³⁹ P. Hodgson,¹³⁹ A. Hoecker,²⁹ M. R. Hoferkamp,¹⁰³ J. Hoffman,³⁹ D. Hoffmann,⁸³ M. Hohlfeld,⁸¹ M. Holder,¹⁴¹ A. Holmes,¹¹⁸ S. O. Holmgren,^{146a} T. Holy,¹²⁷ J. L. Holzbauer,⁸⁸ R. J. Homer,¹⁷ Y. Homma,⁶⁷ T. Horazdovsky,¹²⁷ C. Horn,¹⁴³ S. Horner,⁴⁸ K. Horton,¹¹⁸ J.-Y. Hostachy,⁵⁵ T. Hott,⁹⁹ S. Hou,¹⁵¹ M. A. Houlden,⁷³ A. Hoummada,^{135a} J. Howarth,⁸² D. F. Howell,¹¹⁸ I. Hristova,⁴¹ J. Hrivnac,¹¹⁵ I. Hruska,¹²⁵ T. Hryn'ova,⁴ P. J. Hsu,¹⁷⁵ S.-C. Hsu,¹⁴ G. S. Huang,¹¹¹ Z. Hubacek,¹²⁷ F. Hubaut,⁸³ F. Huegging,²⁰ T. B. Huffman,¹¹⁸ E. W. Hughes,³⁴ G. Hughes,⁷¹ R. E. Hughes-Jones,⁸² M. Huhtinen,²⁹ P. Hurst,⁵⁷ M. Hurwitz,¹⁴ U. Husemann,⁴¹ N. Huseynov,^{65,n} J. Huston,⁸⁸ J. Huth,⁵⁷ G. Iacobucci,^{102a} G. Iakovidis,⁹ M. Ibbotson,⁸² I. Ibragimov,¹⁴¹ R. Ichimiya,⁶⁷ L. Iconomidou-Fayard,¹¹⁵ J. Idarraga,¹¹⁵ M. Idzik,³⁷ P. Inengo,⁴ O. Igonkina,¹⁰⁵ Y. Ikegami,⁶⁶ M. Ikeno,⁶⁶ Y. Ilchenko,³⁹ D. Iliadis,¹⁵⁴ D. Imbault,⁷⁸ M. Imhaeuser,¹⁷⁴ M. Imori,¹⁵⁵ T. Ince,²⁰ J. Inigo-Golfín,²⁹ P. Ioannou,⁸ M. Iodice,^{134a} G. Ionescu,⁴ A. Irlés Quiles,¹⁶⁷ K. Ishii,⁶⁶ A. Ishikawa,⁶⁷ M. Ishino,⁶⁶ R. Ishmukhametov,³⁹ T. Isobe,¹⁵⁵ C. Issever,¹¹⁸ S. Istin,^{18a} Y. Itoh,¹⁰¹ A. V. Ivashin,¹²⁸ W. Iwanski,³⁸ H. Iwasaki,⁶⁶ J. M. Izen,⁴⁰ V. Izzo,^{102a} B. Jackson,¹²⁰ J. N. Jackson,⁷³ P. Jackson,¹⁴³ M. R. Jaekel,²⁹ V. Jain,⁶¹ K. Jakobs,⁴⁸ S. Jakobsen,³⁵ J. Jakubek,¹²⁷ D. K. Jana,¹¹¹ E. Jankowski,¹⁵⁸ E. Jansen,⁷⁷ A. Jantsch,⁹⁹ M. Janus,²⁰ G. Jarlskog,⁷⁹ L. Jeanty,⁵⁷ K. Jelen,³⁷ I. Jen-La Plante,³⁰ P. Jenni,²⁹ A. Jeremie,⁴ P. Jež,³⁵ S. Jézéquel,⁴ H. Ji,¹⁷² W. Ji,⁸¹ J. Jia,¹⁴⁸ Y. Jiang,^{32b} M. Jimenez Belenguer,²⁹ G. Jin,^{32b} S. Jin,^{32a} O. Jinnouchi,¹⁵⁷ M. D. Joergensen,³⁵ D. Joffe,³⁹ L. G. Johansen,¹³ M. Johansen,^{146a,146b} K. E. Johansson,^{146a} P. Johansson,¹³⁹ S. Johnert,⁴¹ K. A. Johns,⁶ K. Jon-And,^{146a,146b} G. Jones,⁸² R. W. L. Jones,⁷¹ T. W. Jones,⁷⁷ T. J. Jones,⁷³ O. Jonsson,²⁹ K. K. Joo,¹⁵⁸ C. Joram,²⁹ P. M. Jorge,^{124a,c} J. Joseph,¹⁴ X. Ju,¹³⁰ V. Juranek,¹²⁵ P. Jussel,⁶² V. V. Kabachenko,¹²⁸ S. Kabana,¹⁶ M. Kaci,¹⁶⁷ A. Kaczmarek,³⁸ P. Kadlecik,³⁵ M. Kado,¹¹⁵ H. Kagan,¹⁰⁹ M. Kagan,⁵⁷ S. Kaiser,⁹⁹ E. Kajomovitz,¹⁵² S. Kalinin,¹⁷⁴ L. V. Kalinovskaya,⁶⁵ S. Kama,³⁹ N. Kanaya,¹⁵⁵ M. Kaneda,¹⁵⁵ T. Kanno,¹⁵⁷ V. A. Kantserov,⁹⁶ J. Kanzaki,⁶⁶ B. Kaplan,¹⁷⁵ A. Kapliy,³⁰ J. Kaplon,²⁹ D. Kar,⁴³ M. Karagoz,¹¹⁸ M. Karnevskiy,⁴¹ K. Karr,⁵ V. Kartvelishvili,⁷¹ A. N. Karyukhin,¹²⁸ L. Kashif,⁵⁷ A. Kasmi,³⁹ R. D. Kass,¹⁰⁹ A. Kastanas,¹³ M. Kataoka,⁴ Y. Kataoka,¹⁵⁵ E. Katsoufis,⁹ J. Katzy,⁴¹ V. Kaushik,⁶ K. Kawagoe,⁶⁷ T. Kawamoto,¹⁵⁵ G. Kawamura,⁸¹ M. S. Kayl,¹⁰⁵ V. A. Kazanin,¹⁰⁷ M. Y. Kazarinov,⁶⁵ S. I. Kazi,⁸⁶ J. R. Keates,⁸² R. Keeler,¹⁶⁹ R. Kehoe,³⁹ M. Keil,⁵⁴ G. D. Kekelidze,⁶⁵ M. Kelly,⁸² J. Kennedy,⁹⁸ C. J. Kenney,¹⁴³ M. Kenyon,⁵³ O. Kepka,¹²⁵ N. Kerschen,²⁹ B. P. Kerševan,⁷⁴ S. Kersten,¹⁷⁴ K. Kessoku,¹⁵⁵ C. Ketterer,⁴⁸ M. Khakzad,²⁸ F. Khalil-zada,¹⁰ H. Khandanyan,¹⁶⁵ A. Khanov,¹¹² D. Kharchenko,⁶⁵ A. Khodinov,¹⁴⁸ A. G. Kholodenko,¹²⁸ A. Khomich,^{58a} T. J. Khoo,²⁷ G. Khorauli,²⁰ N. Khovanskiy,⁶⁵ V. Khovanskiy,⁹⁵ E. Khramov,⁶⁵ J. Khubua,⁵¹ G. Kilvington,⁷⁶ H. Kim,⁷ M. S. Kim,² P. C. Kim,¹⁴³ S. H. Kim,¹⁶⁰ N. Kimura,¹⁷⁰ O. Kind,¹⁵ B. T. King,⁷³ M. King,⁶⁷ R. S. B. King,¹¹⁸ J. Kirk,¹²⁹ G. P. Kirsch,¹¹⁸ L. E. Kirsch,²² A. E. Kiryunin,⁹⁹ D. Kisielewska,³⁷ T. Kittelmann,¹²³ A. M. Kiver,¹²⁸ H. Kiyamura,⁶⁷ E. Kladiva,^{144b} J. Klaiber-Lodewigs,⁴² M. Klein,⁷³ U. Klein,⁷³ K. Kleinknecht,⁸¹ M. Klemetti,⁸⁵ A. Klier,¹⁷¹ A. Klimentov,²⁴ R. Klingenberg,⁴² E. B. Klinkby,³⁵ T. Klioutchnikova,²⁹ P. F. Klok,¹⁰⁴ S. Klous,¹⁰⁵ E.-E. Kluge,^{58a} T. Kluge,⁷³ P. Kluit,¹⁰⁵ S. Kluth,⁹⁹ E. Kneringer,⁶² J. Knobloch,²⁹ A. Knue,⁵⁴ B. R. Ko,⁴⁴ T. Kobayashi,¹⁵⁵ M. Kobel,⁴³ B. Koblitz,²⁹ M. Kocian,¹⁴³ A. Kocnar,¹¹³ P. Kodys,¹²⁶ K. Köneke,²⁹ A. C. König,¹⁰⁴ S. Koenig,⁸¹ S. König,⁴⁸ L. Köpke,⁸¹ F. Koetsveld,¹⁰⁴ P. Kovesarki,²⁰ T. Koffas,²⁹ E. Koffeman,¹⁰⁵ F. Kohn,⁵⁴ Z. Kohout,¹²⁷ T. Kohriki,⁶⁶ T. Koi,¹⁴³ T. Kokott,²⁰ G. M. Kolachev,¹⁰⁷ H. Kolanoski,¹⁵ V. Kolesnikov,⁶⁵ I. Koletsou,^{89a,89b} J. Koll,⁸⁸ D. Kollar,²⁹ M. Kollefrath,⁴⁸ S. D. Kolya,⁸² A. A. Komar,⁹⁴ J. R. Komaragiri,¹⁴²

T. Kondo,⁶⁶ T. Kono,^{41,o} A. I. Kononov,⁴⁸ R. Konoplich,^{108,p} N. Konstantinidis,⁷⁷ A. Kootz,¹⁷⁴ S. Koperny,³⁷
 S. V. Kopikov,¹²⁸ K. Korcyl,³⁸ K. Kordas,¹⁵⁴ V. Koreshev,¹²⁸ A. Korn,¹⁴ A. Korol,¹⁰⁷ I. Korolkov,¹¹
 E. V. Korolkova,¹³⁹ V. A. Korotkov,¹²⁸ O. Kortner,⁹⁹ S. Kortner,⁹⁹ V. V. Kostyukhin,²⁰ M. J. Kotamäki,²⁹ S. Kotov,⁹⁹
 V. M. Kotov,⁶⁵ C. Kourkoumelis,⁸ A. Koutsman,¹⁰⁵ R. Kowalewski,¹⁶⁹ T. Z. Kowalski,³⁷ W. Kozanecki,¹³⁶
 A. S. Kozhin,¹²⁸ V. Kral,¹²⁷ V. A. Kramarenko,⁹⁷ G. Kramberger,⁷⁴ O. Krasel,⁴² M. W. Krasny,⁷⁸
 A. Krasznahorkay,¹⁰⁸ J. Kraus,⁸⁸ A. Kreisel,¹⁵³ F. Krejci,¹²⁷ J. Kretzschmar,⁷³ N. Krieger,⁵⁴ P. Krieger,¹⁵⁸
 K. Kroeninger,⁵⁴ H. Kroha,⁹⁹ J. Kroll,¹²⁰ J. Kroseberg,²⁰ J. Krstic,^{12a} U. Kruchonak,⁶⁵ H. Krüger,²⁰
 Z. V. Krumshteyn,⁶⁵ A. Kruth,²⁰ T. Kubota,¹⁵⁵ S. Kuehn,⁴⁸ A. Kugel,^{58c} T. Kuhl,¹⁷⁴ D. Kuhn,⁶² V. Kukhtin,⁶⁵
 Y. Kulchitsky,⁹⁰ S. Kuleshov,^{31b} C. Kummer,⁹⁸ M. Kuna,⁸³ N. Kundu,¹¹⁸ J. Kunkle,¹²⁰ A. Kupco,¹²⁵ H. Kurashige,⁶⁷
 M. Kurata,¹⁶⁰ Y. A. Kurochkin,⁹⁰ V. Kus,¹²⁵ W. Kuykendall,¹³⁸ M. Kuze,¹⁵⁷ P. Kuzhir,⁹¹ O. Kvasnicka,¹²⁵ R. Kwee,¹⁵
 A. La Rosa,²⁹ L. La Rotonda,^{36a,36b} L. Labarga,⁸⁰ J. Labbe,⁴ C. Lacasta,¹⁶⁷ F. Lacava,^{132a,132b} H. Lacker,¹⁵
 D. Lacour,⁷⁸ V. R. Lacuesta,¹⁶⁷ E. Ladygin,⁶⁵ R. Lafaye,⁴ B. Laforge,⁷⁸ T. Lagouri,⁸⁰ S. Lai,⁴⁸ E. Laisne,⁵⁵
 M. Lamanna,²⁹ C. L. Lampen,⁶ W. Lampl,⁶ E. Lancon,¹³⁶ U. Landgraf,⁴⁸ M. P. J. Landon,⁷⁵ H. Landsman,¹⁵²
 J. L. Lane,⁸² C. Lange,⁴¹ A. J. Lankford,¹⁶³ F. Lanni,²⁴ K. Lantzsch,²⁹ V. V. Lapin,^{128,a} S. Laplace,⁴ C. Lapoire,²⁰
 J. F. Laporte,¹³⁶ T. Lari,^{89a} A. V. Larionov,¹²⁸ A. Lerner,¹¹⁸ C. Lasseur,²⁹ M. Lassnig,²⁹ W. Lau,¹¹⁸ P. Laurelli,⁴⁷
 A. Lavorato,¹¹⁸ W. Lavrijsen,¹⁴ P. Laycock,⁷³ A. B. Lazarev,⁶⁵ A. Lazzaro,^{89a,89b} O. Le Dortz,⁷⁸ E. Le Guirriec,⁸³
 C. Le Maner,¹⁵⁸ E. Le Menedeu,¹³⁶ M. Leahu,²⁹ A. Lebedev,⁶⁴ C. Lebel,⁹³ T. LeCompte,⁵ F. Ledroit-Guillon,⁵⁵
 H. Lee,¹⁰⁵ J. S. H. Lee,¹⁵⁰ S. C. Lee,¹⁵¹ L. Lee,¹⁷⁵ M. Lefebvre,¹⁶⁹ M. Legendre,¹³⁶ A. Leger,⁴⁹ B. C. LeGeyt,¹²⁰
 F. Legger,⁹⁸ C. Leggett,¹⁴ M. Lehmacher,²⁰ G. Lehmann Miotto,²⁹ M. Lehto,¹³⁹ X. Lei,⁶ M. A. L. Leite,^{23b}
 R. Leitner,¹²⁶ D. Lellouch,¹⁷¹ J. Lellouch,⁷⁸ M. Leltchouk,³⁴ V. Lendermann,^{58a} K. J. C. Leney,^{145b} T. Lenz,¹⁷⁴
 G. Lenzen,¹⁷⁴ B. Lenzi,¹³⁶ K. Leonhardt,⁴³ S. Leontsinis,⁹ C. Leroy,⁹³ J-R. Lessard,¹⁶⁹ J. Lesser,^{146a} C. G. Lester,²⁷
 A. Leung Fook Cheong,¹⁷² J. Levêque,⁸³ D. Levin,⁸⁷ L. J. Levinson,¹⁷¹ M. S. Levitski,¹²⁸ M. Lewandowska,²¹
 M. Leyton,¹⁵ B. Li,⁸³ H. Li,¹⁷² S. Li,^{32b} X. Li,⁸⁷ Z. Liang,³⁹ Z. Liang,^{118,q} B. Liberti,^{133a} P. Lichard,²⁹
 M. Lichtnecker,⁹⁸ K. Lie,¹⁶⁵ W. Liebig,¹³ R. Lifshitz,¹⁵² J. N. Lilley,¹⁷ A. Limosani,⁸⁶ M. Limper,⁶³ S. C. Lin,^{151,r}
 F. Linde,¹⁰⁵ J. T. Linnemann,⁸⁸ E. Lipeles,¹²⁰ L. Lipinsky,¹²⁵ A. Lipniacka,¹³ T. M. Liss,¹⁶⁵ A. Lister,⁴⁹
 A. M. Litke,¹³⁷ C. Liu,²⁸ D. Liu,^{151,s} H. Liu,⁸⁷ J. B. Liu,⁸⁷ M. Liu,^{32b} S. Liu,² Y. Liu,^{32b} M. Livan,^{119a,119b}
 S. S. A. Livermore,¹¹⁸ A. Lleres,⁵⁵ S. L. Lloyd,⁷⁵ E. Lobodzinska,⁴¹ P. Loch,⁶ W. S. Lockman,¹³⁷ S. Lockwitz,¹⁷⁵
 T. Loddenkoetter,²⁰ F. K. Loebinger,⁸² A. Loginov,¹⁷⁵ C. W. Loh,¹⁶⁸ T. Lohse,¹⁵ K. Lohwasser,⁴⁸ M. Lokajicek,¹²⁵
 J. Loken,¹¹⁸ V. P. Lombardo,^{89a,89b} R. E. Long,⁷¹ L. Lopes,^{124a,c} D. Lopez Mateos,^{34,l} M. Losada,¹⁶² P. Loscutoff,¹⁴
 F. Lo Sterzo,^{132a,132b} M. J. Losty,^{159a} X. Lou,⁴⁰ A. Lounis,¹¹⁵ K. F. Loureiro,¹⁶² J. Love,²¹ P. A. Love,⁷¹ A. J. Lowe,¹⁴³
 F. Lu,^{32a} J. Lu,² L. Lu,³⁹ H. J. Lubatti,¹³⁸ C. Luci,^{132a,132b} A. Lucotte,⁵⁵ A. Ludwig,⁴³ D. Ludwig,⁴¹ I. Ludwig,⁴⁸
 J. Ludwig,⁴⁸ F. Luehring,⁶¹ G. Luijckx,¹⁰⁵ D. Lumb,⁴⁸ L. Luminari,^{132a} E. Lund,¹¹⁷ B. Lund-Jensen,¹⁴⁷
 B. Lundberg,⁷⁹ J. Lundberg,²⁹ J. Lundquist,³⁵ M. Lungwitz,⁸¹ A. Lupi,^{122a,122b} G. Lutz,⁹⁹ D. Lynn,²⁴ J. Lys,¹⁴
 E. Lytken,⁷⁹ H. Ma,²⁴ L. L. Ma,¹⁷² M. Maaßen,⁴⁸ J. A. Macana Goia,⁹³ G. Maccarrone,⁴⁷ A. Macchiolo,⁹⁹
 B. Maček,⁷⁴ J. Machado Miguens,^{124a,c} D. Macina,⁴⁹ R. Mackeprang,³⁵ R. J. Madaras,¹⁴ W. F. Mader,⁴³
 R. Maenner,^{58c} T. Maeno,²⁴ P. Mättig,¹⁷⁴ S. Mättig,⁴¹ P. J. Magalhaes Martins,^{124a,g} L. Magnoni,²⁹ E. Magradze,⁵¹
 C. A. Magrath,¹⁰⁴ Y. Mahalalel,¹⁵³ K. Mahboubi,⁴⁸ G. Mahout,¹⁷ C. Maiani,^{132a,132b} C. Maidantchik,^{23a}
 A. Maio,^{124a,c} S. Majewski,²⁴ Y. Makida,⁶⁶ N. Makovec,¹¹⁵ P. Mal,⁶ Pa. Malecki,³⁸ P. Malecki,³⁸ V. P. Maleev,¹²¹
 F. Malek,⁵⁵ U. Mallik,⁶³ D. Malon,⁵ S. Maltezos,⁹ V. Malyshev,¹⁰⁷ S. Malyukov,⁶⁵ R. Mameghani,⁹⁸ J. Mamuzic,^{12b}
 A. Manabe,⁶⁶ L. Mandelli,^{89a} I. Mandić,⁷⁴ R. Mandrysch,¹⁵ J. Maneira,^{124a} P. S. Mangeard,⁸⁸ I. D. Manjavidze,⁶⁵
 A. Mann,⁵⁴ P. M. Manning,¹³⁷ A. Manousakis-Katsikakis,⁸ B. Mansoulie,¹³⁶ A. Manz,⁹⁹ A. Mapelli,²⁹ L. Mapelli,²⁹
 L. March,⁸⁰ J. F. Marchand,²⁹ F. Marchese,^{133a,133b} M. Marchesotti,²⁹ G. Marchiori,⁷⁸ M. Marcisovsky,¹²⁵
 A. Marin,^{21,a} C. P. Marino,⁶¹ F. Marroquim,^{23a} R. Marshall,⁸² Z. Marshall,^{34,l} F. K. Martens,¹⁵⁸ S. Marti-Garcia,¹⁶⁷
 A. J. Martin,¹⁷⁵ B. Martin,²⁹ B. Martin,⁸⁸ F. F. Martin,¹²⁰ J. P. Martin,⁹³ Ph. Martin,⁵⁵ T. A. Martin,¹⁷
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 A. Marzin,¹¹¹ L. Masetti,⁸¹ T. Mashimo,¹⁵⁵ R. Mashinistov,⁹⁴ J. Masik,⁸² A. L. Maslennikov,¹⁰⁷ M. Maß,⁴²
 I. Massa,^{19a,19b} G. Massaro,¹⁰⁵ N. Massol,⁴ A. Mastroberardino,^{36a,36b} T. Masubuchi,¹⁵⁵ M. Mathes,²⁰ P. Matricon,¹¹⁵
 H. Matsumoto,¹⁵⁵ H. Matsunaga,¹⁵⁵ T. Matsushita,⁶⁷ C. Mattraversi,^{118,t} J. M. Maugain,²⁹ S. J. Maxfield,⁷³
 E. N. May,⁵ A. Mayne,¹³⁹ R. Mazini,¹⁵¹ M. Mazur,²⁰ M. Mazzanti,^{89a} E. Mazzoni,^{122a,122b} S. P. Mc Kee,⁸⁷
 A. McCarn,¹⁶⁵ R. L. McCarthy,¹⁴⁸ T. G. McCarthy,²⁸ N. A. McCubbin,¹²⁹ K. W. McFarlane,⁵⁶ J. A. Mcfayden,¹³⁹
 H. McGlone,⁵³ G. Mchedlidze,⁵¹ R. A. McLaren,²⁹ T. McLaughlan,¹⁷ S. J. McMahon,¹²⁹ T. R. McMahon,⁷⁶

T. J. McMahon,¹⁷ R. A. McPherson,^{169,i} A. Meade,⁸⁴ J. Mechnich,¹⁰⁵ M. Mechtel,¹⁷⁴ M. Medinnis,⁴¹
R. Meera-Lebbai,¹¹¹ T. Meguro,¹¹⁶ R. Mehdiyev,⁹³ S. Mehlhase,⁴¹ A. Mehta,⁷³ K. Meier,^{58a} J. Meinhardt,⁴⁸
B. Meirose,⁷⁹ C. Melachrinou,³⁰ B. R. Mellado Garcia,¹⁷² L. Mendoza Navas,¹⁶² Z. Meng,^{151,s} A. Mengarelli,^{19a,19b}
S. Menke,⁹⁹ C. Menot,²⁹ E. Meoni,¹¹ D. Merkl,⁹⁸ P. Mermod,¹¹⁸ L. Merola,^{102a,102b} C. Meroni,^{89a} F. S. Merritt,³⁰
A. Messina,²⁹ J. Metcalfe,¹⁰³ A. S. Mete,⁶⁴ S. Meuser,²⁰ C. Meyer,⁸¹ J.-P. Meyer,¹³⁶ J. Meyer,¹⁷³ J. Meyer,⁵⁴
T. C. Meyer,²⁹ W. T. Meyer,⁶⁴ J. Miao,^{32d} S. Michal,²⁹ L. Micu,^{25a} R. P. Middleton,¹²⁹ P. Miele,²⁹ S. Migas,⁷³
L. Mijović,⁴¹ G. Mikenberg,¹⁷¹ M. Mikestikova,¹²⁵ B. Mikulec,⁴⁹ M. Mikuž,⁷⁴ D. W. Miller,¹⁴³ R. J. Miller,⁸⁸
W. J. Mills,¹⁶⁸ C. Mills,⁵⁷ A. Milov,¹⁷¹ D. A. Milstead,^{146a,146b} D. Milstein,¹⁷¹ A. A. Minaenko,¹²⁸ M. Miñano,¹⁶⁷
I. A. Minashvili,⁶⁵ A. I. Mincer,¹⁰⁸ B. Mindur,³⁷ M. Mineev,⁶⁵ Y. Ming,¹³⁰ L. M. Mir,¹¹ G. Mirabelli,^{132a}
L. Miralles Verge,¹¹ A. Misiejuk,⁷⁶ A. Mitra,¹¹⁸ J. Mitrevski,¹³⁷ G. Y. Mitrofanov,¹²⁸ V. A. Mitsou,¹⁶⁷ S. Mitsui,⁶⁶
P. S. Miyagawa,⁸² K. Miyazaki,⁶⁷ J. U. Mjörnmark,⁷⁹ T. Moa,^{146a,146b} P. Mockett,¹³⁸ S. Moed,⁵⁷ V. Moeller,²⁷
K. Mönig,⁴¹ N. Möser,²⁰ S. Mohapatra,¹⁴⁸ B. Mohn,¹³ W. Mohr,⁴⁸ S. Mohrdeiek-Möck,⁹⁹ A. M. Moisseev,^{128,a}
R. Moles-Valls,¹⁶⁷ J. Molina-Perez,²⁹ L. Moneta,⁴⁹ J. Monk,⁷⁷ E. Monnier,⁸³ S. Montesano,^{89a,89b} F. Monticelli,⁷⁰
S. Monzani,^{19a,19b} R. W. Moore,² G. F. Moorhead,⁸⁶ C. Mora Herrera,⁴⁹ A. Moraes,⁵³ A. Morais,^{124a,c} N. Morange,¹³⁶
J. Morel,⁵⁴ G. Morello,^{36a,36b} D. Moreno,⁸¹ M. Moreno Llácer,¹⁶⁷ P. Morettini,^{50a} M. Morii,⁵⁷ J. Morin,⁷⁵
Y. Morita,⁶⁶ A. K. Morley,²⁹ G. Mornacchi,²⁹ M.-C. Morone,⁴⁹ J. D. Morris,⁷⁵ H. G. Moser,⁹⁹ M. Mosidze,⁵¹
J. Moss,¹⁰⁹ R. Mount,¹⁴³ E. Mountricha,⁹ S. V. Mouraviev,⁹⁴ E. J. W. Moyse,⁸⁴ M. Mudrinic,^{12b} F. Mueller,^{58a}
J. Mueller,¹²³ K. Mueller,²⁰ T. A. Müller,⁹⁸ D. Muenstermann,⁴² A. Muijs,¹⁰⁵ A. Muir,¹⁶⁸ Y. Munwes,¹⁵³
K. Murakami,⁶⁶ W. J. Murray,¹²⁹ I. Mussche,¹⁰⁵ E. Musto,^{102a,102b} A. G. Myagkov,¹²⁸ M. Myska,¹²⁵ J. Nadal,¹¹
K. Nagai,¹⁶⁰ K. Nagano,⁶⁶ Y. Nagasaka,⁶⁰ A. M. Nairz,²⁹ Y. Nakahama,¹¹⁵ K. Nakamura,¹⁵⁵ I. Nakano,¹¹⁰
G. Nanava,²⁰ A. Napier,¹⁶¹ M. Nash,^{77,t} I. Nasteva,⁸² N. R. Nation,²¹ T. Nattermann,²⁰ T. Naumann,⁴¹ G. Navarro,¹⁶²
H. A. Neal,⁸⁷ E. Nebot,⁸⁰ P. Yu. Nechaeva,⁹⁴ A. Negri,^{119a,119b} G. Negri,²⁹ S. Nektarijevic,⁴⁹ A. Nelson,⁶⁴
S. Nelson,¹⁴³ T. K. Nelson,¹⁴³ S. Nemecek,¹²⁵ P. Nemethy,¹⁰⁸ A. A. Nepomuceno,^{23a} M. Nessi,²⁹ S. Y. Nesterov,¹²¹
M. S. Neubauer,¹⁶⁵ A. Neusiedl,⁸¹ R. M. Neves,¹⁰⁸ P. Nevski,²⁴ P. R. Newman,¹⁷ R. B. Nickerson,¹¹⁸
R. Nicolaidou,¹³⁶ L. Nicolas,¹³⁹ B. Nicquevert,²⁹ F. Niedercorn,¹¹⁵ J. Nielsen,¹³⁷ T. Niinikoski,²⁹ A. Nikiforov,¹⁵
V. Nikolaenko,¹²⁸ K. Nikolaev,⁶⁵ I. Nikolic-Audit,⁷⁸ K. Nikolopoulos,²⁴ H. Nilsen,⁴⁸ P. Nilsson,⁷ Y. Ninomiya,¹⁵⁵
A. Nisati,^{132a} T. Nishiyama,⁶⁷ R. Nisius,⁹⁹ L. Nodulman,⁵ M. Nomachi,¹¹⁶ I. Nomidis,¹⁵⁴ H. Nomoto,¹⁵⁵
M. Nordberg,²⁹ B. Nordkvist,^{146a,146b} O. Normiella Francisco,¹¹ P. R. Norton,¹²⁹ J. Novakova,¹²⁶ M. Nozaki,⁶⁶
M. Nožička,⁴¹ I. M. Nugent,^{159a} A.-E. Nuncio-Quiroz,²⁰ G. Nunes Hanninger,²⁰ T. Nunnemann,⁹⁸ E. Nurse,⁷⁷
T. Nyman,²⁹ B. J. O'Brien,⁴⁵ S. W. O'Neale,^{17,a} D. C. O'Neil,¹⁴² V. O'Shea,⁵³ F. G. Oakham,^{28,e} H. Oberlack,⁹⁹
J. Ocariz,⁷⁸ A. Ochi,⁶⁷ S. Oda,¹⁵⁵ S. Odaka,⁶⁶ J. Odier,⁸³ G. A. Odino,^{50a,50b} H. Ogren,⁶¹ A. Oh,⁸² S. H. Oh,⁴⁴
C. C. Ohm,^{146a,146b} T. Ohshima,¹⁰¹ H. Ohshita,¹⁴⁰ T. K. Ohska,⁶⁶ T. Ohsugi,⁵⁹ S. Okada,⁶⁷ H. Okawa,¹⁶³
Y. Okumura,¹⁰¹ T. Okuyama,¹⁵⁵ M. Olcese,^{50a} A. G. Olchevski,⁶⁵ M. Oliveira,^{124a,g} D. Oliveira Damazio,²⁴
E. Oliver Garcia,¹⁶⁷ D. Olivito,¹²⁰ A. Olszewski,³⁸ J. Olszowska,³⁸ C. Omachi,⁶⁷ A. Onofre,^{124a,u} P. U. E. Onyisi,³⁰
C. J. Oram,^{159a} G. Ordóñez,¹⁰⁴ M. J. Oreglia,³⁰ F. Orellana,⁴⁹ Y. Oren,¹⁵³ D. Orestano,^{134a,134b} I. Orlov,¹⁰⁷
C. Oropeza Barrera,⁵³ R. S. Orr,¹⁵⁸ E. O. Ortega,¹³⁰ B. Osculati,^{50a,50b} R. Ospanov,¹²⁰ C. Osuna,¹¹
G. Otero y Garzon,²⁶ J. P. Ottersbach,¹⁰⁵ M. Ouchrif,^{135c} F. Ould-Saada,¹¹⁷ A. Ouraou,¹³⁶ Q. Ouyang,^{32a} M. Owen,⁸²
S. Owen,¹³⁹ A. Oyarzun,^{31b} O. K. Øye,¹³ V. E. Ozcan,⁷⁷ N. Ozturk,⁷ A. Pacheco Pages,¹¹ C. Padilla Aranda,¹¹
E. Paganis,¹³⁹ F. Paige,²⁴ K. Pajchel,¹¹⁷ S. Palestini,²⁹ D. Pallin,³³ A. Palma,^{124a,c} J. D. Palmer,¹⁷ Y. B. Pan,¹⁷²
E. Panagiotopoulou,⁹ B. Panes,^{31a} N. Panikashvili,⁸⁷ S. Panitkin,²⁴ D. Pantea,^{25a} M. Panuskova,¹²⁵ V. Paolone,¹²³
A. Paoloni,^{133a,133b} A. Papadelis,^{146a} Th. D. Papadopoulou,⁹ A. Paramonov,⁵ S. J. Park,⁵⁴ W. Park,^{24,v} M. A. Parker,²⁷
F. Parodi,^{50a,50b} J. A. Parsons,³⁴ U. Parzefall,⁴⁸ E. Pasqualucci,^{132a} A. Passeri,^{134a} F. Pastore,^{134a,134b} Fr. Pastore,²⁹
G. Pásztor,^{49,w} S. Patariaia,¹⁷² N. Patel,¹⁵⁰ J. R. Pater,⁸² S. Patricelli,^{102a,102b} T. Pauly,²⁹ M. Pecsý,^{144a}
M. I. Pedraza Morales,¹⁷² S. V. Peleganchuk,¹⁰⁷ H. Peng,¹⁷² R. Pengo,²⁹ A. Penson,³⁴ J. Penwell,⁶¹ M. Perantoni,^{23a}
K. Perez,^{34,t} T. Perez Cavalcanti,⁴¹ E. Perez Codina,¹¹ M. T. Pérez García-Estañ,¹⁶⁷ V. Perez Reale,³⁴ I. Peric,²⁰
L. Perini,^{89a,89b} H. Pernegger,²⁹ R. Perrino,^{72a} P. Perrodo,⁴ S. Persebe,^{3a} P. Perus,¹¹⁵ V. D. Peshekhonov,⁶⁵
O. Peters,¹⁰⁵ B. A. Petersen,²⁹ J. Petersen,²⁹ T. C. Petersen,³⁵ E. Petit,⁸³ A. Petridis,¹⁵⁴ C. Petridou,¹⁵⁴ E. Petrolo,^{132a}
F. Petrucci,^{134a,134b} D. Petschull,⁴¹ M. Petteni,¹⁴² R. Pezoa,^{31b} A. Phan,⁸⁶ A. W. Phillips,²⁷ P. W. Phillips,¹²⁹
G. Piacquadio,²⁹ E. Piccaro,⁷⁵ M. Piccinini,^{19a,19b} A. Pickford,⁵³ R. Piegaia,²⁶ J. E. Pilcher,³⁰ A. D. Pilkington,⁸²
J. Pina,^{124a,c} M. Pinamonti,^{164a,164c} A. Pinder,¹¹⁸ J. L. Pinfeld,² J. Ping,^{32c} B. Pinto,^{124a,c} O. Pirote,²⁹ C. Pizio,^{89a,89b}
R. Placakyte,⁴¹ M. Plamondon,¹⁶⁹ W. G. Plano,⁸² M.-A. Pleier,²⁴ A. V. Pleskach,¹²⁸ A. Poblaguev,²⁴ S. Poddar,^{58a}

F. Podlyski,³³ L. Poggioli,¹¹⁵ T. Poghosyan,²⁰ M. Pohl,⁴⁹ F. Polci,⁵⁵ G. Polesello,^{119a} A. Policicchio,¹³⁸ A. Polini,^{19a} J. Poll,⁷⁵ V. Polychronakos,²⁴ D. M. Pomarede,¹³⁶ D. Pomeroy,²² K. Pommès,²⁹ L. Pontecorvo,^{132a} B. G. Pope,⁸⁸ G. A. Popeneciu,^{25a} D. S. Popovic,^{12a} A. Poppleton,²⁹ X. Portell Bueso,⁴⁸ R. Porter,¹⁶³ C. Posch,²¹ G. E. Pospelov,⁹⁹ S. Pospisil,¹²⁷ I. N. Potrap,⁹⁹ C. J. Potter,¹⁴⁹ C. T. Potter,⁸⁵ G. Poulard,²⁹ J. Poveda,¹⁷² R. Prabhu,⁷⁷ P. Pralavorio,⁸³ S. Prasad,⁵⁷ R. Pravahan,⁷ S. Prell,⁶⁴ K. Pretzl,¹⁶ L. Pribyl,²⁹ D. Price,⁶¹ L. E. Price,⁵ M. J. Price,²⁹ P. M. Prichard,⁷³ D. Prieur,¹²³ M. Primavera,^{72a} K. Prokofiev,²⁹ F. Prokoshin,^{31b} S. Protopopescu,²⁴ J. Proudfoot,⁵ X. Prudent,⁴³ H. Przysiezniak,⁴ S. Psoroulas,²⁰ E. Ptacek,¹¹⁴ J. Purdham,⁸⁷ M. Purohit,^{24,v} P. Puzo,¹¹⁵ Y. Pylypchenko,¹¹⁷ J. Qian,⁸⁷ Z. Qian,⁸³ Z. Qin,⁴¹ A. Quadt,⁵⁴ D. R. Quarrie,¹⁴ W. B. Quayle,¹⁷² F. Quinonez,^{31a} M. Raas,¹⁰⁴ V. Radescu,^{58b} B. Radics,²⁰ T. Rador,^{18a} F. Ragusa,^{89a,89b} G. Rahal,¹⁷⁷ A. M. Rahimi,¹⁰⁹ S. Rajagopalan,²⁴ S. Rajek,⁴² M. Rammensee,⁴⁸ M. Rammes,¹⁴¹ M. Ramstedt,^{146a,146b} K. Randrianarivony,²⁸ P. N. Ratoff,⁷¹ F. Rauscher,⁹⁸ E. Rauter,⁹⁹ M. Raymond,²⁹ A. L. Read,¹¹⁷ D. M. Rebuzzi,^{119a,119b} A. Redelbach,¹⁷³ G. Redlinger,²⁴ R. Reece,¹²⁰ K. Reeves,⁴⁰ A. Reichold,¹⁰⁵ E. Reinherz-Aronis,¹⁵³ A. Reinsch,¹¹⁴ I. Reisinger,⁴² D. Reljic,^{12a} C. Rembser,²⁹ Z. L. Ren,¹⁵¹ A. Renaud,¹¹⁵ P. Renkel,³⁹ B. Rensch,³⁵ M. Rescigno,^{132a} S. Resconi,^{89a} B. Resende,¹³⁶ P. Reznicek,⁹⁸ R. Rezvani,¹⁵⁸ A. Richards,⁷⁷ R. Richter,⁹⁹ E. Richter-Was,^{38,x} M. Ridel,⁷⁸ S. Rieke,⁸¹ M. Rijpstra,¹⁰⁵ M. Rijssenbeek,¹⁴⁸ A. Rimoldi,^{119a,119b} L. Rinaldi,^{19a} R. R. Rios,³⁹ I. Riu,¹¹ G. Rivoltella,^{89a,89b} F. Rizatdinova,¹¹² E. Rizvi,⁷⁵ S. H. Robertson,^{85,i} A. Robichaud-Veronneau,⁴⁹ D. Robinson,²⁷ J. E. M. Robinson,⁷⁷ M. Robinson,¹¹⁴ A. Robson,⁵³ J. G. Rocha de Lima,¹⁰⁶ C. Roda,^{122a,122b} D. Roda Dos Santos,²⁹ S. Rodier,⁸⁰ D. Rodriguez,¹⁶² Y. Rodriguez Garcia,¹⁵ A. Roe,⁵⁴ S. Roe,²⁹ O. Røhne,¹¹⁷ V. Rojo,¹ S. Rolli,¹⁶¹ A. Romaniouk,⁹⁶ V. M. Romanov,⁶⁵ G. Romeo,²⁶ D. Romero Maltrana,^{31a} L. Roos,⁷⁸ E. Ros,¹⁶⁷ S. Rosati,¹³⁸ M. Rose,⁷⁶ G. A. Rosenbaum,¹⁵⁸ E. I. Rosenberg,⁶⁴ P. L. Rosendahl,¹³ L. Rosselet,⁴⁹ V. Rossetti,¹¹ E. Rossi,^{102a,102b} L. P. Rossi,^{50a} L. Rossi,^{89a,89b} M. Rotaru,^{25a} I. Roth,¹⁷¹ J. Rothberg,¹³⁸ I. Rottländer,²⁰ D. Rousseau,¹¹⁵ C. R. Royon,¹³⁶ A. Rozanov,⁸³ Y. Rozen,¹⁵² X. Ruan,¹¹⁵ I. Rubinskiy,⁴¹ B. Ruckert,⁹⁸ N. Ruckstuhl,¹⁰⁵ V. I. Rud,⁹⁷ G. Rudolph,⁶² F. Rühr,⁶ A. Ruiz-Martinez,⁶⁴ E. Rulikowska-Zarebska,³⁷ V. Rumiantsev,^{91,a} L. Romyantsev,⁶⁵ K. Runge,⁴⁸ O. Runolfsson,²⁰ Z. Rurikova,⁴⁸ N. A. Rusakovich,⁶⁵ D. R. Rust,⁶¹ J. P. Rutherford,⁶ C. Ruwiedel,¹⁴ P. Ruzicka,¹²⁵ Y. F. Ryabov,¹²¹ V. Ryadovikov,¹²⁸ P. Ryan,⁸⁸ M. Rybar,¹²⁶ G. Rybkin,¹¹⁵ N. C. Ryder,¹¹⁸ S. Rzaeva,¹⁰ A. F. Saavedra,¹⁵⁰ I. Sadeh,¹⁵³ H. F. W. Sadrozinski,¹³⁷ R. Sadykov,⁶⁵ F. Safai Tehrani,^{132a,132b} H. Sakamoto,¹⁵⁵ G. Salamanna,¹⁰⁵ A. Salamon,^{133a} M. Saleem,¹¹¹ D. Salihagic,⁹⁹ A. Salnikov,¹⁴³ J. Salt,¹⁶⁷ B. M. Salvachua Ferrando,⁵ D. Salvatore,^{36a,36b} F. Salvatore,¹⁴⁹ A. Salzburger,²⁹ D. Sampsonidis,¹⁵⁴ B. H. Samset,¹¹⁷ H. Sandaker,¹³ H. G. Sander,⁸¹ M. P. Sanders,⁹⁸ M. Sandhoff,¹⁷⁴ P. Sandhu,¹⁵⁸ T. Sandoval,²⁷ R. Sandstroem,¹⁰⁵ S. Sandvoss,¹⁷⁴ D. P. C. Sankey,¹²⁹ A. Sansoni,⁴⁷ C. Santamarina Rios,⁸⁵ C. Santoni,³³ R. Santonico,^{133a,133b} H. Santos,^{124a} J. G. Saraiva,^{124a,c} T. Sarangi,¹⁷² E. Sarkisyan-Grinbaum,⁷ F. Sarri,^{122a,122b} G. Sartiso,¹⁷⁴ O. Sasaki,⁶⁶ T. Sasaki,⁶⁶ N. Sasao,⁶⁸ I. Satsounkevitch,⁹⁰ G. Sauvage,⁴ J. B. Sauvan,¹¹⁵ P. Savard,^{158,e} V. Savinov,¹²³ P. Savva,⁹ L. Sawyer,^{24,j} D. H. Saxon,⁵³ L. P. Says,³³ C. Sbarra,^{19a,19b} A. Sbrizzi,^{19a,19b} O. Scallon,⁹³ D. A. Scannicchio,¹⁶³ J. Schaarschmidt,⁴³ P. Schacht,⁹⁹ U. Schäfer,⁸¹ S. Schaezel,^{58b} A. C. Schaffer,¹¹⁵ D. Schaile,⁹⁸ R. D. Schamberger,¹⁴⁸ A. G. Schamov,¹⁰⁷ V. Scharf,^{58a} V. A. Schegelsky,¹²¹ D. Scheirich,⁸⁷ M. I. Scherzer,¹⁴ C. Schiavi,^{50a,50b} J. Schieck,⁹⁸ M. Schioppa,^{36a,36b} S. Schlenker,²⁹ J. L. Schlereth,⁵ E. Schmidt,⁴⁸ M. P. Schmidt,^{175,a} K. Schmieden,²⁰ C. Schmitt,⁸¹ M. Schmitz,²⁰ A. Schöning,^{58b} M. Schott,²⁹ D. Schouten,¹⁴² J. Schovancova,¹²⁵ M. Schram,⁸⁵ A. Schreiner,⁶³ C. Schroeder,⁸¹ N. Schroer,^{58c} S. Schuh,²⁹ G. Schuler,²⁹ J. Schultes,¹⁷⁴ H.-C. Schultz-Coulon,^{58a} H. Schulz,¹⁵ J. W. Schumacher,²⁰ M. Schumacher,⁴⁸ B. A. Schumm,¹³⁷ Ph. Schune,¹³⁶ C. Schwanenberger,⁸² A. Schwartzman,¹⁴³ Ph. Schwemling,⁷⁸ R. Schwienhorst,⁸⁸ R. Schwierz,⁴³ J. Schwindling,¹³⁶ W. G. Scott,¹²⁹ J. Searcy,¹¹⁴ E. Sedykh,¹²¹ E. Segura,¹¹ S. C. Seidel,¹⁰³ A. Seiden,¹³⁷ F. Seifert,⁴³ J. M. Seixas,^{23a} G. Sekhniaidze,^{102a} D. M. Seliverstov,¹²¹ B. Sellden,^{146a} G. Sellers,⁷³ M. Seman,^{144b} N. Semprini-Cesari,^{19a,19b} C. Serfon,⁹⁸ L. Serin,¹¹⁵ R. Seuster,⁹⁹ H. Severini,¹¹¹ M. E. Sevir,⁸⁶ A. Sfyrla,²⁹ E. Shabalina,⁵⁴ M. Shamim,¹¹⁴ L. Y. Shan,^{32a} J. T. Shank,²¹ Q. T. Shao,⁸⁶ M. Shapiro,¹⁴ P. B. Shatalov,⁹⁵ L. Shaver,⁶ C. Shaw,⁵³ K. Shaw,^{164a,164c} D. Sherman,¹⁷⁵ P. Sherwood,⁷⁷ A. Shibata,¹⁰⁸ S. Shimizu,²⁹ M. Shimojima,¹⁰⁰ T. Shin,⁵⁶ A. Shmeleva,⁹⁴ M. J. Shochet,³⁰ D. Short,¹¹⁸ M. A. Shupe,⁶ P. Sicho,¹²⁵ A. Sidoti,¹⁵ A. Siebel,¹⁷⁴ F. Siegert,⁴⁸ J. Siegrist,¹⁴ Dj. Sijacki,^{12a} O. Silbert,¹⁷¹ J. Silva,^{124a,c} Y. Silver,¹⁵³ D. Silverstein,¹⁴³ S. B. Silverstein,^{146a} V. Simak,¹²⁷ Lj. Simic,^{12a} S. Simion,¹¹⁵ B. Simmons,⁷⁷ M. Simonyan,³⁵ P. Sinervo,¹⁵⁸ N. B. Sinev,¹¹⁴ V. Sipica,¹⁴¹ G. Siragusa,⁸¹ A. N. Sisakyan,⁶⁵ S. Yu. Sivoklokov,⁹⁷ J. Sjölin,^{146a,146b} T. B. Sjursen,¹³ L. A. Skinnari,¹⁴ K. Skovpen,¹⁰⁷ P. Skubic,¹¹¹ N. Skvorodnev,²² M. Slater,¹⁷ T. Slavicek,¹²⁷ K. Sliwa,¹⁶¹ T. J. Sloan,⁷¹ J. Sloper,²⁹ V. Smakhtin,¹⁷¹ S. Yu. Smirnov,⁹⁶ L. N. Smirnova,⁹⁷ O. Smirnova,⁷⁹ B. C. Smith,⁵⁷ D. Smith,¹⁴³ K. M. Smith,⁵³ M. Smizanska,⁷¹ K. Smolek,¹²⁷ A. A. Snesarev,⁹⁴ S. W. Snow,⁸² J. Snow,¹¹¹ J. Snuverink,¹⁰⁵

- S. Snyder,²⁴ M. Soares,^{124a} R. Sobie,^{169,i} J. Sodomka,¹²⁷ A. Soffer,¹⁵³ C. A. Solans,¹⁶⁷ M. Solar,¹²⁷ J. Solc,¹²⁷ U. Soldevila,¹⁶⁷ E. Solfaroli Camillocci,^{132a,132b} A. A. Solodkov,¹²⁸ O. V. Solovyanov,¹²⁸ J. Sondericker,²⁴ N. Soni,² V. Sopko,¹²⁷ B. Sopko,¹²⁷ M. Sorbi,^{89a,89b} M. Sosebee,⁷ A. Soukharev,¹⁰⁷ S. Spagnolo,^{72a,72b} F. Spanò,³⁴ R. Spighi,^{19a} G. Spigo,²⁹ F. Spila,^{132a,132b} E. Spiriti,^{134a} R. Spiwoks,²⁹ M. Spousta,¹²⁶ T. Spreitzer,¹⁵⁸ B. Spurlock,⁷ R. D. St. Denis,⁵³ T. Stahl,¹⁴¹ J. Stahlman,¹²⁰ R. Stamen,^{58a} E. Stanecka,²⁹ R. W. Stanek,⁵ C. Stanescu,^{134a} S. Stapnes,¹¹⁷ E. A. Starchenko,¹²⁸ J. Stark,⁵⁵ P. Staroba,¹²⁵ P. Starovoitov,⁹¹ A. Staude,⁹⁸ P. Stavina,^{144a} G. Stavropoulos,¹⁴ G. Steele,⁵³ P. Steinbach,⁴³ P. Steinberg,²⁴ I. Stekl,¹²⁷ B. Stelzer,¹⁴² H. J. Stelzer,⁴¹ O. Stelzer-Chilton,^{159a} H. Stenzel,⁵² K. Stevenson,⁷⁵ G. A. Stewart,⁵³ T. Stockmanns,²⁰ M. C. Stockton,²⁹ K. Stoerig,⁴⁸ G. Stoicea,^{25a} S. Stonjek,⁹⁹ P. Strachota,¹²⁶ A. R. Stradling,⁷ A. Straessner,⁴³ J. Strandberg,⁸⁷ S. Strandberg,^{146a,146b} A. Strandlie,¹¹⁷ M. Strang,¹⁰⁹ E. Strauss,¹⁴³ M. Strauss,¹¹¹ P. Strizenec,^{144b} R. Ströhmer,¹⁷³ D. M. Strom,¹¹⁴ J. A. Strong,^{76,a} R. Stroynowski,³⁹ J. Strube,¹²⁹ B. Stugu,¹³ I. Stumer,^{24,a} J. Stupak,¹⁴⁸ P. Sturm,¹⁷⁴ D. A. Soh,^{151,q} D. Su,¹⁴³ S. Subramania,² Y. Sugaya,¹¹⁶ T. Sugimoto,¹⁰¹ C. Suhr,¹⁰⁶ K. Suita,⁶⁷ M. Suk,¹²⁶ V. V. Sulin,⁹⁴ S. Sultansoy,^{3d} T. Sumida,²⁹ X. Sun,⁵⁵ J. E. Sundermann,⁴⁸ K. Suruliz,^{164a,164b} S. Sushkov,¹¹ G. Susinno,^{36a,36b} M. R. Sutton,¹³⁹ Y. Suzuki,⁶⁶ Yu. M. Sviridov,¹²⁸ S. Swedish,¹⁶⁸ I. Sykora,^{144a} T. Sykora,¹²⁶ B. Szeless,²⁹ J. Sánchez,¹⁶⁷ D. Ta,¹⁰⁵ K. Tackmann,²⁹ A. Taffard,¹⁶³ R. Tafirout,^{159a} A. Taga,¹¹⁷ N. Taiblum,¹⁵³ Y. Takahashi,¹⁰¹ H. Takai,²⁴ R. Takashima,⁶⁹ H. Takeda,⁶⁷ T. Takeshita,¹⁴⁰ M. Talby,⁸³ A. Talyshiev,¹⁰⁷ M. C. Tamssett,²⁴ J. Tanaka,¹⁵⁵ R. Tanaka,¹¹⁵ S. Tanaka,¹³¹ S. Tanaka,⁶⁶ Y. Tanaka,¹⁰⁰ K. Tani,⁶⁷ N. Tannoury,⁸³ G. P. Tappern,²⁹ S. Tapprogge,⁸¹ D. Tardif,¹⁵⁸ S. Tarem,¹⁵² F. Tarrade,²⁴ G. F. Tartarelli,^{89a} P. Tas,¹²⁶ M. Tasevsky,¹²⁵ E. Tassi,^{36a,36b} M. Tatarkhanov,¹⁴ C. Taylor,⁷⁷ F. E. Taylor,⁹² G. Taylor,¹³⁷ G. N. Taylor,⁸⁶ W. Taylor,^{159b} M. Teixeira Dias Castanheira,⁷⁵ P. Teixeira-Dias,⁷⁶ K. K. Temming,⁴⁸ H. Ten Kate,²⁹ P. K. Teng,¹⁵¹ Y. D. Tennenbaum-Katan,¹⁵² S. Terada,⁶⁶ K. Terashi,¹⁵⁵ J. Terron,⁸⁰ M. Terwort,^{41,o} M. Testa,⁴⁷ R. J. Teuscher,^{158,i} C. M. Tevlin,⁸² J. Thadome,¹⁷⁴ J. Therhaag,²⁰ T. Theveneaux-Pelzer,⁷⁸ M. Thioye,¹⁷⁵ S. Thoma,⁴⁸ J. P. Thomas,¹⁷ E. N. Thompson,⁸⁴ P. D. Thompson,¹⁷ P. D. Thompson,¹⁵⁸ A. S. Thompson,⁵³ E. Thomson,¹²⁰ M. Thomson,²⁷ R. P. Thun,⁸⁷ T. Tic,¹²⁵ V. O. Tikhomirov,⁹⁴ Y. A. Tikhonov,¹⁰⁷ C. J. W. P. Timmermans,¹⁰⁴ P. Tipton,¹⁷⁵ F. J. Tique Aires Viegas,²⁹ S. Tisserant,⁸³ J. Tobias,⁴⁸ B. Toczek,³⁷ T. Todorov,⁴ S. Todorova-Nova,¹⁶¹ B. Toggerson,¹⁶³ J. Tojo,⁶⁶ S. Tokár,^{144a} K. Tokunaga,⁶⁷ K. Tokushuku,⁶⁶ K. Tollefson,⁸⁸ M. Tomoto,¹⁰¹ L. Tompkins,¹⁴ K. Toms,¹⁰³ A. Tonazzo,^{134a,134b} G. Tong,^{32a} A. Tonoyan,¹³ C. Topfel,¹⁶ N. D. Topilin,⁶⁵ I. Torchiani,²⁹ E. Torrence,¹¹⁴ E. Torró Pastor,¹⁶⁷ J. Toth,^{83,w} F. Touchard,⁸³ D. R. Tovey,¹³⁹ D. Traynor,⁷⁵ T. Trefzger,¹⁷³ J. Treis,²⁰ L. Tremblet,²⁹ A. Tricoli,²⁹ I. M. Trigger,^{159a} S. Trincaz-Duvoid,⁷⁸ T. N. Trinh,⁷⁸ M. F. Tripiana,⁷⁰ N. Triplett,⁶⁴ W. Trischuk,¹⁵⁸ A. Trivedi,^{24,v} B. Trocmé,⁵⁵ C. Troncon,^{89a} M. Trottier-McDonald,¹⁴² A. Trzupek,³⁸ C. Tsarouchas,²⁹ J. C. L. Tseng,¹¹⁸ M. Tsiakiris,¹⁰⁵ P. V. Tsiarehka,⁹⁰ D. Tsiou,⁴ G. Tsiopolitis,⁹ V. Tsiskaridze,⁴⁸ E. G. Tskhadadze,⁵¹ I. I. Tsukerman,⁹⁵ V. Tsulaia,¹²³ J.-W. Tsung,²⁰ S. Tsuno,⁶⁶ D. Tsybychev,¹⁴⁸ A. Tua,¹³⁹ J. M. Tuggle,³⁰ M. Turala,³⁸ D. Turecek,¹²⁷ I. Turk Cakir,^{3e} E. Turlay,¹⁰⁵ P. M. Tuts,³⁴ A. Tykhonov,⁷⁴ M. Tylmad,^{146a,146b} M. Tyndel,¹²⁹ D. Typaldos,¹⁷ H. Tyrvaïnen,²⁹ G. Tzanakos,⁸ K. Uchida,²⁰ I. Ueda,¹⁵⁵ R. Ueno,²⁸ M. Uglund,¹³ M. Uhlenbrock,²⁰ M. Uhrmacher,⁵⁴ F. Ukegawa,¹⁶⁰ G. Unal,²⁹ D. G. Underwood,⁵ A. Undrus,²⁴ G. Unel,¹⁶³ Y. Unno,⁶⁶ D. Urbaniec,³⁴ E. Urkovsky,¹⁵³ P. Urquijo,⁴⁹ P. Urrejola,^{31a} G. Usai,⁷ M. Uslenghi,^{119a,119b} L. Vacavant,⁸³ V. Vacek,¹²⁷ B. Vachon,⁸⁵ S. Vahsen,¹⁴ C. Valderanis,⁹⁹ J. Valenta,¹²⁵ P. Valente,^{132a} S. Valentinetti,^{19a,19b} S. Valkar,¹²⁶ E. Valladolid Gallego,¹⁶⁷ S. Vallecorsa,¹⁵² J. A. Valls Ferrer,¹⁶⁷ H. van der Graaf,¹⁰⁵ E. van der Kraaij,¹⁰⁵ E. van der Poel,¹⁰⁵ D. van der Ster,²⁹ B. Van Eijk,¹⁰⁵ N. van Eldik,⁸⁴ P. van Gemmeren,⁵ Z. van Kesteren,¹⁰⁵ I. van Vulpen,¹⁰⁵ W. Vandelli,²⁹ G. Vandoni,²⁹ A. Vaniachine,⁵ P. Vankov,⁴¹ F. Vannucci,⁷⁸ F. Varela Rodriguez,²⁹ R. Vari,^{132a} E. W. Varnes,⁶ D. Varouchas,¹⁴ A. Vartapetian,⁷ K. E. Varvell,¹⁵⁰ V. I. Vassilakopoulos,⁵⁶ F. Vazeille,³³ G. Vegni,^{89a,89b} J. J. Veillet,¹¹⁵ C. Vellidis,⁸ F. Veloso,^{124a} R. Veness,²⁹ S. Veneziano,^{132a} A. Ventura,^{72a,72b} D. Ventura,¹³⁸ S. Ventura,⁴⁷ M. Venturi,⁴⁸ N. Venturi,¹⁶ V. Vercesi,^{119a} M. Verducci,¹³⁸ W. Verkerke,¹⁰⁵ J. C. Vermeulen,¹⁰⁵ A. Vest,⁴³ M. C. Vetterli,^{142,e} I. Vichou,¹⁶⁵ T. Vickey,^{145b,y} G. H. A. Viehhauser,¹¹⁸ S. Viel,¹⁶⁸ M. Villa,^{19a,19b} M. Villaplana Perez,¹⁶⁷ E. Vilucchi,⁴⁷ M. G. Vincter,²⁸ E. Vinek,²⁹ V. B. Vinogradov,⁶⁵ M. Virchaux,^{136,a} S. Viret,³³ J. Virzi,¹⁴ A. Vitale,^{19a,19b} O. Vitells,¹⁷¹ I. Vivarelli,⁴⁸ F. Vives Vaque,¹¹ S. Vlachos,⁹ M. Vlasak,¹²⁷ N. Vlasov,²⁰ A. Vogel,²⁰ P. Vokac,¹²⁷ M. Volpi,¹¹ G. Volpini,^{89a} H. von der Schmitt,⁹⁹ J. von Loeben,⁹⁹ H. von Radziewski,⁴⁸ E. von Toerne,²⁰ V. Vorobel,¹²⁶ A. P. Vorobiev,¹²⁸ V. Vorwerk,¹¹ M. Vos,¹⁶⁷ R. Voss,²⁹ T. T. Voss,¹⁷⁴ J. H. Vossebeld,⁷³ A. S. Vovenko,¹²⁸ N. Vranjes,^{12a} M. Vranjes Milosavljevic,^{12a} V. Vrba,¹²⁵ M. Vreeswijk,¹⁰⁵ T. Vu Anh,⁸¹ R. Vuillermet,²⁹ I. Vukotic,¹¹⁵ W. Wagner,¹⁷⁴ P. Wagner,¹²⁰ H. Wahlen,¹⁷⁴ J. Wakabayashi,¹⁰¹ J. Walbersloh,⁴² S. Walch,⁸⁷ J. Walder,⁷¹ R. Walker,⁹⁸

W. Walkowiak,¹⁴¹ R. Wall,¹⁷⁵ P. Waller,⁷³ C. Wang,⁴⁴ H. Wang,¹⁷² J. Wang,^{32d} J. C. Wang,¹³⁸ R. Wang,¹⁰³ S. M. Wang,¹⁵¹ A. Warburton,⁸⁵ C. P. Ward,²⁷ M. Warsinsky,⁴⁸ P. M. Watkins,¹⁷ A. T. Watson,¹⁷ M. F. Watson,¹⁷ G. Watts,¹³⁸ S. Watts,⁸² A. T. Waugh,¹⁵⁰ B. M. Waugh,⁷⁷ J. Weber,⁴² M. Weber,¹²⁹ M. S. Weber,¹⁶ P. Weber,⁵⁴ A. R. Weidberg,¹¹⁸ J. Weingarten,⁵⁴ C. Weiser,⁴⁸ H. Wellenstein,²² P. S. Wells,²⁹ M. Wen,⁴⁷ T. Wenaus,²⁴ S. Wendler,¹²³ Z. Weng,^{151,q} T. Wengler,²⁹ S. Wenig,²⁹ N. Vermes,²⁰ M. Werner,⁴⁸ P. Werner,²⁹ M. Werth,¹⁶³ M. Wessels,^{58a} K. Whalen,²⁸ S. J. Wheeler-Ellis,¹⁶³ S. P. Whitaker,²¹ A. White,⁷ M. J. White,⁸⁶ S. White,²⁴ S. R. Whitehead,¹¹⁸ D. Whiteson,¹⁶³ D. Whittington,⁶¹ F. Wicek,¹¹⁵ D. Wicke,¹⁷⁴ F. J. Wickens,¹²⁹ W. Wiedenmann,¹⁷² M. Wielers,¹²⁹ P. Wienemann,²⁰ C. Wiglesworth,⁷³ L. A. M. Wiik,⁴⁸ A. Wildauer,¹⁶⁷ M. A. Wildt,^{41,o} I. Wilhelm,¹²⁶ H. G. Wilkens,²⁹ J. Z. Will,⁹⁸ E. Williams,³⁴ H. H. Williams,¹²⁰ W. Willis,³⁴ S. Willocq,⁸⁴ J. A. Wilson,¹⁷ M. G. Wilson,¹⁴³ A. Wilson,⁸⁷ I. Wingerter-Seez,⁴ S. Winkelmann,⁴⁸ F. Winklmeier,²⁹ M. Wittgen,¹⁴³ M. W. Wolter,³⁸ H. Wolters,^{124a,g} G. Wooden,¹¹⁸ B. K. Wosiek,³⁸ J. Wotschack,²⁹ M. J. Woudstra,⁸⁴ K. Wraight,⁵³ C. Wright,⁵³ B. Wrona,⁷³ S. L. Wu,¹⁷² X. Wu,⁴⁹ Y. Wu,^{32b} E. Wulf,³⁴ R. Wunstorf,⁴² B. M. Wynne,⁴⁵ L. Xaplanteris,⁹ S. Xella,³⁵ S. Xie,⁴⁸ Y. Xie,^{32a} C. Xu,^{32b} D. Xu,¹³⁹ G. Xu,^{32a} B. Yabsley,¹⁵⁰ M. Yamada,⁶⁶ A. Yamamoto,⁶⁶ K. Yamamoto,⁶⁴ S. Yamamoto,¹⁵⁵ T. Yamamura,¹⁵⁵ J. Yamaoka,⁴⁴ T. Yamazaki,¹⁵⁵ Y. Yamazaki,⁶⁷ Z. Yan,²¹ H. Yang,⁸⁷ U. K. Yang,⁸² Y. Yang,⁶¹ Y. Yang,^{32a} Z. Yang,^{146a,146b} S. Yanush,⁹¹ W-M. Yao,¹⁴ Y. Yao,¹⁴ Y. Yasu,⁶⁶ J. Ye,³⁹ S. Ye,²⁴ M. Yilmaz,^{3c} R. Yoosoofmiya,¹²³ K. Yorita,¹⁷⁰ R. Yoshida,⁵ C. Young,¹⁴³ S. Youssef,²¹ D. Yu,²⁴ J. Yu,⁷ J. Yu,^{32c,z} L. Yuan,^{32a,aa} A. Yurkewicz,¹⁴⁸ V. G. Zaets,¹²⁸ R. Zaidan,⁶³ A. M. Zaitsev,¹²⁸ Z. Zajacova,²⁹ Yo.K. Zalite,¹²¹ L. Zanello,^{132a,132b} P. Zarzhitsky,³⁹ A. Zaytsev,¹⁰⁷ M. Zdrzil,¹⁴ C. Zeitnitz,¹⁷⁴ M. Zeller,¹⁷⁵ P. F. Zema,²⁹ A. Zemla,³⁸ C. Zender,²⁰ A. V. Zenin,¹²⁸ O. Zenin,¹²⁸ T. Ženiš,^{144a} Z. Zenonos,^{122a,122b} S. Zenz,¹⁴ D. Zerwas,¹¹⁵ G. Zevi della Porta,⁵⁷ Z. Zhan,^{32d} D. Zhang,^{32b} H. Zhang,⁸⁸ J. Zhang,⁵ X. Zhang,^{32d} Z. Zhang,¹¹⁵ L. Zhao,¹⁰⁸ T. Zhao,¹³⁸ Z. Zhao,^{32b} A. Zhemchugov,⁶⁵ S. Zheng,^{32a} J. Zhong,^{151,bb} B. Zhou,⁸⁷ N. Zhou,¹⁶³ Y. Zhou,¹⁵¹ C. G. Zhu,^{32d} H. Zhu,⁴¹ Y. Zhu,¹⁷² X. Zhuang,⁹⁸ V. Zhuravlov,⁹⁹ D. Zieminska,⁶¹ B. Zilka,^{144a} R. Zimmermann,²⁰ S. Zimmermann,²⁰ S. Zimmermann,⁴⁸ M. Ziolkowski,¹⁴¹ R. Zitoun,⁴ L. Živković,³⁴ V. V. Zmouchko,^{128,a} G. Zobernig,¹⁷² A. Zoccoli,^{19a,19b} Y. Zolnierowski,⁴ A. Zsenei,²⁹ M. zur Nedden,¹⁵ V. Zutshi,¹⁰⁶ and L. Zwalinski²⁹

(ATLAS Collaboration)

¹University at Albany, 1400 Washington Ave, Albany, New York 12222, USA²University of Alberta, Department of Physics, Centre for Particle Physics, Edmonton, AB T6G 2G7, Canada^{3a}Ankara University, Faculty of Sciences, Department of Physics, TR 061000 Tandogan, Ankara, Turkey^{3b}Dumlupinar University, Faculty of Arts and Sciences, Department of Physics, Kutahya, Turkey^{3c}Gazi University, Faculty of Arts and Sciences, Department of Physics, 06500, Teknikokullar, Ankara, Turkey^{3d}TOBB University of Economics and Technology, Faculty of Arts and Sciences, Division of Physics, 06560, Sogutozu, Ankara, Turkey^{3e}Turkish Atomic Energy Authority, 06530, Lodumlu, Ankara, Turkey⁴LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France⁵Argonne National Laboratory, High Energy Physics Division, 9700 S. Cass Avenue, Argonne Illinois 60439, USA⁶University of Arizona, Department of Physics, Tucson, Arizona 85721, USA⁷The University of Texas at Arlington, Department of Physics, Box 19059, Arlington, Texas 76019, USA⁸University of Athens, Nuclear & Particle Physics, Department of Physics, Panepistimiopouli, Zografou, GR 15771 Athens, Greece⁹National Technical University of Athens, Physics Department, 9-Iroon Polytechniou, GR 15780 Zografou, Greece¹⁰Institute of Physics, Azerbaijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan¹¹Institut de Física d'Altes Energies, IFAE, Edifici Cn, Universitat Autònoma de Barcelona, ES - 08193 Bellaterra (Barcelona), Spain^{12a}University of Belgrade, Institute of Physics, P.O. Box 57, 11001 Belgrade, Serbia^{12b}Vinca Institute of Nuclear Sciences, M. Petrovica Alasa 12-14, 11000 Belgrade, Serbia¹³University of Bergen, Department for Physics and Technology, Allegaten 55, NO - 5007 Bergen, Norway¹⁴Lawrence Berkeley National Laboratory and University of California, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, California 94720, USA¹⁵Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany¹⁶University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH - 3012 Bern, Switzerland¹⁷University of Birmingham, School of Physics and Astronomy, Edgbaston, Birmingham B15 2TT, United Kingdom^{18a}Bogazici University, Faculty of Sciences, Department of Physics, TR - 80815 Bebek-Istanbul, Turkey^{18b}Dogus University, Faculty of Arts and Sciences, Department of Physics, 34722, Kadikoy, Istanbul, Turkey^{18c}Gaziantep University, Faculty of Engineering, Department of Physics Engineering, 27310, Sehitkamil, Gaziantep, Turkey

- ^{18d}*Istanbul Technical University, Faculty of Arts and Sciences, Department of Physics, 34469, Maslak, Istanbul, Turkey*
- ^{19a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{19b}*Università di Bologna, Dipartimento di Fisica, viale C. Berti Pichat, 6/2, IT - 40127 Bologna, Italy*
- ²⁰*University of Bonn, Physikalisches Institut, Nussallee 12, D - 53115 Bonn, Germany*
- ²¹*Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, Massachusetts 02215, USA*
- ²²*Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, Massachusetts 02454, USA*
- ^{23a}*Universidade Federal do Rio De Janeiro, COPPE/EE/IF, Caixa Postal 68528, Ilha do Fundao, BR - 21945-970 Rio de Janeiro, Brazil*
- ^{23b}*Universidade de Sao Paulo, Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo - SP, 05508 - 900, Brazil*
- ²⁴*Brookhaven National Laboratory, Physics Department, Building 510A, Upton, New York 11973, USA*
- ^{25a}*National Institute of Physics and Nuclear Engineering Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125, Romania*
- ^{25b}*University Politehnica Bucharest, Rectorat - AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti, Romania*
- ^{25c}*West University in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania*
- ²⁶*Universidad de Buenos Aires, FCEyN, Dto. Fisica, Pab I - C. Universitaria, 1428 Buenos Aires, Argentina*
- ²⁷*University of Cambridge, Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
- ²⁸*Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada*
- ²⁹*CERN, CH - 1211 Geneva 23, Switzerland*
- ³⁰*University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, Illinois 60637, USA*
- ^{31a}*Pontificia Universidad Católica de Chile, Facultad de Fisica, Departamento de Fisica, Avda. Vicuna Mackenna 4860, San Joaquín, Santiago, Chile*
- ^{31b}*Universidad Técnica Federico Santa María, Departamento de Física, Avda. España 1680, Casilla 110-V, Valparaíso, Chile*
- ^{32a}*Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN - Beijing 100049, China*
- ^{32b}*University of Science & Technology of China (USTC), Department of Modern Physics, Hefei, CN - Anhui 230026, China*
- ^{32c}*Nanjing University, Department of Physics, Nanjing, CN - Jiangsu 210093, China*
- ^{32d}*Shandong University, High Energy Physics Group, Jinan, CN - Shandong 250100, China*
- ³³*Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, FR - 63177 Aubiere Cedex, France*
- ³⁴*Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, New York 10533, USA*
- ³⁵*University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK - 2100 Kobenhavn 0, Denmark*
- ^{36a}*INFN Gruppo Collegato di Cosenza, Cosenza, Italy*
- ^{36b}*Università della Calabria, Dipartimento di Fisica, IT-87036 Arcavacata di Rende, Italy*
- ³⁷*Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology, (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland*
- ³⁸*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL - 31342 Krakow, Poland*
- ³⁹*Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, Texas 75275-0175, USA*
- ⁴⁰*University of Texas at Dallas, 800 West Campbell Road, Richardson, Texas 75080-3021, USA*
- ⁴¹*DESY, Notkestr. 85, D-22603 Hamburg and Platanenallee 6, D-15738 Zeuthen, Germany*
- ⁴²*TU Dortmund, Experimentelle Physik IV, DE - 44221 Dortmund, Germany*
- ⁴³*Technical University Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, D-01069 Dresden, Germany*
- ⁴⁴*Duke University, Department of Physics, Durham, North Carolina 27708, USA*
- ⁴⁵*University of Edinburgh, School of Physics & Astronomy, James Clerk Maxwell Building, The Kings Buildings, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom*
- ⁴⁶*Fachhochschule Wiener Neustadt; Johannes Gutenbergstrasse 3 AT - 2700 Wiener Neustadt, Austria*
- ⁴⁷*INFN Laboratori Nazionali di Frascati, via Enrico Fermi 40, IT-00044 Frascati, Italy*
- ⁴⁸*Albert-Ludwigs-Universität, Fakultät für Mathematik und Physik, Hermann-Herder Str. 3, D - 79104 Freiburg i.Br., Germany*
- ⁴⁹*Université de Genève, Section de Physique, 24 rue Ernest Ansermet, CH - 1211 Geneve 4, Switzerland*
- ^{50a}*INFN Sezione di Genova, Genova, Italy*
- ^{50b}*Università di Genova, Dipartimento di Fisica, via Dodecaneso 33, IT - 16146 Genova, Italy*
- ⁵¹*Institute of Physics of the Georgian Academy of Sciences, 6 Tamarashvili Street, GE - 380077 Tbilisi; Tbilisi State University, HEP Institute, University St. 9, GE - 380086 Tbilisi, Georgia*
- ⁵²*Justus-Liebig-Universität Giessen, II Physikalisches Institut, Heinrich-Buff Ring 16, D-35392 Giessen, Germany*
- ⁵³*University of Glasgow, Department of Physics and Astronomy, Glasgow G12 8QQ, United Kingdom*
- ⁵⁴*Georg-August-Universität, II. Physikalisches Institut, Friedrich-Hund Platz 1, D-37077 Göttingen, Germany*
- ⁵⁵*LPSC, CNRS/IN2P3 and Université Joseph Fourier Grenoble, 53 avenue des Martyrs, FR-38026 Grenoble Cedex, France*
- ⁵⁶*Hampton University, Department of Physics, Hampton, Virginia 23668, USA*
- ⁵⁷*Harvard University, Laboratory for Particle Physics and Cosmology, 18 Hammond Street, Cambridge, Massachusetts 02138, USA*
- ^{58a}*Ruprecht-Karls-Universität Heidelberg: Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, D-69120 Heidelberg, Germany*
- ^{58b}*Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*

- ^{58c}ZITI Ruprecht-Karls-University Heidelberg, Lehrstuhl für Informatik V, B6, 23-29, DE - 68131 Mannheim, Germany
- ⁵⁹Hiroshima University, Faculty of Science, 1-3-1 Kagamiyama, Higashihiroshima-shi, JP - Hiroshima 739-8526, Japan
- ⁶⁰Hiroshima Institute of Technology, Faculty of Applied Information Science, 2-1-1 Miyake Saeki-ku, Hiroshima-shi, JP - Hiroshima 731-5193, Japan
- ⁶¹Indiana University, Department of Physics, Swain Hall West 117, Bloomington, Indiana 47405-7105, USA
- ⁶²Institut für Astro- und Teilchenphysik, Technikerstrasse 25, A - 6020 Innsbruck, Austria
- ⁶³University of Iowa, 203 Van Allen Hall, Iowa City, Iowa 52242-1479, USA
- ⁶⁴Iowa State University, Department of Physics and Astronomy, Ames High Energy Physics Group, Ames, Iowa 50011-3160, USA
- ⁶⁵Joint Institute for Nuclear Research, JINR Dubna, RU-141980 Moscow Region, Russia
- ⁶⁶KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-0801, Japan
- ⁶⁷Kobe University, Graduate School of Science, 1-1 Rokkodai-cho, Nada-ku, JP Kobe 657-8501, Japan
- ⁶⁸Kyoto University, Faculty of Science, Oiwake-cho, Kitashirakawa, Sakyou-ku, Kyoto-shi, JP - Kyoto 606-8502, Japan
- ⁶⁹Kyoto University of Education, 1 Fukakusa, Fujimori, fushimi-ku, Kyoto-shi, JP - Kyoto 612-8522, Japan
- ⁷⁰Universidad Nacional de La Plata, FCE, Departamento de Física, IFLP (CONICET-UNLP), C.C. 67, 1900 La Plata, Argentina
- ⁷¹Lancaster University, Physics Department, Lancaster LA1 4YB, United Kingdom
- ^{72a}INFN Sezione di Lecce, Lecce, Italy
- ^{72b}Università del Salento, Dipartimento di Fisica Via Arnesano IT - 73100 Lecce, Italy
- ⁷³University of Liverpool, Oliver Lodge Laboratory, P.O. Box 147, Oxford Street, Liverpool L69 3BX, United Kingdom
- ⁷⁴Jožef Stefan Institute and University of Ljubljana, Department of Physics, SI-1000 Ljubljana, Slovenia
- ⁷⁵Queen Mary University of London, Department of Physics, Mile End Road, London E1 4NS, United Kingdom
- ⁷⁶Royal Holloway, University of London, Department of Physics, Egham Hill, Egham, Surrey TW20 0EX, United Kingdom
- ⁷⁷University College London, Department of Physics and Astronomy, Gower Street, London WC1E 6BT, United Kingdom
- ⁷⁸Laboratoire de Physique Nucléaire et de Hautes Energies, Université Pierre et Marie Curie (Paris 6), Université Denis Diderot (Paris-7), CNRS/IN2P3, Tour 33, 4 place Jussieu, FR - 75252 Paris Cedex 05, France
- ⁷⁹Fysiska institutionen, Lunds universitet, Box 118, SE - 221 00 Lund, Sweden
- ⁸⁰Universidad Autonoma de Madrid, Facultad de Ciencias, Departamento de Física Teórica, ES - 28049 Madrid, Spain
- ⁸¹Universität Mainz, Institut für Physik, Staudinger Weg 7, DE - 55099 Mainz, Germany
- ⁸²University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom
- ⁸³CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- ⁸⁴University of Massachusetts, Department of Physics, 710 North Pleasant Street, Amherst, Massachusetts 01003, USA
- ⁸⁵McGill University, High Energy Physics Group, 3600 University Street, Montreal, Quebec H3A 2T8, Canada
- ⁸⁶University of Melbourne, School of Physics, AU - Parkville, Victoria 3010, Australia
- ⁸⁷The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, Michigan 48109-1120, USA
- ⁸⁸Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, Michigan 48824-2320, USA
- ^{89a}INFN Sezione di Milano, Milano, Italy
- ^{89b}Università di Milano, Dipartimento di Fisica, via Celoria 16, IT - 20133 Milano, Italy
- ⁹⁰B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Republic of Belarus
- ⁹¹National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Republic of Belarus
- ⁹²Massachusetts Institute of Technology, Department of Physics, Room 24-516, Cambridge, Massachusetts 02139, USA
- ⁹³University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada
- ⁹⁴P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU - 117 924 Moscow, Russia
- ⁹⁵Institute for Theoretical and Experimental Physics (ITEP), B. Chermushkinskaya ul. 25, RU 117 218 Moscow, Russia
- ⁹⁶Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shosse 31, RU - 115409 Moscow, Russia
- ⁹⁷Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 1(2), Leninskie gory, GSP-1, Moscow 119991 Russian Federation, Russia
- ⁹⁸Ludwig-Maximilians-Universität München, Fakultät für Physik, Am Coulombwall 1, DE - 85748 Garching, Germany
- ⁹⁹Max-Planck-Institut für Physik, (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
- ¹⁰⁰Nagasaki Institute of Applied Science, 536 Aba-machi, JP Nagasaki 851-0193, Japan
- ¹⁰¹Nagoya University, Graduate School of Science, Furo-Cho, Chikusa-ku, Nagoya, 464-8602, Japan
- ^{102a}INFN Sezione di Napoli, Napoli, Italy
- ^{102b}Università di Napoli, Dipartimento di Scienze Fisiche, Complesso Universitario di Monte Sant'Angelo, via Cinthia, IT - 80126 Napoli, Italy
- ¹⁰³University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, New Mexico 87131, USA
- ¹⁰⁴Radboud University Nijmegen/NIKHEF, Department of Experimental High Energy Physics, Heyendaalseweg 135, NL-6525 AJ, Nijmegen, Netherlands
- ¹⁰⁵Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands
- ¹⁰⁶Department of Physics, Northern Illinois University, LaTourette Hall Normal Road, DeKalb, Illinois 60115, USA

- ¹⁰⁷*Budker Institute of Nuclear Physics (BINP), RU - Novosibirsk 630 090, Russia*
- ¹⁰⁸*New York University, Department of Physics, 4 Washington Place, New York New York 10003, USA*
- ¹⁰⁹*Ohio State University, 191 West Woodruff Ave, Columbus, Ohio 43210-1117, USA*
- ¹¹⁰*Okayama University, Faculty of Science, Tsushimanaka 3-1-1, Okayama 700-8530, Japan*
- ¹¹¹*University of Oklahoma, Homer L. Dodge Department of Physics and Astronomy,
440 West Brooks, Room 100, Norman, Oklahoma 73019-0225, USA*
- ¹¹²*Oklahoma State University, Department of Physics, 145 Physical Sciences Building, Stillwater, Oklahoma 74078-3072, USA*
- ¹¹³*Palacký University, 17.listopadu 50a, 772 07 Olomouc, Czech Republic*
- ¹¹⁴*University of Oregon, Center for High Energy Physics, Eugene, Oregon 97403-1274, USA*
- ¹¹⁵*LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France*
- ¹¹⁶*Osaka University, Graduate School of Science, Machikaneyama-machi 1-1, Toyonaka, Osaka 560-0043, Japan*
- ¹¹⁷*University of Oslo, Department of Physics, P.O. Box 1048, Blindern, NO - 0316 Oslo 3, Norway*
- ¹¹⁸*Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*
- ^{119a}*INFN Sezione di Pavia, Pavia, Italy*
- ^{119b}*Università di Pavia, Dipartimento di Fisica Nucleare e Teorica, Via Bassi 6, IT-27100 Pavia, Italy*
- ¹²⁰*University of Pennsylvania, Department of Physics, High-Energy Physics Group,
209 S. 33rd Street, Philadelphia, Pennsylvania 19104, USA*
- ¹²¹*Petersburg Nuclear Physics Institute, RU - 188 300 Gatchina, Russia*
- ^{122a}*INFN Sezione di Pisa, Pisa, Italy*
- ^{122b}*Università di Pisa, Dipartimento di Fisica E. Fermi, Largo B. Pontecorvo 3, IT - 56127 Pisa, Italy*
- ¹²³*University of Pittsburgh, Department of Physics and Astronomy, 3941 O'Hara Street, Pittsburgh, Pennsylvania 15260, USA*
- ^{124a}*Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP,
Avenida Elias Garcia 14-1, PT - 1000-149 Lisboa, Portugal*
- ^{124b}*Universidad de Granada, Departamento de Fisica Teorica y del Cosmos and CAFPE, E-18071 Granada, Portugal*
- ¹²⁵*Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ - 18221 Praha 8, Czech Republic*
- ¹²⁶*Charles University in Prague, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, V Holesovickach 2,
CZ - 18000 Praha 8, Czech Republic*
- ¹²⁷*Czech Technical University in Prague, Zikova 4, CZ - 166 35 Praha 6, Czech Republic*
- ¹²⁸*State Research Center Institute for High Energy Physics, Moscow Region, 142281, Protvino, Pobeda Street, 1, Russia*
- ¹²⁹*Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus,
Didcot OX11 0QX, United Kingdom*
- ¹³⁰*University of Regina, Physics Department, Regina, Canada*
- ¹³¹*Ritsumeikan University, Noji Higashi 1 chome 1-1, JP - Kusatsu, Shiga 525-8577, Japan*
- ^{132a}*INFN Sezione di Roma I, Roma, Italy*
- ^{132b}*Università La Sapienza, Dipartimento di Fisica, Piazzale A. Moro 2, IT- 00185 Roma, Italy*
- ^{133a}*INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ^{133b}*Università di Roma Tor Vergata, Dipartimento di Fisica, via della Ricerca Scientifica, IT-00133 Roma, Italy*
- ^{134a}*INFN Sezione di Roma Tre, Roma, Italy*
- ^{134b}*Università Roma Tre, Dipartimento di Fisica, via della Vasca Navale 84, IT-00146 Roma, Italy*
- ^{135a}*Réseau Universitaire de Physique des Hautes Energies (RUPHE): Université Hassan II,
Faculté des Sciences Ain Chock, B.P. 5366, MA - Casablanca, Morocco*
- ^{135b}*Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), B.P. 1382 R.P. 10001 Rabat 10001, Morocco*
- ^{135c}*Université Mohamed Premier, LPTPM, Faculté des Sciences, B.P.717. Bd. Mohamed VI, 60000, Oujda, Morocco*
- ^{135d}*Université Mohammed V, Faculté des Sciences 4 Avenue Ibn Battouta, BP 1014 RP, 10000 Rabat, Morocco*
- ¹³⁶*CEA, DSM/IRFU, Centre d'Etudes de Saclay, FR - 91191 Gif-sur-Yvette, France*
- ¹³⁷*University of California Santa Cruz, Santa Cruz Institute for Particle Physics (SCIPP), Santa Cruz, California 95064, USA*
- ¹³⁸*University of Washington, Seattle, Department of Physics, Box 351560, Seattle, Washington 98195-1560, USA*
- ¹³⁹*University of Sheffield, Department of Physics & Astronomy, Hounsfield Road, Sheffield S3 7RH, United Kingdom*
- ¹⁴⁰*Shinshu University, Department of Physics, Faculty of Science, 3-1-1 Asahi, Matsumoto-shi, JP - Nagano 390-8621, Japan*
- ¹⁴¹*Universität Siegen, Fachbereich Physik, D 57068 Siegen, Germany*
- ¹⁴²*Simon Fraser University, Department of Physics, 8888 University Drive, CA - Burnaby, BC V5A 1S6, Canada*
- ¹⁴³*SLAC National Accelerator Laboratory, Stanford, California 94309, USA*
- ^{144a}*Comenius University, Faculty of Mathematics, Physics & Informatics, Mlynska dolina F2, SK - 84248 Bratislava, Slovak Republic*
- ^{144b}*Institute of Experimental Physics of the Slovak Academy of Sciences, Department of Subnuclear Physics,
Watsonova 47, SK - 04353 Kosice, Slovak Republic*
- ^{145a}*University of Johannesburg, Department of Physics, PO Box 524, Auckland Park, Johannesburg 2006, South Africa*
- ^{145b}*School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa, South Africa*
- ^{146a}*Stockholm University, Department of Physics, Stockholm, Sweden*
- ^{146b}*The Oskar Klein Centre, AlbaNova, SE - 106 91 Stockholm, Sweden*
- ¹⁴⁷*Royal Institute of Technology (KTH), Physics Department, SE - 106 91 Stockholm, Sweden*
- ¹⁴⁸*Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, New York 11794-3800, USA*

- ¹⁴⁹University of Sussex, Department of Physics and Astronomy Pevensey 2 Building, Falmer, Brighton BN1 9QH, United Kingdom
- ¹⁵⁰University of Sydney, School of Physics, AU - Sydney NSW 2006, Australia
- ¹⁵¹Institute of Physics, Academia Sinica, TW - Taipei 11529, Taiwan
- ¹⁵²Technion, Israel Institute of Technology, Department of Physics, Technion City, IL - Haifa 32000, Israel
- ¹⁵³Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL - Tel Aviv 69978, Israel
- ¹⁵⁴Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle Physics, University Campus, GR - 54124, Thessaloniki, Greece
- ¹⁵⁵The University of Tokyo, International Center for Elementary Particle Physics and Department of Physics, 7-3-1 Hongo, Bunkyo-ku, JP - Tokyo 113-0033, Japan
- ¹⁵⁶Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
- ¹⁵⁷Tokyo Institute of Technology, Department of Physics, 2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan
- ¹⁵⁸University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada
- ^{159a}TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada
- ^{159b}York University, Department of Physics and Astronomy, 4700 Keele Street, Toronto, Ontario, M3J 1P3, Canada
- ¹⁶⁰University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP - Ibaraki 305-8571, Japan
- ¹⁶¹Tufts University, Science & Technology Center, 4 Colby Street, Medford, Massachusetts 02155, USA
- ¹⁶²Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia
- ¹⁶³University of California, Irvine, Department of Physics & Astronomy, California 92697-4575, USA
- ^{164a}INFN Gruppo Collegato di Udine, Udine, Italy
- ^{164b}ICTP, Strada Costiera 11, IT-34014, Trieste, Italy
- ^{164c}Università di Udine, Dipartimento di Fisica, via delle Scienze 208, IT - 33100 Udine, Italy
- ¹⁶⁵University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Illinois 61801, USA
- ¹⁶⁶University of Uppsala, Department of Physics and Astronomy, P.O. Box 516, SE -751 20 Uppsala, Sweden
- ¹⁶⁷Instituto de Física Corpuscular (IFIC) Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept. Física At. Mol. y Nuclear; Dept. Ing. Electrónica; Univ. of Valencia, and Inst. de Microelectrónica de Barcelona (IMB-CNM-CSIC) 08193 Bellaterra, Spain
- ¹⁶⁸University of British Columbia, Department of Physics, 6224 Agricultural Road, CA - Vancouver, B.C. V6T 1Z1, Canada
- ¹⁶⁹University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada
- ¹⁷⁰Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
- ¹⁷¹The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL - 76100 Rehovot, Israel
- ¹⁷²University of Wisconsin, Department of Physics, 1150 University Avenue, Wisconsin 53706 Madison, Wisconsin, USA
- ¹⁷³Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany
- ¹⁷⁴Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D- 42097 Wuppertal, Germany
- ¹⁷⁵Yale University, Department of Physics, PO Box 208121, New Haven Connecticut, 06520-8121, USA
- ¹⁷⁶Yerevan Physics Institute, Alikhanian Brothers Street 2, AM - 375036 Yerevan, Armenia
- ¹⁷⁷Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France
- ¹⁷⁸Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
- ¹⁷⁹University of Coimbra, Coimbra, Portugal
- ¹⁸⁰Institute of Particle Physics (IPP), Canada
- ¹⁸¹Università di Napoli Parthenope, Napoli, Italy
- ¹⁸²California Institute of Technology, Pasadena, California, USA
- ¹⁸³Institut für Experimentalphysik, Universität at Hamburg, Hamburg, Germany
- ¹⁸⁴Manhattan College, New York, USA
- ¹⁸⁵Departamento de Física, Universidade de Minho, Braga, Portugal
- ¹⁸⁶School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- ¹⁸⁷KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- ¹⁸⁸Institute of Physics, Jagiellonian University, Cracow, Poland
- ¹⁸⁹Louisiana Tech University, 305 Wisteria Street, P.O. Box 3178, Ruston, Louisiana 71272, USA
- ¹⁹⁰California State University, Department of Physics, Fresno, California, USA
- ¹⁹¹Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, No.128, Sec. 2, Academia Road, Nankang, Taipei, Taiwan 11529
- ¹⁹²University of South Carolina, Department of Physics and Astronomy, 700 S. Main Street, Columbia, South Carolina 29208, USA

^aDeceased.

^bAlso at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Avenida Elias Garcia 14-1, PT - 1000-149 Lisboa, Portugal.

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

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

^eAlso at TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada.

- ^fAlso at Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology, (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland.
- ^gAlso at University of Coimbra, Coimbra, Portugal.
- ^hAlso at Università di Napoli Parthenope, Napoli, Italy.
- ⁱAlso at Institute of Particle Physics (IPP), Canada.
- ^jAlso at Louisiana Tech University, 305 Wisteria Street, P.O. Box 3178, Ruston, LA 71272, USA.
- ^kAlso at California State University, Fresno, Department of Physics , USA
- ^lAlso at California Institute of Technology, Pasadena, USA.
- ^mAlso at University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada.
- ⁿAlso at Institute of Physics, Azerbaijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan.
- ^oAlso at Institut für Experimentalphysik, Universität at Hamburg, Hamburg, Germany.
- ^pAlso at Manhattan College, New York, USA
- ^qAlso at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
- ^rAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, No.128, Sec. 2, Academia Road, Nankang, Taipei, Taiwan 11529.
- ^sAlso at Shandong University, High Energy Physics Group, Jinan, CN - Shandong 250100, China.
- ^tAlso at Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom.
- ^uAlso at Departamento de Física, Universidade de Minho, Braga, Portugal.
- ^vAlso at Department of Physics and Astronomy, 700 S. Main St, Columbia, SC 29208, USA.
- ^wAlso at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
- ^xAlso at Institute of Physics, Jagiellonian University, Cracow, Poland.
- ^yAlso at Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom.
- ^zAlso at CEA, DSM/IRFU, Centre d'Etudes de Saclay, FR - 91191 Gif-sur-Yvette, France.
- ^{aa}Also at Laboratoire de Physique Nucléaire et de Hautes Energies, Université Pierre et Marie Curie (Paris 6), Université Denis Diderot (Paris-7), CNRS/IN2P3, Tour 33, 4 place Jussieu, FR - 75252 Paris Cedex 05, France.
- ^{bb}Also at Nanjing University, Department of Physics, Nanjing, CN - Jiangsu 210093, China.