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Observation of an Excess of Dicharmonium Events in the Four-Muon Final State with the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)

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A search is made for potential $cc\bar{c}\bar{c}$ tetraquarks decaying into a pair of charmonium states in the four muon final state using proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 140 fb^{-1} recorded by the ATLAS experiment at LHC. Two decay channels, $J/\psi + J/\psi \rightarrow 4\mu$ and $J/\psi + \psi(2S) \rightarrow 4\mu$, are studied. Backgrounds are estimated based on a hybrid approach involving Monte Carlo simulations and data-driven methods. Statistically significant excesses with respect to backgrounds dominated by the single parton scattering are seen in the di- J/ψ channel consistent with a narrow resonance at 6.9 GeV and a broader structure at lower mass. A statistically significant excess is also seen in the $J/\psi + \psi(2S)$ channel. The fitted masses and decay widths of the structures are reported.

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Beyond the conventional mesons ($q\bar{q}$) and baryons (qqq or $\bar{q}\bar{q}\bar{q}$), exotic hadrons composed of four ($qqq\bar{q}$) or five quarks ($qqqq\bar{q}$) are also allowed under color confinement. The $X(3872)$ particle discovered by Belle in 2003 was the first tetraquark (TQ) candidate [1], and was followed by a series of further candidates designated as X , Y , and Z states [2]. In 2020, LHCb observed a narrow $X(6900)$ structure in the di- J/ψ channel [3]. The structure could be interpreted as a tetraquark with four charm quarks, $T_{cc\bar{c}\bar{c}}$ [4–11]. An additional enhancement closer to the di- J/ψ mass threshold was also observed in the LHCb data. Since the 6.9 GeV LHCb resonance is above the $J/\psi + \psi(2S)$ mass threshold, a structure in the $J/\psi + \psi(2S)$ channel is also possible. Both channels are investigated by ATLAS in a quite different phase space region from LHCb, and the new channel of $J/\psi + \psi(2S)$ provides more information for dicharmonium excesses. For example in some predictions, the two channels are coupled via Pomeron exchange between the two charmonia, and $X(6900)$ is dynamically produced [12].

A search in the 4μ final state produced through the di- J/ψ and $J/\psi + \psi(2S)$ channels is carried out, using 140 fb^{-1} of LHC proton-proton (pp) data collected by the ATLAS experiment at a center-of-mass energy of $\sqrt{s} = 13$ TeV between the years 2015 and 2018. Only the data where all detector systems are functional and recording high-quality data are used. The ATLAS detector [13] covers nearly the entire solid angle around the collision

point [ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) 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.] with layered tracking detectors, calorimeters, and muon chambers. The muon and tracking systems are of particular importance in the reconstruction of charmonia. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting air-core toroids with eight coils each, a system of tracking chambers, and detectors for triggering. Muons are reconstructed using information from the ID and MS systems.

Background processes are estimated partly by Monte Carlo (MC) simulations and partly from data. The main backgrounds are dicharmonium production via single parton scattering (SPS) [14–20], and double parton scattering (DPS) [21–27], nonprompt J/ψ production from b -hadron decays, prompt single J/ψ production and nonresonant dimuon production. PYTHIA8.244 [28] is used to generate SPS, DPS, and nonprompt dicharmonium events. Both the color-singlet and color-octet intermediate states are included for J/ψ and $\psi(2S)$. The A14 [29] set of parameter values and the NNPDF23LO [30] parton distribution functions (PDF) [31] are used. PHOTOS 3.61 [32] is applied to simulate final state radiation in particle decays. The remaining backgrounds that contain a single or no charmonium are modeled using the data.

The data sample was collected with triggers requiring either two muons with invariant mass compatible with J/ψ or $\psi(2S)$ mesons (mass in the range of [2.5,4.3] GeV), or three muons containing at least one such dimuon pair [33,34]. Combinations of triggers with different prescales [35] depending on the run period are used to give the largest

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

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acceptance. The trigger efficiency for the $X(6900)$ relative to the off-line selection is about 72%. Dedicated ATLAS off-line software is used to reconstruct the charmonium and 4μ candidates in each event recorded by the triggers. In each event containing at least four muons with two opposite-charge pairs, the ID tracks are fit to a common vertex. Afterwards, each vertex of the two pairs is refit with a J/ψ or $\psi(2S)$ mass constraint [36]. The resolution of the TQ mass with these mass constraints ($m_{4\mu}$) is about 0.33% for $X(6900)$.

The *loose* identification selection criteria [37] are required for all muon candidates. Depending on the muon trigger thresholds and muon identification requirements, different muon momenta on the four muons are required. Several requirements are imposed on the following variables to further suppress the background: the vertex fit quality based on χ^2 per degrees of freedom N , the signed distances between the primary (The primary interaction vertex is the collision vertex reconstructed excluding the 4μ candidate tracks and with the smallest distance of closest approach in z from the 4μ vertex.) and reconstructed 4μ vertices ($L_{xy}^{4\mu}$), and between the former vertices and the dimuon mass-constrained subvertices ($L_{xy}^{\text{di-}\mu}$). Events with $\Delta R < 0.25$ (The angular distance is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, with η and ϕ being the pseudorapidity and azimuthal angle of a particle, respectively.) between the two reconstructed charmonia are used to study the signal, whereas events with $\Delta R \geq 0.25$ are used to validate the shape of the 4μ mass distribution for the SPS background and constrain its normalization. The shape of the signal 4μ mass distribution is not much affected by ΔR as well as muon p_T requirements. A summary of the kinematic requirements for the analysis regions is listed in Table I.

The SPS and DPS backgrounds contain two prompt charmonia and are modeled by MC simulations. Because the event generator does not reproduce the data distributions well, kinematic corrections are derived from two dedicated control regions. Since SPS (DPS) events are characterized by two charmonia which are nearby (distant) in $\eta - \phi$ space, the control region is defined with a 4μ mass sideband within [7.5, 12] GeV ([14, 24.5] GeV) without the ΔR requirement. The corrections are implemented by assigning event weights to MC simulations such that distributions of kinematic variables such as di- J/ψ p_T , $\Delta\phi$ and $\Delta\eta$ between charmonia, and the lowest muon p_T

match the data in the control regions. The corrections are then applied to all mass regions and the SPS modeling is validated in the $\Delta R > 0.25$ control region.

The nonprompt background also contains two charmonia, albeit originating from b -hadron decays. These typically contain a decay vertex that is displaced from the primary pp interaction. This background is also modeled using MC simulation, but normalized and validated by dedicated control regions obtained by reversing the vertex quality requirements as shown in Table I. Events from prompt single charmonium production and nonresonant dimuon production are collectively called ‘‘Others,’’ and have at least one charmonium candidate containing random combinations of mostly fake muons. Fake muons are tracks, typically charged hadrons, that are misidentified as muons. A data-driven method is used because MC simulations do not accurately estimate this kind of background. A fake muon control region from data is used to model the Others background, which is defined by requiring that one charmonium candidate contains a track that is not reconstructed as a muon candidate, with all the other requirements kept unchanged. Events in the charmonium mass sidebands are used for both the normalization and shape corrections for Others.

In the di- J/ψ channel, events from resonances in the $J/\psi + \psi(2S)$ channel via $\psi(2S) \rightarrow J/\psi + X$, $\psi(2S) \rightarrow \gamma\chi_{cJ}$, and $\chi_{cJ} \rightarrow \gamma J/\psi$, where particles other than di- J/ψ are ignored, are included as the feed-down background. The feed-down events normalization in di- J/ψ (N_{fd}) and the fitted signal yield in $J/\psi + \psi(2S)$ (N) are related by

$$N_{\text{fd}} = \frac{\mathcal{B}'\epsilon'}{\mathcal{B}(\psi(2S) \rightarrow \mu\mu)\epsilon} N, \quad (1)$$

where ϵ (ϵ') is the signal (feed-down) efficiency in $J/\psi + \psi(2S)$ (di- J/ψ), and the branching fraction $\mathcal{B}' = [\mathcal{B}(\psi(2S) \rightarrow J/\psi + X) + \mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{cJ})\mathcal{B}(\chi_{cJ} \rightarrow \gamma J/\psi)]\mathcal{B}(J/\psi \rightarrow \mu\mu)$, where $X = \pi^+\pi^-, \pi^0\pi^0, \eta, \pi^0$. The systematic uncertainty on N_{fd} is dominated by the uncertainty on N .

Unbinned maximum likelihood fits are performed to extract the signal information from data in the 4μ mass spectra. The likelihood used for the fit is

$$\mathcal{L} = \mathcal{L}_{SR}(\vec{\theta}, \vec{\lambda}) \cdot \mathcal{L}_{CR}(\vec{\theta}) \cdot \prod_{j=1}^K G(\theta_j; \theta_j, \sigma_j), \quad (2)$$

TABLE I. Summary of event selection requirements for different regions.

Signal region	Control region	Nonprompt region
Dimuon or trimuon triggers, oppositely charged muons from each charmonium, <i>loose</i> muons, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $ \eta_{1,2,3,4} < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV, Loose vertex requirements $\chi_{4\mu}^2/N < 40$ ($N = 5$) and $\chi_{\text{di-}\mu}^2/N < 100$ ($N = 2$),		
Vertex $\chi_{4\mu}^2/N < 3$, $L_{xy}^{4\mu} < 0.2$ mm, $ L_{xy}^{\text{di-}\mu} < 0.3$ mm, $m_{4\mu} < 11$ GeV,		Vertex $\chi_{4\mu}^2/N > 6$,
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	or $ L_{xy}^{\text{di-}\mu} > 0.4$ mm

where \mathcal{L}_{SR} (\mathcal{L}_{CR}) is the likelihood in the signal (control) region, $\vec{\lambda}$ are the parameters of interest, θ_j are nuisance parameters (NP) which account for systematic uncertainties shared between the two regions. Each NP has a Gaussian distribution constraint with a subsidiary measurement θ'_j , a mean θ_j and a width set to $\sigma_j = 1$ by construction. Only the background yields in the control regions are used in simultaneous fits with the signal regions. Background yields in the two regions are related by a transfer factor obtained from MC predictions and data-driven estimations, with systematic variations for both components.

In the di- J/ψ channel, the feed-down normalized by Eq. (1) is included as an additional background, and two fit models are considered. In model A, the signal probability density function in \mathcal{L}_{SR} consists of three interfering S -wave Breit-Wigner (BW) resonances multiplied with a phase space factor and convolved with a mass resolution function, which gives

$$f_s(x) = \left| \sum_{i=0}^2 \frac{z_i}{m_i^2 - x^2 - im_i \Gamma_i(x)} \right|^2 \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\theta), \quad (3)$$

where m_i [$\Gamma_i(x)$] are the masses (widths) of resonances, z_i are complex numbers representing the relative magnitudes and phases (z_1 is fixed to unity with zero phase for this purpose), $\Gamma_i(x) = \Gamma_i(m_i/x)(q/q_i)$, where q (q_i) is the momentum of one charmonium in the rest frame of the dicharmonium system at the invariant mass equal to x (m_i) [38], and R is the mass resolution function. The m_i terms are ordered by the subscripts. In model B, two resonances are considered. The first one interferes with the SPS background, while the second is standalone. The signal + SPS probability distribution function gives

$$f(x) = \left(\left| \frac{z_0}{m_0^2 - x^2 - im_0 \Gamma_0(x)} + A(x)e^{i\phi} \right|^2 + \left| \frac{z_2}{m_2^2 - x^2 - im_2 \Gamma_2(x)} \right|^2 \right) \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\theta), \quad (4)$$

where $A(x)$ and ϕ are the SPS background amplitude and phase relative to the resonance at m_0 ($|A(x)|^2$ reproduces the noninterfering SPS background from the MC prediction). In this model, the control region becomes irrelevant and is excluded from the likelihood given in Eq. (2).

Models A and B are analogous to models I and II of the LHCb study [3], respectively. However, interferences between the signal resonances are introduced in model A, which is not done in the analysis by LHCb. The number of resonances in model A starts from one and increases to three with the fit quality gradually improving. A 4th resonance is added only for systematics, as the fit quality does not improve appreciably. For comparison, a two-resonance model with interference, and a three-resonance model without interferences, are also tried. It is found that when

compared with model A, these models are excluded with a confidence level of more than 95% based on toy MC studies.

In the $J/\psi + \psi(2S)$ channel, two fit models are also considered. Model α assumes that the same interfering resonances observed in the di- J/ψ channel also decay into $J/\psi + \psi(2S)$, in addition to a stand-alone fourth resonance in this channel. The signal probability distribution function gives

$$f_s(x) = \left(\left| \sum_{i=0}^2 \frac{z_i}{m_i^2 - x^2 - im_i \Gamma_i(x)} \right|^2 + \left| \frac{z_3}{m_3^2 - x^2 - im_3 \Gamma_3(x)} \right|^2 \right) \times \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x} \right)^2} \otimes R(\theta), \quad (5)$$

where the parameters of the first three resonances, whose contribution appears as a structure just above the $m_{J/\psi} + m_{\psi(2S)}$ mass threshold, are fixed to the values from the fit to the di- J/ψ channel. In contrast, model β assumes a single resonance in this channel [i.e., without the $z_{0,1,2}$ terms in Eq. (5)].

The systematic uncertainties are classified into those affecting exclusively normalizations, and those affecting the mass spectrum shape as well. Only the latter are relevant, since the signal and background normalizations are freely floating parameters. The systematic uncertainties in $m_{4\mu}$, with and without the muon momentum calibration corrections, are treated as resolution uncertainties. Because the resolution of the $m_{4\mu}$ is mass dependent and a constant mass is used in the nominal fit, resolutions in different mass ranges are treated as systematic uncertainties. A shape uncertainty is assigned to account for bin-to-bin fluctuations from the limited MC sample size for backgrounds. In the SPS background, a PYTHIA model parameter uncertainty from `pT0timesMPI` [28], which controls the suppression of the soft double charmonia production, is assigned, and its nominal value is tuned to data in the SPS control region. A shape uncertainty in the background due to residual dicharmonium p_T mismodeling is applied. Based on toy MC studies, biases from the fit in the resonance parameters are also considered as systematic uncertainties. The P and D -wave BW functions are substituted for the S wave for resonances away from the threshold to estimate systematic uncertainties due to different orbital angular momentum assumptions. (The first resonance at the threshold is always assumed to be S wave, as the data has no constraining power for its width when $L = 1, 2$.) Systematic shape variations in the $X(6900)$ in the di- J/ψ channel, and in the second resonance for the $J/\psi + \psi(2S)$ channel due to the ΔR and muon p_T requirements are considered as well. In the di- J/ψ channel, a 4th resonance around 7.2 GeV (hinted by the LHCb analysis) is added to the fit, and the feed-down background normalizations are varied according to the

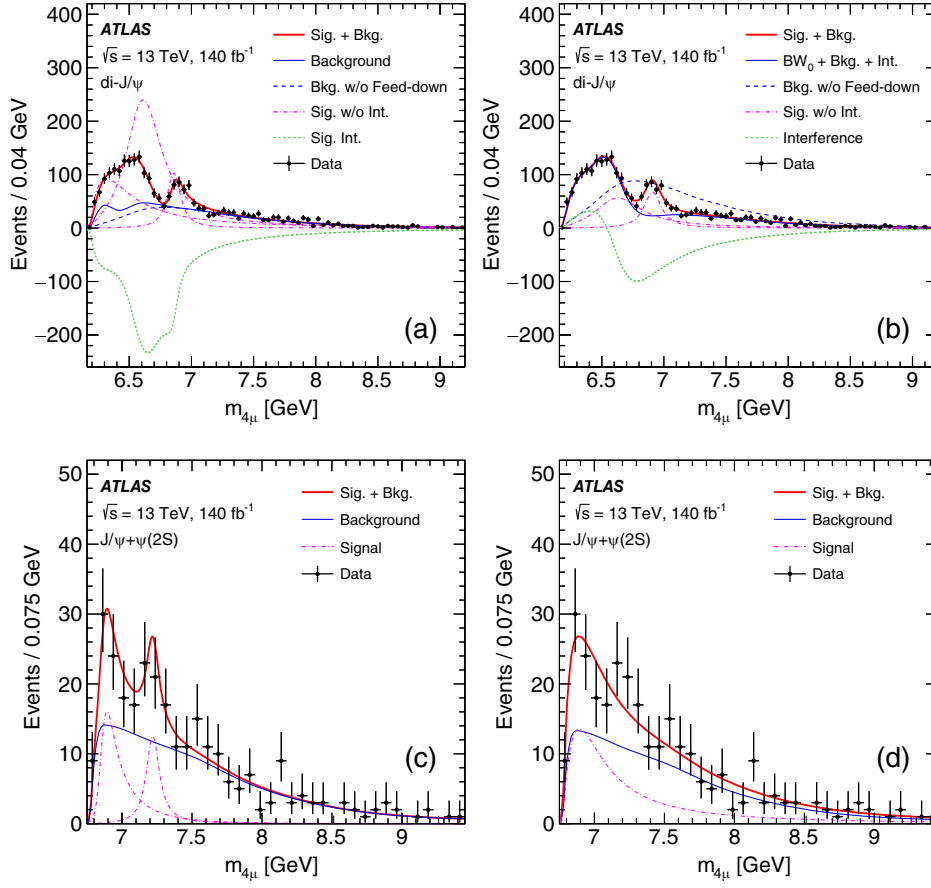


FIG. 1. The fit to the mass spectra in the signal regions in the $di\text{-}J/\psi$ (a,b) and $J/\psi + \psi(2S)$ (c,d) channels. Fit results for models A (a), B (b), α (c), and β (d) are shown. The purple dash-dotted lines represent the components of individual resonances, and the green short dashed ones represent the interferences among them.

uncertainties in $J/\psi + \psi(2S)$. The transfer factor uncertainty is dominated by the SPS model parameter, so it is not treated as a separate NP. In the $J/\psi + \psi(2S)$ channel, the uncertainty in a transfer factor between the signal and control regions, and a shape uncertainty derived from the nonprompt region due to Others (shape inconsistency), are included. Interference between the 4th resonance and the other ones are included in systematic uncertainties. In model α , systematic uncertainties on the lower resonance shape from the $di\text{-}J/\psi$ channel model A fit are also included. Other systematic uncertainties such as the parton PDF and Pythia parameters affect signal and background normalizations only, and are not incorporated in the fits.

The 4μ mass spectra fit to data in the two channels are shown in Fig. 1. The fitted masses and widths of resonances are given in Table II. Both the significance of all resonances, and the one for $X(6900)$ alone, far exceed 5σ . (The asymptotic formula based on the profile likelihood ratio,

$Z = \sqrt{2 \ln[L(\hat{s}, \hat{\theta})/L(0, \hat{\theta})]}$, is used to calculate the overall significance, where s is the signal yield and θ are NPs [39].

Similarly for $X(6900)$ alone, $Z = \sqrt{2 \ln[L(\hat{z}_3, \hat{\theta})/L(0, \hat{\theta})]}$ is used. In the calculations, the signal shape parameters are

TABLE II. The fitted masses and natural widths (in GeV), and relative uncertainties of signal yields ($\Delta s/s$) in the $di\text{-}J/\psi$ and $J/\psi + \psi(2S)$ channels. The results of both the models are given in each channel. The first uncertainties are statistical while the second ones are systematic.

$Di\text{-}J/\psi$	Model A	Model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$...
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$...
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$...
$J/\psi + \psi(2S)$	Model α	Model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

all fixed to their best-fit values.) The mass of the third resonance, m_2 , is consistent with the LHCb mass. Although both the models *A* and *B* describe the data well, the broad structure at the lower mass could result from other physical effects, such as the feed-down from higher dicharmonium resonances, e.g., $T_{cc\bar{c}\bar{c}} \rightarrow \chi_{c1}\chi_{c1'} \rightarrow J/\psi J/\psi\gamma\gamma$ where the soft photons are not reconstructed. In the $J/\psi + \psi(2S)$ channel, the signal significance with signal shape parameters of model α (β) fixed to their best-fit values is 4.7σ (4.3σ). In the fit with model α , the significance of the second resonance alone is found to be 3.0σ .

In conclusion, the results of a search for potential $cc\bar{c}\bar{c}$ tetraquarks decaying into a pair of J/ψ charmonium states, or into a J/ψ and $\psi(2S)$, in the 4μ final state are presented based on pp collisions data collected by the ATLAS experiment at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 140 fb^{-1} . A significant excess of events (far exceeding 5σ) in data above the expected background is observed in the di- J/ψ channel. Analogous to LHCb observations, a broad structure at lower mass and a resonance around 6.9 GeV are observed. A three-resonance model with interferences, or a model with the lower broad structure interfering with the SPS background, describes the excess better than models with fewer interfering resonances or with no interferences. In the $J/\psi + \psi(2S)$ channel, a 4.7σ excess of events is observed when considering a model involving two resonances, one of which is near the 6.9 GeV threshold. In both channels, details of the lower-mass structure cannot be discerned directly from the data, and other interpretations (e.g., multiple noninterfering resonances, reflection effects and threshold enhancements) cannot be excluded. More data are required to better characterize the excesses observed in both channels.

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Appendix.—Signal events are simulated with the event generator JHU [41] and CTEQ6L1 PDF [42], or with

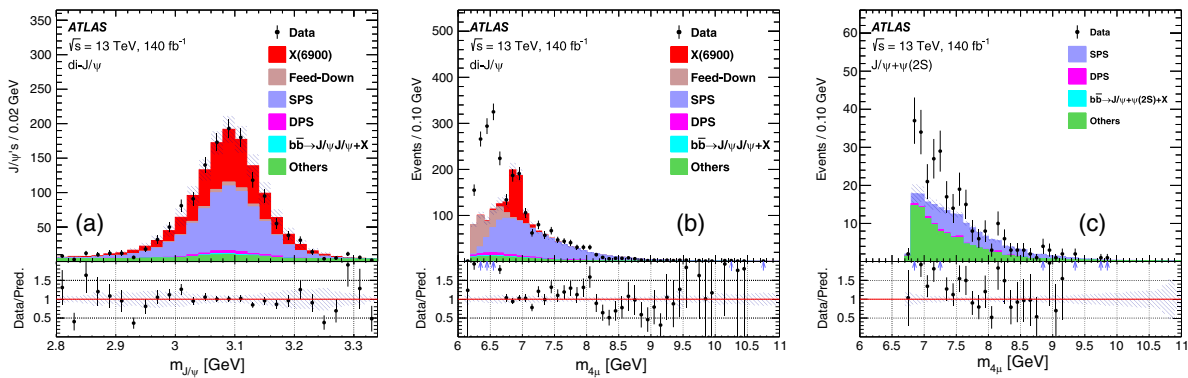


FIG. 2. The J/ψ mass spectrum with $6.7 \text{ GeV} < m_{4\mu} < 7.1 \text{ GeV}$ (a) and the 4μ mass spectrum (b) in the signal region in the di- J/ψ channel, and the similar mass spectrum in the $J/\psi + \psi(2S)$ channel (c). The signal from the $X(6900)$ is scaled to match data around 6.9 GeV. The bars and shaded areas represent uncertainties of data and predictions in each bin, respectively. The arrows in the lower panel indicate that the ratio of data to prediction is out of range in that bin.

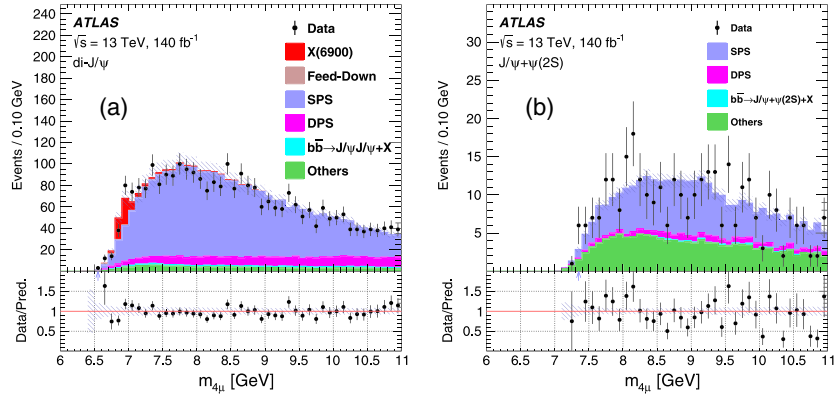


FIG. 3. The 4μ mass spectra in the control regions with $\Delta R \geq 0.25$ in the di- J/ψ (a) and $J/\psi + \psi(2S)$ (b) channels. The bars and shaded areas represent uncertainties of data and predictions in each bin, respectively. The arrows in the lower panel indicate that the ratio of data to prediction is out of range in that bin.

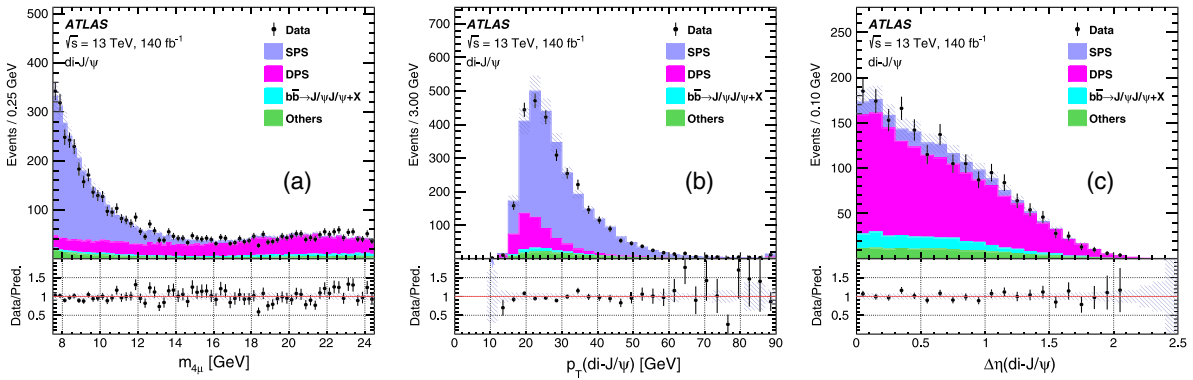


FIG. 4. The 4μ mass spectrum within $[7.5, 24.5]$ GeV and without the ΔR requirement (a), p_T of the dicharmonium in the SPS control region with $7.5 \text{ GeV} < m_{4\mu} < 12.0 \text{ GeV}$ (b), and $\Delta\eta$ between the charmonia in the DPS control region with $14.0 \text{ GeV} < m_{4\mu} < 24.5 \text{ GeV}$ (c), in the di- J/ψ channel.

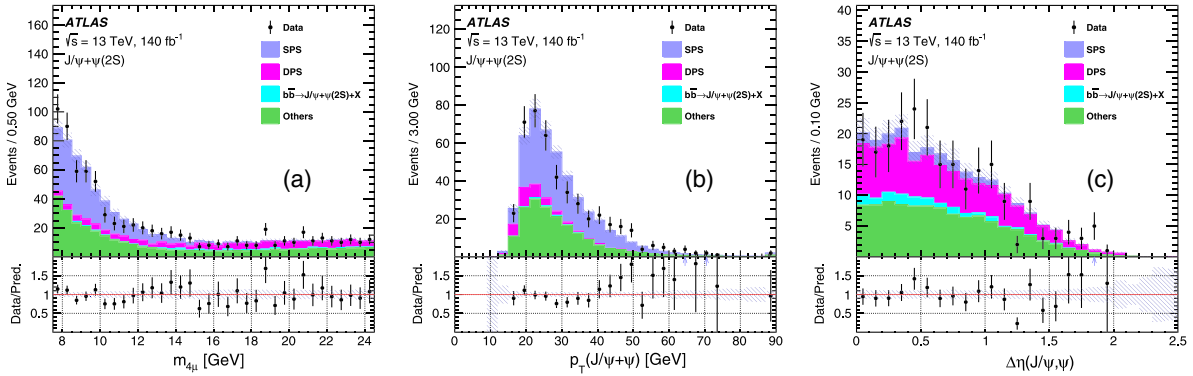


FIG. 5. The 4μ mass spectrum within $[7.5, 24.5]$ GeV and without the ΔR requirement (a), p_T of the dicharmonium in the SPS control region with $7.5 \text{ GeV} < m_{4\mu} < 12.0 \text{ GeV}$ (b), and $\Delta\eta$ between the charmonia in the DPS control region with $14.0 \text{ GeV} < m_{4\mu} < 24.5 \text{ GeV}$ (c), in the $J/\psi + \psi(2S)$ channel.

TABLE III. Different sources of systematic uncertainty in the mass and natural width (in MeV) of the third (second) resonance in model A (α) of the di- J/ψ [$J/\psi + \psi(2S)$] channel.

Systematic uncertainties (MeV)	Di- J/ψ		$J/\psi + \psi(2S)$	
	m_2	Γ_2	m_3	Γ_3
Muon calibration	± 6	± 7	< 1	± 1
SPS model parameter	± 7	± 7	< 1	
SPS dicharmonium p_T	± 7	± 8	< 1	
Background MC sample size	± 7	± 8	± 1	< 1
Mass resolution	± 4	-3	-1	$+2$ -4
Fit bias	-13	$+10$	$+9$ -10	$+50$ -16
Shape inconsistency	< 1		± 4	± 6
Transfer factor	\dots		± 5	± 23
Presence of 4th resonance	< 1		\dots	
Feed-down	$+4$ -1	$+6$ -2	\dots	
Interference of 4th resonance	\dots		-32	-11
P - and D -wave BW	$+9$	$+19$	< 1	± 1
ΔR and muon p_T requirements	$+3$ -2	$+6$ -4	$+1$ -2	-2
Lower resonance shape	\dots		$+3$ -7	$+31$ -34

PYTHIA and the NNPDF23LO PDF. Feed-down backgrounds from the $J/\psi + \psi(2S)$ channel to di- J/ψ are included. A natural width of 100 MeV is assumed for all the resonances with no interference between them. An extensive software suite [43] is used in data simulation [44], in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment. The MC simulated events are weighted to reproduce the same number of pp interactions per bunch crossing (pileup) and trigger conditions as occur in data.

The J/ψ and 4μ mass distributions of data and predictions in the signal regions of the two channels before the fits are shown in Figs. 2(a)–2(c). Similar structures were also observed by CMS [45]. Similar 4μ mass distributions in the control regions are shown in Fig. 3. Distributions in the SPS and DPS control regions without the ΔR requirement between the charmonia are shown in Figs. 4–5. The systematic uncertainties in the fitted masses and widths of the highest resonances in models A and α of the two channels are summarized in Table III.

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H. Bachacou¹³⁵ K. Bachas^{152,f} A. Bachiu³⁴ F. Backman^{47a,47b} A. Badae⁶¹ P. Bagnaia^{75a,75b} M. Bahmani¹⁸
A. J. Bailey¹⁶³ V. R. Bailey¹⁶² J. T. Baines¹³⁴ L. Baines⁹⁴ C. Bakalis¹⁰ O. K. Baker¹⁷² E. Bakos¹⁵
D. Bakshi Gupta⁸ R. Balasubramanian¹¹⁴ E. M. Baldin³⁷ P. Balek^{85a} E. Ballabene^{23b,23a} F. Balli¹³⁵
L. M. Baltes^{63a} W. K. Balunas³² J. Balz¹⁰⁰ E. Banas⁸⁶ M. Bandieramonte¹²⁹ A. Bandyopadhyay²⁴
S. Bansal²⁴ L. Barak¹⁵¹ M. Barakat⁴⁸ E. L. Barberio¹⁰⁵ D. Barberis^{57b,57a} M. Barbero¹⁰² G. Barbour⁹⁶
K. N. Barends^{33a} T. Barillari¹¹⁰ M-S. Barisits³⁶ T. Barklow¹⁴³ P. Baron¹²² D. A. Baron Moreno¹⁰¹
A. Baroncelli^{62a} G. Barone²⁹ A. J. Barr¹²⁶ J. D. Barr⁹⁶ L. Barranco Navarro^{47a,47b} F. Barreiro⁹⁹
J. Barreiro Guimarães da Costa^{14a} U. Barron¹⁵¹ M. G. Barros Teixeira^{130a} S. Barsov³⁷ F. Bartels^{63a}
R. Bartoldus¹⁴³ A. E. Barton⁹¹ P. Bartos^{28a} A. Basan¹⁰⁰ M. Baselga⁴⁹ A. Bassalat^{66,g} M. J. Basso^{156a}
C. R. Basson¹⁰¹ R. L. Bates⁵⁹ S. Batlamous^{35e} J. R. Batley³² B. Batool¹⁴¹ M. Battaglia¹³⁶ D. Battulga¹⁸
M. Bauce^{75a,75b} M. Bauer³⁶ P. Bauer²⁴ L. T. Bazzano Hurrell³⁰ J. B. Beacham⁵¹ T. Beau¹²⁷
P. H. Beauchemin¹⁵⁸ F. Becherer⁵⁴ P. Bechtel²⁴ H. P. Beck^{19,h} K. Becker¹⁶⁷ A. J. Beddall^{21d}
V. A. Bednyakov³⁸ C. P. Bee¹⁴⁵ L. J. Beemster¹⁵ T. A. Beermann³⁶ M. Begalli^{82d} M. Begel²⁹ A. Behera¹⁴⁵
J. K. Behr⁴⁸ J. F. Beirer⁵⁵ F. Beisiegel²⁴ M. Belfkir¹⁵⁹ G. Bella¹⁵¹ L. Bellagamba^{23b} A. Bellerive³⁴
P. Bellos²⁰ K. Beloborodov³⁷ N. L. Belyaev³⁷ D. Benckekroun^{35a} F. Bendebba^{35a} Y. Benhammou¹⁵¹
M. Benoit²⁹ J. R. Bensinger²⁶ S. Bentvelsen¹¹⁴ L. Beresford⁴⁸ M. Beretta⁵³ E. Bergeas Kuutmann¹⁶¹
N. Berger⁴ B. Bergmann¹³² J. Beringer^{17a} G. Bernardi⁵ C. Bernius¹⁴³ F. U. Bernlochner²⁴ F. Bernon^{36,102}
T. Berry⁹⁵ P. Berta¹³³ A. Berthold⁵⁰ I. A. Bertram⁹¹ S. Bethke¹¹⁰ A. Betti^{75a,75b} A. J. Bevan⁹⁴
M. Bhamjee^{33c} S. Bhatta¹⁴⁵ D. S. Bhattacharya¹⁶⁶ P. Bhattacharya²⁶ V. S. Bhopatkar¹²¹ R. Bi^{29,i} R. M. Bianchi¹²⁹
G. Bianco^{23b,23a} O. Biebel¹⁰⁹ R. Bielski¹²³ M. Biglietti^{77a} T. R. V. Billoud¹³² M. Bindi⁵⁵ A. Bingul^{21b}
C. Bini^{75a,75b} A. Biondini⁹² C. J. Birch-sykes¹⁰¹ G. A. Bird^{20,134} M. Birman¹⁶⁹ M. Biros¹³³ T. Bisanz⁴⁹
E. Bisceglie^{43b,43a} D. Biswas¹⁴¹ A. Bitadze¹⁰¹ K. Bjørke¹²⁵ I. Bloch⁴⁸ C. Blocker²⁶ A. Blue⁵⁹
U. Blumenschein⁹⁴ J. Blumenthal¹⁰⁰ G. J. Bobbink¹¹⁴ V. S. Bobrovnikov³⁷ M. Boehler⁵⁴ B. Boehm¹⁶⁶
D. Bogavac³⁶ A. G. Bogdanchikov³⁷ C. Bohm^{47a} V. Boisvert⁹⁵ P. Bokan⁴⁸ T. Bold^{85a} M. Bomben⁵
M. Bona⁹⁴ M. Boonekamp¹³⁵ C. D. Booth⁹⁵ A. G. Borbély⁵⁹ I. S. Bordulev³⁷ H. M. Borecka-Bielska¹⁰⁸
L. S. Borgna⁹⁶ G. Borissov⁹¹ D. Bortoletto¹²⁶ D. Boscherini^{23b} M. Bosman¹³ J. D. Bossio Sola³⁶
K. Bouaouda^{35a} N. Bouchhar¹⁶³ J. Boudreau¹²⁹ E. V. Bouhova-Thacker⁹¹ D. Boumediene⁴⁰ R. Bouquet⁵
A. Boveia¹¹⁹ J. Boyd³⁶ D. Boye²⁹ I. R. Boyko³⁸ J. Bracnik²⁰ N. Brahimi^{62d} G. Brandt¹⁷¹ O. Brandt³²
F. Braren⁴⁸ B. Brau¹⁰³ J. E. Brau¹²³ R. Brenner¹⁶⁹ L. Brenner¹¹⁴ R. Brenner¹⁶¹ S. Bressler¹⁶⁹ D. Britton⁵⁹
D. Britzger¹¹⁰ I. Brock²⁴ G. Brooijmans⁴¹ W. K. Brooks^{137f} E. Brost²⁹ L. M. Brown^{165,j} L. E. Bruce⁶¹
T. L. Bruckler¹²⁶ P. A. Bruckman de Renstrom⁸⁶ B. Brüers⁴⁸ D. Bruncko^{28b,a} A. Bruni^{23b} G. Bruni^{23b}
M. Bruschi^{23b} N. Bruscino^{75a,75b} T. Buanes¹⁶ Q. Buat¹³⁸ D. Buchin¹¹⁰ A. G. Buckley⁵⁹ M. K. Bugge¹²⁵
O. Bulekov³⁷ B. A. Bullard¹⁴³ S. Burdin⁹² C. D. Burgard⁴⁹ A. M. Burger⁴⁰ B. Burghgrave⁸
O. Burlayenko⁵⁴ J. T. P. Burr³² C. D. Burton¹¹ J. C. Burzynski¹⁴² E. L. Busch⁴¹ V. Büscher¹⁰⁰ P. J. Bussey⁵⁹
J. M. Butler²⁵ C. M. Buttar⁵⁹ J. M. Butterworth⁹⁶ W. Buttinger¹³⁴ C. J. Buxo Vazquez¹⁰⁷ A. R. Buzykaev³⁷
G. Cabras^{23b} S. Cabrera Urbán¹⁶³ L. Cadamuro⁶⁶ D. Caforio⁵⁸ H. Cai¹²⁹ Y. Cai^{14a,14e} V. M. M. Cairo³⁶
O. Cakir^{3a} N. Calace³⁶ P. Calafiura^{17a} G. Calderini¹²⁷ P. Calfayan⁶⁸ G. Callea⁵⁹ L. P. Caloba^{82b} D. Calvet⁴⁰
S. Calvet⁴⁰ T. P. Calvet¹⁰² M. Calvetti^{74a,74b} R. Camacho Toro¹²⁷ S. Camarda³⁶ D. Camarero Munoz²⁶
P. Camarri^{76a,76b} M. T. Camerlingo^{72a,72b} D. Cameron¹²⁵ C. Camincher¹⁶⁵ M. Campanelli⁹⁶ A. Camplani⁴²
V. Canale^{72a,72b} A. Canesse¹⁰⁴ M. Cano Bret⁸⁰ J. Cantero¹⁶³ Y. Cao¹⁶² F. Capocasa²⁶ M. Capua^{43b,43a}
A. Carbone^{71a,71b} R. Cardarelli^{76a} J. C. J. Cardenas⁸ F. Cardillo¹⁶³ T. Carli³⁶ G. Carlino^{72a} J. I. Carlotto¹³
B. T. Carlson^{129,k} E. M. Carlson^{165,156a} L. Carminati^{71a,71b} A. Carnelli¹³⁵ M. Carnesale^{75a,75b} S. Caron¹¹³
E. Carquin^{137f} S. Carrá^{71a,71b} G. Carratta^{23b,23a} F. Carrio Argos^{33g} J. W. S. Carter¹⁵⁵ T. M. Carter⁵²
M. P. Casado¹³¹ M. Caspar⁴⁸ E. G. Castiglia¹⁷² F. L. Castillo⁴ L. Castillo Garcia¹³ V. Castillo Gimenez¹⁶³
N. F. Castro^{130a,130e} A. Catinaccio³⁶ J. R. Catmore¹²⁵ V. Cavaliere²⁹ N. Cavalli^{23b,23a} V. Cavasinni^{74a,74b}
Y. C. Cekmecelioglu⁴⁸ E. Celebi^{21a} F. Celli¹²⁶ M. S. Centonze^{70a,70b} K. Cerny¹²² A. S. Cerqueira^{82a}
A. Cerri¹⁴⁶ L. Cerrito^{76a,76b} F. Cerutti^{17a} B. Cervato¹⁴¹ A. Cervelli^{23b} G. Cesarini⁵³ S. A. Cetin^{21d}
Z. Chadi^{35a} D. Chakraborty¹¹⁵ M. Chala^{130f} J. Chan¹⁷⁰ W. Y. Chan¹⁵³ J. D. Chapman³² E. Chapon¹³⁵
B. Chargeishvili^{149b} D. G. Charlton²⁰ T. P. Charman⁹⁴ M. Chatterjee¹⁹ C. Chauhan¹³³ S. Chekanov⁶

S. V. Chekulaev^{156a} G. A. Chelkov^{38,m} A. Chen¹⁰⁶ B. Chen¹⁵¹ B. Chen¹⁶⁵ H. Chen^{14c} H. Chen²⁹
 J. Chen^{62c} J. Chen¹⁴² M. Chen¹²⁶ S. Chen¹⁵³ S. J. Chen^{14c} X. Chen^{62c} X. Chen^{14b,n} Y. Chen^{62a}
 C. L. Cheng¹⁷⁰ H. C. Cheng^{64a} S. Cheong¹⁴³ A. Cheplakov³⁸ E. Cheremushkina⁴⁸ E. Cherepanova¹¹⁴
 R. Cherkaoui El Moursli^{35e} E. Cheu⁷ K. Cheung⁶⁵ L. Chevalier¹³⁵ V. Chiarella⁵³ G. Chiarelli^{74a}
 N. Chiedde¹⁰² G. Chiodini^{70a} A. S. Chisholm²⁰ A. Chitan^{27b} M. Chitishvili¹⁶³ M. V. Chizhov³⁸ K. Choi¹¹
 A. R. Chomont^{75a,75b} Y. Chou¹⁰³ E. Y. S. Chow¹¹⁴ T. Chowdhury^{33g} K. L. Chu¹⁶⁹ M. C. Chu^{64a} X. Chu^{14a,14e}
 J. Chudoba¹³¹ J. J. Chwastowski⁸⁶ D. Cieri¹¹⁰ K. M. Ciesla^{85a} V. Cindro⁹³ A. Ciocio^{17a} F. Cirotto^{72a,72b}
 Z. H. Citron^{169,o} M. Citterio^{71a} D. A. Ciubotaru^{27b} B. M. Ciungu¹⁵⁵ A. Clark⁵⁶ P. J. Clark⁵²
 J. M. Clavijo Columbie⁴⁸ S. E. Clawson⁴⁸ C. Clement^{47a,47b} J. Clercx⁴⁸ L. Clissa^{23b,23a} Y. Coadou¹⁰²
 M. Cobal^{69a,69c} A. Cocco^{57b} R. F. Coelho Barrue^{130a} R. Coelho Lopes De Sa¹⁰³ S. Coelli^{71a} H. Cohen¹⁵¹
 A. E. C. Coimbra^{71a,71b} B. Cole⁴¹ J. Collot⁶⁰ P. Conde Muiño^{130a,130g} M. P. Connell^{33c} S. H. Connell^{33c}
 I. A. Connelly⁵⁹ E. I. Conroy¹²⁶ F. Conventi^{72a,p} H. G. Cooke²⁰ A. M. Cooper-Sarkar¹²⁶
 A. Cordeiro Oudot Choi¹²⁷ F. Cormier¹⁶⁴ L. D. Corpe⁴⁰ M. Corradi^{75a,75b} F. Corriveau^{104,q}
 A. Cortes-Gonzalez¹⁸ M. J. Costa¹⁶³ F. Costanza⁴ D. Costanzo¹³⁹ B. M. Cote¹¹⁹ G. Cowan⁹⁵ K. Cranmer¹⁷⁰
 D. Cremonini^{23b,23a} S. Crépe-Renaudin⁶⁰ F. Crescioli¹²⁷ M. Cristinziani¹⁴¹ M. Cristoforetti^{78a,78b} V. Croft¹¹⁴
 J. E. Crosby¹²¹ G. Crosetti^{43b,43a} A. Cueto⁹⁹ T. Cuhadar Donszelmann¹⁶⁰ H. Cui^{14a,14e} Z. Cui⁷
 W. R. Cunningham⁵⁹ F. Curcio^{43b,43a} P. Czodrowski³⁶ M. M. Czurylo^{63b} M. J. Da Cunha Sargedas De Sousa^{62a}
 J. V. Da Fonseca Pinto^{82b} C. Da Via¹⁰¹ W. Dabrowski^{85a} T. Dado⁴⁹ S. Dahbi^{33g} T. Dai¹⁰⁶ C. Dallapiccola¹⁰³
 M. Dam⁴² G. D'amen²⁹ V. D'Amico¹⁰⁹ J. Damp¹⁰⁰ J. R. Dandoy¹²⁸ M. F. Daneri³⁰ M. Danninger¹⁴²
 V. Dao³⁶ G. Darbo^{57b} S. Darmora⁶ S. J. Das^{29,i} S. D'Auria^{71a,71b} C. David^{156b} T. Davidek¹³³
 B. Davis-Purcell³⁴ I. Dawson⁹⁴ H. A. Day-hall¹³² K. De⁸ R. De Asmundis^{72a} N. De Biase⁴⁸
 S. De Castro^{23b,23a} N. De Groot¹¹³ P. de Jong¹¹⁴ H. De la Torre¹⁰⁷ A. De Maria^{14c} A. De Salvo^{75a}
 U. De Sanctis^{76a,76b} A. De Santo¹⁴⁶ J. B. De Vivie De Regie⁶⁰ D. V. Dedovich³⁸ J. Degen¹¹⁴ A. M. Deiana⁴⁴
 F. Del Corso^{23b,23a} J. Del Peso⁹⁹ F. Del Rio^{63a} F. Deliot¹³⁵ C. M. Delitzsch⁴⁹ M. Della Pietra^{72a,72b}
 D. Della Volpe⁵⁶ A. Dell'Acqua³⁶ L. Dell'Asta^{71a,71b} M. Delmastro⁴ P. A. Delsart⁶⁰ S. Demers¹⁷²
 M. Demichev³⁸ S. P. Denisov³⁷ L. D'Eramo⁴⁰ D. Derendarz⁸⁶ F. Derue¹²⁷ P. Dervan⁹² K. Desch²⁴
 C. Deutsch²⁴ F. A. Di Bello^{57b,57a} A. Di Ciaccio^{76a,76b} L. Di Ciaccio⁴ A. Di Domenico^{75a,75b}
 C. Di Donato^{72a,72b} A. Di Girolamo³⁶ G. Di Gregorio⁵ A. Di Luca^{78a,78b} B. Di Micco^{77a,77b} R. Di Nardo^{77a,77b}
 C. Diaconu¹⁰² F. A. Dias¹¹⁴ T. Dias Do Vale¹⁴² M. A. Diaz^{137a,137b} F. G. Diaz Capriles²⁴ M. Didenko¹⁶³
 E. B. Diehl¹⁰⁶ L. Diehl⁵⁴ S. Díez Cornell⁴⁸ C. Díez Pardos¹⁴¹ C. Dimitriadi^{24,161} A. Dimitrievska^{17a}
 J. Dingfelder²⁴ I-M. Dinu^{27b} S. J. Dittmeier^{63b} F. Dittus³⁶ F. Djama¹⁰² T. Djobava^{149b} J. I. Djuvsland¹⁶
 C. Doglioni^{101,98} J. Dolejsi¹³³ Z. Dolezal¹³³ M. Donadelli^{82c} B. Dong¹⁰⁷ J. Donini⁴⁰ A. D'Onofrio^{77a,77b}
 M. D'Onofrio⁹² J. Dopke¹³⁴ A. Doria^{72a} N. Dos Santos Fernandes^{130a} M. T. Dova⁹⁰ A. T. Doyle⁵⁹
 M. A. Dragnet¹²⁶ E. Dreyer¹⁶⁹ I. Drivas-koulouris¹⁰ A. S. Drobac¹⁵⁸ M. Drozdova⁵⁶ D. Du^{62a}
 T. A. du Pree¹¹⁴ F. Dubinin³⁷ M. Dubovsky^{28a} E. Duchovni¹⁶⁹ G. Duckeck¹⁰⁹ O. A. Ducu^{27b} D. Duda⁵²
 A. Dudarev³⁶ E. R. Duden²⁶ M. D'uffizi¹⁰¹ L. Duflot⁶⁶ M. Dührssen³⁶ C. Dülsen¹⁷¹ A. E. Dumitriu^{27b}
 M. Dunford^{63a} S. Dungs⁴⁹ K. Dunne^{47a,47b} A. Duperrin¹⁰² H. Duran Yildiz^{3a} M. Düren⁵⁸ A. Durglishvili^{149b}
 B. L. Dwyer¹¹⁵ G. I. Dyckes^{17a} M. Dyndal^{85a} S. Dysch¹⁰¹ B. S. Dziedzic⁸⁶ Z. O. Earnshaw¹⁴⁶
 G. H. Eberwein¹²⁶ B. Eckerova^{28a} S. Eggebrecht⁵⁵ M. G. Eggleston⁵¹ E. Egidio Purcino De Souza¹²⁷
 L. F. Ehrke⁵⁶ G. Eigen¹⁶ K. Einsweiler^{17a} T. Ekelof¹⁶¹ P. A. Ekman⁹⁸ S. El Farkh^{35b} Y. El Ghazali^{35b}
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 N. Ellis³⁶ J. Elmsheuser²⁹ M. Elsing³⁶ D. Emelianov¹³⁴ Y. Enari¹⁵³ I. Ene^{17a} S. Epari¹³ J. Erdmann⁴⁹
 P. A. Erland⁸⁶ M. Errenst¹⁷¹ M. Escalier⁶⁶ C. Escobar¹⁶³ E. Etzion¹⁵¹ G. Evans^{130a} H. Evans⁶⁸
 L. S. Evans⁹⁵ M. O. Evans¹⁴⁶ A. Ezhilov³⁷ S. Ezzarqtouni^{35a} F. Fabbri⁵⁹ L. Fabbri^{23b,23a} G. Facini⁹⁶
 V. Fadeyev¹³⁶ R. M. Fakhruddinov³⁷ S. Falciano^{75a} L. F. Falda Ulhoa Coelho³⁶ P. J. Falke²⁴ J. Faltova¹³³
 C. Fan¹⁶² Y. Fan^{14a} Y. Fang^{14a,14e} M. Fanti^{71a,71b} M. Faraj^{69a,69b} Z. Farazpay⁹⁷ A. Farbin⁸ A. Farilla^{77a}
 T. Farooque¹⁰⁷ S. M. Farrington⁵² F. Fassi^{35e} D. Fassouliotis⁹ M. Fauci Giannelli^{76a,76b} W. J. Fawcett³²
 L. Fayard⁶⁶ P. Federic¹³³ P. Federicova¹³¹ O. L. Fedin^{37,m} G. Fedotov³⁷ M. Feickert¹⁷⁰ L. Feligioni¹⁰²
 D. E. Fellers¹²³ C. Feng^{62b} M. Feng^{14b} Z. Feng¹¹⁴ M. J. Fenton¹⁶⁰ A. B. Fenyuk³⁷ L. Ferencz⁴⁸

R. A. M. Ferguson⁹¹ S. I. Fernandez Luengo^{137f} M. J. V. Fernoux¹⁰² J. Ferrando⁴⁸ A. Ferrari¹⁶¹ P. Ferrari^{114,113}
 R. Ferrari^{73a} D. Ferrere⁵⁶ C. Ferretti¹⁰⁶ F. Fiedler¹⁰⁰ A. Filipčič⁹³ E. K. Filmer¹ F. Filthaut¹¹³
 M. C. N. Fiolhais^{130a,130c,r} L. Fiorini¹⁶³ W. C. Fisher¹⁰⁷ T. Fitschen¹⁰¹ P. M. Fitzhugh¹³⁵ I. Fleck¹⁴¹
 P. Fleischmann¹⁰⁶ T. Flick¹⁷¹ L. Flores¹²⁸ M. Flores^{33d,s} L. R. Flores Castillo^{64a} L. Flores Sanz De Acedo³⁶
 F. M. Follega^{78a,78b} N. Fomin¹⁶ J. H. Foo¹⁵⁵ B. C. Forland⁶⁸ A. Formica¹³⁵ A. C. Forti¹⁰¹ E. Fortin³⁶
 A. W. Fortman⁶¹ M. G. Foti^{17a} L. Fountas^{9,t} D. Fournier⁶⁶ H. Fox⁹¹ P. Francavilla^{74a,74b} S. Francescato⁶¹
 S. Franchellucci⁵⁶ M. Franchini^{23b,23a} S. Franchino^{63a} D. Francis³⁶ L. Franco¹¹³ L. Franconi⁴⁸ M. Franklin⁶¹
 G. Frattari²⁶ A. C. Freegard⁹⁴ W. S. Freund^{82b} Y. Y. Frid¹⁵¹ N. Fritzsche⁵⁰ A. Froch⁵⁴ D. Froidevaux³⁶
 J. A. Frost¹²⁶ Y. Fu^{62a} M. Fujimoto¹¹⁸ E. Fullana Torregrosa^{163,a} K. Y. Fung^{64a} E. Furtado De Simas Filho^{82b}
 M. Furukawa¹⁵³ J. Fuster¹⁶³ A. Gabrielli^{23b,23a} A. Gabrielli¹⁵⁵ P. Gadow⁴⁸ G. Gagliardi^{57b,57a}
 L. G. Gagnon^{17a} E. J. Gallas¹²⁶ B. J. Gallop¹³⁴ K. K. Gan¹¹⁹ S. Ganguly¹⁵³ J. Gao^{62a} Y. Gao⁵²
 F. M. Garay Walls^{137a,137b} B. Garcia^{29,i} C. García¹⁶³ A. Garcia Alonso¹¹⁴ A. G. Garcia Caffaro¹⁷²
 J. E. García Navarro¹⁶³ M. Garcia-Sciveres^{17a} G. L. Gardner¹²⁸ R. W. Gardner³⁹ N. Garelli¹⁵⁸ D. Garg⁸⁰
 R. B. Garg^{143,u} J. M. Gargan⁵² C. A. Garner¹⁵⁵ S. J. Gasiorowski¹³⁸ P. Gaspar^{82b} G. Gaudio^{73a} V. Gautam¹³
 P. Gauzzi^{75a,75b} I. L. Gavrilenko³⁷ A. Gavrilyuk³⁷ C. Gay¹⁶⁴ G. Gaycken⁴⁸ E. N. Gazis¹⁰ A. A. Geanta^{27b}
 C. M. Gee¹³⁶ C. Gemme^{57b} M. H. Genest⁶⁰ S. Gentile^{75a,75b} S. George⁹⁵ W. F. George²⁰ T. Geralis⁴⁶
 P. Gessinger-Befurt³⁶ M. E. Geyik¹⁷¹ M. Ghneimat¹⁴¹ K. Ghorbanian⁹⁴ A. Ghosal¹⁴¹ A. Ghosh¹⁶⁰
 A. Ghosh⁷ B. Giacobbe^{23b} S. Giagu^{75a,75b} P. Giannetti^{74a} A. Giannini^{62a} S. M. Gibson⁹⁵ M. Gignac¹³⁶
 D. T. Gil^{85b} A. K. Gilbert^{85a} B. J. Gilbert⁴¹ D. Gillberg³⁴ G. Gilles¹¹⁴ N. E. K. Gillwald⁴⁸ L. Ginabat¹²⁷
 D. M. Gingrich^{2,e} M. P. Giordani^{69a,69c} P. F. Giraud¹³⁵ G. Giugliarelli^{69a,69c} D. Giugni^{71a} F. Giuli³⁶
 I. Gkialas^{9,t} L. K. Gladilin³⁷ C. Glasman⁹⁹ G. R. Gledhill¹²³ M. Glisic¹²³ I. Gnesi^{43b,v} Y. Go^{29,i}
 M. Goblirsch-Kolb³⁶ B. Gocke⁴⁹ D. Godin¹⁰⁸ B. Gokturk^{21a} S. Goldfarb¹⁰⁵ T. Golling⁵⁶ M. G. D. Gololo^{33g}
 D. Golubkov³⁷ J. P. Gombas¹⁰⁷ A. Gomes^{130a,130b} G. Gomes Da Silva¹⁴¹ A. J. Gomez Delegido¹⁶³
 R. Gonçalo^{130a,130c} G. Gonella¹²³ L. Gonella²⁰ A. Gongadze³⁸ F. Gonnella²⁰ J. L. Gonski⁴¹
 R. Y. González Andana⁵² S. González de la Hoz¹⁶³ S. Gonzalez Fernandez¹³ R. Gonzalez Lopez⁹²
 C. Gonzalez Renteria^{17a} R. Gonzalez Suarez¹⁶¹ S. Gonzalez-Sevilla⁵⁶ G. R. Gonzalvo Rodriguez¹⁶³
 L. Goossens³⁶ P. A. Gorbounov³⁷ B. Gorini³⁶ E. Gorini^{70a,70b} A. Gorišek⁹³ T. C. Gosart¹²⁸ A. T. Goshaw⁵¹
 M. I. Gostkin³⁸ S. Goswami¹²¹ C. A. Gottardo³⁶ M. Gouighri^{35b} V. Goumarre⁴⁸ A. G. Goussiou¹³⁸
 N. Govender^{33c} I. Grabowska-Bold^{85a} K. Graham³⁴ E. Gramstad¹²⁵ S. Grancagnolo^{70a,70b} M. Grandi¹⁴⁶
 V. Gratchev^{37,a} P. M. Gravila^{27f} F. G. Gravili^{70a,70b} H. M. Gray^{17a} M. Greco^{70a,70b} C. Greife²⁴ I. M. Gregor⁴⁸
 P. Grenier¹⁴³ C. Grieco¹³ A. A. Grillo¹³⁶ K. Grimm³¹ S. Grinstein^{13,w} J.-F. Grivaz⁶⁶ E. Gross¹⁶⁹
 J. Grosse-Knetter⁵⁵ C. Grud¹⁰⁶ J. C. Grundy¹²⁶ L. Guan¹⁰⁶ W. Guan¹⁷⁰ C. Gubbels¹⁶⁴
 J. G. R. Guerrero Rojas¹⁶³ G. Guerrieri^{69a,69b} F. Guescini¹¹⁰ R. Gugel¹⁰⁰ J. A. M. Guhit¹⁰⁶ A. Guida¹⁸
 T. Guillemín⁴ E. Guilloton^{167,134} S. Guindon³⁶ F. Guo^{14a,14e} J. Guo^{62c} L. Guo⁴⁸ Y. Guo¹⁰⁶ R. Gupta⁴⁸
 S. Gurbuz²⁴ S. S. Gurdasani⁵⁴ G. Gustavino³⁶ M. Guth⁵⁶ P. Gutierrez¹²⁰ L. F. Gutierrez Zagazeta¹²⁸
 C. Gutschow⁹⁶ C. Gwenlan¹²⁶ C. B. Gwilliam⁹² E. S. Haaland¹²⁵ A. Haas¹¹⁷ M. Habedank⁴⁸ C. Haber^{17a}
 H. K. Hadavand⁸ A. Hadeef¹⁰⁰ S. Hadzic¹¹⁰ J. J. Hahn¹⁴¹ E. H. Haines⁹⁶ M. Haleem¹⁶⁶ J. Haley¹²¹
 J. J. Hall¹³⁹ G. D. Hallowell¹⁰² L. Halser¹⁹ K. Hamano¹⁶⁵ H. Hamdaoui^{35e} M. Hamer²⁴ G. N. Hamity⁵²
 E. J. Hampshire⁹⁵ J. Han^{62b} K. Han^{62a} L. Han^{14c} L. Han^{62a} S. Han^{17a} Y. F. Han¹⁵⁵ K. Hanagaki⁸³
 M. Hance¹³⁶ D. A. Hangal^{41,d} H. Hanif¹⁴² M. D. Hank¹²⁸ R. Hankache¹⁰¹ J. B. Hansen⁴² J. D. Hansen⁴²
 P. H. Hansen⁴² K. Hara¹⁵⁷ D. Harada⁵⁶ T. Harenberg¹⁷¹ S. Harkusha³⁷ M. L. Harris¹⁰³ Y. T. Harris¹²⁶
 J. Harrison¹³ N. M. Harrison¹¹⁹ P. F. Harrison¹⁶⁷ N. M. Hartman¹¹⁰ N. M. Hartmann¹⁰⁹ Y. Hasegawa¹⁴⁰
 A. Hasib⁵² S. Haug¹⁹ R. Hauser¹⁰⁷ C. M. Hawkes²⁰ R. J. Hawkins³⁶ Y. Hayashi¹⁵³ S. Hayashida¹¹¹
 D. Hayden¹⁰⁷ C. Hayes¹⁰⁶ R. L. Hayes¹¹⁴ C. P. Hays¹²⁶ J. M. Hays⁹⁴ H. S. Hayward⁹² F. He^{62a}
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 C. Heidegger⁵⁴ K. K. Heidegger⁵⁴ W. D. Heidorn⁸¹ J. Heilmann³⁴ S. Heim⁴⁸ T. Heim^{17a} J. G. Heinlein¹²⁸
 J. J. Heinrich¹²³ L. Heinrich^{110,x} J. Hejbal¹³¹ L. Helary⁴⁸ A. Held¹⁷⁰ S. Hellesund¹⁶ C. M. Helling¹⁶⁴
 S. Hellman^{47a,47b} C. Helsen³⁶ R. C. W. Henderson⁹¹ L. Henkelmann³² A. M. Henriques Correia³⁶ H. Herde⁹⁸
 Y. Hernández Jiménez¹⁴⁵ L. M. Herrmann²⁴ T. Herrmann⁵⁰ G. Herten⁵⁴ R. Hertenberger¹⁰⁹ L. Hervas³⁶

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 S. Hirose¹⁵⁷, D. Hirschbuehl¹⁷¹, T. G. Hitchings¹⁰¹, B. Hiti⁹³, J. Hobbs¹⁴⁵, R. Hobincu^{27e}, N. Hod¹⁶⁹,
 M. C. Hodgkinson¹³⁹, B. H. Hodkinson³², A. Hoecker³⁶, J. Hofer⁴⁸, T. Holm²⁴, M. Holzbock¹¹⁰,
 L. B. A. H. Hommels³², B. P. Honan¹⁰¹, J. Hong^{62c}, T. M. Hong¹²⁹, B. H. Hooberman¹⁶², W. H. Hopkins⁶,
 Y. Horii¹¹¹, S. Hou¹⁴⁸, A. S. Howard⁹³, J. Howarth⁵⁹, J. Hoya⁶, M. Hrabovsky¹²², A. Hrynevich⁴⁸,
 T. Hryn'ova⁴, P. J. Hsu⁶⁵, S.-C. Hsu¹³⁸, Q. Hu⁴¹, Y. F. Hu^{14a,14e}, S. Huang^{64b}, X. Huang^{14c}, Y. Huang^{62a},
 Y. Huang^{14a}, Z. Huang¹⁰¹, Z. Hubacek¹³², M. Huebner²⁴, F. Huegging²⁴, T. B. Huffman¹²⁶, C. A. Hugli⁴⁸,
 M. Huhtinen³⁶, S. K. Huiberts¹⁶, R. Hulsken¹⁰⁴, N. Huseynov^{12,m}, J. Huston¹⁰⁷, J. Huth⁶¹, R. Hyneman¹⁴³,
 G. Iacobucci⁵⁶, G. Iakovidis²⁹, I. Ibragimov¹⁴¹, L. Iconomidou-Fayard⁶⁶, P. Iengo^{72a,72b}, R. Iguchi¹⁵³,
 T. Iizawa⁸³, Y. Ikegami⁸³, N. Ilic¹⁵⁵, H. Imam^{35a}, M. Ince Lezki⁵⁶, T. Ingebretsen Carlson^{47a,47b},
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 S. Istin^{21a,y}, H. Ito¹⁶⁸, J. M. Iturbe Ponce^{64a}, R. Iuppa^{78a,78b}, A. Ivina¹⁶⁹, J. M. Izen⁴⁵, V. Izzo^{72a}, P. Jacka^{131,132},
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 T. Jakoubek¹⁶⁹, J. Jamieson⁵⁹, K. W. Janas^{85a}, A. E. Jaspán⁹², M. Javurkova¹⁰³, F. Jeanneau¹³⁵, L. Jeanty¹²³,
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 Y. Jiang^{62a}, S. Jiggins⁴⁸, J. Jimenez Pena¹³, S. Jin^{14c}, A. Jinaru^{27b}, O. Jinnouchi¹⁵⁴, P. Johansson¹³⁹,
 K. A. Johns⁷, J. W. Johnson¹³⁶, D. M. Jones³², E. Jones⁴⁸, P. Jones³², R. W. L. Jones⁹¹, T. J. Jones⁹²,
 R. Joshi¹¹⁹, J. Jovicevic¹⁵, X. Ju^{17a}, J. J. Junggeburth³⁶, T. Junkermann^{63a}, A. Juste Rozas^{13,w}, M. K. Juzek⁸⁶,
 S. Kabana^{137e}, A. Kaczmarzka⁸⁶, M. Kado¹¹⁰, H. Kagan¹¹⁹, M. Kagan¹⁴³, A. Kahn⁴¹, A. Kahn¹²⁸, C. Kahra¹⁰⁰,
 T. Kaji¹⁶⁸, E. Kajomovitz¹⁵⁰, N. Kakati¹⁶⁹, I. Kalaitzidou⁵⁴, C. W. Kalderon²⁹, A. Kamenshchikov¹⁵⁵,
 S. Kanayama¹⁵⁴, N. J. Kang¹³⁶, D. Kar^{33g}, K. Karava¹²⁶, M. J. Kareem^{156b}, E. Karentzos⁵⁴, I. Karkanas¹⁵²,
 O. Karkout¹¹⁴, S. N. Karpov³⁸, Z. M. Karpova³⁸, V. Kartvelishvili⁹¹, A. N. Karyukhin³⁷, E. Kasimi¹⁵²,
 J. Katzy⁴⁸, S. Kaur³⁴, K. Kawade¹⁴⁰, T. Kawamoto¹³⁵, E. F. Kay³⁶, F. I. Kaya¹⁵⁸, S. Kazakos¹⁰⁷,
 V. F. Kazanin³⁷, Y. Ke¹⁴⁵, J. M. Keaveney^{33a}, R. Keeler¹⁶⁵, G. V. Kehris⁶¹, J. S. Keller³⁴, A. S. Kelly⁹⁶,
 J. J. Kempster¹⁴⁶, K. E. Kennedy⁴¹, P. D. Kennedy¹⁰⁰, O. Kepka¹³¹, B. P. Kerridge¹⁶⁷, S. Kersten¹⁷¹,
 B. P. Kerševan⁹³, S. Keshri⁶⁶, L. Keszeghova^{28a}, S. Ketabchi Haghighat¹⁵⁵, M. Khandoga¹²⁷, A. Khanov¹²¹,
 A. G. Kharlamov³⁷, T. Kharlamova³⁷, E. E. Khoda¹³⁸, T. J. Khoo¹⁸, G. Khoraiuli¹⁶⁶, J. Khubua^{149b},
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 C. Kirfel²⁴, F. Kirfel²⁴, J. Kirk¹³⁴, A. E. Kiryunin¹¹⁰, C. Kitsaki¹⁰, O. Kivernyk²⁴, M. Klassen^{63a}, C. Klein³⁴,
 L. Klein¹⁶⁶, M. H. Klein¹⁰⁶, M. Klein⁹², S. B. Klein⁵⁶, U. Klein⁹², P. Klimek³⁶, A. Klimentov²⁹,
 T. Klioutchnikova³⁶, P. Kluit¹¹⁴, S. Kluth¹¹⁰, E. Kneringer⁷⁹, T. M. Knight¹⁵⁵, A. Knue⁵⁴, R. Kobayashi⁸⁷,
 S. F. Koch¹²⁶, M. Kocian¹⁴³, P. Kodyš¹³³, D. M. Koeck¹²³, P. T. Koenig²⁴, T. Koffas³⁴, M. Kolb¹³⁵,
 I. Koletsou⁴, T. Komarek¹²², K. Köneke⁵⁴, A. X. Y. Kong¹, T. Kono¹¹⁸, N. Konstantinidis⁹⁶, B. Konya⁹⁸,
 R. Kopeliansky⁶⁸, S. Koperny^{85a}, K. Korcyl⁸⁶, K. Kordas^{152,bb}, G. Koren¹⁵¹, A. Korn⁹⁶, S. Korn⁵⁵,
 I. Korolkov¹³, N. Korotkova³⁷, B. Kortman¹¹⁴, O. Kortner¹¹⁰, S. Kortner¹¹⁰, W. H. Kostecka¹¹⁵,
 V. V. Kostyukhin¹⁴¹, A. Kotskechagia¹³⁵, A. Kotwal⁵¹, A. Koulouris³⁶, A. Kourkoumeli-Charalampidi^{73a,73b},
 C. Kourkoumelis⁹, E. Kourlitis⁶, O. Kovanda¹⁴⁶, R. Kowalewski¹⁶⁵, W. Kozanecki¹³⁵, A. S. Kozhin³⁷,
 V. A. Kramarenko³⁷, G. Kramberger⁹³, P. Kramer¹⁰⁰, M. W. Krasny¹²⁷, A. Krasznahorkay³⁶, J. W. Kraus¹⁷¹,
 J. A. Kremer¹⁰⁰, T. Kresse⁵⁰, J. Kretzschmar⁹², K. Kreul¹⁸, P. Krieger¹⁵⁵, S. Krishnamurthy¹⁰³, M. Krivos¹³³,
 K. Krizka²⁰, K. Kroeninger⁴⁹, H. Kroha¹¹⁰, J. Kroll¹³¹, J. Kroll¹²⁸, K. S. Krowpman¹⁰⁷, U. Kruchonak³⁸,
 H. Krüger²⁴, N. Krumnack⁸¹, M. C. Kruse⁵¹, J. A. Krzysiak⁸⁶, O. Kuchinskaia³⁷, S. Kuday^{3a}, S. Kuehn³⁶,
 R. Kuesters⁵⁴, T. Kuhl⁴⁸, V. Kukhtin³⁸, Y. Kulchitsky^{37,m}, S. Kuleshov^{137d,137b}, M. Kumar^{33g}, N. Kumari¹⁰²,
 A. Kupco¹³¹, T. Kupfer⁴⁹, A. Kupich³⁷, O. Kuprash⁵⁴, H. Kurashige⁸⁴, L. L. Kurchaninov^{156a}, O. Kurdysh⁶⁶,
 Y. A. Kurochkin³⁷, A. Kurova³⁷, M. Kuze¹⁵⁴, A. K. Kvam¹⁰³, J. Kvita¹²², T. Kwan¹⁰⁴, N. G. Kyriacou¹⁰⁶,
 L. A. O. Laatu¹⁰², C. Lacasta¹⁶³, F. Lacava^{75a,75b}, H. Lacker¹⁸, D. Lacour¹²⁷, N. N. Lad⁹⁶, E. Ladygin³⁸,
 B. Laforge¹²⁷, T. Lagouri^{137e}, S. Lai⁵⁵, I. K. Lakomic^{85a}, N. Lalloue⁶⁰, J. E. Lambert^{165,j}, S. Lammers⁶⁸,
 W. Lampl⁷, C. Lampoudis^{152,bb}, A. N. Lancaster¹¹⁵, E. Lançon²⁹, U. Landgraf⁵⁴, M. P. J. Landon⁹⁴,
 V. S. Lang⁵⁴, R. J. Langenberg¹⁰³, O. K. B. Langrekken¹²⁵, A. J. Lankford¹⁶⁰, F. Lanni³⁶, K. Lantzsch²⁴,
 A. Lanza^{73a}, A. Lapertosa^{57b,57a}, J. F. Laporte¹³⁵, T. Lari^{71a}, F. Lasagni Manghi^{23b}, M. Lassnig³⁶, V. Latonova¹³¹

A. Laudrain¹⁰⁰ A. Laurier¹⁵⁰ S. D. Lawlor⁹⁵ Z. Lawrence¹⁰¹ M. Lazzaroni^{71a,71b} B. Le,¹⁰¹
 E. M. Le Boulicaut⁵¹ B. Leban⁹³ A. Lebedev⁸¹ M. LeBlanc³⁶ F. Ledroit-Guillon⁶⁰ A. C. A. Lee,⁹⁶ S. C. Lee¹⁴⁸
 S. Lee^{47a,47b} T. F. Lee⁹² L. L. Leeuw^{33c} H. P. Lefebvre⁹⁵ M. Lefebvre¹⁶⁵ C. Leggett^{17a} G. Lehmann Miotto³⁶
 M. Leigh⁵⁶ W. A. Leight¹⁰³ W. Leinonen¹¹³ A. Leisos^{152,cc} M. A. L. Leite^{82c} C. E. Leitgeb⁴⁸ R. Leitner¹³³
 K. J. C. Leney⁴⁴ T. Lenz²⁴ S. Leone^{74a} C. Leonidopoulos⁵² A. Leopold¹⁴⁴ C. Leroy¹⁰⁸ R. Les¹⁰⁷
 C. G. Lester³² M. Levchenko³⁷ J. Levêque⁴ D. Levin¹⁰⁶ L. J. Levinson¹⁶⁹ M. P. Lewicki⁸⁶ D. J. Lewis⁴
 A. Li⁵ B. Li^{62b} C. Li,^{62a} C-Q. Li^{62c} H. Li^{62a} H. Li^{62b} H. Li^{14c} H. Li^{62b} K. Li¹³⁸ L. Li^{62c} M. Li^{14a,14e}
 Q. Y. Li^{62a} S. Li^{14a,14e} S. Li^{62d,62c,dd} T. Li^{5,ee} X. Li¹⁰⁴ Z. Li¹²⁶ Z. Li¹⁰⁴ Z. Li⁹² Z. Li^{14a,14e} Z. Liang^{14a}
 M. Liberatore⁴⁸ B. Liberti^{76a} K. Lie^{64c} J. Lieber Marin^{82b} H. Lien⁶⁸ K. Lin¹⁰⁷ R. E. Lindley⁷
 J. H. Lindon² A. Linss⁴⁸ E. Lipeles¹²⁸ A. Lipniacka¹⁶ A. Lister¹⁶⁴ J. D. Little⁴ B. Liu^{14a} B. X. Liu¹⁴²
 D. Liu^{62d,62c} J. B. Liu^{62a} J. K. K. Liu³² K. Liu^{62d,62c} M. Liu^{62a} M. Y. Liu^{62a} P. Liu^{14a} Q. Liu^{62d,138,62c}
 X. Liu^{62a} Y. Liu^{14d,14e} Y. L. Liu¹⁰⁶ Y. W. Liu^{62a} J. Llorente Merino¹⁴² S. L. Lloyd⁹⁴ E. M. Lobodzinska⁴⁸
 P. Loch⁷ S. Loffredo^{76a,76b} T. Lohse¹⁸ K. Lohwasser¹³⁹ E. Loiacono⁴⁸ M. Lokajicek^{131,a} J. D. Lomas²⁰
 J. D. Long¹⁶² I. Longarini¹⁶⁰ L. Longo^{70a,70b} R. Longo¹⁶² I. Lopez Paz⁶⁷ A. Lopez Solis⁴⁸ J. Lorenz¹⁰⁹
 N. Lorenzo Martinez⁴ A. M. Lory¹⁰⁹ O. Loseva³⁷ X. Lou^{47a,47b} X. Lou^{14a,14e} A. Lounis⁶⁶ J. Love⁶
 P. A. Love⁹¹ G. Lu^{14a,14e} M. Lu⁸⁰ S. Lu¹²⁸ Y. J. Lu⁶⁵ H. J. Lubatti¹³⁸ C. Luci^{75a,75b} F. L. Lucio Alves^{14c}
 A. Lucotte⁶⁰ F. Luehring⁶⁸ I. Luise¹⁴⁵ O. Lukianchuk⁶⁶ O. Lundberg¹⁴⁴ B. Lund-Jensen¹⁴⁴ N. A. Luongo¹²³
 M. S. Lutz¹⁵¹ D. Lynn²⁹ H. Lyons⁹² R. Lysak¹³¹ E. Lytken⁹⁸ V. Lyubushkin³⁸ T. Lyubushkina³⁸
 M. M. Lyukova¹⁴⁵ H. Ma²⁹ K. Ma,^{62a} L. L. Ma^{62b} Y. Ma¹²¹ D. M. Mac Donell¹⁶⁵ G. Maccarrone⁵³
 J. C. MacDonald¹⁰⁰ R. Madar⁴⁰ W. F. Mader⁵⁰ J. Maeda⁸⁴ T. Maeno²⁹ M. Maerker⁵⁰ H. Maguire¹³⁹
 V. Maiboroda¹³⁵ A. Maio^{130a,130b,130d} K. Maj^{85a} O. Majersky⁴⁸ S. Majewski¹²³ N. Makovec⁶⁶
 V. Maksimovic¹⁵ B. Malaescu¹²⁷ Pa. Malecki⁸⁶ V. P. Maleev³⁷ F. Malek⁶⁰ M. Mali⁹³ D. Malito^{95,ff}
 U. Mallik⁸⁰ S. Maltezos¹⁰ S. Malyukov³⁸ J. Mamuzic¹³ G. Mancini⁵³ G. Manco^{73a,73b} J. P. Mandalia⁹⁴
 I. Mandić⁹³ L. Manhaes de Andrade Filho^{82a} I. M. Maniatis¹⁶⁹ J. Manjarres Ramos^{102,gg} D. C. Mankad¹⁶⁹
 A. Mann¹⁰⁹ B. Mansoulie¹³⁵ S. Manzoni³⁶ A. Marantis^{152,cc} G. Marchiori⁵ M. Marcisovsky¹³¹
 C. Marcon^{71a,71b} M. Marinescu²⁰ M. Marjanovic¹²⁰ E. J. Marshall⁹¹ Z. Marshall^{17a} S. Marti-Garcia¹⁶³
 T. A. Martin¹⁶⁷ V. J. Martin⁵² B. Martin dit Latour¹⁶ L. Martinelli^{75a,75b} M. Martinez^{13,w} P. Martinez Agullo¹⁶³
 V. I. Martinez Outschoorn¹⁰³ P. Martinez Suarez¹³ S. Martin-Haugh¹³⁴ V. S. Martoiu^{27b} A. C. Martyniuk⁹⁶
 A. Marzin³⁶ D. Mascione^{78a,78b} L. Masetti¹⁰⁰ T. Mashimo¹⁵³ J. Masik¹⁰¹ A. L. Maslennikov³⁷ L. Massa^{23b}
 P. Massarotti^{72a,72b} P. Mastrandrea^{74a,74b} A. Mastroberardino^{43b,43a} T. Masubuchi¹⁵³ T. Mathisen¹⁶¹
 J. Matousek¹³³ N. Matsuzawa¹⁵³ J. Maurer^{27b} B. Maček⁹³ D. A. Maximov³⁷ R. Mazini¹⁴⁸ I. Maznas¹⁵²
 M. Mazza¹⁰⁷ S. M. Mazza¹³⁶ E. Mazzeo^{71a,71b} C. Mc Ginn²⁹ J. P. Mc Gowan¹⁰⁴ S. P. Mc Kee¹⁰⁶
 E. F. McDonald¹⁰⁵ A. E. McDougall¹¹⁴ J. A. Mcfayden¹⁴⁶ R. P. McGovern¹²⁸ G. Mchedlidze^{149b}
 R. P. McKenzie^{33g} T. C. Mclachlan⁴⁸ D. J. Mclaughlin⁹⁶ K. D. McLean¹⁶⁵ S. J. McMahan¹³⁴
 P. C. McNamara¹⁰⁵ C. M. Mcpartland⁹² R. A. McPherson^{165,q} S. Mehlhase¹⁰⁹ A. Mehta⁹² D. Melini¹⁵⁰
 B. R. Mellado Garcia^{33g} A. H. Melo⁵⁵ F. Meloni⁴⁸ A. M. Mendes Jacques Da Costa¹⁰¹ H. Y. Meng¹⁵⁵
 L. Meng⁹¹ S. Menke¹¹⁰ M. Mentink³⁶ E. Meoni^{43b,43a} C. Merlassino¹²⁶ L. Merola^{72a,72b} C. Meroni^{71a}
 G. Merz¹⁰⁶ O. Meshkov³⁷ J. Metcalfe⁶ A. S. Mete⁶ C. Meyer⁶⁸ J-P. Meyer¹³⁵ R. P. Middleton¹³⁴
 L. Mijović⁵² G. Mikenberg¹⁶⁹ M. Mikestikova¹³¹ M. Mikuž⁹³ H. Mildner¹⁰⁰ A. Milic³⁶ C. D. Milke⁴⁴
 D. W. Miller³⁹ L. S. Miller³⁴ A. Milov¹⁶⁹ D. A. Milstead^{47a,47b} T. Min^{14c} A. A. Minaenko³⁷ I. A. Minashvili^{149b}
 L. Mince⁵⁹ A. I. Mincer¹¹⁷ B. Mindur^{85a} M. Mineev³⁸ Y. Mino⁸⁷ L. M. Mir¹³ M. Miralles Lopez¹⁶³
 M. Mironova^{17a} A. Mishima¹⁵³ M. C. Missio¹¹³ T. Mitani¹⁶⁸ A. Mitra¹⁶⁷ V. A. Mitsou¹⁶³ O. Miu¹⁵⁵
 P. S. Miyagawa⁹⁴ Y. Miyazaki⁸⁹ A. Mizukami⁸³ T. Mkrtychyan^{63a} M. Mlinarevic⁹⁶ T. Mlinarevic⁹⁶
 M. Mlynarikova³⁶ S. Mobius¹⁹ K. Mochizuki¹⁰⁸ P. Moder⁴⁸ P. Mogg¹⁰⁹ A. F. Mohammed^{14a,14e}
 S. Mohapatra⁴¹ G. Mokgatitswane^{33g} L. Moleri¹⁶⁹ B. Mondal¹⁴¹ S. Mondal¹³² G. Monig¹⁴⁶ K. Mönig⁴⁸
 E. Monnier¹⁰² L. Monsonis Romero¹⁶³ J. Montejo Berlingen^{13,83} M. Montella¹¹⁹ F. Montekali^{77a,77b}
 F. Monticelli⁹⁰ S. Monzani^{69a,69c} N. Morange⁶⁶ A. L. Moreira De Carvalho^{130a} M. Moreno Llácer¹⁶³
 C. Moreno Martinez⁵⁶ P. Morettini^{57b} S. Morgenstern³⁶ M. Morii⁶¹ M. Morinaga¹⁵³ A. K. Morley³⁶
 F. Morodei^{75a,75b} L. Morvaj³⁶ P. Moschovakos³⁶ B. Moser³⁶ M. Mosidze^{149b} T. Moskalets⁵⁴ P. Moskvitina¹¹³

J. Moss^{31,hh} E. J. W. Moyses¹⁰³ O. Mtintsilana^{33g} S. Muanza¹⁰² J. Mueller¹²⁹ D. Muenstermann⁹¹
 R. Müller¹⁹ G. A. Mullier¹⁶¹ A. J. Mullin³² J. J. Mullin¹²⁸ D. P. Mungo¹⁵⁵ D. Munoz Perez¹⁶³
 F. J. Munoz Sanchez¹⁰¹ M. Murin¹⁰¹ W. J. Murray^{167,134} A. Murrone^{71a,71b} J. M. Muse¹²⁰ M. Muškinja^{17a}
 C. Mwewa²⁹ A. G. Myagkov^{37,m} A. J. Myers⁸ A. A. Myers¹²⁹ G. Myers⁶⁸ M. Myska¹³² B. P. Nachman^{17a}
 O. Nackenhorst⁴⁹ A. Nag⁵⁰ K. Nagai¹²⁶ K. Nagano⁸³ J. L. Nagle^{29,i} E. Nagy¹⁰² A. M. Nairz³⁶
 Y. Nakahama⁸³ K. Nakamura⁸³ K. Nakkalil⁵ H. Nanjo¹²⁴ R. Narayan⁴⁴ E. A. Narayanan¹¹² I. Naryshkin³⁷
 M. Naseri³⁴ S. Nasri¹⁵⁹ C. Nass²⁴ G. Navarro^{22a} J. Navarro-Gonzalez¹⁶³ R. Nayak¹⁵¹ A. Nayaz¹⁸
 P. Y. Nechaeva³⁷ F. Nechansky⁴⁸ L. Nedic¹²⁶ T. J. Neep²⁰ A. Negri^{73a,73b} M. Negrini^{23b} C. Nellist¹¹⁴
 C. Nelson¹⁰⁴ K. Nelson¹⁰⁶ S. Nemecek¹³¹ M. Nessi^{36,ii} M. S. Neubauer¹⁶² F. Neuhaus¹⁰⁰ J. Neundorff⁴⁸
 R. Newhouse¹⁶⁴ P. R. Newman²⁰ C. W. Ng¹²⁹ Y. W. Y. Ng⁴⁸ B. Ngair^{35e} H. D. N. Nguyen¹⁰⁸
 R. B. Nickerson¹²⁶ R. Nicolaidou¹³⁵ J. Nielsen¹³⁶ M. Niemeyer⁵⁵ J. Niemann^{55,36} N. Nikiforou³⁶
 V. Nikolaenko^{37,m} I. Nikolic-Audit¹²⁷ K. Nikolopoulos²⁰ P. Nilsson²⁹ I. Ninca⁴⁸ H. R. Nindhito⁵⁶
 G. Ninio¹⁵¹ A. Nisati^{75a} N. Nishu² R. Nisius¹¹⁰ J-E. Nitschke⁵⁰ E. K. Nkadameng^{33g} S. J. Noacco Rosende⁹⁰
 T. Nobe¹⁵³ D. L. Noel³² T. Nommensen¹⁴⁷ M. B. Norfolk¹³⁹ R. R. B. Norisam⁹⁶ B. J. Norman³⁴ J. Novak⁹³
 T. Novak⁴⁸ L. Novotny¹³² R. Novotny¹¹² L. Nozka¹²² K. Ntekas¹⁶⁰ N. M. J. Nunes De Moura Junior^{82b}
 E. Nurse⁹⁶ J. Ocariz¹²⁷ A. Ochi⁸⁴ I. Ochoa^{130a} S. Oerdek¹⁶¹ J. T. Offermann³⁹ A. Ogrodnik¹³³ A. Oh¹⁰¹
 C. C. Ohm¹⁴⁴ H. Oide⁸³ R. Oishi¹⁵³ M. L. Ojeda⁴⁸ Y. Okazaki⁸⁷ M. W. O'Keefe⁹² Y. Okumura¹⁵³
 L. F. Oleiro Seabra^{130a} S. A. Olivares Pino^{137d} D. Oliveira Damazio²⁹ D. Oliveira Goncalves^{82a} J. L. Oliver¹⁶⁰
 M. J. R. Olsson¹⁶⁰ A. Olszewski⁸⁶ Ö. O. Öncel⁵⁴ D. C. O'Neil¹⁴² A. P. O'Neill¹⁹ A. Onofre^{130a,130e}
 P. U. E. Onyisi¹¹ M. J. Oreglia³⁹ G. E. Orellana⁹⁰ D. Orestano^{77a,77b} N. Orlando¹³ R. S. Orr¹⁵⁵ V. O'Shea⁵⁹
 L. M. Osojnak¹²⁸ R. Ospanov^{62a} G. Otero y Garzon³⁰ H. Otono⁸⁹ P. S. Ott^{63a} G. J. Ottino^{17a} M. Ouchrif^{35d}
 J. Ouellette²⁹ F. Ould-Saada¹²⁵ M. Owen⁵⁹ R. E. Owen¹³⁴ K. Y. Oyulmaz^{21a} V. E. Ozcan^{21a} N. Ozturk⁸
 S. Ozturk^{21d} H. A. Pacey³² A. Pacheco Pages¹³ C. Padilla Aranda¹³ G. Padovano^{75a,75b} S. Pagan Griso^{17a}
 G. Palacino⁶⁸ A. Palazzo^{70a,70b} S. Palestini³⁶ J. Pan¹⁷² T. Pan^{64a} D. K. Panchal¹¹ C. E. Pandini¹¹⁴
 J. G. Panduro Vazquez⁹⁵ H. Pang^{14b} P. Pani⁴⁸ G. Panizzo^{69a,69c} L. Paolozzi⁵⁶ C. Papadatos¹⁰⁸ S. Parajuli⁴⁴
 A. Paramonov⁶ C. Paraskevopoulos¹⁰ D. Paredes Hernandez^{64b} T. H. Park¹⁵⁵ M. A. Parker³² F. Parodi^{57b,57a}
 E. W. Parrish¹¹⁵ V. A. Parrish⁵² J. A. Parsons⁴¹ U. Parzefall⁵⁴ B. Pascual Dias¹⁰⁸ L. Pascual Dominguez¹⁵¹
 F. Pasquali¹¹⁴ E. Pasqualucci^{75a} S. Passaggio^{57b} F. Pastore⁹⁵ P. Pasuwan^{47a,47b} P. Patel⁸⁶ U. M. Patel⁵¹
 J. R. Pater¹⁰¹ T. Pauly³⁶ J. Parkes¹⁴³ M. Pedersen¹²⁵ R. Pedro^{130a} S. V. Peleganchuk³⁷ O. Penc³⁶
 E. A. Pender⁵² H. Peng^{62a} K. E. Pensi¹⁰⁹ M. Penzin³⁷ B. S. Peralva^{82d} A. P. Pereira Peixoto⁶⁰
 L. Pereira Sanchez^{47a,47b} D. V. Perepelitsa^{29,i} E. Perez Codina^{156a} M. Perganti¹⁰ L. Perini^{71a,71b,a}
 H. Pernegger³⁶ A. Perrevoort¹¹³ O. Perrin⁴⁰ K. Peters⁴⁸ R. F. Y. Peters¹⁰¹ B. A. Petersen³⁶ T. C. Petersen⁴²
 E. Petit¹⁰² V. Petousis¹³² C. Petridou^{152,bb} A. Petrukhin¹⁴¹ M. Pettee^{17a} N. E. Pettersson³⁶ A. Petukhov³⁷
 K. Petukhova¹³³ A. Peyaud¹³⁵ R. Pezoa^{137f} L. Pezzotti³⁶ G. Pezzullo¹⁷² T. M. Pham¹⁷⁰ T. Pham¹⁰⁵
 P. W. Phillips¹³⁴ G. Piacquadio¹⁴⁵ E. Pianori^{17a} F. Piazza^{71a,71b} R. Piegai³⁰ D. Pietreanu^{27b}
 A. D. Pilkington¹⁰¹ M. Pinamonti^{69a,69c} J. L. Pinfold² B. C. Pinheiro Pereira^{130a} A. E. Pinto Pinoargote¹³⁵
 K. M. Piper¹⁴⁶ A. Pirttikoski⁵⁶ C. Pitman Donaldson⁹⁶ D. A. Pizzi³⁴ L. Pizzimento^{76a,76b} A. Pizzini¹¹⁴
 M.-A. Pleier²⁹ V. Plesanovs⁵⁴ V. Pleskot¹³³ E. Plotnikova³⁸ G. Poddar⁴ R. Poettgen⁹⁸ L. Poggioli¹²⁷
 I. Pokharel⁵⁵ S. Polacek¹³³ G. Polesello^{73a} A. Poley^{142,156a} R. Polifka¹³² A. Polini^{23b} C. S. Pollard¹⁶⁷
 Z. B. Pollock¹¹⁹ V. Polychronakos²⁹ E. Pompa Pacchi^{75a,75b} D. Ponomarenko¹¹³ L. Pontecorvo³⁶ S. Popa^{27a}
 G. A. Popeneciu^{27d} A. Poreba³⁶ D. M. Portillo Quintero^{156a} S. Pospisil¹³² M. A. Postill¹³⁹ P. Postolache^{27c}
 K. Potamianos¹⁶⁷ P. A. Potepa^{85a} I. N. Potrap³⁸ C. J. Potter³² H. Potti¹ T. Poulsen⁴⁸ J. Poveda¹⁶³
 M. E. Pozo Astigarraga³⁶ A. Prades Ibanez¹⁶³ J. Pretel⁵⁴ D. Price¹⁰¹ M. Primavera^{70a} M. A. Principe Martin⁹⁹
 R. Privara¹²² T. Procter⁵⁹ M. L. Proffitt¹³⁸ N. Proklova¹²⁸ K. Prokofiev^{64c} G. Proto¹¹⁰ S. Protopopescu²⁹
 J. Proudfoot⁶ M. Przybycien^{85a} W. W. Przygoda^{85b} J. E. Puddefoot¹³⁹ D. Pudzha³⁷ D. Pyatizbyantseva³⁷
 J. Qian¹⁰⁶ D. Qichen¹⁰¹ Y. Qin¹⁰¹ T. Qiu⁵² A. Quadt⁵⁵ M. Queitsch-Maitland¹⁰¹ G. Quetant⁵⁶
 G. Rabanal Bolanos⁶¹ D. Rafanoharana⁵⁴ F. Ragusa^{71a,71b} J. L. Rainbolt³⁹ J. A. Raine⁵⁶ S. Rajagopalan²⁹
 E. Ramakoti³⁷ K. Ran^{48,14e} N. P. Rapheeha^{33g} H. Rasheed^{27b} V. Raskina¹²⁷ D. F. Rassloff^{63a} S. Rave¹⁰⁰
 B. Ravina⁵⁵ I. Ravinovich¹⁶⁹ M. Raymond³⁶ A. L. Read¹²⁵ N. P. Readioff¹³⁹ D. M. Rebuffi^{73a,73b}

G. Redlinger²⁹ A. S. Reed¹¹⁰ K. Reeves²⁶ J. A. Reidelsturz^{171,ij} D. Reikher¹⁵¹ A. Rej¹⁴¹ C. Rembser³⁶
A. Renardi⁴⁸ M. Renda^{27b} M. B. Rendel¹¹⁰ F. Renner⁴⁸ A. G. Rennie⁵⁹ S. Resconi^{71a} M. Ressegotti^{57b,57a}
S. Rettie³⁶ J. G. Reyes Rivera¹⁰⁷ B. Reynolds¹¹⁹ E. Reynolds^{17a} O. L. Rezanova³⁷ P. Reznicek¹³³ N. Ribaric⁹¹
E. Ricci^{78a,78b} R. Richter¹¹⁰ S. Richter^{47a,47b} E. Richter-Was^{85b} M. Ridel¹²⁷ S. Ridouani^{35d} P. Rieck¹¹⁷
P. Riedler³⁶ M. Rijssenbeek¹⁴⁵ A. Rimoldi^{73a,73b} M. Rimoldi⁴⁸ L. Rinaldi^{23b,23a} T. T. Rinn²⁹
M. P. Rinnagel¹⁰⁹ G. Ripellino¹⁶¹ I. Riu¹³ P. Rivadeneira⁴⁸ J. C. Rivera Vergara¹⁶⁵ F. Rizatdinova¹²¹
E. Rizvi⁹⁴ B. A. Roberts¹⁶⁷ B. R. Roberts^{17a} S. H. Robertson^{104,q} M. Robin⁴⁸ D. Robinson³²
C. M. Robles Gajardo^{137f} M. Robles Manzano¹⁰⁰ A. Robson⁵⁹ A. Rocchi^{76a,76b} C. Roda^{74a,74b}
S. Rodriguez Bosca^{63a} Y. Rodriguez Garcia^{22a} A. Rodriguez Rodriguez⁵⁴ A. M. Rodríguez Vera^{156b} S. Roe³⁶
J. T. Roemer¹⁶⁰ A. R. Roepe-Gier¹³⁶ J. Roggel¹⁷¹ O. Røhne¹²⁵ R. A. Rojas¹⁰³ C. P. A. Roland⁶⁸ J. Roloff²⁹
A. Romaniouk³⁷ E. Romano^{73a,73b} M. Romano^{23b} A. C. Romero Hernandez¹⁶² N. Rompotis⁹² L. Roos¹²⁷
S. Rosati^{75a} B. J. Rosser³⁹ E. Rossi¹²⁶ E. Rossi^{72a,72b} L. P. Rossi^{57b} L. Rossini⁴⁸ R. Rosten¹¹⁹
M. Rotaru^{27b} B. Rottler⁵⁴ C. Rougier^{102,gg} D. Rousseau⁶⁶ D. Rouso³² A. Roy¹⁶² S. Roy-Garand¹⁵⁵
A. Rozanov¹⁰² Y. Rozen¹⁵⁰ X. Ruan^{33g} A. Rubio Jimenez¹⁶³ A. J. Ruby⁹² V. H. Ruelas Rivera¹⁸
T. A. Ruggeri¹ A. Ruggiero¹²⁶ A. Ruiz-Martinez¹⁶³ A. Rummeler³⁶ Z. Rurikova⁵⁴ N. A. Rusakovich³⁸
H. L. Russell¹⁶⁵ G. Russo^{75a,75b} J. P. Rutherford⁷ S. Rutherford Colmenares³² K. Rybacki⁹¹ M. Rybar¹³³
E. B. Rye¹²⁵ A. Ryzhov⁴⁴ J. A. Sabater Iglesias⁵⁶ P. Sabatini¹⁶³ L. Sabetta^{75a,75b} H. F.-W. Sadrozinski¹³⁶
F. Safai Tehrani^{75a} B. Safarzadeh Samani¹⁴⁶ M. Safdari¹⁴³ S. Saha¹⁶⁵ M. Sahinsoy¹¹⁰ M. Saimpert¹³⁵
M. Saito¹⁵³ T. Saito¹⁵³ D. Salamani³⁶ A. Salmikov¹⁴³ J. Salt¹⁶³ A. Salvador Salas¹³ D. Salvatore^{43b,43a}
F. Salvatore¹⁴⁶ A. Salzburger³⁶ D. Sammel⁵⁴ D. Sampsonidis^{152,bb} D. Sampsonidou¹²³ J. Sánchez¹⁶³
A. Sanchez Pineda⁴ V. Sanchez Sebastian¹⁶³ H. Sandaker¹²⁵ C. O. Sander⁴⁸ J. A. Sandesara¹⁰³ M. Sandhoff¹⁷¹
C. Sandoval^{22b} D. P. C. Sankey¹³⁴ T. Sano⁸⁷ A. Sansoni⁵³ L. Santi^{75a,75b} C. Santoni⁴⁰ H. Santos^{130a,130b}
S. N. Santpur^{17a} A. Santra¹⁶⁹ K. A. Saoucha¹³⁹ J. G. Saraiva^{130a,130d} J. Sardain⁷ O. Sasaki⁸³ K. Sato¹⁵⁷
C. Sauer^{63b} F. Sauerburger⁵⁴ E. Sauvan⁴ P. Savard^{155,e} R. Sawada¹⁵³ C. Sawyer¹³⁴ L. Sawyer⁹⁷
I. Sayago Galvan¹⁶³ C. Sbarra^{23b} A. Sbrizzi^{23b,23a} T. Scanlon⁹⁶ J. Schaarschmidt¹³⁸ P. Schacht¹¹⁰
D. Schaefer³⁹ U. Schäfer¹⁰⁰ A. C. Schaffer^{66,44} D. Schaile¹⁰⁹ R. D. Schamberger¹⁴⁵ C. Scharf¹⁸
M. M. Schefer¹⁹ V. A. Schegelsky³⁷ D. Scheirich¹³³ F. Schenck¹⁸ M. Schernau¹⁶⁰ C. Scheulen⁵⁵
C. Schiavi^{57b,57a} E. J. Schioppa^{70a,70b} M. Schioppa^{43b,43a} B. Schlag^{143,u} K. E. Schleicher⁵⁴ S. Schlenker³⁶
J. Schmeing¹⁷¹ M. A. Schmidt¹⁷¹ K. Schmieden¹⁰⁰ C. Schmitt¹⁰⁰ S. Schmitt⁴⁸ L. Schoeffel¹³⁵
A. Schoening^{63b} P. G. Scholer⁵⁴ E. Schopf¹²⁶ M. Schott¹⁰⁰ J. Schovancova³⁶ S. Schramm⁵⁶ F. Schroeder¹⁷¹
T. Schroer⁵⁶ H.-C. Schultz-Coulon^{63a} M. Schumacher⁵⁴ B. A. Schumm¹³⁶ Ph. Schune¹³⁵ A. J. Schuy¹³⁸
H. R. Schwartz¹³⁶ A. Schwartzman¹⁴³ T. A. Schwarz¹⁰⁶ Ph. Schwemling¹³⁵ R. Schwienhorst¹⁰⁷
A. Sciandra¹³⁶ G. Sciolla²⁶ F. Scuri^{74a} C. D. Sebastiani⁹² K. Sedlaczek¹¹⁵ P. Seema¹⁸ S. C. Seidel¹¹²
A. Seiden¹³⁶ B. D. Seidlitz⁴¹ C. Seitz⁴⁸ J. M. Seixas^{82b} G. Sekhniaidze^{72a} S. J. Sekula⁴⁴ L. Selem⁶⁰
N. Semprini-Cesari^{23b,23a} D. Sengupta⁵⁶ V. Senthikumar¹⁶³ L. Serin⁶⁶ L. Serkin^{69a,69b} M. Sessa^{76a,76b}
H. Severini¹²⁰ F. Sforza^{57b,57a} A. Sfyrila⁵⁶ E. Shabalina⁵⁵ R. Shaheen¹⁴⁴ J. D. Shahinian¹²⁸
D. Shaked Renous¹⁶⁹ L. Y. Shan^{14a} M. Shapiro^{17a} A. Sharma³⁶ A. S. Sharma¹⁶⁴ P. Sharma⁸⁰ S. Sharma⁴⁸
P. B. Shatalov³⁷ K. Shaw¹⁴⁶ S. M. Shaw¹⁰¹ A. Shcherbakova³⁷ Q. Shen^{62c,5} P. Sherwood⁹⁶ L. Shi⁹⁶
X. Shi^{14a} C. O. Shimmin¹⁷² Y. Shimogama¹⁶⁸ J. D. Shinner⁹⁵ I. P. J. Shipsey¹²⁶ S. Shirabe^{56,ii}
M. Shiyakova^{38,kk} J. Shlomi¹⁶⁹ M. J. Shochet³⁹ J. Shojaii¹⁰⁵ D. R. Shope¹²⁵ S. Shrestha^{119,11} E. M. Shrif^{33g}
M. J. Shroff¹⁶⁵ P. Sicho¹³¹ A. M. Sickles¹⁶² E. Sideras Haddad^{33g} A. Sidoti^{23b} F. Siegert⁵⁰ Dj. Sijacki¹⁵
R. Sikora^{85a} F. Sili⁹⁰ J. M. Silva²⁰ M. V. Silva Oliveira²⁹ S. B. Silverstein^{47a} S. Simion⁶⁶ R. Simoniello³⁶
E. L. Simpson⁵⁹ H. Simpson¹⁴⁶ L. R. Simpson¹⁰⁶ N. D. Simpson⁹⁸ S. Simsek^{21d} S. Sindhu⁵⁵ P. Sinervo¹⁵⁵
S. Singh¹⁵⁵ S. Sinha⁴⁸ S. Sinha¹⁰¹ M. Sioli^{23b,23a} I. Siral³⁶ E. Sitnikova⁴⁸ S. Yu. Sivoklov^{37,a}
J. Sjölin^{47a,47b} A. Skaf⁵⁵ E. Skorda⁹⁸ P. Skubic¹²⁰ M. Slawinska⁸⁶ V. Smakhtin¹⁶⁹ B. H. Smart¹³⁴
J. Smiesko³⁶ S. Yu. Smirnov³⁷ Y. Smirnov³⁷ L. N. Smirnova^{37,m} O. Smirnova⁹⁸ A. C. Smith⁴¹ E. A. Smith³⁹
H. A. Smith¹²⁶ J. L. Smith⁹² R. Smith¹⁴³ M. Smizanska⁹¹ K. Smolek¹³² A. A. Snesarev³⁷ S. R. Snider¹⁵⁵
H. L. Snoek¹¹⁴ S. Snyder²⁹ R. Sobie^{165,q} A. Soffer¹⁵¹ C. A. Solans Sanchez³⁶ E. Yu. Soldatov³⁷
U. Soldevila¹⁶³ A. A. Solodkov³⁷ S. Solomon²⁶ A. Soloshenko³⁸ K. Solovieva⁵⁴ O. V. Solovyanov⁴⁰

V. Solovyev³⁷ P. Sommer³⁶ A. Sonay¹³ W. Y. Song^{156b} J. M. Sonneveld¹¹⁴ A. Sopczak¹³² A. L. Sopio⁹⁶
 F. Sopkova^{28b} V. Sothilingam^{63a} S. Sottocornola⁶⁸ R. Soualah^{116b} Z. Soumami^{35e} D. South⁴⁸
 S. Spagnolo^{70a,70b} M. Spalla¹¹⁰ D. Sperlich⁵⁴ G. Spigo³⁶ M. Spina¹⁴⁶ S. Spinali⁹¹ D. P. Spiteri⁵⁹
 M. Spousta¹³³ E. J. Staats³⁴ A. Stabile^{71a,71b} R. Stamen^{63a} M. Stamenkovic¹¹⁴ A. Stampekis²⁰ M. Standke²⁴
 E. Stanecka⁸⁶ M. V. Stange⁵⁰ B. Stanislaus^{17a} M. M. Stanitzki⁴⁸ B. Stapf⁴⁸ E. A. Starchenko³⁷
 G. H. Stark¹³⁶ J. Stark^{102,gg} D. M. Starko^{156b} P. Staroba¹³¹ P. Starovoitov^{63a} S. Stärz¹⁰⁴ R. Staszewski⁸⁶
 G. Stavropoulos⁴⁶ J. Steentoft¹⁶¹ P. Steinberg²⁹ B. Stelzer^{142,156a} H. J. Stelzer¹²⁹ O. Stelzer-Chilton^{156a}
 H. Stenzel⁵⁸ T. J. Stevenson¹⁴⁶ G. A. Stewart³⁶ J. R. Stewart¹²¹ M. C. Stockton³⁶ G. Stoicea^{27b}
 M. Stolarski^{130a} S. Stonjek¹¹⁰ A. Straessner⁵⁰ J. Strandberg¹⁴⁴ S. Strandberg^{47a,47b} M. Strauss¹²⁰
 T. Streblner¹⁰² P. Striznec^{28b} R. Ströhmer¹⁶⁶ D. M. Strom¹²³ L. R. Strom⁴⁸ R. Stroynowski⁴⁴
 A. Strubig^{47a,47b} S. A. Stucci²⁹ B. Stugu¹⁶ J. Stupak¹²⁰ N. A. Styles⁴⁸ D. Su¹⁴³ S. Su^{62a} W. Su^{62d}
 X. Su^{62a,66} K. Sugizaki¹⁵³ V. V. Sulim³⁷ M. J. Sullivan⁹² D. M. S. Sultan^{78a,78b} L. Sultaniyeva³⁷
 S. Sultansoy^{3b} T. Sumida⁸⁷ S. Sun¹⁰⁶ S. Sun¹⁷⁰ O. Sunneborn Gudnadottir¹⁶¹ M. R. Sutton¹⁴⁶ H. Suzuki¹⁵⁷
 M. Svatos¹³¹ M. Swiatlowski^{156a} T. Swirski¹⁶⁶ I. Sykora^{28a} M. Sykora¹³³ T. Sykora¹³³ D. Ta¹⁰⁰
 K. Tackmann^{48,mm} A. Taffard¹⁶⁰ R. Tafirout^{156a} J. S. Tafoya Vargas⁶⁶ R. Takashima⁸⁸ E. P. Takeva⁵²
 Y. Takubo⁸³ M. Talby¹⁰² A. A. Talyshev³⁷ K. C. Tam^{64b} N. M. Tamir¹⁵¹ A. Tanaka¹⁵³ J. Tanaka¹⁵³
 R. Tanaka⁶⁶ M. Tanasini^{57b,57a} Z. Tao¹⁶⁴ S. Tapia Araya^{137f} S. Tapprogge¹⁰⁰ A. Tarek Abouelfadl Mohamed¹⁰⁷
 S. Tarem¹⁵⁰ K. Tariq^{62b} G. Tarna^{102,27b} G. F. Tartarelli^{71a} P. Tas¹³³ M. Tasevsky¹³¹ E. Tassi^{43b,43a}
 A. C. Tate¹⁶² G. Tateno¹⁵³ Y. Tayalati^{35e,nn} G. N. Taylor¹⁰⁵ W. Taylor^{156b} H. Teagle⁹² A. S. Tee¹⁷⁰
 R. Teixeira De Lima¹⁴³ P. Teixeira-Dias⁹⁵ J. J. Teoh¹⁵⁵ K. Terashi¹⁵³ J. Terron⁹⁹ S. Terzo¹³ M. Testa⁵³
 R. J. Teuscher^{155,q} A. Thaler⁷⁹ O. Theiner⁵⁶ N. Themistokleous⁵² T. Thevenaux-Pelzer¹⁰² O. Thielmann¹⁷¹
 D. W. Thomas⁹⁵ J. P. Thomas²⁰ E. A. Thompson^{17a} P. D. Thompson²⁰ E. Thomson¹²⁸ Y. Tian⁵⁵
 V. Tikhomirov^{37,m} Yu. A. Tikhonov³⁷ S. Timoshenko³⁷ D. Timoshyn¹³³ E. X. L. Ting¹ P. Tipton¹⁷²
 S. H. Tlou^{33g} A. Tmourji⁴⁰ K. Todome^{23b,23a} S. Todorova-Nova¹³³ S. Todt⁵⁰ M. Togawa⁸³ J. Tojo⁸⁹
 S. Tokár^{28a} K. Tokushuku⁸³ O. Toldaiev⁶⁸ R. Tombs³² M. Tomoto^{83,111} L. Tompkins^{143,u}
 K. W. Topolnicki^{85b} E. Torrence¹²³ H. Torres^{102,gg} E. Torró Pastor¹⁶³ M. Toscani³⁰ C. Toscirri³⁹ M. Tost¹¹
 D. R. Tovey¹³⁹ A. Traeet¹⁶ I. S. Trandafir^{27b} T. Trefzger¹⁶⁶ A. Tricoli²⁹ I. M. Trigger^{156a} S. Trincaz-Duvoid¹²⁷
 D. A. Trischuk²⁶ B. Trocmé⁶⁰ C. Troncon^{71a} L. Truong^{33c} M. Trzebinski⁸⁶ A. Trzupek⁸⁶ F. Tsai¹⁴⁵
 M. Tsai¹⁰⁶ A. Tsiamis^{152,bb} P. V. Tsiarshka³⁷ S. Tsigaridas^{156a} A. Tsigiriotis^{152,cc} V. Tsiskaridze¹⁵⁵
 E. G. Tskhadadze^{149a} M. Tsopoulou^{152,bb} Y. Tsujikawa⁸⁷ I. I. Tsukerman³⁷ V. Tsulaia^{17a} S. Tsuno⁸³ O. Tsur¹⁵⁰
 K. Tsurii¹¹⁸ D. Tsybychev¹⁴⁵ Y. Tu^{64b} A. Tudorache^{27b} V. Tudorache^{27b} A. N. Tuna³⁶ S. Turchikhin³⁸
 I. Turk Cakir^{3a} R. Turra^{71a} T. Turtuvshin^{38,oo} P. M. Tuts⁴¹ S. Tzamarias^{152,bb} P. Tzanis¹⁰ E. Tzovara¹⁰⁰
 K. Uchida¹⁵³ F. Ukegawa¹⁵⁷ P. A. Ulloa Poblete^{137c,137b} E. N. Umaka²⁹ G. Unal³⁶ M. Unal¹¹ A. Undrus²⁹
 G. Unel¹⁶⁰ J. Urban^{28b} P. Urquijo¹⁰⁵ G. Usai⁸ R. Ushioda¹⁵⁴ M. Usman¹⁰⁸ Z. Uysal^{21b} L. Vacavant¹⁰²
 V. Vacek¹³² B. Vachon¹⁰⁴ K. O. H. Vadla¹²⁵ T. Vafeiadis³⁶ A. Vaitkus⁹⁶ C. Valderanis¹⁰⁹
 E. Valdes Santurio^{47a,47b} M. Valente^{156a} S. Valentinetti^{23b,23a} A. Valero¹⁶³ E. Valiente Moreno¹⁶³
 A. Vallier^{102,gg} J. A. Valls Ferrer¹⁶³ D. R. Van Arneman¹¹⁴ T. R. Van Daalen¹³⁸ A. Van Der Graaf⁴⁹
 P. Van Gemmeren⁶ M. Van Rijnbach^{125,36} S. Van Stroud⁹⁶ I. Van Vulpen¹¹⁴ M. Vanadia^{76a,76b} W. Vandelli³⁶
 M. Vandenbroucke¹³⁵ E. R. Vandewall¹²¹ D. Vannicola¹⁵¹ L. Vannoli^{57b,57a} R. Vari^{75a} E. W. Varnes⁷
 C. Varni^{17a} T. Varol¹⁴⁸ D. Varouchas⁶⁶ L. Variale¹⁶³ K. E. Varvell¹⁴⁷ M. E. Vasile^{27b} L. Vaslin⁴⁰
 G. A. Vasquez¹⁶⁵ F. Vazeille⁴⁰ T. Vazquez Schroeder³⁶ J. Veatch³¹ V. Vecchio¹⁰¹ M. J. Veen¹⁰³ I. Velisek¹²⁶
 L. M. Veloce¹⁵⁵ F. Veloso^{130a,130c} S. Veneziano^{75a} A. Ventura^{70a,70b} A. Verbytskyi¹¹⁰ M. Verducci^{74a,74b}
 C. Vergis²⁴ M. Verissimo De Araujo^{82b} W. Verkerke¹¹⁴ J. C. Vermeulen¹¹⁴ C. Vermieri¹⁴³ P. J. Verschuuren⁹⁵
 M. Vessella¹⁰³ M. C. Vetterli^{142,e} A. Vgenopoulos^{152,bb} N. Viaux Maira^{137f} T. Vickey¹³⁹
 O. E. Vickey Boeriu¹³⁹ G. H. A. Viehhauser¹²⁶ L. Vigani^{63b} M. Villa^{23b,23a} M. Villaplana Perez¹⁶³
 E. M. Villhauer⁵² E. Vilucchi⁵³ M. G. Vincker³⁴ G. S. Virdee²⁰ A. Vishwakarma⁵² A. Visibile¹¹⁴ C. Vittori³⁶
 I. Vivarelli¹⁴⁶ V. Vladimirov¹⁶⁷ E. Voevodina¹¹⁰ F. Vogel¹⁰⁹ P. Vokac¹³² J. Von Ahnen⁴⁸ E. Von Toerne²⁴
 B. Vormwald³⁶ V. Vorobel¹³³ K. Vorobev³⁷ M. Vos¹⁶³ K. Voss¹⁴¹ J. H. Vosseveld⁹² M. Vozak¹¹⁴
 L. Vozdecky⁹⁴ N. Vranjes¹⁵ M. Vranjes Milosavljevic¹⁵ M. Vreeswijk¹¹⁴ N. K. Vu^{62d,62c} R. Vuillermet³⁶

O. Vujanovic¹⁰⁰ I. Vukotic³⁹ S. Wada¹⁵⁷ C. Wagner,¹⁰³ J. M. Wagner^{17a} W. Wagner¹⁷¹ S. Wahdan¹⁷¹
 H. Wahlberg⁹⁰ R. Wakasa¹⁵⁷ M. Wakida¹¹¹ J. Walder¹³⁴ R. Walker¹⁰⁹ W. Walkowiak¹⁴¹ A. Wall¹²⁸
 T. Wamorkar⁶ A. Z. Wang¹⁷⁰ C. Wang¹⁰⁰ C. Wang^{62c} H. Wang^{17a} J. Wang^{64a} R.-J. Wang¹⁰⁰ R. Wang⁶¹
 R. Wang⁶ S. M. Wang¹⁴⁸ S. Wang^{62b} T. Wang^{62a} W. T. Wang⁸⁰ W. Wang^{14a} X. Wang^{14c} X. Wang¹⁶²
 X. Wang^{62c} Y. Wang^{62d} Y. Wang^{14c} Z. Wang¹⁰⁶ Z. Wang^{62d,51,62c} Z. Wang¹⁰⁶ A. Warburton¹⁰⁴
 R. J. Ward²⁰ N. Warrack⁵⁹ A. T. Watson²⁰ H. Watson⁵⁹ M. F. Watson²⁰ E. Watton^{59,134} G. Watts¹³⁸
 B. M. Waugh⁹⁶ C. Weber²⁹ H. A. Weber¹⁸ M. S. Weber¹⁹ S. M. Weber^{63a} C. Wei^{62a} Y. Wei¹²⁶
 A. R. Weidberg¹²⁶ E. J. Weik¹¹⁷ J. Weingarten⁴⁹ M. Weirich¹⁰⁰ C. Weiser⁵⁴ C. J. Wells⁴⁸ T. Wenaus²⁹
 B. Wendland⁴⁹ T. Wengler³⁶ N. S. Wenke¹¹⁰ N. Wermes²⁴ M. Wessels^{63a} K. Whalen¹²³ A. M. Wharton⁹¹
 A. S. White⁶¹ A. White⁸ M. J. White¹ D. Whiteson¹⁶⁰ L. Wickremasinghe¹²⁴ W. Wiedenmann¹⁷⁰ C. Wiel⁵⁰
 M. Wielers¹³⁴ C. Wiglesworth⁴² D. J. Wilbern¹²⁰ H. G. Wilkens³⁶ D. M. Williams⁴¹ H. H. Williams¹²⁸
 S. Williams³² S. Willocq¹⁰³ B. J. Wilson¹⁰¹ P. J. Windischhofer³⁹ F. I. Winkel³⁰ F. Winklmeier¹²³
 B. T. Winter⁵⁴ J. K. Winter¹⁰¹ M. Wittgen¹⁴³ M. Wobisch⁹⁷ Z. Wolfs¹¹⁴ R. Wölker¹²⁶ J. Wollrath¹⁶⁰
 M. W. Wolter⁸⁶ H. Wolters^{130a,130c} A. F. Wongel⁴⁸ S. D. Worm⁴⁸ B. K. Wosiek⁸⁶ K. W. Woźniak⁸⁶
 S. Wozniewski⁵⁵ K. Wraight⁵⁹ C. Wu²⁰ J. Wu^{14a,14e} M. Wu^{64a} M. Wu¹¹³ S. L. Wu¹⁷⁰ X. Wu⁵⁶ Y. Wu^{62a}
 Z. Wu¹³⁵ J. Wuerzinger¹¹⁰ T. R. Wyatt¹⁰¹ B. M. Wynne⁵² S. Xella⁴² L. Xia^{14c} M. Xia^{14b} J. Xiang^{64c}
 X. Xiao¹⁰⁶ M. Xie^{62a} X. Xie^{62a} S. Xin^{14a,14e} J. Xiong^{17a} D. Xu^{14a} H. Xu^{62a} L. Xu^{62a} R. Xu¹²⁸ T. Xu¹⁰⁶
 Y. Xu^{14b} Z. Xu⁵² Z. Xu^{14a} B. Yabsley¹⁴⁷ S. Yacoob^{33a} N. Yamaguchi⁸⁹ Y. Yamaguchi¹⁵⁴ E. Yamashita¹⁵³
 H. Yamauchi¹⁵⁷ T. Yamazaki^{17a} Y. Yamazaki⁸⁴ J. Yan^{62c} S. Yan¹²⁶ Z. Yan²⁵ H. J. Yang^{62c,62d} H. T. Yang^{62a}
 S. Yang^{62a} T. Yang^{64c} X. Yang^{62a} X. Yang^{14a} Y. Yang⁴⁴ Y. Yang^{62a} Z. Yang^{62a} W.-M. Yao^{17a} Y. C. Yap⁴⁸
 H. Ye^{14c} H. Ye⁵⁵ J. Ye⁴⁴ S. Ye²⁹ X. Ye^{62a} Y. Yeh⁹⁶ I. Yeletsikh³⁸ B. K. Yeo^{17a} M. R. Yexley⁹⁶
 P. Yin⁴¹ K. Yorita¹⁶⁸ S. Younas^{27b} C. J. S. Young⁵⁴ C. Young¹⁴³ Y. Yu^{62a} M. Yuan¹⁰⁶ R. Yuan^{62b,pp}
 L. Yue⁹⁶ M. Zaazoua^{62a} B. Zabinski⁸⁶ E. Zaid⁵² T. Zakareishvili^{149b} N. Zakharchuk³⁴ S. Zambito⁵⁶
 J. A. Zamora Saa^{137d,137b} J. Zang¹⁵³ D. Zanzi⁵⁴ O. Zaplatilek¹³² C. Zeitnitz¹⁷¹ H. Zeng^{14a} J. C. Zeng¹⁶²
 D. T. Zenger Jr.,²⁶ O. Zenin³⁷ T. Ženiš^{28a} S. Zenz⁹⁴ S. Zerradi^{35a} D. Zerwas⁶⁶ M. Zhai^{14a,14e} B. Zhang^{14c}
 D. F. Zhang¹³⁹ J. Zhang^{62b} J. Zhang⁶ K. Zhang^{14a,14e} L. Zhang^{14c} P. Zhang^{14a,14e} R. Zhang¹⁷⁰ S. Zhang¹⁰⁶
 T. Zhang¹⁵³ X. Zhang^{62c} X. Zhang^{62b} Y. Zhang^{62c,5} Y. Zhang⁹⁶ Z. Zhang^{17a} Z. Zhang⁶⁶ H. Zhao¹³⁸
 P. Zhao⁵¹ T. Zhao^{62b} Y. Zhao¹³⁶ Z. Zhao^{62a} A. Zhemchugov³⁸ K. Zheng¹⁶² X. Zheng^{62a} Z. Zheng¹⁴³
 D. Zhong¹⁶² B. Zhou¹⁰⁶ H. Zhou⁷ N. Zhou^{62c} Y. Zhou⁷ C. G. Zhu^{62b} J. Zhu¹⁰⁶ Y. Zhu^{62c} Y. Zhu^{62a}
 X. Zhuang^{14a} K. Zhukov³⁷ V. Zhulanov³⁷ N. I. Zimine³⁸ J. Zinsser^{63b} M. Ziolkowski¹⁴¹ L. Živković¹⁵
 A. Zoccoli^{23b,23a} K. Zoch⁵⁶ T. G. Zorbas¹³⁹ O. Zormpa⁴⁶ W. Zou⁴¹ and L. Zwalinski³⁶

(ATLAS Collaboration)

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

²Department of Physics, University of Alberta, Edmonton, Alberta, Canada

^{3a}Department of Physics, Ankara University, Ankara, Türkiye

^{3b}Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye

⁴LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

⁵APC, Université Paris Cité, CNRS/IN2P3, Paris, France

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

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

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

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

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

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

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

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

^{14a}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

^{14b}Physics Department, Tsinghua University, Beijing, China

^{14c}Department of Physics, Nanjing University, Nanjing, China

- ^{14d}*School of Science, Shenzhen Campus of Sun Yat-sen University, China*
^{14e}*University of Chinese Academy of Science (UCAS), Beijing, China*
¹⁵*Institute of Physics, University of Belgrade, Belgrade, Serbia*
¹⁶*Department for Physics and Technology, University of Bergen, Bergen, Norway*
^{17a}*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
^{17b}*University of California, Berkeley, California, USA*
¹⁸*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
¹⁹*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
²⁰*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
^{21a}*Department of Physics, Bogazici University, Istanbul, Türkiye*
^{21b}*Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye*
^{21c}*Department of Physics, Istanbul University, Istanbul, Türkiye*
^{21d}*Istinye University, Sariyer, Istanbul, Türkiye*
^{22a}*Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia*
^{22b}*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
^{22c}*Pontificia Universidad Javeriana, Bogota, Colombia*
^{23a}*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy*
^{23b}*INFN Sezione di Bologna, Italy*
²⁴*Physikalisches Institut, Universität Bonn, Bonn, Germany*
²⁵*Department of Physics, Boston University, Boston, Massachusetts, USA*
²⁶*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
^{27a}*Transilvania University of Brasov, Brasov, Romania*
^{27b}*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
^{27c}*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
^{27d}*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
^{27e}*University Politehnica Bucharest, Bucharest, Romania*
^{27f}*West University in Timisoara, Timisoara, Romania*
^{27g}*Faculty of Physics, University of Bucharest, Bucharest, Romania*
^{28a}*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
^{28b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
²⁹*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
³⁰*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
³¹*California State University, Fresno, California, USA*
³²*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
^{33a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
^{33b}*iThemba Labs, Western Cape, South Africa*
^{33c}*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
^{33d}*National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines*
^{33e}*University of South Africa, Department of Physics, Pretoria, South Africa*
^{33f}*University of Zululand, KwaDlangezwa, South Africa*
^{33g}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
³⁴*Department of Physics, Carleton University, Ottawa, Ontario, 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}*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
^{35e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
^{35f}*Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
³⁶*CERN, Geneva, Switzerland*
³⁷*Affiliated with an institute covered by a cooperation agreement with CERN*
³⁸*Affiliated with an international laboratory covered by a cooperation agreement with CERN*
³⁹*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
⁴⁰*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
⁴¹*Nevis Laboratory, Columbia University, Irvington, New York, USA*
⁴²*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
^{43a}*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
^{43b}*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*

- ⁴⁴*Physics Department, Southern Methodist University, Dallas, Texas, USA*
- ⁴⁵*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
- ⁴⁶*National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- ^{47a}*Department of Physics, Stockholm University, Sweden*
- ^{47b}*Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁸*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁹*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
- ⁵⁰*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁵¹*Department of Physics, Duke University, Durham, North Carolina, USA*
- ⁵²*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵³*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵⁴*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵⁵*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵⁶*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ^{57a}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- ^{57b}*INFN Sezione di Genova, Italy*
- ⁵⁸*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁹*SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁶⁰*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁶¹*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- ^{62a}*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- ^{62b}*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- ^{62c}*School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China*
- ^{62d}*Tsung-Dao Lee Institute, Shanghai, China*
- ^{63a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{63b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{64a}*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
- ^{64b}*Department of Physics, University of Hong Kong, Hong Kong, China*
- ^{64c}*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶⁵*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶⁶*IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
- ⁶⁷*Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain*
- ⁶⁸*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- ^{69a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- ^{69b}*ICTP, Trieste, Italy*
- ^{69c}*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
- ^{70a}*INFN Sezione di Lecce, Italy*
- ^{70b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ^{71a}*INFN Sezione di Milano, Italy*
- ^{71b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ^{72a}*INFN Sezione di Napoli, Italy*
- ^{72b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ^{73a}*INFN Sezione di Pavia, Italy*
- ^{73b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ^{74a}*INFN Sezione di Pisa, Italy*
- ^{74b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ^{75a}*INFN Sezione di Roma, Italy*
- ^{75b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- ^{76a}*INFN Sezione di Roma Tor Vergata, Italy*
- ^{76b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{77a}*INFN Sezione di Roma Tre, Italy*
- ^{77b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ^{78a}*INFN-TIFPA, Italy*
- ^{78b}*Università degli Studi di Trento, Trento, Italy*
- ⁷⁹*Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
- ⁸⁰*University of Iowa, Iowa City, Iowa, USA*

- ⁸¹*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
- ^{82a}*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
- ^{82b}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
- ^{82c}*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- ^{82d}*Rio de Janeiro State University, Rio de Janeiro, Brazil*
- ⁸³*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- ⁸⁴*Graduate School of Science, Kobe University, Kobe, Japan*
- ^{85a}*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
- ^{85b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- ⁸⁶*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- ⁸⁷*Faculty of Science, Kyoto University, Kyoto, Japan*
- ⁸⁸*Kyoto University of Education, Kyoto, Japan*
- ⁸⁹*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- ⁹⁰*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- ⁹¹*Physics Department, Lancaster University, Lancaster, United Kingdom*
- ⁹²*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁹³*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- ⁹⁴*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- ⁹⁵*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
- ⁹⁶*Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁹⁷*Louisiana Tech University, Ruston, Los Angeles, USA*
- ⁹⁸*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁹⁹*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
- ¹⁰⁰*Institut für Physik, Universität Mainz, Mainz, Germany*
- ¹⁰¹*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ¹⁰²*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- ¹⁰³*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- ¹⁰⁴*Department of Physics, McGill University, Montreal, Quebec, Canada*
- ¹⁰⁵*School of Physics, University of Melbourne, Victoria, Australia*
- ¹⁰⁶*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
- ¹⁰⁷*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ¹⁰⁸*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
- ¹⁰⁹*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ¹¹⁰*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹¹¹*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ¹¹²*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹¹³*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
- ¹¹⁴*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹¹⁵*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ^{116a}*New York University Abu Dhabi, Abu Dhabi, United Arab Emirates*
- ^{116b}*University of Sharjah, Sharjah, United Arab Emirates*
- ¹¹⁷*Department of Physics, New York University, New York, New York, USA*
- ¹¹⁸*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- ¹¹⁹*Ohio State University, Columbus, Ohio, USA*
- ¹²⁰*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹²¹*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹²²*Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹²³*Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA*
- ¹²⁴*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹²⁵*Department of Physics, University of Oslo, Oslo, Norway*
- ¹²⁶*Department of Physics, Oxford University, Oxford, United Kingdom*
- ¹²⁷*LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
- ¹²⁸*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹²⁹*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- ^{130a}*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*
- ^{130b}*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{130c}*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- ^{130d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{130e}*Departamento de Física, Universidade do Minho, Braga, Portugal*

- ^{130f} *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
- ^{130g} *Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
- ¹³¹ *Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- ¹³² *Czech Technical University in Prague, Prague, Czech Republic*
- ¹³³ *Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹³⁴ *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹³⁵ *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ¹³⁶ *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ^{137a} *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{137b} *Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile*
- ^{137c} *Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile*
- ^{137d} *Universidad Andres Bello, Department of Physics, Santiago, Chile*
- ^{137e} *Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile*
- ^{137f} *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ¹³⁸ *Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹³⁹ *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴⁰ *Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴¹ *Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁴² *Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
- ¹⁴³ *SLAC National Accelerator Laboratory, Stanford, California, USA*
- ¹⁴⁴ *Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁴⁵ *Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
- ¹⁴⁶ *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁴⁷ *School of Physics, University of Sydney, Sydney, Australia*
- ¹⁴⁸ *Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ^{149a} *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
- ^{149b} *High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- ^{149c} *University of Georgia, Tbilisi, Georgia*
- ¹⁵⁰ *Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
- ¹⁵¹ *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵² *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵³ *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
- ¹⁵⁴ *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁵⁵ *Department of Physics, University of Toronto, Toronto, Ontario, Canada*
- ^{156a} *TRIUMF, Vancouver, British Columbia, Canada*
- ^{156b} *Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
- ¹⁵⁷ *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
- ¹⁵⁸ *Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
- ¹⁵⁹ *United Arab Emirates University, Al Ain, United Arab Emirates*
- ¹⁶⁰ *Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- ¹⁶¹ *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶² *Department of Physics, University of Illinois, Urbana, Illinois, USA*
- ¹⁶³ *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
- ¹⁶⁴ *Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
- ¹⁶⁵ *Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
- ¹⁶⁶ *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
- ¹⁶⁷ *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ¹⁶⁸ *Waseda University, Tokyo, Japan*
- ¹⁶⁹ *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷⁰ *Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
- ¹⁷¹ *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- ¹⁷² *Department of Physics, Yale University, New Haven, Connecticut, USA*

^aDeceased.

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

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

^dAlso at Lawrence Livermore National Laboratory, Livermore, California, USA.

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

^fAlso at Department of Physics, University of Thessaly, Greece.

- ^gAlso at An-Najah National University, Nablus, Palestine.
- ^hAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.
- ⁱAlso at University of Colorado Boulder, Department of Physics, Boulder, Colorado, USA.
- ^jAlso at Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.
- ^kAlso at Department of Physics, Westmont College, Santa Barbara, California, USA.
- ^lAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
- ^mAlso at Affiliated with an institute covered by a cooperation agreement with CERN.
- ⁿAlso at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
- ^oAlso at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
- ^pAlso at Università di Napoli Parthenope, Napoli, Italy.
- ^qAlso at Institute of Particle Physics (IPP), Canada.
- ^rAlso at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
- ^sAlso at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines.
- ^tAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
- ^uAlso at Department of Physics, Stanford University, Stanford, California, USA.
- ^vAlso at Centro Studi e Ricerche Enrico Fermi, Italy.
- ^wAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
- ^xAlso at Technical University of Munich, Munich, Germany.
- ^yAlso at Yeditepe University, Physics Department, Istanbul, Türkiye.
- ^zAlso at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
- ^{aa}Also at CERN, Geneva, Switzerland.
- ^{bb}Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.
- ^{cc}Also at Hellenic Open University, Patras, Greece.
- ^{dd}Also at Center for High Energy Physics, Peking University, China.
- ^{ee}Also at APC, Université Paris Cité, CNRS/IN2P3, Paris, France.
- ^{ff}Also at Department of Physics, Royal Holloway University of London, Egham, United Kingdom.
- ^{gg}Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France.
- ^{hh}Also at Department of Physics, California State University, Sacramento, California, USA.
- ⁱⁱAlso at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
- ^{jj}Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany.
- ^{kk}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{ll}Also at Washington College, Chestertown, Maryland, USA.
- ^{mmm}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ⁿⁿAlso at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
- ^{oo}Also at Institute of Physics and Technology, Ulaanbaatar, Mongolia.
- ^{pp}Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.