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Aaboud, M.; Collaboration, ATLAS; Newman, Paul

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Probing the Quantum Interference between Singly and Doubly Resonant Top-Quark Production in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

M. Aaboud *et al.**
(ATLAS Collaboration)

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This Letter presents a normalized differential cross-section measurement in a fiducial phase-space region where interference effects between top-quark pair production and associated production of a single top quark with a W boson and a b -quark are significant. Events with exactly two leptons (ee , $\mu\mu$, or $e\mu$) and two b -tagged jets that satisfy a multiparticle invariant mass requirement are selected from 36.1 fb^{-1} of proton-proton collision data taken at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC in 2015 and 2016. The results are compared with predictions from simulations using various strategies for the interference. The standard prescriptions for interference modeling are significantly different from each other but are within 2σ of the data. State-of-the-art predictions that naturally incorporate interference effects provide the best description of the data in the measured region of phase space most sensitive to these effects. These results provide an important constraint on interference models and will guide future model development and tuning.

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Top-quark pair ($t\bar{t}$) production is one of the most widely studied processes at the Large Hadron Collider (LHC) and is a key background to many searches for physics beyond the standard model (BSM). The differential cross section for $t\bar{t}$ has been measured [1–5] and calculated [6–8] across a wide kinematic range with high accuracy. However, all of these results treat the decay of the top quark to a b -quark and W boson in the narrow-width approximation, separating $t\bar{t}$ production from production of a single top quark in association with a W boson and a b -quark (tWb). Because of their identical $WWb\bar{b}$ final states, processes with one or two timelike top-quark propagators (called singly and doubly resonant, respectively) interfere. Standard *ad hoc* methods of modeling this interference [9–12] are a significant source of uncertainty for many BSM searches [13–18]. Traditional measurements of production of a single top quark with an associated W boson (tW) are designed to be insensitive to such effects [19–21]. Recent fixed-order calculations of the full next-to-leading-order (NLO) $pp \rightarrow \ell^+\nu\ell^-\bar{b}b\bar{b}$ process [22–26] include proper treatment of the interference and have set the stage for corresponding predictions matched to a parton shower [27]. However, there are no measurements available to assess the modeling in a region sensitive to interference effects.

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

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This Letter presents a novel way to test different models of the interference between $t\bar{t}$ and tWb , using 36.1 fb^{-1} of proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector in 2015 and 2016. The measurement targets the dilepton final state, characterized by a pair of oppositely charged leptons (ee , $\mu\mu$, or $e\mu$) originating from W -boson decays [28], associated with jets containing b -hadrons (b -jets) and missing transverse momentum due to undetected neutrinos. The contributions from doubly and singly resonant amplitudes (and hence also their interference) to the combined cross section depend on the invariant mass of the bW pairs in the event, m_{bW} . In this analysis, the charged lepton is used as a proxy for the W boson and a differential cross section is measured as a function of the invariant mass of a b -jet and a lepton. There is ambiguity in forming this mass, so

$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

is used, where the b_i and ℓ_i represent the two b -jets and leptons, respectively. This choice is inspired by the minimax procedure used to construct the transverse mass [29,30] and measure the top mass [31]. At leading order, for doubly resonant events at parton level, $m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$, where m_t and m_W are the top-quark and W -boson masses, respectively. Because of suppression of the doubly resonant contribution, the differential cross section above this kinematic endpoint has increased sensitivity to interference effects.

ATLAS is a multipurpose particle detector designed with nearly full 4π coverage in a solid angle [32]. Lepton and jet reconstruction and identification used in this paper are

described in Ref. [33] and are briefly summarized in the following. Electrons and muons are required to have transverse momentum $p_T > 28$ GeV, pseudorapidity [34] η satisfying $|\eta| < 2.47$ (2.5) for electrons (muons), and meet a series of quality criteria [35,36], denoted “tight” in Ref. [33]. Jets are clustered from topologically connected calorimeter cells [37] using the anti- k_r jet algorithm [38] with radius parameter $R = 0.4$ implemented in FASTJET [39] and calibrated to particle level [40]. Jets are identified as originating from b -quarks with a multivariate classifier using observables sensitive to lifetimes, production mechanisms, and decay properties of b -hadrons [41]. The tagging efficiency is determined in simulated $t\bar{t}$ events to be 60% (85%) for the tight (loose) tagging criterion.

Samples of simulated data are used in the design of the measurement, estimation of the background, and the unfolding procedure. POWHEG-BOX [42] v1 and v2 were used to simulate tW and $t\bar{t}$ events, respectively, with PYTHIA 6.428 [43], the five-flavor scheme (5FS) CT10 [44] parton distribution function (PDF) set, and Perugia 2012 [45] collection of tuned parameters. An identical configuration except using PYTHIA 8.183 and POWHEG-BOX-v2 for tW was included for particle-level comparisons. Alternative samples used POWHEG-BOX-v2 or MADGRAPH5_aMC@NLO (MG5_aMC) 2.2.2 [46], each interfaced to Herwig++ 2.7.1 [47] with the UE-EE-5 set of tuned parameters [48] and CT10 PDF set. The $t\bar{t} + b\bar{b}$ process [49] was generated using SHERPA 2.1.1 [50] plus OPENLOOPS [51] with the CT10 four-flavor scheme PDF. The $V + \text{jets}$ and $VV + \text{jets}$ ($V = W, Z$) processes were generated with SHERPA 2.2.1 and the CT10 PDF set. Associated production of $t\bar{t}$ with a boson ($t\bar{t}V$) was generated using MG5_aMC 2.2.2 combined with PYTHIA 8.186 [52], the NNPDF2.3LO PDF set [53] and the A14 set of tuned parameters [54]. All predictions, including the $t\bar{t}$ and tW processes, are normalized to next-to-next-to-leading-order or next-to-leading-order cross sections [6,46,50,55,56]. All samples of simulated data were processed using the full ATLAS detector simulation [57] based on GEANT 4 [58].

The signal process is combined $t\bar{t} + tWb$ production [59]. A calculation of the $e^\pm \nu \mu^\mp \bar{\nu} b \bar{b}$ process in the four-flavor scheme at NLO was implemented in POWHEG-BOX-RES [27,60] with PYTHIA 8.226. Here, resonance-aware matching allows the inclusion of off-shell top-quark effects at NLO, and the interference term is included. Alternatively, predictions are obtained from the exclusive $t\bar{t}$ and tWb samples described above, where the definition of the tW process is chosen to enable combination with the corresponding $t\bar{t}$ calculation. This is nontrivial at NLO, where care must be taken to avoid double-counting tWb events with $m_{bW} \sim m_t$. The default scheme for combining the $t\bar{t}$ and tW processes at NLO adopted here is diagram removal (DR) [9] in which all doubly resonant amplitudes are removed from the tW sample. Other choices exist where

doubly resonant contributions are canceled out by gauge-invariant subtraction terms (diagram subtraction, DS) [9] or are only included in the interference terms (DR2) [10,12]. For a more detailed review of possible tW definitions, see Ref. [11]. Finally, all $t\bar{t}$ events with b -jets not associated with top-quark decays are classified as $t\bar{t} + \text{heavy flavor}$ ($t\bar{t} + \text{HF}$) and treated separately from the signal process.

Events are selected with single-lepton triggers [61] and required to have a pair of opposite-charge leptons ($e^\pm e^\mp$, $\mu^\pm \mu^\mp$, $e^\pm \mu^\mp$). Events with a same-flavor lepton pair having invariant mass $m_{\ell\ell} < 10$ GeV or within 15 GeV of the Z -boson mass are rejected to suppress contributions from low-mass resonances and $Z + \text{jets}$. Events are required to have exactly two jets with $p_T > 25$ GeV and $|\eta| < 2.5$ which satisfy the tight b -tagging criterion and no additional jets that pass the looser b -tagging requirement. This b -jet veto suppresses $t\bar{t} + \text{HF}$ events, which can have large $m_{b\ell}^{\text{minimax}}$ when a selected b -jet does not originate from a top-quark decay.

A combination of data-driven and simulation-based methods is used to estimate backgrounds to the $t\bar{t} + tWb$ signal process. The dominant background at high $m_{b\ell}^{\text{minimax}}$ is $t\bar{t} + \text{HF}$, where a b -jet from a top-quark decay is not identified. This contribution is estimated from data events with at least three jets that are b -tagged according to the tight criterion. Simulated data is used to extrapolate the $t\bar{t} + \text{HF}$ yield measured in this region to the two- b -tag signal selection, giving a prediction $1.49 \pm 0.05(\text{stat}) \pm 0.20(\text{syst})$ times larger than the prediction obtained using POWHEG+PYTHIA 6. This is consistent with the results of previous measurements, finding scale factors from 1.1 to 1.7 depending on the selection criteria [62–66]. Figure 1(a) shows the $m_{b\ell}^{\text{minimax}}$ distribution for events passing the three- b -tag selection, constructed from the two b -jets with largest p_T . The leading two b -jets are both found to originate from top decays in 60% of simulated $t\bar{t} + \text{HF}$ events when $m_{b\ell}^{\text{minimax}}$ is below 160 GeV and less than 10% when above. Good agreement between data and prediction across the distribution demonstrates that the additional jet from heavy flavor is well modeled. The next largest background is from $Z + \text{jets}$ production, which is estimated in an analogous manner from data events with same-flavor leptons satisfying an inverted $m_{\ell\ell}$ requirement. In both cases, the $t\bar{t}$ contribution is subtracted before estimating the scale factor. Various checks show that this does not bias the measurement in the signal region phase space. Finally, there is a small contribution from non-prompt and misidentified leptons arising from photon conversions, heavy-flavor hadrons decaying leptonically, and jets misidentified as leptons. Following Ref. [67], this background is estimated using events with same-charge lepton pairs, after subtracting the prompt lepton contribution. Minor contributions from $t\bar{t}V$ and $VV + \text{jets}$ are estimated using simulation. Uncertainties in the simulation-based extrapolations are described below. The $t\bar{t} + tWb$ signal

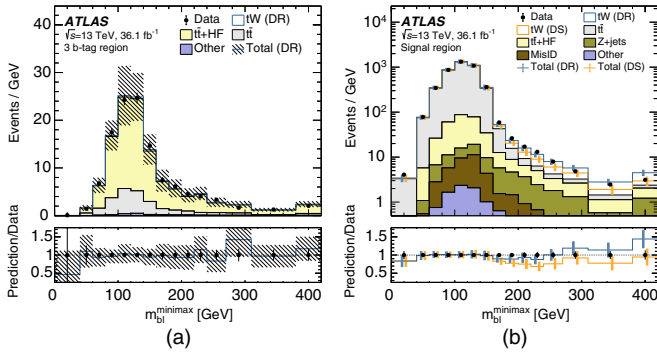


FIG. 1. (a) The $m_{b\ell}^{\text{minimax}}$ distribution in the three- b -tag region, constructed from the two b -jets with largest p_T . The predicted $t\bar{t} + \text{HF}$ contribution from simulation is scaled to match observed data in this region. The hashed band indicates the uncertainty on the total number of predicted events, where the DR scheme is used to estimate the minor contribution from the tW process. (b) The detector-level $m_{b\ell}^{\text{minimax}}$ distribution, with signal selection and background estimation as described in the text. The total predicted events are shown for both the DR and DS definitions of the tW process, with uncertainties on the respective estimates indicated by separate error bars. Uncertainties include all statistical and systematic sources. The rightmost bin of each distribution includes contributions from events beyond the displayed axis limit.

process accounts for 95% of events passing the full selection, with remaining background contributions subtracted from the data before unfolding the signal process to particle level. In Fig. 1(b), the data are compared to the predicted event yields for both the DR and DS schemes.

The unfolding procedure corrects detector-level [68] observables to particle level using a Bayesian method [69] with one iteration, optimized to minimize the average uncertainty per bin. The particle-level selection is defined to be as close as possible to the detector-level selection to minimize simulation-based corrections for acceptance effects and the detector resolution when unfolding. The definitions of particle-level objects are given in Ref. [70] with the following choices and modifications: (1) jets are clustered from all simulated particles with a mean lifetime $\tau > 30$ ps excluding muons and neutrinos to reduce model dependence, (2) jets are identified as b -jets if a b -hadron is found within the jet cone. Particle-level events must pass the same event selection as detector-level events, including the $m_{\ell\ell}$ requirement. To avoid contamination from $t\bar{t} + \text{HF}$ production, events with three or more particle-level b -jets with $p_T > 5$ GeV are rejected.

There are two categories of systematic uncertainties in the measurement: experimental and theoretical modeling. These affect the result via the background prediction that is subtracted from data or through the model used to unfold the data to particle level. Experimental uncertainties result from potential mismodeling in the reconstruction and identification of the jets [40], b -jets [71], and leptons

[35,36]. The background subtraction introduces uncertainty from the limited number of events in the control regions. A suite of simulation samples with alternative settings are used to assess the theoretical uncertainties in modeling the $t\bar{t}$, tW , $t\bar{t} + \text{HF}$, and $Z + \text{jets}$ processes [72,73]. A further uncertainty is assessed by varying the composition of the $t\bar{t} + tWb$ signal according to the uncertainty in the total cross sections of the singly and doubly resonant processes. An additional uncertainty is assessed for $t\bar{t} + \text{HF}$ by comparing the prediction obtained using POWHEG +PYTHIA 6 with that using the SHERPA $t\bar{t} + b\bar{b}$ sample. Furthermore, to ensure that the bias from the choice of interference scheme used in the unfolding is small, the procedure is repeated using the DS scheme. Finally, as another test of the unfolding, the particle-level $m_{b\ell}^{\text{minimax}}$ spectrum is reweighted to attain better agreement between the corresponding detector-level distribution and the data. Unfolding this reweighted distribution using the nominal unweighted simulation gives a measure of the method non-closure, which is assessed as an additional uncertainty [74]. The systematic uncertainty due to experimental sources ranges from 1% to 14%, with leading contributions from the jet energy scale and resolution and the b -tagging efficiency. Theoretical uncertainties associated with the modeling of processes with top quarks are generally the most important and range from 1% to 22% of the unfolded yields. The separate uncertainty due to the interference treatment is subdominant (22% in the largest bin of $m_{b\ell}^{\text{minimax}}$, elsewhere 1%–8%), and everywhere much smaller than the raw difference between the DR and DS scheme predictions. The size of the data set leads to statistical uncertainties of up to 20%.

Figure 2 presents the differential cross section observed in data, normalized to the total observed cross section with this selection. Various predictions are also shown, with uncertainties included from varying the PDF set [75] and the renormalization and factorization scales. A χ^2 test statistic is constructed for the various models to assess the level of agreement with the data. Correlations among uncertainties of the unfolded distribution are included, as well as theory uncertainties on the signal predictions. Results of the test are presented in Table I as p values, corresponding to the observed level of agreement over the full distribution as well as the subset $m_{b\ell}^{\text{minimax}} > 160$ GeV where the predicted differences due to interference are largest.

The tWb prediction using the DR scheme gives a better description of the relative normalization of the region $m_{b\ell}^{\text{minimax}} \gtrsim m_t$ than the DS scheme. However, the DS scheme better models the $m_{b\ell}^{\text{minimax}}$ shape over the same range of values. The DR and DS predictions generally bracket the data in the region of large $m_{b\ell}^{\text{minimax}}$, justifying the practice of applying their difference as a systematic uncertainty. The DR2 scheme describes the data well up to the top-quark mass, but significantly underpredicts the data

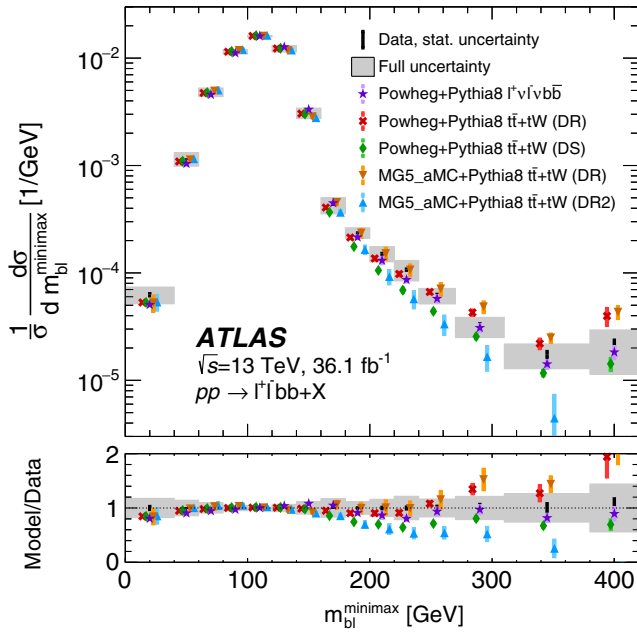


FIG. 2. The unfolded normalized differential $m_{b\ell}^{\text{minimax}}$ cross section compared with theoretical models of the $t\bar{t} + tWb$ signal with various implementations of interference effects. The uncertainty of each data point includes all statistical and systematic sources, while uncertainties for each of the MC predictions correspond to variations of the PDF set and renormalization and factorization scales. The rightmost bin of the distribution includes contributions from events beyond the displayed axis limit.

at higher masses [76]. The calculation from MG5_aMC using the DR scheme is presented alongside the corresponding DR2 calculation to directly compare the two interference treatments with other inputs held constant. The full $\ell^+\nu\ell^-\nu b\bar{b}$ prediction [77] obtained from POWHEG-BOX-RES models $m_{b\ell}^{\text{minimax}}$ well across the full distribution, including the region beyond the top-quark mass where predictions using traditional models of the interference diverge.

In summary, a measurement of a region sensitive to the interference between doubly and singly resonant top-quark pair production is presented. This is an original constraint on this interesting region of phase space that will be important for future model development and tuning.

TABLE I. p values comparing data and predictions from events simulated with various models of the interference, all interfaced to PYTHIA 8. Test statistics are constructed from the full $m_{b\ell}^{\text{minimax}}$ distribution and for the subset $m_{b\ell}^{\text{minimax}} > 160$ GeV.

Model	All bins	$m_{b\ell}^{\text{minimax}} > 160$ GeV
POWHEG-BOX $t\bar{t} + tW$ (DR)	0.71	0.40
POWHEG-BOX $t\bar{t} + tW$ (DS)	0.77	0.56
MG5_aMC $t\bar{t} + tW$ (DR)	0.14	0.17
MG5_aMC $t\bar{t} + tW$ (DR2)	0.02	0.08
POWHEG-BOX $\ell^+\nu\ell^-\nu b\bar{b}$	0.92	0.95

The results are presented as a normalized fiducial differential cross section, giving constraints on predictions for the full $t\bar{t} + tWb$ process.

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K. Bouaouda,^{34a} J. Boudreau,¹³⁵ E. V. Bouhova-Thacker,⁸⁷ D. Boumediene,³⁷ C. Bourdarios,¹²⁸ S. K. Boutle,⁵⁵
 A. Boveia,¹²² J. Boyd,³⁵ I. R. Boyko,⁷⁷ A. J. Bozson,⁹¹ J. Bracinik,²¹ N. Brahimi,⁹⁹ A. Brandt,⁸ G. Brandt,¹⁷⁹ O. Brandt,^{59a}
 F. Braren,⁴⁴ U. Bratzler,¹⁶¹ B. Brau,¹⁰⁰ J. E. Brau,¹²⁷ W. D. Breaden Madden,⁵⁵ K. Brendlinger,⁴⁴ A. J. Brennan,¹⁰²
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 D. Bruncko,^{28b} A. Bruni,^{23b} G. Bruni,^{23b} L. S. Bruni,¹¹⁸ S. Bruno,^{71a,71b} B. H. Brunt,³¹ M. Bruschi,^{23b} N. Brusino,¹³⁵
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 M. K. Bugge,¹³⁰ O. Bulekov,¹¹⁰ D. Bullock,⁸ T. J. Burch,¹¹⁹ S. Burdin,⁸⁸ C. D. Burgard,¹¹⁸ A. M. Burger,⁵ B. Burghgrave,¹¹⁹
 K. Burka,⁸² S. Burke,¹⁴¹ I. Burmeister,⁴⁵ J. T. P. Burr,¹³¹ D. Büscher,⁵⁰ V. Büscher,⁹⁷ E. Buschmann,⁵¹ P. Bussey,⁵⁵
 J. M. Butler,²⁵ C. M. Buttar,⁵⁵ J. M. Butterworth,⁹² P. Butti,³⁵ W. Buttinger,³⁵ A. Buzatu,¹⁵⁵ A. R. Buzykaev,^{120b,120a}
 G. Cabras,^{23b,23a} S. Cabrera Urbán,¹⁷¹ D. Caforio,¹³⁸ H. Cai,¹⁷⁰ V. M. M. Cairo,² O. Cakir,^{4a} N. Calace,⁵² P. Calafiura,¹⁸
 A. Calandri,⁹⁹ G. Calderini,¹³² P. Calfayan,⁶³ G. Callea,^{40b,40a} L. P. Caloba,^{78b} S. Calvente Lopez,⁹⁶ D. Calvet,³⁷ S. Calvet,³⁷
 T. P. Calvet,¹⁵² M. Calvetti,^{69a,69b} R. Camacho Toro,¹³² S. Camarda,³⁵ P. Camarri,^{71a,71b} D. Cameron,¹³⁰
 R. Caminal Armadans,¹⁰⁰ C. Camincher,³⁵ S. Campana,³⁵ M. Campanelli,⁹² A. Camplani,³⁹ A. Campoverde,¹⁴⁸
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 B. T. Carlson,¹³⁵ L. Carminati,^{66a,66b} R. M. D. Carney,^{43a,43b} S. Caron,¹¹⁷ E. Carquin,^{144b} S. Carrá,^{66a,66b}
 G. D. Carrillo-Montoya,³⁵ D. Casadei,^{32b} M. P. Casado,¹⁴ⁱ A. F. Casha,¹⁶⁴ M. Casolino,¹⁴ D. W. Casper,¹⁶⁸ R. Castelijin,¹¹⁸
 F. L. Castillo,¹⁷¹ V. Castillo Gimenez,¹⁷¹ N. F. Castro,^{136a,136e} A. Catinaccio,³⁵ J. R. Catmore,¹³⁰ A. Cattai,³⁵ J. Caudron,²⁴
 V. Cavaliere,²⁹ E. Cavallaro,¹⁴ D. Cavalli,^{66a} M. Cavalli-Sforza,¹⁴ V. Cavasinni,^{69a,69b} E. Celebi,^{12b} F. Ceradini,^{72a,72b}
 L. Cerda Alberich,¹⁷¹ A. S. Cerqueira,^{78a} A. Cerri,¹⁵³ L. Cerrito,^{71a,71b} F. Cerutti,¹⁸ A. Cervelli,^{23b,23a} S. A. Cetin,^{12b}
 A. Chafaq,^{34a} D. Chakraborty,¹¹⁹ S. K. Chan,⁵⁷ W. S. Chan,¹¹⁸ Y. L. Chan,^{61a} J. D. Chapman,³¹ D. G. Charlton,²¹
 C. C. Chau,³³ C. A. Chavez Barajas,¹⁵³ S. Che,¹²² A. Chegwidan,¹⁰⁴ S. Chekanov,⁶ S. V. Chekulaev,^{165a} G. A. Chelkov,^{77j}
 M. A. Chelstowska,³⁵ C. Chen,^{58a} C. H. Chen,⁷⁶ H. Chen,²⁹ J. Chen,^{58a} J. Chen,³⁸ S. Chen,¹³³ S. J. Chen,^{15c} X. Chen,^{15b,k}
 Y. Chen,⁸⁰ Y.-H. Chen,⁴⁴ H. C. Cheng,¹⁰³ H. J. Cheng,^{15d} A. Cheplakov,⁷⁷ E. Cheremushkina,¹⁴⁰ R. Cherkaoui El Moursli,^{34e}
 E. Cheu,⁷ K. Cheung,⁶² L. Chevalier,¹⁴² V. Chiarella,⁴⁹ G. Chiarelli,^{69a} G. Chiodini,^{65a} A. S. Chisholm,³⁵ A. Chitan,^{27b}
 I. Chiu,¹⁶⁰ Y. H. Chiu,¹⁷³ M. V. Chizhov,⁷⁷ K. Choi,⁶³ A. R. Chomont,¹²⁸ S. Chouridou,¹⁵⁹ Y. S. Chow,¹¹⁸
 V. Christodoulou,⁹² M. C. Chu,^{61a} J. Chudoba,¹³⁷ A. J. Chuinard,¹⁰¹ J. J. Chwastowski,⁸² L. Chytka,¹²⁶ D. Cinca,⁴⁵
 V. Cindro,⁸⁹ I. A. Cioară,²⁴ A. Ciocio,¹⁸ F. Ciroto,^{67a,67b} Z. H. Citron,¹⁷⁷ M. Citterio,^{66a} A. Clark,⁵² M. R. Clark,³⁸
 P. J. Clark,⁴⁸ C. Clement,^{43a,43b} Y. Coadou,⁹⁹ M. Cobal,^{64a,64c} A. Coccaro,^{53b,53a} J. Cochran,⁷⁶ A. E. C. Coimbra,¹⁷⁷
 L. Colasurdo,¹¹⁷ B. Cole,³⁸ A. P. Colijn,¹¹⁸ J. Collot,⁵⁶ P. Conde Muiño,^{136a,136b} E. Coniavitis,⁵⁰ S. H. Connell,^{32b}
 I. A. Connelly,⁹⁸ S. Constantinescu,^{27b} F. Conventi,^{67a,1} A. M. Cooper-Sarkar,¹³¹ F. Cormier,¹⁷² K. J. R. Cormier,¹⁶⁴
 M. Corradi,^{70a,70b} E. E. Corrigan,⁹⁴ F. Corriveau,^{101,m} A. Cortes-Gonzalez,³⁵ M. J. Costa,¹⁷¹ D. Costanzo,¹⁴⁶ G. Cottin,³¹
 G. Cowan,⁹¹ B. E. Cox,⁹⁸ J. Crane,⁹⁸ K. Cranmer,¹²¹ S. J. Crawley,⁵⁵ R. A. Creager,¹³³ G. Cree,³³ S. Crépe-Renaudin,⁵⁶
 F. Crescioli,¹³² M. Cristinziani,²⁴ V. Croft,¹²¹ G. Crosetti,^{40b,40a} A. Cueto,⁹⁶ T. Cuhadar Donszelmann,¹⁴⁶
 A. R. Cukierman,¹⁵⁰ J. Cúth,⁹⁷ S. Czekierda,⁸² P. Czodrowski,³⁵ M. J. Da Cunha Sargedas De Sousa,^{58b,136b} C. Da Via,⁹⁸
 W. Dabrowski,^{81a} T. Dado,^{28a,n} S. Dahbi,^{34e} T. Dai,¹⁰³ F. Dallaire,¹⁰⁷ C. Dallapiccola,¹⁰⁰ M. Dam,³⁹ G. D'amen,^{23b,23a}
 J. Damp,⁹⁷ J. R. Dandoy,¹³³ M. F. Daneri,³⁰ N. P. Dang,^{178,f} N. D. Dann,⁹⁸ M. Danninger,¹⁷² V. Dao,³⁵ G. Darbo,^{53b}
 S. Darmora,⁸ O. Dartsis,⁵ A. Dattagupta,¹²⁷ T. Daubney,⁴⁴ S. D'Auria,⁵⁵ W. Davey,²⁴ C. David,⁴⁴ T. Davidek,¹³⁹
 D. R. Davis,⁴⁷ E. Dawe,¹⁰² I. Dawson,¹⁴⁶ K. De,⁸ R. De Asmundis,^{67a} A. De Benedetti,¹²⁴ M. De Beurs,¹¹⁸
 S. De Castro,^{23b,23a} S. De Cecco,^{70a,70b} N. De Groot,¹¹⁷ P. de Jong,¹¹⁸ H. De la Torre,¹⁰⁴ F. De Lorenzi,⁷⁶ A. De Maria,^{51,o}
 D. De Pedis,^{70a} A. De Salvo,^{70a} U. De Sanctis,^{71a,71b} A. De Santo,¹⁵³ K. De Vasconcelos Corga,⁹⁹ J. B. De Vivie De Regie,¹²⁸
 C. Debenedetti,¹⁴³ D. V. Dedovich,⁷⁷ N. Dehghanian,³ M. Del Gaudio,^{40b,40a} J. Del Peso,⁹⁶ Y. Delabat Diaz,⁴⁴ D. Delgove,¹²⁸
 F. Deliot,¹⁴² C. M. Delitzsch,⁷ M. Della Pietra,^{67a,67b} D. Della Volpe,⁵² A. Dell'Acqua,³⁵ L. Dell'Asta,²⁵ M. Delmastro,⁵
 C. Delporte,¹²⁸ P. A. Delsart,⁵⁶ D. A. DeMarco,¹⁶⁴ S. Demers,¹⁸⁰ M. Demichev,⁷⁷ S. P. Denisov,¹⁴⁰ D. Denysiuk,¹¹⁸
 L. D'Eramo,¹³² D. Derendarz,⁸² J. E. Derkaoui,^{34d} F. Derue,¹³² P. Dervan,⁸⁸ K. Desch,²⁴ C. Deterre,⁴⁴ K. Dette,¹⁶⁴
 M. R. Devesa,³⁰ P. O. Deviveiros,³⁵ A. Dewhurst,¹⁴¹ S. Dhaliwal,²⁶ F. A. Di Bello,⁵² A. Di Ciaccio,^{71a,71b} L. Di Ciaccio,⁵
 W. K. Di Clemente,¹³³ C. Di Donato,^{67a,67b} A. Di Girolamo,³⁵ B. Di Micco,^{72a,72b} R. Di Nardo,¹⁰⁰ K. F. Di Petrillo,⁵⁷
 A. Di Simone,⁵⁰ R. Di Sipio,¹⁶⁴ D. Di Valentino,³³ C. Diaconu,⁹⁹ M. Diamond,¹⁶⁴ F. A. Dias,³⁹ T. Dias Do Vale,^{136a}

M. A. Diaz,^{144a} J. Dickinson,¹⁸ E. B. Diehl,¹⁰³ J. Dietrich,¹⁹ S. Díez Cornell,⁴⁴ A. Dimitrievska,¹⁸ J. Dingfelder,²⁴ F. Dittus,³⁵ F. Djama,⁹⁹ T. Djobava,^{156b} J. I. Djuvslund,^{59a} M. A. B. Do Vale,^{78c} M. Dobre,^{27b} D. Dodsworth,²⁶ C. Doglioni,⁹⁴ J. Dolejsi,¹³⁹ Z. Dolezal,¹³⁹ M. Donadelli,^{78d} J. Donini,³⁷ A. D'onofrio,⁹⁰ M. D'Onofrio,⁸⁸ J. Dopke,¹⁴¹ A. Doria,^{67a} M. T. Dova,⁸⁶ A. T. Doyle,⁵⁵ E. Drechsler,⁵¹ E. Dreyer,¹⁴⁹ T. Dreyer,⁵¹ Y. Du,^{58b} J. Duarte-Campderros,¹⁵⁸ F. Dubinin,¹⁰⁸ M. Dubovsky,^{28a} A. Dubreuil,⁵² E. Duchovni,¹⁷⁷ G. Duckeck,¹¹² A. Ducourthial,¹³² O. A. Ducu,^{107,p} D. Duda,¹¹³ A. Dudarev,³⁵ A. C. Dudder,⁹⁷ E. M. Duffield,¹⁸ L. Dufлот,¹²⁸ M. Dührssen,³⁵ C. Dülsen,¹⁷⁹ M. Dumancic,¹⁷⁷ A. E. Dumitriu,^{27b,q} A. K. Duncan,⁵⁵ M. Dunford,^{59a} A. Duperrin,⁹⁹ H. Duran Yildiz,^{4a} M. Düren,⁵⁴ A. Durglishvili,^{156b} D. Duschinger,⁴⁶ B. Dutta,⁴⁴ D. Duvnjak,¹ M. Dyndal,⁴⁴ S. Dysch,⁹⁸ B. S. Dziedzic,⁸² C. Eckardt,⁴⁴ K. M. Ecker,¹¹³ R. C. Edgar,¹⁰³ T. Eifert,³⁵ G. Eigen,¹⁷ K. Einsweiler,¹⁸ T. Ekelof,¹⁶⁹ M. El Kacimi,^{34c} R. El Kosseifi,⁹⁹ V. Ellajosyula,⁹⁹ M. Ellert,¹⁶⁹ F. Ellinghaus,¹⁷⁹ A. A. Elliot,⁹⁰ N. Ellis,³⁵ J. Elmsheuser,²⁹ M. Elsing,³⁵ D. Emelianov,¹⁴¹ Y. Enari,¹⁶⁰ J. S. Ennis,¹⁷⁵ M. B. Epland,⁴⁷ J. Erdmann,⁴⁵ A. Ereditato,²⁰ S. Errede,¹⁷⁰ M. Escalier,¹²⁸ C. Escobar,¹⁷¹ O. Estrada Pastor,¹⁷¹ A. I. Etievre,¹⁴² E. Etzion,¹⁵⁸ H. Evans,⁶³ A. Ezhilov,¹³⁴ M. Ezzi,^{34e} F. Fabbri,⁵⁵ L. Fabbri,^{23b,23a} V. Fabiani,¹¹⁷ G. Facini,⁹² R. M. Faisca Rodrigues Pereira,^{136a} R. M. Fakhruddinov,¹⁴⁰ S. Falciano,^{70a} P. J. Falke,⁵ S. Falke,⁵ J. Faltova,¹³⁹ Y. Fang,^{15a} M. Fanti,^{66a,66b} A. Farbin,⁸ A. Farilla,^{72a} E. M. Farina,^{68a,68b} T. Farooque,¹⁰⁴ S. Farrell,¹⁸ S. M. Farrington,¹⁷⁵ P. Farthouat,³⁵ F. Fassi,^{34e} P. Fassnacht,³⁵ D. Fassouliotis,⁹ M. Faucci Giannelli,⁴⁸ A. Favareto,^{53b,53a} W. J. Fawcett,⁵² L. Fayard,¹²⁸ O. L. Fedin,^{134,r} W. Fedorko,¹⁷² M. Feickert,⁴¹ S. Feigl,¹³⁰ L. Feligioni,⁹⁹ C. Feng,^{58b} E. J. Feng,³⁵ M. Feng,⁴⁷ M. J. Fenton,⁵⁵ A. B. Fenyuk,¹⁴⁰ L. Feremenga,⁸ J. Ferrando,⁴⁴ A. Ferrari,¹⁶⁹ P. Ferrari,¹¹⁸ R. Ferrari,^{68a} D. E. Ferreira de Lima,^{59b} A. Ferrer,¹⁷¹ D. Ferrere,⁵² C. Ferretti,¹⁰³ F. Fiedler,⁹⁷ A. Filipčič,⁸⁹ F. Filthaut,¹¹⁷ K. D. Finelli,²⁵ M. C. N. Fiolhais,^{136a,136c,s} L. Fiorini,¹⁷¹ C. Fischer,¹⁴ W. C. Fisher,¹⁰⁴ N. Flaschel,⁴⁴ I. Fleck,¹⁴⁸ P. Fleischmann,¹⁰³ R. R. M. Fletcher,¹³³ T. Flick,¹⁷⁹ B. M. Flierl,¹¹² L. M. Flores,¹³³ L. R. Flores Castillo,^{61a} N. Fomin,¹⁷ G. T. Forcolin,⁹⁸ A. Formica,¹⁴² F. A. Förster,¹⁴ A. C. Forti,⁹⁸ A. G. Foster,²¹ D. Fournier,¹²⁸ H. Fox,⁸⁷ S. Fracchia,¹⁴⁶ P. Francavilla,^{69a,69b} M. Franchini,^{23b,23a} S. Franchino,^{59a} D. Francis,³⁵ L. Franconi,¹³⁰ M. Franklin,⁵⁷ M. Frate,¹⁶⁸ M. Fraternali,^{68a,68b} D. Freeborn,⁹² S. M. Fressard-Batranceanu,³⁵ B. Freund,¹⁰⁷ W. S. Freund,^{78b} D. Froidevaux,³⁵ J. A. Frost,¹³¹ C. Fukunaga,¹⁶¹ E. Fullana Torregrosa,¹⁷¹ T. Fusayasu,¹¹⁴ J. Fuster,¹⁷¹ O. Gabizon,¹⁵⁷ A. Gabrielli,^{23b,23a} A. Gabrielli,¹⁸ G. P. Gach,^{81a} S. Gadatsch,⁵² P. Gadow,¹¹³ G. Gagliardi,^{53b,53a} L. G. Gagnon,¹⁰⁷ C. Galea,^{27b} B. Galhardo,^{136a,136c} E. J. Gallas,¹³¹ B. J. Gallop,¹⁴¹ P. Gallus,¹³⁸ G. Galster,³⁹ R. Gamboa Goni,⁹⁰ K. K. Gan,¹²² S. Ganguly,¹⁷⁷ Y. Gao,⁸⁸ Y. S. Gao,^{150,g} C. García,¹⁷¹ J. E. García Navarro,¹⁷¹ J. A. García Pascual,^{15a} M. Garcia-Sciveres,¹⁸ R. W. Gardner,³⁶ N. Garelli,¹⁵⁰ V. Garonne,¹³⁰ K. Gasnikova,⁴⁴ A. Gaudiello,^{53b,53a} G. Gaudio,^{68a} I. L. Gavrilenko,¹⁰⁸ A. Gavriluk,¹⁰⁹ C. Gay,¹⁷² G. Gaycken,²⁴ E. N. Gazis,¹⁰ C. N. P. Gee,¹⁴¹ J. Geisen,⁵¹ M. Geisen,⁹⁷ M. P. Geisler,^{59a} K. Gellerstedt,^{43a,43b} C. Gemme,^{53b} M. H. Genest,⁵⁶ C. Geng,¹⁰³ S. Gentile,^{70a,70b} C. Gentsos,¹⁵⁹ S. George,⁹¹ D. Gerbaudo,¹⁴ G. Gessner,⁴⁵ S. Ghasemi,¹⁴⁸ M. Ghasemi Bostanabad,¹⁷³ M. Ghneimat,²⁴ B. Giacobbe,^{23b} S. Giagu,^{70a,70b} N. Giangiacomi,^{23b,23a} P. Giannetti,^{69a} A. Giannini,^{67a,67b} S. M. Gibson,⁹¹ M. Gignac,¹⁴³ D. Gillberg,³³ G. Gilles,¹⁷⁹ D. M. Gingrich,^{3,e} M. P. Giordani,^{64a,64c} F. M. Giorgi,^{23b} P. F. Giraud,¹⁴² P. Giromini,⁵⁷ G. Giugliarelli,^{64a,64c} D. Giugni,^{66a} F. Giuli,¹³¹ M. Giulini,^{59b} S. Gkaitatzis,¹⁵⁹ I. Gkialas,^{9,t} E. L. Gkougkousis,¹⁴ P. Gkoutoumis,¹⁰ L. K. Gladilin,¹¹¹ C. Glasman,⁹⁶ J. Glatzer,¹⁴ P. C. F. Glaysher,⁴⁴ A. Glazov,⁴⁴ M. Goblirsch-Kolb,²⁶ J. Godlewski,⁸² S. Goldfarb,¹⁰² T. Golling,⁵² D. Golubkov,¹⁴⁰ A. Gomes,^{136a,136b,136d} R. Goncalves Gama,^{78a} R. Gonçalves,^{136a} G. Gonella,⁵⁰ L. Gonella,²¹ A. Gongadze,⁷⁷ F. Gonnella,²¹ J. L. Gonski,⁵⁷ S. González de la Hoz,¹⁷¹ S. Gonzalez-Sevilla,⁵² L. Goossens,³⁵ P. A. Gorbounov,¹⁰⁹ H. A. Gordon,²⁹ B. Gorini,³⁵ E. Gorini,^{65a,65b} A. Gorišek,⁸⁹ A. T. Goshaw,⁴⁷ C. Gössling,⁴⁵ M. I. Gostkin,⁷⁷ C. A. Gottardo,²⁴ C. R. Goudet,¹²⁸ D. Goujdami,^{34c} A. G. Goussiou,¹⁴⁵ N. Govender,^{32b,u} C. Goy,⁵ E. Gozani,¹⁵⁷ I. Grabowska-Bold,^{81a} P. O. J. Gradin,¹⁶⁹ E. C. Graham,⁸⁸ J. Gramling,¹⁶⁸ E. Gramstad,¹³⁰ S. Grancagnolo,¹⁹ V. Gratchev,¹³⁴ P. M. Gravila,^{27f} F. G. Gravili,^{65a,65b} C. Gray,⁵⁵ H. M. Gray,¹⁸ Z. D. Greenwood,^{93,v} C. Greife,²⁴ K. Gregersen,⁹² I. M. Gregor,⁴⁴ P. Grenier,¹⁵⁰ K. Grevtsov,⁴⁴ J. Griffiths,⁸ A. A. Grillo,¹⁴³ K. Grimm,¹⁵⁰ S. Grinstein,^{14,w} Ph. Gris,³⁷ J.-F. Grivaz,¹²⁸ S. Groh,⁹⁷ E. Gross,¹⁷⁷ J. Grosse-Knetter,⁵¹ G. C. Grossi,⁹³ Z. J. Grout,⁹² C. Grud,¹⁰³ A. Grummer,¹¹⁶ L. Guan,¹⁰³ W. Guan,¹⁷⁸ J. Guenther,³⁵ A. Guerguichon,¹²⁸ F. Guescini,^{165a} D. Guest,¹⁶⁸ R. Gugel,⁵⁰ B. Gui,¹²² T. Guillemin,⁵ S. Guindon,³⁵ U. Gul,⁵⁵ C. Gumpert,³⁵ J. Guo,^{58c} W. Guo,¹⁰³ Y. Guo,^{58a,x} Z. Guo,⁹⁹ R. Gupta,⁴¹ S. Gurbuz,^{12c} G. Gustavino,¹²⁴ B. J. Gutelman,¹⁵⁷ P. Gutierrez,¹²⁴ C. Gutsche,⁹² C. Guyot,¹⁴² M. P. Guzik,^{81a} C. Gwenlan,¹³¹ C. B. Gwilliam,⁸⁸ A. Haas,¹²¹ C. Haber,¹⁸ H. K. Hadavand,⁸ N. Haddad,^{34e} A. Hadeef,^{58a} S. Hageböck,²⁴ M. Hagihara,¹⁶⁶ H. Hakobyan,^{181,a} M. Haleem,¹⁷⁴ J. Haley,¹²⁵ G. Halladjian,¹⁰⁴ G. D. Hallewell,⁹⁹ K. Hamacher,¹⁷⁹ P. Hamal,¹²⁶ K. Hamano,¹⁷³ A. Hamilton,^{32a} G. N. Hamity,¹⁴⁶ K. Han,^{58a,y} L. Han,^{58a} S. Han,^{15d} K. Hanagaki,^{79,z} M. Hance,¹⁴³ D. M. Handl,¹¹² B. Haney,¹³³ R. Hankache,¹³² P. Hanke,^{59a} E. Hansen,⁹⁴

J. B. Hansen,³⁹ J. D. Hansen,³⁹ M. C. Hansen,²⁴ P. H. Hansen,³⁹ K. Hara,¹⁶⁶ A. S. Hard,¹⁷⁸ T. Harenberg,¹⁷⁹ S. Harkusha,¹⁰⁵
P. F. Harrison,¹⁷⁵ N. M. Hartmann,¹¹² Y. Hasegawa,¹⁴⁷ A. Hasib,⁴⁸ S. Hassani,¹⁴² S. Haug,²⁰ R. Hauser,¹⁰⁴ L. Hauswald,⁴⁶
L. B. Havener,³⁸ M. Havranek,¹³⁸ C. M. Hawkes,²¹ R. J. Hawkings,³⁵ D. Hayden,¹⁰⁴ C. Hayes,¹⁵² C. P. Hays,¹³¹
J. M. Hays,⁹⁰ H. S. Hayward,⁸⁸ S. J. Haywood,¹⁴¹ M. P. Heath,⁴⁸ V. Hedberg,⁹⁴ L. Heelan,⁸ S. Heer,²⁴ K. K. Heidegger,⁵⁰
J. Heilman,³³ S. Heim,⁴⁴ T. Heim,¹⁸ B. Heinemann,^{44,aa} J. J. Heinrich,¹¹² L. Heinrich,¹²¹ C. Heinz,⁵⁴ J. Hejbal,¹³⁷ L. Helary,³⁵
A. Held,¹⁷² S. Hellesund,¹³⁰ S. Hellman,^{43a,43b} C. Helsens,³⁵ R. C. W. Henderson,⁸⁷ Y. Heng,¹⁷⁸ S. Henkelmann,¹⁷²
A. M. Henriques Correia,³⁵ G. H. Herbert,¹⁹ H. Herde,²⁶ V. Herget,¹⁷⁴ Y. Hernández Jiménez,^{32c} H. Herr,⁹⁷
M. G. Herrmann,¹¹² G. Herten,⁵⁰ R. Hertenberger,¹¹² L. Hervas,³⁵ T. C. Herwig,¹³³ G. G. Hesketh,⁹² N. P. Hesse,^{165a}
J. W. Hetherly,⁴¹ S. Higashino,⁷⁹ E. Higón-Rodríguez,¹⁷¹ K. Hildebrand,³⁶ E. Hill,¹⁷³ J. C. Hill,³¹ K. K. Hill,²⁹ K. H. Hiller,⁴⁴
S. J. Hillier,²¹ M. Hils,⁴⁶ I. Hinchliffe,¹⁸ M. Hirose,¹²⁹ D. Hirschbuehl,¹⁷⁹ B. Hiti,⁸⁹ O. Hladik,¹³⁷ D. R. Hlaluku,^{32c}
X. Hoad,⁴⁸ J. Hobbs,¹⁵² N. Hod,^{165a} M. C. Hodgkinson,¹⁴⁶ A. Hoecker,³⁵ M. R. Hoferkamp,¹¹⁶ F. Hoenig,¹¹² D. Hohn,²⁴
D. Hohov,¹²⁸ T. R. Holmes,³⁶ M. Holzbock,¹¹² M. Homann,⁴⁵ S. Honda,¹⁶⁶ T. Honda,⁷⁹ T. M. Hong,¹³⁵ A. Hönle,¹¹³
B. H. Hooberman,¹⁷⁰ W. H. Hopkins,¹²⁷ Y. Horii,¹¹⁵ P. Horn,⁴⁶ A. J. Horton,¹⁴⁹ L. A. Horyn,³⁶ J.-Y. Hostachy,⁵⁶
A. Hostiuc,¹⁴⁵ S. Hou,¹⁵⁵ A. Hoummada,^{34a} J. Howarth,⁹⁸ J. Hoya,⁸⁶ M. Hrabovsky,¹²⁶ J. Hrdinka,³⁵ I. Hristova,¹⁹
J. Hrivnac,¹²⁸ A. Hrynevich,¹⁰⁶ T. Hryn'ova,⁵ P. J. Hsu,⁶² S.-C. Hsu,¹⁴⁵ Q. Hu,²⁹ S. Hu,^{58c} Y. Huang,^{15a} Z. Hubacek,¹³⁸
F. Hubaut,⁹⁹ M. Huebner,²⁴ F. Huegging,²⁴ T. B. Huffman,¹³¹ E. W. Hughes,³⁸ M. Huhtinen,³⁵ R. F. H. Hunter,³³ P. Huo,¹⁵²
A. M. Hupe,³³ N. Huseynov,^{77,d} J. Huston,¹⁰⁴ J. Huth,⁵⁷ R. Hyneman,¹⁰³ G. Iacobucci,⁵² G. Iakovidis,²⁹ I. Ibragimov,¹⁴⁸
L. Iconomidou-Fayard,¹²⁸ Z. Idrissi,^{34e} P. Iengo,³⁵ R. Ignazzi,³⁹ O. Igonkina,^{118,bb} R. Iguchi,¹⁶⁰ T. Iizawa,⁵² Y. Ikegami,⁷⁹
M. Ikeno,⁷⁹ D. Iliadis,¹⁵⁹ N. Ilic,¹⁵⁰ F. Iltzsche,⁴⁶ G. Introzzi,^{68a,68b} M. Iodice,^{72a} K. Iordanidou,³⁸ V. Ippolito,^{70a,70b}
M. F. Isacson,¹⁶⁹ N. Ishijima,¹²⁹ M. Ishino,¹⁶⁰ M. Ishitsuka,¹⁶² W. Islam,¹²⁵ C. Issever,¹³¹ S. Istin,^{12c,cc} F. Ito,¹⁶⁶
J. M. Iturbe Ponce,^{61a} R. Iuppa,^{73a,73b} A. Ivina,¹⁷⁷ H. Iwasaki,⁷⁹ J. M. Izen,⁴² V. Izzo,^{67a} S. Jabbar,³ P. Jacka,¹³⁷ P. Jackson,¹
R. M. Jacobs,²⁴ V. Jain,² G. Jäkel,¹⁷⁹ K. B. Jakobi,⁹⁷ K. Jakobs,⁵⁰ S. Jakobsen,⁷⁴ T. Jakoubek,¹³⁷ D. O. Jamin,¹²⁵
D. K. Jana,⁹³ R. Jansky,⁵² J. Janssen,²⁴ M. Janus,⁵¹ P. A. Janus,^{81a} G. Jarlskog,⁹⁴ N. Javadov,^{77,d} T. Javůrek,⁵⁰
M. Javurkova,⁵⁰ F. Jeanneau,¹⁴² L. Jeanty,¹⁸ J. Jejelava,^{156a,dd} A. Jelinskas,¹⁷⁵ P. Jenni,^{50,ee} J. Jeong,⁴⁴ S. Jézéquel,⁵ H. Ji,¹⁷⁸
J. Jia,¹⁵² H. Jiang,⁷⁶ Y. Jiang,^{58a} Z. Jiang,^{150,ff} S. Jiggins,⁵⁰ F. A. Jimenez Morales,³⁷ J. Jimenez Pena,¹⁷¹ S. Jin,^{15c}
A. Jinaru,^{27b} O. Jinnouchi,¹⁶² H. Jivan,^{32c} P. Johansson,¹⁴⁶ K. A. Johns,⁷ C. A. Johnson,⁶³ W. J. Johnson,¹⁴⁵
K. Jon-And,^{43a,43b} R. W. L. Jones,⁸⁷ S. D. Jones,¹⁵³ S. Jones,⁷ T. J. Jones,⁸⁸ J. Jongmanns,^{59a} P. M. Jorge,^{136a,136b}
J. Jovicevic,^{165a} X. Ju,¹⁷⁸ J. J. Jungeburth,¹¹³ A. Juste Rozas,^{14,w} A. Kaczmarska,⁸² M. Kado,¹²⁸ H. Kagan,¹²² M. Kagan,¹⁵⁰
T. Kaji,¹⁷⁶ E. Kajomovitz,¹⁵⁷ C. W. Kalderon,⁹⁴ A. Kaluza,⁹⁷ S. Kama,⁴¹ A. Kamenshchikov,¹⁴⁰ L. Kanjir,⁸⁹ Y. Kano,¹⁶⁰
V. A. Kantserov,¹¹⁰ J. Kanzaki,⁷⁹ B. Kaplan,¹²¹ L. S. Kaplan,¹⁷⁸ D. Kar,^{32c} M. J. Kareem,^{165b} E. Karentzos,¹⁰ S. N. Karpov,⁷⁷
Z. M. Karpova,⁷⁷ V. Kartvelishvili,⁸⁷ A. N. Karyukhin,¹⁴⁰ K. Kasahara,¹⁶⁶ L. Kashif,¹⁷⁸ R. D. Kass,¹²² A. Kastanas,¹⁵¹
Y. Kataoka,¹⁶⁰ C. Kato,¹⁶⁰ J. Katzy,⁴⁴ K. Kawade,⁸⁰ K. Kawagoe,⁸⁵ T. Kawamoto,¹⁶⁰ G. Kawamura,⁵¹ E. F. Kay,⁸⁸
V. F. Kazanin,^{120b,120a} R. Keeler,¹⁷³ R. Kehoe,⁴¹ J. S. Keller,³³ E. Kellermann,⁹⁴ J. J. Kempster,²¹ J. Kendrick,²¹ O. Kepka,¹³⁷
S. Kersten,¹⁷⁹ B. P. Kerševan,⁸⁹ R. A. Keyes,¹⁰¹ M. Khader,¹⁷⁰ F. Khalil-Zada,¹³ A. Khanov,¹²⁵ A. G. Kharlamov,^{120b,120a}
T. Kharlamova,^{120b,120a} A. Khodinov,¹⁶³ T. J. Khoo,⁵² E. Khramov,⁷⁷ J. Khubua,^{156b} S. Kido,⁸⁰ M. Kiehn,⁵² C. R. Kilby,⁹¹
S. H. Kim,¹⁶⁶ Y. K. Kim,³⁶ N. Kimura,^{64a,64c} O. M. Kind,¹⁹ B. T. King,⁸⁸ D. Kirchmeier,⁴⁶ J. Kirk,¹⁴¹ A. E. Kiryunin,¹¹³
T. Kishimoto,¹⁶⁰ D. Kisieleska,^{81a} V. Kitali,⁴⁴ O. Kivernyk,⁵ E. Kladiva,^{28b} T. Klapdor-Kleingrothaus,⁵⁰ M. H. Klein,¹⁰³
M. Klein,⁸⁸ U. Klein,⁸⁸ K. Kleinknecht,⁹⁷ P. Klimek,¹¹⁹ A. Klimentov,²⁹ R. Klingenberg,^{45,a} T. Klingl,²⁴
T. Klioutchnikova,³⁵ F. F. Klitzner,¹¹² P. Kluit,¹¹⁸ S. Kluth,¹¹³ E. Kneringer,⁷⁴ E. B. F. G. Knoops,⁹⁹ A. Knue,⁵⁰
A. Kobayashi,¹⁶⁰ D. Kobayashi,⁸⁵ T. Kobayashi,¹⁶⁰ M. Kobel,⁴⁶ M. Kocian,¹⁵⁰ P. Kodys,¹³⁹ T. Koffas,³³ E. Koffeman,¹¹⁸
N. M. Köhler,¹¹³ T. Koi,¹⁵⁰ M. Kolb,^{59b} I. Koletsou,⁵ T. Kondo,⁷⁹ N. Kondrashova,^{58c} K. Köneke,⁵⁰ A. C. König,¹¹⁷
T. Kono,⁷⁹ R. Konoplich,^{121,gg} V. Konstantinides,⁹² N. Konstantinidis,⁹² B. Konya,⁹⁴ R. Kopeliansky,⁶³ S. Koperny,^{81a}
K. Korcyl,⁸² K. Kordas,¹⁵⁹ A. Korn,⁹² I. Korolkov,¹⁴ E. V. Korolkova,¹⁴⁶ O. Kortner,¹¹³ S. Kortner,¹¹³ T. Kosek,¹³⁹
V. V. Kostyukhin,²⁴ A. Kotwal,⁴⁷ A. Koulouris,¹⁰ A. Kourkoumeli-Charalampidi,^{68a,68b} C. Kourkoumelis,⁹ E. Kourlitis,¹⁴⁶
V. Kouskoura,²⁹ A. B. Kowalewska,⁸² R. Kowalewski,¹⁷³ T. Z. Kowalski,^{81a} C. Kozakai,¹⁶⁰ W. Kozanecki,¹⁴²
A. S. Kozhin,¹⁴⁰ V. A. Kramarenko,¹¹¹ G. Kramberger,⁸⁹ D. Krasnopevtsev,¹¹⁰ M. W. Krasny,¹³² A. Krasznahorkay,³⁵
D. Krauss,¹¹³ J. A. Kremer,^{81a} J. Kretschmar,⁸⁸ P. Krieger,¹⁶⁴ K. Krizka,¹⁸ K. Kroeninger,⁴⁵ H. Kroha,¹¹³ J. Kroll,¹³⁷
J. Kroll,¹³³ J. Krstic,¹⁶ U. Kruchonak,⁷⁷ H. Krüger,²⁴ N. Krumnack,⁷⁶ M. C. Kruse,⁴⁷ T. Kubota,¹⁰² S. Kuday,^{4b}
J. T. Kuechler,¹⁷⁹ S. Kuehn,³⁵ A. Kugel,^{59a} F. Kuger,¹⁷⁴ T. Kuhl,⁴⁴ V. Kukhtin,⁷⁷ R. Kukla,⁹⁹ Y. Kulchitsky,¹⁰⁵

S. Kuleshov,^{144b} Y. P. Kulinich,¹⁷⁰ M. Kuna,⁵⁶ T. Kunigo,⁸³ A. Kupco,¹³⁷ T. Kupfer,⁴⁵ O. Kuprash,¹⁵⁸ H. Kurashige,⁸⁰
 L. L. Kurchaninov,^{165a} Y. A. Kurochkin,¹⁰⁵ M. G. Kurth,^{15d} E. S. Kuwertz,¹⁷³ M. Kuze,¹⁶² J. Kvita,¹²⁶ T. Kwan,¹⁰¹
 A. La Rosa,¹¹³ J. L. La Rosa Navarro,^{78d} L. La Rotonda,^{40b,40a} F. La Ruffa,^{40b,40a} C. Lacasta,¹⁷¹ F. Lacava,^{70a,70b} J. Lacey,⁴⁴
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 R. J. Langenberg,³⁵ A. J. Lankford,¹⁶⁸ F. Lanni,²⁹ K. Lantzsich,²⁴ A. Lanza,^{68a} A. Lapertosa,^{53b,53a} S. Laplace,¹³²
 J. F. Laporte,¹⁴² T. Lari,^{66a} F. Lasagni Manghi,^{23b,23a} M. Lassnig,³⁵ T. S. Lau,^{61a} A. Laudrain,¹²⁸ M. Lavorgna,^{67a,67b}
 A. T. Law,¹⁴³ P. Laycock,⁸⁸ M. Lazzaroni,^{66a,66b} B. Le,¹⁰² O. Le Dortz,¹³² E. Le Guirriec,⁹⁹ E. P. Le Quilleuc,¹⁴² M. LeBlanc,⁷
 T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁶ C. A. Lee,²⁹ G. R. Lee,^{144a} L. Lee,⁵⁷ S. C. Lee,¹⁵⁵ B. Lefebvre,¹⁰¹ M. Lefebvre,¹⁷³
 F. Legger,¹¹² C. Leggett,¹⁸ N. Lehmann,¹⁷⁹ G. Lehmann Miotto,³⁵ W. A. Leight,⁴⁴ A. Leisos,^{159,hh} M. A. L. Leite,^{78d}
 R. Leitner,¹³⁹ D. Lellouch,¹⁷⁷ B. Lemmer,⁵¹ K. J. C. Leney,⁹² T. Lenz,²⁴ B. Lenzi,³⁵ R. Leone,⁷ S. Leone,^{69a}
 C. Leonidopoulos,⁴⁸ G. Lerner,¹⁵³ C. Leroy,¹⁰⁷ R. Les,¹⁶⁴ A. A. J. Lesage,¹⁴² C. G. Lester,³¹ M. Levchenko,¹³⁴ J. Levêque,⁵
 D. Levin,¹⁰³ L. J. Levinson,¹⁷⁷ D. Lewis,⁹⁰ B. Li,¹⁰³ C-Q. Li,^{58a} H. Li,^{58b} L. Li,^{58c} Q. Li,^{15d} Q. Y. Li,^{58a} S. Li,^{58d,58c} X. Li,^{58c}
 Y. Li,¹⁴⁸ Z. Liang,^{15a} B. Liberti,^{71a} A. Liblong,¹⁶⁴ K. Lie,^{61c} S. Liem,¹¹⁸ A. Limosani,¹⁵⁴ C. Y. Lin,³¹ K. Lin,¹⁰⁴ T. H. Lin,⁹⁷
 R. A. Linck,⁶³ B. E. Lindquist,¹⁵² A. L. Lioni,⁵² E. Lipeles,¹³³ A. Lipniacka,¹⁷ M. Lisovyi,^{59b} T. M. Liss,^{170,ii} A. Lister,¹⁷²
 A. M. Litke,¹⁴³ J. D. Little,⁸ B. Liu,⁷⁶ B. L. Liu,⁶ H. B. Liu,²⁹ H. Liu,¹⁰³ J. B. Liu,^{58a} J. K. K. Liu,¹³¹ K. Liu,¹³² M. Liu,^{58a}
 P. Liu,¹⁸ Y. Liu,^{15a} Y. L. Liu,^{58a} Y. W. Liu,^{58a} M. Livan,^{68a,68b} A. Lleres,⁵⁶ J. Llorente Merino,^{15a} S. L. Lloyd,⁹⁰ C. Y. Lo,^{61b}
 F. Lo Sterzo,⁴¹ E. M. Lobodzinska,⁴⁴ P. Loch,⁷ A. Loesle,⁵⁰ K. M. Loew,²⁶ T. Lohse,¹⁹ K. Lohwasser,¹⁴⁶ M. Lokajicek,¹³⁷
 B. A. Long,²⁵ J. D. Long,¹⁷⁰ R. E. Long,⁸⁷ L. Longo,^{65a,65b} K. A.Looper,¹²² J. A. Lopez,^{144b} I. Lopez Paz,¹⁴
 A. Lopez Solis,¹⁴⁶ J. Lorenz,¹¹² N. Lorenzo Martinez,⁵ M. Losada,²² P. J. Lösel,¹¹² X. Lou,⁴⁴ X. Lou,^{15a} A. Lounis,¹²⁸
 J. Love,⁶ P. A. Love,⁸⁷ J. J. Lozano Bahilo,¹⁷¹ H. Lu,^{61a} M. Lu,^{58a} N. Lu,¹⁰³ Y. J. Lu,⁶² H. J. Lubatti,¹⁴⁵ C. Luci,^{70a,70b}
 A. Lucotte,⁵⁶ C. Luedtke,⁵⁰ F. Luehring,⁶³ I. Luise,¹³² W. Lukas,⁷⁴ L. Luminari,^{70a} B. Lund-Jensen,¹⁵¹ M. S. Lutz,¹⁰⁰
 P. M. Luzi,¹³² D. Lynn,²⁹ R. Lysak,¹³⁷ E. Lytken,⁹⁴ F. Lyu,^{15a} V. Lyubushkin,⁷⁷ H. Ma,²⁹ L. L. Ma,^{58b} Y. Ma,^{58b}
 G. Maccarrone,⁴⁹ A. Macchiolo,¹¹³ C. M. Macdonald,¹⁴⁶ J. Machado Miguens,^{133,136b} D. Madaffari,¹⁷¹ R. Madar,³⁷
 W. F. Mader,⁴⁶ A. Madsen,⁴⁴ N. Madysa,⁴⁶ J. Maeda,⁸⁰ K. Maekawa,¹⁶⁰ S. Maeland,¹⁷ T. Maeno,²⁹ A. S. Maevskiy,¹¹¹
 V. Magerl,⁵⁰ C. Maidantchik,^{78b} T. Maier,¹¹² A. Maio,^{136a,136b,136d} O. Majersky,^{28a} S. Majewski,¹²⁷ Y. Makida,⁷⁹
 N. Makovec,¹²⁸ B. Malaescu,¹³² Pa. Malecki,⁸² V. P. Maleev,¹³⁴ F. Malek,⁵⁶ U. Mallik,⁷⁵ D. Malon,⁶ C. Malone,³¹
 S. Maltezos,¹⁰ S. Malyukov,³⁵ J. Mamuzic,¹⁷¹ G. Mancini,⁴⁹ I. Mandić,⁸⁹ J. Maneira,^{136a} L. Manhaes de Andrade Filho,^{78a}
 J. Manjarres Ramos,⁴⁶ K. H. Mankinen,⁹⁴ A. Mann,¹¹² A. Manousos,⁷⁴ B. Mansoulie,¹⁴² J. D. Mansour,^{15a} M. Mantoani,⁵¹
 S. Manzoni,^{66a,66b} G. Marceca,³⁰ L. March,⁵² L. Marchese,¹³¹ G. Marchiori,¹³² M. Marcisovsky,¹³⁷ C. A. Marin Tobon,³⁵
 M. Marjanovic,³⁷ D. E. Marley,¹⁰³ F. Marroquim,^{78b} Z. Marshall,¹⁸ M. U. F. Martensson,¹⁶⁹ S. Marti-Garcia,¹⁷¹
 C. B. Martin,¹²² T. A. Martin,¹⁷⁵ V. J. Martin,⁴⁸ B. Martin dit Latour,¹⁷ M. Martinez,^{14,w} V. I. Martinez Outschoorn,¹⁰⁰
 S. Martin-Haugh,¹⁴¹ V. S. Martoiu,^{27b} A. C. Martyniuk,⁹² A. Marzin,³⁵ L. Masetti,⁹⁷ T. Mashimo,¹⁶⁰ R. Mashinistov,¹⁰⁸
 J. Masik,⁹⁸ A. L. Maslennikov,^{120b,120a} L. H. Mason,¹⁰² L. Massa,^{71a,71b} P. Mastrandrea,⁵ A. Mastroberardino,^{40b,40a}
 T. Masubuchi,¹⁶⁰ P. Mättig,¹⁷⁹ J. Maurer,^{27b} B. Maček,⁸⁹ S. J. Maxfield,⁸⁸ D. A. Maximov,^{120b,120a} R. Mazini,¹⁵⁵ I. Maznas,¹⁵⁹
 S. M. Mazza,¹⁴³ N. C. Mc Fadden,¹¹⁶ G. Mc Goldrick,¹⁶⁴ S. P. Mc Kee,¹⁰³ A. McCam,¹⁰³ T. G. McCarthy,¹¹³
 L. I. McClymont,⁹² E. F. McDonald,¹⁰² J. A. Mcfayden,³⁵ G. Mchedlidze,⁵¹ M. A. McKay,⁴¹ K. D. McLean,¹⁷³
 S. J. McMahon,¹⁴¹ P. C. McNamara,¹⁰² C. J. McNicol,¹⁷⁵ R. A. McPherson,^{173,m} J. E. Mdhluhi,^{32c} Z. A. Meadows,¹⁰⁰
 S. Meehan,¹⁴⁵ T. M. Megy,⁵⁰ S. Mehlhase,¹¹² A. Mehta,⁸⁸ T. Meideck,⁵⁶ B. Meirose,⁴² D. Melini,^{171,ji}
 B. R. Mellado Garcia,^{32c} J. D. Mellenthin,⁵¹ M. Melo,^{28a} F. Meloni,⁴⁴ A. Melzer,²⁴ S. B. Menary,⁹⁸
 E. D. Mendes Gouveia,^{136a} L. Meng,⁸⁸ X. T. Meng,¹⁰³ A. Mengarelli,^{23b,23a} S. Menke,¹¹³ E. Meoni,^{40b,40a} S. Mergelmeyer,¹⁹
 C. Merlassino,²⁰ P. Mermod,⁵² L. Merola,^{67a,67b} C. Meroni,^{66a} F. S. Merritt,³⁶ A. Messina,^{70a,70b} J. Metcalfe,⁶ A. S. Mete,¹⁶⁸
 C. Meyer,¹³³ J. Meyer,¹⁵⁷ J-P. Meyer,¹⁴² H. Meyer Zu Theenhausen,^{59a} F. Miano,¹⁵³ R. P. Middleton,¹⁴¹ L. Mijović,⁴⁸
 G. Mikenberg,¹⁷⁷ M. Mikestikova,¹³⁷ M. Mikuž,⁸⁹ M. Milesi,¹⁰² A. Milic,¹⁶⁴ D. A. Millar,⁹⁰ D. W. Miller,³⁶ A. Milov,¹⁷⁷
 D. A. Milstead,^{43a,43b} A. A. Minaenko,¹⁴⁰ M. Miñano Moya,¹⁷¹ I. A. Minashvili,^{156b} A. I. Mincer,¹²¹ B. Mindur,^{81a}
 M. Mineev,⁷⁷ Y. Minegishi,¹⁶⁰ Y. Ming,¹⁷⁸ L. M. Mir,¹⁴ A. Mirto,^{65a,65b} K. P. Mistry,¹³³ T. Mitani,¹⁷⁶ J. Mitrevski,¹¹²
 V. A. Mitsou,¹⁷¹ A. Miucci,²⁰ P. S. Miyagawa,¹⁴⁶ A. Mizukami,⁷⁹ J. U. Mjörnmark,⁹⁴ T. Mkrtchyan,¹⁸¹ M. Mlynarikova,¹³⁹
 T. Moa,^{43a,43b} K. Mochizuki,¹⁰⁷ P. Mogg,⁵⁰ S. Mohapatra,³⁸ S. Molander,^{43a,43b} R. Moles-Valls,²⁴ M. C. Mondragon,¹⁰⁴
 K. Mönig,⁴⁴ J. Monk,³⁹ E. Monnier,⁹⁹ A. Montalbano,¹⁴⁹ J. Montejo Berlingen,³⁵ F. Monticelli,⁸⁶ S. Monzani,^{66a}

R. W. Moore,³ N. Morange,¹²⁸ D. Moreno,²² M. Moreno Llácer,³⁵ P. Morettini,^{53b} M. Morgenstern,¹¹⁸ S. Morgenstern,⁴⁶ D. Mori,¹⁴⁹ T. Mori,¹⁶⁰ M. Morii,⁵⁷ M. Morinaga,¹⁷⁶ V. Morisbak,¹³⁰ A. K. Morley,³⁵ G. Mornacchi,³⁵ A. P. Morris,⁹² J. D. Morris,⁹⁰ L. Morvaj,¹⁵² P. Moschovakos,¹⁰ M. Mosidze,^{156b} H. J. Moss,¹⁴⁶ J. Moss,^{150,kk} K. Motohashi,¹⁶² R. Mount,¹⁵⁰ E. Mountricha,³⁵ E. J. W. Moyse,¹⁰⁰ S. Muanza,⁹⁹ F. Mueller,¹¹³ J. Mueller,¹³⁵ R. S. P. Mueller,¹¹² D. Muenstermann,⁸⁷ P. Mullen,⁵⁵ G. A. Mullier,²⁰ F. J. Munoz Sanchez,⁹⁸ P. Murin,^{28b} W. J. Murray,^{175,141} A. Murrone,^{66a,66b} M. Muškinja,⁸⁹ C. Mwewa,^{32a} A. G. Myagkov,^{140,II} J. Myers,¹²⁷ M. Myska,¹³⁸ B. P. Nachman,¹⁸ O. Nackenhorst,⁴⁵ K. Nagai,¹³¹ K. Nagano,⁷⁹ Y. Nagasaka,⁶⁰ K. Nagata,¹⁶⁶ M. Nagel,⁵⁰ E. Nagy,⁹⁹ A. M. Nairz,³⁵ Y. Nakahama,¹¹⁵ K. Nakamura,⁷⁹ T. Nakamura,¹⁶⁰ I. Nakano,¹²³ H. Nanjo,¹²⁹ F. Napolitano,^{59a} R. F. Naranjo Garcia,⁴⁴ R. Narayan,¹¹ D. I. Narrias Villar,^{59a} I. Naryshkin,¹³⁴ T. Naumann,⁴⁴ G. Navarro,²² R. Nayyar,⁷ H. A. Neal,¹⁰³ P. Y. Nechaeva,¹⁰⁸ T. J. Neep,¹⁴² A. Negri,^{68a,68b} M. Negrini,^{23b} S. Nektarijevic,¹¹⁷ C. Nellist,⁵¹ M. E. Nelson,¹³¹ S. Nemecek,¹³⁷ P. Nemethy,¹²¹ M. Nessi,^{35,mm} M. S. Neubauer,¹⁷⁰ M. Neumann,¹⁷⁹ P. R. Newman,²¹ T. Y. Ng,^{61c} Y. S. Ng,¹⁹ H. D. N. Nguyen,⁹⁹ T. Nguyen Manh,¹⁰⁷ E. Nibigira,³⁷ R. B. Nickerson,¹³¹ R. Nicolaidou,¹⁴² J. Nielsen,¹⁴³ N. Nikiforou,¹¹ V. Nikolaenko,^{140,II} I. Nikolic-Audit,¹³² K. Nikolopoulos,²¹ P. Nilsson,²⁹ Y. Ninomiya,⁷⁹ A. Nisati,^{70a} N. Nishu,^{58c} R. Nisius,¹¹³ I. Nitsche,⁴⁵ T. Nitta,¹⁷⁶ T. Nobe,¹⁶⁰ Y. Noguchi,⁸³ M. Nomachi,¹²⁹ I. Nomidis,¹³² M. A. Nomura,²⁹ T. Nooney,⁹⁰ M. Nordberg,³⁵ N. Norjoharuddeen,¹³¹ T. Novak,⁸⁹ O. Novgorodova,⁴⁶ R. Novotny,¹³⁸ L. Nozka,¹²⁶ K. Ntekas,¹⁶⁸ E. Nurse,⁹² F. Nuti,¹⁰² F. G. Oakham,^{33,e} H. Oberlack,¹¹³ T. Obermann,²⁴ J. Ocariz,¹³² A. Ochi,⁸⁰ I. Ochoa,³⁸ J. P. Ochoa-Ricoux,^{144a} K. O'Connor,²⁶ S. Oda,⁸⁵ S. Odaka,⁷⁹ S. Oerdek,⁵¹ A. Oh,⁹⁸ S. H. Oh,⁴⁷ C. C. Ohm,¹⁵¹ H. Oide,^{53b,53a} H. Okawa,¹⁶⁶ Y. Okazaki,⁸³ Y. Okumura,¹⁶⁰ T. Okuyama,⁷⁹ A. Olariu,^{27b} L. F. Oleiro Seabra,^{136a} S. A. Olivares Pino,^{144a} D. Oliveira Damazio,²⁹ J. L. Oliver,¹ M. J. R. Olsson,³⁶ A. Olszewski,⁸² J. Olszowska,⁸² D. C. O'Neil,¹⁴⁹ A. Onofre,^{136a,136e} K. Onogi,¹¹⁵ P. U. E. Onyisi,¹¹ H. Oppen,¹³⁰ M. J. Oreglia,³⁶ Y. Oren,¹⁵⁸ D. Orestano,^{72a,72b} E. C. Orgill,⁹⁸ N. Orlando,^{61b} A. A. O'Rourke,⁴⁴ R. S. Orr,¹⁶⁴ B. Osculati,^{53b,53a,a} V. O'Shea,⁵⁵ R. Ospanov,^{58a} G. Otero y Garzon,³⁰ H. Otono,⁸⁵ M. Ouchrif,^{34d} F. Ould-Saada,¹³⁰ A. Ouraou,¹⁴² Q. Ouyang,^{15a} M. Owen,⁵⁵ R. E. Owen,²¹ V. E. Ozcan,^{12c} N. Ozturk,⁸ J. Pacalt,¹²⁶ H. A. Pacey,³¹ K. Pachal,¹⁴⁹ A. Pacheco Pages,¹⁴ L. Pacheco Rodriguez,¹⁴² C. Padilla Aranda,¹⁴ S. Pagan Griso,¹⁸ M. Paganini,¹⁸⁰ G. Palacino,⁶³ S. Palazzo,^{40b,40a} S. Palestini,³⁵ M. Palka,^{81b} D. Pallin,³⁷ I. Panagoulas,¹⁰ C. E. Pandini,³⁵ J. G. Panduro Vazquez,⁹¹ P. Pani,³⁵ G. Panizzo,^{64a,64c} L. Paolozzi,⁵² T. D. Papadopoulou,¹⁰ K. Papageorgiou,⁹¹ A. Paramonov,⁶ D. Paredes Hernandez,^{61b} S. R. Paredes Saenz,¹³¹ B. Parida,^{58c} A. J. Parker,⁸⁷ K. A. Parker,⁴⁴ M. A. Parker,³¹ F. Parodi,^{53b,53a} J. A. Parsons,³⁸ U. Parzefall,⁵⁰ V. R. Pascuzzi,¹⁶⁴ J. M. P. Pasner,¹⁴³ E. Pasqualucci,^{70a} S. Passaggio,^{53b} F. Pastore,⁹¹ P. Pasuwan,^{43a,43b} S. Pataria,⁹⁷ J. R. Pater,⁹⁸ A. Pathak,^{178,f} T. Pauly,³⁵ B. Pearson,¹¹³ M. Pedersen,¹³⁰ L. Pedraza Diaz,¹¹⁷ R. Pedro,^{136a,136b} S. V. Peleganchuk,^{120b,120a} O. Penc,¹³⁷ C. Peng,^{15d} H. Peng,^{58a} B. S. Peralva,^{78a} M. M. Perego,¹⁴² A. P. Pereira Peixoto,^{136a} D. V. Perepelitsa,²⁹ F. Peri,¹⁹ L. Perini,^{66a,66b} H. Pernegger,³⁵ S. Perrella,^{67a,67b} V. D. Peshekhonov,^{77,a} K. Peters,⁴⁴ R. F. Y. Peters,⁹⁸ B. A. Petersen,³⁵ T. C. Petersen,³⁹ E. Petit,⁵⁶ A. Petridis,¹ C. Petridou,¹⁵⁹ P. Petroff,¹²⁸ E. Petrolo,^{70a} M. Petrov,¹³¹ F. Petrucci,^{72a,72b} M. Pettee,¹⁸⁰ N. E. Pettersson,¹⁰⁰ A. Peyaud,¹⁴² R. Pezoa,^{144b} T. Pham,¹⁰² F. H. Phillips,¹⁰⁴ P. W. Phillips,¹⁴¹ G. Piacquadio,¹⁵² E. Pianori,¹⁸ A. Picazio,¹⁰⁰ M. A. Pickering,¹³¹ R. Piegai,³⁰ J. E. Pilcher,³⁶ A. D. Pilkington,⁹⁸ M. Pinamonti,^{71a,71b} J. L. Pinfold,³ M. Pitt,¹⁷⁷ M-A. Pleier,²⁹ V. Pleskot,¹³⁹ E. Plotnikova,⁷⁷ D. Pluth,⁷⁶ P. Podberezko,^{120b,120a} R. Poettgen,⁹⁴ R. Poggi,⁵² L. Poggioli,¹²⁸ I. Pogrebnyak,¹⁰⁴ D. Pohl,²⁴ I. Pokharel,⁵¹ G. Polesello,^{68a} A. Poley,⁴⁴ A. Policicchio,^{40b,40a} R. Polifka,³⁵ A. Polini,^{23b} C. S. Pollard,⁴⁴ V. Polychronakos,²⁹ D. Ponomarenko,¹¹⁰ L. Pontecorvo,^{70a} G. A. Popeneciu,^{27d} D. M. Portillo Quintero,¹³² S. Pospisil,¹³⁸ K. Potamianos,⁴⁴ I. N. Potrap,⁷⁷ C. J. Potter,³¹ H. Potti,¹¹ T. Poulsen,⁹⁴ J. Poveda,³⁵ T. D. Powell,¹⁴⁶ M. E. Pozo Astigarraga,³⁵ P. Pralavorio,⁹⁹ S. Prell,⁷⁶ D. Price,⁹⁸ M. Primavera,^{65a} S. Prince,¹⁰¹ N. Proklova,¹¹⁰ K. Prokofiev,^{61c} F. Prokoshin,^{144b} S. Protopopescu,²⁹ J. Proudfoot,⁶ M. Przybycien,^{81a} A. Puri,¹⁷⁰ P. Puzo,¹²⁸ J. Qian,¹⁰³ Y. Qin,⁹⁸ A. Quadt,⁵¹ M. Queitsch-Maitland,⁴⁴ A. Qureshi,¹ P. Rados,¹⁰² F. Ragusa,^{66a,66b} G. Rahal,⁹⁵ J. A. Raine,⁹⁸ S. Rajagopalan,²⁹ A. Ramirez Morales,⁹⁰ T. Rashid,¹²⁸ S. Raspopov,⁵ M. G. Ratti,^{66a,66b} D. M. Rauch,⁴⁴ F. Rauscher,¹¹² S. Rave,⁹⁷ B. Ravina,¹⁴⁶ I. Ravinovich,¹⁷⁷ J. H. Rawling,⁹⁸ M. Raymond,³⁵ A. L. Read,¹³⁰ N. P. Readioff,⁵⁶ M. Reale,^{65a,65b} D. M. Rebuffi,^{68a,68b} A. Redelbach,¹⁷⁴ G. Redlinger,²⁹ R. Reece,¹⁴³ R. G. Reed,^{32c} K. Reeves,⁴² L. Rehnisch,¹⁹ J. Reichert,¹³³ A. Reiss,⁹⁷ C. Rembser,³⁵ H. Ren,^{15d} M. Rescigno,^{70a} S. Resconi,^{66a} E. D. Resseguie,¹³³ S. Rettie,¹⁷² E. Reynolds,²¹ O. L. Rezanova,^{120b,120a} P. Reznicek,¹³⁹ R. Richter,¹¹³ S. Richter,⁹² E. Richter-Was,^{81b} O. Ricken,²⁴ M. Ridel,¹³² P. Rieck,¹¹³ C. J. Riegel,¹⁷⁹ O. Rifki,⁴⁴ M. Rijssenbeek,¹⁵² A. Rimoldi,^{68a,68b} M. Rimoldi,²⁰ L. Rinaldi,^{23b} G. Ripellino,¹⁵¹ B. Ristić,⁸⁷ E. Ritsch,³⁵ I. Riu,¹⁴ J. C. Rivera Vergara,^{144a} F. Rizatdinova,¹²⁵ E. Rizvi,⁹⁰ C. Rizzi,¹⁴ R. T. Roberts,⁹⁸ S. H. Robertson,^{101,m} A. Robichaud-Veronneau,¹⁰¹ D. Robinson,³¹ J. E. M. Robinson,⁴⁴ A. Robson,⁵⁵ E. Rocco,⁹⁷ C. Roda,^{69a,69b} Y. Rodina,⁹⁹ S. Rodriguez Bosca,¹⁷¹ A. Rodriguez Perez,¹⁴

D. Rodriguez Rodriguez,¹⁷¹ A. M. Rodríguez Vera,^{165b} S. Roe,³⁵ C. S. Rogan,⁵⁷ O. Røhne,¹³⁰ R. Röhrig,¹¹³
C. P. A. Roland,⁶³ J. Roloff,⁵⁷ A. Romaniouk,¹¹⁰ M. Romano,^{23b,23a} N. Rompotis,⁸⁸ M. Ronzani,¹²¹ L. Roos,¹³² S. Rosati,^{70a}
K. Rosbach,⁵⁰ P. Rose,¹⁴³ N.-A. Rosien,⁵¹ E. Rossi,^{67a,67b} L. P. Rossi,^{53b} L. Rossini,^{66a,66b} J. H. N. Rosten,³¹ R. Rosten,¹⁴
M. Rotaru,^{27b} J. Rothberg,¹⁴⁵ D. Rousseau,¹²⁸ D. Roy,^{32c} A. Rozanov,⁹⁹ Y. Rozen,¹⁵⁷ X. Ruan,^{32c} F. Rubbo,¹⁵⁰ F. Rühr,⁵⁰
A. Ruiz-Martinez,¹⁷¹ Z. Rurikova,⁵⁰ N. A. Rusakovich,⁷⁷ H. L. Russell,¹⁰¹ J. P. Rutherford,⁷ E. M. Rüttinger,^{44,nn}
Y. F. Ryabov,¹³⁴ M. Rybar,¹⁷⁰ G. Rybkin,¹²⁸ S. Ryu,⁶ A. Ryzhov,¹⁴⁰ G. F. Rzehorz,⁵¹ P. Sabatini,⁵¹ G. Sabato,¹¹⁸
S. Sacerdoti,¹²⁸ H. F.-W. Sadrozinski,¹⁴³ R. Sadykov,⁷⁷ F. Safai Tehrani,^{70a} P. Saha,¹¹⁹ M. Sahinsoy,^{59a} A. Sahu,¹⁷⁹
M. Saimpert,⁴⁴ M. Saito,¹⁶⁰ T. Saito,¹⁶⁰ H. Sakamoto,¹⁶⁰ A. Sakharov,^{121,gg} D. Salamani,⁵² G. Salamanna,^{72a,72b}
J. E. Salazar Loyola,^{144b} D. Salek,¹¹⁸ P. H. Sales De Bruin,¹⁶⁹ D. Salihagic,¹¹³ A. Salnikov,¹⁵⁰ J. Salt,¹⁷¹ D. Salvatore,^{40b,40a}
F. Salvatore,¹⁵³ A. Salvucci,^{61a,61b,61c} A. Salzburger,³⁵ J. Samarati,³⁵ D. Sammel,⁵⁰ D. Sampsonidis,¹⁵⁹ D. Sampsonidou,¹⁵⁹
J. Sánchez,¹⁷¹ A. Sanchez Pineda,^{64a,64c} H. Sandaker,¹³⁰ C. O. Sander,⁴⁴ M. Sandhoff,¹⁷⁹ C. Sandoval,²² D. P. C. Sankey,¹⁴¹
M. Sannino,^{53b,53a} Y. Sano,¹¹⁵ A. Sansoni,⁴⁹ C. Santoni,³⁷ H. Santos,^{136a} I. Santoyo Castillo,¹⁵³ A. Saponov,⁷⁷
J. G. Saraiva,^{136a,136d} O. Sasaki,⁷⁹ K. Sato,¹⁶⁶ E. Sauvan,⁵ P. Savard,^{164,e} N. Savic,¹¹³ R. Sawada,¹⁶⁰ C. Sawyer,¹⁴¹
L. Sawyer,^{93,v} C. Sbarra,^{23b} A. Sbrizzi,^{23b,23a} T. Scanlon,⁹² J. Schaarschmidt,¹⁴⁵ P. Schacht,¹¹³ B. M. Schachtner,¹¹²
D. Schaefer,³⁶ L. Schaefer,¹³³ J. Schaeffer,⁹⁷ S. Schaepe,³⁵ U. Schäfer,⁹⁷ A. C. Schaffer,¹²⁸ D. Schaile,¹¹²
R. D. Schamberger,¹⁵² N. Scharmberg,⁹⁸ V. A. Schegelsky,¹³⁴ D. Scheirich,¹³⁹ F. Schenck,¹⁹ M. Schernau,¹⁶⁸
C. Schiavi,^{53b,53a} S. Schier,¹⁴³ L. K. Schildgen,²⁴ Z. M. Schillaci,²⁶ E. J. Schioppa,³⁵ M. Schioppa,^{40b,40a} K. E. Schleicher,⁵⁰
S. Schlenker,³⁵ K. R. Schmidt-Sommerfeld,¹¹³ K. Schmieden,³⁵ C. Schmitt,⁹⁷ S. Schmitt,⁴⁴ S. Schmitz,⁹⁷ U. Schnoor,⁵⁰
L. Schoeffel,¹⁴² A. Schoening,^{59b} E. Schopf,²⁴ M. Schott,⁹⁷ J. F. P. Schouwenberg,¹¹⁷ J. Schovancova,³⁵ S. Schramm,⁵²
A. Schulte,⁹⁷ H.-C. Schultz-Coulon,^{59a} M. Schumacher,⁵⁰ B. A. Schumm,¹⁴³ Ph. Schune,¹⁴² A. Schwartzman,¹⁵⁰
T. A. Schwarz,¹⁰³ H. Schweiger,⁹⁸ Ph. Schwemling,¹⁴² R. Schwienhorst,¹⁰⁴ A. Sciandra,²⁴ G. Sciolla,²⁶
M. Scornajenghi,^{40b,40a} F. Scuri,^{69a} F. Scutti,¹⁰² L. M. Scyboz,¹¹³ J. Searcy,¹⁰³ C. D. Sebastiani,^{70a,70b} P. Seema,²⁴
S. C. Seidel,¹¹⁶ A. Seiden,¹⁴³ T. Seiss,³⁶ J. M. Seixas,^{78b} G. Sekhniaidze,^{67a} K. Sekhon,¹⁰³ S. J. Sekula,⁴¹
N. Semprini-Cesari,^{23b,23a} S. Sen,⁴⁷ S. Senkin,³⁷ C. Serfon,¹³⁰ L. Serin,¹²⁸ L. Serkin,^{64a,64b} M. Sessa,^{72a,72b} H. Severini,¹²⁴
F. Sforza,¹⁶⁷ A. Sfyrila,⁵² E. Shabalina,⁵¹ J. D. Shahinian,¹⁴³ N. W. Shaikh,^{43a,43b} L. Y. Shan,^{15a} R. Shang,¹⁷⁰ J. T. Shank,²⁵
M. Shapiro,¹⁸ A. S. Sharma,¹ A. Sharma,¹³¹ P. B. Shatalov,¹⁰⁹ K. Shaw,¹⁵³ S. M. Shaw,⁹⁸ A. Shcherbakova,¹³⁴ Y. Shen,¹²⁴
N. Sherafati,³³ A. D. Sherman,²⁵ P. Sherwood,⁹² L. Shi,^{155,oo} S. Shimizu,⁸⁰ C. O. Shimmin,¹⁸⁰ M. Shimojima,¹¹⁴
I. P. J. Shipsey,¹³¹ S. Shirabe,⁸⁵ M. Shiyakova,⁷⁷ J. Shlomi,¹⁷⁷ A. Shmeleva,¹⁰⁸ D. Shoaleh Saadi,¹⁰⁷ M. J. Shochet,³⁶
S. Shojaii,¹⁰² D. R. Shope,¹²⁴ S. Shrestha,¹²² E. Shulga,¹¹⁰ P. Sicho,¹³⁷ A. M. Sickles,¹⁷⁰ P. E. Sidebo,¹⁵¹
E. Sideras Haddad,^{32c} O. Sidiropoulou,¹⁷⁴ A. Sidoti,^{23b,23a} F. Siegert,⁴⁶ Dj. Sijacki,¹⁶ J. Silva,^{136a} M. Silva Jr.,¹⁷⁸
M. V. Silva Oliveira,^{78a} S. B. Silverstein,^{43a} L. Simic,⁷⁷ S. Simion,¹²⁸ E. Simioni,⁹⁷ M. Simon,⁹⁷ R. Simoniello,⁹⁷
P. Sinervo,¹⁶⁴ N. B. Sinev,¹²⁷ M. Sioli,^{23b,23a} G. Siragusa,¹⁷⁴ I. Siral,¹⁰³ S. Yu. Sivoklokov,¹¹¹ J. Sjölin,^{43a,43b} M. B. Skinner,⁸⁷
P. Skubic,¹²⁴ M. Slater,²¹ T. Slavicek,¹³⁸ M. Slawinska,⁸² K. Sliwa,¹⁶⁷ R. Slovak,¹³⁹ V. Smakhtin,¹⁷⁷ B. H. Smart,⁵
J. Smiesko,^{28a} N. Smirnov,¹¹⁰ S. Yu. Smirnov,¹¹⁰ Y. Smirnov,¹¹⁰ L. N. Smirnova,¹¹¹ O. Smirnova,⁹⁴ J. W. Smith,⁵¹
M. N. K. Smith,³⁸ R. W. Smith,³⁸ M. Smizanska,⁸⁷ K. Smolek,¹³⁸ A. A. Snesarev,¹⁰⁸ I. M. Snyder,¹²⁷ S. Snyder,²⁹
R. Sobie,^{173,m} A. M. Soffa,¹⁶⁸ A. Soffer,¹⁵⁸ A. Søggaard,⁴⁸ D. A. Soh,¹⁵⁵ G. Sokhrannyi,⁸⁹ C. A. Solans Sanchez,³⁵
M. Solar,¹³⁸ E. Yu. Soldatov,¹¹⁰ U. Soldevila,¹⁷¹ A. A. Solodkov,¹⁴⁰ A. Soloshenko,⁷⁷ O. V. Solovyanov,¹⁴⁰ V. Solovyev,¹³⁴
P. Sommer,¹⁴⁶ H. Son,¹⁶⁷ W. Song,¹⁴¹ A. Sopczak,¹³⁸ F. Sopkova,^{28b} D. Sosa,^{59b} C. L. Sotiropoulou,^{69a,69b}
S. Sottocornola,^{68a,68b} R. Soualah,^{64a,64c,pp} A. M. Soukharev,^{120b,120a} D. South,⁴⁴ B. C. Sowden,⁹¹ S. Spagnolo,^{65a,65b}
M. Spalla,¹¹³ M. Spangenberg,¹⁷⁵ F. Spanò,⁹¹ D. Sperlich,¹⁹ F. Spettel,¹¹³ T. M. Spieker,^{59a} R. Spighi,^{23b} G. Spigo,³⁵
L. A. Spiller,¹⁰² D. P. Spiteri,⁵⁵ M. Spousta,¹³⁹ A. Stabile,^{66a,66b} R. Stamen,^{59a} S. Stamm,¹⁹ E. Stanecka,⁸² R. W. Stanek,⁶
C. Stancu,^{72a} B. Stanislaus,¹³¹ M. M. Stanitzki,⁴⁴ B. Stapf,¹¹⁸ S. Stapnes,¹³⁰ E. A. Starchenko,¹⁴⁰ G. H. Stark,³⁶ J. Stark,⁵⁶
S. H. Stark,³⁹ P. Staroba,¹³⁷ P. Starovoitov,^{59a} S. Stärz,³⁵ R. Staszewski,⁸² M. Stegler,⁴⁴ P. Steinberg,²⁹ B. Stelzer,¹⁴⁹
H. J. Stelzer,³⁵ O. Stelzer-Chilton,^{165a} H. Stenzel,⁵⁴ T. J. Stevenson,⁹⁰ G. A. Stewart,⁵⁵ M. C. Stockton,¹²⁷ G. Stoica,^{27b}
P. Stolte,⁵¹ S. Stonjek,¹¹³ A. Straessner,⁴⁶ J. Strandberg,¹⁵¹ S. Strandberg,^{43a,43b} M. Strauss,¹²⁴ P. Strizenc,^{28b} R. Ströhmer,¹⁷⁴
D. M. Strom,¹²⁷ R. Stroynowski,⁴¹ A. Strubig,⁴⁸ S. A. Stucci,²⁹ B. Stugu,¹⁷ J. Stupak,¹²⁴ N. A. Styles,⁴⁴ D. Su,¹⁵⁰ J. Su,¹³⁵
S. Suchek,^{59a} Y. Sugaya,¹²⁹ M. Suk,¹³⁸ V. V. Sulin,¹⁰⁸ D. M. S. Sultan,⁵² S. Sultansoy,^{4c} T. Sumida,⁸³ S. Sun,¹⁰³ X. Sun,³
K. Suruliz,¹⁵³ C. J. E. Suster,¹⁵⁴ M. R. Sutton,¹⁵³ S. Suzuki,⁷⁹ M. Svatos,¹³⁷ M. Swiatlowski,³⁶ S. P. Swift,² A. Sydorenko,⁹⁷
I. Sykora,^{28a} T. Sykora,¹³⁹ D. Ta,⁹⁷ K. Tackmann,^{44,qq} J. Taenzer,¹⁵⁸ A. Taffard,¹⁶⁸ R. Tafirout,^{165a} E. Tahirovic,⁹⁰

N. Taiblum,¹⁵⁸ H. Takai,²⁹ R. Takashima,⁸⁴ E. H. Takasugi,¹¹³ K. Takeda,⁸⁰ T. Takeshita,¹⁴⁷ Y. Takubo,⁷⁹ M. Talby,⁹⁹ A. A. Talyshev,^{120b,120a} J. Tanaka,¹⁶⁰ M. Tanaka,¹⁶² R. Tanaka,¹²⁸ R. Tanioka,⁸⁰ B. B. Tannenwald,¹²² S. Tapia Araya,^{144b} S. Tapprogge,⁹⁷ A. Tarek Abouelfadl Mohamed,¹³² S. Tarem,¹⁵⁷ G. Tarna,^{27b,q} G. F. Tartarelli,^{66a} P. Tas,¹³⁹ M. Tasevsky,¹³⁷ T. Tashiro,⁸³ E. Tassi,^{40b,40a} A. Tavares Delgado,^{136a,136b} Y. Tayalati,^{34e} A. C. Taylor,¹¹⁶ A. J. Taylor,⁴⁸ G. N. Taylor,¹⁰² P. T. E. Taylor,¹⁰² W. Taylor,^{165b} A. S. Tee,⁸⁷ P. Teixeira-Dias,⁹¹ H. Ten Kate,³⁵ P. K. Teng,¹⁵⁵ J. J. Teoh,¹¹⁸ F. Tepel,¹⁷⁹ S. Terada,⁷⁹ K. Terashi,¹⁶⁰ J. Terron,⁹⁶ S. Terzo,¹⁴ M. Testa,⁴⁹ R. J. Teuscher,^{164,m} S. J. Thais,¹⁸⁰ T. Theveneaux-Pelzer,⁴⁴ F. Thiele,³⁹ J. P. Thomas,²¹ A. S. Thompson,⁵⁵ P. D. Thompson,²¹ L. A. Thomsen,¹⁸⁰ E. Thomson,¹³³ Y. Tian,³⁸ R. E. Ticse Torres,⁵¹ V. O. Tikhomirov,^{108,rr} Yu. A. Tikhonov,^{120b,120a} S. Timoshenko,¹¹⁰ P. Tipton,¹⁸⁰ S. Tisserant,⁹⁹ K. Todome,¹⁶² S. Todorova-Nova,⁵ S. Todt,⁴⁶ J. Tojo,⁸⁵ S. Tokár,^{28a} K. Tokushuku,⁷⁹ E. Tolley,¹²² K. G. Tomiwa,^{32c} M. Tomoto,¹¹⁵ L. Tompkins,^{150,ff} K. Toms,¹¹⁶ B. Tong,⁵⁷ P. Tornambe,⁵⁰ E. Torrence,¹²⁷ H. Torres,⁴⁶ E. Torró Pastor,¹⁴⁵ C. Toscirì,¹³¹ J. Toth,^{99,ss} F. Touchard,⁹⁹ D. R. Tovey,¹⁴⁶ C. J. Treado,¹²¹ T. Trefzger,¹⁷⁴ F. Tresoldi,¹⁵³ A. Tricoli,²⁹ I. M. Trigger,^{165a} S. Trincaz-Duvoid,¹³² M. F. Tripiana,¹⁴ W. Trischuk,¹⁶⁴ B. Trocmé,⁵⁶ A. Trofymov,¹²⁸ C. Troncon,^{66a} M. Trovatelli,¹⁷³ F. Trovato,¹⁵³ L. Truong,^{32b} M. Trzebinski,⁸² A. Trzupek,⁸² F. Tsai,⁴⁴ J. C.-L. Tseng,¹³¹ P. V. Tsiarshka,¹⁰⁵ N. Tsirintanis,⁹ V. Tsiskaridze,¹⁵² E. G. Tskhadadze,^{156a} I. I. Tsukerman,¹⁰⁹ V. Tsulaia,¹⁸ S. Tsuno,⁷⁹ D. Tsybychev,¹⁵² Y. Tu,^{61b} A. Tudorache,^{27b} V. Tudorache,^{27b} T. T. Tulbure,^{27a} A. N. Tuna,⁵⁷ S. Turchikhin,⁷⁷ D. Turgeman,¹⁷⁷ I. Turk Cakir,^{4b,tt} R. Turra,^{66a} P. M. Tuts,³⁸ E. Tzovara,⁹⁷ G. Ucchielli,^{23b,23a} I. Ueda,⁷⁹ M. Ughetto,^{43a,43b} F. Ukegawa,¹⁶⁶ G. Unal,³⁵ A. Undrus,²⁹ G. Unel,¹⁶⁸ F. C. Ungaro,¹⁰² Y. Unno,⁷⁹ K. Uno,¹⁶⁰ J. Urban,^{28b} P. Urquijo,¹⁰² P. Urrejola,⁹⁷ G. Usai,⁸ J. Usui,⁷⁹ L. Vacavant,⁹⁹ V. Vacek,¹³⁸ B. Vachon,¹⁰¹ K. O. H. Vadla,¹³⁰ A. Vaidya,⁹² C. Valderanis,¹¹² E. Valdes Santurio,^{43a,43b} M. Valente,⁵² S. Valentinetti,^{23b,23a} A. Valero,¹⁷¹ L. Valéry,⁴⁴ R. A. Vallance,²¹ A. Vallier,⁵ J. A. Valls Ferrer,¹⁷¹ T. R. Van Daalen,¹⁴ W. Van Den Wollenberg,¹¹⁸ H. Van der Graaf,¹¹⁸ P. Van Gemmeren,⁶ J. Van Nieuwkoop,¹⁴⁹ I. Van Vulpen,¹¹⁸ M. Vanadia,^{71a,71b} W. Vandelli,³⁵ A. Vaniachine,¹⁶³ P. Vankov,¹¹⁸ R. Vari,^{70a} E. W. Varnes,⁷ C. Varni,^{53b,53a} T. Varol,⁴¹ D. Varouchas,¹²⁸ K. E. Varvell,¹⁵⁴ G. A. Vasquez,^{144b} J. G. Vasquez,¹⁸⁰ F. Vazeille,³⁷ D. Vazquez Furelos,¹⁴ T. Vazquez Schroeder,¹⁰¹ J. Veatch,⁵¹ V. Vecchio,^{72a,72b} L. M. Veloce,¹⁶⁴ F. Veloso,^{136a,136c} S. Veneziano,^{70a} A. Ventura,^{65a,65b} M. Venturi,¹⁷³ N. Venturi,³⁵ V. Vercesi,^{68a} M. Verducci,^{72a,72b} C. M. Vergel Infante,⁷⁶ W. Verkerke,¹¹⁸ A. T. Vermeulen,¹¹⁸ J. C. Vermeulen,¹¹⁸ M. C. Vetterli,^{149,e} N. Viaux Maira,^{144b} M. Vicente Barreto Pinto,⁵² I. Vichou,^{170,a} T. Vickey,¹⁴⁶ O. E. Vickey Boeriu,¹⁴⁶ G. H. A. Viehhauser,¹³¹ S. Viel,¹⁸ L. Vigani,¹³¹ M. Villa,^{23b,23a} M. Villaplana Perez,^{66a,66b} E. Vilucchi,⁴⁹ M. G. Vincter,³³ V. B. Vinogradov,⁷⁷ A. Vishwakarma,⁴⁴ C. Vittori,^{23b,23a} I. Vivarelli,¹⁵³ S. Vlachos,¹⁰ M. Vogel,¹⁷⁹ P. Vokac,¹³⁸ G. Volpi,¹⁴ S. E. von Buddenbrock,^{32c} E. Von Toerne,²⁴ V. Vorobel,¹³⁹ K. Vorobev,¹¹⁰ M. Vos,¹⁷¹ J. H. Vosseveld,⁸⁸ N. Vranjes,¹⁶ M. Vranjes Milosavljevic,¹⁶ V. Vrba,¹³⁸ M. Vreeswijk,¹¹⁸ T. Šfiligoj,⁸⁹ R. Vuillermet,³⁵ I. Vukotic,³⁶ T. Ženiš,^{28a} L. Živković,¹⁶ P. Wagner,²⁴ W. Wagner,¹⁷⁹ J. Wagner-Kuhr,¹¹² H. Wahlberg,⁸⁶ S. Wahrmond,⁴⁶ K. Wakamiya,⁸⁰ V. M. Walbrecht,¹¹³ J. Walder,⁸⁷ R. Walker,¹¹² S. D. Walker,⁹¹ W. Walkowiak,¹⁴⁸ V. Wallangen,^{43a,43b} A. M. Wang,⁵⁷ C. Wang,^{58b,q} F. Wang,¹⁷⁸ H. Wang,¹⁸ H. Wang,³ J. Wang,¹⁵⁴ J. Wang,^{59b} P. Wang,⁴¹ Q. Wang,¹²⁴ R.-J. Wang,¹³² R. Wang,^{58a} R. Wang,⁶ S. M. Wang,¹⁵⁵ W. T. Wang,^{58a} W. Wang,^{15c,uu} W. X. Wang,^{58a,uu} Y. Wang,^{58a} Z. Wang,^{58c} C. Wanotayaroj,⁴⁴ A. Warburton,¹⁰¹ C. P. Ward,³¹ D. R. Wardrope,⁹² A. Washbrook,⁴⁸ P. M. Watkins,²¹ A. T. Watson,²¹ M. F. Watson,²¹ G. Watts,¹⁴⁵ S. Watts,⁹⁸ B. M. Waugh,⁹² A. F. Webb,¹¹ S. Webb,⁹⁷ C. Weber,¹⁸⁰ M. S. Weber,²⁰ S. A. Weber,³³ S. M. Weber,^{59a} J. S. Webster,⁶ A. R. Weidberg,¹³¹ B. Weinert,⁶³ J. Weingarten,⁵¹ M. Weirich,⁹⁷ C. Weiser,⁵⁰ P. S. Wells,³⁵ T. Wenaus,²⁹ T. Wengler,³⁵ S. Wenig,³⁵ N. Wermes,²⁴ M. D. Werner,⁷⁶ P. Werner,³⁵ M. Wessels,^{59a} T. D. Weston,²⁰ K. Whalen,¹²⁷ N. L. Whallon,¹⁴⁵ A. M. Wharton,⁸⁷ A. S. White,¹⁰³ A. White,⁸ M. J. White,¹ R. White,^{144b} D. Whiteson,¹⁶⁸ B. W. Whitmore,⁸⁷ F. J. Wickens,¹⁴¹ W. Wiedenmann,¹⁷⁸ M. Wielers,¹⁴¹ C. Wiglesworth,³⁹ L. A. M. Wiik-Fuchs,⁵⁰ A. Wildauer,¹¹³ F. Wilk,⁹⁸ H. G. Wilkens,³⁵ L. J. Wilkins,⁹¹ H. H. Williams,¹³³ S. Williams,³¹ C. Willis,¹⁰⁴ S. Willocq,¹⁰⁰ J. A. Wilson,²¹ I. Wingerter-Seez,⁵ E. Winkels,¹⁵³ F. Winklmeier,¹²⁷ O. J. Winston,¹⁵³ B. T. Winter,²⁴ M. Wittgen,¹⁵⁰ M. Wobisch,⁹³ A. Wolf,⁹⁷ T. M. H. Wolf,¹¹⁸ R. Wolff,⁹⁹ M. W. Wolter,⁸² H. Wolters,^{136a,136c} V. W. S. Wong,¹⁷² N. L. Woods,¹⁴³ S. D. Worm,²¹ B. K. Wosiek,⁸² K. W. Woźniak,⁸² K. Wraight,⁵⁵ M. Wu,³⁶ S. L. Wu,¹⁷⁸ X. Wu,⁵² Y. Wu,^{58a} T. R. Wyatt,⁹⁸ B. M. Wynne,⁴⁸ S. Xella,³⁹ Z. Xi,¹⁰³ L. Xia,¹⁷⁵ D. Xu,^{15a} H. Xu,^{58a} L. Xu,²⁹ T. Xu,¹⁴² W. Xu,¹⁰³ B. Yabsley,¹⁵⁴ S. Yacoob,^{32a} K. Yajima,¹²⁹ D. P. Yallup,⁹² D. Yamaguchi,¹⁶² Y. Yamaguchi,¹⁶² A. Yamamoto,⁷⁹ T. Yamanaka,¹⁶⁰ F. Yamane,⁸⁰ M. Yamatani,¹⁶⁰ T. Yamazaki,¹⁶⁰ Y. Yamazaki,⁸⁰ Z. Yan,²⁵ H. J. Yang,^{58c,58d} H. T. Yang,¹⁸ S. Yang,⁷⁵ Y. Yang,¹⁶⁰ Z. Yang,¹⁷ W.-M. Yao,¹⁸ Y. C. Yap,⁴⁴ Y. Yasu,⁷⁹ E. Yatsenko,^{58c,58d} J. Ye,⁴¹ S. Ye,²⁹ I. Yeletsikh,⁷⁷ E. Yigitbasi,²⁵ E. Yildirim,⁹⁷ K. Yorita,¹⁷⁶ K. Yoshihara,¹³³ C. J. S. Young,³⁵ C. Young,¹⁵⁰ J. Yu,⁸ J. Yu,⁷⁶ X. Yue,^{59a} S. P. Y. Yuen,²⁴

B. Zabinski,⁸² G. Zacharis,¹⁰ E. Zaffaroni,⁵² R. Zaidan,¹⁴ A. M. Zaitsev,^{140,11} N. Zakharchuk,⁴⁴ J. Zalieckas,¹⁷ S. Zambito,⁵⁷
D. Zanzi,³⁵ D. R. Zariповas,⁵⁵ S. V. Zeiβner,⁴⁵ C. Zeitnitz,¹⁷⁹ G. Zemaityte,¹³¹ J. C. Zeng,¹⁷⁰ Q. Zeng,¹⁵⁰ O. Zenin,¹⁴⁰
D. Zerwas,¹²⁸ M. Zgubič,¹³¹ D. F. Zhang,^{58b} D. Zhang,¹⁰³ F. Zhang,¹⁷⁸ G. Zhang,^{58a} H. Zhang,^{15c} J. Zhang,⁶ L. Zhang,^{15c}
L. Zhang,^{58a} M. Zhang,¹⁷⁰ P. Zhang,^{15c} R. Zhang,^{58a} R. Zhang,²⁴ X. Zhang,^{58b} Y. Zhang,^{15d} Z. Zhang,¹²⁸ P. Zhao,⁴⁷
X. Zhao,⁴¹ Y. Zhao,^{58b,128,y} Z. Zhao,^{58a} A. Zhemchugov,⁷⁷ B. Zhou,¹⁰³ C. Zhou,¹⁷⁸ L. Zhou,⁴¹ M. S. Zhou,^{15d} M. Zhou,¹⁵²
N. Zhou,^{58c} Y. Zhou,⁷ C. G. Zhu,^{58b} H. L. Zhu,^{58a} H. Zhu,^{15a} J. Zhu,¹⁰³ Y. Zhu,^{58a} X. Zhuang,^{15a} K. Zhukov,¹⁰⁸
V. Zhulanov,^{120b,120a} A. Zibell,¹⁷⁴ D. Zieminska,⁶³ N. I. Zimine,⁷⁷ S. Zimmermann,⁵⁰ Z. Zinonos,¹¹³ M. Zinser,⁹⁷
M. Ziolkowski,¹⁴⁸ G. Zobernig,¹⁷⁸ A. Zoccoli,^{23b,23a} K. Zoch,⁵¹ T. G. Zorbas,¹⁴⁶ R. Zou,³⁶
M. Zur Nedden,¹⁹ and L. Zwalinski³⁵

(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, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, 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, 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, University of Texas at Austin, Austin, Texas, USA*

^{12a}*Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*

^{12b}*Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*

^{12c}*Department of Physics, Bogazici University, Istanbul, Turkey*

^{12d}*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*

¹³*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*

¹⁴*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*

^{15a}*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*

^{15b}*Physics Department, Tsinghua University, Beijing, China*

^{15c}*Department of Physics, Nanjing University, Nanjing, China*

^{15d}*University of Chinese Academy of Science (UCAS), Beijing, China*

¹⁶*Institute of Physics, University of Belgrade, Belgrade, Serbia*

¹⁷*Department for Physics and Technology, University of Bergen, Bergen, Norway*

¹⁸*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*

¹⁹*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*

²⁰*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*

²¹*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*

²²*Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia*

^{23a}*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*

^{23b}*INFN Sezione di Bologna, Bologna, Italy*

²⁴*Physikalisches Institut, Universität Bonn, Bonn, Germany*

²⁵*Department of Physics, Boston University, Boston, Massachusetts, USA*

²⁶*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*

^{27a}*Transilvania University of Brasov, Brasov, Romania*

^{27b}*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*

^{27c}*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*

^{27d}*National Institute for Research and Development of Isotopic and Molecular Technologies,
Physics Department, Cluj-Napoca, Romania*

^{27e}*University Politehnica Bucharest, Bucharest, Romania*

^{27f}*West University in Timisoara, Timisoara, Romania*

^{28a}*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*

^{28b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*

- ²⁹*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
- ³⁰*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- ³¹*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ^{32a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
- ^{32b}*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
- ^{32c}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ³³*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
- ^{34a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco*
- ^{34b}*Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat, Morocco*
- ^{34c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- ^{34d}*Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda, Morocco*
- ^{34e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ³⁵*CERN, Geneva, Switzerland*
- ³⁶*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
- ³⁷*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
- ³⁸*Nevis Laboratory, Columbia University, Irvington, New York, USA*
- ³⁹*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- ^{40a}*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- ^{40b}*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- ⁴¹*Physics Department, Southern Methodist University, Dallas, Texas, USA*
- ⁴²*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
- ^{43a}*Department of Physics, Stockholm University, Sweden*
- ^{43b}*Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁴*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁵*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁶*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁴⁷*Department of Physics, Duke University, Durham, North Carolina, USA*
- ⁴⁸*SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁴⁹*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵⁰*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵¹*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵²*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ^{53a}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- ^{53b}*INFN Sezione di Genova, Italy*
- ⁵⁴*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁵*SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁶*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁵⁷*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- ^{58a}*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- ^{58b}*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- ^{58c}*School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China*
- ^{58d}*Tsung-Dao Lee Institute, Shanghai, China*
- ^{59a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{59b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁶⁰*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ^{61a}*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
- ^{61b}*Department of Physics, University of Hong Kong, Hong Kong, China*
- ^{61c}*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶²*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶³*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- ^{64a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- ^{64b}*ICTP, Trieste, Italy*
- ^{64c}*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
- ^{65a}*INFN Sezione di Lecce, Lecce, Italy*
- ^{65b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ^{66a}*INFN Sezione di Milano, Milano, Italy*

- ^{66b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
^{67a}*INFN Sezione di Napoli, Napoli, Italy*
^{67b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
^{68a}*INFN Sezione di Pavia, Pavia, Italy*
^{68b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
^{69a}*INFN Sezione di Pisa, Pisa, Italy*
^{69b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
^{70a}*INFN Sezione di Roma, Roma, Italy*
^{70b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
^{71a}*INFN Sezione di Roma Tor Vergata, Roma, Italy*
^{71b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
^{72a}*INFN Sezione di Roma Tre, Roma, Italy*
^{72b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
^{73a}*INFN-TIFPA, Trento, Italy*
^{73b}*Università degli Studi di Trento, Trento, Italy*
⁷⁴*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
⁷⁵*University of Iowa, Iowa City, Iowa, USA*
⁷⁶*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
⁷⁷*Joint Institute for Nuclear Research, Dubna, Russia*
^{78a}*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
^{78b}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
^{78c}*Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil*
^{78d}*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
⁷⁹*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
⁸⁰*Graduate School of Science, Kobe University, Kobe, Japan*
^{81a}*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
^{81b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
⁸²*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
⁸³*Faculty of Science, Kyoto University, Kyoto, Japan*
⁸⁴*Kyoto University of Education, Kyoto, Japan*
⁸⁵*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
⁸⁶*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
⁸⁷*Physics Department, Lancaster University, Lancaster, United Kingdom*
⁸⁸*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
⁸⁹*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
⁹⁰*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
⁹¹*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
⁹²*Department of Physics and Astronomy, University College London, London, United Kingdom*
⁹³*Louisiana Tech University, Ruston, Louisiana, USA*
⁹⁴*Fysiska institutionen, Lunds universitet, Lund, Sweden*
⁹⁵*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
⁹⁶*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
⁹⁷*Institut für Physik, Universität Mainz, Mainz, Germany*
⁹⁸*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
⁹⁹*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
¹⁰⁰*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
¹⁰¹*Department of Physics, McGill University, Montreal, Quebec, Canada*
¹⁰²*School of Physics, University of Melbourne, Victoria, Australia*
¹⁰³*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
¹⁰⁴*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
¹⁰⁵*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
¹⁰⁶*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
¹⁰⁷*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
¹⁰⁸*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
¹⁰⁹*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
¹¹⁰*National Research Nuclear University MEPhI, Moscow, Russia*
¹¹¹*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
¹¹²*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
¹¹³*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*

- ¹¹⁴*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹¹⁵*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ¹¹⁶*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹¹⁷*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹¹⁸*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹¹⁹*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ^{120a}*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
- ^{120b}*Novosibirsk State University, Novosibirsk, Russia*
- ¹²¹*Department of Physics, New York University, New York, New York, USA*
- ¹²²*Ohio State University, Columbus, Ohio, USA*
- ¹²³*Faculty of Science, Okayama University, Okayama, Japan*
- ¹²⁴*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹²⁵*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹²⁶*Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹²⁷*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹²⁸*LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- ¹²⁹*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹³⁰*Department of Physics, University of Oslo, Oslo, Norway*
- ¹³¹*Department of Physics, Oxford University, Oxford, United Kingdom*
- ¹³²*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
- ¹³³*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹³⁴*Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia*
- ¹³⁵*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- ^{136a}*Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Portugal*
- ^{136b}*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{136c}*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- ^{136d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{136e}*Departamento de Física, Universidade do Minho, Braga, Portugal*
- ^{136f}*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain*
- ^{136g}*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
- ¹³⁷*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
- ¹³⁸*Czech Technical University in Prague, Prague, Czech Republic*
- ¹³⁹*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹⁴⁰*State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia*
- ¹⁴¹*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁴²*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ¹⁴³*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ^{144a}*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{144b}*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ¹⁴⁵*Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹⁴⁶*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴⁷*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴⁸*Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁴⁹*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
- ¹⁵⁰*SLAC National Accelerator Laboratory, Stanford, California, USA*
- ¹⁵¹*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁵²*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
- ¹⁵³*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁵⁴*School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵⁵*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ^{156a}*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
- ^{156b}*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- ¹⁵⁷*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
- ¹⁵⁸*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵⁹*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁶⁰*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
- ¹⁶¹*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁶²*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁶³*Tomsk State University, Tomsk, Russia*
- ¹⁶⁴*Department of Physics, University of Toronto, Toronto, Ontario, Canada*

- ^{165a}*TRIUMF, Vancouver, British Columbia, Canada*
^{165b}*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
¹⁶⁶*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
¹⁶⁷*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
¹⁶⁸*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
¹⁶⁹*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
¹⁷⁰*Department of Physics, University of Illinois, Urbana, Illinois, USA*
¹⁷¹*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
¹⁷²*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
¹⁷³*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
¹⁷⁴*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
¹⁷⁵*Department of Physics, University of Warwick, Coventry, United Kingdom*
¹⁷⁶*Waseda University, Tokyo, Japan*
¹⁷⁷*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
¹⁷⁸*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
¹⁷⁹*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
¹⁸⁰*Department of Physics, Yale University, New Haven, Connecticut, USA*
¹⁸¹*Yerevan Physics Institute, Yerevan, Armenia*

^aDeceased.

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

^cAlso at Istanbul University, Dept. of Physics, Istanbul, Turkey.

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

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

^fAlso at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

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

^hAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.

ⁱAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

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

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

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

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

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

^oAlso at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.

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

^qAlso at CPPM, Aix-Marseille Université, 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, 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, Louisiana, USA.

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

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

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

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

^{aa}Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

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

^{cc}Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey.

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

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

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

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

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

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

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

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

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

^{mmm}Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

ⁿⁿAlso at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

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

^{pp}Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.

^{qq}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

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

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

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

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