


Measurement of Azimuthal Anisotropy of Muons from Charm and Bottom Hadrons in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

G. Aad *et al.*^{*}
(ATLAS Collaboration)

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The elliptic flow of muons from the decay of charm and bottom hadrons is measured in pp collisions at $\sqrt{s} = 13$ TeV using a data sample with an integrated luminosity of 150 pb^{-1} recorded by the ATLAS detector at the LHC. The muons from heavy-flavor decay are separated from light-hadron decay muons using momentum imbalance between the tracking and muon spectrometers. The heavy-flavor decay muons are further separated into those from charm decay and those from bottom decay using the distance-of-closest-approach to the collision vertex. The measurement is performed for muons in the transverse momentum range 4–7 GeV and pseudorapidity range $|\eta| < 2.4$. A significant nonzero elliptic anisotropy coefficient v_2 is observed for muons from charm decays, while the v_2 value for muons from bottom decays is consistent with zero within uncertainties.

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In high-energy collisions between large nuclei at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), a quark-gluon plasma is formed, which rapidly expands as described by nearly inviscid hydrodynamics [1,2]. Heavy quarks, which have a large mass and dead-cone radiation region [3], are expected to interact with the medium through a different interplay of radiative and collisional processes with respect to ordinary light quarks [4]. However, it was hypothesized that even these massive heavy quarks may scatter within the medium and be redirected in a way that results in collective flow patterns [5]. Measurements of decay electrons from charm and bottom hadrons by the PHENIX experiment in Au + Au collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV revealed that heavy quarks undergo significant scattering in the medium and thus lose energy and align with the geometry of the expanding medium [6]. More recent measurements using decay leptons and full reconstruction of charm and bottom hadrons indicate substantial modifications to the momentum distributions of heavy quarks in heavy-ion collisions relative to that in proton-proton (pp) collisions at both RHIC and the LHC (see Ref. [7] for a recent review).

Smaller collision systems, including $p + \text{Pb}$ and even pp , have particle emission patterns with large azimuthal anisotropies, also described by nearly inviscid

hydrodynamics [1,8,9]. A common hydrodynamic description of pp , $p + \text{Pb}$, and $\text{Pb} + \text{Pb}$ azimuthal anisotropies as resulting from initial geometry anisotropies is compelling [10]. New measurements of similar anisotropies for reconstructed D mesons and heavy-flavor decay electrons in $p + \text{Pb}$ collisions [11,12] highlight that charm quarks are scattered in the medium in smaller collision systems as well. These measurements of anisotropies with almost no modification to the transverse momentum (p_T) distribution [13] are somewhat surprising, because such scattering in the A + A case leads simultaneously to azimuthal anisotropies and a softening of the transverse momentum distributions [14]. It is of interest to measure heavy-flavor anisotropies in pp collisions in order to obtain information about the interaction of heavy quarks with the medium in the smallest hadronic collision system at the LHC. In this Letter, measurements of azimuthal anisotropies for muons from heavy-flavor decays in pp collisions at 13 TeV are presented. Additionally, the heavy-flavor muons are separated to provide information about the anisotropies of muons from charm and bottom decay separately.

The ATLAS experiment [15] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle. [Coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.] It consists of an inner tracking

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

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detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. The muon spectrometer (MS) surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. The trigger system consists of a hardware-based first-level trigger and a software-based high-level trigger (HLT) [16], which reconstructs the event in a manner similar to that performed off-line.

Data for this analysis were recorded during a special running period in 2017 in which the mean number of pp interactions per beam crossing was two. Events were recorded using triggers that require a muon at the HLT stage with p_T larger than 4 GeV in coincidence with various triggers designed to select high-multiplicity events [17]. The latter included requirements on the transverse energy in the calorimeter, and the number of space points recorded in the silicon microstrip detector, and the number of charged-particle tracks reconstructed by the HLT. The trigger with the highest threshold for the number of tracks sampled 150 pb^{-1} , while triggers with lower thresholds were prescaled and sampled less integrated luminosities. For each charged-track multiplicity range reported here, analyzed events are taken exclusively from the trigger that sampled the largest integrated luminosity.

Charged-particle tracks and collision vertices are reconstructed in the ID using algorithms described in Ref. [18]. Tracks with $p_T > 0.4 \text{ GeV}$ and $|\eta| < 2.5$ satisfying the set of quality requirements [17] are used in this analysis. Muons with $4 < p_T < 7 \text{ GeV}$ and $|\eta| < 2.4$ reconstructed in both the ID and the MS are selected and required to pass “medium” selection requirements described in Ref. [19]. Events are required to have at least one but not more than four reconstructed vertices to reduce the contribution from in-time pileup events containing multiple pp collisions per event. The number of reconstructed tracks with $p_T > 0.4 \text{ GeV}$ associated with the vertex containing the muon is denoted by $N_{\text{ch}}^{\text{rec}}$.

Simulated events were generated using PYTHIA8 [20] with the NNPDF23LO parton distribution function set [21] and A14 [22] set of tuned parameters. Multijet hard-scattering events filtered on the presence of a generator-level muon were passed through a GEANT4 simulation [23,24] of the detector and reconstructed under the same conditions as the data including pileup background events. A muon trigger emulator is included in the simulation to evaluate the trigger efficiency.

This analysis follows two-particle correlation methods used in previous ATLAS measurements [17,25] and summarized here. Two-particle correlations are measured as a

function of $\Delta\phi \equiv \phi^\mu - \phi^h$ and $\Delta\eta \equiv \eta^\mu - \eta^h$, where particles μ and h are muons and charged hadrons, respectively. For each muon, correlation functions $S(\Delta\eta, \Delta\phi)$ and $B(\Delta\eta, \Delta\phi)$ are formed [26]. The correlation function $S(\Delta\eta, \Delta\phi)$ uses charged hadrons from the same event. The function $B(\Delta\eta, \Delta\phi)$ is constructed by selecting charged hadrons from different events of similar $N_{\text{ch}}^{\text{rec}}$ ($|\Delta N_{\text{ch}}^{\text{rec}}| < 10$) and vertex position z_{vtx} ($|\Delta z_{\text{vtx}}| < 10 \text{ mm}$). Detector acceptance effects largely cancel out in the ratio S/B within the precision of these measurements. Each muon-hadron pair is weighted by the inverse product of the trigger and reconstruction efficiencies for the muon and the reconstruction efficiency for the charged hadron.

One-dimensional correlation functions $C(\Delta\phi)$ are obtained by integrating $S(\Delta\eta, \Delta\phi)$ and $B(\Delta\eta, \Delta\phi)$ over the pseudorapidity interval $1.5 < |\Delta\eta| < 5$:

$$C(\Delta\phi) = \frac{\int_{1.5}^5 d|\Delta\eta| S(|\Delta\eta|, \Delta\phi)}{\int_{1.5}^5 d|\Delta\eta| B(|\Delta\eta|, \Delta\phi)} \equiv \frac{S(\Delta\phi)}{B(\Delta\phi)},$$

and $S(\Delta\phi)$ and $B(\Delta\phi)$ are normalized such that the average value of $C(\Delta\phi)$ is unity. Requiring a gap in $\Delta\eta$ that excludes $|\Delta\eta| < 1.5$ reduces the contribution to the correlations from jet fragmentation. Previous hadron-hadron correlation results used a larger gap, integrating over $2 < |\Delta\eta| < 5$ instead [17,25]; however, studies of shape variation versus different $|\Delta\eta|$ selections with the PYTHIA8 sample described above indicate that the jet-fragmentation correlation for heavy-flavor quarks is insignificant for muon-hadron pairs with $|\Delta\eta| > 1.5$.

In order to separate the flow contribution from back-to-back dijets and resonance decays, together referred to as nonflow, a template fitting method developed for previous ATLAS analyses [17,25] is used. This method assumes that the shape of non-flow correlations is independent of the particle multiplicity in the events, an assumption which results in a good description of the correlation functions in these measurements and is tested in simulation [27]. Hence the correlation function in low particle-multiplicity (LM) events dominated by nonflow is used to estimate the nonflow contribution in high multiplicity (HM) events. The resulting template fit function:

$$C^{\text{templ}}(\Delta\phi) = FC^{\text{LM}}(\Delta\phi) + C^{\text{ridge}}(\Delta\phi),$$

where

$$C^{\text{ridge}}(\Delta\phi) = G \left[1 + \sum_{n=2}^4 2v_{n,n} \cos(n\Delta\phi) \right],$$

has free parameters F and n th-order flow (anisotropy) coefficients $v_{n,n}$; the coefficient G is fixed by requiring that the integrals of $C^{\text{templ}}(\Delta\phi)$ and $C(\Delta\phi)$ are equal. The template fits include harmonics 2–4 because the contribution

from higher-order coefficients is negligible. Based on the assumption of flow factorization [28], the flow coefficients v_n of muons are obtained as $v_n^\mu(p_T^\mu) = v_{n,n}(p_T^\mu, p_T^h) / v_n^h(p_T^h)$, where $v_n^h(p_T^h)$ are the flow coefficients of charged hadrons previously measured by ATLAS using the same template fit method in different analyses [17,25].

The selected muon sample includes background muons from particles produced from light-hadron decay and from punch-through hadrons. Previous studies [29,30] showed that the signal (heavy-flavor) and background muons can be separated statistically using the fractional momentum imbalance, $\Delta p/p_{\text{ID}} = (p_{\text{ID}} - p_{\text{MS}})/p_{\text{ID}}$, where p_{ID} is the muon momentum measured in the ID, and p_{MS} is that measured in the MS corrected via simulation for the energy loss inside the calorimeter. The signal fraction f^{sig} is obtained by fitting the measured $\Delta p/p_{\text{ID}}$ distribution with signal and background template distributions obtained from simulation. The signal muon sample includes remaining contributions from non-heavy-flavor components such as quarkonia, low-mass resonances, and τ leptons; these amount to $\sim 2.5\%$, based on PYTHIA8 simulation.

Figure 1 shows muon-hadron correlation functions and template fits for muons with $4 < p_T < 6$ GeV and charged hadrons with $0.5 < p_T < 5$ GeV from events with $110 \leq N_{\text{ch}}^{\text{rec}} < 120$; the $N_{\text{ch}}^{\text{rec}} < 40$ region is used for LM events. The two panels represent different $\Delta p/p_{\text{ID}}$ regions, characterized by different f^{sig} values, as indicated in the plots. The amplitude of the $v_{2,2}$ modulation changes with the signal fraction. The values of $v_{2,2}$ are determined from muon-hadron correlation functions generated using muons in three different regions of $\Delta p/p_{\text{ID}}$, and $v_{2,2}$ as a function of f^{sig} is extracted from a linear fit to the points. Then $v_{2,2}$ from heavy-flavor muon-hadron correlations $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ is calculated by extrapolating to $f^{\text{sig}} = 1$, based on

$$v_{2,2}(p_T^\mu, p_T^h) = f^{\text{sig}} v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h) + (1 - f^{\text{sig}}) v_{2,2}^{\text{bkg}}(p_T^\mu, p_T^h),$$

where $v_{2,2}^{\text{bkg}}(p_T^\mu, p_T^h)$ is $v_{2,2}$ from background muon-hadron correlations.

Muons from heavy-flavor decays can be further separated into those from charm and those from bottom decays, based on the different decay lengths of charm and bottom hadrons. Template distributions of the impact parameter of the muon relative to the associated collision vertex in the transverse direction (d_0) for charm, bottom, non-heavy-flavor signal, and background muons obtained from the full detector simulation are used to fit the data distributions differentially in p_T and η . The d_0 resolution of charged hadrons with $4 < p_T < 7$ GeV is 20–40 μm , depending on p_T and η , and independent of $N_{\text{ch}}^{\text{rec}}$. Figure 2 shows the fit to the d_0 distribution for muons with $-0.2 < \Delta p/p_{\text{ID}} < 0.4$ and $4.5 < p_T < 5$ GeV in events with $80 \leq N_{\text{ch}}^{\text{rec}} < 90$. The background fraction is fixed in accord with the fit results in $\Delta p/p_{\text{ID}}$. The contribution from non-heavy-flavor signal muons is also fixed, using the fraction obtained from PYTHIA8 simulation. The $|d_0| < 0.02$ mm region is dominated by non-heavy-flavor signal and background muons and is excluded in the fit procedure. The fraction of muons from bottom decays relative to all heavy-flavor muons, $f^{b \rightarrow \mu} = (b \rightarrow \mu)/(c \rightarrow \mu + b \rightarrow \mu)$, is found to be ~ 0.4 at $p_T = 4$ GeV and increases to ~ 0.6 at $p_T = 7$ GeV. These values are compatible with those determined via a fixed-order plus next-to-leading-logarithm (FONLL) calculation [31] and the PYTHIA8 simulation.

In order to measure $v_{2,2}$ from charm muon-hadron correlations and bottom muon-hadron correlations separately, muons are divided into two d_0 regions, $|d_0| < 0.12$ mm and $|d_0| > 0.12$ mm. In the $|d_0| < 0.12$ mm region where $f^{c \rightarrow \mu} > f^{b \rightarrow \mu}$, there is a significant hadronic background contribution and thus $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ is

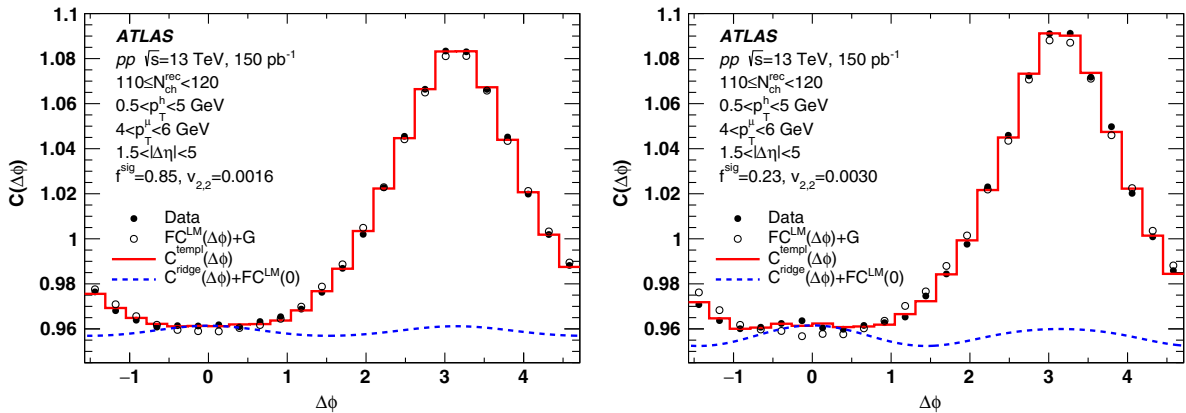


FIG. 1. Template fit to the muon-hadron correlation function, $C(\Delta\phi)$, with pseudorapidity interval $1.5 < |\Delta\eta| < 5$ and track multiplicity $110 \leq N_{\text{ch}}^{\text{rec}} < 120$. Muons with transverse momentum $4 < p_T < 6$ GeV and charged particles with $0.5 < p_T < 5$ GeV are used. Each panel shows the muon-hadron correlation function for muons of a different signal fraction (f^{sig}). The solid red lines show the final function $C^{\text{templ}}(\Delta\phi)$, while the open points and dashed blue lines show the scaled $C^{\text{LM}}(\Delta\phi)$ and $v_{n,n}$ components, each above a vertical pedestal for visibility.

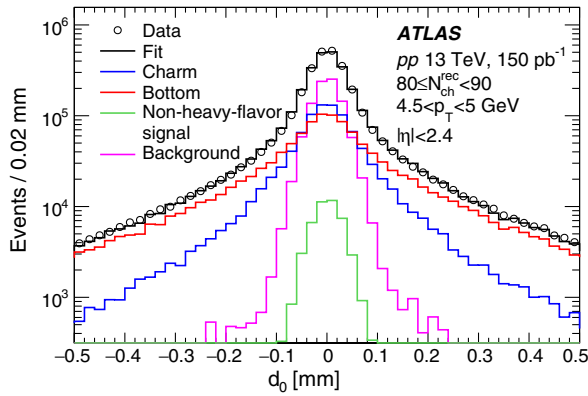


FIG. 2. Fit (gray histogram) to the transverse impact parameter, d_0 , distribution of muons with transverse momentum $4.5 < p_T < 5$ GeV and pseudorapidity $|\eta| < 2.4$, with template d_0 distributions of different components obtained from PYTHIA8 simulations.

obtained in three different $\Delta p/p_{ID}$ bins and extrapolated to $f^{\text{sig}} = 1$. In contrast, in the region $|d_0| > 0.12$ mm where $f^{c \rightarrow \mu} < f^{b \rightarrow \mu}$, there is negligible background and thus $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ is obtained directly. Given two $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ values with different $f^{b \rightarrow \mu}$ values, $v_{2,2}^c(p_T^\mu, p_T^h)$ and $v_{2,2}^b(p_T^\mu, p_T^h)$ can be determined separately.

The sources of systematic uncertainty in $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ originate from the LM event selection, the $\Delta\eta$ -gap selection, event pileup, trigger and reconstruction efficiency, and signal fraction extraction. The impact on the $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ measurement is evaluated by repeating the analysis with variations intended to test the sensitivity to these effects. In many cases, the evaluated variation in $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ is driven by statistical fluctuations. Sensitivity to the choice of the LM range may arise due to a change in the dijet shape from the LM to HM events. The uncertainty is studied using two alternative $N_{\text{ch}}^{\text{rec}}$ ranges, 0–30 and 20–40, for

$C^{\text{LM}}(\Delta\phi)$. The resulting variation in $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ is 15–35% depending on $N_{\text{ch}}^{\text{rec}}$, and is the largest systematic uncertainty. The sensitivity to the width of the $\Delta\eta$ gap is tested by using $2 < |\Delta\eta| < 5$ to obtain a wider excluded range ($|\Delta\eta| < 2$), and the resulting change in $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ is smaller than the statistical uncertainty. The results may be sensitive to a residual in-time pileup contribution when two closely spaced pp events are reconstructed with a single merged vertex. This effect is studied using a tighter event selection to reject events containing more than two reconstructed vertices per event. The $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ obtained is consistent with the $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ from the nominal event selection within the statistical uncertainties. The uncertainty associated with the signal fraction extraction is evaluated by modifying the momentum-imbalance templates from simulation, and considering the systematic uncertainties in the muon momentum resolution and scale. For signal muons, the impact of using a data-driven template with muons from $J/\psi \rightarrow \mu\mu$ candidates is also considered. No systematic uncertainty on the $v_{2,2}^{\text{sig}}(p_T^\mu, p_T^h)$ is assigned from this study.

The uncertainty in $v_{2,2}^c(p_T^\mu, p_T^h)$ and $v_{2,2}^b(p_T^\mu, p_T^h)$ additionally includes the uncertainty in $f^{b \rightarrow \mu}$. The extracted $f^{b \rightarrow \mu}$ values are sensitive to the shape of the p_T spectra of initial charm and bottom hadrons, the background muon fraction, the non-heavy-flavor muon contribution, fit range, and d_0 -template shapes. The shape of the initial hadron p_T distribution is varied from PYTHIA8 to that from a fixed-order plus next-to-leading-logarithm. The non-heavy-flavor muon contribution, which is estimated to be 2.5% of the signal muon yield using simulation, is varied in the range 0%–5% and included in the d_0 fit procedure to evaluate the impact on $f^{b \rightarrow \mu}$. The sensitivity to the fit range is evaluated by repeating the d_0 fit with different exclusion regions, either 0 or 0.04 mm, and the uncertainty from the d_0 -template shape is evaluated with d_0 -template shape

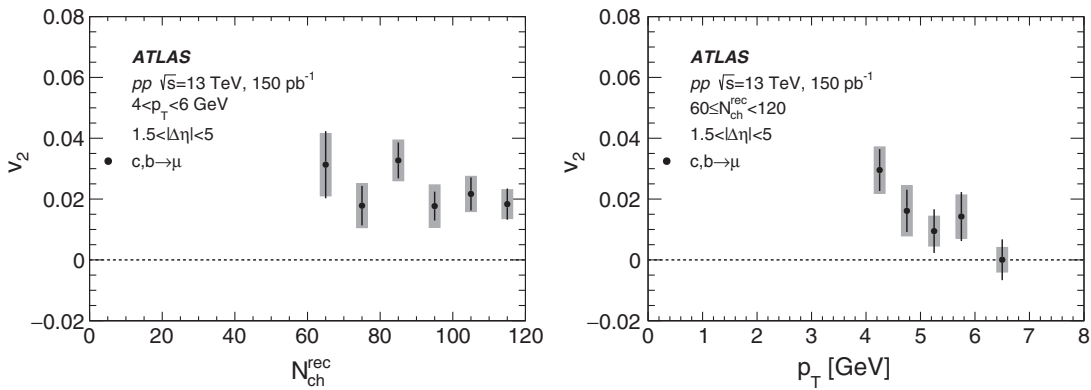


FIG. 3. Elliptic anisotropy coefficient v_2 of inclusive heavy-flavor muons as a function of track multiplicity $N_{\text{ch}}^{\text{rec}}$ for muons with transverse momentum $4 < p_T < 6$ GeV (left) and as a function of p_T for the $60 \leq N_{\text{ch}}^{\text{rec}} < 120$ multiplicity range (right). The vertical bars and shaded bands represent statistical and systematic uncertainties, respectively.

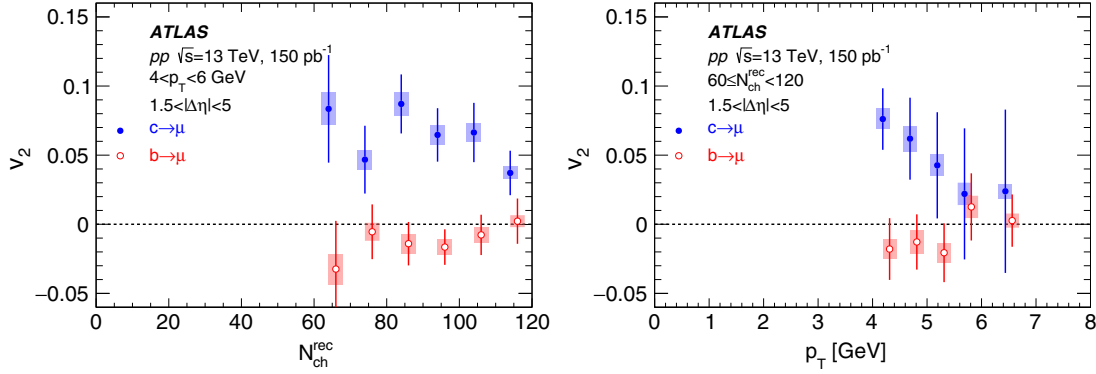


FIG. 4. Elliptic anisotropy coefficient v_2 of muons from charm and bottom decays as a function of track multiplicity N_{ch}^{rec} for muons with transverse momentum $4 < p_T < 6$ GeV (left) and as a function of p_T for the $60 \leq N_{ch}^{rec} < 120$ multiplicity range (right). Data points are shifted by ± 1 in N_{ch}^{rec} and ± 0.125 GeV in p_T for better visibility. The vertical bars and shaded bands represent statistical and systematic uncertainties, respectively.

variation extracted from the d_0 shape comparison between the data and simulation. These variations are included in the final systematic uncertainties. The resulting systematic uncertainty in $f^{b \rightarrow \mu}$ is 8%–10%, and this uncertainty is propagated into the uncertainties in $v_{2,2}^c(p_T^\mu, p_T^h)$ and $v_{2,2}^b(p_T^\mu, p_T^h)$ by combining it in quadrature with those in $v_{2,2}^{sig}(p_T^\mu, p_T^h)$. Finally, it was checked in the generation-level and reconstruction-level PYTHIA8 events that $v_{2,2}(p_T^\mu, p_T^h)$ for inclusive heavy-flavor muons as well as for muons from c and b decays is consistent with zero as expected.

Figure 3 shows the v_2 of inclusive heavy-flavor muons, determined as $v_2^\mu(p_T^\mu) = v_{2,2}(p_T^\mu, p_T^h) / v_2^h(p_T^h)$, where $v_2^h(p_T^h)$ is taken from Ref. [17]. The systematic uncertainty in the charged-hadron v_2 is included in the total uncertainty, but is negligible compared with the other uncertainties introduced in this measurement. The v_2 value is presented as a function of N_{ch}^{rec} for $4 < p_T < 6$ GeV (left) and as a function of p_T for $60 \leq N_{ch}^{rec} < 120$ (right). Within the uncertainties there is no clear N_{ch}^{rec} dependence, but the value decreases as the heavy-flavor muon p_T increases from 4 to 7 GeV.

Figure 4 shows the v_2 values for muons from charm and bottom decays separately, as a function of N_{ch}^{rec} for $4 < p_T < 6$ GeV (left) and as a function of p_T for $60 \leq N_{ch}^{rec} < 120$ (right). The v_2 of muons from bottom decays is consistent with zero in the entire N_{ch}^{rec} range of the measurement and has no discernible p_T dependence. In contrast, the v_2 of muons from charm decays is nonzero at lower p_T but consistent with zero at higher p_T within the sizable uncertainties. It also shows no significant N_{ch}^{rec} dependence within the uncertainties.

In summary, a measurement of elliptic flow coefficients for heavy-flavor decay muons in pp collisions at 13 TeV is presented, including a separation between charm and bottom contributions. The measurement uses a dataset corresponding to an integrated luminosity of 150 pb^{-1} recorded by the ATLAS experiment at the LHC. The

inclusive heavy-flavor muon v_2 values are not dependent on N_{ch}^{rec} in the range 60–120 and show a clear decrease with p_T from 4 to 7 GeV. The bottom-decay muons have v_2 values consistent with zero within statistical and systematic uncertainties, while the charm-decay muons have significant non-zero v_2 values. These results indicate that bottom quarks, unlike light and charm quarks, do not participate in the collective behavior in high-multiplicity pp collisions. There are theoretical calculations within a linearized Boltzmann-Langevin transport framework for Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV predicting larger v_2 for D meson than v_2 for B meson at $p_T < 10$ GeV and similar v_2 at $p_T > 10$ GeV [32]. However, no such calculations have been published for smaller systems including high-multiplicity pp events. The results will provide fundamental new input to the theoretical models which attempt to describe heavy-quark transport and energy loss in these smallest collision systems.

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Allbrooke,¹⁵⁶ B. W. Allen,¹³¹ P. P. Allport,²¹ A. Aloisio,^{69a,69b} A. Alonso,⁴⁰ F. Alonso,⁸⁸ C. Alpigiani,¹⁴⁸ A. A. Alshehri,⁵⁷ M. Alvarez Estevez,⁹⁸ D. Álvarez Piqueras,¹⁷⁴ M. G. Alvigi,^{69a,69b} Y. Amaral Coutinho,^{80b} A. Ambler,¹⁰³ L. Ambroz,¹³⁵ C. Amelung,²⁷ D. Amidei,¹⁰⁵ S. P. Amor Dos Santos,^{140a} S. Amoroso,⁴⁶ C. S. Amrouche,⁵⁴ F. An,⁷⁸ C. Anastopoulos,¹⁴⁹ N. Andari,¹⁴⁵ T. Andeen,¹¹ C. F. Anders,^{61b} J. K. Anders,²⁰ A. Andreazza,^{68a,68b} V. Andrei,^{61a} C. R. Anelli,¹⁷⁶ S. Angelidakis,³⁸ A. Angerami,³⁹ A. V. Anisenkov,^{121b,121a} A. Annovi,^{71a} C. Antel,^{61a} M. T. Anthony,¹⁴⁹ E. Antipov,¹²⁹ M. Antonelli,⁵¹ D. J. A. Antrim,¹⁷¹ F. Anulli,^{72a} M. Aoki,⁸¹ J. A. Aparisi Pozo,¹⁷⁴ L. Aperio Bella,^{15a} G. Arabidze,¹⁰⁶ J. P. Araque,^{140a} V. Araujo Ferraz,^{80b} R. Araujo Pereira,^{80b} C. Arcangeletti,⁵¹ A. T. H. Arce,⁴⁹ F. A. Arduh,⁸⁸ J-F. Arguin,¹⁰⁹ S. Argyropoulos,⁷⁷ J.-H. Arling,⁴⁶ A. J. Armbruster,³⁶ A. Armstrong,¹⁷¹ O. Arnæz,¹⁶⁷ H. Arnold,¹¹⁹ Z. P. Arrubarrena Tame,¹¹³ A. Artamonov,^{123,a} G. Artoni,¹³⁵ S. Artz,⁹⁹ S. Asai,¹⁶³ N. Asbah,⁵⁹ E. M. Asimakopoulou,¹⁷² L. Asquith,¹⁵⁶ J. Assahsah,^{35d} K. Assamagan,^{26b} R. Astalos,^{29a} R. J. Atkin,^{33a} M. Atkinson,¹⁷³ N. B. Atlay,¹⁹ H. Atmani,¹³² K. Augsten,¹⁴² G. Avolio,³⁶ R. Avramidou,^{60a} M. K. Ayoub,^{15a} A. M. Azoulay,^{168b} G. Azuelos,^{109,d} H. Bachacou,¹⁴⁵ K. Bachas,^{67a,67b} M. Backes,¹³⁵ F. Backman,^{45a,45b} P. Bagnaia,^{72a,72b} M. Bahmani,⁸⁴ H. Bahrasemani,¹⁵² A. J. Bailey,¹⁷⁴ V. R. Bailey,¹⁷³ J. T. Baines,¹⁴⁴ M. Bajic,⁴⁰ C. Bakalis,¹⁰ O. K. Baker,¹⁸³ P. J. Bakker,¹¹⁹ D. Bakshi Gupta,⁸ S. Balaji,¹⁵⁷ E. M. Baldin,^{121b,121a} P. Balek,¹⁸⁰ F. Balli,¹⁴⁵ W. K. Balunas,¹³⁵ J. Balz,⁹⁹ E. Banas,⁸⁴ A. Bandyopadhyay,²⁴ Sw. Banerjee,^{181,e} A. A. E. Bannoura,¹⁸² L. Barak,¹⁶¹ W. M. Barbe,³⁸ E. L. Barberio,¹⁰⁴ D. Barberis,^{55b,55a} M. Barbero,¹⁰¹ G. Barbour,⁹⁴ T. Barillari,¹¹⁴ M-S. Barisits,³⁶ J. Barkeloo,¹³¹ T. Barklow,¹⁵³ R. Barnea,¹⁶⁰ S. L. Barnes,^{60c} B. M. Barnett,¹⁴⁴ R. M. Barnett,¹⁸ Z. Barnovska-Blenessy,^{60a} A. Baroncelli,^{60a} G. Barone,^{26b} A. J. Barr,¹³⁵ L. Barranco Navarro,^{45a,45b} F. Barreiro,⁹⁸ J. Barreiro Guimarães da Costa,^{15a} S. Barsov,¹³⁸ R. Bartoldus,¹⁵³ G. Bartolini,¹⁰¹ A. E. Barton,⁸⁹ P. Bartos,^{29a} A. Basalaeu,⁴⁶ A. Bassalat,^{132,f} M. J. Basso,¹⁶⁷ R. L. Bates,⁵⁷ S. Batlamous,^{35e} J. R. Batley,³² B. Batool,¹⁵¹ M. Battaglia,¹⁴⁶ M. Bause,^{72a,72b} F. Bauer,¹⁴⁵ K. T. Bauer,¹⁷¹ H. S. Bawa,^{31,g} J. B. Beacham,⁴⁹ T. Beau,¹³⁶ P. H. Beauchemin,¹⁷⁰ F. Becherer,⁵² P. Bechtel,²⁴ H. C. Beck,⁵³ H. P. Beck,^{20,h} K. Becker,⁵² M. Becker,⁹⁹ C. Becot,⁴⁶ A. Beddall,^{12d} A. J. Beddall,^{12a} V. A. Bednyakov,⁷⁹ M. Bedognetti,¹¹⁹ C. P. Bee,¹⁵⁵ T. A. Beermann,¹⁸² M. Begalli,^{80b} M. Begel,^{26b} A. Behera,¹⁵⁵ J. K. Behr,⁴⁶ F. Beisiegel,²⁴ A. S. Bell,⁹⁴ G. Bella,¹⁶¹ L. Bellagamba,^{23b} A. Bellerive,³⁴ P. Bellos,⁹ K. Beloborodov,^{121b,121a} K. Belotskiy,¹¹¹ N. L. Belyaev,¹¹¹ D. Benckekroun,^{35a} N. Benekos,¹⁰ Y. Benhammou,¹⁶¹ D. P. Benjamin,⁶ M. Benoit,⁵⁴ J. R. Bensinger,²⁷ S. Bentvelsen,¹¹⁹ L. Beresford,¹³⁵ M. Beretta,⁵¹ D. Berge,⁴⁶ E. Bergeas Kuutmann,¹⁷² N. Berger,⁵ B. Bergmann,¹⁴² L. J. Bergsten,²⁷ J. Beringer,¹⁸ S. Berlendis,⁷ G. Bernardi,¹³⁶ C. Bernius,¹⁵³ F. U. Bernlochner,²⁴ T. Berry,⁹³ P. Berta,⁹⁹ C. Bertella,^{15a} I. A. Bertram,⁸⁹ O. Bessidskaia Bylund,¹⁸² N. Besson,¹⁴⁵ A. Bethani,¹⁰⁰ S. Bethke,¹¹⁴ A. Betti,⁴² A. J. Bevan,⁹² J. Beyer,¹¹⁴ D. S. Bhattacharya,¹⁷⁷ P. Bhattarai,²⁷ R. Bi,¹³⁹ R. M. Bianchi,¹³⁹ O. Biebel,¹¹³ D. Biedermann,¹⁹ R. Bielski,³⁶ K. Bierwagen,⁹⁹ N. V. Biesuz,^{71a,71b} M. Biglietti,^{74a} T. R. V. Billoud,¹⁰⁹ M. Bindi,⁵³ A. Bingul,^{12d} C. Bini,^{72a,72b} S. Biondi,^{23b,23a} M. Birman,¹⁸⁰ T. Bisanz,⁵³ J. P. Biswal,¹⁶¹ D. Biswas,^{181,e} A. Bitadze,¹⁰⁰ C. Bittrich,⁴⁸ K. Björke,¹³⁴ K. M. Black,²⁵ T. Blazek,^{29a} I. Bloch,⁴⁶ C. Blocker,²⁷ A. Blue,⁵⁷ U. Blumenschein,⁹² G. J. Bobbink,¹¹⁹ V. S. Bobrovnikov,^{121b,121a} S. S. Bocchetta,⁹⁶ A. Bocci,⁴⁹ D. Boerner,⁴⁶ D. Bogavac,¹⁴ A. G. Bogdanchikov,^{121b,121a} C. Bohm,^{45a} V. Boisvert,⁹³ P. Bokač,^{53,172} T. Bold,^{83a} A. S. Boldyrev,¹¹² A. E. Bolz,^{61b}

M. Bomben,¹³⁶ M. Bona,⁹² J. S. Bonilla,¹³¹ M. Boonekamp,¹⁴⁵ C. D. Booth,⁹³ H. M. Borecka-Bielska,⁹⁰ A. Borisov,¹²²
 G. Borissou,⁸⁹ J. Bortfeldt,³⁶ D. Bortoletto,¹³⁵ D. Boscherini,^{23b} M. Bosman,¹⁴ J. D. Bossio Sola,¹⁰³ K. Bouaouda,^{35a}
 J. Boudreau,¹³⁹ E. V. Bouhova-Thacker,⁸⁹ D. Boumediene,³⁸ S. K. Boutle,⁵⁷ A. Boveia,¹²⁶ J. Boyd,³⁶ D. Boye,^{33b,i}
 I. R. Boyko,⁷⁹ A. J. Bozson,⁹³ J. Bracini,²¹ N. Brahimi,¹⁰¹ G. Brandt,¹⁸² O. Brandt,³² F. Braren,⁴⁶ B. Brau,¹⁰² J. E. Brau,¹³¹
 W. D. Breaden Madden,⁵⁷ K. Brendlinger,⁴⁶ L. Brenner,⁴⁶ R. Brenner,¹⁷² S. Bressler,¹⁸⁰ B. Brickwedde,⁹⁹ D. L. Briglin,²¹
 D. Britton,⁵⁷ D. Britzger,¹¹⁴ I. Brock,²⁴ R. Brock,¹⁰⁶ G. Brooijmans,³⁹ W. K. Brooks,^{147c} E. Brost,¹²⁰ J. H. Broughton,²¹
 P. A. Bruckman de Renstrom,⁸⁴ D. Bruncko,^{29b} A. Bruni,^{23b} G. Bruni,^{23b} L. S. Bruni,¹¹⁹ S. Bruno,^{73a,73b} M. Bruschi,^{23b}
 N. Bruscolo,¹³⁹ P. Bryant,³⁷ L. Bryngemark,⁹⁶ T. Buanes,¹⁷ Q. Buat,³⁶ P. Buchholz,¹⁵¹ A. G. Buckley,⁵⁷ I. A. Budagov,⁷⁹
 M. K. Bugge,¹³⁴ F. Bühner,⁵² O. Bulekov,¹¹¹ T. J. Burch,¹²⁰ S. Burdin,⁹⁰ C. D. Burgard,¹¹⁹ A. M. Burger,¹²⁹ B. Burghgrave,⁸
 J. T. P. Burr,⁴⁶ C. D. Burton,¹¹ J. C. Burzynski,¹⁰² V. Büscher,⁹⁹ E. Buschmann,⁵³ P. J. Bussey,⁵⁷ J. M. Butler,²⁵
 C. M. Buttar,⁵⁷ J. M. Butterworth,⁹⁴ P. Butti,³⁶ W. Buttinger,³⁶ C. J. Buxo Vazquez,¹⁰⁶ A. Buzatu,¹⁵⁸ A. R. Buzykaev,^{121b,121a}
 G. Cabras,^{23b,23a} S. Cabrera Urbán,¹⁷⁴ D. Caforio,⁵⁶ H. Cai,¹⁷³ V. M. M. Cairo,¹⁵³ O. Cakir,^{4a} N. Calace,³⁶ P. Calafiura,¹⁸
 A. Calandri,¹⁰¹ G. Calderini,¹³⁶ P. Calfayan,⁶⁵ G. Callea,⁵⁷ L. P. Caloba,^{80b} S. Calvente Lopez,⁹⁸ D. Calvet,³⁸ S. Calvet,³⁸
 T. P. Calvet,¹⁵⁵ M. Calvetti,^{71a,71b} R. Camacho Toro,¹³⁶ S. Camarda,³⁶ D. Camarero Munoz,⁹⁸ P. Camarri,^{73a,73b}
 D. Cameron,¹³⁴ R. Caminal Armadans,¹⁰² C. Camincher,³⁶ S. Campana,³⁶ M. Campanelli,⁹⁴ A. Camplani,⁴⁰
 A. Campoverde,¹⁵¹ V. Canale,^{69a,69b} A. Canesse,¹⁰³ M. Cano Bret,^{60c} J. Cantero,¹²⁹ T. Cao,¹⁶¹ Y. Cao,¹⁷³
 M. D. M. Capeans Garrido,³⁶ M. Capua,^{41b,41a} R. Cardarelli,^{73a} F. Cardillo,¹⁴⁹ G. Carducci,^{41b,41a} I. Carli,¹⁴³ T. Carli,³⁶
 G. Carlino,^{69a} B. T. Carlson,¹³⁹ L. Carminati,^{68a,68b} R. M. D. Carney,^{45a,45b} S. Caron,¹¹⁸ E. Carquin,^{147c} S. Carrá,⁴⁶
 J. W. S. Carter,¹⁶⁷ M. P. Casado,^{14j} A. F. Casha,¹⁶⁷ D. W. Casper,¹⁷¹ R. Castelijn,¹¹⁹ F. L. Castillo,¹⁷⁴ V. Castillo Gimenez,¹⁷⁴
 N. F. Castro,^{140a,140e} A. Catinaccio,³⁶ J. R. Catmore,¹³⁴ A. Cattai,³⁶ J. Caudron,²⁴ V. Cavaliere,^{26b} E. Cavallaro,¹⁴
 M. Cavalli-Sforza,¹⁴ V. Cavasinni,^{71a,71b} E. Celebi,^{12b} F. Ceradini,^{74a,74b} L. Cerda Alberich,¹⁷⁴ K. Cerny,¹³⁰
 A. S. Cerqueira,^{80a} A. Cerri,¹⁵⁶ L. Cerrito,^{73a,73b} F. Cerutti,¹⁸ A. Cervelli,^{23b,23a} S. A. Cetin,^{12b} Z. Chadi,^{35a} D. Chakraborty,¹²⁰
 S. K. Chan,⁵⁹ W. S. Chan,¹¹⁹ W. Y. Chan,⁹⁰ J. D. Chapman,³² B. Chargeishvili,^{159b} D. G. Charlton,²¹ T. P. Charman,⁹²
 C. C. Chau,³⁴ S. Che,¹²⁶ S. Chekanov,⁶ S. V. Chekulaev,^{168a} G. A. Chelkov,^{79k} M. A. Chelstowska,³⁶ B. Chen,⁷⁸ C. Chen,^{60a}
 C. H. Chen,⁷⁸ H. Chen,^{26b} J. Chen,^{60a} J. Chen,³⁹ S. Chen,¹³⁷ S. J. Chen,^{15c} X. Chen,^{15b,1} Y. Chen,⁸² Y.-H. Chen,⁴⁶
 H. C. Cheng,^{63a} H. J. Cheng,^{15a} A. Cheplakov,⁷⁹ E. Cheremushkina,¹²² R. Cherkaoui El Moursli,^{35e} E. Cheu,⁷ K. Cheung,⁶⁴
 T. J. A. Chevaléras,¹⁴⁵ L. Chevalier,¹⁴⁵ V. Chiarella,⁵¹ G. Chiarelli,^{71a} G. Chiodini,^{67a} A. S. Chisholm,²¹ A. Chitan,^{28b}
 I. Chiu,¹⁶³ Y. H. Chiu,¹⁷⁶ M. V. Chizhov,⁷⁹ K. Choi,⁶⁵ A. R. Chomont,^{72a,72b} S. Chouridou,¹⁶² Y. S. Chow,¹¹⁹ M. C. Chu,^{63a}
 X. Chu,^{15a,15d} J. Chudoba,¹⁴¹ A. J. Chuinard,¹⁰³ J. J. Chwastowski,⁸⁴ L. Chytka,¹³⁰ D. Cieri,¹¹⁴ K. M. Ciesla,⁸⁴ D. Cinca,⁴⁷
 V. Cindro,⁹¹ I. A. Cioară,^{28b} A. Ciocio,¹⁸ F. Ciroto,^{69a,69b} Z. H. Citron,^{180,m} M. Citterio,^{68a} D. A. Ciubotaru,^{28b}
 B. M. Ciungu,¹⁶⁷ A. Clark,⁵⁴ M. R. Clark,³⁹ P. J. Clark,⁵⁰ C. Clement,^{45a,45b} Y. Coadou,¹⁰¹ M. Cobal,^{66a,66c} A. Coccaro,^{55b}
 J. Cochran,⁷⁸ H. Cohen,¹⁶¹ A. E. C. Coimbra,³⁶ L. Colasurdo,¹¹⁸ B. Cole,³⁹ A. P. Colijn,¹¹⁹ J. Collot,⁵⁸ P. Conde Muño,^{140a,n}
 E. Coniavitis,⁵² S. H. Connell,^{33b} I. A. Connelly,⁵⁷ S. Constantinescu,^{28b} F. Conventi,^{69a,o} A. M. Cooper-Sarkar,¹³⁵
 F. Cormier,¹⁷⁵ K. J. R. Cormier,¹⁶⁷ L. D. Corpe,⁹⁴ M. Corradi,^{72a,72b} E. E. Corrigan,⁹⁶ F. Corriveau,^{103,p}
 A. Cortes-Gonzalez,³⁶ M. J. Costa,¹⁷⁴ F. Costanza,⁵ D. Costanzo,¹⁴⁹ G. Cowan,⁹³ J. W. Cowley,³² J. Crane,¹⁰⁰ K. Cranmer,¹²⁴
 S. J. Crawley,⁵⁷ R. A. Creager,¹³⁷ S. Crépe-Renaudin,⁵⁸ F. Crescioli,¹³⁶ M. Cristinziani,²⁴ V. Croft,¹¹⁹ G. Crosetti,^{41b,41a}
 A. Cueto,⁵ T. Cuhadar Donszelmann,¹⁴⁹ A. R. Cukierman,¹⁵³ W. R. Cunningham,⁵⁷ S. Czekierda,⁸⁴ P. Czodrowski,³⁶
 M. J. Da Cunha Sargedas De Sousa,^{60b} J. V. Da Fonseca Pinto,^{80b} C. Da Via,¹⁰⁰ W. Dabrowski,^{83a} T. Dado,^{29a} S. Dahbi,^{35e}
 T. Dai,¹⁰⁵ C. Dallapiccola,¹⁰² M. Dam,⁴⁰ G. D'amen,^{26b} V. D'Amico,^{74a,74b} J. Damp,⁹⁹ J. R. Dandoy,¹³⁷ M. F. Daneri,³⁰
 N. P. Dang,^{181,e} N. S. Dann,¹⁰⁰ M. Danninger,¹⁷⁵ V. Dao,³⁶ G. Darbo,^{55b} O. Dartsis,⁵ A. Dattagupta,¹³¹ T. Daubney,⁴⁶
 S. D'Auria,^{68a,68b} W. Davey,²⁴ C. David,⁴⁶ T. Davidek,¹⁴³ D. R. Davis,⁴⁹ I. Dawson,¹⁴⁹ K. De,⁸ R. De Asmundis,^{69a}
 M. De Beurs,¹¹⁹ S. De Castro,^{23b,23a} S. De Cecco,^{72a,72b} N. De Groot,¹¹⁸ P. de Jong,¹¹⁹ H. De la Torre,¹⁰⁶ A. De Maria,^{15c}
 D. De Pedis,^{72a} A. De Salvo,^{72a} U. De Sanctis,^{73a,73b} M. De Santis,^{73a,73b} A. De Santo,¹⁵⁶ K. De Vasconcelos Corga,¹⁰¹
 J. B. De Vivie De Regie,¹³² C. Debenedetti,¹⁴⁶ D. V. Dedovich,⁷⁹ A. M. Deiana,⁴² M. Del Gaudio,^{41b,41a} J. Del Peso,⁹⁸
 Y. Delabat Diaz,⁴⁶ D. Delgove,¹³² F. Deliot,^{145,q} C. M. Delitzsch,⁷ M. Della Pietra,^{69a,69b} D. Della Volpe,⁵⁴ A. Dell'Acqua,³⁶
 L. Dell'Asta,^{73a,73b} M. Delmastro,⁵ C. Delporte,¹³² P. A. Delsart,⁵⁸ D. A. DeMarco,¹⁶⁷ S. Demers,¹⁸³ M. Demichev,⁷⁹
 G. Demontigny,¹⁰⁹ S. P. Denisov,¹²² D. Denysiuk,¹¹⁹ L. D'Eramo,¹³⁶ D. Derendarz,⁸⁴ J. E. Derkaoui,^{35d} F. Derue,¹³⁶
 P. Dervan,⁹⁰ K. Desch,²⁴ C. Deterre,⁴⁶ K. Dette,¹⁶⁷ C. Deutsch,²⁴ M. R. Devesa,³⁰ P. O. Deviveiros,³⁶ A. Dewhurst,¹⁴⁴
 F. A. Di Bello,⁵⁴ A. Di Ciaccio,^{73a,73b} L. Di Ciaccio,⁵ W. K. Di Clemente,¹³⁷ C. Di Donato,^{69a,69b} A. Di Girolamo,³⁶

G. Di Gregorio,^{71a,71b} B. Di Micco,^{74a,74b} R. Di Nardo,¹⁰² K. F. Di Petrillo,⁵⁹ R. Di Sipio,¹⁶⁷ D. Di Valentino,³⁴ C. Diaconu,¹⁰¹
 F. A. Dias,⁴⁰ T. Dias Do Vale,^{140a} M. A. Diaz,^{147a} J. Dickinson,¹⁸ E. B. Diehl,¹⁰⁵ J. Dietrich,¹⁹ S. Díez Cornell,⁴⁶
 A. Dimitrievska,¹⁸ W. Ding,^{15b} J. Dingfelder,²⁴ F. Dittus,³⁶ F. Djama,¹⁰¹ T. Djobava,^{159b} J. I. Djuvsland,¹⁷
 M. A. B. Do Vale,^{80c} M. Dobre,^{28b} D. Dodsworth,²⁷ C. Doglioni,⁹⁶ J. Dolejsi,¹⁴³ Z. Dolezal,¹⁴³ M. Donadelli,^{80d} B. Dong,^{60c}
 J. Donini,³⁸ A. D'onofrio,⁹² M. D'Onofrio,⁹⁰ J. Dopke,¹⁴⁴ A. Doria,^{69a} M. T. Dova,⁸⁸ A. T. Doyle,⁵⁷ E. Drechsler,¹⁵²
 E. Dreyer,¹⁵² T. Dreyer,⁵³ A. S. Drobac,¹⁷⁰ D. Du,^{60b} Y. Duan,^{60b} F. Dubinin,¹¹⁰ M. Dubovsky,^{29a} A. Dubreuil,⁵⁴
 E. Duchovni,¹⁸⁰ G. Duckeck,¹¹³ A. Ducourthial,¹³⁶ O. A. Ducu,¹⁰⁹ D. Duda,¹¹⁴ A. Dudarev,³⁶ A. C. Dudder,⁹⁹
 E. M. Duffield,¹⁸ L. Dufлот,¹³² M. Dührssen,³⁶ C. Dülsen,¹⁸² M. Dumancic,¹⁸⁰ A. E. Dumitriu,^{28b} A. K. Duncan,⁵⁷
 M. Dunford,^{61a} A. Duperrin,¹⁰¹ H. Duran Yildiz,^{4a} M. Düren,⁵⁶ A. Durglishvili,^{159b} D. Duschinger,⁴⁸ B. Dutta,⁴⁶
 D. Duvnjak,¹ G. I. Dyckes,¹³⁷ M. Dyndal,³⁶ S. Dysch,¹⁰⁰ B. S. Dziedzic,⁸⁴ K. M. Ecker,¹¹⁴ R. C. Edgar,¹⁰⁵
 M. G. Eggleston,⁴⁹ T. Eifert,³⁶ G. Eigen,¹⁷ K. Einsweiler,¹⁸ T. Ekelof,¹⁷² H. El Jarrari,^{35e} M. El Kacimi,^{35c} R. El Kosseifi,¹⁰¹
 V. Ellajosyula,¹⁷² M. Ellert,¹⁷² F. Ellinghaus,¹⁸² A. A. Elliot,⁹² N. Ellis,³⁶ J. Elmsheuser,^{26b} M. Elsing,³⁶ D. Emelianov,¹⁴⁴
 A. Emerman,³⁹ Y. Enari,¹⁶³ M. B. Epland,⁴⁹ J. Erdmann,⁴⁷ A. Ereditato,²⁰ M. Errenst,³⁶ M. Escalier,¹³² C. Escobar,¹⁷⁴
 O. Estrada Pastor,¹⁷⁴ E. Etzion,¹⁶¹ H. Evans,⁶⁵ A. Ezhilov,¹³⁸ F. Fabbri,⁵⁷ L. Fabbri,^{23b,23a} V. Fabiani,¹¹⁸ G. Facini,⁹⁴
 R. M. Faisca Rodrigues Pereira,^{140a} R. M. Fakhruddinov,¹²² S. Falciano,^{72a} P. J. Falke,⁵ S. Falke,⁵ J. Faltova,¹⁴³ Y. Fang,^{15a}
 Y. Fang,^{15a} G. Fanourakis,⁴⁴ M. Fanti,^{68a,68b} M. Faraj,^{66a,66c,r} A. Farbin,⁸ A. Farilla,^{74a} E. M. Farina,^{70a,70b} T. Faroque,¹⁰⁶
 S. Farrell,¹⁸ S. M. Farrington,⁵⁰ P. Farthouat,³⁶ F. Fassi,^{35e} P. Fassnacht,³⁶ D. Fassouliotis,⁹ M. Fauci Giannelli,⁵⁰
 W. J. Fawcett,³² L. Fayard,¹³² O. L. Fedin,^{138,s} W. Fedorko,¹⁷⁵ A. Fehr,²⁰ M. Feickert,⁴² L. Feligioni,¹⁰¹ A. Fell,¹⁴⁹
 C. Feng,^{60b} E. J. Feng,³⁶ M. Feng,⁴⁹ M. J. Fenton,⁵⁷ A. B. Fenyuk,¹²² J. Ferrando,⁴⁶ A. Ferrante,¹⁷³ A. Ferrari,¹⁷² P. Ferrari,¹¹⁹
 R. Ferrari,^{70a} D. E. Ferreira de Lima,^{61b} A. Ferrer,¹⁷⁴ D. Ferrere,⁵⁴ C. Ferretti,¹⁰⁵ F. Fiedler,⁹⁹ A. Filipčič,⁹¹ F. Filthaut,¹¹⁸
 K. D. Finelli,²⁵ M. C. N. Fiolhais,^{140a,140c,t} L. Fiorini,¹⁷⁴ F. Fischer,¹¹³ W. C. Fisher,¹⁰⁶ I. Fleck,¹⁵¹ P. Fleischmann,¹⁰⁵
 R. R. M. Fletcher,¹³⁷ T. Flick,¹⁸² B. M. Flierl,¹¹³ L. Flores,¹³⁷ L. R. Flores Castillo,^{63a} F. M. Follega,^{75a,75b} N. Fomin,¹⁷
 J. H. Foo,¹⁶⁷ G. T. Forcolin,^{75a,75b} A. Formica,¹⁴⁵ F. A. Förster,¹⁴ A. C. Forti,¹⁰⁰ A. G. Foster,²¹ M. G. Foti,¹³⁵ D. Fournier,¹³²
 H. Fox,⁸⁹ P. Francavilla,^{71a,71b} S. Francescato,^{72a,72b} M. Franchini,^{23b,23a} S. Franchino,^{61a} D. Francis,³⁶ L. Franconi,²⁰
 M. Franklin,⁵⁹ A. N. Fray,⁹² P. M. Freeman,²¹ B. Freund,¹⁰⁹ W. S. Freund,^{80b} E. M. Freundlich,⁴⁷ D. C. Frizzell,¹²⁸
 D. Froidevaux,³⁶ J. A. Frost,¹³⁵ C. Fukunaga,¹⁶⁴ E. Fullana Torregrosa,¹⁷⁴ E. Fumagalli,^{55b,55a} T. Fusayasu,¹¹⁵ J. Fuster,¹⁷⁴
 A. Gabrielli,^{23b,23a} A. Gabrielli,¹⁸ G. P. Gach,^{83a} S. Gadatsch,⁵⁴ P. Gadow,¹¹⁴ G. Gagliardi,^{55b,55a} L. G. Gagnon,¹⁰⁹
 C. Galea,^{28b} B. Galhardo,^{140a} G. E. Gallardo,¹³⁵ E. J. Gallas,¹³⁵ B. J. Gallop,¹⁴⁴ G. Galster,⁴⁰ R. Gamboa Goni,⁹²
 K. K. Gan,¹²⁶ S. Ganguly,¹⁸⁰ J. Gao,^{60a} Y. Gao,⁵⁰ Y. S. Gao,^{31,g} C. García,¹⁷⁴ J. E. García Navarro,¹⁷⁴ J. A. García Pascual,^{15a}
 C. Garcia-Argos,⁵² M. Garcia-Sciveres,¹⁸ R. W. Gardner,³⁷ N. Garelli,¹⁵³ S. Gargiulo,⁵² V. Garonne,¹³⁴ A. Gaudiello,^{55b,55a}
 G. Gaudio,^{70a} I. L. Gavrilenko,¹¹⁰ A. Gavrilyuk,¹²³ C. Gay,¹⁷⁵ G. Gaycken,⁴⁶ E. N. Gazis,¹⁰ A. A. Geanta,^{28b} C. M. Gee,¹⁴⁶
 C. N. P. Gee,¹⁴⁴ J. Geisen,⁵³ M. Geisen,⁹⁹ C. Gemme,^{55b} M. H. Genest,⁵⁸ C. Geng,¹⁰⁵ S. Gentile,^{72a,72b} S. George,⁹³
 T. Geralis,⁴⁴ L. O. Gerlach,⁵³ P. Gessinger-Befurt,⁹⁹ G. Gessner,⁴⁷ S. Ghasemi,¹⁵¹ M. Ghasemi Bostanabad,¹⁷⁶ A. Ghosh,¹³²
 A. Ghosh,⁷⁷ B. Giacobbe,^{23b} S. Giagu,^{72a,72b} N. Giangiacomi,^{23b,23a} P. Giannetti,^{71a} A. Giannini,^{69a,69b} G. Giannini,¹⁴
 S. M. Gibson,⁹³ M. Gignac,¹⁴⁶ D. Gillberg,³⁴ G. Gilles,¹⁸² D. M. Gingrich,^{3,d} M. P. Giordani,^{66a,66c} F. M. Giorgi,^{23b}
 P. F. Giraud,¹⁴⁵ G. Giugliarelli,^{66a,66c} D. Giugni,^{68a} F. Giuli,^{73a,73b} S. Gkaitatzis,¹⁶² I. Gkialas,^{9,u} E. L. Gkoukousis,¹⁴
 P. Gkoutoumis,¹⁰ L. K. Gladilin,¹¹² C. Glasman,⁹⁸ J. Glatzer,¹⁴ P. C. F. Glaysher,⁴⁶ A. Glazov,⁴⁶ G. R. Gledhill,¹³¹
 M. Goblirsch-Kolb,²⁷ D. Godin,¹⁰⁹ S. Goldfarb,¹⁰⁴ T. Golling,⁵⁴ D. Golubkov,¹²² A. Gomes,^{140a,140b} R. Goncalves Gama,⁵³
 R. Gonçalves,^{140a,140b} G. Gonella,⁵² L. Gonella,²¹ A. Gongadze,⁷⁹ F. Gonnella,²¹ J. L. Gonski,⁵⁹ S. González de la Hoz,¹⁷⁴
 S. Gonzalez-Sevilla,⁵⁴ G. R. Gonzalvo Rodriguez,¹⁷⁴ L. Goossens,³⁶ P. A. Gorbounov,¹²³ H. A. Gordon,^{26b} B. Gorini,³⁶
 E. Gorini,^{67a,67b} A. Gorišek,⁹¹ A. T. Goshaw,⁴⁹ M. I. Gostkin,⁷⁹ C. A. Gottardo,¹¹⁸ M. Gouighri,^{35b} D. Goujdami,^{35c}
 A. G. Goussiou,¹⁴⁸ N. Govender,^{33b} C. Goy,⁵ E. Gozani,¹⁶⁰ I. Grabowska-Bold,^{83a} E. C. Graham,⁹⁰ J. Gramling,¹⁷¹
 E. Gramstad,¹³⁴ S. Grancagnolo,¹⁹ M. Grandi,¹⁵⁶ V. Gratchev,¹³⁸ P. M. Gravila,^{28f} F. G. Gravili,^{67a,67b} C. Gray,⁵⁷
 H. M. Gray,¹⁸ C. Grefe,²⁴ K. Gregersen,⁹⁶ I. M. Gregor,⁴⁶ P. Grenier,¹⁵³ K. Grevtsov,⁴⁶ C. Grieco,¹⁴ N. A. Grieser,¹²⁸
 A. A. Grillo,¹⁴⁶ K. Grimm,^{31,v} S. Grinstein,^{14,w} J.-F. Grivaz,¹³² S. Groh,⁹⁹ E. Gross,¹⁸⁰ J. Grosse-Knetter,⁵³ Z. J. Groat,⁹⁴
 C. Grud,¹⁰⁵ A. Grummer,¹¹⁷ L. Guan,¹⁰⁵ W. Guan,¹⁸¹ J. Guenther,³⁶ A. Guerguichon,¹³² J. G. R. Guerrero Rojas,¹⁷⁴
 F. Guescini,¹¹⁴ D. Guest,¹⁷¹ R. Gugel,⁹⁹ T. Guillemin,⁵ S. Guindon,³⁶ U. Gul,⁵⁷ J. Guo,^{60c} W. Guo,¹⁰⁵ Y. Guo,^{60a,x} Z. Guo,¹⁰¹
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J. Haley,¹²⁹ G. Halladjian,¹⁰⁶ G. D. Hallewell,¹⁰¹ K. Hamacher,¹⁸² P. Hamal,¹³⁰ K. Hamano,¹⁷⁶ H. Hamdaoui,^{35e}
G. N. Hamity,¹⁴⁹ K. Han,^{60a,y} L. Han,^{60a} S. Han,^{15a} Y. F. Han,¹⁶⁷ K. Hanagaki,^{81,z} M. Hance,¹⁴⁶ D. M. Handl,¹¹³ B. Haney,¹³⁷
R. Hankache,¹³⁶ E. Hansen,⁹⁶ J. B. Hansen,⁴⁰ J. D. Hansen,⁴⁰ M. C. Hansen,²⁴ P. H. Hansen,⁴⁰ E. C. Hanson,¹⁰⁰ K. Hara,¹⁶⁹
T. Harenberg,¹⁸² S. Harkusha,¹⁰⁷ P. F. Harrison,¹⁷⁸ N. M. Hartmann,¹¹³ Y. Hasegawa,¹⁵⁰ A. Hasib,⁵⁰ S. Hassani,¹⁴⁵ S. Haug,²⁰
R. Hauser,¹⁰⁶ L. B. Havener,³⁹ M. Havranek,¹⁴² C. M. Hawkes,²¹ R. J. Hawkings,³⁶ D. Hayden,¹⁰⁶ C. Hayes,¹⁵⁵
R. L. Hayes,¹⁷⁵ C. P. Hays,¹³⁵ J. M. Hays,⁹² H. S. Hayward,⁹⁰ S. J. Haywood,¹⁴⁴ F. He,^{60a} M. P. Heath,⁵⁰ V. Hedberg,⁹⁶
L. Heelan,⁸ S. Heer,²⁴ K. K. Heidegger,⁵² W. D. Heidorn,⁷⁸ J. Heilman,³⁴ S. Heim,⁴⁶ T. Heim,¹⁸ B. Heinemann,^{46,aa}
J. J. Heinrich,¹³¹ L. Heinrich,³⁶ C. Heinz,⁵⁶ J. Hejbal,¹⁴¹ L. Helary,^{61b} A. Held,¹⁷⁵ S. Hellesund,¹³⁴ C. M. Helling,¹⁴⁶
S. Hellman,^{45a,45b} C. Hensens,³⁶ R. C. W. Henderson,⁸⁹ Y. Heng,¹⁸¹ S. Henkelmann,¹⁷⁵ A. M. Henriques Correia,³⁶
G. H. Herbert,¹⁹ H. Herde,²⁷ V. Herget,¹⁷⁷ Y. Hernández Jiménez,^{33d} H. Herr,⁹⁹ M. G. Herrmann,¹¹³ T. Herrmann,⁴⁸
G. Herten,⁵² R. Hertenberger,¹¹³ L. Hervas,³⁶ T. C. Herwig,¹³⁷ G. G. Hesketh,⁹⁴ N. P. Hessey,^{168a} A. Higashida,¹⁶³
S. Higashino,⁸¹ E. Higón-Rodríguez,¹⁷⁴ K. Hildebrand,³⁷ E. Hill,¹⁷⁶ J. C. Hill,³² K. K. Hill,^{26b} K. H. Hiller,⁴⁶ S. J. Hillier,²¹
M. Hils,⁴⁸ I. Hinchliffe,¹⁸ F. Hinterkeuser,²⁴ M. Hirose,¹³³ S. Hirose,⁵² D. Hirschbuehl,¹⁸² B. Hiti,⁹¹ O. Hladik,¹⁴¹
D. R. Hlaluku,^{33d} X. Hoad,⁵⁰ J. Hobbs,¹⁵⁵ N. Hod,¹⁸⁰ M. C. Hodgkinson,¹⁴⁹ A. Hoecker,³⁶ F. Hoenig,¹¹³ D. Hohn,⁵²
D. Hohov,¹³² T. R. Holmes,³⁷ M. Holzbock,¹¹³ L. B. A. H. Hommels,³² S. Honda,¹⁶⁹ T. M. Hong,¹³⁹ J. C. Honig,⁵²
A. Hönle,¹¹⁴ B. H. Hooberman,¹⁷³ W. H. Hopkins,⁶ Y. Horii,¹¹⁶ P. Horn,⁴⁸ L. A. Horyn,³⁷ S. Hou,¹⁵⁸ A. Houmada,^{35a}
J. Howarth,¹⁰⁰ J. Hoya,⁸⁸ M. Hrabovsky,¹³⁰ J. Hrdinka,⁷⁶ I. Hristova,¹⁹ J. Hrivnac,¹³² A. Hrynevich,¹⁰⁸ T. Hryn'ova,⁵
P. J. Hsu,⁶⁴ S.-C. Hsu,¹⁴⁸ Q. Hu,^{26b} S. Hu,^{60c} Y. F. Hu,^{15a,15d} D. P. Huang,⁹⁴ Y. Huang,^{60a} Y. Huang,^{15a} Z. Hubacek,¹⁴²
F. Hubaut,¹⁰¹ M. Huebner,²⁴ F. Huegging,²⁴ T. B. Huffman,¹³⁵ M. Huhtinen,³⁶ R. F. H. Hunter,³⁴ P. Huo,¹⁵⁵ A. M. Hupe,³⁴
N. Huseynov,^{79,bb} J. Huston,¹⁰⁶ J. Huth,⁵⁹ R. Hyneman,¹⁰⁵ S. Hyrych,^{29a} G. Iacobucci,⁵⁴ G. Iakovidis,^{26b} I. Ibragimov,¹⁵¹
L. Iconomidou-Fayard,¹³² Z. Idrissi,^{35e} P. Iengo,³⁶ R. Ignazzi,⁴⁰ O. Igonkina,^{119,acc} R. Iguchi,¹⁶³ T. Iizawa,⁵⁴ Y. Ikegami,⁸¹
M. Ikeno,⁸¹ D. Iliadis,¹⁶² N. Ilic,^{118,167,p} F. Iltzsche,⁴⁸ G. Introzzi,^{70a,70b} M. Iodice,^{74a} K. Iordanidou,^{168a} V. Ippolito,^{72a,72b}
M. F. Isacson,¹⁷² M. Ishino,¹⁶³ W. Islam,¹²⁹ C. Issever,^{19,46} S. Istin,¹⁶⁰ F. Ito,¹⁶⁹ J. M. Iturbe Ponce,^{63a} R. Iuppa,^{75a,75b}
A. Ivina,¹⁸⁰ H. Iwasaki,⁸¹ J. M. Izen,⁴³ V. Izzo,^{69a} P. Jacka,¹⁴¹ P. Jackson,¹ R. M. Jacobs,²⁴ B. P. Jaeger,¹⁵² V. Jain,²
G. Jäkel,¹⁸² K. B. Jakobi,⁹⁹ K. Jakobs,⁵² T. Jakoubek,¹⁴¹ J. Jamieson,⁵⁷ K. W. Janas,^{83a} R. Jansky,⁵⁴ J. Janssen,²⁴ M. Janus,⁵³
P. A. Janus,^{83a} G. Jarlskog,⁹⁶ N. Javadov,^{79,bb} T. Javůrek,³⁶ M. Javurkova,⁵² F. Jeanneau,¹⁴⁵ L. Jeanty,¹³¹ J. Jejelava,^{159a,dd}
A. Jelinskas,¹⁷⁸ P. Jenni,^{52,ee} J. Jeong,⁴⁶ N. Jeong,⁴⁶ S. Jézéquel,⁵ H. Ji,¹⁸¹ J. Jia,¹⁵⁵ H. Jiang,⁷⁸ Y. Jiang,^{60a} Z. Jiang,^{153,ff}
S. Jiggins,⁵² F. A. Jimenez Morales,³⁸ J. Jimenez Pena,¹¹⁴ S. Jin,^{15c} A. Jinaru,^{28b} O. Jinnouchi,¹⁶⁵ H. Jivan,^{33d}
P. Johansson,¹⁴⁹ K. A. Johns,⁷ C. A. Johnson,⁶⁵ K. Jon-And,^{45a,45b} R. W. L. Jones,⁸⁹ S. D. Jones,¹⁵⁶ S. Jones,⁷ T. J. Jones,⁹⁰
J. Jongmanns,^{61a} P. M. Jorge,^{140a} J. Jovicevic,³⁶ X. Ju,¹⁸ J. J. Junggeburth,¹¹⁴ A. Juste Rozas,^{14,w} A. Kaczmarska,⁸⁴
M. Kado,^{72a,72b} H. Kagan,¹²⁶ M. Kagan,¹⁵³ A. Kahn,³⁹ C. Kahra,⁹⁹ T. Kaji,¹⁷⁹ E. Kajomovitz,¹⁶⁰ C. W. Kalderon,⁹⁶
A. Kaluza,⁹⁹ A. Kamenshchikov,¹²² M. Kaneda,¹⁶³ L. Kanjir,⁹¹ Y. Kano,¹¹⁶ V. A. Kantserov,¹¹¹ J. Kanzaki,⁸¹ L. S. Kaplan,¹⁸¹
D. Kar,^{33d} K. Karava,¹³⁵ M. J. Kareem,^{168b} S. N. Karpov,⁷⁹ Z. M. Karpova,⁷⁹ V. Kartvelishvili,⁸⁹ A. N. Karyukhin,¹²²
L. Kashif,¹⁸¹ R. D. Kass,¹²⁶ A. Kastanas,^{45a,45b} C. Kato,^{60d,60c} J. Katzy,⁴⁶ K. Kawade,¹⁵⁰ K. Kawagoe,⁸⁷ T. Kawaguchi,¹¹⁶
T. Kawamoto,¹⁶³ G. Kawamura,⁵³ E. F. Kay,¹⁷⁶ V. F. Kazanin,^{121b,121a} R. Keeler,¹⁷⁶ R. Kehoe,⁴² J. S. Keller,³⁴
E. Kellermann,⁹⁶ D. Kelsey,¹⁵⁶ J. J. Kempster,²¹ J. Kendrick,²¹ K. E. Kennedy,³⁹ O. Kepka,¹⁴¹ S. Kersten,¹⁸²
B. P. Kerševan,⁹¹ S. Ketabchi Haghighat,¹⁶⁷ M. Khader,¹⁷³ F. Khalil-Zada,¹³ M. Khandoga,¹⁴⁵ A. Khanov,¹²⁹
A. G. Kharlamov,^{121b,121a} T. Kharlamova,^{121b,121a} E. E. Khoda,¹⁷⁵ A. Khodinov,¹⁶⁶ T. J. Khoo,⁵⁴ E. Khramov,⁷⁹
J. Khubua,^{159b} S. Kido,⁸² M. Kiehn,⁵⁴ C. R. Kilby,⁹³ Y. K. Kim,³⁷ N. Kimura,⁹⁴ O. M. Kind,¹⁹ B. T. King,^{90,a}
D. Kirchmeier,⁴⁸ J. Kirk,¹⁴⁴ A. E. Kiryunin,¹¹⁴ T. Kishimoto,¹⁶³ D. P. Kisliuk,¹⁶⁷ V. Kitali,⁴⁶ O. Kivernyk,⁵
T. Klapdor-Kleingrothaus,⁵² M. Klassen,^{61a} M. H. Klein,¹⁰⁵ M. Klein,⁹⁰ U. Klein,⁹⁰ K. Kleinknecht,⁹⁹ P. Klimek,¹²⁰
A. Klimentov,^{26b} T. Klingl,²⁴ T. Klioutchnikova,³⁶ F. F. Klitzner,¹¹³ P. Kluit,¹¹⁹ S. Kluth,¹¹⁴ E. Kneringer,⁷⁶
E. B. F. G. Knoop,¹⁰¹ A. Knue,⁵² D. Kobayashi,⁸⁷ T. Kobayashi,¹⁶³ M. Kobel,⁴⁸ M. Kocian,¹⁵³ P. Kodys,¹⁴³ P. T. Koenig,²⁴
T. Koffas,³⁴ N. M. Köhler,³⁶ T. Koi,¹⁵³ M. Kolb,^{61b} I. Koletsou,⁵ T. Komarek,¹³⁰ T. Kondo,⁸¹ N. Kondrashova,^{60c}
K. Köneke,⁵² A. C. König,¹¹⁸ T. Kono,¹²⁵ R. Konoplich,^{124,gg} V. Konstantinides,⁹⁴ N. Konstantinidis,⁹⁴ B. Konya,⁹⁶
R. Kopeliansky,⁶⁵ S. Koperny,^{83a} K. Korcyl,⁸⁴ K. Kordas,¹⁶² G. Koren,¹⁶¹ A. Korn,⁹⁴ I. Korolkov,¹⁴ E. V. Korolkova,¹⁴⁹
N. Korotkova,¹¹² O. Kortner,¹¹⁴ S. Kortner,¹¹⁴ T. Kosek,¹⁴³ V. V. Kostyukhin,^{166,166} A. Kotskechagia,¹³² A. Kotwal,⁴⁹
A. Koulouris,¹⁰ A. Kourkoumeli-Charalampidi,^{70a,70b} C. Kourkoumelis,⁹ E. Kourlitis,¹⁴⁹ V. Kouskoura,^{26b}
A. B. Kowalewska,⁸⁴ R. Kowalewski,¹⁷⁶ C. Kozakai,¹⁶³ W. Kozanecki,¹⁴⁵ A. S. Kozhin,¹²² V. A. Kramarenko,¹¹²

G. Kramberger,⁹¹ D. Krasnopevtsev,^{60a} M. W. Krasny,¹³⁶ A. Krasznahorkay,³⁶ D. Krauss,¹¹⁴ J. A. Kremer,^{83a}
 J. Kretzschmar,⁹⁰ P. Krieger,¹⁶⁷ F. Krieter,¹¹³ A. Krishnan,^{61b} K. Krizka,¹⁸ K. Kroeninger,⁴⁷ H. Kroha,¹¹⁴ J. Kroll,¹⁴¹
 J. Kroll,¹³⁷ K. S. Krowpman,¹⁰⁶ J. Krstic,¹⁶ U. Kruchonak,⁷⁹ H. Krüger,²⁴ N. Krumnack,⁷⁸ M. C. Kruse,⁴⁹ J. A. Krzysiak,⁸⁴
 T. Kubota,¹⁰⁴ O. Kuchinskaiia,¹⁶⁶ S. Kuday,^{4b} J. T. Kuechler,⁴⁶ S. Kuehn,³⁶ A. Kugel,^{61a} T. Kuhl,⁴⁶ V. Kukhtin,⁷⁹ R. Kukla,¹⁰¹
 Y. Kulchitsky,^{107,hh} S. Kuleshov,^{147c} Y. P. Kulinich,¹⁷³ M. Kuna,⁵⁸ T. Kunigo,⁸⁵ A. Kupco,¹⁴¹ T. Kupfer,⁴⁷ O. Kuprash,⁵²
 H. Kurashige,⁸² L. L. Kurchaninov,^{168a} Y. A. Kurochkin,¹⁰⁷ A. Kurova,¹¹¹ M. G. Kurth,^{15a,15d} E. S. Kuwertz,³⁶ M. Kuze,¹⁶⁵
 A. K. Kvam,¹⁴⁸ J. Kvita,¹³⁰ T. Kwan,¹⁰³ A. La Rosa,¹¹⁴ L. La Rotonda,^{41b,41a} F. La Ruffa,^{41b,41a} C. Lacasta,¹⁷⁴ F. Lacava,^{72a,72b}
 D. P. J. Lack,¹⁰⁰ H. Lacker,¹⁹ D. Lacour,¹³⁶ E. Ladygin,⁷⁹ R. Lafaye,⁵ B. Laforge,¹³⁶ T. Lagouri,^{33d} S. Lai,⁵³ S. Lammers,⁶⁵
 W. Lampl,⁷ C. Lampoudis,¹⁶² E. Lançon,^{26b} U. Landgraf,⁵² M. P. J. Landon,⁹² M. C. Lanfermann,⁵⁴ V. S. Lang,⁴⁶
 J. C. Lange,⁵³ R. J. Langenberg,³⁶ A. J. Lankford,¹⁷¹ F. Lanni,^{26b} K. Lantzsch,²⁴ A. Lanza,^{70a} A. Lapertosa,^{55b,55a}
 S. Laplace,¹³⁶ J. F. Laporte,¹⁴⁵ T. Lari,^{68a} F. Lasagni Manghi,^{23b,23a} M. Lassnig,³⁶ T. S. Lau,^{63a} A. Laudrain,¹³² A. Laurier,³⁴
 M. Lavorgna,^{69a,69b} S. D. Lawlor,⁹³ M. Lazzaroni,^{68a,68b} B. Le,¹⁰⁴ E. Le Guirriec,¹⁰¹ M. LeBlanc,⁷ T. LeCompte,⁶
 F. Ledroit-Guillon,⁵⁸ A. C. A. Lee,⁹⁴ C. A. Lee,^{26b} G. R. Lee,¹⁷ L. Lee,⁵⁹ S. C. Lee,¹⁵⁸ S. J. Lee,³⁴ S. Lee,⁷⁸ B. Lefebvre,^{168a}
 H. P. Lefebvre,⁹³ M. Lefebvre,¹⁷⁶ F. Legger,¹¹³ C. Leggett,¹⁸ K. Lehmann,¹⁵² N. Lehmann,¹⁸² G. Lehmann Miotto,³⁶
 W. A. Leight,⁴⁶ A. Leisos,^{162,ii} M. A. L. Leite,^{80d} C. E. Leitgeb,¹¹³ R. Leitner,¹⁴³ D. Lellouch,^{180,a} K. J. C. Leney,⁴² T. Lenz,²⁴
 B. Lenzi,³⁶ R. Leone,⁷ S. Leone,^{71a} C. Leonidopoulos,⁵⁰ A. Leopold,¹³⁶ G. Lerner,¹⁵⁶ C. Leroy,¹⁰⁹ R. Les,¹⁶⁷ C. G. Lester,³²
 M. Levchenko,¹³⁸ J. Levêque,⁵ D. Levin,¹⁰⁵ L. J. Levinson,¹⁸⁰ D. J. Lewis,²¹ B. Li,^{15b} B. Li,¹⁰⁵ C-Q. Li,^{60a} F. Li,^{60c} H. Li,^{60a}
 H. Li,^{60b} J. Li,^{60c} K. Li,¹⁵³ L. Li,^{60c} M. Li,^{15a,15d} Q. Li,^{15a,15d} Q. Y. Li,^{60a} S. Li,^{60d,60c} X. Li,⁴⁶ Y. Li,⁴⁶ Z. Li,^{60b} Z. Liang,^{15a}
 B. Liberti,^{73a} A. Liblong,¹⁶⁷ K. Lie,^{63c} S. Lim,^{26a} C. Y. Lin,³² K. Lin,¹⁰⁶ T. H. Lin,⁹⁹ R. A. Linck,⁶⁵ J. H. Lindon,²¹
 A. L. Lioni,⁵⁴ E. Lipeles,¹³⁷ A. Lipniacka,¹⁷ M. Lisovyi,^{61b} T. M. Liss,^{173,ji} A. Lister,¹⁷⁵ A. M. Litke,¹⁴⁶ J. D. Little,⁸
 B. Liu,⁷⁸ B. L. Liu,⁶ H. B. Liu,^{26b} H. Liu,¹⁰⁵ J. B. Liu,^{60a} J. K. K. Liu,¹³⁵ K. Liu,¹³⁶ M. Liu,^{60a} P. Liu,¹⁸ Y. Liu,^{15a,15d}
 Y. L. Liu,¹⁰⁵ Y. W. Liu,^{60a} M. Livan,^{70a,70b} A. Lleres,⁵⁸ J. Llorente Merino,¹⁵² S. L. Lloyd,⁹² C. Y. Lo,^{63b} F. Lo Sterzo,⁴²
 E. M. Lobodzinska,⁴⁶ P. Loch,⁷ S. Loffredo,^{73a,73b} T. Lohse,¹⁹ K. Lohwasser,¹⁴⁹ M. Lokajicek,¹⁴¹ J. D. Long,¹⁷³ R. E. Long,⁸⁹
 L. Longo,³⁶ K. A. Looper,¹²⁶ J. A. Lopez,^{147c} I. Lopez Paz,¹⁰⁰ A. Lopez Solis,¹⁴⁹ J. Lorenz,¹¹³ N. Lorenzo Martinez,⁵
 M. Losada,²² P. J. Lösel,¹¹³ A. Lösle,⁵² X. Lou,⁴⁶ X. Lou,^{15a} A. Lounis,¹³² J. Love,⁶ P. A. Love,⁸⁹ J. J. Lozano Bahilo,¹⁷⁴
 M. Lu,^{60a} Y. J. Lu,⁶⁴ H. J. Lubatti,¹⁴⁸ C. Luci,^{72a,72b} A. Lucotte,⁵⁸ C. Luedtke,⁵² F. Luehring,⁶⁵ I. Luise,¹³⁶ L. Luminari,^{72a}
 B. Lund-Jensen,¹⁵⁴ M. S. Lutz,¹⁰² D. Lynn,^{26b} H. Lyons,⁹⁰ R. Lysak,¹⁴¹ E. Lytken,⁹⁶ F. Lyu,^{15a} V. Lyubushkin,⁷⁹
 T. Lyubushkina,⁷⁹ H. Ma,^{26b} L. L. Ma,^{60b} Y. Ma,^{60b} G. Maccarrone,⁵¹ A. Macchiolo,¹¹⁴ C. M. Macdonald,¹⁴⁹
 J. Machado Miguens,¹³⁷ D. Madaffari,¹⁷⁴ R. Madar,³⁸ W. F. Mader,⁴⁸ N. Madysa,⁴⁸ J. Maeda,⁸² T. Maeno,^{26b} M. Maerker,⁴⁸
 A. S. Maevskiy,¹¹² V. Magerl,⁵² N. Magini,⁷⁸ D. J. Mahon,³⁹ C. Maidantchik,^{80b} T. Maier,¹¹³ A. Maio,^{140a,140b,140d} K. Maj,^{83a}
 O. Majersky,^{29a} S. Majewski,¹³¹ Y. Makida,⁸¹ N. Makovec,¹³² B. Malaescu,¹³⁶ Pa. Malecki,⁸⁴ V. P. Maleev,¹³⁸ F. Malek,⁵⁸
 U. Mallik,⁷⁷ D. Malon,⁶ C. Malone,³² S. Maltezos,¹⁰ S. Malyukov,⁷⁹ J. Mamuzic,¹⁷⁴ G. Mancini,⁵¹ I. Mandić,⁹¹
 L. Manhaes de Andrade Filho,^{80a} I. M. Maniatis,¹⁶² J. Manjarres Ramos,⁴⁸ K. H. Mankinen,⁹⁶ A. Mann,¹¹³ A. Manousos,⁷⁶
 B. Mansoulie,¹⁴⁵ I. Manthos,¹⁶² S. Manzoni,¹¹⁹ A. Marantis,¹⁶² G. Marceca,³⁰ L. Marchese,¹³⁵ G. Marchiori,¹³⁶
 M. Marcisovsky,¹⁴¹ L. Marcoccia,^{73a,73b} C. Marcon,⁹⁶ C. A. Marin Tobon,³⁶ M. Marjanovic,¹²⁸ Z. Marshall,¹⁸
 M. U. F. Martensson,¹⁷² S. Marti-Garcia,¹⁷⁴ C. B. Martin,¹²⁶ T. A. Martin,¹⁷⁸ V. J. Martin,⁵⁰ B. Martin dit Latour,¹⁷
 L. Martinelli,^{74a,74b} M. Martinez,^{14,w} V. I. Martinez Outschoorn,¹⁰² S. Martin-Haugh,¹⁴⁴ V. S. Martoiu,^{28b} A. C. Martyniuk,⁹⁴
 A. Marzin,³⁶ S. R. Maschek,¹¹⁴ L. Masetti,⁹⁹ T. Mashimo,¹⁶³ R. Mashinistov,¹¹⁰ J. Masik,¹⁰⁰ A. L. Maslennikov,^{121b,121a}
 L. Massa,^{73a,73b} P. Massarotti,^{69a,69b} P. Mastrandrea,^{71a,71b} A. Mastroberardino,^{41b,41a} T. Masubuchi,¹⁶³ D. Matakias,¹⁰
 A. Matic,¹¹³ P. Mättig,²⁴ J. Maurer,^{28b} B. Maček,⁹¹ D. A. Maximov,^{121b,121a} R. Mazini,¹⁵⁸ I. Maznas,¹⁶² S. M. Mazza,¹⁴⁶
 S. P. Mc Kee,¹⁰⁵ T. G. McCarthy,¹¹⁴ W. P. McCormack,¹⁸ E. F. McDonald,¹⁰⁴ J. A. Mcfayden,³⁶ G. Mchedlidze,^{159b}
 M. A. McKay,⁴² K. D. McLean,¹⁷⁶ S. J. McMahon,¹⁴⁴ P. C. McNamara,¹⁰⁴ C. J. McNicol,¹⁷⁸ R. A. McPherson,^{176,p}
 J. E. Mdhluli,^{33d} Z. A. Meadows,¹⁰² S. Meehan,³⁶ T. Megy,⁵² S. Mehlhase,¹¹³ A. Mehta,⁹⁰ T. Meideck,⁵⁸ B. Meirose,⁴³
 D. Melini,¹⁷⁴ B. R. Mellado Garcia,^{33d} J. D. Mellenthin,⁵³ M. Melo,^{29a} F. Meloni,⁴⁶ A. Melzer,²⁴ S. B. Menary,¹⁰⁰
 E. D. Mendes Gouveia,^{140a,140e} L. Meng,³⁶ X. T. Meng,¹⁰⁵ S. Menke,¹¹⁴ E. Meoni,^{41b,41a} S. Mergelmeyer,¹⁹
 S. A. M. Merkt,¹³⁹ C. Merlassino,²⁰ P. Mermod,⁵⁴ L. Merola,^{69a,69b} C. Meroni,^{68a} O. Meshkov,^{112,110} J. K. R. Meshreki,¹⁵¹
 A. Messina,^{72a,72b} J. Metcalfe,⁶ A. S. Mete,¹⁷¹ C. Meyer,⁶⁵ J. Meyer,¹⁶⁰ J-P. Meyer,¹⁴⁵ H. Meyer Zu Theenhausen,^{61a}
 F. Miano,¹⁵⁶ M. Michetti,¹⁹ R. P. Middleton,¹⁴⁴ L. Mijović,⁵⁰ G. Mikenberg,¹⁸⁰ M. Mikesikova,¹⁴¹ M. Mikuz,⁹¹
 H. Mildner,¹⁴⁹ M. Milesi,¹⁰⁴ A. Milic,¹⁶⁷ D. A. Millar,⁹² D. W. Miller,³⁷ A. Milov,¹⁸⁰ D. A. Milstead,^{45a,45b} R. A. Mina,^{153,ff}

A. A. Minaenko,¹²² M. Miñano Moya,¹⁷⁴ I. A. Minashvili,^{159b} A. I. Mincer,¹²⁴ B. Mindur,^{83a} M. Mineev,⁷⁹ Y. Minegishi,¹⁶³
 L. M. Mir,¹⁴ A. Mirto,^{67a,67b} K. P. Mistry,¹³⁷ T. Mitani,¹⁷⁹ J. Mitrevski,¹¹³ V. A. Mitsou,¹⁷⁴ M. Mittal,^{60c} O. Miu,¹⁶⁷
 A. Miucci,²⁰ P. S. Miyagawa,¹⁴⁹ A. Mizukami,⁸¹ J. U. Mjörnmark,⁹⁶ T. Mkrtchyan,¹⁸⁴ M. Mlynarikova,¹⁴³ T. Moa,^{45a,45b}
 K. Mochizuki,¹⁰⁹ P. Mogg,⁵² S. Mohapatra,³⁹ R. Moles-Valls,²⁴ M. C. Mondragon,¹⁰⁶ K. Mönig,⁴⁶ J. Monk,⁴⁰ E. Monnier,¹⁰¹
 A. Montalbano,¹⁵² J. Montejo Berlingen,³⁶ M. Montella,⁹⁴ F. Monticelli,⁸⁸ S. Monzani,^{68a} N. Morange,¹³² D. Moreno,²²
 M. Moreno Llácer,¹⁷⁴ C. Moreno Martinez,¹⁴ P. Morettini,^{55b} M. Morgenstern,¹¹⁹ S. Morgenstern,⁴⁸ D. Mori,¹⁵² M. Morii,⁵⁹
 M. Morinaga,¹⁷⁹ V. Morisbak,¹³⁴ A. K. Morley,³⁶ G. Mornacchi,³⁶ A. P. Morris,⁹⁴ L. Morvaj,¹⁵⁵ P. Moschovakos,³⁶
 B. Moser,¹¹⁹ M. Mosidze,^{159b} T. Moskalets,¹⁴⁵ H. J. Moss,¹⁴⁹ J. Moss,^{31,kk} E. J. W. Moyse,¹⁰² S. Muanza,¹⁰¹ J. Mueller,¹³⁹
 R. S. P. Mueller,¹¹³ D. Muenstermann,⁸⁹ G. A. Mullier,⁹⁶ D. P. Mungo,^{68a,68b} J. L. Munoz Martinez,¹⁴
 F. J. Munoz Sanchez,¹⁰⁰ P. Murin,^{29b} W. J. Murray,^{178,144} A. Murrone,^{68a,68b} M. Muškinja,¹⁸ C. Mwewa,^{33a}
 A. G. Myagkov,^{122,ll} J. Myers,¹³¹ M. Myska,¹⁴² B. P. Nachman,¹⁸ O. Nackenhorst,⁴⁷ A. Nag Nag,⁴⁸ K. Nagai,¹³⁵
 K. Nagano,⁸¹ Y. Nagasaka,⁶² M. Nagel,⁵² J. L. Nagle,^{26b} E. Nagy,¹⁰¹ A. M. Nairz,³⁶ Y. Nakahama,¹¹⁶ K. Nakamura,⁸¹
 T. Nakamura,¹⁶³ I. Nakano,¹²⁷ H. Nanjo,¹³³ F. Napolitano,^{61a} R. F. Naranjo Garcia,⁴⁶ R. Narayan,⁴² I. Naryshkin,¹³⁸
 T. Naumann,⁴⁶ G. Navarro,²² P. Y. Nechaeva,¹¹⁰ F. Nechansky,⁴⁶ T. J. Neep,²¹ A. Negri,^{70a,70b} M. Negrini,^{23b} C. Nellist,⁵³
 M. E. Nelson,¹³⁵ S. Nemecek,¹⁴¹ P. Nemethy,¹²⁴ M. Nessi,^{36,mm} M. S. Neubauer,¹⁷³ M. Neumann,¹⁸² P. R. Newman,²¹
 Y. S. Ng,¹⁹ Y. W. Y. Ng,¹⁷¹ B. Ngair,^{35e} H. D. N. Nguyen,¹⁰¹ T. Nguyen Manh,¹⁰⁹ E. Nibigira,³⁸ R. B. Nickerson,¹³⁵
 R. Nicolaidou,¹⁴⁵ D. S. Nielsen,⁴⁰ J. Nielsen,¹⁴⁶ N. Nikiforou,¹¹ V. Nikolaenko,^{122,ll} I. Nikolic-Audit,¹³⁶ K. Nikolopoulos,²¹
 P. Nilsson,^{26b} H. R. Nindhito,⁵⁴ Y. Ninomiya,⁸¹ A. Nisati,^{72a} N. Nishu,^{60c} R. Nisius,¹¹⁴ I. Nitsche,⁴⁷ T. Nitta,¹⁷⁹ T. Nobe,¹⁶³
 Y. Noguchi,⁸⁵ I. Nomidis,¹³⁶ M. A. Nomura,^{26b} M. Nordberg,³⁶ N. Norjoharuddeen,¹³⁵ T. Novak,⁹¹ O. Novgorodova,⁴⁸
 R. Novotny,¹⁴² L. Nozka,¹³⁰ K. Ntekas,¹⁷¹ E. Nurse,⁹⁴ F. G. Oakham,^{34,d} H. Oberlack,¹¹⁴ J. Ocariz,¹³⁶ A. Ochi,⁸² I. Ochoa,³⁹
 J. P. Ochoa-Ricoux,^{147a} K. O'Connor,²⁷ S. Oda,⁸⁷ S. Odaka,⁸¹ S. Oerdek,⁵³ A. Ogrodnik,^{83a} A. Oh,¹⁰⁰ S. H. Oh,⁴⁹
 C. C. Ohm,¹⁵⁴ H. Oide,¹⁶⁵ M. L. Ojeda,¹⁶⁷ H. Okawa,¹⁶⁹ Y. Okazaki,⁸⁵ M. W. O'Keefe,⁹⁰ Y. Okumura,¹⁶³ T. Okuyama,⁸¹
 A. Olariu,^{28b} L. F. Oleiro Seabra,^{140a} S. A. Olivares Pino,^{147a} D. Oliveira Damazio,^{26b} J. L. Oliver,¹ M. J. R. Olsson,¹⁷¹
 A. Olszewski,⁸⁴ J. Olszowska,⁸⁴ D. C. O'Neil,¹⁵² A. P. O'Neill,¹³⁵ A. Onofre,^{140a,140e} P. U. E. Onyisi,¹¹ H. Oppen,¹³⁴
 M. J. Oreglia,³⁷ G. E. Orellana,⁸⁸ D. Orestano,^{74a,74b} N. Orlando,¹⁴ R. S. Orr,¹⁶⁷ V. O'Shea,⁵⁷ R. Ospanov,^{60a}
 G. Otero y Garzon,³⁰ H. Otono,⁸⁷ P. S. Ott,^{61a} M. Ouchrif,^{35d} J. Ouellette,^{26b} F. Ould-Saada,¹³⁴ A. Ouraou,¹⁴⁵ Q. Ouyang,^{15a}
 M. Owen,⁵⁷ R. E. Owen,²¹ V. E. Ozcan,^{12c} N. Ozturk,⁸ J. Pacalt,¹³⁰ H. A. Pacey,³² K. Pachal,⁴⁹ A. Pacheco Pages,¹⁴
 C. Padilla Aranda,¹⁴ S. Pagan Griso,¹⁸ M. Paganini,¹⁸³ G. Palacino,⁶⁵ S. Palazzo,⁵⁰ S. Palestini,³⁶ M. Palka,^{83b} D. Pallin,³⁸
 I. Panagoulas,¹⁰ C. E. Pandini,³⁶ J. G. Panduro Vazquez,⁹³ P. Pani,⁴⁶ G. Panizzo,^{66a,66c} L. Paolozzi,⁵⁴ C. Papadatos,¹⁰⁹
 K. Papageorgiou,^{9,u} S. Parajuli,⁴³ A. Paramonov,⁶ D. Paredes Hernandez,^{63b} S. R. Paredes Saenz,¹³⁵ B. Parida,¹⁶⁶
 T. H. Park,¹⁶⁷ A. J. Parker,³¹ M. A. Parker,³² F. Parodi,^{55b,55a} E. W. Parrish,¹²⁰ J. A. Parsons,³⁹ U. Parzefall,⁵²
 L. Pascual Dominguez,¹³⁶ V. R. Pascuzzi,¹⁶⁷ J. M. P. Pasner,¹⁴⁶ F. Pasquali,¹¹⁹ E. Pasqualucci,^{72a} S. Passaggio,^{55b}
 F. Pastore,⁹³ P. Pasuwan,^{45a,45b} S. Patarraia,⁹⁹ J. R. Pater,¹⁰⁰ A. Pathak,^{181,e} T. Pauly,³⁶ B. Pearson,¹¹⁴ M. Pedersen,¹³⁴
 L. Pedraza Diaz,¹¹⁸ R. Pedro,^{140a} T. Peiffer,⁵³ S. V. Peleganchuk,^{121b,121a} O. Penc,¹⁴¹ H. Peng,^{60a} B. S. Peralva,^{80a}
 M. M. Perego,¹³² A. P. Pereira Peixoto,^{140a} D. V. Perepelitsa,^{26b} F. Peri,¹⁹ L. Perini,^{68a,68b} H. Pernegger,³⁶ S. Perrella,^{69a,69b}
 K. Peters,⁴⁶ R. F. Y. Peters,¹⁰⁰ B. A. Petersen,³⁶ T. C. Petersen,⁴⁰ E. Petit,¹⁰¹ A. Petridis,¹ C. Petridou,¹⁶² P. Petroff,¹³²
 M. Petrov,¹³⁵ F. Petrucci,^{74a,74b} M. Pettee,¹⁸³ N. E. Pettersson,¹⁰² K. Petukhova,¹⁴³ A. Peyaud,¹⁴⁵ R. Pezoa,^{147c}
 L. Pezzotti,^{70a,70b} T. Pham,¹⁰⁴ F. H. Phillips,¹⁰⁶ P. W. Phillips,¹⁴⁴ M. W. Phipps,¹⁷³ G. Piacquadio,¹⁵⁵ E. Pianori,¹⁸
 A. Picazio,¹⁰² R. H. Pickles,¹⁰⁰ R. Piegaiia,³⁰ D. Pietreanu,^{28b} J. E. Pilcher,³⁷ A. D. Pilkington,¹⁰⁰ M. Pinamonti,^{73a,73b}
 J. L. Pinfold,³ M. Pitt,¹⁶¹ L. Pizzimento,^{73a,73b} M.-A. Pleier,^{26b} V. Pleskot,¹⁴³ E. Plotnikova,⁷⁹ P. Podberezko,^{121b,121a}
 R. Poettgen,⁹⁶ R. Poggi,⁵⁴ L. Poggioli,¹³² I. Pogrebnnyak,¹⁰⁶ D. Pohl,²⁴ I. Pokharel,⁵³ G. Polesello,^{70a} A. Poley,¹⁸
 A. Policicchio,^{72a,72b} R. Polifka,¹⁴³ A. Polini,^{23b} C. S. Pollard,⁴⁶ V. Polychronakos,^{26b} D. Ponomarenko,¹¹¹ L. Pontecorvo,³⁶
 S. Popa,^{28a} G. A. Popeneciu,^{28d} L. Portales,⁵ D. M. Portillo Quintero,⁵⁸ S. Pospisil,¹⁴² K. Potamianos,⁴⁶ I. N. Potrap,⁷⁹
 C. J. Potter,³² H. Potti,¹¹ T. Poulsen,⁹⁶ J. Poveda,³⁶ T. D. Powell,¹⁴⁹ G. Pownall,⁴⁶ M. E. Pozo Astigarraga,³⁶ P. Pralavorio,¹⁰¹
 S. Prell,⁷⁸ D. Price,¹⁰⁰ M. Primavera,^{67a} S. Prince,¹⁰³ M. L. Proffitt,¹⁴⁸ N. Proklova,¹¹¹ K. Prokofiev,^{63c} F. Prokoshin,⁷⁹
 S. Protopopescu,^{26b} J. Proudfoot,⁶ M. Przybycien,^{83a} D. Pudzha,¹³⁸ A. Puri,¹⁷³ P. Puzo,¹³² J. Qian,¹⁰⁵ Y. Qin,¹⁰⁰ A. Quadt,⁵³
 M. Queitsch-Maitland,⁴⁶ A. Qureshi,¹ M. Racko,^{29a} P. Rados,¹⁰⁴ F. Ragusa,^{68a,68b} G. Rahal,⁹⁷ J. A. Raine,⁵⁴
 S. Rajagopalan,^{26b} A. Ramirez Morales,⁹² K. Ran,^{15a,15d} T. Rashid,¹³² S. Raspopov,⁵ D. M. Rauch,⁴⁶ F. Rauscher,¹¹³
 S. Rave,⁹⁹ B. Ravina,¹⁴⁹ I. Ravinovich,¹⁸⁰ J. H. Rawling,¹⁰⁰ M. Raymond,³⁶ A. L. Read,¹³⁴ N. P. Readioff,⁵⁸ M. Reale,^{67a,67b}

D. M. Rebuzzi,^{70a,70b} A. Redelbach,¹⁷⁷ G. Redlinger,^{26b} K. Reeves,⁴³ L. Rehnisch,¹⁹ J. Reichert,¹³⁷ D. Reikher,¹⁶¹ A. Reiss,⁹⁹
A. Rej,¹⁵¹ C. Rembser,³⁶ M. Renda,^{28b} M. Rescigno,^{72a} S. Resconi,^{68a} E. D. Resseguie,¹³⁷ S. Rettie,¹⁷⁵ E. Reynolds,²¹
O. L. Rezanova,^{121b,121a} P. Reznicek,¹⁴³ E. Ricci,^{75a,75b} R. Richter,¹¹⁴ S. Richter,⁴⁶ E. Richter-Was,^{83b} O. Ricken,²⁴
M. Ridel,¹³⁶ P. Rieck,¹¹⁴ O. Rifki,⁴⁶ M. Rijssenbeek,¹⁵⁵ A. Rimoldi,^{70a,70b} M. Rimoldi,⁴⁶ L. Rinaldi,^{23b} G. Ripellino,¹⁵⁴
I. Riu,¹⁴ J. C. Rivera Vergara,¹⁷⁶ F. Rizatdinova,¹²⁹ E. Rizvi,⁹² C. Rizzi,³⁶ R. T. Roberts,¹⁰⁰ S. H. Robertson,^{103,p} M. Robin,⁴⁶
D. Robinson,³² J. E. M. Robinson,⁴⁶ C. M. Robles Gajardo,^{147c} A. Robson,⁵⁷ A. Rocchi,^{73a,73b} E. Rocco,⁹⁹ C. Roda,^{71a,71b}
S. Rodriguez Bosca,¹⁷⁴ A. Rodriguez Perez,¹⁴ D. Rodriguez Rodriguez,¹⁷⁴ A. M. Rodríguez Vera,^{168b} S. Roe,³⁶ O. Røhne,¹³⁴
R. Röhrig,¹¹⁴ R. A. Rojas,^{147c} C. P. A. Roland,⁶⁵ J. Roloff,^{26b} A. Romaniouk,¹¹¹ M. Romano,^{23b,23a} N. Rompotis,⁹⁰
M. Ronzani,¹²⁴ L. Roos,¹³⁶ S. Rosati,^{72a} K. Rosbach,⁵² G. Rosin,¹⁰² B. J. Rosser,¹³⁷ E. Rossi,⁴⁶ E. Rossi,^{74a,74b} E. Rossi,^{69a,69b}
L. P. Rossi,^{55b} L. Rossini,^{68a,68b} R. Rosten,¹⁴ M. Rotaru,^{28b} J. Rothberg,¹⁴⁸ D. Rousseau,¹³² G. Rovelli,^{70a,70b} A. Roy,¹¹
D. Roy,^{33d} A. Rozanov,¹⁰¹ Y. Rozen,¹⁶⁰ X. Ruan,^{33d} F. Rühr,⁵² A. Ruiz-Martinez,¹⁷⁴ A. Rummeler,³⁶ Z. Rurikova,⁵²
N. A. Rusakovich,⁷⁹ H. L. Russell,¹⁰³ L. Rustige,^{38,47} J. P. Rutherford,⁷ E. M. Rüttinger,¹⁴⁹ M. Rybar,³⁹ G. Rybkin,¹³²
E. B. Rye,¹³⁴ A. Ryzhov,¹²² J. A. Sabater Iglesias,⁴⁶ P. Sabatini,⁵³ G. Sabato,¹¹⁹ S. Sacerdoti,¹³² H. F.-W. Sadrozinski,¹⁴⁶
R. Sadykov,⁷⁹ F. Safai Tehrani,^{72a} B. Safarzadeh Samani,¹⁵⁶ P. Saha,¹²⁰ S. Saha,¹⁰³ M. Sahinsoy,^{61a} A. Sahu,¹⁸²
M. Saimpert,⁴⁶ M. Saito,¹⁶³ T. Saito,¹⁶³ H. Sakamoto,¹⁶³ A. Sakharov,^{124,gg} D. Salamani,⁵⁴ G. Salamanna,^{74a,74b}
J. E. Salazar Loyola,^{147c} A. Salmikov,¹⁵³ J. Salt,¹⁷⁴ D. Salvatore,^{41b,41a} F. Salvatore,¹⁵⁶ A. Salvucci,^{63a,63b,63c} A. Salzburger,³⁶
J. Samarati,³⁶ D. Sammel,⁵² D. Sampsonidis,¹⁶² D. Sampsonidou,¹⁶² J. Sánchez,¹⁷⁴ A. Sanchez Pineda,^{66a,36,66c}
H. Sandaker,¹³⁴ C. O. Sander,⁴⁶ I. G. Sanderswood,⁸⁹ M. Sandhoff,¹⁸² C. Sandoval,²² D. P. C. Sankey,¹⁴⁴ M. Sannino,^{55b,55a}
Y. Sano,¹¹⁶ A. Sansoni,⁵¹ C. Santoni,³⁸ H. Santos,^{140a,140b} S. N. Santpur,¹⁸ A. Santra,¹⁷⁴ A. Sapronov,⁷⁹ J. G. Saraiva,^{140a,140d}
O. Sasaki,⁸¹ K. Sato,¹⁶⁹ F. Sauerburger,⁵² E. Sauvan,⁵ P. Savard,^{167,d} N. Savic,¹¹⁴ R. Sawada,¹⁶³ C. Sawyer,¹⁴⁴ L. Sawyer,^{95,nn}
C. Sbarra,^{23b} A. Sbrizzi,^{23a} T. Scanlon,⁹⁴ J. Schaarschmidt,¹⁴⁸ P. Schacht,¹¹⁴ B. M. Schachtner,¹¹³ D. Schaefer,³⁷
L. Schaefer,¹³⁷ J. Schaeffer,⁹⁹ S. Schaepe,³⁶ U. Schäfer,⁹⁹ A. C. Schaffer,¹³² D. Schaile,¹¹³ R. D. Schamberger,¹⁵⁵
N. Scharmberg,¹⁰⁰ V. A. Schegelsky,¹³⁸ D. Scheirich,¹⁴³ F. Schenck,¹⁹ M. Schernau,¹⁷¹ C. Schiavi,^{55b,55a} S. Schier,¹⁴⁶
L. K. Schildgen,²⁴ Z. M. Schillaci,²⁷ E. J. Schioppa,³⁶ M. Schioppa,^{41b,41a} K. E. Schleicher,⁵² S. Schlenker,³⁶
K. R. Schmidt-Sommerfeld,¹¹⁴ K. Schmieden,³⁶ C. Schmitt,⁹⁹ S. Schmitt,⁴⁶ S. Schmitz,⁹⁹ J. C. Schmoeckel,⁴⁶ U. Schnoor,⁵²
L. Schoeffel,¹⁴⁵ A. Schoening,^{61b} P. G. Scholer,⁵² E. Schopf,¹³⁵ M. Schott,⁹⁹ J. F. P. Schouwenberg,¹¹⁸ J. Schovancova,³⁶
S. Schramm,⁵⁴ F. Schroeder,¹⁸² A. Schulte,⁹⁹ H.-C. Schultz-Coulon,^{61a} M. Schumacher,⁵² B. A. Schumm,¹⁴⁶ Ph. Schune,¹⁴⁵
A. Schwartzman,¹⁵³ T. A. Schwarz,¹⁰⁵ Ph. Schwemling,¹⁴⁵ R. Schwienhorst,¹⁰⁶ A. Sciandra,¹⁴⁶ G. Sciolla,²⁷
M. Scodeggio,⁴⁶ M. Scornajenghi,^{41b,41a} F. Scuri,^{71a} F. Scutti,¹⁰⁴ L. M. Scyboz,¹¹⁴ C. D. Sebastiani,^{72a,72b} P. Seema,¹⁹
S. C. Seidel,¹¹⁷ A. Seiden,¹⁴⁶ B. D. Seidlitz,^{26b} T. Seiss,³⁷ J. M. Seixas,^{80b} G. Sekhniaidze,^{69a} K. Sekhon,¹⁰⁵ S. J. Sekula,⁴²
N. Semprini-Cesari,^{23b,23a} S. Sen,⁴⁹ C. Serfon,⁷⁶ L. Serin,¹³² L. Serkin,^{66a,66b} M. Sessa,^{60a} H. Severini,¹²⁸ T. Šfiligoj,⁹¹
F. Sforza,^{55b,55a} A. Sfyrla,⁵⁴ E. Shabalina,⁵³ J. D. Shahinian,¹⁴⁶ N. W. Shaikh,^{45a,45b} D. Shaked Renous,¹⁸⁰ L. Y. Shan,^{15a}
J. T. Shank,²⁵ M. Shapiro,¹⁸ A. Sharma,¹³⁵ A. S. Sharma,¹ P. B. Shatalov,¹²³ K. Shaw,¹⁵⁶ S. M. Shaw,¹⁰⁰ A. Shcherbakova,¹³⁸
M. Shehade,¹⁸⁰ Y. Shen,¹²⁸ N. Sherafati,³⁴ A. D. Sherman,²⁵ P. Sherwood,⁹⁴ L. Shi,^{158,oo} S. Shimizu,⁸¹ C. O. Shimmin,¹⁸³
Y. Shimogama,¹⁷⁹ M. Shimojima,¹¹⁵ I. P. J. Shipsey,¹³⁵ S. Shirabe,⁸⁷ M. Shiyakova,^{79,pp} J. Shlomi,¹⁸⁰ A. Shmeleva,¹¹⁰
M. J. Shochet,³⁷ J. Shojaii,¹⁰⁴ D. R. Shope,¹²⁸ S. Shrestha,¹²⁶ E. M. Shrif,^{33d} E. Shulga,¹⁸⁰ P. Sicho,¹⁴¹ A. M. Sickles,¹⁷³
P. E. Sidebo,¹⁵⁴ E. Sideras Haddad,^{33d} O. Sidiropoulou,³⁶ A. Sidoti,^{23b,23a} F. Siegert,⁴⁸ Dj. Sijacki,¹⁶ M. Silva Jr.,¹⁸¹
M. V. Silva Oliveira,^{80a} S. B. Silverstein,^{45a} S. Simion,¹³² E. Simioni,⁹⁹ R. Simoniello,⁹⁹ S. Simsek,^{12b} P. Sinervo,¹⁶⁷
V. Sinetckii,^{112,110} N. B. Sinev,¹³¹ M. Sioli,^{23b,23a} I. Siral,¹⁰⁵ S. Yu. Sivoklokov,¹¹² J. Sjölin,^{45a,45b} E. Skorda,⁹⁶ P. Skubic,¹²⁸
M. Slawinska,⁸⁴ K. Sliwa,¹⁷⁰ R. Slovak,¹⁴³ V. Smakhtin,¹⁸⁰ B. H. Smart,¹⁴⁴ J. Smiesko,^{29a} N. Smirnov,¹¹¹ S. Yu. Smirnov,¹¹¹
Y. Smirnov,¹¹¹ L. N. Smirnova,^{112,qq} O. Smirnova,⁹⁶ J. W. Smith,⁵³ M. Smizanska,⁸⁹ K. Smolek,¹⁴² A. Smykiewicz,⁸⁴
A. A. Snesarev,¹¹⁰ H. L. Snoek,¹¹⁹ I. M. Snyder,¹³¹ S. Snyder,^{26b} R. Sobie,^{176,p} A. Soffer,¹⁶¹ A. Sogaard,⁵⁰ F. Sohns,⁵³
C. A. Solans Sanchez,³⁶ E. Yu. Soldatov,¹¹¹ U. Soldevila,¹⁷⁴ A. A. Solodkov,¹²² A. Soloshenko,⁷⁹ O. V. Solovyanov,¹²²
V. Solovyev,¹³⁸ P. Sommer,¹⁴⁹ H. Son,¹⁷⁰ W. Song,¹⁴⁴ W. Y. Song,^{168b} A. Sopczak,¹⁴² F. Sopkova,^{29b}
C. L. Sotiropoulou,^{71a,71b} S. Sottocornola,^{70a,70b} R. Soualah,^{66a,66c,rr} A. M. Soukharev,^{121b,121a} D. South,⁴⁶ S. Spagnolo,^{67a,67b}
M. Spalla,¹¹⁴ M. Spangenberg,¹⁷⁸ F. Spanò,⁹³ D. Sperlich,⁵² T. M. Spieker,^{61a} R. Spighi,^{23b} G. Spigo,³⁶ M. Spina,¹⁵⁶
D. P. Spiteri,⁵⁷ M. Spousta,¹⁴³ A. Stabile,^{68a,68b} B. L. Stamas,¹²⁰ R. Stamen,^{61a} M. Stamenkovic,¹¹⁹ E. Stanecka,⁸⁴
B. Stanislaus,¹³⁵ M. M. Stanitzki,⁴⁶ M. Stankaityte,¹³⁵ B. Stapf,¹¹⁹ E. A. Starchenko,¹²² G. H. Stark,¹⁴⁶ J. Stark,⁵⁸
S. H. Stark,⁴⁰ P. Staroba,¹⁴¹ P. Starovoitov,^{61a} S. Stärz,¹⁰³ R. Staszewski,⁸⁴ G. Stavropoulos,⁴⁴ M. Stegler,⁴⁶ P. Steinberg,^{26b}

A. L. Steinhebel,¹³¹ B. Stelzer,¹⁵² H. J. Stelzer,¹³⁹ O. Stelzer-Chilton,^{168a} H. Stenzel,⁵⁶ T. J. Stevenson,¹⁵⁶ G. A. Stewart,³⁶ M. C. Stockton,³⁶ G. Stoicea,^{28b} M. Stolarski,^{140a} S. Stonjek,¹¹⁴ A. Straessner,⁴⁸ J. Strandberg,¹⁵⁴ S. Strandberg,^{45a,45b} M. Strauss,¹²⁸ P. Strizenec,^{29b} R. Ströhmer,¹⁷⁷ D. M. Strom,¹³¹ R. Stroynowski,⁴² A. Strubig,⁵⁰ S. A. Stucci,^{26b} B. Stugu,¹⁷ J. Stupak,¹²⁸ N. A. Styles,⁴⁶ D. Su,¹⁵³ S. Suchek,^{61a} V. V. Sulin,¹¹⁰ M. J. Sullivan,⁹⁰ D. M. S. Sultan,⁵⁴ S. Sultansoy,^{4c} T. Sumida,⁸⁵ S. Sun,¹⁰⁵ X. Sun,³ K. Suruliz,¹⁵⁶ C. J. E. Suster,¹⁵⁷ M. R. Sutton,¹⁵⁶ S. Suzuki,⁸¹ M. Svatos,¹⁴¹ M. Swiatlowski,³⁷ S. P. Swift,² T. Swirski,¹⁷⁷ A. Sydorenko,⁹⁹ I. Sykora,^{29a} M. Sykora,¹⁴³ T. Sykora,¹⁴³ D. Ta,⁹⁹ K. Tackmann,^{46,ss} J. Taenzer,¹⁶¹ A. Taffard,¹⁷¹ R. Tafirout,^{168a} H. Takai,^{26b} R. Takashima,⁸⁶ K. Takeda,⁸² T. Takeshita,¹⁵⁰ E. P. Takeva,⁵⁰ Y. Takubo,⁸¹ M. Talby,¹⁰¹ A. A. Talyshev,^{121b,121a} N. M. Tamir,¹⁶¹ J. Tanaka,¹⁶³ M. Tanaka,¹⁶⁵ R. Tanaka,¹³² S. Tapia Araya,¹⁷³ S. Tapprogge,⁹⁹ A. Tarek Abouelfadl Mohamed,¹³⁶ S. Tarem,¹⁶⁰ K. Tariq,^{60b} G. Tarna,^{28b,tt} G. F. Tartarelli,^{68a} P. Tas,¹⁴³ M. Tasevsky,¹⁴¹ T. Tashiro,⁸⁵ E. Tassi,^{41b,41a} A. Tavares Delgado,^{140a,140b} Y. Tayalati,^{35e} A. J. Taylor,⁵⁰ G. N. Taylor,¹⁰⁴ W. Taylor,^{168b} A. S. Tee,⁸⁹ R. Teixeira De Lima,¹⁵³ P. Teixeira-Dias,⁹³ H. Ten Kate,³⁶ J. J. Teoh,¹¹⁹ S. Terada,⁸¹ K. Terashi,¹⁶³ J. Terron,⁹⁸ S. Terzo,¹⁴ M. Testa,⁵¹ R. J. Teuscher,^{167,p} S. J. Thais,¹⁸³ T. Theveneaux-Pelzer,⁴⁶ F. Thiele,⁴⁰ D. W. Thomas,⁹³ J. O. Thomas,⁴² J. P. Thomas,²¹ A. S. Thompson,⁵⁷ P. D. Thompson,²¹ L. A. Thomsen,¹⁸³ E. Thomson,¹³⁷ E. J. Thorpe,⁹² R. E. Ticse Torres,⁵³ V. O. Tikhomirov,^{110,uu} Yu. A. Tikhonov,^{121b,121a} S. Timoshenko,¹¹¹ P. Tipton,¹⁸³ S. Tisserant,¹⁰¹ K. Todome,^{23b,23a} S. Todorova-Nova,⁵ S. Todt,⁴⁸ J. Tojo,⁸⁷ S. Tokár,^{29a} K. Tokushuku,⁸¹ E. Tolley,¹²⁶ K. G. Tomiwa,^{33d} M. Tomoto,¹¹⁶ L. Tompkins,^{153,ff} B. Tong,⁵⁹ P. Tornambe,¹⁰² E. Torrence,¹³¹ H. Torres,⁴⁸ E. Torró Pastor,¹⁴⁸ C. Toscirri,¹³⁵ J. Toth,^{101,vv} D. R. Tovey,¹⁴⁹ A. Traeet,¹⁷ C. J. Treado,¹²⁴ T. Trefzger,¹⁷⁷ F. Tresoldi,¹⁵⁶ A. Tricoli,^{26b} I. M. Trigger,^{168a} S. Trincaz-Duvoid,¹³⁶ W. Trischuk,¹⁶⁷ B. Trocmé,⁵⁸ A. Trofymov,¹⁴⁵ C. Troncon,^{68a} M. Trovatelli,¹⁷⁶ F. Trovato,¹⁵⁶ L. Truong,^{33b} M. Trzebinski,⁸⁴ A. Trzupek,⁸⁴ F. Tsai,⁴⁶ J. C.-L. Tseng,¹³⁵ P. V. Tsiarehka,^{107,hh} A. Tsirigotis,¹⁶² V. Tsiskaridze,¹⁵⁵ E. G. Tskhadadze,^{159a} M. Tsopoulou,¹⁶² I. I. Tsukerman,¹²³ V. Tsulaia,¹⁸ S. Tsuno,⁸¹ D. Tsybychev,¹⁵⁵ Y. Tu,^{63b} A. Tudorache,^{28b} V. Tudorache,^{28b} T. T. Tulbure,^{28a} A. N. Tuna,⁵⁹ S. Turchikhin,⁷⁹ D. Turgeman,¹⁸⁰ I. Turk Cakir,^{4b,ww} R. J. Turner,²¹ R. T. Turra,^{68a} P. M. Tuts,³⁹ S. Tzamarias,¹⁶² E. Tzovara,⁹⁹ G. Uccielli,⁴⁷ K. Uchida,¹⁶³ I. Ueda,⁸¹ M. Ughetto,^{45a,45b} F. Ukegawa,¹⁶⁹ G. Unal,³⁶ A. Undrus,^{26b} G. Unel,¹⁷¹ F. C. Ungaro,¹⁰⁴ Y. Unno,⁸¹ K. Uno,¹⁶³ J. Urban,^{29b} P. Urquijo,¹⁰⁴ G. Usai,⁸ Z. Uysal,^{12d} V. Vacek,¹⁴² B. Vachon,¹⁰³ K. O. H. Vadla,¹³⁴ A. Vaidya,⁹⁴ C. Valderanis,¹¹³ E. Valdes Santurio,^{45a,45b} M. Valente,⁵⁴ S. Valentinetti,^{23b,23a} A. Valero,¹⁷⁴ L. Valéry,⁴⁶ R. A. Vallance,²¹ A. Vallier,³⁶ J. A. Valls Ferrer,¹⁷⁴ T. R. Van Daalen,¹⁴ P. Van Gemmeren,⁶ I. Van Vulpen,¹¹⁹ M. Vanadia,^{73a,73b} W. Vandelli,³⁶ E. R. Vandewall,¹²⁹ A. Vaniachine,¹⁶⁶ D. Vannicola,^{72a,72b} R. Vari,^{72a} E. W. Varnes,⁷ C. Varni,^{55b,55a} T. Varol,¹⁵⁸ D. Varouchas,¹³² K. E. Varvell,¹⁵⁷ M. E. Vasile,^{28b} G. A. Vasquez,¹⁷⁶ J. G. Vasquez,¹⁸³ F. Vazeille,³⁸ D. Vazquez Furelos,¹⁴ T. Vazquez Schroeder,³⁶ J. Veatch,⁵³ V. Vecchio,^{74a,74b} M. J. Veen,¹¹⁹ L. M. Veloce,¹⁶⁷ F. Veloso,^{140a,140c} S. Veneziano,^{72a} A. Ventura,^{67a,67b} N. Venturi,³⁶ A. Verbytskyi,¹¹⁴ V. Vercesi,^{70a} M. Verducci,^{71a,71b} C. M. Vergel Infante,⁷⁸ C. Vergis,²⁴ W. Verkerke,¹¹⁹ A. T. Vermeulen,¹¹⁹ J. C. Vermeulen,¹¹⁹ M. C. Vetterli,^{152,d} N. Viaux Maira,^{147c} M. Vicente Barreto Pinto,⁵⁴ T. Vickey,¹⁴⁹ O. E. Vickey Boeriu,¹⁴⁹ G. H. A. Viehhauser,¹³⁵ L. Viganì,^{61b} M. Villa,^{23b,23a} M. Villaplana Perez,^{68a,68b} E. Vilucchi,⁵¹ M. G. Vincter,³⁴ G. S. Virdee,²¹ A. Vishwakarma,⁴⁶ C. Vittori,^{23b,23a} I. Vivarelli,¹⁵⁶ M. Vogel,¹⁸² P. Vokac,¹⁴² S. E. von Buddenbrock,^{33d} E. Von Toerne,²⁴ V. Vorobel,¹⁴³ K. Vorobev,¹¹¹ M. Vos,¹⁷⁴ J. H. Vosseveld,⁹⁰ M. Vozak,¹⁰⁰ N. Vranjes,¹⁶ M. Vranjes Milosavljevic,¹⁶ V. Vrba,¹⁴² M. Vreeswijk,¹¹⁹ R. Vuillermet,³⁶ I. Vukotic,³⁷ P. Wagner,²⁴ W. Wagner,¹⁸² J. Wagner-Kuhr,¹¹³ S. Wahdan,¹⁸² H. Wahlberg,⁸⁸ V. M. Walbrecht,¹¹⁴ J. Walder,⁸⁹ R. Walker,¹¹³ S. D. Walker,⁹³ W. Walkowiak,¹⁵¹ V. Wallangen,^{45a,45b} A. M. Wang,⁵⁹ C. Wang,^{60c} C. Wang,^{60b} F. Wang,¹⁸¹ H. Wang,¹⁸ H. Wang,³ J. Wang,^{63a} J. Wang,¹⁵⁷ J. Wang,^{61b} P. Wang,⁴² Q. Wang,¹²⁸ R.-J. Wang,⁹⁹ R. Wang,^{60a} R. Wang,⁶ S. M. Wang,¹⁵⁸ W. T. Wang,^{60a} W. Wang,^{15c,xx} W. X. Wang,^{60a,xx} Y. Wang,^{60a,yy} Z. Wang,^{60c} C. Wanotayaroj,⁴⁶ A. Warburton,¹⁰³ C. P. Ward,³² D. R. Wardrope,⁹⁴ N. Warrack,⁵⁷ A. Washbrook,⁵⁰ A. T. Watson,²¹ M. F. Watson,²¹ G. Watts,¹⁴⁸ B. M. Waugh,⁹⁴ A. F. Webb,¹¹ S. Webb,⁹⁹ C. Weber,¹⁸³ M. S. Weber,²⁰ S. A. Weber,³⁴ S. M. Weber,^{61a} A. R. Weidberg,¹³⁵ J. Weingarten,⁴⁷ M. Weirich,⁹⁹ C. Weiser,⁵² P. S. Wells,³⁶ T. Wenaus,^{26b} T. Wengler,³⁶ S. Wenig,³⁶ N. Wermes,²⁴ M. D. Werner,⁷⁸ M. Wessels,^{61a} T. D. Weston,²⁰ K. Whalen,¹³¹ N. L. Whallon,¹⁴⁸ A. M. Wharton,⁸⁹ A. S. White,¹⁰⁵ A. White,⁸ M. J. White,¹ D. Whiteson,¹⁷¹ B. W. Whitmore,⁸⁹ W. Wiedenmann,¹⁸¹ M. Wielers,¹⁴⁴ N. Wieseotte,⁹⁹ C. Wiglesworth,⁴⁰ L. A. M. Wiik-Fuchs,⁵² F. Wilk,¹⁰⁰ H. G. Wilkens,³⁶ L. J. Wilkins,⁹³ H. H. Williams,¹³⁷ S. Williams,³² C. Willis,¹⁰⁶ S. Willocq,¹⁰² J. A. Wilson,²¹ I. Wingerter-Seez,⁵ E. Winkels,¹⁵⁶ F. Winklmeier,¹³¹ O. J. Winston,¹⁵⁶ B. T. Winter,⁵² M. Wittgen,¹⁵³ M. Wobisch,⁹⁵ A. Wolf,⁹⁹ T. M. H. Wolf,¹¹⁹ R. Wolff,¹⁰¹ R. W. Wölker,¹³⁵ J. Wollrath,⁵² M. W. Wolter,⁸⁴ H. Wolters,^{140a,140c} V. W. S. Wong,¹⁷⁵ N. L. Woods,¹⁴⁶ S. D. Worm,²¹ B. K. Wosiek,⁸⁴ K. W. Woźniak,⁸⁴ K. Wraight,⁵⁷ S. L. Wu,¹⁸¹ X. Wu,⁵⁴ Y. Wu,^{60a} T. R. Wyatt,¹⁰⁰ B. M. Wynne,⁵⁰ S. Xella,⁴⁰

Z. Xi,¹⁰⁵ L. Xia,¹⁷⁸ X. Xiao,¹⁰⁵ I. Xioidis,¹⁵⁶ D. Xu,^{15a} H. Xu,^{60a,tt} L. Xu,^{26b} T. Xu,¹⁴⁵ W. Xu,¹⁰⁵ Z. Xu,^{60b} Z. Xu,¹⁵³
 B. Yabsley,¹⁵⁷ S. Yacoob,^{33a} K. Yajima,¹³³ D. P. Yallup,⁹⁴ D. Yamaguchi,¹⁶⁵ Y. Yamaguchi,¹⁶⁵ A. Yamamoto,⁸¹
 M. Yamatani,¹⁶³ T. Yamazaki,¹⁶³ Y. Yamazaki,⁸² Z. Yan,²⁵ H. J. Yang,^{60c,60d} H. T. Yang,¹⁸ S. Yang,⁷⁷ X. Yang,^{60b,58}
 Y. Yang,¹⁶³ W.-M. Yao,¹⁸ Y. C. Yap,⁴⁶ Y. Yasu,⁸¹ E. Yatsenko,^{60c,60d} J. Ye,⁴² S. Ye,^{26b} I. Yeletsikh,⁷⁹ M. R. Yexley,⁸⁹
 E. Yigitbasi,²⁵ K. Yorita,¹⁷⁹ K. Yoshihara,¹³⁷ C. J. S. Young,³⁶ C. Young,¹⁵³ J. Yu,⁷⁸ R. Yuan,^{60b,zz} X. Yue,^{61a} S. P. Y. Yuen,²⁴
 M. Zaazoua,^{35e} B. Zabinski,⁸⁴ G. Zacharis,¹⁰ E. Zaffaroni,⁵⁴ J. Zahreddine,¹³⁶ A. M. Zaitsev,^{122,ll} T. Zakareishvili,^{159b}
 N. Zakharchuk,³⁴ S. Zambito,⁵⁹ D. Zanzi,³⁶ D. R. Zaripovas,⁵⁷ S. V. Zeiβner,⁴⁷ C. Zeitnitz,¹⁸² G. Zemaityte,¹³⁵ J. C. Zeng,¹⁷³
 O. Zenin,¹²² T. Ženiš,^{29a} D. Zerwas,¹³² M. Zgubič,¹³⁵ B. Zhang,^{15c} D. F. Zhang,^{15b} G. Zhang,^{15b} H. Zhang,^{15c} J. Zhang,⁶
 L. Zhang,^{15c} L. Zhang,^{60a} M. Zhang,¹⁷³ R. Zhang,²⁴ X. Zhang,^{60b} Y. Zhang,^{15a,15d} Z. Zhang,^{63a} Z. Zhang,¹³² P. Zhao,⁴⁹
 Y. Zhao,^{60b} Z. Zhao,^{60a} A. Zhemchugov,⁷⁹ Z. Zheng,¹⁰⁵ D. Zhong,¹⁷³ B. Zhou,¹⁰⁵ C. Zhou,¹⁸¹ M. S. Zhou,^{15a,15d} M. Zhou,¹⁵⁵
 N. Zhou,^{60c} Y. Zhou,⁷ C. G. Zhu,^{60b} C. Zhu,^{15a,15d} H. L. Zhu,^{60a} H. Zhu,^{15a} J. Zhu,¹⁰⁵ Y. Zhu,^{60a} X. Zhuang,^{15a} K. Zhukov,¹¹⁰
 V. Zhulanov,^{121b,121a} D. Zieminska,⁶⁵ N. I. Zimine,⁷⁹ S. Zimmermann,⁵² Z. Zinonos,¹¹⁴ M. Ziolkowski,¹⁵¹ L. Živković,¹⁶
 G. Zobernig,¹⁸¹ A. Zoccoli,^{23b,23a} K. Zoch,⁵³ T. G. Zorbas,¹⁴⁹ R. Zou,³⁷ and L. Zwalinski³⁶

(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 AB, 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*Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia*^{23a}*INFN Bologna and Università di Bologna, Dipartimento di Fisica, Italy*^{23b}*INFN Sezione di Bologna, Italy*²⁴*Physikalisches Institut, Universität Bonn, Bonn, Germany*²⁵*Department of Physics, Boston University, Boston, Massachusetts, USA*^{26a}*University of Colorado Boulder, Department of Physics, Colorado, USA*^{26b}*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*²⁷*Department of Physics, Brandeis University, Waltham, Massachusetts, 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*
- ^{29a}*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{29b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ³⁰*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- ³¹*California State University, California, USA*
- ³²*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ^{33a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
- ^{33b}*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
- ^{33c}*University of South Africa, Department of Physics, Pretoria, South Africa*
- ^{33d}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ³⁴*Department of Physics, Carleton University, Ottawa ON, Canada*
- ^{35a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
- ^{35b}*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
- ^{35c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- ^{35d}*Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda, Morocco*
- ^{35e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ³⁶*CERN, Geneva, Switzerland*
- ³⁷*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
- ³⁸*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
- ³⁹*Nevis Laboratory, Columbia University, Irvington, New York, USA*
- ⁴⁰*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- ^{41a}*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- ^{41b}*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- ⁴²*Physics Department, Southern Methodist University, Dallas, Texas, USA*
- ⁴³*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
- ⁴⁴*National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- ^{45a}*Department of Physics, Stockholm University, Sweden*
- ^{45b}*Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁶*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁷*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁸*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁴⁹*Department of Physics, Duke University, Durham, North Carolina, USA*
- ⁵⁰*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵¹*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵²*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵³*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵⁴*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ^{55a}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- ^{55b}*INFN Sezione di Genova, Italy*
- ⁵⁶*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁷*SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁸*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁵⁹*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- ^{60a}*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- ^{60b}*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- ^{60c}*School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China*
- ^{60d}*Tsung-Dao Lee Institute, Shanghai, China*
- ^{61a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{61b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁶²*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ^{63a}*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
- ^{63b}*Department of Physics, University of Hong Kong, Hong Kong, China*

- ^{63c}*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶⁴*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶⁵*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- ^{66a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
^{66b}*ICTP, Trieste, Italy*
- ^{66c}*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
^{67a}*INFN Sezione di Lecce, Italy*
- ^{67b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
^{68a}*INFN Sezione di Milano, Italy*
- ^{68b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
^{69a}*INFN Sezione di Napoli, Italy*
- ^{69b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
^{70a}*INFN Sezione di Pavia, Italy*
- ^{70b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
^{71a}*INFN Sezione di Pisa, Italy*
- ^{71b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
^{72a}*INFN Sezione di Roma, Italy*
- ^{72b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
^{73a}*INFN Sezione di Roma Tor Vergata, Italy*
- ^{73b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
^{74a}*INFN Sezione di Roma Tre, Italy*
- ^{74b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
^{75a}*INFN-TIFPA, Italy*
^{75b}*Università degli Studi di Trento, Trento, Italy*
- ⁷⁶*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
⁷⁷*University of Iowa, Iowa City, Iowa, USA*
- ⁷⁸*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
⁷⁹*Joint Institute for Nuclear Research, Dubna, Russia*
- ^{80a}*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
^{80b}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
- ^{80c}*Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil*
^{80d}*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- ⁸¹*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
⁸²*Graduate School of Science, Kobe University, Kobe, Japan*
- ^{83a}*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
^{83b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
⁸⁴*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
⁸⁵*Faculty of Science, Kyoto University, Kyoto, Japan*
⁸⁶*Kyoto University of Education, Kyoto, Japan*
- ⁸⁷*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- ⁸⁸*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
⁸⁹*Physics Department, Lancaster University, Lancaster, United Kingdom*
- ⁹⁰*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁹¹*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- ⁹²*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
⁹³*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
⁹⁴*Department of Physics and Astronomy, University College London, London, United Kingdom*
⁹⁵*Louisiana Tech University, Ruston, Louisiana, USA*
⁹⁶*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁹⁷*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- ⁹⁸*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
⁹⁹*Institut für Physik, Universität Mainz, Mainz, Germany*
- ¹⁰⁰*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
¹⁰¹*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- ¹⁰²*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
¹⁰³*Department of Physics, McGill University, Montreal QC, Canada*
¹⁰⁴*School of Physics, University of Melbourne, Victoria, Australia*
¹⁰⁵*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*

- ¹⁰⁶*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ¹⁰⁷*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
- ¹⁰⁸*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
- ¹⁰⁹*Group of Particle Physics, University of Montreal, Montreal QC, Canada*
- ¹¹⁰*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- ¹¹¹*National Research Nuclear University MEPhI, Moscow, Russia*
- ¹¹²*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- ¹¹³*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ¹¹⁴*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹¹⁵*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹¹⁶*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ¹¹⁷*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹¹⁸*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹¹⁹*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹²⁰*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ^{121a}*Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia*
- ^{121b}*Novosibirsk State University Novosibirsk, Russia*
- ¹²²*Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia*
- ¹²³*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre “Kurchatov Institute”, Moscow, Russia*
- ¹²⁴*Department of Physics, New York University, New York, New York, USA*
- ¹²⁵*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- ¹²⁶*The Ohio State University, Columbus, Ohio, USA*
- ¹²⁷*Faculty of Science, Okayama University, Okayama, Japan*
- ¹²⁸*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹²⁹*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹³⁰*Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹³¹*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹³²*LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- ¹³³*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹³⁴*Department of Physics, University of Oslo, Oslo, Norway*
- ¹³⁵*Department of Physics, Oxford University, Oxford, United Kingdom*
- ¹³⁶*LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France*
- ¹³⁷*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹³⁸*Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia*
- ¹³⁹*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- ^{140a}*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*
- ^{140b}*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{140c}*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- ^{140d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{140e}*Departamento de Física, Universidade do Minho, Braga, Portugal*
- ^{140f}*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain*
- ^{140g}*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
- ^{140h}*Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
- ¹⁴¹*Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- ¹⁴²*Czech Technical University in Prague, Prague, Czech Republic*
- ¹⁴³*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹⁴⁴*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁴⁵*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ¹⁴⁶*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ^{147a}*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{147b}*Universidad Andres Bello, Department of Physics, Santiago, Chile*
- ^{147c}*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ¹⁴⁸*Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹⁴⁹*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁵⁰*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁵¹*Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁵²*Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- ¹⁵³*SLAC National Accelerator Laboratory, Stanford, California, USA*
- ¹⁵⁴*Physics Department, Royal Institute of Technology, Stockholm, Sweden*

- ¹⁵⁵*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
¹⁵⁶*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
¹⁵⁷*School of Physics, University of Sydney, Sydney, Australia*
¹⁵⁸*Institute of Physics, Academia Sinica, Taipei, Taiwan*
^{159a}*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
^{159b}*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
¹⁶⁰*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
¹⁶¹*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
¹⁶²*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
¹⁶³*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
¹⁶⁴*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
¹⁶⁵*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
¹⁶⁶*Tomsk State University, Tomsk, Russia*
¹⁶⁷*Department of Physics, University of Toronto, Toronto ON, Canada*
^{168a}*TRIUMF, Vancouver BC, Canada*
^{168b}*Department of Physics and Astronomy, York University, Toronto ON, Canada*
¹⁶⁹*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
¹⁷⁰*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
¹⁷¹*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
¹⁷²*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
¹⁷³*Department of Physics, University of Illinois, Urbana, Illinois, USA*
¹⁷⁴*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
¹⁷⁵*Department of Physics, University of British Columbia, Vancouver BC, Canada*
¹⁷⁶*Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
¹⁷⁷*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
¹⁷⁸*Department of Physics, University of Warwick, Coventry, United Kingdom*
¹⁷⁹*Waseda University, Tokyo, Japan*
¹⁸⁰*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
¹⁸¹*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
¹⁸²*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
¹⁸³*Department of Physics, Yale University, New Haven, Connecticut, USA*
¹⁸⁴*Yerevan Physics Institute, Yerevan, Armenia*

^aDeceased.

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

^cAlso at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.

^dAlso at TRIUMF, Vancouver BC, Canada.

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

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

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

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

ⁱAlso at Physics Dept, University of South Africa, Pretoria, South Africa.

^jAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

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

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

^mAlso at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.

ⁿAlso at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

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

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

^qAlso at Department of Physics, University of Adelaide, Adelaide, Australia.

^rAlso at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.

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

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

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

^vAlso at Department of Physics, California State University, East Bay, 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.

- ^z Also at Graduate School of Science, Osaka University, Osaka, Japan.
- ^{aa} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
- ^{bb} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- ^{cc} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
- ^{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, Stanford, California, USA.
- ^{gg} Also at Manhattan College, New York, New York, USA.
- ^{hh} Also at Joint Institute for Nuclear Research, Dubna, Russia.
- ⁱⁱ Also at Hellenic Open University, Patras, Greece.
- ^{jj} Also at The City College of New York, New York, New York, USA.
- ^{kk} Also at Department of Physics, California State University, Sacramento, USA.
- ^{ll} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{mm} Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
- ⁿⁿ Also at Louisiana Tech University, Ruston, Louisiana, USA.
- ^{oo} Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
- ^{pp} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{qq} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- ^{rr} Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
- ^{ss} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ^{tt} Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
- ^{uu} Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{vv} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ww} Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
- ^{xx} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{yy} Also at LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France.
- ^{zz} Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.