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Kurashige, Hisaya
et. al.

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Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment

M. Aaboud *et al.*^{*}
(ATLAS Collaboration)



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A direct search for the standard model Higgs boson decaying to a pair of charm quarks is presented. Associated production of the Higgs and Z bosons, in the decay mode $ZH \rightarrow \ell^+ \ell^- c \bar{c}$ is studied. A data set with an integrated luminosity of 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS experiment at the LHC is used. The $H \rightarrow c \bar{c}$ signature is identified using charm-tagging algorithms. The observed (expected) upper limit on $\sigma(pp \rightarrow ZH) \times \mathcal{B}(H \rightarrow c \bar{c})$ is $2.7 (3.9^{+2.1}_{-1.1}) \text{ pb}$ at the 95% confidence level for a Higgs boson mass of 125 GeV, while the standard model value is 26 fb.

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In July 2012, the ATLAS and CMS collaborations announced the discovery of a new particle with a mass of approximately 125 GeV [1,2] in searches for the standard model (SM) Higgs boson at the Large Hadron Collider (LHC) [3]. Subsequent measurements indicate that this particle is consistent with the SM Higgs boson [4–10]. Direct evidence for the Yukawa coupling of the Higgs boson to the top [11] and bottom [12,13] quarks was recently obtained. Measurements of the Yukawa coupling of the Higgs boson to quarks in generations other than the third are difficult at hadron colliders, due to small branching fractions, large backgrounds, and challenges in jet flavor identification [14,15]. This Letter presents a direct search by the ATLAS experiment for the decay of the Higgs boson to a pair of charm (c) quarks. This search targets the production of the Higgs boson in association with a Z boson decaying to charged leptons: $Z(\ell^+ \ell^-)H(c \bar{c})$, where $\ell = e, \mu$.

The SM branching fraction for a Higgs boson with a mass of 125 GeV to decay to a pair of charm quarks is predicted to be 2.9% [16]. The inclusive cross section for $\sigma(pp \rightarrow ZH) \times \mathcal{B}(H \rightarrow c \bar{c})$ is 26 fb at $\sqrt{s} = 13 \text{ TeV}$ [17]. Rare exclusive decays of the Higgs boson to a light vector meson or quarkonium state and a photon can also probe the couplings of the second-generation quarks to the Higgs boson [18–21]. Previously, the ATLAS Collaboration presented an indirect search for the decay of the Higgs boson to c quarks via the decay to $J/\psi \gamma$, obtaining a branching fraction limit of 1.5×10^{-3} at the 95% confidence level (C.L.), which approximately corresponds to a limit of 540 times the SM branching fraction prediction

[14,20]. Bounds on the Higgs boson branching fractions to unobserved final states and fits to global rates constrain $\mathcal{B}(H \rightarrow c \bar{c}) < 20\%$ at the 95% C.L., assuming SM production cross sections [22]. These limits can still accommodate large modifications to the Higgs boson coupling to charm quarks from new physics [22]. In this Letter, a new approach is introduced to investigate the coupling of the Higgs boson to charm quarks.

The search is performed using pp collision data recorded in 2015 and 2016 with the ATLAS detector [23] at $\sqrt{s} = 13 \text{ TeV}$. The ATLAS detector at the LHC covers nearly the entire solid angle around the collision point [24]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets. An additional pixel layer was installed for the $\sqrt{s} = 13 \text{ TeV}$ running period [25]. After the application of beam, detector, and data-quality requirements, the integrated luminosity corresponds to $36.1 \pm 0.8 \text{ fb}^{-1}$, measured following Ref. [26]. Events are required to contain exactly two same-flavor leptons with an invariant mass consistent with that of the Z boson, and at least two jets of which one or two are identified as charm jets (c jets). In this Letter, lepton refers to only electrons or muons. The analysis procedure is validated by measuring the yield of ZW and ZZ production, where the sample is enriched in $W \rightarrow cs, cd$ and $Z \rightarrow c \bar{c}$ decays. Further details can be found in Ref. [12].

Monte Carlo (MC) simulated samples were produced for signal and background processes using the full ATLAS detector simulation [27] using GEANT4 [28]. Table I provides details of the event generators used for each signal and background sample. Signal events were produced at next-to-leading order (NLO) for the $q \bar{q} \rightarrow ZH$ process and at leading order (LO) for the $gg \rightarrow ZH$ process with POWHEG-BOX v2 [32]. The dominant Z + jets background and the resonant diboson ZW and ZZ processes were generated using SHERPA 2.2.1 [54]. The $t \bar{t}$ background was

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

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TABLE I. The configurations used for event generation of the signal and background processes. If two parton distribution functions (PDFs) are shown, the first is for the matrix element calculation and the second for the parton shower, otherwise the same is used for both. Alternative event generators and configurations, used to estimate systematic uncertainties, are in parentheses. Tune refers to the underlying-event tuned parameters of the parton shower event generator. MG5_AMC refers to MADGRAPH5_AMC@NLO 2.2.2 [29]; PYTHIA 8 refers to version 8.212 [30]. Heavy-flavor hadron decays modeled by EVTGEN 1.2.0 [31] are used for all samples except those generated using SHERPA. The order of the calculation of the cross sections used to normalize the predictions is indicated. The $q\bar{q} \rightarrow ZH$ cross section is estimated by subtracting the $gg \rightarrow ZH$ cross section from the $pp \rightarrow ZH$ cross section. The asterisk (*) in the last column denotes that the indicated order is for the $pp \rightarrow ZH$ cross section. NNLO denotes next-to-next-to-leading order; NLL denotes next-to-leading log and NNLL denotes next-to-next-to-leading log.

Process	Event Generator (alternative)	Parton Shower (alternative)	PDF (alternative)	Tune	Cross section
$q\bar{q} \rightarrow ZH$	POWHEG-BOX v2 [32] +GoSAM [35] +MiNLO [45,46]	PYTHIA 8 (HERWIG 7 [47])	PDF4LHC15NLO [33] /CTEQ6L1 [36,37]	AZNLO [34] (A14 [48])	NNLO (QCD)* +NLO (EW) [38–44]
$gg \rightarrow ZH$	POWHEG-BOX v2	PYTHIA 8 (HERWIG 7)	PDF4LHC15NLO /CTEQ6L1	AZNLO (A14)	NLO+NLL (QCD) [17,49–51]
$t\bar{t}$	POWHEG-BOX v2	PYTHIA 8 (HERWIG 7)	NNPDF3.0NLO [52] /NNPDF2.3LO	A14	NNLO + NNLL [53]
ZW, ZZ	SHERPA 2.2.1 [54] (POWHEG-BOX)	SHERPA (PYTHIA 8)	NNPDF3.0NNLO	SHERPA	NLO
$Z + \text{jets}$	SHERPA 2.2.1 (MG5_AMC)	SHERPA (PYTHIA 8)	NNPDF3.0NNLO (NNPDF2.3LO)	SHERPA (A14)	NNLO [55]

generated using POWHEG-BOX v2. Backgrounds from single top and multijet production and the contribution from Higgs decays other than $b\bar{b}$ and $c\bar{c}$ are assessed to be negligible and not considered further. The Higgs boson mass is set to $m_H = 125$ GeV and the top-quark mass is set to 172.5 GeV.

Events are required to have at least one reconstructed primary vertex. Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter that are associated with charged-particle tracks reconstructed in the inner detector [56,57]. Muon candidates are reconstructed by combining inner detector tracks with muon spectrometer tracks or energy deposits in the calorimeters consistent with the passage of minimum-ionizing particles [58]. For data recorded in 2015, the single-electron (muon) trigger required a candidate with $p_T > 24(20)$ GeV; in 2016 the lepton p_T threshold was raised to 26 GeV. Events are required to contain a pair of same-flavor leptons, both satisfying $p_T > 7$ GeV and $|\eta| < 2.5$. At least one lepton must have $p_T > 27$ GeV and correspond to a lepton that passed the trigger. The two leptons are required to satisfy loose track-isolation criteria with an efficiency greater than 99%. They are required to have opposite charge in dimuon events, but not in dielectron events due to the non-negligible charge misidentification rate of electrons. The invariant mass of the dilepton system is required to be consistent with the mass of the Z boson: $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$.

Jets are reconstructed from topological energy clusters in the calorimeters [59,60] using the anti- k_t algorithm [61] with a radius parameter of 0.4 implemented in the FASTJET package [62]. The jet energy is corrected using a jet-area-

based technique [63,64] and calibrated [65,66] using p_T - and η -dependent correction factors determined from simulation, with residual corrections from internal jet properties. Further corrections from *in situ* measurements are applied to data. Selected jets must have $p_T > 20$ GeV and $|\eta| < 2.5$. Events are required to contain at least two jets. If a muon is found within a jet, its momentum is added to the selected jet. An overlap removal procedure resolves cases in which the same physical object is reconstructed multiple times, e.g. an electron also reconstructed as a jet.

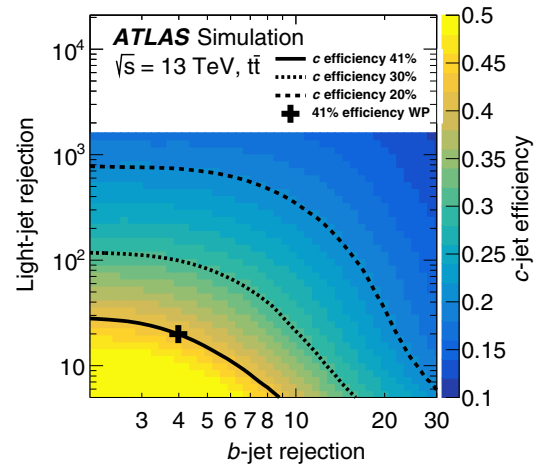


FIG. 1. The c -jet-tagging efficiency (colored scale) as a function of the b jet and l jet rejection as obtained from simulated $t\bar{t}$ events. The cross, labeled as working point, WP, denotes the selection criterion used in this analysis. The solid and dotted black lines indicate the contours in rejection space for the fixed c -tagging efficiency used in the analysis and two alternatives.

TABLE II. Breakdown of the relative contributions to the total uncertainty in μ . The statistical uncertainty includes the contribution from the floating Z + jets normalization parameters. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components.

Source	$\sigma/\sigma_{\text{tot}}$
Statistical	49%
Floating Z + jets normalization	31%
Systematic	87%
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

Jets in simulated events are labeled according to the presence of a heavy-flavor hadron with $p_T > 5$ GeV within $\Delta R = 0.3$ from the jet axis. If a b hadron is found the jet is labeled as a b jet. If no b hadron is found, but a c hadron is present, then the jet is labeled as a c jet. Otherwise the jet is labeled as a light-flavor jet (l jet).

Flavor-tagging algorithms exploit the different lifetimes of b , c , and light-flavor hadrons. A c -tagging algorithm is used to identify c jets. Charm jets are particularly challenging to tag because c hadrons have shorter lifetimes and decay to fewer charged particles than b hadrons. Boosted decision trees are trained to obtain two multivariate discriminants: to separate c jets from l jets and c jets from b jets. The same variables used for b tagging [67,68] are used. Figure 1 shows the selection criteria applied in the two-dimensional multivariate discriminant space, to obtain an efficiency of 41% for c jets and rejection factors of 4.0 and 20 for b jets and l jets. The efficiencies are calibrated to data using b quarks from $t \rightarrow Wb$ and c quarks from $W \rightarrow cs$, cd with methods identical to the b -tagging algorithms [67]. Statistical uncertainties in the simulation are reduced, by weighting events according to the tagging efficiencies of their jets, parametrized as a function of jet

flavor, p_T , η and the angular separation between jets, rather than imposing a direct requirement on the c -tagging discriminants.

Data are analyzed in four categories with different expected signal purities. The dijet invariant mass, $m_{c\bar{c}}$, constructed using the two highest- p_T jets, is the discriminating variable in each category. Categories are defined using the transverse momentum of the reconstructed Z boson, p_T^Z ($75 \text{ GeV} \leq p_T^Z < 150 \text{ GeV}$ and $p_T^Z \geq 150 \text{ GeV}$) and the number of c tags amongst the leading jets (either one or two). The p_T^Z requirements exploit the harder p_T^Z distribution in ZH compared to Z + jets production. Background events are rejected by requiring the angular separation between the two jets constituting the dijet system, $\Delta R_{c\bar{c}}$, to be less than 2.2, 1.5, or 1.3 for events satisfying $75 \leq p_T^Z < 150 \text{ GeV}$, $150 \leq p_T^Z < 200 \text{ GeV}$, or $p_T^Z \geq 200 \text{ GeV}$. The signal acceptance ranges from 0.5% to 3.4% depending on the category. A joint binned maximum-profile-likelihood fit to $m_{c\bar{c}}$ in the categories is used to extract the signal yield and the Z + jets background normalization. The fit uses 15 bins in each category within the range of $50 \text{ GeV} < m_{c\bar{c}} < 200 \text{ GeV}$, with a bin width of 10 GeV. The parameter of interest, μ , common to all categories, is the signal strength, defined as the ratio of the measured signal yield to the SM prediction.

Systematic uncertainties affecting the signal and background predictions include theoretical uncertainties in the signal and background modeling and experimental uncertainties. Table II shows their relative impact on the fitted value of μ . Uncertainties in the $m_{c\bar{c}}$ shape of the backgrounds are assessed by comparisons between nominal and alternative event generators as indicated in Table I.

Systematic uncertainties are incorporated within the statistical model through nuisance parameters that modify the shape and/or normalization of the distributions. Statistical uncertainties in the simulation samples are accounted for. The Z + jets background is normalized from the data through the inclusion of an unconstrained normalization parameter for each category. The fitted

TABLE III. Postfit yields for the signal and background processes in each category from the profile likelihood fit. Uncertainties include statistical and systematic contributions. The prefit SM expected $ZH(c\bar{c})$ signal yields are indicated in parenthesis.

Sample	Yield, $50 \text{ GeV} < m_{c\bar{c}} < 200 \text{ GeV}$			
	1 c tag		2 c tags	
	$75 \leq p_T^Z < 150 \text{ GeV}$	$p_T^Z \geq 150 \text{ GeV}$	$75 \leq p_T^Z < 150 \text{ GeV}$	$p_T^Z \geq 150 \text{ GeV}$
Z + jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	-143 ± 170 (2.4)	-84 ± 100 (1.4)	-30 ± 40 (0.7)	-20 ± 29 (0.5)
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

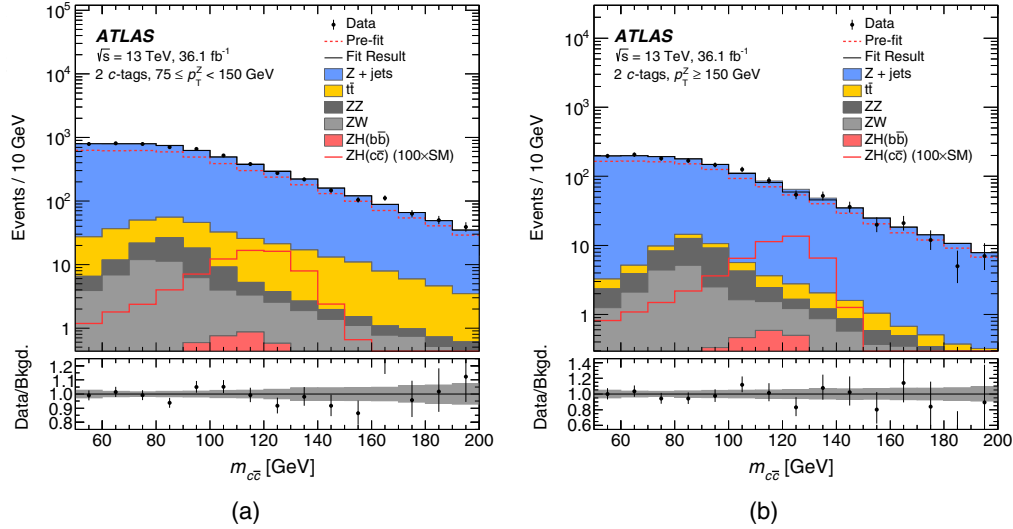


FIG. 2. Observed and predicted $m_{c\bar{c}}$ distributions in the 2 c -tag analysis categories. The expected signal is scaled by a factor of 100. Backgrounds are corrected to the results of the fit to the data. The predicted background from the simulation is shown as red dashed histograms. The ratios of the data to the fitted background are shown in the lower panels. The error bands indicate the sum in quadrature of the statistical and systematic uncertainties in the background prediction.

normalization parameters range between 1.13 and 1.30. All other background normalization factors are correlated between categories, with acceptance uncertainties of order 10% to account for relative variations between categories.

The dominant contributions to the uncertainty in μ are the efficiency of the tagging algorithms, the jet energy scale and resolution, and the background modeling. The largest uncertainty is due to the normalization of the dominant $Z + \text{jets}$ background. The typical uncertainty in the tagging efficiency is 25% for c jets, 5% for b jets, and 20% for l jets.

Table III shows the fitted signal and background yields. The $m_{c\bar{c}}$ distributions in the 2 c tag categories are shown in Fig. 2 with the background shapes and normalizations according to the result of the fit. Good agreement is observed between the postfit shapes of the distributions and the data.

The analysis procedure is validated by measuring the yield of ZV production, where V denotes a W or Z boson, with the same event selection. The fraction of the ZZ yield from $Z \rightarrow c\bar{c}$ decays is $\sim 55\%$ (20%) in the 2 c tag (1 c tag) category, while the fraction of the ZW yield from $W \rightarrow cs, cd$ is $\sim 65\%$ for both the 2 and 1 c tag categories. Contributions of Higgs boson decays to $c\bar{c}$ and $b\bar{b}$ are treated as background and constrained to the SM predictions within its theoretical uncertainties. The diboson signal strength is measured to be $\mu_{ZV} = 0.6^{+0.5}_{-0.4}$ with an observed (expected) significance of 1.4 (2.2) standard deviations.

The best-fit value for the $ZH(c\bar{c})$ signal strength is $\mu_{ZH} = -69 \pm 101$. By assuming a signal with the kinematics of the SM Higgs boson, model-dependent corrections are made to extrapolate to the inclusive phase space. Hence, an upper limit on $\sigma(pp \rightarrow ZH) \times \mathcal{B}(H \rightarrow c\bar{c})$ is computed using a modified frequentist CL_s method [69,70]

with the profile likelihood ratio as the test statistic. The observed (expected) upper limit is found to be 2.7 ($3.9^{+2.1}_{-1.1}$) pb at the 95% C.L. This corresponds to an observed (expected) upper limit on μ at the 95% C.L. of 110 (150^{+80}_{-40}). The uncertainties in the expected limits correspond to the $\pm 1\sigma$ interval of background-only pseudoexperiments. With the current sensitivity, the result depends weakly on the assumption of the SM rate for $H \rightarrow b\bar{b}$. The observed limit remains within 5% of the nominal value when the assumed value for normalization of the $ZH(b\bar{b})$ background is varied from zero to twice the SM prediction.

A search for the decay of the Higgs boson to charm quarks has been performed using 36.1 fb^{-1} of data collected with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV at the LHC. No significant excess of $ZH(c\bar{c})$ production is observed over the SM background expectation. The observed upper limit on $\sigma(pp \rightarrow ZH) \times \mathcal{B}(H \rightarrow c\bar{c})$ is 2.7 pb at the 95% C.L. The corresponding expected upper limit is $3.9^{+2.1}_{-1.1}$ pb. This is the most stringent limit to date in direct searches for the inclusive decay of the Higgs boson to charm quarks.

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M. Aaboud,^{137d} G. Aad,⁸⁸ B. Abbott,¹¹⁵ O. Abidinov,^{12,a} B. Abeloos,¹¹⁹ S. H. Abidi,¹⁶¹ O. S. AbouZeid,¹³⁹ N. L. Abraham,¹⁵¹ H. Abramowicz,¹⁵⁵ H. Abreu,¹⁵⁴ Y. Abulaiti,⁶ B. S. Acharya,^{167a,167b,b} S. Adachi,¹⁵⁷ L. Adamczyk,^{41a} J. Adelman,¹¹⁰ M. Adersberger,¹⁰² T. Adye,¹³³ A. A. Affolder,¹³⁹ Y. Afik,¹⁵⁴ C. Agheorghiesei,^{28c} J. A. Aguilar-Saavedra,^{128a,128f} S. P. Ahlen,²⁴ F. Ahmadov,^{68,c} G. Aielli,^{135a,135b} S. Akatsuka,⁷¹ T. P. A. Åkesson,⁸⁴ E. Akilli,⁵² A. V. Akimov,⁹⁸ G. L. Alberghi,^{22a,22b} J. Albert,¹⁷² P. Albicocco,⁵⁰ M. J. Alconada Verzini,⁷⁴ S. Alderweireldt,¹⁰⁸ M. Aleksa,³² I. N. Aleksandrov,⁶⁸ C. Alexa,^{28b} G. Alexander,¹⁵⁵ T. Alexopoulos,¹⁰ M. Alhroob,¹¹⁵ B. Ali,¹³⁰ M. Aliev,^{76a,76b} G. Alimonti,^{94a} J. Alison,³³ S. P. Alkire,³⁸ C. Allaire,¹¹⁹ B. M. M. Allbrooke,¹⁵¹ B. W. Allen,¹¹⁸ P. P. Allport,¹⁹ A. Aloisio,^{106a,106b} A. Alonso,³⁹ F. Alonso,⁷⁴ C. Alpigiani,¹⁴⁰ A. A. Alshehri,⁵⁶ M. I. Alstady,⁸⁸ B. Alvarez Gonzalez,³² D. Álvarez Piqueras,¹⁷⁰ M. G. Alvigi,^{106a,106b} B. T. Amadio,¹⁶ Y. Amaral Coutinho,^{26a} L. Ambroz,¹²² C. Amelung,²⁵ D. Amidei,⁹² S. P. Amor Dos Santos,^{128a,128c} S. Amoroso,³² C. Anastopoulos,¹⁴¹ L. S. Ancu,⁵² N. Andari,¹⁹ T. Andeen,¹¹ C. F. Anders,^{60b} J. K. Anders,¹⁸ K. J. Anderson,³³ A. Andreazza,^{94a,94b} V. Andrei,^{60a} S. Angelidakis,³⁷ I. Angelozzi,¹⁰⁹ A. Angerami,³⁸ A. V. Anisenkov,^{111,d} A. Annovi,^{126a} C. Antel,^{60a} M. Antonelli,⁵⁰ A. Antonov,^{100,a} D. J. Antrim,¹⁶⁶ F. Anulli,^{134a} M. Aoki,⁶⁹ L. Aperio Bella,³² G. Arabidze,⁹³ Y. Arai,⁶⁹ J. P. Araque,^{128a} V. Araujo Ferraz,^{26a} R. Araujo Pereira,^{26a} A. T. H. Arce,⁴⁸ R. E. Ardell,⁸⁰ F. A. Arduh,⁷⁴ J.-F. Arguin,⁹⁷ S. Argyropoulos,⁶⁶ A. J. Armbruster,³² L. J. Armitage,⁷⁹ O. Arnaez,¹⁶¹ H. Arnold,¹⁰⁹ M. Arratia,³⁰ O. Arslan,²³ A. Artamonov,^{99,a} G. Artoni,¹²² S. Artz,⁸⁶ S. Asai,¹⁵⁷ N. Asbah,⁴⁵ A. Ashkenazi,¹⁵⁵ L. Asquith,¹⁵¹ K. Assamagan,²⁷ R. Astalos,^{146a} R. J. Atkin,^{147a} M. Atkinson,¹⁶⁹ N. B. Atlay,¹⁴³ K. Augsten,¹³⁰ G. Avolio,³² R. Avramidou,^{36a} B. Axen,¹⁶ M. K. Ayoub,^{35a} G. Azuelos,^{97,e} A. E. Baas,^{60a} M. J. Baca,¹⁹ H. Bachacou,¹³⁸ K. Bachas,^{76a,76b} M. Backes,¹²² P. Bagnaia,^{134a,134b} M. Bahmani,⁴² H. Bahrasemani,¹⁴⁴ J. T. Baines,¹³³ M. Bajic,³⁹ O. K. Baker,¹⁷⁹ P. J. Bakker,¹⁰⁹ D. Bakshi Gupta,⁸² E. M. Baldin,^{111,d} P. Balek,¹⁷⁵ F. Balli,¹³⁸ W. K. Balunas,¹²⁴ E. Banas,⁴² A. Bandyopadhyay,²³ Sw. Banerjee,^{176,f} A. A. E. Bannoura,¹⁷⁷ L. Barak,¹⁵⁵ E. L. Barberio,⁹¹ D. Barberis,^{53a,53b} M. Barbero,⁸⁸ T. Barillari,¹⁰³ M.-S. Barisits,⁶⁵ J. T. Barkeloo,¹¹⁸ T. Barklow,¹⁴⁵ N. Barlow,³⁰ R. Barnea,¹⁵⁴ S. L. Barnes,^{36c} B. M. Barnett,¹³³ R. M. Barnett,¹⁶ Z. Barnovska-Blenessy,^{36a} A. Baroncelli,^{136a} G. Barone,²⁵ A. J. Barr,¹²² L. Barranco Navarro,¹⁷⁰ F. Barreiro,⁸⁵ J. Barreiro Guimarães da Costa,^{35a} R. Bartoldus,¹⁴⁵ A. E. Barton,⁷⁵ P. Bartos,^{146a} A. Basalaeu,¹²⁵ A. Bassalat,^{119,g} R. L. Bates,⁵⁶ S. J. Batista,¹⁶¹ J. R. Batley,³⁰ M. Battaglia,¹³⁹ M. Bause,^{134a,134b} F. Bauer,¹³⁸ K. T. Bauer,¹⁶⁶ H. S. Bawa,^{145,h} J. B. Beacham,¹¹³ M. D. Beattie,⁷⁵ T. Beau,⁸³ P. H. Beauchemin,¹⁶⁵ P. Bechtel,²³ H. P. Beck,^{18,i} H. C. Beck,⁵⁸ K. Becker,¹²² M. Becker,⁸⁶ C. Becot,¹¹² A. J. Beddall,^{20e} A. Beddall,^{20b} V. A. Bednyakov,⁶⁸ M. Bedognetti,¹⁰⁹ C. P. Bee,¹⁵⁰ T. A. Beermann,³² M. Begalli,^{26a} M. Begel,²⁷ A. Behara,¹⁵⁰ J. K. Behr,⁴⁵ A. S. Bell,⁸¹ G. Bella,¹⁵⁵ L. Bellagamba,^{22a} A. Bellerive,³¹ M. Bellomo,¹⁵⁴ K. Belotskiy,¹⁰⁰ N. L. Belyaev,¹⁰⁰ O. Benary,^{155,a} D. Bencheikroun,^{137a} M. Bender,¹⁰² N. Benekos,¹⁰ Y. Benhammou,¹⁵⁵ E. Benhar Nocchioli,¹⁷⁹ J. Benitez,⁶⁶ D. P. Benjamin,⁴⁸ M. Benoit,⁵² J. R. Bensinger,²⁵ S. Bentvelsen,¹⁰⁹ L. Beresford,¹²² M. Beretta,⁵⁰ D. Berge,⁴⁵ E. Bergeaas Kuutmann,¹⁶⁸ N. Berger,⁵ L. J. Bergsten,²⁵ J. Beringer,¹⁶ S. Berlendis,⁵⁷ N. R. Bernard,⁸⁹ G. Bernardi,⁸³ C. Bernius,¹⁴⁵ F. U. Bernlochner,²³

T. Berry,⁸⁰ P. Berta,⁸⁶ C. Bertella,^{35a} G. Bertoli,^{148a,148b} I. A. Bertram,⁷⁵ C. Bertsche,⁴⁵ G. J. Besjes,³⁹
 O. Bessidskaia Bylund,^{148a,148b} M. Bessner,⁴⁵ N. Besson,¹³⁸ A. Bethani,⁸⁷ S. Bethke,¹⁰³ A. Betti,²³ A. J. Bevan,⁷⁹ J. Beyer,¹⁰³
 R. M. Bianchi,¹²⁷ O. Biebel,¹⁰² D. Biedermann,¹⁷ R. Bielski,⁸⁷ K. Bierwagen,⁸⁶ N. V. Biesuz,^{126a,126b} M. Biglietti,^{136a}
 T. R. V. Billoud,⁹⁷ M. Bindi,⁵⁸ A. Bingul,^{20b} C. Bini,^{134a,134b} S. Biondi,^{22a,22b} T. Bisanz,⁵⁸ C. Bittrich,⁴⁷ D. M. Bjergaard,⁴⁸
 J. E. Black,¹⁴⁵ K. M. Black,²⁴ R. E. Blair,⁶ T. Blazek,^{146a} I. Bloch,⁴⁵ C. Blocker,²⁵ A. Blue,⁵⁶ U. Blumenschein,⁷⁹
 Dr. Blunier,^{34a} G. J. Bobbink,¹⁰⁹ V. S. Bobrovnikov,^{111,d} S. S. Bocchetta,⁸⁴ A. Bocci,⁴⁸ C. Bock,¹⁰² D. Boerner,¹⁷⁷
 D. Bogavac,¹⁰² A. G. Bogdanchikov,¹¹¹ C. Bohm,^{148a} V. Boisvert,⁸⁰ P. Bokan,^{168,j} T. Bold,^{41a} A. S. Boldyrev,¹⁰¹
 A. E. Bolz,^{60b} M. Bomben,⁸³ M. Bona,⁷⁹ J. S. Bonilla,¹¹⁸ M. Boonekamp,¹³⁸ A. Borisov,¹³² G. Borissov,⁷⁵ J. Bortfeldt,³²
 D. Bortoletto,¹²² V. Bortolotto,^{62a} D. Boscherini,^{22a} M. Bosman,¹³ J. D. Bossio Sola,²⁹ J. Boudreau,¹²⁷
 E. V. Bouhova-Thacker,⁷⁵ D. Boumediene,³⁷ C. Bourdarios,¹¹⁹ S. K. Boutle,⁵⁶ A. Boveia,¹¹³ J. Boyd,³² I. R. Boyko,⁶⁸
 A. J. Bozson,⁸⁰ J. Bracinik,¹⁹ A. Brandt,⁸ G. Brandt,¹⁷⁷ O. Brandt,^{60a} F. Braren,⁴⁵ U. Bratzler,¹⁵⁸ B. Brau,⁸⁹ J. E. Brau,¹¹⁸
 W. D. Breaden Madden,⁵⁶ K. Brendlinger,⁴⁵ A. J. Brennan,⁹¹ L. Brenner,⁴⁵ R. Brenner,¹⁶⁸ S. Bressler,¹⁷⁵ D. L. Briglin,¹⁹
 T. M. Bristow,⁴⁹ D. Britton,⁵⁶ D. Britzger,^{60b} I. Brock,²³ R. Brock,⁹³ G. Brooijmans,³⁸ T. Brooks,⁸⁰ W. K. Brooks,^{34b}
 E. Brost,¹¹⁰ J. H. Broughton,¹⁹ P. A. Bruckman de Renstrom,⁴² D. Bruncko,^{146b} A. Bruni,^{22a} G. Bruni,^{22a} L. S. Bruni,¹⁰⁹
 S. Bruno,^{135a,135b} B. H. Brunt,³⁰ M. Bruschi,^{22a} N. Bruscino,¹²⁷ P. Bryant,³³ L. Bryngemark,⁴⁵ T. Buanes,¹⁵ Q. Buat,³²
 P. Buchholz,¹⁴³ A. G. Buckley,⁵⁶ I. A. Budagov,⁶⁸ F. Buehrer,⁵¹ M. K. Bugge,¹²¹ O. Bulekov,¹⁰⁰ D. Bullock,⁸ T. J. Burch,¹¹⁰
 S. Burdin,⁷⁷ C. D. Burgard,¹⁰⁹ A. M. Burger,⁵ B. Burghgrave,¹¹⁰ K. Burka,⁴² S. Burke,¹³³ I. Burmeister,⁴⁶ J. T. P. Burr,¹²²
 D. Büscher,⁵¹ V. Büscher,⁸⁶ E. Buschmann,⁵⁸ P. Bussey,⁵⁶ J. M. Butler,²⁴ C. M. Buttar,⁵⁶ J. M. Butterworth,⁸¹ P. Butti,³²
 W. Buttinger,³² A. Buzatu,¹⁵³ A. R. Buzykaev,^{111,d} G. Cabras,^{22a,22b} S. Cabrera Urbán,¹⁷⁰ D. Caforio,¹³⁰ H. Cai,¹⁶⁹
 V. M. M. Cairo,² O. Cakir,^{4a} N. Calace,⁵² P. Calafiura,¹⁶ A. Calandri,⁸⁸ G. Calderini,⁸³ P. Calfayan,⁶⁴ G. Callea,^{40a,40b}
 L. P. Caloba,^{26a} S. Calvente Lopez,⁸⁵ D. Calvet,³⁷ S. Calvet,³⁷ T. P. Calvet,⁸⁸ M. Calvetti,^{126a,126b} R. Camacho Toro,³³
 S. Camarda,³² P. Camarri,^{135a,135b} D. Cameron,¹²¹ R. Caminal Armadans,⁸⁹ C. Camincher,⁵⁷ S. Campana,³²
 M. Campanelli,⁸¹ A. Camplani,^{94a,94b} A. Campoverde,¹⁴³ V. Canale,^{106a,106b} M. Cano Bret,^{36c} J. Cantero,¹¹⁶ T. Cao,¹⁵⁵
 Y. Cao,¹⁶⁹ M. D. M. Capeans Garrido,³² I. Caprini,^{28b} M. Caprini,^{28b} M. Capua,^{40a,40b} R. M. Carbone,³⁸ R. Cardarelli,^{135a}
 F. Cardillo,⁵¹ I. Carli,¹³¹ T. Carli,³² G. Carlino,^{106a} B. T. Carlson,¹²⁷ L. Carminati,^{94a,94b} R. M. D. Carney,^{148a,148b} S. Caron,¹⁰⁸
 E. Carquin,^{34b} S. Carrá,^{94a,94b} G. D. Carrillo-Montoya,³² D. Casadei,¹⁹ M. P. Casado,^{13,k} A. F. Casha,¹⁶¹ M. Casolino,¹³
 D. W. Casper,¹⁶⁶ R. Castelijns,¹⁰⁹ V. Castillo Gimenez,¹⁷⁰ N. F. Castro,^{128a} A. Catinaccio,³² J. R. Catmore,¹²¹ A. Cattai,³²
 J. Caudron,²³ V. Cavaliere,²⁷ E. Cavallaro,¹³ D. Cavalli,^{94a} M. Cavalli-Sforza,¹³ V. Cavasinni,^{126a,126b} E. Celebi,^{20d}
 F. Ceradini,^{136a,136b} L. Cerda Alberich,¹⁷⁰ A. S. Cerqueira,^{26b} A. Cerri,¹⁵¹ L. Cerrito,^{135a,135b} F. Cerutti,¹⁶ A. Cervelli,^{22a,22b}
 S. A. Cetin,^{20d} A. Chafaq,^{137a} D. Chakraborty,¹¹⁰ S. K. Chan,⁵⁹ W. S. Chan,¹⁰⁹ Y. L. Chan,^{62a} P. Chang,¹⁶⁹ J. D. Chapman,³⁰
 D. G. Charlton,¹⁹ C. C. Chau,³¹ C. A. Chavez Barajas,¹⁵¹ S. Che,¹¹³ A. Chegwidan,⁹³ S. Chekanov,⁶ S. V. Chekulaev,^{163a}
 G. A. Chelkov,^{68,l} M. A. Chelstowska,³² C. Chen,^{36a} C. Chen,⁶⁷ H. Chen,²⁷ J. Chen,^{36a} J. Chen,³⁸ S. Chen,^{35b} S. Chen,¹²⁴
 X. Chen,^{35c,m} Y. Chen,⁷⁰ H. C. Cheng,⁹² H. J. Cheng,^{35a,35d} A. Cheplakov,⁶⁸ E. Cheremushkina,¹³²
 R. Cherkaoui El Moursli,^{137e} E. Cheu,⁷ K. Cheung,⁶³ L. Chevalier,¹³⁸ V. Chiarella,⁵⁰ G. Chiarelli,^{126a} G. Chiodini,^{76a}
 A. S. Chisholm,³² A. Chitan,^{28b} I. Chiu,¹⁵⁷ Y. H. Chiu,¹⁷² M. V. Chizhov,⁶⁸ K. Choi,⁶⁴ A. R. Chomont,³⁷ S. Chouridou,¹⁵⁶
 Y. S. Chow,¹⁰⁹ V. Christodoulou,⁸¹ M. C. Chu,^{62a} J. Chudoba,¹²⁹ A. J. Chuinard,⁹⁰ J. J. Chwastowski,⁴² L. Chytka,¹¹⁷
 D. Cinca,⁴⁶ V. Cindro,⁷⁸ I. A. Cioară,²³ A. Ciochio,¹⁶ F. Ciotto,^{106a,106b} Z. H. Citron,¹⁷⁵ M. Citterio,^{94a} A. Clark,⁵²
 M. R. Clark,³⁸ P. J. Clark,⁴⁹ R. N. Clarke,¹⁶ C. Clement,^{148a,148b} Y. Coadou,⁸⁸ M. Cobal,^{167a,167c} A. Coccaro,^{53a,53b}
 J. Cochran,⁶⁷ L. Colasurdo,¹⁰⁸ B. Cole,³⁸ A. P. Colijn,¹⁰⁹ J. Collot,⁵⁷ P. Conde Muiño,^{128a,128b} E. Coniavitis,⁵¹
 S. H. Connell,^{147b} I. A. Connelly,⁸⁷ S. Constantinescu,^{28b} G. Conti,³² F. Conventi,^{106a,n} A. M. Cooper-Sarkar,¹²²
 F. Cormier,¹⁷¹ K. J. R. Cormier,¹⁶¹ M. Corradi,^{134a,134b} E. E. Corrigan,⁸⁴ F. Corriveau,^{90,o} A. Cortes-Gonzalez,³²
 M. J. Costa,¹⁷⁰ D. Costanzo,¹⁴¹ G. Cottin,³⁰ G. Cowan,⁸⁰ B. E. Cox,⁸⁷ K. Cranmer,¹¹² S. J. Crawley,⁵⁶ R. A. Creager,¹²⁴
 G. Cree,³¹ S. Crépe-Renaudin,⁵⁷ F. Crescioli,⁸³ M. Cristinziani,²³ V. Croft,¹¹² G. Crosetti,^{40a,40b} A. Cueto,⁸⁵
 T. Cuhadar Donszelmann,¹⁴¹ A. R. Cukierman,¹⁴⁵ J. Cummings,¹⁷⁹ M. Curatolo,⁵⁰ J. Cúth,⁸⁶ S. Czekierda,⁴²
 P. Czodrowski,³² G. D'amen,^{22a,22b} S. D'Auria,⁵⁶ L. D'eraimo,⁸³ M. D'Onofrio,⁷⁷ M. J. Da Cunha Sargedadas De Sousa,^{128a,128b}
 C. Da Via,⁸⁷ W. Dabrowski,^{41a} T. Dado,^{146a} S. Lahbi,^{137e} T. Dai,⁹² O. Dale,¹⁵ F. Dallaire,⁹⁷ C. Dallapiccola,⁸⁹ M. Dam,³⁹
 J. R. Dandoy,¹²⁴ M. F. Daneri,²⁹ N. P. Dang,^{176,f} N. S. Dann,⁸⁷ M. Danninger,¹⁷¹ M. Dano Hoffmann,¹³⁸ V. Dao,³²
 G. Darbo,^{53a} S. Darmora,⁸ O. Dartsis,⁵ A. Dattagupta,¹¹⁸ T. Daubney,⁴⁵ W. Davey,²³ C. David,⁴⁵ T. Davidek,¹³¹ D. R. Davis,⁴⁸
 P. Davison,⁸¹ E. Dawe,⁹¹ I. Dawson,¹⁴¹ K. De,⁸ R. de Asmundis,^{106a} A. De Benedetti,¹¹⁵ S. De Castro,^{22a,22b} S. De Cecco,⁸³

- N. De Groot,¹⁰⁸ P. de Jong,¹⁰⁹ H. De la Torre,⁹³ F. De Lorenzi,⁶⁷ A. De Maria,⁵⁸ D. De Pedis,^{134a} A. De Salvo,^{134a}
 U. De Sanctis,^{135a,135b} A. De Santo,¹⁵¹ K. De Vasconcelos Corga,⁸⁸ J. B. De Vivie De Regie,¹¹⁹ C. Debenedetti,¹³⁹
 D. V. Dedovich,⁶⁸ N. Dehghanian,³ I. Deigaard,¹⁰⁹ M. Del Gaudio,^{40a,40b} J. Del Peso,⁸⁵ D. Delgove,¹¹⁹ F. Deliot,¹³⁸
 C. M. Delitzsch,⁷ A. Dell'Acqua,³² L. Dell'Asta,²⁴ M. Della Pietra,^{106a,106b} D. della Volpe,⁵² M. Delmastro,⁵ C. Delporte,¹¹⁹
 P. A. Delsart,⁵⁷ D. A. DeMarco,¹⁶¹ S. Demers,¹⁷⁹ M. Demichev,⁶⁸ S. P. Denisov,¹³² D. Denysiuk,¹⁰⁹ D. Derendarz,⁴²
 J. E. Derkaoui,^{137d} F. Derue,⁸³ P. Dervan,⁷⁷ K. Desch,²³ C. Deterre,⁴⁵ K. Dette,¹⁶¹ M. R. Devesa,²⁹ P. O. Deviveiros,³²
 A. Dewhurst,¹³³ S. Dhaliwal,²⁵ F. A. Di Bello,⁵² A. Di Ciaccio,^{135a,135b} L. Di Ciaccio,⁵ W. K. Di Clemente,¹²⁴
 C. Di Donato,^{106a,106b} A. Di Girolamo,³² B. Di Micco,^{136a,136b} R. Di Nardo,³² K. F. Di Petrillo,⁵⁹ A. Di Simone,⁵¹
 R. Di Sipio,¹⁶¹ D. Di Valentino,³¹ C. Diaconu,⁸⁸ M. Diamond,¹⁶¹ F. A. Dias,³⁹ M. A. Diaz,^{34a} J. Dickinson,¹⁶ E. B. Diehl,⁹²
 J. Dietrich,¹⁷ S. Díez Cornell,⁴⁵ A. Dimitrievska,¹⁶ J. Dingfelder,²³ P. Dita,^{28b} S. Dita,^{28b} F. Dittus,³² F. Djama,⁸⁸
 T. Djobava,^{54b} J. I. Djuvsland,^{60a} M. A. B. do Vale,^{26c} M. Dobre,^{28b} D. Dodsworth,²⁵ C. Doglioni,⁸⁴ J. Dolejsi,¹³¹
 Z. Dolezal,¹³¹ M. Donadelli,^{26d} J. Donini,³⁷ J. Dopke,¹³³ A. Doria,^{106a} M. T. Dova,⁷⁴ A. T. Doyle,⁵⁶ E. Drechsler,⁵⁸
 E. Dreyer,¹⁴⁴ M. Dris,¹⁰ Y. Du,^{36b} J. Duarte-Camperros,¹⁵⁵ F. Dubinin,⁹⁸ A. Dubreuil,⁵² E. Duchovni,¹⁷⁵ G. Duckeck,¹⁰²
 A. Ducourthial,⁸³ O. A. Ducu,^{97p} D. Duda,¹⁰⁹ A. Dudarev,³² A. Chr. Dudder,⁸⁶ E. M. Duffield,¹⁶ L. Duflot,¹¹⁹
 M. Dührssen,³² C. Dulsen,¹⁷⁷ M. Dumancic,¹⁷⁵ A. E. Dumitriu,^{28b,q} A. K. Duncan,⁵⁶ M. Dunford,^{60a} A. Duperrin,⁸⁸
 H. Duran Yildiz,^{4a} M. Düren,⁵⁵ A. Durglishvili,^{54b} D. Duschinger,⁴⁷ B. Dutta,⁴⁵ D. Duvnjak,¹ M. Dyndal,⁴⁵ B. S. Dziedzic,⁴²
 C. Eckardt,⁴⁵ K. M. Ecker,¹⁰³ R. C. Edgar,⁹² T. Eifert,³² G. Eigen,¹⁵ K. Einsweiler,¹⁶ T. Ekelof,¹⁶⁸ M. El Kacimi,^{137c}
 R. El Kosseifi,⁸⁸ V. Ellajosyula,⁸⁸ M. Ellert,¹⁶⁸ F. Ellinghaus,¹⁷⁷ A. A. Elliot,¹⁷² N. Ellis,³² J. Elmsheuser,²⁷ M. Elsing,³²
 D. Emelianov,¹³³ Y. Enari,¹⁵⁷ J. S. Ennis,¹⁷³ M. B. Epland,⁴⁸ J. Erdmann,⁴⁶ A. Ereditato,¹⁸ S. Errede,¹⁶⁹ M. Escalier,¹¹⁹
 C. Escobar,¹⁷⁰ B. Esposito,⁵⁰ O. Estrada Pastor,¹⁷⁰ A. I. Etienne,¹³⁸ E. Etzion,¹⁵⁵ H. Evans,⁶⁴ A. Ezhilov,¹²⁵ M. Ezzi,^{137e}
 F. Fabbri,^{22a,22b} L. Fabbri,^{22a,22b} V. Fabiani,¹⁰⁸ G. Facini,⁸¹ R. M. Fakhruddinov,¹³² S. Falciano,^{134a} J. Faltova,¹³¹ Y. Fang,^{35a}
 M. Fanti,^{94a,94b} A. Farbin,⁸ A. Farilla,^{136a} E. M. Farina,^{123a,123b} T. Farooque,⁹³ S. Farrell,¹⁶ S. M. Farrington,¹⁷³ P. Farthouat,³²
 F. Fassi,^{137e} P. Fassnacht,³² D. Fassouliotis,⁹ M. Fauci Giannelli,⁴⁹ A. Favareto,^{53a,53b} W. J. Fawcett,⁵² L. Fayard,¹¹⁹
 O. L. Fedin,^{125,r} W. Fedorko,¹⁷¹ M. Feickert,⁴³ S. Feigl,¹²¹ L. Feligioni,⁸⁸ C. Feng,^{36b} E. J. Feng,³² M. Feng,⁴⁸ M. J. Fenton,⁵⁶
 A. B. Fenyuk,¹³² L. Feremenga,⁸ P. Fernandez Martinez,¹⁷⁰ J. Ferrando,⁴⁵ A. Ferrari,¹⁶⁸ P. Ferrari,¹⁰⁹ R. Ferrari,^{123a}
 D. E. Ferreira de Lima,^{60b} A. Ferrer,¹⁷⁰ D. Ferrere,⁵² C. Ferretti,⁹² F. Fiedler,⁸⁶ A. Filipčič,⁷⁸ F. Filthaut,¹⁰⁸
 M. Fincke-Keeler,¹⁷² K. D. Finelli,²⁴ M. C. N. Fiolhais,^{128a,128c,s} L. Fiorini,¹⁷⁰ C. Fischer,¹³ J. Fischer,¹⁷⁷ W. C. Fisher,⁹³
 N. Flaschel,⁴⁵ I. Fleck,¹⁴³ P. Fleischmann,⁹² R. R. M. Fletcher,¹²⁴ T. Flick,¹⁷⁷ B. M. Flierl,¹⁰² L. M. Flores,¹²⁴
 L. R. Flores Castillo,^{62a} N. Fomin,¹⁵ G. T. Forcolin,⁸⁷ A. Formica,¹³⁸ F. A. Förster,¹³ A. Forti,⁸⁷ A. G. Foster,¹⁹
 D. Fournier,¹¹⁹ H. Fox,⁷⁵ S. Fracchia,¹⁴¹ P. Francavilla,^{126a,126b} M. Franchini,^{22a,22b} S. Franchino,^{60a} D. Francis,³²
 L. Franconi,¹²¹ M. Franklin,⁵⁹ M. Frate,¹⁶⁶ M. Fraternali,^{123a,123b} D. Freeborn,⁸¹ S. M. Fressard-Batraneanu,³² B. Freund,⁹⁷
 W. S. Freund,^{26a} D. Froidevaux,³² J. A. Frost,¹²² C. Fukunaga,¹⁵⁸ T. Fusayasu,¹⁰⁴ J. Fuster,¹⁷⁰ O. Gabizon,¹⁵⁴
 A. Gabrielli,^{22a,22b} A. Gabrielli,¹⁶ G. P. Gach,^{41a} S. Gadatsch,⁵² S. Gadomski,⁸⁰ P. Gadow,¹⁰³ G. Gagliardi,^{53a,53b}
 L. G. Gagnon,⁹⁷ C. Galea,¹⁰⁸ B. Galhardo,^{128a,128c} E. J. Gallas,¹²² B. J. Gallop,¹³³ P. Gallus,¹³⁰ G. Galster,³⁹
 R. Gamboa Goni,⁷⁹ K. K. Gan,¹¹³ S. Ganguly,¹⁷⁵ Y. Gao,⁷⁷ Y. S. Gao,^{145,h} F. M. Garay Walls,^{34a} C. García,¹⁷⁰
 J. E. García Navarro,¹⁷⁰ J. A. García Pascual,^{35a} M. Garcia-Sciveres,¹⁶ R. W. Gardner,³³ N. Garelli,¹⁴⁵ V. Garonne,¹²¹
 K. Gasnikova,⁴⁵ A. Gaudiello,^{53a,53b} G. Gaudio,^{123a} I. L. Gavrilenko,⁹⁸ C. Gay,¹⁷¹ G. Gaycken,²³ E. N. Gazis,¹⁰
 C. N. P. Gee,¹³³ J. Geisen,⁵⁸ M. Geisen,⁸⁶ M. P. Geisler,^{60a} K. Gellerstedt,^{148a,148b} C. Gemme,^{53a} M. H. Genest,⁵⁷ C. Geng,⁹²
 S. Gentile,^{134a,134b} C. Gentsos,¹⁵⁶ S. George,⁸⁰ D. Gerbaudo,¹³ G. Geßner,⁴⁶ S. Ghasemi,¹⁴³ M. Ghneimat,²³ B. Giacobbe,^{22a}
 S. Giagu,^{134a,134b} N. Giangiacomi,^{22a,22b} P. Giannetti,^{126a} S. M. Gibson,⁸⁰ M. Gignac,¹³⁹ M. Gilchriese,¹⁶ D. Gillberg,³¹
 G. Gilles,¹⁷⁷ D. M. Gingrich,^{3,e} M. P. Giordani,^{167a,167c} F. M. Giorgi,^{22a} P. F. Giraud,¹³⁸ P. Giromini,⁵⁹ G. Giugliarelli,^{167a,167c}
 D. Giugni,^{94a} F. Giuli,¹²² M. Giulini,^{60b} S. Gkaitatzis,¹⁵⁶ I. Gkialas,^{9,t} E. L. Gkougkousis,¹³ P. Gkoutoumis,¹⁰
 L. K. Gladilin,¹⁰¹ C. Glasman,⁸⁵ J. Glatzer,¹³ P. C. F. Glaysheer,⁴⁵ A. Glazov,⁴⁵ M. Goblirsch-Kolb,²⁵ J. Godlewski,⁴²
 S. Goldfarb,⁹¹ T. Golling,⁵² D. Golubkov,¹³² A. Gomes,^{128a,128b,128d} R. Gonçalo,^{128a} R. Goncalves Gama,^{26b} G. Gonella,⁵¹
 L. Gonella,¹⁹ A. Gongadze,⁶⁸ F. Gonnella,¹⁹ J. L. Gonski,⁵⁹ S. González de la Hoz,¹⁷⁰ S. Gonzalez-Sevilla,⁵² L. Goossens,³²
 P. A. Gorbounov,⁹⁹ H. A. Gordon,²⁷ B. Gorini,³² E. Gorini,^{76a,76b} A. Gorišek,⁷⁸ A. T. Goshaw,⁴⁸ C. Gössling,⁴⁶
 M. I. Gostkin,⁶⁸ C. A. Gottardo,²³ C. R. Goudet,¹¹⁹ D. Goudami,^{137c} A. G. Goussiou,¹⁴⁰ N. Govender,^{147b,u} C. Goy,⁵
 E. Gozani,¹⁵⁴ I. Grabowska-Bold,^{41a} P. O. J. Gradin,¹⁶⁸ E. C. Graham,⁷⁷ J. Gramling,¹⁶⁶ E. Gramstad,¹²¹ S. Grancagnolo,¹⁷
 V. Gratchev,¹²⁵ P. M. Gravila,^{28f} C. Gray,⁵⁶ H. M. Gray,¹⁶ Z. D. Greenwood,^{82,v} C. Greife,²³ K. Gregersen,⁸¹ I. M. Gregor,⁴⁵

- P. Grenier,¹⁴⁵ K. Grevtsov,⁴⁵ J. Griffiths,⁸ A. A. Grillo,¹³⁹ K. Grimm,¹⁴⁵ S. Grinstein,^{13,w} Ph. Gris,³⁷ J.-F. Grivaz,¹¹⁹
 S. Groh,⁸⁶ E. Gross,¹⁷⁵ J. Grosse-Knetter,⁵⁸ G. C. Grossi,⁸² Z. J. Grout,⁸¹ A. Grummer,¹⁰⁷ L. Guan,⁹² W. Guan,¹⁷⁶
 J. Guenther,³² A. Guerguichon,¹¹⁹ F. Guescini,^{163a} D. Guest,¹⁶⁶ O. Gueta,¹⁵⁵ R. Gugel,⁵¹ B. Gui,¹¹³ T. Guillemain,⁵
 S. Guindon,³² U. Gul,⁵⁶ C. Gumpert,³² J. Guo,^{36c} W. Guo,⁹² Y. Guo,^{36a,x} R. Gupta,⁴³ S. Gurbuz,^{20a} G. Gustavino,¹¹⁵
 B. J. Gutelman,¹⁵⁴ P. Gutierrez,¹¹⁵ N. G. Gutierrez Ortiz,⁸¹ C. Gutschow,⁸¹ C. Guyot,¹³⁸ M. P. Guzik,^{41a} C. Gwenlan,¹²²
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 H. Hakobyan,^{180,a} M. Haleem,¹⁷⁸ J. Haley,¹¹⁶ G. Halladjian,⁹³ G. D. Hallewell,⁸⁸ K. Hamacher,¹⁷⁷ P. Hamal,¹¹⁷
 K. Hamano,¹⁷² A. Hamilton,^{147a} G. N. Hamity,¹⁴¹ K. Han,^{36a,y} L. Han,^{36a} S. Han,^{35a,35d} K. Hanagaki,^{69,z} M. Hance,¹³⁹
 D. M. Handl,¹⁰² B. Haney,¹²⁴ R. Hankache,⁸³ P. Hanke,^{60a} E. Hansen,⁸⁴ J. B. Hansen,³⁹ J. D. Hansen,³⁹ M. C. Hansen,²³
 P. H. Hansen,³⁹ K. Hara,¹⁶⁴ A. S. Hard,¹⁷⁶ T. Harenberg,¹⁷⁷ S. Harkusha,⁹⁵ P. F. Harrison,¹⁷³ N. M. Hartmann,¹⁰²
 Y. Hasegawa,¹⁴² A. Hasib,⁴⁹ S. Hassani,¹³⁸ S. Haug,¹⁸ R. Hauser,⁹³ L. Hauswald,⁴⁷ L. B. Havener,³⁸ M. Havranek,¹³⁰
 C. M. Hawkes,¹⁹ R. J. Hawkings,³² D. Hayden,⁹³ C. P. Hays,¹²² J. M. Hays,⁷⁹ H. S. Hayward,⁷⁷ S. J. Haywood,¹³³ T. Heck,⁸⁶
 V. Hedberg,⁸⁴ L. Heelan,⁸ S. Heer,²³ K. K. Heidegger,⁵¹ S. Heim,⁴⁵ T. Heim,¹⁶ B. Heinemann,^{45,aa} J. J. Heinrich,¹⁰²
 L. Heinrich,¹¹² C. Heinz,⁵⁵ J. Hejbal,¹²⁹ L. Helary,³² A. Held,¹⁷¹ S. Hellesund,¹²¹ S. Hellman,^{148a,148b} C. Helsen,³²
 R. C. W. Henderson,⁷⁵ Y. Heng,¹⁷⁶ S. Henkelmann,¹⁷¹ A. M. Henriques Correia,³² G. H. Herbert,¹⁷ H. Herde,²⁵ V. Herget,¹⁷⁸
 Y. Hernández Jiménez,^{147c} H. Herr,⁸⁶ G. Herten,⁵¹ R. Hertenberger,¹⁰² L. Hervas,³² T. C. Herwig,¹²⁴ G. G. Hesketh,⁸¹
 N. P. Hessey,^{163a} J. W. Hetherly,⁴³ S. Higashino,⁶⁹ E. Higón-Rodríguez,¹⁷⁰ K. Hildebrand,³³ E. Hill,¹⁷² J. C. Hill,³⁰
 K. H. Hiller,⁴⁵ S. J. Hillier,¹⁹ M. Hils,⁴⁷ I. Hinchliffe,¹⁶ M. Hirose,⁵¹ D. Hirschbuehl,¹⁷⁷ B. Hiti,⁷⁸ O. Hladik,¹²⁹
 D. R. Hlaluku,^{147c} X. Hoad,⁴⁹ J. Hobbs,¹⁵⁰ N. Hod,^{163a} M. C. Hodgkinson,¹⁴¹ A. Hoecker,³² M. R. Hoferkamp,¹⁰⁷
 F. Hoenig,¹⁰² D. Hohn,²³ D. Hohov,¹¹⁹ T. R. Holmes,³³ M. Holzbock,¹⁰² M. Homann,⁴⁶ S. Honda,¹⁶⁴ T. Honda,⁶⁹
 T. M. Hong,¹²⁷ B. H. Hooberman,¹⁶⁹ W. H. Hopkins,¹¹⁸ Y. Horii,¹⁰⁵ A. J. Horton,¹⁴⁴ L. A. Horyn,³³ J.-Y. Hostachy,⁵⁷
 A. Hostiuc,¹⁴⁰ S. Hou,¹⁵³ A. Hoummada,^{137a} J. Howarth,⁸⁷ J. Hoya,⁷⁴ M. Hrabovsky,¹¹⁷ J. Hrdinka,³² I. Hristova,¹⁷
 J. Hrivnac,¹¹⁹ T. Hryn'ova,⁵ A. Hrynevich,⁹⁶ P. J. Hsu,⁶³ S.-C. Hsu,¹⁴⁰ Q. Hu,²⁷ S. Hu,^{36c} Y. Huang,^{35a} Z. Hubacek,¹³⁰
 F. Hubaut,⁸⁸ F. Huegging,²³ T. B. Huffman,¹²² E. W. Hughes,³⁸ M. Huhtinen,³² R. F. H. Hunter,³¹ P. Huo,¹⁵⁰ A. M. Hupe,³¹
 N. Huseynov,^{68,c} J. Huston,⁹³ J. Huth,⁵⁹ R. Hyneman,⁹² G. Iacobucci,⁵² G. Iakovidis,²⁷ I. Ibragimov,¹⁴³
 L. Iconomidou-Fayard,¹¹⁹ Z. Idrissi,^{137e} P. Iengo,³² O. Igonkina,^{109,bb} R. Iguchi,¹⁵⁷ T. Iizawa,¹⁷⁴ Y. Ikegami,⁶⁹ M. Ikeno,⁶⁹
 D. Iliadis,¹⁵⁶ N. Ilic,¹⁴⁵ F. Iltzsche,⁴⁷ G. Introzzi,^{123a,123b} M. Iodice,^{136a} K. Iordanidou,³⁸ V. Ippolito,^{134a,134b} M. F. Isacson,¹⁶⁸
 N. Ishijima,¹²⁰ M. Ishino,¹⁵⁷ M. Ishitsuka,¹⁵⁹ C. Issever,¹²² S. Istin,^{20a} F. Ito,¹⁶⁴ J. M. Iturbe Ponce,^{62a} R. Iuppa,^{162a,162b}
 H. Iwasaki,⁶⁹ J. M. Izen,⁴⁴ V. Izzo,^{106a} S. Jabbar,³ P. Jacka,¹²⁹ P. Jackson,¹ R. M. Jacobs,²³ V. Jain,² G. Jakel,¹⁷⁷
 K. B. Jakobi,⁸⁶ K. Jakobs,⁵¹ S. Jakobsen,⁶⁵ T. Jakoubek,¹²⁹ D. O. Jamin,¹¹⁶ D. K. Jana,⁸² R. Jansky,⁵² J. Janssen,²³
 M. Janus,⁵⁸ P. A. Janus,^{41a} G. Jarlskog,⁸⁴ N. Javadov,^{68,c} T. Javůrek,⁵¹ M. Javurkova,⁵¹ F. Jeanneau,¹³⁸ L. Jeanty,¹⁶
 J. Jejelava,^{54a,cc} A. Jelinskas,¹⁷³ P. Jenni,^{51,dd} C. Jeske,¹⁷³ S. Jézéquel,⁵ H. Ji,¹⁷⁶ J. Jia,¹⁵⁰ H. Jiang,⁶⁷ Y. Jiang,^{36a} Z. Jiang,¹⁴⁵
 S. Jiggins,⁸¹ J. Jimenez Pena,¹⁷⁰ S. Jin,^{35b} A. Jinaru,^{28b} O. Jinnouchi,¹⁵⁹ H. Jivan,^{147c} P. Johansson,¹⁴¹ K. A. Johns,⁷
 C. A. Johnson,⁶⁴ W. J. Johnson,¹⁴⁰ K. Jon-And,^{148a,148b} R. W. L. Jones,⁷⁵ S. D. Jones,¹⁵¹ S. Jones,⁷ T. J. Jones,⁷⁷
 J. Jongmanns,^{60a} P. M. Jorge,^{128a,128b} J. Jovicevic,^{163a} X. Ju,¹⁷⁶ J. J. Junggeburth,¹⁰³ A. Juste Rozas,^{13,w} A. Kaczmarska,⁴²
 M. Kado,¹¹⁹ H. Kagan,¹¹³ M. Kagan,¹⁴⁵ S. J. Kahn,⁸⁸ T. Kajii,¹⁷⁴ E. Kajomovitz,¹⁵⁴ C. W. Kalderon,⁸⁴ A. Kaluza,⁸⁶
 S. Kama,⁴³ A. Kamenshchikov,¹³² L. Kanjir,⁷⁸ Y. Kano,¹⁵⁷ V. A. Kantserov,¹⁰⁰ J. Kanzaki,⁶⁹ B. Kaplan,¹¹² L. S. Kaplan,¹⁷⁶
 D. Kar,^{147c} K. Karakostas,¹⁰ N. Karastathis,¹⁰ M. J. Kareem,^{163b} E. Karentzos,¹⁰ S. N. Karpov,⁶⁸ Z. M. Karpova,⁶⁸
 V. Kartvelishvili,⁷⁵ A. N. Karyukhin,¹³² K. Kasahara,¹⁶⁴ L. Kashif,¹⁷⁶ R. D. Kass,¹¹³ A. Kastanas,¹⁴⁹ Y. Kataoka,¹⁵⁷
 C. Kato,¹⁵⁷ A. Katre,⁵² J. Katzy,⁴⁵ K. Kawade,⁷⁰ K. Kawagoe,⁷³ T. Kawamoto,¹⁵⁷ G. Kawamura,⁵⁸ E. F. Kay,⁷⁷
 V. F. Kazanin,^{111,d} R. Keeler,¹⁷² R. Kehoe,⁴³ J. S. Keller,³¹ E. Kellermann,⁸⁴ J. J. Kempster,¹⁹ J. Kendrick,¹⁹
 H. Keoshkerian,¹⁶¹ O. Kepka,¹²⁹ B. P. Kerševan,⁷⁸ S. Kersten,¹⁷⁷ R. A. Keyes,⁹⁰ M. Khader,¹⁶⁹ F. Khalil-zada,¹²
 A. Khanov,¹¹⁶ A. G. Kharlamov,^{111,d} T. Kharlamova,^{111,d} A. Khodinov,¹⁶⁰ T. J. Khoo,⁵² V. Khovanskiy,^{99,a} E. Khramov,⁶⁸
 J. Khubua,^{54b,ee} S. Kido,⁷⁰ M. Kiehn,⁵² C. R. Kilby,⁸⁰ H. Y. Kim,⁸ S. H. Kim,¹⁶⁴ Y. K. Kim,³³ N. Kimura,^{167a,167c}
 O. M. Kind,¹⁷ B. T. King,⁷⁷ D. Kirchmeier,⁴⁷ J. Kirk,¹³³ A. E. Kiryunin,¹⁰³ T. Kishimoto,¹⁵⁷ D. Kisielewska,^{41a} V. Kitali,⁴⁵
 O. Kivernyk,⁵ E. Kladiva,^{146b} T. Klapdor-Kleingrothaus,⁵¹ M. H. Klein,⁹² M. Klein,⁷⁷ U. Klein,⁷⁷ K. Kleinknecht,⁸⁶
 P. Klimek,¹¹⁰ A. Klimentov,²⁷ R. Klingenberg,^{46,a} T. Klingl,²³ T. Klioutchnikova,³² F. F. Klitzner,¹⁰² E.-E. Kluge,^{60a}
 P. Kluit,¹⁰⁹ S. Kluth,¹⁰³ E. Kneringer,⁶⁵ E. B. F. G. Knoops,⁸⁸ A. Knue,⁵¹ A. Kobayashi,¹⁵⁷ D. Kobayashi,⁷³ T. Kobayashi,¹⁵⁷
 M. Kobel,⁴⁷ M. Kocian,¹⁴⁵ P. Kodys,¹³¹ T. Koffas,³¹ E. Koffeman,¹⁰⁹ N. M. Köhler,¹⁰³ T. Koi,¹⁴⁵ M. Kolb,^{60b} I. Koletsou,⁵

- T. Kondo,⁶⁹ N. Kondrashova,^{36c} K. Köneke,⁵¹ A. C. König,¹⁰⁸ T. Kono,^{69,ff} R. Konoplich,^{112,gg} N. Konstantinidis,⁸¹
 B. Konya,⁸⁴ R. Kopeliansky,⁶⁴ S. Koperny,^{41a} K. Korcyl,⁴² K. Kordas,¹⁵⁶ A. Korn,⁸¹ I. Korolkov,¹³ E. V. Korolkova,¹⁴¹
 O. Kortner,¹⁰³ S. Kortner,¹⁰³ T. Kosek,¹³¹ V. V. Kostyukhin,²³ A. Kotwal,⁴⁸ A. Koulouris,¹⁰
 A. Kourkouveli-Charalampidi,^{123a,123b} C. Kourkouvelis,⁹ E. Kourlitis,¹⁴¹ V. Kouskoura,²⁷ A. B. Kowalewska,⁴²
 R. Kowalewski,¹⁷² T. Z. Kowalski,^{41a} C. Kozakai,¹⁵⁷ W. Kozanecki,¹³⁸ A. S. Kozhin,¹³² V. A. Kramarenko,¹⁰¹
 G. Kramberger,⁷⁸ D. Krasnopevtsev,¹⁰⁰ M. W. Krasny,⁸³ A. Krasznahorkay,³² D. Krauss,¹⁰³ J. A. Kremer,^{41a}
 J. Kretzschmar,⁷⁷ K. Kreutzfeldt,⁵⁵ P. Krieger,¹⁶¹ K. Krizka,¹⁶ K. Kroeninger,⁴⁶ H. Kroha,¹⁰³ J. Kroll,¹²⁹ J. Kroll,¹²⁴
 J. Kroseberg,²³ J. Krstic,¹⁴ U. Kruchonak,⁶⁸ H. Krüger,²³ N. Krumnack,⁶⁷ M. C. Kruse,⁴⁸ T. Kubota,⁹¹ S. Kuday,^{4b}
 J. T. Kuechler,¹⁷⁷ S. Kuehn,³² A. Kugel,^{60a} F. Kuger,¹⁷⁸ T. Kuhl,⁴⁵ V. Kukhtin,⁶⁸ R. Kukla,⁸⁸ Y. Kulchitsky,⁹⁵ S. Kuleshov,^{34b}
 Y. P. Kulinich,¹⁶⁹ M. Kuna,⁵⁷ T. Kunigo,⁷¹ A. Kupco,¹²⁹ T. Kupfer,⁴⁶ O. Kuprash,¹⁵⁵ H. Kurashige,⁷⁰ L. L. Kurchaninov,^{163a}
 Y. A. Kurochkin,⁹⁵ M. G. Kurth,^{35a,35d} E. S. Kuwertz,¹⁷² M. Kuze,¹⁵⁹ J. Kvita,¹¹⁷ T. Kwan,¹⁷² A. La Rosa,¹⁰³
 J. L. La Rosa Navarro,^{26d} L. La Rotonda,^{40a,40b} F. La Ruffa,^{40a,40b} C. Lacasta,¹⁷⁰ F. Lacava,^{134a,134b} J. Lacey,⁴⁵ D. P. J. Lack,⁸⁷
 H. Lacker,¹⁷ D. Lacour,⁸³ E. Ladygin,⁶⁸ R. Lafaye,⁵ B. Laforge,⁸³ S. Lai,⁵⁸ S. Lammers,⁶⁴ W. Lampl,⁷ E. Lançon,²⁷
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 F. Lanni,²⁷ K. Lantzsch,²³ A. Lanza,^{123a} A. Lapertosa,^{53a,53b} S. Laplace,⁸³ J. F. Laporte,¹³⁸ T. Lari,^{94a}
 F. Lasagni Manghi,^{22a,22b} M. Lassnig,³² T. S. Lau,^{62a} A. Laudrain,¹¹⁹ A. T. Law,¹³⁹ P. Laycock,⁷⁷ M. Lazzaroni,^{94a,94b} B. Le,⁹¹
 O. Le Dortz,⁸³ E. Le Guirriec,⁸⁸ E. P. Le Quilleuc,¹³⁸ M. LeBlanc,⁷ T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁷ C. A. Lee,²⁷
 G. R. Lee,^{34a} S. C. Lee,¹⁵³ L. Lee,⁵⁹ B. Lefebvre,⁹⁰ M. Lefebvre,¹⁷² F. Legger,¹⁰² C. Leggett,¹⁶ G. Lehmann Miotto,³²
 W. A. Leight,⁴⁵ A. Leisos,^{156,hh} M. A. L. Leite,^{26d} R. Leitner,¹³¹ D. Lellouch,¹⁷⁵ B. Lemmer,⁵⁸ K. J. C. Leney,⁸¹ T. Lenz,²³
 B. Lenzi,³² R. Leone,⁷ S. Leone,^{126a} C. Leonidopoulos,⁴⁹ G. Lerner,¹⁵¹ C. Leroy,⁹⁷ R. Les,¹⁶¹ A. A. J. Lesage,¹³⁸
 C. G. Lester,³⁰ M. Levchenko,¹²⁵ J. Levêque,⁵ D. Levin,⁹² L. J. Levinson,¹⁷⁵ M. Levy,¹⁹ D. Lewis,⁷⁹ B. Li,^{36a,x} C.-Q. Li,^{36a}
 H. Li,^{36b} L. Li,^{36c} Q. Li,^{35a,35d} Q. Li,^{36a} S. Li,^{36c,36d} X. Li,^{36c} Y. Li,¹⁴³ Z. Liang,^{35a} B. Liberti,^{135a} A. Liblong,¹⁶¹ K. Lie,^{62c}
 A. Limosani,¹⁵² C. Y. Lin,³⁰ K. Lin,⁹³ S. C. Lin,¹⁸² T. H. Lin,⁸⁶ R. A. Linck,⁶⁴ B. E. Lindquist,¹⁵⁰ A. E. Lioni,⁵² E. Lipeles,¹²⁴
 A. Lipniacka,¹⁵ M. Lisovyi,^{60b} T. M. Liss,^{169,ii} A. Lister,¹⁷¹ A. M. Litke,¹³⁹ J. D. Little,⁸ B. Liu,⁶⁷ H. Liu,⁹² H. Liu,²⁷
 J. K. K. Liu,¹²² J. B. Liu,^{36a} K. Liu,⁸³ M. Liu,^{36a} P. Liu,¹⁶ Y. L. Liu,^{36a} Y. Liu,^{36a} M. Livan,^{123a,123b} A. Lleres,⁵⁷
 J. Llorente Merino,^{35a} S. L. Lloyd,⁷⁹ C. Y. Lo,^{62b} F. Lo Sterzo,⁴³ E. M. Lobodzinska,⁴⁵ P. Loch,⁷ F. K. Loebinger,⁸⁷
 A. Loesle,⁵¹ K. M. Loew,²⁵ T. Lohse,¹⁷ K. Lohwasser,¹⁴¹ M. Lokajicek,¹²⁹ B. A. Long,²⁴ J. D. Long,¹⁶⁹ R. E. Long,⁷⁵
 L. Longo,^{76a,76b} K. A. Looper,¹¹³ J. A. Lopez,^{34b} I. Lopez Paz,¹³ A. Lopez Solis,⁸³ J. Lorenz,¹⁰² N. Lorenzo Martinez,⁵
 M. Losada,²¹ P. J. Lösel,¹⁰² X. Lou,^{35a} A. Lounis,¹¹⁹ J. Love,⁶ P. A. Love,⁷⁵ H. Lu,^{62a} N. Lu,⁹² Y. J. Lu,⁶³ H. J. Lubatti,¹⁴⁰
 C. Luci,^{134a,134b} A. Lucotte,⁵⁷ C. Luedtke,⁵¹ F. Luehring,⁶⁴ I. Luise,⁸³ W. Lukas,⁶⁵ L. Luminari,^{134a} B. Lund-Jensen,¹⁴⁹
 M. S. Lutz,⁸⁹ P. M. Luzi,⁸³ D. Lynn,²⁷ R. Lysak,¹²⁹ E. Lytken,⁸⁴ F. Lyu,^{35a} V. Lyubushkin,⁶⁸ H. Ma,²⁷ L. L. Ma,^{36b} Y. Ma,^{36b}
 G. Maccarrone,⁵⁰ A. Macchiolo,¹⁰³ C. M. Macdonald,¹⁴¹ B. Maček,⁷⁸ J. Machado Miguens,^{124,128b} D. Madaffari,¹⁷⁰
 R. Madar,³⁷ W. F. Mader,⁴⁷ A. Madsen,⁴⁵ N. Madysa,⁴⁷ J. Maeda,⁷⁰ S. Maeland,¹⁵ T. Maeno,²⁷ A. S. Maeviskiy,¹⁰¹
 V. Magerl,⁵¹ C. Maidantchik,^{26a} T. Maier,¹⁰² A. Maio,^{128a,128b,128d} O. Majersky,^{146a} S. Majewski,¹¹⁸ Y. Makida,⁶⁹
 N. Makovec,¹¹⁹ B. Malaescu,⁸³ Pa. Malecki,⁴² V. P. Maleev,¹²⁵ F. Malek,⁵⁷ U. Mallik,⁶⁶ D. Malon,⁶ C. Malone,³⁰
 S. Maltezos,¹⁰ S. Malyukov,³² J. Mamuzic,¹⁷⁰ G. Mancini,⁵⁰ I. Mandić,⁷⁸ J. Maneira,^{128a,128b}
 L. Manhaes de Andrade Filho,^{26b} J. Manjarres Ramos,⁴⁷ K. H. Mankinen,⁸⁴ A. Mann,¹⁰² A. Manousos,³² B. Mansoulie,¹³⁸
 J. D. Mansour,^{35a} R. Mantifel,⁹⁰ M. Mantoani,⁵⁸ S. Manzoni,^{94a,94b} G. Marceca,²⁹ L. March,⁵² L. Marchese,¹²²
 G. Marchiori,⁸³ M. Marcisovsky,¹²⁹ C. A. Marin Tobon,³² M. Marjanovic,³⁷ D. E. Marley,⁹² F. Marroquim,^{26a} Z. Marshall,¹⁶
 M. U. F. Martensson,¹⁶⁸ S. Marti-Garcia,¹⁷⁰ C. B. Martin,¹¹³ T. A. Martin,¹⁷³ V. J. Martin,⁴⁹ B. Martin dit Latour,¹⁵
 M. Martinez,^{13,w} V. I. Martinez Outschoorn,⁸⁹ S. Martin-Haugh,¹³³ V. S. Martoiu,^{28b} A. C. Martyniuk,⁸¹ A. Marzin,³²
 L. Masetti,⁸⁶ T. Mashimo,¹⁵⁷ R. Mashinistov,⁹⁸ J. Masik,⁸⁷ A. L. Maslennikov,^{111,d} L. H. Mason,⁹¹ L. Massa,^{135a,135b}
 P. Mastrandrea,⁵ A. Mastroberardino,^{40a,40b} T. Masubuchi,¹⁵⁷ P. Mättig,¹⁷⁷ J. Maurer,^{28b} S. J. Maxfield,⁷⁷
 D. A. Maximov,^{111,d} R. Mazini,¹⁵³ I. Maznas,¹⁵⁶ S. M. Mazza,¹³⁹ N. C. Mc Fadden,¹⁰⁷ G. Mc Goldrick,¹⁶¹ S. P. Mc Kee,⁹²
 A. McCarn,⁹² T. G. McCarthy,¹⁰³ L. I. McClymont,⁸¹ E. F. McDonald,⁹¹ J. A. Mcfayden,³² G. Mchedlidze,⁵⁸
 M. A. McKay,⁴³ S. J. McMahon,¹³³ P. C. McNamara,⁹¹ C. J. McNicol,¹⁷³ R. A. McPherson,^{172,o} Z. A. Meadows,⁸⁹
 S. Meehan,¹⁴⁰ T. J. Megy,⁵¹ S. Mehlhase,¹⁰² A. Mehta,⁷⁷ T. Meideck,⁵⁷ K. Meier,^{60a} B. Meirose,⁴⁴ D. Melini,^{170,jj}
 B. R. Mellado Garcia,^{147c} J. D. Mellenthin,⁵⁸ M. Melo,^{146a} F. Meloni,¹⁸ A. Melzer,²³ S. B. Menary,⁸⁷ L. Meng,⁷⁷
 X. T. Meng,⁹² A. Mengarelli,^{22a,22b} S. Menke,¹⁰³ E. Meoni,^{40a,40b} S. Mergelmeyer,¹⁷ C. Merlassino,¹⁸ P. Mermod,⁵²

- L. Merola,^{106a,106b} C. Meroni,^{94a} F. S. Merritt,³³ A. Messina,^{134a,134b} J. Metcalfe,⁶ A. S. Mete,¹⁶⁶ C. Meyer,¹²⁴ J.-P. Meyer,¹³⁸
 J. Meyer,¹⁰⁹ H. Meyer Zu Theenhausen,^{60a} F. Miano,¹⁵¹ R. P. Middleton,¹³³ S. Miglioranza,^{53a,53b} L. Mijović,⁴⁹
 G. Mikenberg,¹⁷⁵ M. Mikestikova,¹²⁹ M. Mikuž,⁷⁸ M. Milesi,⁹¹ A. Milic,¹⁶¹ D. A. Millar,⁷⁹ D. W. Miller,³³ A. Milov,¹⁷⁵
 D. A. Milstead,^{148a,148b} A. A. Minaenko,¹³² I. A. Minashvili,^{54b} A. I. Mincer,¹¹² B. Mindur,^{41a} M. Mineev,⁶⁸ Y. Minegishi,¹⁵⁷
 Y. Ming,¹⁷⁶ L. M. Mir,¹³ A. Mirto,^{76a,76b} K. P. Mistry,¹²⁴ T. Mitani,¹⁷⁴ J. Mitrevski,¹⁰² V. A. Mitsou,¹⁷⁰ A. Miucci,¹⁸
 P. S. Miyagawa,¹⁴¹ A. Mizukami,⁶⁹ J. U. Mjörnmark,⁸⁴ T. Mkrtchyan,¹⁸⁰ M. Mlynarikova,¹³¹ T. Moa,^{148a,148b}
 K. Mochizuki,⁹⁷ P. Mogg,⁵¹ S. Mohapatra,³⁸ S. Molander,^{148a,148b} R. Moles-Valls,²³ M. C. Mondragon,⁹³ K. Mönig,⁴⁵
 J. Monk,³⁹ E. Monnier,⁸⁸ A. Montalbano,¹⁴⁴ J. Montejo Berlingen,³² F. Monticelli,⁷⁴ S. Monzani,^{94a} R. W. Moore,³
 N. Morange,¹¹⁹ D. Moreno,²¹ M. Moreno Llácer,³² P. Morettini,^{53a} M. Morgenstern,¹⁰⁹ S. Morgenstern,³² D. Mori,¹⁴⁴
 T. Mori,¹⁵⁷ M. Morii,⁵⁹ M. Morinaga,¹⁷⁴ V. Morisbak,¹²¹ A. K. Morley,³² G. Mornacchi,³² J. D. Morris,⁷⁹ L. Morvaj,¹⁵⁰
 P. Moschovakos,¹⁰ M. Mosidze,^{54b} H. J. Moss,¹⁴¹ J. Moss,^{145,kk} K. Motohashi,¹⁵⁹ R. Mount,¹⁴⁵ E. Mountricha,²⁷
 E. J. W. Moyses,⁸⁹ S. Muanza,⁸⁸ F. Mueller,¹⁰³ J. Mueller,¹²⁷ R. S. P. Mueller,¹⁰² D. Muenstermann,⁷⁵ P. Mullen,⁵⁶
 G. A. Mullier,¹⁸ F. J. Munoz Sanchez,⁸⁷ P. Murin,^{146b} W. J. Murray,^{173,133} A. Murrone,^{94a,94b} M. Muškinja,⁷⁸ C. Mwewa,^{147a}
 A. G. Myagkov,^{132,II} J. Myers,¹¹⁸ M. Myska,¹³⁰ B. P. Nachman,¹⁶ O. Nackenhorst,⁴⁶ K. Nagai,¹²² R. Nagai,^{69,ff} K. Nagano,⁶⁹
 Y. Nagasaka,⁶¹ K. Nagata,¹⁶⁴ M. Nagel,⁵¹ E. Nagy,⁸⁸ A. M. Nairz,³² Y. Nakahama,¹⁰⁵ K. Nakamura,⁶⁹ T. Nakamura,¹⁵⁷
 I. Nakano,¹¹⁴ R. F. Naranjo Garcia,⁴⁵ R. Narayan,¹¹ D. I. Narrias Villar,^{60a} I. Naryshkin,¹²⁵ T. Naumann,⁴⁵ G. Navarro,²¹
 R. Nayyar,⁷ H. A. Neal,⁹² P. Yu. Nechaeva,⁹⁸ T. J. Neep,¹³⁸ A. Negri,^{123a,123b} M. Negrini,^{22a} S. Nektarijevic,¹⁰⁸ C. Nellist,⁵⁸
 M. E. Nelson,¹²² S. Nemecek,¹²⁹ P. Nemethy,¹¹² M. Nessi,^{32,mm} M. S. Neubauer,¹⁶⁹ M. Neumann,¹⁷⁷ P. R. Newman,¹⁹
 T. Y. Ng,^{62c} Y. S. Ng,¹⁷ H. D. N. Nguyen,⁸⁸ T. Nguyen Manh,⁹⁷ R. B. Nickerson,¹²² R. Nicolaidou,¹³⁸ J. Nielsen,¹³⁹
 N. Nikiforou,¹¹ V. Nikolaenko,^{132,II} I. Nikolic-Audit,⁸³ K. Nikolopoulos,¹⁹ P. Nilsson,²⁷ Y. Ninomiya,⁶⁹ A. Nisati,^{134a}
 N. Nishu,^{36c} R. Nisius,¹⁰³ I. Nitsche,⁴⁶ T. Nitta,¹⁷⁴ T. Nobe,¹⁵⁷ Y. Noguchi,⁷¹ M. Nomachi,¹²⁰ I. Nomidis,³¹ M. A. Nomura,²⁷
 T. Nooney,⁷⁹ M. Nordberg,³² N. Norjoharuddeen,¹²² T. Novak,⁷⁸ O. Novgorodova,⁴⁷ R. Novotny,¹³⁰ M. Nozaki,⁶⁹
 L. Nozka,¹¹⁷ K. Ntekas,¹⁶⁶ E. Nurse,⁸¹ F. Nuti,⁹¹ K. O'Connor,²⁵ D. C. O'Neil,¹⁴⁴ A. A. O'Rourke,⁴⁵ V. O'Shea,⁵⁶
 F. G. Oakham,^{31,e} H. Oberlack,¹⁰³ T. Obermann,²³ J. Ocariz,⁸³ A. Ochi,⁷⁰ I. Ochoa,³⁸ J. P. Ochoa-Ricoux,^{34a} S. Oda,⁷³
 S. Odaka,⁶⁹ A. Oh,⁸⁷ S. H. Oh,⁴⁸ C. C. Ohm,¹⁴⁹ H. Ohman,¹⁶⁸ H. Oide,^{53a,53b} H. Okawa,¹⁶⁴ Y. Okumura,¹⁵⁷ T. Okuyama,⁶⁹
 A. Olariu,^{28b} L. F. Oleiro Seabra,^{128a} S. A. Olivares Pino,^{34a} D. Oliveira Damazio,²⁷ J. L. Oliver,¹ M. J. R. Olsson,³³
 A. Olszewski,⁴² J. Olszowska,⁴² A. Onofre,^{128a,128e} K. Onogi,¹⁰⁵ P. U. E. Onyisi,^{11,nn} H. Oppen,¹²¹ M. J. Oreglia,³³
 Y. Oren,¹⁵⁵ D. Orestano,^{136a,136b} E. C. Orgill,⁸⁷ N. Orlando,^{62b} R. S. Orr,¹⁶¹ B. Osculati,^{53a,53b,a} R. Ospanov,^{36a}
 G. Otero y Garzon,²⁹ H. Otono,⁷³ M. Ouchrif,^{137d} F. Ould-Saada,¹²¹ A. Ouraou,¹³⁸ K. P. Oussoren,¹⁰⁹ Q. Ouyang,^{35a}
 M. Owen,⁵⁶ R. E. Owen,¹⁹ V. E. Ozcan,^{20a} N. Ozturk,⁸ K. Pachal,¹⁴⁴ A. Pacheco Pages,¹³ L. Pacheco Rodriguez,¹³⁸
 C. Padilla Aranda,¹³ S. Pagan Griso,¹⁶ M. Paganini,¹⁷⁹ F. Paige,²⁷ G. Palacino,⁶⁴ S. Palazzo,^{40a,40b} S. Palestini,³² M. Palka,^{41b}
 D. Pallin,³⁷ E. St. Panagiotopoulou,¹⁰ I. Panagoulas,¹⁰ C. E. Pandini,⁵² J. G. Panduro Vazquez,⁸⁰ P. Pani,³² D. Pantea,^{28b}
 L. Paolozzi,⁵² Th. D. Papadopoulou,¹⁰ K. Papageorgiou,^{9,t} A. Paramonov,⁶ D. Paredes Hernandez,^{62b} B. Parida,^{36c}
 A. J. Parker,⁷⁵ M. A. Parker,³⁰ K. A. Parker,⁴⁵ F. Parodi,^{53a,53b} J. A. Parsons,³⁸ U. Parzefall,⁵¹ V. R. Pascuzzi,¹⁶¹
 J. M. Pasner,¹³⁹ E. Pasqualucci,^{134a} S. Passaggio,^{53a} Fr. Pastore,⁸⁰ P. Pasuwan,^{148a,148b} S. Pataraja,⁸⁶ J. R. Pater,⁸⁷ T. Pauly,³²
 B. Pearson,¹⁰³ S. Pedraza Lopez,¹⁷⁰ R. Pedro,^{128a,128b} S. V. Peleganchuk,^{111,d} O. Penc,¹²⁹ C. Peng,^{35a,35d} H. Peng,^{36a}
 J. Penwell,⁶⁴ B. S. Peralva,^{26b} M. M. Perego,¹³⁸ D. V. Perepelitsa,²⁷ F. Peri,¹⁷ L. Perini,^{94a,94b} H. Pernegger,³²
 S. Perrella,^{106a,106b} V. D. Peshekhonov,^{68,a} K. Peters,⁴⁵ R. F. Y. Peters,⁸⁷ B. A. Petersen,³² T. C. Petersen,³⁹ E. Petit,⁵⁷
 A. Petridis,¹ C. Petridou,¹⁵⁶ P. Petroff,¹¹⁹ E. Petrolo,^{134a} M. Petrov,¹²² F. Petrucci,^{136a,136b} N. E. Pettersson,⁸⁹ A. Peyaud,¹³⁸
 R. Pezoa,^{34b} T. Pham,⁹¹ F. H. Phillips,⁹³ P. W. Phillips,¹³³ G. Piacquadio,¹⁵⁰ E. Pianori,¹⁷³ A. Picazio,⁸⁹ M. A. Pickering,¹²²
 R. Piegaia,²⁹ J. E. Pilcher,³³ A. D. Pilkington,⁸⁷ M. Pinamonti,^{135a,135b} J. L. Pinfold,³ M. Pitt,¹⁷⁵ M.-A. Pleier,²⁷ V. Pleskot,¹³¹
 E. Plotnikova,⁶⁸ D. Pluth,⁶⁷ P. Podberezko,¹¹¹ R. Poettgen,⁸⁴ R. Poggi,^{123a,123b} L. Poggioli,¹¹⁹ I. Pogrebnyak,⁹³ D. Pohl,²³
 I. Pokharel,⁵⁸ G. Polesello,^{123a} A. Poley,⁴⁵ A. Policicchio,^{40a,40b} R. Polifka,³² A. Polini,^{22a} C. S. Pollard,⁴⁵
 V. Polychronakos,²⁷ D. Ponomarenko,¹⁰⁰ L. Pontecorvo,^{134a} G. A. Popeneciu,^{28d} D. M. Portillo Quintero,⁸³ S. Pospisil,¹³⁰
 K. Potamianos,⁴⁵ I. N. Potrap,⁶⁸ C. J. Potter,³⁰ H. Potti,¹¹ T. Poulsen,⁸⁴ J. Poveda,³² M. E. Pozo Astigarraga,³²
 P. Pralavorio,⁸⁸ S. Prell,⁶⁷ D. Price,⁸⁷ M. Primavera,^{76a} S. Prince,⁹⁰ N. Proklova,¹⁰⁰ K. Prokofiev,^{62c} F. Prokoshin,^{34b}
 S. Protopopescu,²⁷ J. Proudfoot,⁶ M. Przybycien,^{41a} A. Puri,¹⁶⁹ P. Puzo,¹¹⁹ J. Qian,⁹² Y. Qin,⁸⁷ A. Quadt,⁵⁸
 M. Queitsch-Maitland,⁴⁵ A. Qureshi,¹ V. Radeka,²⁷ S. K. Radhakrishnan,¹⁵⁰ P. Rados,⁹¹ F. Ragusa,^{94a,94b} G. Rahal,¹⁸¹
 J. A. Raine,⁸⁷ S. Rajagopalan,²⁷ T. Rashid,¹¹⁹ S. Raspopov,⁵ M. G. Ratti,^{94a,94b} D. M. Rauch,⁴⁵ F. Rauscher,¹⁰² S. Rave,⁸⁶

- I. Ravinovich,¹⁷⁵ J. H. Rawling,⁸⁷ M. Raymond,³² A. L. Read,¹²¹ N. P. Readioff,⁵⁷ M. Reale,^{76a,76b} D. M. Rebuzzi,^{123a,123b}
 A. Redelbach,¹⁷⁸ G. Redlinger,²⁷ R. Reece,¹³⁹ R. G. Reed,^{147c} K. Reeves,⁴⁴ L. Rehnisch,¹⁷ J. Reichert,¹²⁴ A. Reiss,⁸⁶
 C. Rembser,³² H. Ren,^{35a,35d} M. Rescigno,^{134a} S. Resconi,^{94a} E. D. Resseguie,¹²⁴ S. Rettie,¹⁷¹ E. Reynolds,¹⁹
 O. L. Rezanova,^{111,d} P. Reznicek,¹³¹ R. Richter,¹⁰³ S. Richter,⁸¹ E. Richter-Was,^{41b} O. Ricken,²³ M. Ridel,⁸³ P. Rieck,¹⁰³
 C. J. Riegel,¹⁷⁷ O. Rifki,⁴⁵ M. Rijssenbeek,¹⁵⁰ A. Rimoldi,^{123a,123b} M. Rimoldi,¹⁸ L. Rinaldi,^{22a} G. Ripellino,¹⁴⁹ B. Ristić,³²
 E. Ritsch,³² I. Riu,¹³ J. C. Rivera Vergara,^{34a} F. Rizatdinova,¹¹⁶ E. Rizvi,⁷⁹ C. Rizzi,¹³ R. T. Roberts,⁸⁷ S. H. Robertson,^{90,o}
 A. Robichaud-Veronneau,⁹⁰ D. Robinson,³⁰ J. E. M. Robinson,⁴⁵ A. Robson,⁵⁶ E. Rocco,⁸⁶ C. Roda,^{126a,126b} Y. Rodina,^{88,oo}
 S. Rodriguez Bosca,¹⁷⁰ A. Rodriguez Perez,¹³ D. Rodriguez Rodriguez,¹⁷⁰ A. M. Rodríguez Vera,^{163b} S. Roe,³²
 C. S. Rogan,⁵⁹ O. Røhne,¹²¹ R. Röhrig,¹⁰³ J. Roloff,⁵⁹ A. Romaniouk,¹⁰⁰ M. Romano,^{22a,22b} S. M. Romano Saez,³⁷
 E. Romero Adam,¹⁷⁰ N. Rompotis,⁷⁷ M. Ronzani,⁵¹ L. Roos,⁸³ S. Rosati,^{134a} K. Rosbach,⁵¹ P. Rose,¹³⁹ N.-A. Rosien,⁵⁸
 E. Rossi,^{106a,106b} L. P. Rossi,^{53a} L. Rossini,^{94a,94b} J. H. N. Rosten,³⁰ R. Rosten,¹⁴⁰ M. Rotaru,^{28b} J. Rothberg,¹⁴⁰
 D. Rousseau,¹¹⁹ D. Roy,^{147c} A. Rozanov,⁸⁸ Y. Rozen,¹⁵⁴ X. Ruan,^{147c} F. Rubbo,¹⁴⁵ F. Rühr,⁵¹ A. Ruiz-Martinez,³¹
 Z. Rurikova,⁵¹ N. A. Rusakovich,⁶⁸ H. L. Russell,⁹⁰ J. P. Rutherford,⁷ N. Ruthmann,³² E. M. Rüttinger,⁴⁵ Y. F. Ryabov,¹²⁵
 M. Rybar,¹⁶⁹ G. Rybkin,¹¹⁹ S. Ryu,⁶ A. Ryzhov,¹³² G. F. Rzehorz,⁵⁸ A. F. Saavedra,¹⁵² G. Sabato,¹⁰⁹ S. Sacerdoti,¹¹⁹
 H. F.-W. Sadrozinski,¹³⁹ R. Sadykov,⁶⁸ F. Safai Tehrani,^{134a} P. Saha,¹¹⁰ M. Sahinsoy,^{60a} M. Saimpert,⁴⁵ M. Saito,¹⁵⁷
 T. Saito,¹⁵⁷ H. Sakamoto,¹⁵⁷ G. Salamanna,^{136a,136b} J. E. Salazar Loyola,^{34b} D. Salek,¹⁰⁹ P. H. Sales De Bruin,¹⁶⁸
 D. Salihagic,¹⁰³ A. Salnikov,¹⁴⁵ J. Salt,¹⁷⁰ D. Salvatore,^{40a,40b} F. Salvatore,¹⁵¹ A. Salvucci,^{62a,62b,62c} A. Salzburger,³²
 D. Sammel,⁵¹ D. Sampsonidis,¹⁵⁶ D. Sampsonidou,¹⁵⁶ J. Sánchez,¹⁷⁰ A. Sanchez Pineda,^{167a,167c} H. Sandaker,¹²¹
 C. O. Sander,⁴⁵ M. Sandhoff,¹⁷⁷ C. Sandoval,²¹ D. P. C. Sankey,¹³³ M. Sannino,^{53a,53b} Y. Sano,¹⁰⁵ A. Sansoni,⁵⁰ C. Santoni,³⁷
 H. Santos,^{128a} I. Santoyo Castillo,¹⁵¹ A. Sapronov,⁶⁸ J. G. Saraiva,^{128a,128d} O. Sasaki,⁶⁹ K. Sato,¹⁶⁴ E. Sauvan,⁵ P. Savard,^{161,e}
 N. Savić,¹⁰³ R. Sawada,¹⁵⁷ C. Sawyer,¹³³ L. Sawyer,^{82,v} C. Sbarra,^{22a} A. Sbrizzi,^{22a,22b} T. Scanlon,⁸¹ D. A. Scannicchio,¹⁶⁶
 J. Schaarschmidt,¹⁴⁰ P. Schacht,¹⁰³ B. M. Schachtner,¹⁰² D. Schaefer,³³ L. Schaefer,¹²⁴ J. Schaeffer,⁸⁶ S. Schaepe,³²
 U. Schäfer,⁸⁶ A. C. Schaffer,¹¹⁹ D. Schaile,¹⁰² R. D. Schamberger,¹⁵⁰ V. A. Schegelsky,¹²⁵ D. Scheirich,¹³¹ F. Schenck,¹⁷
 M. Schernau,¹⁶⁶ C. Schiavi,^{53a,53b} S. Schier,¹³⁹ L. K. Schildgen,²³ Z. M. Schillaci,²⁵ C. Schillo,⁵¹ E. J. Schioppa,³²
 M. Schioppa,^{40a,40b} K. E. Schleicher,⁵¹ S. Schlenker,³² K. R. Schmidt-Sommerfeld,¹⁰³ K. Schmieden,³² C. Schmitt,⁸⁶
 S. Schmitt,⁴⁵ S. Schmitz,⁸⁶ U. Schnoor,⁵¹ L. Schoeffel,¹³⁸ A. Schoening,^{60b} E. Schopf,²³ M. Schott,⁸⁶
 J. F. P. Schouwenberg,¹⁰⁸ J. Schovancova,³² S. Schramm,⁵² N. Schuh,⁸⁶ A. Schulte,⁸⁶ H.-C. Schultz-Coulon,^{60a}
 M. Schumacher,⁵¹ B. A. Schumm,¹³⁹ Ph. Schune,¹³⁸ A. Schwartzman,¹⁴⁵ T. A. Schwarz,⁹² H. Schweiger,⁸⁷
 Ph. Schwemling,¹³⁸ R. Schwienhorst,⁹³ J. Schwindling,¹³⁸ A. Sciandra,²³ G. Sciolla,²⁵ M. Scornajenghi,^{40a,40b} F. Scuri,^{126a}
 F. Scutti,⁹¹ L. M. Scyboz,¹⁰³ J. Searcy,⁹² P. Seema,²³ S. C. Seidel,¹⁰⁷ A. Seiden,¹³⁹ J. M. Seixas,^{26a} G. Sekhniaidze,^{106a}
 K. Sekhon,⁹² S. J. Sekula,⁴³ N. Semprini-Cesari,^{22a,22b} S. Senkin,³⁷ C. Serfon,¹²¹ L. Serin,¹¹⁹ L. Serkin,^{167a,167b}
 M. Sessa,^{136a,136b} H. Severini,¹¹⁵ T. Šfiligoj,⁷⁸ F. Sforza,¹⁶⁵ A. Sfyrila,⁵² E. Shabalina,⁵⁸ J. D. Shahinian,¹³⁹
 N. W. Shaikh,^{148a,148b} L. Y. Shan,^{35a} R. Shang,¹⁶⁹ J. T. Shank,²⁴ M. Shapiro,¹⁶ A. S. Sharma,¹ P. B. Shatalov,⁹⁹
 K. Shaw,^{167a,167b} S. M. Shaw,⁸⁷ A. Shcherbakova,^{148a,148b} C. Y. Shehu,¹⁵¹ Y. Shen,¹¹⁵ N. Sherafati,³¹ A. D. Sherman,²⁴
 P. Sherwood,⁸¹ L. Shi,^{153,pp} S. Shimizu,⁷⁰ C. O. Shimmin,¹⁷⁹ M. Shimojima,¹⁰⁴ I. P. J. Shipsey,¹²² S. Shirabe,⁷³
 M. Shiyakova,^{68,qq} J. Shlomi,¹⁷⁵ A. Shmeleva,⁹⁸ D. Shoaleh Saadi,⁹⁷ M. J. Shochet,³³ S. Shojaii,⁹¹ D. R. Shope,¹¹⁵
 S. Shrestha,¹¹³ E. Shulga,¹⁰⁰ P. Sicho,¹²⁹ A. M. Sickles,¹⁶⁹ P. E. Sidebo,¹⁴⁹ E. Sideras Haddad,^{147c} O. Sidiropoulou,¹⁷⁸
 A. Sidoti,^{22a,22b} F. Siegert,⁴⁷ Dj. Sijacki,¹⁴ J. Silva,^{128a,128d} M. Silva Jr.,¹⁷⁶ S. B. Silverstein,^{148a} L. Simic,⁶⁸ S. Simion,¹¹⁹
 E. Simioni,⁸⁶ B. Simmons,⁸¹ M. Simon,⁸⁶ P. Sinervo,¹⁶¹ N. B. Sinev,¹¹⁸ M. Sioli,^{22a,22b} G. Siragusa,¹⁷⁸ I. Siral,⁹²
 S. Yu. Sivoklov,¹⁰¹ J. Sjölin,^{148a,148b} M. B. Skinner,⁷⁵ P. Skubic,¹¹⁵ M. Slater,¹⁹ T. Slavicek,¹³⁰ M. Slawinska,⁴²
 K. Sliwa,¹⁶⁵ R. Slovak,¹³¹ V. Smakhtin,¹⁷⁵ B. H. Smart,⁵ J. Smiesko,^{146a} N. Smirnov,¹⁰⁰ S. Yu. Smirnov,¹⁰⁰ Y. Smirnov,¹⁰⁰
 L. N. Smirnova,^{101,rr} O. Smirnova,⁸⁴ J. W. Smith,⁵⁸ M. N. K. Smith,³⁸ R. W. Smith,³⁸ M. Smizanska,⁷⁵ K. Smolek,¹³⁰
 A. A. Snesarev,⁹⁸ I. M. Snyder,¹¹⁸ S. Snyder,²⁷ R. Sobie,^{172,o} F. Socher,⁴⁷ A. M. Soffa,¹⁶⁶ A. Soffer,¹⁵⁵ A. Sogaard,⁴⁹
 D. A. Soh,¹⁵³ G. Sokhrannyi,⁷⁸ C. A. Solans Sanchez,³² M. Solar,¹³⁰ E. Yu. Soldatov,¹⁰⁰ U. Soldevila,¹⁷⁰ A. A. Solodkov,¹³²
 A. Soloshenko,⁶⁸ O. V. Solovyanov,¹³² V. Solovyev,¹²⁵ P. Sommer,¹⁴¹ H. Son,¹⁶⁵ W. Song,¹³³ A. Sopczak,¹³⁰ F. Sopkova,^{146b}
 D. Sosa,^{60b} C. L. Sotiropoulou,^{126a,126b} S. Sottocornola,^{123a,123b} R. Soualah,^{167a,167c} A. M. Soukharev,^{111,d} D. South,⁴⁵
 B. C. Sowden,⁸⁰ S. Spagnolo,^{76a,76b} M. Spalla,¹⁰³ M. Spangenberg,¹⁷³ F. Spanò,⁸⁰ D. Sperlich,¹⁷ F. Spettel,¹⁰³
 T. M. Spieker,^{60a} R. Spighi,^{22a} G. Spigo,³² L. A. Spiller,⁹¹ M. Spousta,¹³¹ R. D. St. Denis,^{56,a} A. Stabile,^{94a,94b} R. Stamen,^{60a}
 S. Stamm,¹⁷ E. Stanecka,⁴² R. W. Stanek,⁶ C. Stancu,^{136a} M. M. Stanitzki,⁴⁵ B. S. Stapf,¹⁰⁹ S. Stapnes,¹²¹

- E. A. Starchenko,¹³² G. H. Stark,³³ J. Stark,⁵⁷ S. H. Stark,³⁹ P. Staroba,¹²⁹ P. Starovoitov,^{60a} S. Stärz,³² R. Staszewski,⁴²
 M. Stegler,⁴⁵ P. Steinberg,²⁷ B. Stelzer,¹⁴⁴ H. J. Stelzer,³² O. Stelzer-Chilton,^{163a} H. Stenzel,⁵⁵ T. J. Stevenson,⁷⁹
 G. A. Stewart,³² M. C. Stockton,¹¹⁸ G. Stoicea,^{28b} P. Stolte,⁵⁸ S. Stonjek,¹⁰³ A. Straessner,⁴⁷ M. E. Stramaglia,¹⁸
 J. Strandberg,¹⁴⁹ S. Strandberg,^{148a,148b} M. Strauss,¹¹⁵ P. Strizenec,^{146b} R. Ströhmer,¹⁷⁸ D. M. Strom,¹¹⁸ R. Stroynowski,⁴³
 A. Strubig,⁴⁹ S. A. Stucci,²⁷ B. Stugu,¹⁵ N. A. Styles,⁴⁵ D. Su,¹⁴⁵ J. Su,¹²⁷ S. Suchek,^{60a} Y. Sugaya,¹²⁰ M. Suk,¹³⁰
 V. V. Sulin,⁹⁸ DMS Sultan,⁵² S. Sultansoy,^{4c} T. Sumida,⁷¹ S. Sun,⁹² X. Sun,³ K. Suruliz,¹⁵¹ C. J. E. Suster,¹⁵² M. R. Sutton,¹⁵¹
 S. Suzuki,⁶⁹ M. Svatos,¹²⁹ M. Swiatlowski,³³ S. P. Swift,² A. Sydorenko,⁸⁶ I. Sykora,^{146a} T. Sykora,¹³¹ D. Ta,⁸⁶
 K. Tackmann,⁴⁵ J. Taenzer,¹⁵⁵ A. Taffard,¹⁶⁶ R. Tafirout,^{163a} E. Tahirovic,⁷⁹ N. Taiblum,¹⁵⁵ H. Takai,²⁷ R. Takashima,⁷²
 E. H. Takasugi,¹⁰³ K. Takeda,⁷⁰ T. Takeshita,¹⁴² Y. Takubo,⁶⁹ M. Talby,⁸⁸ A. A. Talyshev,^{111,d} J. Tanaka,¹⁵⁷ M. Tanaka,¹⁵⁹
 R. Tanaka,¹¹⁹ R. Tanioka,⁷⁰ B. B. Tannenwald,¹¹³ S. Tapia Araya,^{34b} S. Tapprogge,⁸⁶ A. T. Tarek Abouelfadl Mohamed,⁸³
 S. Tarem,¹⁵⁴ G. Tarna,^{28b,q} G. F. Tartarelli,^{94a} P. Tas,¹³¹ M. Tasevsky,¹²⁹ T. Tashiro,⁷¹ E. Tassi,^{40a,40b}
 A. Tavares Delgado,^{128a,128b} Y. Tayalati,^{137e} A. C. Taylor,¹⁰⁷ A. J. Taylor,⁴⁹ G. N. Taylor,⁹¹ P. T. E. Taylor,⁹¹ W. Taylor,^{163b}
 P. Teixeira-Dias,⁸⁰ D. Temple,¹⁴⁴ H. Ten Kate,³² P. K. Teng,¹⁵³ J. J. Teoh,¹²⁰ F. Tepel,¹⁷⁷ S. Terada,⁶⁹ K. Terashi,¹⁵⁷
 J. Terron,⁸⁵ S. Terzo,¹³ M. Testa,⁵⁰ R. J. Teuscher,^{161,o} S. J. Thais,¹⁷⁹ T. Thevenaux-Pelzer,⁴⁵ F. Thiele,³⁹ J. P. Thomas,¹⁹
 P. D. Thompson,¹⁹ A. S. Thompson,⁵⁶ L. A. Thomsen,¹⁷⁹ E. Thomson,¹²⁴ Y. Tian,³⁸ R. E. Ticse Torres,⁵⁸
 V. O. Tikhomirov,^{98,ss} Yu. A. Tikhonov,^{111,d} S. Timoshenko,¹⁰⁰ P. Tipton,¹⁷⁹ S. Tisserant,⁸⁸ K. Todome,¹⁵⁹
 S. Todorova-Nova,⁵ S. Todt,⁴⁷ J. Tojo,⁷³ S. Tokár,^{146a} K. Tokushuku,⁶⁹ E. Tolley,¹¹³ M. Tomoto,¹⁰⁵ L. Tompkins,^{145,t}
 K. Toms,¹⁰⁷ B. Tong,⁵⁹ P. Tornambe,⁵¹ E. Torrence,¹¹⁸ H. Torres,⁴⁷ E. Torró Pastor,¹⁴⁰ J. Toth,^{88,uu} F. Touchard,⁸⁸
 D. R. Tovey,¹⁴¹ C. J. Treado,¹¹² T. Trefzger,¹⁷⁸ F. Tresoldi,¹⁵¹ A. Tricoli,²⁷ I. M. Trigger,^{163a} S. Trincas-Duvold,⁸³
 M. F. Tripijana,¹³ W. Trischuk,¹⁶¹ B. Trocmé,⁵⁷ A. Trofymov,⁴⁵ C. Troncon,^{94a} M. Trovatelli,¹⁷² L. Truong,^{147b}
 M. Trzebinski,⁴² A. Trzupek,⁴² K. W. Tsang,^{62a} J. C.-L. Tseng,¹²² P. V. Tsiarashka,⁹⁵ N. Tsirintanis,⁹ S. Tsiskaridze,¹³
 V. Tsiskaridze,¹⁵⁰ E. G. Tskhadadze,^{54a} I. I. Tsukerman,⁹⁹ V. Tsulaia,¹⁶ S. Tsuno,⁶⁹ D. Tsybychev,¹⁵⁰ Y. Tu,^{62b}
 A. Tudorache,^{28b} V. Tudorache,^{28b} T. T. Tulbure,^{28a} A. N. Tuna,⁵⁹ S. Turchikhin,⁶⁸ D. Turgeman,¹⁷⁵ I. Turk Cakir,^{4b,vv}
 R. Turra,^{94a} P. M. Tuts,³⁸ G. Uccielli,^{22a,22b} I. Ueda,⁶⁹ M. Ughetto,^{148a,148b} F. Ukegawa,¹⁶⁴ G. Unal,³² A. Undrus,²⁷
 G. Unel,¹⁶⁶ F. C. Ungaro,⁹¹ Y. Unno,⁶⁹ K. Uno,¹⁵⁷ J. Urban,^{146b} P. Urquijo,⁹¹ P. Urrejola,⁸⁶ G. Usai,⁸ J. Usui,⁶⁹ L. Vacavant,⁸⁸
 V. Vacek,¹³⁰ B. Vachon,⁹⁰ K. O. H. Vadla,¹²¹ A. Vaidya,⁸¹ C. Valderanis,¹⁰² E. Valdes Santurio,^{148a,148b} M. Valente,⁵²
 S. Valentinetti,^{22a,22b} A. Valero,¹⁷⁰ L. Valéry,⁴⁵ A. Vallier,⁵ J. A. Valls Ferrer,¹⁷⁰ W. Van Den Wollenberg,¹⁰⁹
 H. van der Graaf,¹⁰⁹ P. van Gemmeren,⁶ J. Van Nieuwkoop,¹⁴⁴ I. van Vulpen,¹⁰⁹ M. C. van Woerden,¹⁰⁹ M. Vanadia,^{135a,135b}
 W. Vandelli,³² A. Vaniachine,¹⁶⁰ P. Vankov,¹⁰⁹ R. Vari,^{134a} E. W. Varnes,⁷ C. Varni,^{53a,53b} T. Varol,⁴³ D. Varouchas,¹¹⁹
 A. Vartapetian,⁸ K. E. Varvell,¹⁵² J. G. Vasquez,¹⁷⁹ G. A. Vasquez,^{34b} F. Vazeille,³⁷ D. Vazquez Furelos,¹³
 T. Vazquez Schroeder,⁹⁰ J. Veatch,⁵⁸ L. M. Veloce,¹⁶¹ F. Veloso,^{128a,128c} S. Veneziano,^{134a} A. Ventura,^{76a,76b} M. Venturi,¹⁷²
 N. Venturi,³² V. Vercesi,^{123a} M. Verducci,^{136a,136b} W. Verkerke,¹⁰⁹ A. T. Vermeulen,¹⁰⁹ J. C. Vermeulen,¹⁰⁹ M. C. Vetterli,^{144,e}
 N. Viaux Maira,^{34b} O. Viazlo,⁸⁴ I. Vichou,^{169,a} T. Vickey,¹⁴¹ O. E. Vickey Boeriu,¹⁴¹ G. H. A. Viehhauser,¹²² S. Viel,¹⁶
 L. Vigani,¹²² M. Villa,^{22a,22b} M. Villaplana Perez,^{94a,94b} E. Vilucchi,⁵⁰ M. G. Vinciter,³¹ V. B. Vinogradov,⁶⁸
 A. Vishwakarma,⁴⁵ C. Vittori,^{22a,22b} I. Vivarelli,¹⁵¹ S. Vlachos,¹⁰ M. Vogel,¹⁷⁷ P. Vokac,¹³⁰ G. Volpi,¹³
 S. E. von Buddenbrock,^{147c} E. von Toerne,²³ V. Vorobel,¹³¹ K. Vorobev,¹⁰⁰ M. Vos,¹⁷⁰ J. H. Vosseveld,⁷⁷ N. Vranjes,¹⁴
 M. Vranjes Milosavljevic,¹⁴ V. Vrba,¹³⁰ M. Vreeswijk,¹⁰⁹ R. Vuillermet,³² I. Vukotic,³³ P. Wagner,²³ W. Wagner,¹⁷⁷
 J. Wagner-Kuhr,¹⁰² H. Wahlberg,⁷⁴ S. Wahrmund,⁴⁷ K. Wakamiya,⁷⁰ J. Walder,⁷⁵ R. Walker,¹⁰² W. Walkowiak,¹⁴³
 V. Wallangen,^{148a,148b} A. M. Wang,⁵⁹ C. Wang,^{36b,q} F. Wang,¹⁷⁶ H. Wang,¹⁶ H. Wang,³ J. Wang,^{60b} J. Wang,¹⁵² Q. Wang,¹¹⁵
 R.-J. Wang,⁸³ R. Wang,⁶ S. M. Wang,¹⁵³ T. Wang,³⁸ W. Wang,^{35b} W. Wang,^{36a,ww} Z. Wang,^{36c} C. Wanotayaroj,⁴⁵
 A. Warburton,⁹⁰ C. P. Ward,³⁰ D. R. Wardrope,⁸¹ A. Washbrook,⁴⁹ P. M. Watkins,¹⁹ A. T. Watson,¹⁹ M. F. Watson,¹⁹
 G. Watts,¹⁴⁰ S. Watts,⁸⁷ B. M. Waugh,⁸¹ A. F. Webb,¹¹ S. Webb,⁸⁶ M. S. Weber,¹⁸ S. M. Weber,^{60a} S. A. Weber,³¹
 J. S. Webster,⁶ A. R. Weidberg,¹²² B. Weinert,⁶⁴ J. Weingarten,⁵⁸ M. Weirich,⁸⁶ C. Weiser,⁵¹ P. S. Wells,³² T. Wenaus,²⁷
 T. Wengler,³² S. Wenig,³² N. Wermes,²³ M. D. Werner,⁶⁷ P. Werner,³² M. Wessels,^{60a} T. D. Weston,¹⁸ K. Whalen,¹¹⁸
 N. L. Whallon,¹⁴⁰ A. M. Wharton,⁷⁵ A. S. White,⁹² A. White,⁸ M. J. White,¹ R. White,^{34b} D. Whiteson,¹⁶⁶ B. W. Whitmore,⁷⁵
 F. J. Wickens,¹³³ W. Wiedenmann,¹⁷⁶ M. Wielers,¹³³ C. Wigglesworth,³⁹ L. A. M. Wiik-Fuchs,⁵¹ A. Wildauer,¹⁰³ F. Wilk,⁸⁷
 H. G. Wilkens,³² H. H. Williams,¹²⁴ S. Williams,³⁰ C. Willis,⁹³ S. Willocq,⁸⁹ J. A. Wilson,¹⁹ I. Wingerter-Seez,⁵
 E. Winkels,¹⁵¹ F. Winklmeier,¹¹⁸ O. J. Winston,¹⁵¹ B. T. Winter,²³ M. Wittgen,¹⁴⁵ M. Wobisch,^{82,v} A. Wolf,⁸⁶
 T. M. H. Wolf,¹⁰⁹ R. Wolff,⁸⁸ M. W. Wolter,⁴² H. Wolters,^{128a,128c} V. W. S. Wong,¹⁷¹ N. L. Woods,¹³⁹ S. D. Worm,¹⁹

B. K. Wosiek,⁴² K. W. Wozniak,⁴² M. Wu,³³ S. L. Wu,¹⁷⁶ X. Wu,⁵² Y. Wu,^{36a} T. R. Wyatt,⁸⁷ B. M. Wynne,⁴⁹ S. Xella,³⁹
 Z. Xi,⁹² L. Xia,^{35c} D. Xu,^{35a} H. Xu,^{36a} L. Xu,²⁷ T. Xu,¹³⁸ W. Xu,⁹² B. Yabsley,¹⁵² S. Yacoob,^{147a} K. Yajima,¹²⁰ D. P. Yallup,⁸¹
 D. Yamaguchi,¹⁵⁹ Y. Yamaguchi,¹⁵⁹ A. Yamamoto,⁶⁹ T. Yamanaka,¹⁵⁷ F. Yamane,⁷⁰ M. Yamatani,¹⁵⁷ T. Yamazaki,¹⁵⁷
 Y. Yamazaki,⁷⁰ Z. Yan,²⁴ H. Yang,^{36c,36d} H. Yang,¹⁶ S. Yang,⁶⁶ Y. Yang,¹⁵³ Y. Yang,¹⁵⁷ Z. Yang,¹⁵ W.-M. Yao,¹⁶ Y. C. Yap,⁴⁵
 Y. Yasu,⁶⁹ E. Yatsenko,⁵ K. H. Yau Wong,²³ J. Ye,⁴³ S. Ye,²⁷ I. Yeletsikh,⁶⁸ E. Yigitbasi,²⁴ E. Yildirim,⁸⁶ K. Yorita,¹⁷⁴
 K. Yoshihara,¹²⁴ C. Young,¹⁴⁵ C. J. S. Young,³² J. Yu,⁸ J. Yu,⁶⁷ S. P. Y. Yuen,²³ I. Yusuff,^{30,xx} B. Zabinski,⁴² G. Zacharis,¹⁰
 R. Zaidan,¹³ A. M. Zaitsev,^{132,II} N. Zakharchuk,⁴⁵ J. Zalieckas,¹⁵ S. Zambito,⁵⁹ D. Zanzi,³² C. Zeitnitz,¹⁷⁷ G. Zemaityte,¹²²
 J. C. Zeng,¹⁶⁹ Q. Zeng,¹⁴⁵ O. Zenin,¹³² T. Ženiš,^{146a} D. Zerwas,¹¹⁹ D. Zhang,^{36b} D. Zhang,⁹² F. Zhang,¹⁷⁶ G. Zhang,^{36a,ww}
 H. Zhang,¹¹⁹ J. Zhang,⁶ L. Zhang,⁵¹ L. Zhang,^{36a} M. Zhang,¹⁶⁹ P. Zhang,^{35b} R. Zhang,²³ R. Zhang,^{36a,q} X. Zhang,^{36b}
 Y. Zhang,^{35a,35d} Z. Zhang,¹¹⁹ X. Zhao,⁴³ Y. Zhao,^{36b,y} Z. Zhao,^{36a} A. Zhemchugov,⁶⁸ B. Zhou,⁹² C. Zhou,¹⁷⁶ L. Zhou,⁴³
 M. Zhou,^{35a,35d} M. Zhou,¹⁵⁰ N. Zhou,^{36c} Y. Zhou,⁷ C. G. Zhu,^{36b} H. Zhu,^{35a} J. Zhu,⁹² Y. Zhu,^{36a} X. Zhuang,^{35a} K. Zhukov,⁹⁸
 V. Zhulanov,^{111,yy} A. Zibell,¹⁷⁸ D. Zieminska,⁶⁴ N. I. Zimine,⁶⁸ S. Zimmermann,⁵¹ Z. Zinonos,¹⁰³ M. Zinser,⁸⁶
 M. Ziolkowski,¹⁴³ L. Živković,¹⁴ G. Zobernig,¹⁷⁶ A. Zoccoli,^{22a,22b} T. G. Zorbas,¹⁴¹ R. Zou,³³
 M. zur Nedden,¹⁷ and L. Zwalinski³²

(ATLAS Collaboration)

¹*Department of Physics, University of Adelaide, Adelaide, Australia*

²*Physics Department, SUNY Albany, Albany, New York, USA*

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

^{4a}*Department of Physics, Ankara University, Ankara, Turkey*

^{4b}*Istanbul Aydin University, Istanbul, Turkey*

^{4c}*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*

⁵*LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France*

⁶*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*

⁷*Department of Physics, University of Arizona, Tucson, Arizona, USA*

⁸*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*

⁹*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*

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

¹¹*Department of Physics, The University of Texas at Austin, Austin, Texas, USA*

¹²*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*

¹³*Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain*

¹⁴*Institute of Physics, University of Belgrade, Belgrade, Serbia*

¹⁵*Department for Physics and Technology, University of Bergen, Bergen, Norway*

¹⁶*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*

¹⁷*Department of Physics, Humboldt University, Berlin, Germany*

¹⁸*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*

¹⁹*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*

^{20a}*Department of Physics, Bogazici University, Istanbul, Turkey*

^{20b}*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*

^{20d}*Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*

^{20e}*Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*

²¹*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*

^{22a}*INFN Sezione di Bologna, Bologna, Italy*

^{22b}*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*

²³*Physikalisches Institut, University of Bonn, Bonn, Germany*

²⁴*Department of Physics, Boston University, Boston, Massachusetts, USA*

²⁵*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*

^{26a}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*

^{26b}*Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*

^{26c}*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*

^{26d}*Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil*

²⁷*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*

^{28a}*Transilvania University of Brasov, Brasov, Romania*

^{28b}*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*

- ^{28c}*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
- ^{28d}*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania*
- ^{28e}*University Politehnica Bucharest, Bucharest, Romania*
- ^{28f}*West University in Timisoara, Timisoara, Romania*
- ²⁹*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- ³⁰*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ³¹*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
- ³²*CERN, Geneva, Switzerland*
- ³³*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
- ^{34a}*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{34b}*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ^{35a}*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
- ^{35b}*Department of Physics, Nanjing University, Jiangsu, China*
- ^{35c}*Physics Department, Tsinghua University, Beijing, China*
- ^{35d}*University of Chinese Academy of Science (UCAS), Beijing, China*
- ^{36a}*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China*
- ^{36b}*School of Physics, Shandong University, Shandong, China*
- ^{36c}*School of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China*
- ^{36d}*Tsung-Dao Lee Institute, Shanghai, China*
- ³⁷*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
- ³⁸*Nevis Laboratory, Columbia University, Irvington, New York, USA*
- ³⁹*Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
- ^{40a}*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{40b}*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- ^{41a}*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
- ^{41b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- ⁴²*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- ⁴³*Physics Department, Southern Methodist University, Dallas, Texas, USA*
- ⁴⁴*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
- ⁴⁵*DESY, Hamburg and Zeuthen, Hamburg and Berlin, Germany*
- ⁴⁶*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁷*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁴⁸*Department of Physics, Duke University, Durham, North Carolina, USA*
- ⁴⁹*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵⁰*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵¹*Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*
- ⁵²*Département de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland*
- ^{53a}*INFN Sezione di Genova, Genova, Italy*
- ^{53b}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- ^{54a}*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
- ^{54b}*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- ⁵⁵*II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁶*SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁷*Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France*
- ⁵⁸*II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
- ⁵⁹*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- ^{60a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{60b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁶¹*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ^{62a}*Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
- ^{62b}*Department of Physics, The University of Hong Kong, Hong Kong, China*
- ^{62c}*Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶³*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶⁴*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- ⁶⁵*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- ⁶⁶*University of Iowa, Iowa City, Iowa, USA*

- ⁶⁷*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
- ⁶⁸*Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
- ⁶⁹*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- ⁷⁰*Graduate School of Science, Kobe University, Kobe, Japan*
- ⁷¹*Faculty of Science, Kyoto University, Kyoto, Japan*
- ⁷²*Kyoto University of Education, Kyoto, Japan*
- ⁷³*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- ⁷⁴*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- ⁷⁵*Physics Department, Lancaster University, Lancaster, United Kingdom*
- ^{76a}*INFN Sezione di Lecce, Lecce, Italy*
- ^{76b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ⁷⁷*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁷⁸*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- ⁷⁹*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- ⁸⁰*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
- ⁸¹*Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁸²*Louisiana Tech University, Ruston, Louisiana, USA*
- ⁸³*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
- ⁸⁴*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁸⁵*Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain*
- ⁸⁶*Institut für Physik, Universität Mainz, Mainz, Germany*
- ⁸⁷*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁸⁸*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
- ⁸⁹*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- ⁹⁰*Department of Physics, McGill University, Montreal, Québec, Canada*
- ⁹¹*School of Physics, University of Melbourne, Victoria, Australia*
- ⁹²*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
- ⁹³*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ^{94a}*INFN Sezione di Milano, Milano, Italy*
- ^{94b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ⁹⁵*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
- ⁹⁶*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus*
- ⁹⁷*Group of Particle Physics, University of Montreal, Montreal, Québec, Canada*
- ⁹⁸*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- ⁹⁹*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ¹⁰⁰*National Research Nuclear University MEPhI, Moscow, Russia*
- ¹⁰¹*D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- ¹⁰²*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ¹⁰³*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹⁰⁴*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹⁰⁵*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ^{106a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{106b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ¹⁰⁷*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹⁰⁸*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹⁰⁹*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹¹⁰*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ¹¹¹*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
- ¹¹²*Department of Physics, New York University, New York, New York, USA*
- ¹¹³*The Ohio State University, Columbus, Ohio, USA*
- ¹¹⁴*Faculty of Science, Okayama University, Okayama, Japan*
- ¹¹⁵*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹¹⁶*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹¹⁷*Palacký University, RCPTM, Olomouc, Czech Republic*
- ¹¹⁸*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹¹⁹*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- ¹²⁰*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹²¹*Department of Physics, University of Oslo, Oslo, Norway*
- ¹²²*Department of Physics, Oxford University, Oxford, United Kingdom*

- ^{123a}*INFN Sezione di Pavia, Pavia, Italy*
^{123b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
¹²⁴*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
¹²⁵*National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
^{126a}*INFN Sezione di Pisa, Pisa, Italy*
^{126b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
¹²⁷*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
^{128a}*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*
^{128b}*Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
^{128c}*Department of Physics, University of Coimbra, Coimbra, Portugal*
^{128d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
^{128e}*Departamento de Física, Universidade do Minho, Braga, Portugal*
^{128f}*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal*
^{128g}*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
¹²⁹*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
¹³⁰*Czech Technical University in Prague, Praha, Czech Republic*
¹³¹*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
¹³²*State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia*
¹³³*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
^{134a}*INFN Sezione di Roma, Roma, Italy*
^{134b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
^{135a}*INFN Sezione di Roma Tor Vergata, Roma, Italy*
^{135b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
^{136a}*INFN Sezione di Roma Tre, Roma, Italy*
^{136b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
^{137a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
^{137b}*Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
^{137c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
^{137d}*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
^{137e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
¹³⁸*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France*
¹³⁹*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
¹⁴⁰*Department of Physics, University of Washington, Seattle, Washington, USA*
¹⁴¹*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
¹⁴²*Department of Physics, Shinshu University, Nagano, Japan*
¹⁴³*Department Physik, Universität Siegen, Siegen, Germany*
¹⁴⁴*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
¹⁴⁵*SLAC National Accelerator Laboratory, Stanford, California, USA*
^{146a}*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
^{146b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
^{147a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
^{147b}*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
^{147c}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
^{148a}*Department of Physics, Stockholm University, Sweden*
^{148b}*The Oskar Klein Centre, Stockholm, Sweden*
¹⁴⁹*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
¹⁵⁰*Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA*
¹⁵¹*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
¹⁵²*School of Physics, University of Sydney, Sydney, Australia*
¹⁵³*Institute of Physics, Academia Sinica, Taipei, Taiwan*
¹⁵⁴*Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
¹⁵⁵*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
¹⁵⁶*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
¹⁵⁷*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
¹⁵⁸*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
¹⁵⁹*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
¹⁶⁰*Tomsk State University, Tomsk, Russia*
¹⁶¹*Department of Physics, University of Toronto, Toronto, Ontario, Canada*

- ^{162a}*INFN-TIFPA, Trento, Italy*
^{162b}*University of Trento, Trento, Italy*
^{163a}*TRIUMF, Vancouver, British Columbia, Canada*
^{163b}*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
¹⁶⁴*Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan*
¹⁶⁵*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
¹⁶⁶*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
^{167a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
^{167b}*ICTP, Trieste, Italy*
^{167c}*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
¹⁶⁸*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
¹⁶⁹*Department of Physics, University of Illinois, Urbana, Illinois, USA*
¹⁷⁰*Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Spain*
¹⁷¹*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
¹⁷²*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
¹⁷³*Department of Physics, University of Warwick, Coventry, United Kingdom*
¹⁷⁴*Waseda University, Tokyo, Japan*
¹⁷⁵*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
¹⁷⁶*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
¹⁷⁷*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
¹⁷⁸*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
¹⁷⁹*Department of Physics, Yale University, New Haven, Connecticut, USA*
¹⁸⁰*Yerevan Physics Institute, Yerevan, Armenia*
¹⁸¹*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
¹⁸²*Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan*

^aDeceased.

^bAlso at Department of Physics, King's College London, London, United Kingdom.

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

^dAlso at Novosibirsk State University, Novosibirsk, Russia.

^eAlso at TRIUMF, Vancouver, British Columbia, Canada.

^fAlso at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.

^gAlso at Physics Department, An-Najah National University, Nablus, Palestine.

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

ⁱAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.

^jAlso at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.

^kAlso at Departament de Fisica de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^lAlso at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^mAlso at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

ⁿAlso at Università di Napoli Parthenope, Napoli, Italy.

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

^pAlso at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

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

^rAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^sAlso at Borough of Manhattan Community College, City University of New York, New York City, NY, USA.

^tAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

^uAlso at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

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

^wAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

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

^yAlso at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

^zAlso at Graduate School of Science, Osaka University, Osaka, Japan.

^{aa}Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.

^{bb}Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

^{cc}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^{dd}Also at CERN, Geneva, Switzerland.

^{ee}Also at Georgian Technical University (GTU), Tbilisi, Georgia.

^{ff}Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

^{gg}Also at Manhattan College, New York, NY, USA.

^{hh}Also at Hellenic Open University, Patras, Greece.

ⁱⁱAlso at The City College of New York, New York, NY, USA.

^{jj}Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal.

^{kk}Also at Department of Physics, California State University, Sacramento, CA, USA.

^{ll}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^{mm}Also at Département de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.

ⁿⁿAlso at Department of Physics, The University of Texas at Austin, Austin, TX, USA.

^{oo}Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

^{pp}Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

^{qq}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

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

^{ss}Also at National Research Nuclear University MEPhI, Moscow, Russia.

^{tt}Also at Department of Physics, Stanford University, Stanford, CA, USA.

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

^{vv}Also at Giresun University, Faculty of Engineering, Turkey.

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

^{xx}Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

^{yy}Also at Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia.