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Measurement of $D^{*\pm}$ meson production in jets from pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector

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This paper reports a measurement of $D^{*\pm}$ meson production in jets from proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV at the CERN Large Hadron Collider. The measurement is based on a data sample recorded with the ATLAS detector with an integrated luminosity of 0.30 pb^{-1} for jets with transverse momentum between 25 and 70 GeV in the pseudorapidity range $|\eta| < 2.5$. $D^{*\pm}$ mesons found in jets are fully reconstructed in the decay chain: $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, and its charge conjugate. The production rate is found to be $N(D^{*\pm})/N(\text{jet}) = 0.025 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.})$ for $D^{*\pm}$ mesons that carry a fraction z of the jet momentum in the range $0.3 < z < 1$. Monte Carlo predictions fail to describe the data at small values of z, and this is most marked at low jet transverse momentum.

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I. INTRODUCTION

Heavy flavor production in high-energy interactions has produced interesting tests of quantum chromodynamics (QCD) and valuable information on fragmentation and decay properties. Early measurements of b-hadron production cross sections in high-energy $p\bar{p}$ collisions [1–4] were higher than the available theoretical calculations. A satisfactory agreement between measurement and theory was reached for b-hadron production with improved analysis methods, see for example [5,6], and more accurate QCD predictions, as discussed in [7–9]. Measurements of c-hadron production [10–12] are however less conclusive and additional experimental data are needed to probe the theory, in which nonperturbative effects such as fragmentation have a significant impact on the theoretical calculations. With collisions at higher center-of-mass energy at the CERN Large Hadron Collider (LHC), the kinematical range accessible to experiment has been significantly extended [13–16]. New measurements of heavy flavor production will help in testing improved QCD-based models. Moreover, precise knowledge of heavy quark production is important for an understanding of the backgrounds in searches for new phenomena beyond the standard model if they include decays to heavy quarks.

One method to study the production of heavy quarks is to measure $D^{*\pm}$ mesons produced inside jets [10,11,17,18] by fully reconstructing the decay chain: $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ and its charge conjugate. This paper reports a measurement of $D^{*\pm}$ meson production in jets from proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV at the LHC. The measured quantity reported here is $\mathcal{R}$, the ratio of $D^{*\pm}$ produced in jets, hereafter denoted "$D^{*\pm}$ jets", to any type of jet, called "inclusive jets", as a function of the jet transverse momentum p_T, and the ratio, z, of the $D^{*\pm}$ momentum along the jet axis to the jet energy, $z = p_{\parallel}(D^{*\pm})/E(\text{jet})$. $\mathcal{R}$ is defined by

$$\mathcal{R}\,(p_T, z) = \frac{N_{D^{*\pm}}(p_T, z)}{N_{\text{jet}}(p_T)}, \qquad (1)$$

where $p_{\parallel}(D^{*\pm})$ is the momentum of the $D^{*\pm}$ meson along the jet axis; $E(\text{jet})$ is the energy of the $D^{*\pm}$ jet; $N_{D^{*\pm}}(p_T, z)$ is the number of jets that contain a $D^{*\pm}$ meson, in the corresponding p_T and z bin, and $N_{\text{jet}}(p_T)$ is the number of inclusive jets in the p_T bin.

II. THE ATLAS DETECTOR

The ATLAS detector is described in detail elsewhere [19]; only the components relevant to this analysis are described here. The ATLAS coordinate system has the origin at the nominal beam-beam interaction point. The azimuthal angle ϕ is measured around the beam axis, z, in the $x - y$ transverse plane, and the polar angle θ is the angle from the beam axis. For particles and jets, the transverse momentum is defined as $p_T = p\sin\theta$, where p is the momentum, and the pseudorapidity is defined as $\eta = -\ln\tan\theta/2$.

The inner tracking detector (ID) has full coverage in ϕ and is contained inside a central solenoid providing a 2 T magnetic field. The ID consists of a silicon pixel detector, a silicon microstrip detector (SCT) and a transition radiation tracker (TRT). The pixel detector and SCT cover the pseudorapidity range $|\eta| < 2.5$ and the TRT covers $|\eta| < 2.0$. Reconstructed charged tracks traversing the central part of the detector typically have 11 silicon hits (3 pixel clusters and 8 strip clusters), and more than 30 TRT hits.

The calorimeter system used to reconstruct jets is placed immediately outside the solenoid. A high granularity lead

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liquid-argon electromagnetic sampling calorimeter, with excellent energy and position resolution, covers the pseudorapidity range $|\eta| < 3.2$ (a barrel covers $|\eta| < 1.475$ and two end-caps cover $1.375 < |\eta| < 3.2$). Two different detector technologies are used for the hadronic calorimetry. The barrel ($|\eta| < 1.0$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are made of steel and scintillator tiles while in the end-caps ($1.5 < |\eta| < 3.2$) copper and liquid-argon are used. Forward copper and tungsten liquid-argon calorimeters provide both electromagnetic and hadronic measurements with coverage of $|\eta| < 4.9$.

The ATLAS detector has a three-level trigger system: Level 1 (L1), Level 2 (L2) and Event Filter (EF). L1 is a hardware trigger system, while L2 and EF are software based. For the measurement described here, the data are collected using the L1 calorimeter-based jet trigger and a system of minimum-bias trigger scintillators (MBTS) [20]. The L1 calorimeter trigger uses coarse detector information to identify areas in the calorimeter with energy deposits above a certain threshold. A simplified jet finding algorithm based on a sliding window of configurable size is used to trigger events. This algorithm uses towers with a granularity of $\Delta\phi \times \Delta\eta = 0.2 \times 0.2$ as inputs. The MBTS consist of 32 scintillator counters that are each 2 cm thick, organized into two disks perpendicular to the beam located at $z = \pm 3.56$ m. This leads to a coverage of $2.09 < |\eta| < 3.84$. The MBTS trigger is configured to require at least one hit above threshold from each side of the detector.

III. DATA AND MONTE CARLO SAMPLES

The analysis uses an integrated luminosity of 0.30 pb^{-1}, measured with an error of 3.4% [21,22], recorded between April and July 2010 with three L1 calorimeter jet triggers, requiring a transverse energy associated to the L1 jet above 5, 10 and 15 GeV, respectively. Because of the increase in instantaneous luminosity during the data taking period, the 5 and 10 GeV triggers were progressively prescaled. In the subsequent data taking periods the prescale factors of low-threshold jet triggers became too prohibitive to extend the analysis to higher integrated luminosity.

To validate the Monte Carlo (MC) simulation of the jet trigger efficiency, a data sample collected with the MBTS trigger is used, whose integrated luminosity corresponds to approximately 1 nb^{-1} after taking into account its prescale factor.

The MC simulated events used for the correction of the signal yield for detector effects are produced with the PYTHIA 6.421 event generator [23]. It implements leading-order (LO) perturbative QCD (pQCD) matrix elements for $2 \to 2$ processes, p_T-ordered parton showers calculated in a leading-logarithmic approximation, an underlying event simulation using multiple-parton interactions, and uses the Lund string model for hadronization. The Martin-Stirling-Thorne-Watt LO proton structure functions [24,25] with the generator tune described in Ref. [26] are used for the generation of the MC sample. The generated samples are passed through a full simulation [27] of the ATLAS detector and trigger based on GEANT4 [28]. Finally, the simulated events are reconstructed and selected using identical procedures as for the data.

The measured $D^{*\pm}$ jet production rates are compared to predictions from different MC generators: PYTHIA, described above, and HERWIG 6 [29], with the AUET1 generator tune described in Ref. [30], which also employs LO pQCD matrix elements, but uses an angle-ordered parton shower model and a cluster hadronization model. The underlying event for the HERWIG 6 samples is generated using the JIMMY [31] package to model multiple-parton interactions. Further comparison of the measurement is performed to the next-to-leading-order (NLO) pQCD calculation implemented in POWHEG [32–35]. The CTEQ 6.6 [36] parametrization is chosen as the parton density function of the proton. In order to compare with data at the particle level, nonperturbative corrections have to be applied. This is done using leading-logarithmic parton shower MC programs: the PYTHIA and HERWIG models introduced above. $D^{*\pm}$ mesons are produced either directly in the fragmentation of charm quarks or via a cascade in the fragmentation of bottom quarks and the subsequent decay of a b hadron. The charm and bottom quark masses are set to 1.5 GeV and 4.75 GeV, respectively. The fraction of charm quarks that fragment to a $D^{*\pm}$ meson, $f(c \to D^{*+})$, is set to 0.224 ± 0.028 [37–41]; the fraction of b hadrons that decay to a final state with a $D^{*\pm}$ meson, $f(b \to D^{*+}X)$, is 0.17 ± 0.02 [42].

IV. EVENT SELECTION

Events are required to have at least one pp primary vertex reconstructed from at least five charged tracks with $p_T > 150$ MeV each. Only vertices lying within ± 10 cm along the beam axis of the nominal interaction point are considered. In events with multiple vertices, the vertex with the largest $\sum p_T^2$ of associated charged tracks is taken as the primary event vertex. For the values of instantaneous luminosity used in this analysis the average number of additional interactions per beam crossing was small, about 0.3.

The anti-k_t algorithm [43] with radius parameter 0.6 is used to reconstruct jets from topological energy clusters [44] assuming that the reconstructed primary event vertex is at the origin of the jet. The clusters in the calorimeter are seeded by calorimeter cells with energy $|E_{\text{cell}}| > 4\sigma$, where σ is the RMS of the cell noise distribution. All directly neighboring cells are added, then neighbors of neighbors are iteratively added for all cells with signals above a secondary threshold $|E_{\text{cell}}| > 2\sigma$. Finally the energy in all further adjacent neighbors is added. Clusters are split or merged based on the position of local minima and maxima. The energies of cells of a cluster are summed to give the cluster energy, and the clusters are treated as massless with energy $E = \sum E_{\text{cell}}$. The baseline calibration for these clusters corrects their energy to the electromagnetic (EM) scale [45–47], which is derived in test-beams, and properly calibrates the energy of particles interacting electromagnetically in the electromagnetic and hadronic calorimeters. Finally, a p_{T} and η dependent jet energy scale (JES) [48,49] is applied to the jets to correct effects of hadronic shower response and detector-material distributions. The JES is determined based on the detector simulation and validated with extensive test beam and collision data studies. The jets used in the measurement are required to have $25 < p_{\text{T}} < 70$ GeV and $|\eta| < 2.5$. Jets that are likely to have arisen from detector noise or cosmic rays are rejected [50].

Candidates for $D^{*\pm}$ mesons inside jets are reconstructed in the decay chain: $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ and its charge conjugate. Two oppositely-charged tracks with $p_{\text{T}} > 1$ GeV are combined to form a $D^0 \to K^-\pi^+$ candidate and a second candidate $\bar{D}^0 \to K^+\pi^-$ with the K and π mass hypotheses swapped. The D^0 ($\bar{D}^0$) candidate whose mass is within 50 MeV of the PDG value [51], corresponding to slightly more than twice the measured mass resolution, is then combined with a third track with $p_{\text{T}} > 0.5$ GeV having the same charge as the pion to form a $D^{*+} \to D^0\pi^+$ ($D^{*-} \to \bar{D}^0\pi^-$) candidate. To reduce the combinatorial background of uncorrelated pairs, the $D^{*\pm}$ mesons are required to have a transverse momentum larger than 7.5 GeV, and the measured D^0 ($\bar{D}^0$) transverse decay length is required to be greater than zero. The transverse decay length is defined as $L_{xy} = \vec{r} \cdot \vec{p}_{\text{T}}/|\vec{p}_{\text{T}}|$, where $\vec{r}$ is the displacement vector pointing to the D^0 ($\bar{D}^0$) decay vertex from the primary vertex in the transverse plane, and the $\vec{p}_{\text{T}}$ is the transverse momentum of the D^0 ($\bar{D}^0$) candidate. The D^0 ($\bar{D}^0$) decay vertex is obtained extrapolating the K and π tracks. The MC simulation predicts that the selection $L_{xy} > 0$ rejects half of the combinatorial background and retains 89% of the signal, consistent with what has been observed in the data.

The reconstructed $D^{*\pm}$ candidates are matched with the reconstructed jets in the event. A jet is considered as a $D^{*\pm}$ jet candidate if the $D^{*\pm}$ direction is in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.6$ centered on the jet axis, the same value as the radius parameter of the anti-k_{t} jet algorithm. The momentum fraction z of the $D^{*\pm}$ jet candidates is required to be larger than 0.3 due to the low reconstruction efficiency and large combinatorial background for $D^{*\pm}$ jets with $z < 0.3$.

The $D^{*\pm}$ jet yield is extracted from the distribution of $\Delta m = m(K^{\mp}\pi^{\pm}\pi^{\pm}) - m(K^{\mp}\pi^{\pm}) - m(\pi^{\pm})$, where $m(K^{\mp}\pi^{\pm}\pi^{\pm})$ is the invariant mass of the $D^{*\pm}$ candidate and $m(K^{\mp}\pi^{\pm})$ is the invariant mass of the D^0 ($\bar{D}^0$) candidate. The signal probability density function (PDF) is modeled as a double Gaussian with equal mean based on MC studies, and the background is characterized by $\Delta m^a e^{b\Delta m}$, where a and b are free parameters in the fit. The $D^{*\pm}$ jet candidate sample is divided into several bins in p_{T} and z of the $D^{*\pm}$ jet. A simultaneous unbinned maximum likelihood fit is then performed. In the fit, the parameters of the signal and background PDFs are constrained to be the same in each p_{T} and z bin, and the fit returns the normalizations of the signal and the background. The assumption of shapes being constant with p_{T} and z has been checked in MC. After applying all the event selection criteria, a total of 4282 ± 93 $D^{*\pm}$ jet signal candidates are obtained, where the error is statistical only. Examples of the Δm distribution for the data are shown in Fig. 1 together with the fit result.

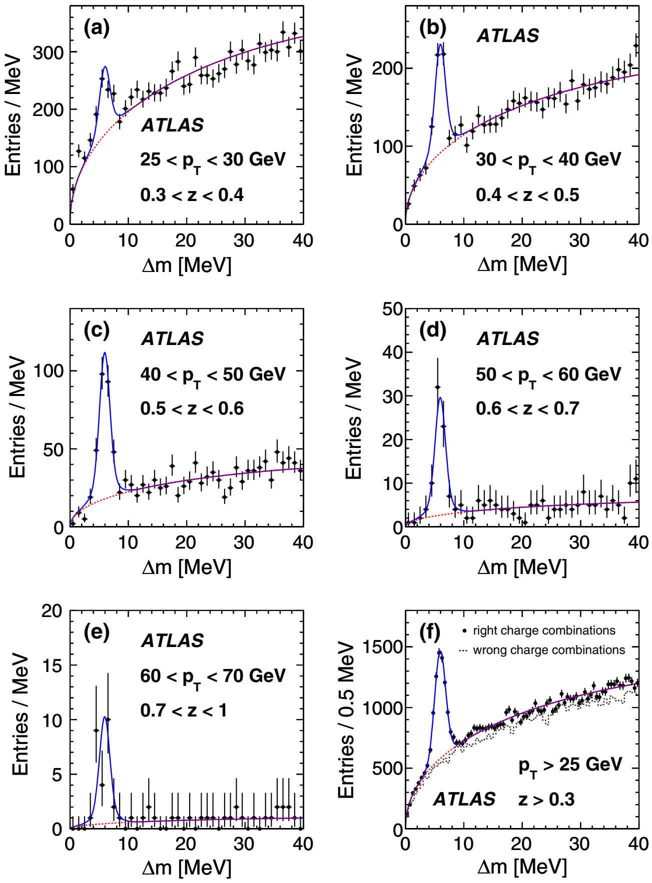

FIG. 1 (color online). Examples of the distributions of the mass difference of the $D^{*+} \to D^0\pi^+$ and its charge conjugate inside jets for different p_{T} and z bins. The solid line is the fit result. The dotted line represents the background component. For comparison, the distribution of the difference between the invariant mass of the wrong sign candidates, $m(K^{\pm}\pi^{\pm}\pi^{\mp}) - m(K^{\pm}\pi^{\pm}) - m(\pi^{\mp})$, is also shown with a dashed line in Figure (f), where identical event selection criteria as the signal reconstruction have been applied except that the two tracks from the D^0 ($\bar{D}^0$) candidates are required to have the same charge. No structure is observed and the distribution of wrong sign candidates can be also well described by the same PDF as the signal candidates with slightly different values of the PDF parameters.

V. UNFOLDING

The signal yield of the reconstructed $D^{*\pm}$ jets is extracted in bins of the jet p_{T} and z. If detector resolution effects are negligible, the $D^{*\pm}$ jet production rate can be calculated as

$$\mathcal{R}\,(p_{\mathrm{T}}, z) = \frac{N^{\mathrm{reco}}_{D^{*\pm}}(p_{\mathrm{T}}, z)/\epsilon_{D^{*\pm}}(p_{\mathrm{T}}, z)}{\mathcal{B}(D^{*\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm})N^{\mathrm{reco}}_{\mathrm{jet}}(p_{\mathrm{T}})/\epsilon_{\mathrm{jet}}(p_{\mathrm{T}})}, \quad (2)$$

where $\mathcal{B}$ is the decay branching fraction, $\epsilon_{D^{*\pm}}$ is the trigger and reconstruction efficiency of $D^{*\pm}$ jets identified by the decay $D^{*\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$, ϵ_{jet} is the trigger and reconstruction efficiency of inclusive jets, $N^{\mathrm{reco}}_{D^{*\pm}}$ and $N^{\mathrm{reco}}_{\mathrm{jet}}$ are the numbers of reconstructed $D^{*\pm}$ and inclusive jets, respectively. MC studies show that for a given $D^{*\pm}$ jet that passes the trigger selection and falls within the kinematic range of the measurement, the probability to reconstruct it offline is between 15% and 45%, depending on the jet p_{T} and z. However, the reconstructed values of the p_{T} and z will be different from the true values at the particle level due to the finite resolution of the jet energy measurement. In order to obtain the true distributions at the particle level from the measured quantities, a Bayesian iterative unfolding algorithm [52] is used to correct for the detector efficiency and bin-to-bin migration due to the detector resolution. The $D^{*\pm}$ jet production rate is subsequently calculated as

$$\mathcal{R}\,(p_{\mathrm{T}}, z) = \frac{N_{D^{*\pm}}(p_{\mathrm{T}}, z)}{\mathcal{B}(D^{*\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm})N_{\mathrm{jet}}(p_{\mathrm{T}})}, \quad (3)$$

where $N_{D^{*\pm}}$ and N_{jet} are the number of the $D^{*\pm}$ and inclusive jets after unfolding, respectively.

The corrections of this algorithm are based on a response matrix that is derived from MC simulated events, which encapsulates the probability for a true $D^{*\pm}$ jet at the particle level with a particular p_{T} and z to be reconstructed in any possible p_{T} and z bin. The MC p_{T} and z distributions of $D^{*\pm}$ jets are reweighted to match the measured distributions, the comparison is shown in Fig. 2. Similar correction procedures are also applied to the reconstructed inclusive jets to obtain the number of jets at the particle level as a function of the jet p_{T}.

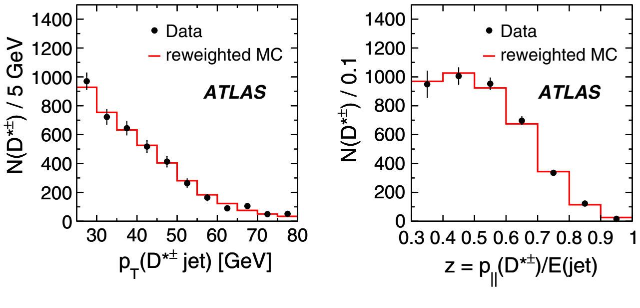

FIG. 2 (color online). Comparison of the p_{T} and z distributions of the $D^{*\pm}$ jets between data and MC. The $D^{*\pm}$ decay products are matched to jets at the particle level by using a geometrical matching with $\Delta R < 0.6$. The MC distributions are then reweighted and subsequently normalized to have the same number of events as the data.

The unfolding algorithm has been validated using MC simulated events and no bias is observed. To evaluate the statistical uncertainties on the unfolded variables, 1000 ensembles of the unfolding sample are generated. For each ensemble, the number of reconstructed jets in each bin is generated randomly according to a Gaussian distribution, where its mean is the number of jets reconstructed in that bin before unfolding, and its width is the corresponding statistical uncertainty. The unfolding is subsequently performed for each ensemble. The deviations of the numbers of jets after unfolding with respect to the nominal results are fitted to a Gaussian distribution. The means of the Gaussian distributions are found to be consistent with zero. The widths of those Gaussian distributions are taken as the statistical uncertainties of the measured numbers of jets after unfolding.

VI. SYSTEMATIC UNCERTAINTIES

The fractional systematic uncertainties of the measured $\mathcal{R}$ in each bin of p_{T} and z are shown in Fig. 3 while the total uncertainties are summarized in Table I. A brief description of the sources of systematic uncertainties in the measurement and how they are estimated is given below.

Trigger efficiency effects largely cancel in the calculation of the ratio $\mathcal{R}$. However, the different flavor composition of $D^{*\pm}$ jets and inclusive jets could cause differences in the trigger efficiencies of the two samples. To study the effect of these possible differences on $\mathcal{R}$, a variable $r = N^{\mathrm{reco}}_{D^{*\pm}}/N^{\mathrm{reco}}_{\mathrm{jet}}$ is defined, where $N^{\mathrm{reco}}_{D^{*\pm}}$ is the number of reconstructed $D^{*\pm}$ jets and $N^{\mathrm{reco}}_{\mathrm{jet}}$ is the number of reconstructed inclusive jets. Subsequently a double ratio ρ is defined as $\rho = r_{\mathrm{jet\ trig}}/r_{\mathrm{MBTS}}$, where $r_{\mathrm{jet\ trig}}$ and r_{MBTS} are the ratio r measured in the data collected by the L1 calorimeter jet trigger and the MBTS trigger, respectively. Since the MBTS trigger makes no jet selection in contrast to the L1 jet triggers, the double ratio ρ gives a good estimate of the size of flavor-dependent trigger efficiency effects. The values of ρ determined in data and MC are found to agree within the statistical uncertainty. Further comparisons between the values of the double ratio ρ measured in data and MC simulation are made as a function of the jet p_{T}, z and η, and no significant difference between data and the MC simulation is observed. As a result, the relative statistical uncertainty (14%) of the measured ρ in the data is taken as the relative uncertainty of the measurement due to potential bias from trigger effects. This large systematic uncertainty is due to the limited size of the data sample from the MBTS trigger, which was heavily prescaled during data taking.

To estimate the systematic uncertainties due to track reconstruction efficiencies, which only affect the $D^{*\pm}$ jets, a weight factor w_{trks} is assigned to each reconstructed $D^{*\pm}$ jet candidate in the MC simulation:

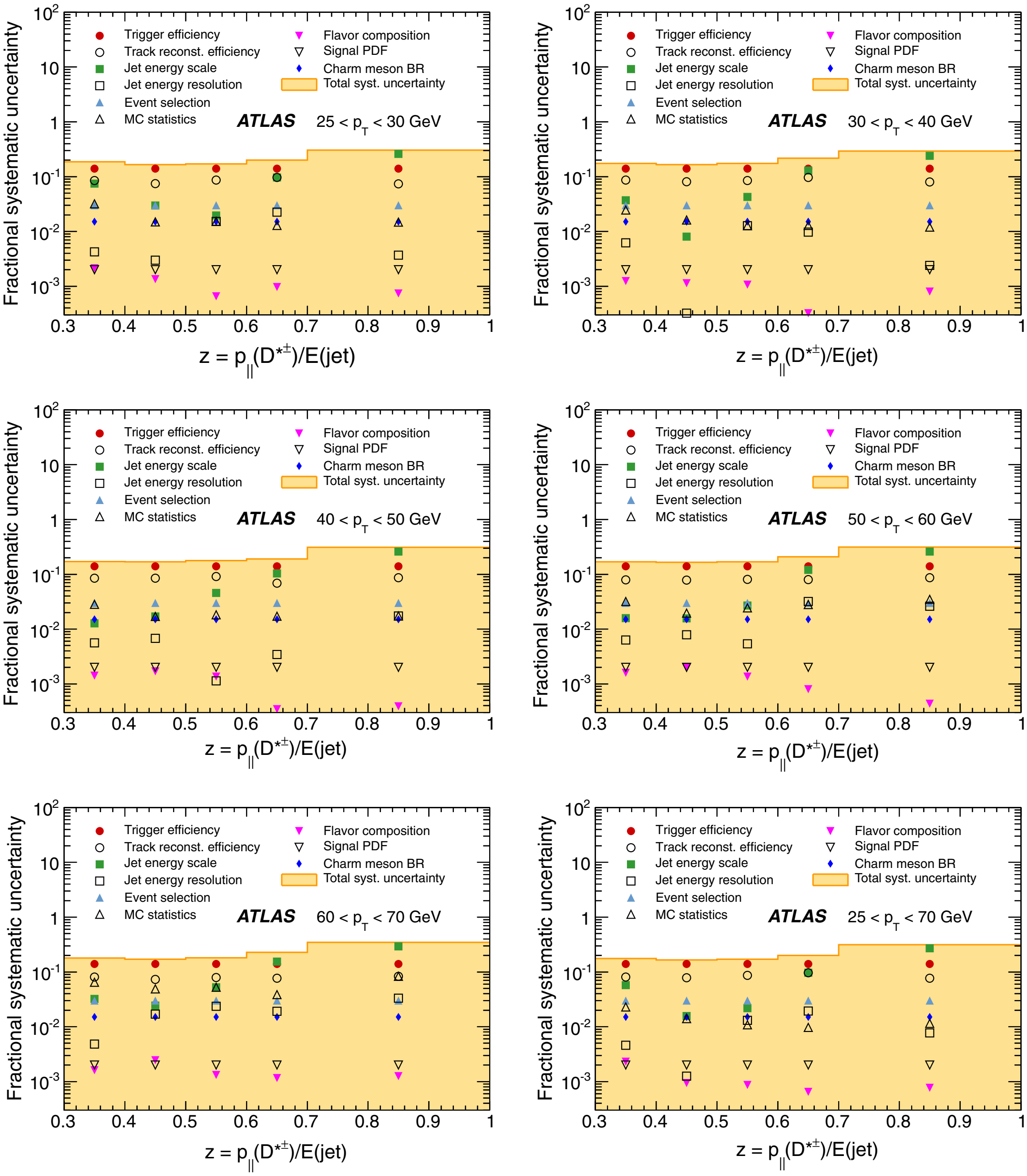

FIG. 3 (color online). Relative systematic uncertainties of the measured $D^{*\pm}$ jet production rate $\mathcal{R}(p_T, z)$ in different jet p_T and z bins. The values corresponding to the integrated p_T range are shown in the bottom right Figure.

$$w_{\text{trks}} = (1 + s_K) \times (1 + s_{\pi_1}) \times (1 + s_{\pi_2}), \tag{4}$$

where s_K, s_{π_1} and s_{π_2} are $\pm 1\sigma$ of the uncertainties on the track reconstruction efficiencies for the $D^{*\pm}$ decay daughters. These uncertainties are derived from data as a function of track p_T and η [53]. The response matrix for $D^{*\pm}$ jets is recalculated using values of w_{trks} with the individual factors: s_K, s_{π_1} and s_{π_2}, all positive or all negative and new values of $\mathcal{R}$ are derived. The deviations of the newly measured $D^{*\pm}$ production rates in each p_T and z bin with respect to their nominal measurement values are taken as the corresponding systematic uncertainties. The overall relative systematic uncertainty on $\mathcal{R}$ integrated over p_T and z due to the track reconstruction efficiency is 8%.

The systematic uncertainty on the jet energy scale is evaluated in Ref. [44]. The maximum JES uncertainty in the central region is approximately 6.5% for jets with $20 < p_T < 70$ GeV. The uncertainties of jets in the end-cap regions are slightly larger because additional uncertainties due to the intercalibration are added. This brings the uncertainties in the end-cap region up to approximately 9% for jets with $20 < p_T < 70$ GeV. To estimate the corresponding systematic uncertainties of the measured $D^{*\pm}$ jet production rate, the values of the reconstructed p_T and z of the $D^{*\pm}$ jets and p_T of the inclusive jets are varied

TABLE I. $D^{*\pm}$ jet production rate $\mathcal{R}$ calculated in each p_T and z bin, and in the full p_T range. The first uncertainty shown here is statistical and the second is systematic.

	$\mathcal{R}(p_T, z)$ $[10^{-2}]$				
Jet p_T [GeV]	$0.3 < z < 0.4$	$0.4 < z < 0.5$	$0.5 < z < 0.6$	$0.6 < z < 0.7$	$0.7 < z < 1.0$
25–30	$0.94 \pm 0.11 \pm 0.18$	$0.67 \pm 0.05 \pm 0.11$	$0.46 \pm 0.03 \pm 0.08$	$0.31 \pm 0.01 \pm 0.06$	$0.27 \pm 0.01 \pm 0.08$
30–40	$0.81 \pm 0.09 \pm 0.15$	$0.62 \pm 0.04 \pm 0.10$	$0.47 \pm 0.02 \pm 0.08$	$0.31 \pm 0.01 \pm 0.07$	$0.25 \pm 0.01 \pm 0.07$
40–50	$0.71 \pm 0.09 \pm 0.13$	$0.59 \pm 0.04 \pm 0.10$	$0.44 \pm 0.03 \pm 0.08$	$0.29 \pm 0.02 \pm 0.06$	$0.23 \pm 0.02 \pm 0.07$
50–60	$0.63 \pm 0.09 \pm 0.11$	$0.51 \pm 0.05 \pm 0.09$	$0.37 \pm 0.03 \pm 0.06$	$0.25 \pm 0.02 \pm 0.05$	$0.23 \pm 0.02 \pm 0.07$
60–70	$0.62 \pm 0.16 \pm 0.12$	$0.41 \pm 0.08 \pm 0.07$	$0.38 \pm 0.07 \pm 0.07$	$0.26 \pm 0.05 \pm 0.06$	$0.24 \pm 0.05 \pm 0.08$
25–70	$0.87 \pm 0.08 \pm 0.16$	$0.64 \pm 0.03 \pm 0.11$	$0.46 \pm 0.02 \pm 0.08$	$0.31 \pm 0.01 \pm 0.06$	$0.26 \pm 0.01 \pm 0.08$

coherently in the MC according to the JES uncertainties when calculating their response matrices. Measurements of the $D^{*\pm}$ jet production rates are then performed with the new response matrices. The deviations of the measured $D^{*\pm}$ jet production rate in each p_T and z bin with respect to their nominal values are taken as the corresponding systematic uncertainties, which gives a relative systematic uncertainty of 3% in the measurement of $\mathcal{R}$ integrated over p_T and z.

Using MC simulated events, the JES of $D^{*\pm}$ jets and inclusive jets are found to be slightly different in the low p_T region but are consistent with each other in the high p_T region. Varying the JES by this full difference, the corresponding systematic uncertainty on the measured $\mathcal{R}$ is estimated to be less than 1%.

The resolution of the jet energy measurement has been verified to be in agreement within 14% between data and MC simulation for jets in the pseudorapidity range $|\eta| < 2.8$ using control samples [54]. To estimate the corresponding effects on the measurement, the nominal jet energy resolution in the MC simulation is artificially degraded to account for this uncertainty for both the $D^{*\pm}$ and inclusive jets. The $D^{*\pm}$ jet production rate measurements are then repeated using the newly calculated response matrices. The deviations of the measured $D^{*\pm}$ production rate in each p_T and z bin with respect to their nominal values are taken as the corresponding systematic uncertainties, and are found to be below 1%.

In the analysis, an event selection of $L_{xy} > 0$ is applied. The $D^{*\pm}$ jets can be directly produced in pp interactions (c jets) or from b-hadron decays (b jets). The efficiency of the $L_{xy} > 0$ cut depends on the fractions of c and b jets since they have different L_{xy} distributions. The relative efficiency of the requirement of $L_{xy} > 0$ is estimated by comparing the $D^{*\pm}$ jet signal yields with and without such a selection. Its value in data is measured to be 0.87 ± 0.03, consistent with the MC predicted value of 0.890 ± 0.003, where the uncertainties are statistical only. As a result, a 3% relative systematic uncertainty on the measured $\mathcal{R}$ is assigned independent of the jet p_T and z.

The measurement depends on the decay branching fraction of $D^{*\pm}$ [51]. The uncertainties of the decay branching fractions give a 1.5% relative systematic uncertainty of the measured $\mathcal{R}$, independently of the jet p_T and η.

Other systematic sources considered in the measurement include the finite size of the MC sample, and the signal and background PDFs. All of them are found to have negligible effects on the measurement ($\sim 1\%$). The total systematic uncertainty is calculated by summing the individual systematic uncertainties in quadrature.

VII. RESULTS AND DISCUSSION

The measured $D^{*\pm}$ jet production rates $\mathcal{R}$ in each bin of p_T and z are listed in Table I and shown in Fig. 4. Integrating over all the p_T and z bins, the production rate is found to be

$$\mathcal{R} = 0.025 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.}), \qquad (5)$$

for $D^{*\pm}$ jets with transverse momentum between 25 and 70 GeV, in the range $|\eta| < 2.5$, and with momentum fraction $0.3 < z < 1$.

Comparisons between the measurement and predictions from various MC calculations are shown in Fig. 4 as a function of z for different p_T ranges. The corresponding c and b jet fractions predicted by MC are also shown in Fig. 5. The predicted values of $\mathcal{R}$ by PYTHIA and POWHEG +PYTHIA are very similar, which is also the case when comparing calculations from HERWIG and POWHEG +HERWIG, as expected. Since $\mathcal{R}$ is defined as the ratio between the number of $D^{*\pm}$ jets and inclusive jets, the changes of total jet cross sections and p_T distributions between LO and NLO QCD calculations largely cancel. The values of $\mathcal{R}$ predicted by MC calculations are lower than the data by a factor 2 to 3 in the bins with lowest z, and this is especially significant at low p_T. The predictions are consistent with the data for $z > 0.7$ at all p_T. Integrating over all the p_T and z bins, the production rate $\mathcal{R}$ is estimated to be 0.0133 ± 0.0008 by POWHEG+PYTHIA, which is just about half of the measured value.

The various MC predictions share the feature that the z distribution shape is essentially independent of p_T. In the data, there is a general trend that $\mathcal{R}(p_T, z)$ falls with p_T for a fixed z bin, as is visible in Table I, in qualitative disagreement with the MC prediction.

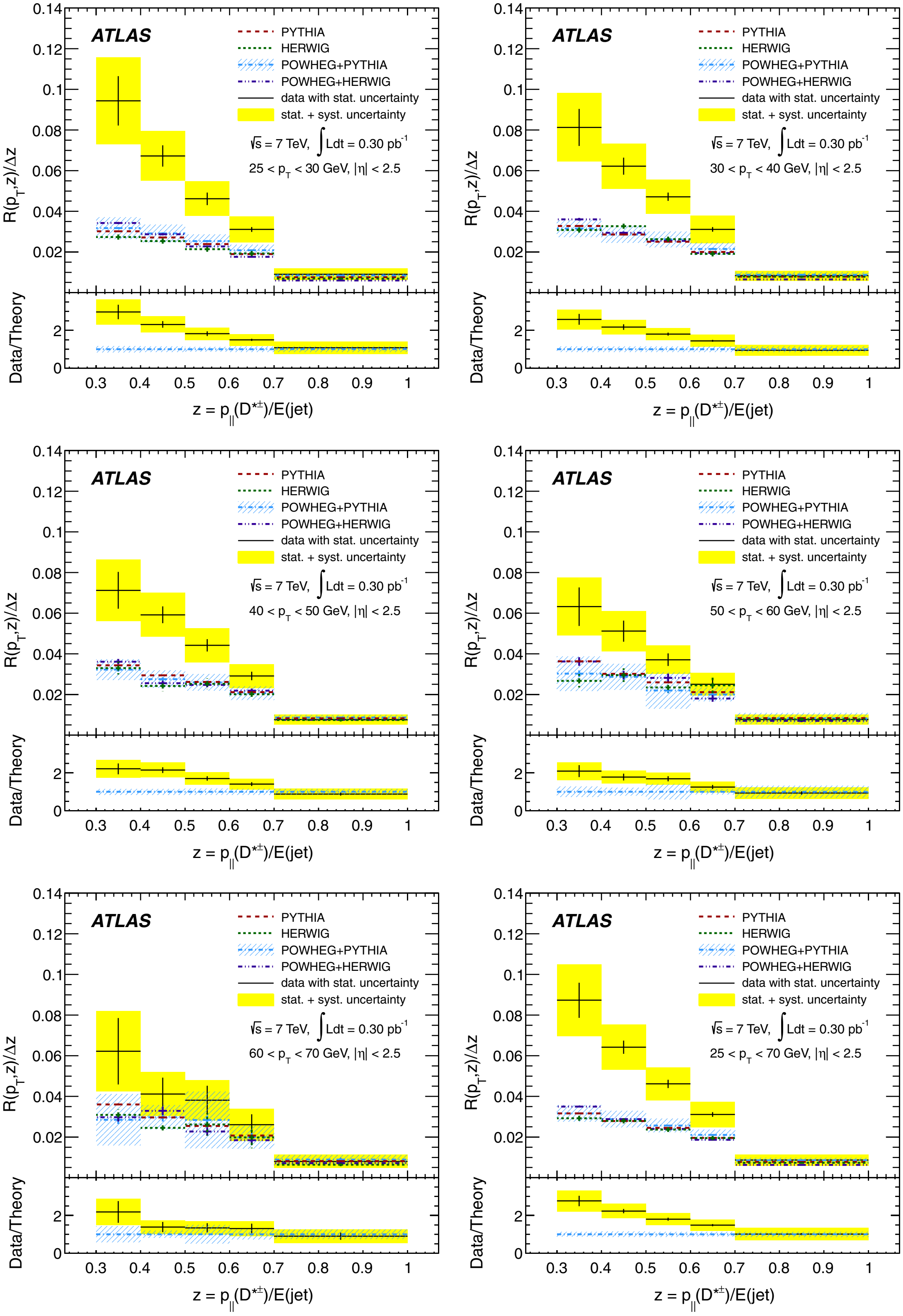

FIG. 4 (color online). Comparison of the $D^{*\pm}$ production rate $\mathcal{R}(p_T, z)/\Delta z$ in different jet p_T and z bins between the measurement and the MC predictions of PYTHIA, HERWIG, POWHEG+PYTHIA and POWHEG+HERWIG. The values corresponding to the integrated p_T range are shown in the bottom right Figure. The insets show the ratio of the measurement to the POWHEG+PYTHIA prediction.

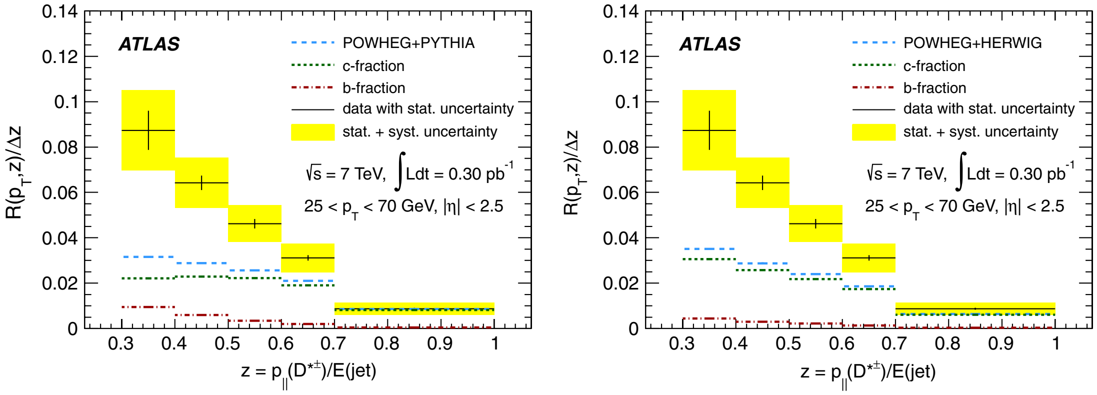

FIG. 5 (color online). Comparison of the $D^{*\pm}$ production rate $\mathcal{R}(p_T, z)/\Delta z$ in different jet p_T and z bins between the measurement and the MC predictions of POWHEG+PYTHIA (left) and POWHEG+HERWIG (right). The c- and b fractions predicted by MC are also shown. Only the central values of the MC predictions are shown here.

To further understand the discrepancies between the measurement and the MC predictions, studies of the effects of various sources of systematic uncertainty in the MC predictions are carried out using the POWHEG+PYTHIA MC program. The uncertainties on the calculated $\mathcal{R}$ are evaluated by varying independently the renormalization and factorization scales between 0.5 and 2 times the default scale. The largest shift of $\mathcal{R}$ with respect to the default calculation is taken as the corresponding systematic error due to the uncertainties of the renormalization and factorization scales. Similarly the possible systematic uncertainties associated with the charm and bottom quark masses are estimated by varying them independently within ±0.2 GeV and ±0.25 GeV, respectively. The systematic uncertainties due to $f(c \rightarrow D^{*+})$ and $f(b \rightarrow D^{*+}X)$ are evaluated by changing their values according to their measured uncertainties [37–42]. Contributions from other sources, such as the value of the strong coupling constant and the uncertainty of the parton density function of the proton are much smaller and they are not taken into account. The total systematic uncertainty of the MC calculations is computed by summing each individual systematic uncertainty in quadrature. As shown in Fig. 4, although the predicted values of $\mathcal{R}$ have sizable systematic uncertainties in each bin, especially for large p_T and z, the systematic errors become much smaller (less than 10%) when integrating over the p_T bins. The change of the calculated $\mathcal{R}$ in each bin is dominated by the variation of p_T distributions of the $D^{*\pm}$ jets and of the inclusive jets when different heavy quark masses and renormalization and factorization scales are used. Nevertheless, it is clear that the systematic uncertainties that are considered in the MC calculation of $\mathcal{R}$ do not explain the discrepancies between data and MC predictions.

VIII. CONCLUSIONS

This paper reports a first measurement of $D^{*\pm}$ meson production in jets in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV at the LHC using 0.30 pb^{-1} of ATLAS data. The production rate is found to be $N(D^{*\pm})/N(\text{jet}) = 0.025 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.})$ for jets with transverse momentum between 25 and 70 GeV in the range $|\eta| < 2.5$, and with $D^{*\pm}$ momentum fraction $0.3 < z < 1$. Large discrepancies are observed between data and MC predictions for low z, decreasing a little at higher p_T. The $D^{*\pm}$ z distributions in data differ from the predictions of all the generators considered, PYTHIA, HERWIG and POWHEG, both in overall normalization and shape. The shapes of the z distributions arising from c and b jets are expected to be different. However, the differences observed between the data and MC predictions cannot be explained by varying the mixture of c and b jets in the MC. Contrary to the MC predictions, the measured $\mathcal{R}$ values listed in Table I show a small, though monotonic decrease as a function of the jet p_T in all the z bins. These observations indicate that the production of c jets (b jets) or their fragmentation into $D^{*\pm}$ mesons is not well modeled in current MC generators. These results show the need of further QCD refinements to improve the description of high transverse momentum D-meson production in this new energy range of hadron collisions.

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T. N. Addy,[55] J. Adelman,[174] M. Aderholz,[98] S. Adomeit,[97] P. Adragna,[74] T. Adye,[128] S. Aefsky,[22]

J. A. Aguilar-Saavedra,[123b,b] M. Aharrouche,[80] S. P. Ahlen,[21] F. Ahles,[47] A. Ahmad,[147] M. Ahsan,[40]
G. Aielli,[132a,132b] T. Akdogan,[18a] T. P. A. Åkesson,[78] G. Akimoto,[154] A. V. Akimov,[93] A. Akiyama,[66] M. S. Alam,[1]
M. A. Alam,[75] J. Albert,[168] S. Albrand,[54] M. Aleksa,[29] I. N. Aleksandrov,[64] F. Alessandria,[88a] C. Alexa,[25a]
G. Alexander,[152] G. Alexandre,[48] T. Alexopoulos,[9] M. Alhroob,[20] M. Aliev,[15] G. Alimonti,[88a] J. Alison,[119]
M. Aliyev,[10] P. P. Allport,[72] S. E. Allwood-Spiers,[52] J. Almond,[81] A. Aloisio,[101a,101b] R. Alon,[170] A. Alonso,[78]
B. Alvarez Gonzalez,[87] M. G. Alviggi,[101a,101b] K. Amako,[65] P. Amaral,[29] C. Amelung,[22] V. V. Ammosov,[127]
A. Amorim,[123a,c] G. Amorós,[166] N. Amram,[152] C. Anastopoulos,[29] L. S. Ancu,[16] N. Andari,[114] T. Andeen,[34]
C. F. Anders,[20] G. Anders,[57a] K. J. Anderson,[30] A. Andreazza,[88a,88b] V. Andrei,[57a] M-L. Andrieux,[54]
X. S. Anduaga,[69] A. Angerami,[34] F. Anghinolfi,[29] N. Anjos,[123a] A. Annovi,[46] A. Antonaki,[8] M. Antonelli,[46]
A. Antonov,[95] J. Antos,[143b] F. Anulli,[131a] S. Aoun,[82] L. Aperio Bella,[4] R. Apolle,[117,d] G. Arabidze,[87]
I. Aracena,[142] Y. Arai,[65] A. T. H. Arce,[44] J. P. Archambault,[28] S. Arfaoui,[82] J-F. Arguin,[14] E. Arik,[18a,a] M. Arik,[18a]
A. J. Armbruster,[86] O. Arnaez,[80] A. Artamonov,[94] G. Artoni,[131a,131b] D. Arutinov,[20] S. Asai,[154]
R. Asfandiyarov,[171] S. Ask,[27] B. Åsman,[145a,145b] L. Asquith,[5] K. Assamagan,[24] A. Astbury,[168]
A. Astvatsatourov,[51] G. Atoian,[174] B. Aubert,[4] E. Auge,[114] K. Augsten,[126] M. Aurousseau,[144a] G. Avolio,[162]
R. Avramidou,[9] D. Axen,[167] C. Ay,[53] G. Azuelos,[92,e] Y. Azuma,[154] M. A. Baak,[29] G. Baccaglioni,[88a]
C. Bacci,[133a,133b] A. M. Bach,[14] H. Bachacou,[135] K. Bachas,[29] G. Bachy,[29] M. Backes,[48] M. Backhaus,[20]
E. Badescu,[25a] P. Bagnaia,[131a,131b] S. Bahinipati,[2] Y. Bai,[32a] D. C. Bailey,[157] T. Bain,[157] J. T. Baines,[128]
O. K. Baker,[174] M. D. Baker,[24] S. Baker,[76] E. Banas,[38] P. Banerjee,[92] Sw. Banerjee,[171] D. Banfi,[29] A. Bangert,[149]
V. Bansal,[168] H. S. Bansil,[17] L. Barak,[170] S. P. Baranov,[93] A. Barashkou,[64] A. Barbaro Galtieri,[14] T. Barber,[27]
E. L. Barberio,[85] D. Barberis,[49a,49b] M. Barbero,[20] D. Y. Bardin,[64] T. Barillari,[98] M. Barisonzi,[173] T. Barklow,[142]
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J. R. Batley,[27] A. Battaglia,[16] M. Battistin,[29] G. Battistoni,[88a] F. Bauer,[135] H. S. Bawa,[142,f] B. Beare,[157] T. Beau,[77]
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A. J. Beddall,[18c] A. Beddall,[18c] S. Bedikian,[174] V. A. Bednyakov,[64] C. P. Bee,[82] M. Begel,[24] S. Behar Harpaz,[151]
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G. J. Bobbink,[104] V. B. Bobrovnikov,[106] S. S. Bocchetta,[78] A. Bocci,[44] C. R. Boddy,[117] M. Boehler,[41] J. Boek,[173]
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G. Boorman,[75] C. N. Booth,[138] S. Bordoni,[77] C. Borer,[16] A. Borisov,[127] G. Borissov,[70] I. Borjanovic,[12a]
S. Borroni,[86] K. Bos,[104] D. Boscherini,[19a] M. Bosman,[11] H. Boterenbrood,[104] D. Botterill,[128] J. Bouchami,[92]
J. Boudreau,[122] E. V. Bouhova-Thacker,[70] C. Bourdarios,[114] N. Bousson,[82] A. Boveia,[30] J. Boyd,[29] I. R. Boyko,[64]
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J. Bremer,[29] R. Brenner,[165] S. Bressler,[151] D. Breton,[114] D. Britton,[52] F. M. Brochu,[27] I. Brock,[20] R. Brock,[87]
T. J. Brodbeck,[70] E. Brodet,[152] F. Broggi,[88a] C. Bromberg,[87] G. Brooijmans,[34] W. K. Brooks,[31b] G. Brown,[81]
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R. M. Buckingham,[117] A. G. Buckley,[45] S. I. Buda,[25a] I. A. Budagov,[64] B. Budick,[107] V. Büscher,[80] L. Bugge,[116]
D. Buira-Clark,[117] O. Bulekov,[95] M. Bunse,[42] T. Buran,[116] H. Burckhart,[29] S. Burdin,[72] T. Burgess,[13] S. Burke,[128]
E. Busato,[33] P. Bussey,[52] C. P. Buszello,[165] F. Butin,[29] B. Butler,[142] J. M. Butler,[21] C. M. Buttar,[52]
J. M. Butterworth,[76] W. Buttinger,[27] S. Cabrera Urbán,[166] D. Caforio,[19a,19b] O. Cakir,[3a] P. Calafiura,[14]

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Cavalleri,[77] D. Cavalli,[88a] M. Cavalli-Sforza,[11] V. Cavasinni,[121a,121b] F. Ceradini,[133a,133b] A.S. Cerqueira,[23b] A. Cerri,[29] L. Cerrito,[74] F. Cerutti,[46] S.A. Cetin,[18b] F. Cevenini,[101a,101b] A. Chafaq,[134a] D. Chakraborty,[105] K. Chan,[2] B. Chapleau,[84] J.D. Chapman,[27] J.W. Chapman,[86] E. Chareyre,[77] D.G. Charlton,[17] V. Chavda,[81] C.A. Chavez Barajas,[29] S. Cheatham,[84] S. Chekanov,[5] S.V. Chekulaev,[158a] G.A. Chelkov,[64] M.A. Chelstowska,[103] C. Chen,[63] H. Chen,[24] S. Chen,[32c] T. Chen,[32c] X. Chen,[171] S. Cheng,[32a] A. Cheplakov,[64] V.F. Chepurnov,[64] R. Cherkaoui El Moursli,[134e] V. Chernyatin,[24] E. Cheu,[6] S.L. Cheung,[157] L. Chevalier,[135] G. Chiefari,[101a,101b] L. Chikovani,[50a] J.T. Childers,[57a] A. Chilingarov,[70] G. Chiodini,[71a] M.V. Chizhov,[64] G. Choudalakis,[30] S. Chouridou,[136] I.A. Christidi,[76] A. Christov,[47] D. Chromek-Burckhart,[29] M.L. Chu,[150] J. Chudoba,[124] G. Ciapetti,[131a,131b] K. Ciba,[37] A.K. Ciftci,[3a] R. Ciftci,[3a] D. Cinca,[33] V. Cindro,[73] M.D. Ciobotaru,[162] C. Ciocca,[19a] A. Ciocio,[14] M. Cirilli,[86] M. Ciubancan,[25a] A. Clark,[48] P.J. Clark,[45] W. Cleland,[122] J.C. Clemens,[82] B. Clement,[54] C. Clement,[145a,145b] R.W. Clifft,[128] Y. Coadou,[82] M. Cobal,[163a,163c] A. Coccaro,[49a,49b] J. Cochran,[63] P. Coe,[117] J.G. Cogan,[142] J. Coggeshall,[164] E. Cogneras,[176] C.D. Cojocaru,[28] J. Colas,[4] A.P. Colijn,[104] C. Collard,[114] N.J. Collins,[17] C. Collins-Tooth,[52] J. Collot,[54] G. Colon,[83] P. Conde Muiño,[123a] E. Coniavitis,[117] M.C. Conidi,[11] M. Consonni,[103] V. Consorti,[47] S. Constantinescu,[25a] C. Conta,[118a,118b] F. Conventi,[101a,i] J. Cook,[29] M. Cooke,[14] B.D. Cooper,[76] A.M. Cooper-Sarkar,[117] K. Copic,[14] T. Cornelissen,[173] M. Corradi,[19a] F. Corriveau,[84,j] A. Cortes-Gonzalez,[164] G. Cortiana,[98] G. Costa,[88a] M.J. Costa,[166] D. Costanzo,[138] T. Costin,[30] D. Côté,[29] L. Courneyea,[168] G. Cowan,[75] C. Cowden,[27] B.E. Cox,[81] K. Cranmer,[107] F. Crescioli,[121a,121b] M. Cristinziani,[20] G. Crosetti,[36a,36b] R. Crupi,[71a,71b] S. Crépé-Renaudin,[54] C.-M. Cuciuc,[25a] C. Cuenca Almenar,[174] T. Cuhadar Donszelmann,[138] M. Curatolo,[46] C.J. Curtis,[17] P. Cwetanski,[60] H. Czirr,[140] Z. Czyczula,[174] S. D'Auria,[52] M. D'Onofrio,[72] A. D'Orazio,[131a,131b] P.V.M. Da Silva,[23a] C. Da Via,[81] W. Dabrowski,[37] T. Dai,[86] C. Dallapiccola,[83] M. Dam,[35] M. Dameri,[49a,49b] D.S. Damiani,[136] H.O. Danielsson,[29] D. Dannheim,[98] V. Dao,[48] G. Darbo,[49a] G.L. Darlea,[25b] C. Daum,[104] W. Davey,[20] T. Davidek,[125] N. Davidson,[85] R. Davidson,[70] E. Davies,[117,d] M. Davies,[92] A.R. Davison,[76] Y. Davygora,[57a] E. Dawe,[141] I. Dawson,[138] J.W. Dawson,[5,a] R.K. Daya,[39] K. De,[7] R. de Asmundis,[101a] S. De Castro,[19a,19b] P.E. De Castro Faria Salgado,[24] S. De Cecco,[77] J. de Graat,[97] N. De Groot,[103] P. de Jong,[104] C. De La Taille,[114] H. De la Torre,[79] B. De Lotto,[163a,163c] L. de Mora,[70] L. De Nooij,[104] D. De Pedis,[131a] A. De Salvo,[131a] U. De Sanctis,[163a,163c] A. De Santo,[148] J.B. De Vivie De Regie,[114] S. Dean,[76] R. Debbe,[24] C. Debenedetti,[45] D.V. Dedovich,[64] J. Degenhardt,[119] M. Dehchar,[117] C. Del Papa,[163a,163c] J. Del Peso,[79] T. Del Prete,[121a,121b] T. Delemontex,[54] M. Deliyergiyev,[73] A. Dell'Acqua,[29] L. Dell'Asta,[21] M. Della Pietra,[101a,i] D. della Volpe,[101a,101b] M. Delmastro,[29] N. Delruelle,[29] P.A. Delsart,[54] C. Deluca,[147] S. Demers,[174] M. Demichev,[64] B. Demirkoz,[11,k] J. Deng,[162] S.P. Denisov,[127] D. Derendarz,[38] J.E. Derkaoui,[134d] F. Derue,[77] P. Dervan,[72] K. Desch,[20] E. Devetak,[147] P.O. Deviveiros,[157] A. Dewhurst,[128] B. DeWilde,[147] S. Dhaliwal,[157] R. Dhullipudi,[24,l] A. Di Ciaccio,[132a,132b] L. Di Ciaccio,[4] A. Di Girolamo,[29] B. Di Girolamo,[29] S. Di Luise,[133a,133b] A. Di Mattia,[171] B. Di Micco,[29] R. Di Nardo,[46] A. Di Simone,[132a,132b] R. Di Sipio,[19a,19b] M.A. Diaz,[31a] F. Diblen,[18c] E.B. Diehl,[86] J. Dietrich,[41] T.A. Dietzsch,[57a] S. Diglio,[85] K. Dindar Yagci,[39] J. Dingfelder,[20] C. Dionisi,[131a,131b] P. Dita,[25a] S. Dita,[25a] F. Dittus,[29] F. Djama,[82] T. Djobava,[50b] M.A.B. do Vale,[23a] A. Do Valle Wemans,[123a] T.K.O. Doan,[4] M. Dobbs,[84] R. Dobinson,[29,a] D. Dobos,[29] E. Dobson,[29] M. Dobson,[162] J. Dodd,[34] C. Doglioni,[117] T. Doherty,[52] Y. Doi,[65,a] J. Dolejsi,[125] I. Dolenc,[73] Z. Dolezal,[125] B.A. Dolgoshein,[95,a] T. Dohmae,[154] M. Donadelli,[23d] M. Donega,[119] J. Donini,[54] J. Dopke,[29] A. Doria,[101a] A. Dos Anjos,[171] M. Dosil,[11] A. Dotti,[121a,121b] M.T. Dova,[69] J.D. Dowell,[17] A.D. Doxiadis,[104] A.T. Doyle,[52] Z. Drasal,[125] J. Drees,[173] N. Dressnandt,[119] H. Drevermann,[29] C. Driouichi,[35] M. Dris,[9] J. Dubbert,[98] S. Dube,[14] E. Duchovni,[170] G. Duckeck,[97] A. Dudarev,[29] F. Dudziak,[63] M. Dührssen,[29] I.P. Duerdoth,[81] L. Duflot,[114] M-A. Dufour,[84] M. Dunford,[29] H. Duran Yildiz,[3b] R. Duxfield,[138] M. Dwuznik,[37]

F. Dydak,[29] M. Düren,[51] W. L. Ebenstein,[44] J. Ebke,[97] S. Eckweiler,[80] K. Edmonds,[80] C. A. Edwards,[75]
N. C. Edwards,[52] W. Ehrenfeld,[41] T. Ehrich,[98] T. Eifert,[29] G. Eigen,[13] K. Einsweiler,[14] E. Eisenhandler,[74]
T. Ekelof,[165] M. El Kacimi,[134c] M. Ellert,[165] S. Elles,[4] F. Ellinghaus,[80] K. Ellis,[74] N. Ellis,[29] J. Elmsheuser,[97]
M. Elsing,[29] D. Emeliyanov,[128] R. Engelmann,[147] A. Engl,[97] B. Epp,[61] A. Eppig,[86] J. Erdmann,[53] A. Ereditato,[16]
D. Eriksson,[145a] J. Ernst,[1] M. Ernst,[24] J. Ernwein,[135] D. Errede,[164] S. Errede,[164] E. Ertel,[80] M. Escalier,[114]
C. Escobar,[122] X. Espinal Curull,[11] B. Esposito,[46] F. Etienne,[82] A. I. Etienvre,[135] E. Etzion,[152] D. Evangelakou,[53]
H. Evans,[60] L. Fabbri,[19a,19b] C. Fabre,[29] R. M. Fakhrutdinov,[127] S. Falciano,[131a] Y. Fang,[171] M. Fanti,[88a,88b]
A. Farbin,[7] A. Farilla,[133a] J. Farley,[147] T. Farooque,[157] S. M. Farrington,[117] P. Farthouat,[29] P. Fassnacht,[29]
D. Fassouliotis,[8] B. Fatholahzadeh,[157] A. Favareto,[88a,88b] L. Fayard,[114] S. Fazio,[36a,36b] R. Febbraro,[33]
P. Federic,[143a] O. L. Fedin,[120] W. Fedorko,[87] M. Fehling-Kaschek,[47] L. Feligioni,[82] C. Feng,[32d] E. J. Feng,[30]
A. B. Fenyuk,[127] J. Ferencei,[143b] J. Ferland,[92] W. Fernando,[108] S. Ferrag,[52] J. Ferrando,[52] V. Ferrara,[41]
A. Ferrari,[165] P. Ferrari,[104] R. Ferrari,[118a] A. Ferrer,[166] M. L. Ferrer,[46] D. Ferrere,[48] C. Ferretti,[86]
A. Ferretto Parodi,[49a,49b] M. Fiascaris,[30] F. Fiedler,[80] A. Filipčič,[73] A. Filippas,[9] F. Filthaut,[103]
M. Fincke-Keeler,[168] M. C. N. Fiolhais,[123a,h] L. Fiorini,[166] A. Firan,[39] G. Fischer,[41] P. Fischer,[20] M. J. Fisher,[108]
M. Flechl,[47] I. Fleck,[140] J. Fleckner,[80] P. Fleischmann,[172] S. Fleischmann,[173] T. Flick,[173] L. R. Flores Castillo,[171]
M. J. Flowerdew,[98] M. Fokitis,[9] T. Fonseca Martin,[16] D. A. Forbush,[137] A. Formica,[135] A. Forti,[81] D. Fortin,[158a]
J. M. Foster,[81] D. Fournier,[114] A. Foussat,[29] A. J. Fowler,[44] K. Fowler,[136] H. Fox,[70] P. Francavilla,[121a,121b]
S. Franchino,[118a,118b] D. Francis,[29] T. Frank,[170] M. Franklin,[56] S. Franz,[29] M. Fraternali,[118a,118b] S. Fratina,[119]
S. T. French,[27] F. Friedrich,[43] R. Froeschl,[29] D. Froidevaux,[29] J. A. Frost,[27] C. Fukunaga,[155]
E. Fullana Torregrosa,[29] J. Fuster,[166] C. Gabaldon,[29] O. Gabizon,[170] T. Gadfort,[24] S. Gadomski,[48]
G. Gagliardi,[49a,49b] P. Gagnon,[60] C. Galea,[97] E. J. Gallas,[117] V. Gallo,[16] B. J. Gallop,[128] P. Gallus,[124] K. K. Gan,[108]
Y. S. Gao,[142,f] V. A. Gapienko,[127] A. Gaponenko,[14] F. Garberson,[174] M. Garcia-Sciveres,[14] C. García,[166]
J. E. García Navarro,[48] R. W. Gardner,[30] N. Garelli,[29] H. Garitaonandia,[104] V. Garonne,[29] J. Garvey,[17] C. Gatti,[46]
G. Gaudio,[118a] O. Gaumer,[48] B. Gaur,[140] L. Gauthier,[135] I. L. Gavrilenko,[93] C. Gay,[167] G. Gaycken,[20]
J-C. Gayde,[29] E. N. Gazis,[9] P. Ge,[32d] C. N. P. Gee,[128] D. A. A. Geerts,[104] Ch. Geich-Gimbel,[20]
K. Gellerstedt,[145a,145b] C. Gemme,[49a] A. Gemmell,[52] M. H. Genest,[97] S. Gentile,[131a,131b] M. George,[53]
S. George,[75] P. Gerlach,[173] A. Gershon,[152] C. Geweniger,[57a] H. Ghazlane,[134b] P. Ghez,[4] N. Ghodbane,[33]
B. Giacobbe,[19a] S. Giagu,[131a,131b] V. Giakoumopoulou,[8] V. Giangiobbe,[121a,121b] F. Gianotti,[29] B. Gibbard,[24]
A. Gibson,[157] S. M. Gibson,[29] L. M. Gilbert,[117] V. Gilewsky,[90] D. Gillberg,[28] A. R. Gillman,[128] D. M. Gingrich,[2,e]
J. Ginzburg,[152] N. Giokaris,[8] M. P. Giordani,[163c] R. Giordano,[101a,101b] F. M. Giorgi,[15] P. Giovannini,[98]
P. F. Giraud,[135] D. Giugni,[88a] M. Giunta,[92] P. Giusti,[19a] B. K. Gjelsten,[116] L. K. Gladilin,[96] C. Glasman,[79]
J. Glatzer,[47] A. Glazov,[41] K. W. Glitza,[173] G. L. Glonti,[64] J. Godfrey,[141] J. Godlewski,[29] M. Goebel,[41]
T. Göpfert,[43] C. Goeringer,[80] C. Gössling,[42] T. Göttfert,[98] S. Goldfarb,[86] T. Golling,[174] S. N. Golovnia,[127]
A. Gomes,[123a,c] L. S. Gomez Fajardo,[41] R. Gonçalo,[75] J. Goncalves Pinto Firmino Da Costa,[41] L. Gonella,[20]
A. Gonidec,[29] S. Gonzalez,[171] S. González de la Hoz,[166] G. Gonzalez Parra,[11] M. L. Gonzalez Silva,[26]
S. Gonzalez-Sevilla,[48] J. J. Goodson,[147] L. Goossens,[29] P. A. Gorbounov,[94] H. A. Gordon,[24] I. Gorelov,[102]
G. Gorfine,[173] B. Gorini,[29] E. Gorini,[71a,71b] A. Gorišek,[73] E. Gornicki,[38] S. A. Gorokhov,[127] V. N. Goryachev,[127]
B. Gosdzik,[41] M. Gosselink,[104] M. I. Gostkin,[64] I. Gough Eschrich,[162] M. Gouighri,[134a] D. Goujdami,[134c]
M. P. Goulette,[48] A. G. Goussiou,[137] C. Goy,[4] S. Gozpinar,[22] I. Grabowska-Bold,[37] P. Grafström,[29] K-J. Grahn,[41]
F. Grancagnolo,[71a] S. Grancagnolo,[15] V. Grassi,[147] V. Gratchev,[120] N. Grau,[34] H. M. Gray,[29] J. A. Gray,[147]
E. Graziani,[133a] O. G. Grebenyuk,[120] T. Greenshaw,[72] Z. D. Greenwood,[24,l] K. Gregersen,[35] I. M. Gregor,[41]
P. Grenier,[142] J. Griffiths,[137] N. Grigalashvili,[64] A. A. Grillo,[136] S. Grinstein,[11] Y. V. Grishkevich,[96]
J.-F. Grivaz,[114] M. Groh,[98] E. Gross,[170] J. Grosse-Knetter,[53] J. Groth-Jensen,[170] K. Grybel,[140] V. J. Guarino,[5]
D. Guest,[174] C. Guicheney,[33] A. Guida,[71a,71b] S. Guindon,[53] H. Guler,[84,m] J. Gunther,[124] B. Guo,[157] J. Guo,[34]
A. Gupta,[30] Y. Gusakov,[64] V. N. Gushchin,[127] A. Gutierrez,[92] P. Gutierrez,[110] N. Guttman,[152] O. Gutzwiller,[171]
C. Guyot,[135] C. Gwenlan,[117] C. B. Gwilliam,[72] A. Haas,[142] S. Haas,[29] C. Haber,[14] R. Hackenburg,[24]
H. K. Hadavand,[39] D. R. Hadley,[17] P. Haefner,[98] F. Hahn,[29] S. Haider,[29] Z. Hajduk,[38] H. Hakobyan,[175] J. Haller,[53]
K. Hamacher,[173] P. Hamal,[112] M. Hamer,[53] A. Hamilton,[48] S. Hamilton,[160] H. Han,[32a] L. Han,[32b] K. Hanagaki,[115]
K. Hanawa,[159] M. Hance,[14] C. Handel,[80] P. Hanke,[57a] J. R. Hansen,[35] J. B. Hansen,[35] J. D. Hansen,[35]
P. H. Hansen,[35] P. Hansson,[142] K. Hara,[159] G. A. Hare,[136] T. Harenberg,[173] S. Harkusha,[89] D. Harper,[86]
R. D. Harrington,[45] O. M. Harris,[137] K. Harrison,[17] J. Hartert,[47] F. Hartjes,[104] T. Haruyama,[65] A. Harvey,[55]

S. Hasegawa,[100] Y. Hasegawa,[139] S. Hassani,[135] M. Hatch,[29] D. Hauff,[98] S. Haug,[16] M. Hauschild,[29] R. Hauser,[87]
M. Havranek,[20] B. M. Hawes,[117] C. M. Hawkes,[17] R. J. Hawkings,[29] D. Hawkins,[162] T. Hayakawa,[66]
T. Hayashi,[159] D. Hayden,[75] H. S. Hayward,[72] S. J. Haywood,[128] E. Hazen,[21] M. He,[32d] S. J. Head,[17]
V. Hedberg,[78] L. Heelan,[7] S. Heim,[87] B. Heinemann,[14] S. Heisterkamp,[35] L. Helary,[4] S. Hellman,[145a,145b]
D. Hellmich,[20] C. Helsens,[11] R. C. W. Henderson,[70] M. Henke,[57a] A. Henrichs,[53] A. M. Henriques Correia,[29]
S. Henrot-Versille,[114] F. Henry-Couannier,[82] C. Hensel,[53] T. Henß,[173] C. M. Hernandez,[7]
Y. Hernández Jiménez,[166] R. Herrberg,[15] A. D. Hershenhorn,[151] G. Herten,[47] R. Hertenberger,[97] L. Hervas,[29]
N. P. Hessey,[104] E. Higón-Rodriguez,[166] D. Hill,[5,a] J. C. Hill,[27] N. Hill,[5] K. H. Hiller,[41] S. Hillert,[20] S. J. Hillier,[17]
I. Hinchliffe,[14] E. Hines,[119] M. Hirose,[115] F. Hirsch,[42] D. Hirschbuehl,[173] J. Hobbs,[147] N. Hod,[152]
M. C. Hodgkinson,[138] P. Hodgson,[138] A. Hoecker,[29] M. R. Hoeferkamp,[102] J. Hoffman,[39] D. Hoffmann,[82]
M. Hohlfeld,[80] M. Holder,[140] S. O. Holmgren,[145a] T. Holy,[126] J. L. Holzbauer,[87] Y. Homma,[66] T. M. Hong,[119]
L. Hooft van Huysduynen,[107] T. Horazdovsky,[126] C. Horn,[142] S. Horner,[47] K. Horton,[117] J-Y. Hostachy,[54]
S. Hou,[150] M. A. Houlden,[72] A. Hoummada,[134a] J. Howarth,[81] D. F. Howell,[117] I. Hristova,[15] J. Hrivnac,[114]
I. Hruska,[124] T. Hryn'ova,[4] P. J. Hsu,[80] S.-C. Hsu,[14] G. S. Huang,[110] Z. Hubacek,[126] F. Hubaut,[82] F. Huegging,[20]
T. B. Huffman,[117] E. W. Hughes,[34] G. Hughes,[70] R. E. Hughes-Jones,[81] M. Huhtinen,[29] P. Hurst,[56] M. Hurwitz,[14]
U. Husemann,[41] N. Huseynov,[64,n] J. Huston,[87] J. Huth,[56] G. Iacobucci,[48] G. Iakovidis,[9] M. Ibbotson,[81]
I. Ibragimov,[140] R. Ichimiya,[66] L. Iconomidou-Fayard,[114] J. Idarraga,[114] P. Iengo,[101a,101b] O. Igonkina,[104]
Y. Ikegami,[65] M. Ikeno,[65] Y. Ilchenko,[39] D. Iliadis,[153] D. Imbault,[77] M. Imori,[154] T. Ince,[20] J. Inigo-Golfin,[29]
P. Ioannou,[8] M. Iodice,[133a] A. Irles Quiles,[166] C. Isaksson,[165] A. Ishikawa,[66] M. Ishino,[67] R. Ishmukhametov,[39]
C. Issever,[117] S. Istin,[18a] A. V. Ivashin,[127] W. Iwanski,[38] H. Iwasaki,[65] J. M. Izen,[40] V. Izzo,[101a] B. Jackson,[119]
J. N. Jackson,[72] P. Jackson,[142] M. R. Jaekel,[29] V. Jain,[60] K. Jakobs,[47] S. Jakobsen,[35] J. Jakubek,[126] D. K. Jana,[110]
E. Jankowski,[157] E. Jansen,[76] A. Jantsch,[98] M. Janus,[20] G. Jarlskog,[78] L. Jeanty,[56] K. Jelen,[37] I. Jen-La Plante,[30]
P. Jenni,[29] A. Jeremie,[4] P. Jež,[35] S. Jézéquel,[4] M. K. Jha,[19a] H. Ji,[171] W. Ji,[80] J. Jia,[147] Y. Jiang,[32b]
M. Jimenez Belenguer,[41] G. Jin,[32b] S. Jin,[32a] O. Jinnouchi,[156] M. D. Joergensen,[35] D. Joffe,[39] L. G. Johansen,[13]
M. Johansen,[145a,145b] K. E. Johansson,[145a] P. Johansson,[138] S. Johnert,[41] K. A. Johns,[6] K. Jon-And,[145a,145b]
G. Jones,[81] R. W. L. Jones,[70] T. W. Jones,[76] T. J. Jones,[72] O. Jonsson,[29] C. Joram,[29] P. M. Jorge,[123a,c] J. Joseph,[14]
T. Jovin,[12b] X. Ju,[129] C. A. Jung,[42] V. Juranek,[124] P. Jussel,[61] A. Juste Rozas,[11] V. V. Kabachenko,[127] S. Kabana,[16]
M. Kaci,[166] A. Kaczmarska,[38] P. Kadlecik,[35] M. Kado,[114] H. Kagan,[108] M. Kagan,[56] S. Kaiser,[98]
E. Kajomovitz,[151] S. Kalinin,[173] L. V. Kalinovskaya,[64] S. Kama,[39] N. Kanaya,[154] M. Kaneda,[29] T. Kanno,[156]
V. A. Kantserov,[95] J. Kanzaki,[65] B. Kaplan,[174] A. Kapliy,[30] J. Kaplon,[29] D. Kar,[43] M. Karagoz,[117]
M. Karnevskiy,[41] K. Karr,[5] V. Kartvelishvili,[70] A. N. Karyukhin,[127] L. Kashif,[171] G. Kasieczka,[57b] A. Kasmi,[39]
R. D. Kass,[108] A. Kastanas,[13] M. Kataoka,[4] Y. Kataoka,[154] E. Katsoufis,[9] J. Katzy,[41] V. Kaushik,[6] K. Kawagoe,[66]
T. Kawamoto,[154] G. Kawamura,[80] M. S. Kayl,[104] V. A. Kazanin,[106] M. Y. Kazarinov,[64] J. R. Keates,[81]
R. Keeler,[168] R. Kehoe,[39] M. Keil,[53] G. D. Kekelidze,[64] J. Kennedy,[97] C. J. Kenney,[142] M. Kenyon,[52] O. Kepka,[124]
N. Kerschen,[29] B. P. Kerševan,[73] S. Kersten,[173] K. Kessoku,[154] J. Keung,[157] M. Khakzad,[28] F. Khalil-zada,[10]
H. Khandanyan,[164] A. Khanov,[111] D. Kharchenko,[64] A. Khodinov,[95] A. G. Kholodenko,[127] A. Khomich,[57a]
T. J. Khoo,[27] G. Khoriauli,[20] A. Khoroshilov,[173] N. Khovanskiy,[64] V. Khovanskiy,[94] E. Khramov,[64] J. Khubua,[50b]
H. Kim,[145a,145b] M. S. Kim,[2] P. C. Kim,[142] S. H. Kim,[159] N. Kimura,[169] O. Kind,[15] B. T. King,[72] M. King,[66]
R. S. B. King,[117] J. Kirk,[128] L. E. Kirsch,[22] A. E. Kiryunin,[98] T. Kishimoto,[66] D. Kisielewska,[37] T. Kittelmann,[122]
A. M. Kiver,[127] E. Kladiva,[143b] J. Klaiber-Lodewigs,[42] M. Klein,[72] U. Klein,[72] K. Kleinknecht,[80] M. Klemetti,[84]
A. Klier,[170] A. Klimentov,[24] R. Klingenberg,[42] E. B. Klinkby,[35] T. Klioutchnikova,[29] P. F. Klok,[103] S. Klous,[104]
E.-E. Kluge,[57a] T. Kluge,[72] P. Kluit,[104] S. Kluth,[98] N. S. Knecht,[157] E. Kneringer,[61] J. Knobloch,[29]
E. B. F. G. Knoops,[82] A. Knue,[53] B. R. Ko,[44] T. Kobayashi,[154] M. Kobel,[43] M. Kocian,[142] P. Kodys,[125]
K. Köneke,[29] A. C. König,[103] S. Koenig,[80] L. Köpke,[80] F. Koetsveld,[103] P. Koevesarki,[20] T. Koffas,[28]
E. Koffeman,[104] F. Kohn,[53] Z. Kohout,[126] T. Kohriki,[65] T. Koi,[142] T. Kokott,[20] G. M. Kolachev,[106] H. Kolanoski,[15]
V. Kolesnikov,[64] I. Koletsou,[88a] J. Koll,[87] D. Kollar,[29] M. Kollefrath,[47] S. D. Kolya,[81] A. A. Komar,[93]
Y. Komori,[154] T. Kondo,[65] T. Kono,[41,o] A. I. Kononov,[47] R. Konoplich,[107,p] N. Konstantinidis,[76] A. Kootz,[173]
S. Koperny,[37] S. V. Kopikov,[127] K. Korcyl,[38] K. Kordas,[153] V. Koreshev,[127] A. Korn,[117] A. Korol,[106] I. Korolkov,[11]
E. V. Korolkova,[138] V. A. Korotkov,[127] O. Kortner,[98] S. Kortner,[98] V. V. Kostyukhin,[20] M. J. Kotamäki,[29]
S. Kotov,[98] V. M. Kotov,[64] A. Kotwal,[44] C. Kourkoumelis,[8] V. Kouskoura,[153] A. Koutsman,[158a] R. Kowalewski,[168]
T. Z. Kowalski,[37] W. Kozanecki,[135] A. S. Kozhin,[127] V. Kral,[126] V. A. Kramarenko,[96] G. Kramberger,[73]

M. W. Krasny,[77] A. Krasznahorkay,[107] J. Kraus,[87] J. K. Kraus,[20] A. Kreisel,[152] F. Krejci,[126] J. Kretzschmar,[72]
N. Krieger,[53] P. Krieger,[157] K. Kroeninger,[53] H. Kroha,[98] J. Kroll,[119] J. Kroseberg,[20] J. Krstic,[12a] U. Kruchonak,[64]
H. Krüger,[20] T. Kruker,[16] N. Krumnack,[63] Z. V. Krumshteyn,[64] A. Kruth,[20] T. Kubota,[85] S. Kuehn,[47] A. Kugel,[57c]
T. Kuhl,[41] D. Kuhn,[61] V. Kukhtin,[64] Y. Kulchitsky,[89] S. Kuleshov,[31b] C. Kummer,[97] M. Kuna,[77] N. Kundu,[117]
J. Kunkle,[119] A. Kupco,[124] H. Kurashige,[66] M. Kurata,[159] Y. A. Kurochkin,[89] V. Kus,[124] M. Kuze,[156] J. Kvita,[29]
R. Kwee,[15] A. La Rosa,[48] L. La Rotonda,[36a,36b] L. Labarga,[79] J. Labbe,[4] S. Lablak,[134a] C. Lacasta,[166]
F. Lacava,[131a,131b] H. Lacker,[15] D. Lacour,[77] V. R. Lacuesta,[166] E. Ladygin,[64] R. Lafaye,[4] B. Laforge,[77]
T. Lagouri,[79] S. Lai,[47] E. Laisne,[54] M. Lamanna,[29] C. L. Lampen,[6] W. Lampl,[6] E. Lancon,[135] U. Landgraf,[47]
M. P. J. Landon,[74] H. Landsman,[151] J. L. Lane,[81] C. Lange,[41] A. J. Lankford,[162] F. Lanni,[24] K. Lantzsch,[173]
S. Laplace,[77] C. Lapoire,[20] J. F. Laporte,[135] T. Lari,[88a] A. V. Larionov,[127] A. Larner,[117] C. Lasseur,[29]
M. Lassnig,[29] P. Laurelli,[46] W. Lavrijsen,[14] P. Laycock,[72] A. B. Lazarev,[64] O. Le Dortz,[77] E. Le Guirriec,[82]
C. Le Maner,[157] E. Le Menedeu,[135] C. Lebel,[92] T. LeCompte,[5] F. Ledroit-Guillon,[54] H. Lee,[104] J. S. H. Lee,[115]
S. C. Lee,[150] L. Lee,[174] M. Lefebvre,[168] M. Legendre,[135] A. Leger,[48] B. C. LeGeyt,[119] F. Legger,[97] C. Leggett,[14]
M. Lehmacher,[20] G. Lehmann Miotto,[29] X. Lei,[6] M. A. L. Leite,[23d] R. Leitner,[125] D. Lellouch,[170] M. Leltchouk,[34]
B. Lemmer,[53] V. Lendermann,[57a] K. J. C. Leney,[144b] T. Lenz,[104] G. Lenzen,[173] B. Lenzi,[29] K. Leonhardt,[43]
S. Leontsinis,[9] C. Leroy,[92] J-R. Lessard,[168] J. Lesser,[145a] C. G. Lester,[27] A. Leung Fook Cheong,[171] J. Levêque,[4]
D. Levin,[86] L. J. Levinson,[170] M. S. Levitski,[127] A. Lewis,[117] G. H. Lewis,[107] A. M. Leyko,[20] M. Leyton,[15]
B. Li,[82] H. Li,[171] S. Li,[32b,q] X. Li,[86] Z. Liang,[39] Z. Liang,[117,r] H. Liao,[33] B. Liberti,[132a] P. Lichard,[29]
M. Lichtnecker,[97] K. Lie,[164] W. Liebig,[13] R. Lifshitz,[151] J. N. Lilley,[17] C. Limbach,[20] A. Limosani,[85]
M. Limper,[62] S. C. Lin,[150,s] F. Linde,[104] J. T. Linnemann,[87] E. Lipeles,[119] L. Lipinsky,[124] A. Lipniacka,[13]
T. M. Liss,[164] D. Lissauer,[24] A. Lister,[48] A. M. Litke,[136] C. Liu,[28] D. Liu,[150,t] H. Liu,[86] J. B. Liu,[86] M. Liu,[32b]
S. Liu,[2] Y. Liu,[32b] M. Livan,[118a,118b] S. S. A. Livermore,[117] A. Lleres,[54] J. Llorente Merino,[79] S. L. Lloyd,[74]
E. Lobodzinska,[41] P. Loch,[6] W. S. Lockman,[136] T. Loddenkoetter,[20] F. K. Loebinger,[81] A. Loginov,[174]
C. W. Loh,[167] T. Lohse,[15] K. Lohwasser,[47] M. Lokajicek,[124] J. Loken,[117] V. P. Lombardo,[4] R. E. Long,[70]
L. Lopes,[123a,c] D. Lopez Mateos,[56] M. Losada,[161] P. Loscutoff,[14] F. Lo Sterzo,[131a,131b] M. J. Losty,[158a] X. Lou,[40]
A. Lounis,[114] K. F. Loureiro,[161] J. Love,[21] P. A. Love,[70] A. J. Lowe,[142,f] F. Lu,[32a] H. J. Lubatti,[137] C. Luci,[131a,131b]
A. Lucotte,[54] A. Ludwig,[43] D. Ludwig,[41] I. Ludwig,[47] J. Ludwig,[47] F. Luehring,[60] G. Luijckx,[104] D. Lumb,[47]
L. Luminari,[131a] E. Lund,[116] B. Lund-Jensen,[146] B. Lundberg,[78] J. Lundberg,[145a,145b] J. Lundquist,[35]
M. Lungwitz,[80] G. Lutz,[98] D. Lynn,[24] J. Lys,[14] E. Lytken,[78] H. Ma,[24] L. L. Ma,[171] J. A. Macana Goia,[92]
G. Maccarrone,[46] A. Macchiolo,[98] B. Maček,[73] J. Machado Miguens,[123a] R. Mackeprang,[35] R. J. Madaras,[14]
W. F. Mader,[43] R. Maenner,[57c] T. Maeno,[24] P. Mättig,[173] S. Mättig,[41] L. Magnoni,[29] E. Magradze,[53]
Y. Mahalalel,[152] K. Mahboubi,[47] G. Mahout,[17] C. Maiani,[131a,131b] C. Maidantchik,[23a] A. Maio,[123a,c]
S. Majewski,[24] Y. Makida,[65] N. Makovec,[114] P. Mal,[135] Pa. Malecki,[38] P. Malecki,[38] V. P. Maleev,[120] F. Malek,[54]
U. Mallik,[62] D. Malon,[5] C. Malone,[142] S. Maltezos,[9] V. Malyshev,[106] S. Malyukov,[29] R. Mameghani,[97]
J. Mamuzic,[12b] A. Manabe,[65] L. Mandelli,[88a] I. Mandić,[73] R. Mandrysch,[15] J. Maneira,[123a] P. S. Mangeard,[87]
I. D. Manjavidze,[64] A. Mann,[53] P. M. Manning,[136] A. Manousakis-Katsikakis,[8] B. Mansoulie,[135] A. Manz,[98]
A. Mapelli,[29] L. Mapelli,[29] L. March,[79] J. F. Marchand,[29] F. Marchese,[132a,132b] G. Marchiori,[77]
M. Marcisovsky,[124] A. Marin,[21,a] C. P. Marino,[168] F. Marroquim,[23a] R. Marshall,[81] Z. Marshall,[29]
F. K. Martens,[157] S. Marti-Garcia,[166] A. J. Martin,[174] B. Martin,[29] B. Martin,[87] F. F. Martin,[119] J. P. Martin,[92]
Ph. Martin,[54] T. A. Martin,[17] V. J. Martin,[45] B. Martin dit Latour,[48] S. Martin-Haugh,[148] M. Martinez,[11]
V. Martinez Outschoorn,[56] A. C. Martyniuk,[81] M. Marx,[81] F. Marzano,[131a] A. Marzin,[110] L. Masetti,[80]
T. Mashimo,[154] R. Mashinistov,[93] J. Masik,[81] A. L. Maslennikov,[106] I. Massa,[19a,19b] G. Massaro,[104] N. Massol,[4]
P. Mastrandrea,[131a,131b] A. Mastroberardino,[36a,36b] T. Masubuchi,[154] M. Mathes,[20] H. Matsumoto,[154]
H. Matsunaga,[154] T. Matsushita,[66] C. Mattravers,[117,d] J. M. Maugain,[29] J. Maurer,[82] S. J. Maxfield,[72]
D. A. Maximov,[106] E. N. May,[5] A. Mayne,[138] R. Mazini,[150] M. Mazur,[20] M. Mazzanti,[88a] E. Mazzoni,[121a,121b]
S. P. Mc Kee,[86] A. McCarn,[164] R. L. McCarthy,[147] T. G. McCarthy,[28] N. A. McCubbin,[128] K. W. McFarlane,[55]
J. A. Mcfayden,[138] H. McGlone,[52] G. Mchedlidze,[50b] R. A. McLaren,[29] T. Mclaughlan,[17] S. J. McMahon,[128]
R. A. McPherson,[168,j] A. Meade,[83] J. Mechnich,[104] M. Mechtel,[173] M. Medinnis,[41] R. Meera-Lebbai,[110]
T. Meguro,[115] R. Mehdiyev,[92] S. Mehlhase,[35] A. Mehta,[72] K. Meier,[57a] B. Meirose,[78] C. Melachrinos,[30]
B. R. Mellado Garcia,[171] L. Mendoza Navas,[161] Z. Meng,[150,t] A. Mengarelli,[19a,19b] S. Menke,[98] C. Menot,[29]
E. Meoni,[11] K. M. Mercurio,[56] P. Mermod,[117] L. Merola,[101a,101b] C. Meroni,[88a] F. S. Merritt,[30] A. Messina,[29]

J. Metcalfe,[102] A. S. Mete,[63] C. Meyer,[80] C. Meyer,[30] J-P. Meyer,[135] J. Meyer,[172] J. Meyer,[53] T. C. Meyer,[29]
W. T. Meyer,[63] J. Miao,[32d] S. Michal,[29] L. Micu,[25a] R. P. Middleton,[128] P. Miele,[29] S. Migas,[72] L. Mijović,[41]
G. Mikenberg,[170] M. Mikestikova,[124] M. Mikuž,[73] D. W. Miller,[30] R. J. Miller,[87] W. J. Mills,[167] C. Mills,[56]
A. Milov,[170] D. A. Milstead,[145a,145b] D. Milstein,[170] A. A. Minaenko,[127] M. Miñano Moya,[166] I. A. Minashvili,[64]
A. I. Mincer,[107] B. Mindur,[37] M. Mineev,[64] Y. Ming,[129] L. M. Mir,[11] G. Mirabelli,[131a] L. Miralles Verge,[11]
A. Misiejuk,[75] J. Mitrevski,[136] G. Y. Mitrofanov,[127] V. A. Mitsou,[166] S. Mitsui,[65] P. S. Miyagawa,[138]
K. Miyazaki,[66] J. U. Mjörnmark,[78] T. Moa,[145a,145b] P. Mockett,[137] S. Moed,[56] V. Moeller,[27] K. Mönig,[41]
N. Möser,[20] S. Mohapatra,[147] W. Mohr,[47] S. Mohrdieck-Möck,[98] A. M. Moisseev,[127,a] R. Moles-Valls,[166]
J. Molina-Perez,[29] J. Monk,[76] E. Monnier,[82] S. Montesano,[88a,88b] F. Monticelli,[69] S. Monzani,[19a,19b]
R. W. Moore,[2] G. F. Moorhead,[85] C. Mora Herrera,[48] A. Moraes,[52] N. Morange,[135] J. Morel,[53] G. Morello,[36a,36b]
D. Moreno,[80] M. Moreno Llácer,[166] P. Morettini,[49a] M. Morii,[56] J. Morin,[74] A. K. Morley,[29] G. Mornacchi,[29]
S. V. Morozov,[95] J. D. Morris,[74] L. Morvaj,[100] H. G. Moser,[98] M. Mosidze,[50b] J. Moss,[108] R. Mount,[142]
E. Mountricha,[135] S. V. Mouraviev,[93] E. J. W. Moyse,[83] M. Mudrinic,[12b] F. Mueller,[57a] J. Mueller,[122] K. Mueller,[20]
T. A. Müller,[97] D. Muenstermann,[29] A. Muir,[167] Y. Munwes,[152] W. J. Murray,[128] I. Mussche,[104] E. Musto,[101a,101b]
A. G. Myagkov,[127] M. Myska,[124] J. Nadal,[11] K. Nagai,[159] K. Nagano,[65] Y. Nagasaka,[59] A. M. Nairz,[29]
Y. Nakahama,[29] K. Nakamura,[154] T. Nakamura,[154] I. Nakano,[109] G. Nanava,[20] A. Napier,[160] M. Nash,[76,d]
N. R. Nation,[21] T. Nattermann,[20] T. Naumann,[41] G. Navarro,[161] H. A. Neal,[86] E. Nebot,[79] P. Yu. Nechaeva,[93]
A. Negri,[118a,118b] G. Negri,[29] S. Nektarijevic,[48] A. Nelson,[162] S. Nelson,[142] T. K. Nelson,[142] S. Nemecek,[124]
P. Nemethy,[107] A. A. Nepomuceno,[23a] M. Nessi,[29,u] M. S. Neubauer,[164] A. Neusiedl,[80] R. M. Neves,[107]
P. Nevski,[24] P. R. Newman,[17] V. Nguyen Thi Hong,[135] R. B. Nickerson,[117] R. Nicolaidou,[135] L. Nicolas,[138]
B. Nicquevert,[29] F. Niedercorn,[114] J. Nielsen,[136] T. Niinikoski,[29] N. Nikiforou,[34] A. Nikiforov,[15]
V. Nikolaenko,[127] K. Nikolaev,[64] I. Nikolic-Audit,[77] K. Nikolics,[48] K. Nikolopoulos,[24] H. Nilsen,[47] P. Nilsson,[7]
Y. Ninomiya,[154] A. Nisati,[131a] T. Nishiyama,[66] R. Nisius,[98] L. Nodulman,[5] M. Nomachi,[115] I. Nomidis,[153]
M. Nordberg,[29] B. Nordkvist,[145a,145b] P. R. Norton,[128] J. Novakova,[125] M. Nozaki,[65] L. Nozka,[112]
I. M. Nugent,[158a] A.-E. Nuncio-Quiroz,[20] G. Nunes Hanninger,[85] T. Nunnemann,[97] E. Nurse,[76] T. Nyman,[29]
B. J. O'Brien,[45] S. W. O'Neale,[17,a] D. C. O'Neil,[141] V. O'Shea,[52] F. G. Oakham,[28,e] H. Oberlack,[98] J. Ocariz,[77]
A. Ochi,[66] S. Oda,[154] S. Odaka,[65] J. Odier,[82] H. Ogren,[60] A. Oh,[81] S. H. Oh,[44] C. C. Ohm,[145a,145b] T. Ohshima,[100]
H. Ohshita,[139] T. Ohsugi,[58] S. Okada,[66] H. Okawa,[162] Y. Okumura,[100] T. Okuyama,[154] A. Olariu,[25a] M. Olcese,[49a]
A. G. Olchevski,[64] M. Oliveira,[123a,h] D. Oliveira Damazio,[24] E. Oliver Garcia,[166] D. Olivito,[119] A. Olszewski,[38]
J. Olszowska,[38] C. Omachi,[66] A. Onofre,[123a,v] P. U. E. Onyisi,[30] C. J. Oram,[158a] M. J. Oreglia,[30] Y. Oren,[152]
D. Orestano,[133a,133b] I. Orlov,[106] C. Oropeza Barrera,[52] R. S. Orr,[157] B. Osculati,[49a,49b] R. Ospanov,[119]
C. Osuna,[11] G. Otero y Garzon,[26] J. P. Ottersbach,[104] M. Ouchrif,[134d] F. Ould-Saada,[116] A. Ouraou,[135]
Q. Ouyang,[32a] M. Owen,[81] S. Owen,[138] V. E. Ozcan,[18a] N. Ozturk,[7] A. Pacheco Pages,[11] C. Padilla Aranda,[11]
S. Pagan Griso,[14] E. Paganis,[138] F. Paige,[24] P. Pais,[83] K. Pajchel,[116] G. Palacino,[158b] C. P. Paleari,[6] S. Palestini,[29]
D. Pallin,[33] A. Palma,[123a,c] J. D. Palmer,[17] Y. B. Pan,[171] E. Panagiotopoulou,[9] B. Panes,[31a] N. Panikashvili,[86]
S. Panitkin,[24] D. Pantea,[25a] M. Panuskova,[124] V. Paolone,[122] A. Papadelis,[145a] Th. D. Papadopoulou,[9]
A. Paramonov,[5] W. Park,[24,w] M. A. Parker,[27] F. Parodi,[49a,49b] J. A. Parsons,[34] U. Parzefall,[47] E. Pasqualucci,[131a]
A. Passeri,[133a] F. Pastore,[133a,133b] Fr. Pastore,[75] G. Pásztor,[48,x] S. Pataraia,[173] N. Patel,[149] J. R. Pater,[81]
S. Patricelli,[101a,101b] T. Pauly,[29] M. Pecsy,[143a] M. I. Pedraza Morales,[171] S. V. Peleganchuk,[106] H. Peng,[32b]
R. Pengo,[29] A. Penson,[34] J. Penwell,[60] M. Perantoni,[23a] K. Perez,[34,y] T. Perez Cavalcanti,[41] E. Perez Codina,[11]
M. T. Pérez García-Estañ,[166] V. Perez Reale,[34] L. Perini,[88a,88b] H. Pernegger,[29] R. Perrino,[71a] P. Perrodo,[4]
S. Persembe,[3a] V. D. Peshekhonov,[64] B. A. Petersen,[29] J. Petersen,[29] T. C. Petersen,[35] E. Petit,[82] A. Petridis,[153]
C. Petridou,[153] E. Petrolo,[131a] F. Petrucci,[133a,133b] D. Petschull,[41] M. Petteni,[141] R. Pezoa,[31b] A. Phan,[85]
P. W. Phillips,[128] G. Piacquadio,[29] E. Piccaro,[74] M. Piccinini,[19a,19b] S. M. Piec,[41] R. Piegaia,[26] J. E. Pilcher,[30]
A. D. Pilkington,[81] J. Pina,[123a,c] M. Pinamonti,[163a,163c] A. Pinder,[117] J. L. Pinfold,[2] J. Ping,[32c] B. Pinto,[123a,c]
O. Pirotte,[29] C. Pizio,[88a,88b] R. Placakyte,[41] M. Plamondon,[168] M.-A. Pleier,[24] A. V. Pleskach,[127] A. Poblaguev,[24]
S. Poddar,[57a] F. Podlyski,[33] L. Poggioli,[114] T. Poghosyan,[20] M. Pohl,[48] F. Polci,[54] G. Polesello,[118a]
A. Policicchio,[137] A. Polini,[19a] J. Poll,[74] V. Polychronakos,[24] D. M. Pomarede,[135] D. Pomeroy,[22] K. Pommès,[29]
L. Pontecorvo,[131a] B. G. Pope,[87] G. A. Popeneciu,[25a] D. S. Popovic,[12a] A. Poppleton,[29] X. Portell Bueso,[29]
C. Posch,[21] G. E. Pospelov,[98] S. Pospisil,[126] I. N. Potrap,[98] C. J. Potter,[148] C. T. Potter,[113] G. Poulard,[29]
J. Poveda,[171] R. Prabhu,[76] P. Pralavorio,[82] A. Pranko,[14] S. Prasad,[56] R. Pravahan,[7] S. Prell,[63] K. Pretzl,[16]

L. Pribyl,[29] D. Price,[60] L. E. Price,[5] M. J. Price,[29] D. Prieur,[122] M. Primavera,[71a] K. Prokofiev,[107] F. Prokoshin,[31b]
S. Protopopescu,[24] J. Proudfoot,[5] X. Prudent,[43] H. Przysiezniak,[4] S. Psoroulas,[20] E. Ptacek,[113] E. Pueschel,[83]
J. Purdham,[86] M. Purohit,[24,w] P. Puzo,[114] Y. Pylypchenko,[116] J. Qian,[86] Z. Qian,[82] Z. Qin,[41] A. Quadt,[53]
D. R. Quarrie,[14] W. B. Quayle,[171] F. Quinonez,[31a] M. Raas,[103] V. Radescu,[57b] B. Radics,[20] T. Rador,[18a]
F. Ragusa,[88a,88b] G. Rahal,[176] A. M. Rahimi,[108] D. Rahm,[24] S. Rajagopalan,[24] M. Rammensee,[47] M. Rammes,[140]
M. Ramstedt,[145a,145b] A. S. Randle-Conde,[39] K. Randrianarivony,[28] P. N. Ratoff,[70] F. Rauscher,[97] M. Raymond,[29]
A. L. Read,[116] D. M. Rebuzzi,[118a,118b] A. Redelbach,[172] G. Redlinger,[24] R. Reece,[119] K. Reeves,[40] A. Reichold,[104]
E. Reinherz-Aronis,[152] A. Reinsch,[113] I. Reisinger,[42] D. Reljic,[12a] C. Rembser,[29] Z. L. Ren,[150] A. Renaud,[114]
P. Renkel,[39] M. Rescigno,[131a] S. Resconi,[88a] B. Resende,[135] P. Reznicek,[97] R. Rezvani,[157] A. Richards,[76]
R. Richter,[98] E. Richter-Was,[4,z] M. Ridel,[77] M. Rijpstra,[104] M. Rijssenbeek,[147] A. Rimoldi,[118a,118b] L. Rinaldi,[19a]
R. R. Rios,[39] I. Riu,[11] G. Rivoltella,[88a,88b] F. Rizatdinova,[111] E. Rizvi,[74] S. H. Robertson,[84,j]
A. Robichaud-Veronneau,[117] D. Robinson,[27] J. E. M. Robinson,[76] M. Robinson,[113] A. Robson,[52]
J. G. Rocha de Lima,[105] C. Roda,[121a,121b] D. Roda Dos Santos,[29] S. Rodier,[79] D. Rodriguez,[161] A. Roe,[53]
S. Roe,[29] O. Røhne,[116] V. Rojo,[1] S. Rolli,[160] A. Romaniouk,[95] M. Romano,[19a,19b] V. M. Romanov,[64] G. Romeo,[26]
L. Roos,[77] E. Ros,[166] S. Rosati,[131a,131b] K. Rosbach,[48] A. Rose,[148] M. Rose,[75] G. A. Rosenbaum,[157]
E. I. Rosenberg,[63] P. L. Rosendahl,[13] O. Rosenthal,[140] L. Rosselet,[48] V. Rossetti,[11] E. Rossi,[131a,131b] L. P. Rossi,[49a]
M. Rotaru,[25a] I. Roth,[170] J. Rothberg,[137] D. Rousseau,[114] C. R. Royon,[135] A. Rozanov,[82] Y. Rozen,[151] X. Ruan,[114]
I. Rubinskiy,[41] B. Ruckert,[97] N. Ruckstuhl,[104] V. I. Rud,[96] C. Rudolph,[43] G. Rudolph,[61] F. Rühr,[6]
F. Ruggieri,[133a,133b] A. Ruiz-Martinez,[63] V. Rumiantsev,[90,a] L. Rumyantsev,[64] K. Runge,[47] O. Runolfsson,[20]
Z. Rurikova,[47] N. A. Rusakovich,[64] D. R. Rust,[60] J. P. Rutherfoord,[6] C. Ruwiedel,[14] P. Ruzicka,[124]
Y. F. Ryabov,[120] V. Ryadovikov,[127] P. Ryan,[87] M. Rybar,[125] G. Rybkin,[114] N. C. Ryder,[117] S. Rzaeva,[10]
A. F. Saavedra,[149] I. Sadeh,[152] H. F-W. Sadrozinski,[136] R. Sadykov,[64] F. Safai Tehrani,[131a,131b] H. Sakamoto,[154]
G. Salamanna,[74] A. Salamon,[132a] M. Saleem,[110] D. Salihagic,[98] A. Salnikov,[142] J. Salt,[166]
B. M. Salvachua Ferrando,[5] D. Salvatore,[36a,36b] F. Salvatore,[148] A. Salvucci,[103] A. Salzburger,[29]
D. Sampsonidis,[153] B. H. Samset,[116] A. Sanchez,[101a,101b] H. Sandaker,[13] H. G. Sander,[80] M. P. Sanders,[97]
M. Sandhoff,[173] T. Sandoval,[27] C. Sandoval,[161] R. Sandstroem,[98] S. Sandvoss,[173] D. P. C. Sankey,[128] A. Sansoni,[46]
C. Santamarina Rios,[84] C. Santoni,[33] R. Santonico,[132a,132b] H. Santos,[123a] J. G. Saraiva,[123a,c] T. Sarangi,[171]
E. Sarkisyan-Grinbaum,[7] F. Sarri,[121a,121b] G. Sartisohn,[173] O. Sasaki,[65] T. Sasaki,[65] N. Sasao,[67]
I. Satsounkevitch,[89] G. Sauvage,[4] E. Sauvan,[4] J. B. Sauvan,[114] P. Savard,[157,e] V. Savinov,[122] D. O. Savu,[29]
L. Sawyer,[24,l] D. H. Saxon,[52] L. P. Says,[33] C. Sbarra,[19a] A. Sbrizzi,[19a,19b] O. Scallon,[92] D. A. Scannicchio,[162]
J. Schaarschmidt,[114] P. Schacht,[98] U. Schäfer,[80] S. Schaepe,[20] S. Schaetzel,[57b] A. C. Schaffer,[114] D. Schaile,[97]
R. D. Schamberger,[147] A. G. Schamov,[106] V. Scharf,[57a] V. A. Schegelsky,[120] D. Scheirich,[86] M. Schernau,[162]
M. I. Scherzer,[14] C. Schiavi,[49a,49b] J. Schieck,[97] M. Schioppa,[36a,36b] S. Schlenker,[29] J. L. Schlereth,[5] E. Schmidt,[47]
K. Schmieden,[20] C. Schmitt,[80] S. Schmitt,[57b] M. Schmitz,[20] A. Schöning,[57b] M. Schott,[29] D. Schouten,[158a]
J. Schovancova,[124] M. Schram,[84] C. Schroeder,[80] N. Schroer,[57c] S. Schuh,[29] G. Schuler,[29] J. Schultes,[173]
H.-C. Schultz-Coulon,[57a] H. Schulz,[15] J. W. Schumacher,[20] M. Schumacher,[47] B. A. Schumm,[136] Ph. Schune,[135]
C. Schwanenberger,[81] A. Schwartzman,[142] Ph. Schwemling,[77] R. Schwienhorst,[87] R. Schwierz,[43]
J. Schwindling,[135] T. Schwindt,[20] W. G. Scott,[128] J. Searcy,[113] G. Sedov,[41] E. Sedykh,[120] E. Segura,[11]
S. C. Seidel,[102] A. Seiden,[136] F. Seifert,[43] J. M. Seixas,[23a] G. Sekhniaidze,[101a] D. M. Seliverstov,[120] B. Sellden,[145a]
G. Sellers,[72] M. Seman,[143b] N. Semprini-Cesari,[19a,19b] C. Serfon,[97] L. Serin,[114] R. Seuster,[98] H. Severini,[110]
M. E. Sevior,[85] A. Sfyrla,[29] E. Shabalina,[53] M. Shamim,[113] L. Y. Shan,[32a] J. T. Shank,[21] Q. T. Shao,[85]
M. Shapiro,[14] P. B. Shatalov,[94] L. Shaver,[6] K. Shaw,[163a,163c] D. Sherman,[174] P. Sherwood,[76] A. Shibata,[107]
H. Shichi,[100] S. Shimizu,[29] M. Shimojima,[99] T. Shin,[55] M. Shiyakova,[64] A. Shmeleva,[93] M. J. Shochet,[30]
D. Short,[117] S. Shrestha,[63] M. A. Shupe,[6] P. Sicho,[124] A. Sidoti,[131a,131b] A. Siebel,[173] F. Siegert,[47] Dj. Sijacki,[12a]
O. Silbert,[170] J. Silva,[123a,c] Y. Silver,[152] D. Silverstein,[142] S. B. Silverstein,[145a] V. Simak,[126] O. Simard,[135]
Lj. Simic,[12a] S. Simion,[114] B. Simmons,[76] M. Simonyan,[35] P. Sinervo,[157] N. B. Sinev,[113] V. Sipica,[140]
G. Siragusa,[172] A. Sircar,[24] A. N. Sisakyan,[64] S. Yu. Sivoklokov,[96] J. Sjölin,[145a,145b] T. B. Sjursen,[13]
L. A. Skinnari,[14] H. P. Skottowe,[56] K. Skovpen,[106] P. Skubic,[110] N. Skvorodnev,[22] M. Slater,[17] T. Slavicek,[126]
K. Sliwa,[160] J. Sloper,[29] V. Smakhtin,[170] S. Yu. Smirnov,[95] L. N. Smirnova,[96] O. Smirnova,[78] B. C. Smith,[56]
D. Smith,[142] K. M. Smith,[52] M. Smizanska,[70] K. Smolek,[126] A. A. Snesarev,[93] S. W. Snow,[81] J. Snow,[110]
J. Snuverink,[104] S. Snyder,[24] M. Soares,[123a] R. Sobie,[168,j] J. Sodomka,[126] A. Soffer,[152] C. A. Solans,[166]

M. Solar,[126] J. Solc,[126] E. Soldatov,[95] U. Soldevila,[166] E. Solfaroli Camillocci,[131a,131b] A. A. Solodkov,[127]
O. V. Solovyanov,[127] J. Sondericker,[24] N. Soni,[2] V. Sopko,[126] B. Sopko,[126] M. Sosebee,[7] R. Soualah,[163a,163c]
A. Soukharev,[106] S. Spagnolo,[71a,71b] F. Spanò,[75] R. Spighi,[19a] G. Spigo,[29] F. Spila,[131a,131b] R. Spiwoks,[29]
M. Spousta,[125] T. Spreitzer,[157] B. Spurlock,[7] R. D. St. Denis,[52] T. Stahl,[140] J. Stahlman,[119] R. Stamen,[57a]
E. Stanecka,[38] R. W. Stanek,[5] C. Stanescu,[133a] S. Stapnes,[116] E. A. Starchenko,[127] J. Stark,[54] P. Staroba,[124]
P. Starovoitov,[90] A. Staude,[97] P. Stavina,[143a] G. Stavropoulos,[14] G. Steele,[52] P. Steinbach,[43] P. Steinberg,[24]
I. Stekl,[126] B. Stelzer,[141] H. J. Stelzer,[87] O. Stelzer-Chilton,[158a] H. Stenzel,[51] K. Stevenson,[74] G. A. Stewart,[29]
J. A. Stillings,[20] M. C. Stockton,[29] K. Stoerig,[47] G. Stoicea,[25a] S. Stonjek,[98] P. Strachota,[125] A. R. Stradling,[7]
A. Straessner,[43] J. Strandberg,[146] S. Strandberg,[145a,145b] A. Strandlie,[116] M. Strang,[108] E. Strauss,[142]
M. Strauss,[110] P. Strizenec,[143b] R. Ströhmer,[172] D. M. Strom,[113] J. A. Strong,[75,a] R. Stroynowski,[39] J. Strube,[128]
B. Stugu,[13] I. Stumer,[24,a] J. Stupak,[147] P. Sturm,[173] D. A. Soh,[150,r] D. Su,[142] HS. Subramania,[2] A. Succurro,[11]
Y. Sugaya,[115] T. Sugimoto,[100] C. Suhr,[105] K. Suita,[66] M. Suk,[125] V. V. Sulin,[93] S. Sultansoy,[3d] T. Sumida,[29]
X. Sun,[54] J. E. Sundermann,[47] K. Suruliz,[138] S. Sushkov,[11] G. Susinno,[36a,36b] M. R. Sutton,[148] Y. Suzuki,[65]
Y. Suzuki,[66] M. Svatos,[124] Yu. M. Sviridov,[127] S. Swedish,[167] I. Sykora,[143a] T. Sykora,[125] B. Szeless,[29]
J. Sánchez,[166] D. Ta,[104] K. Tackmann,[41] A. Taffard,[162] R. Tafirout,[158a] N. Taiblum,[152] Y. Takahashi,[100] H. Takai,[24]
R. Takashima,[68] H. Takeda,[66] T. Takeshita,[139] M. Talby,[82] A. Talyshev,[106] M. C. Tamsett,[24] J. Tanaka,[154]
R. Tanaka,[114] S. Tanaka,[130] S. Tanaka,[65] Y. Tanaka,[99] K. Tani,[66] N. Tannoury,[82] G. P. Tappern,[29] S. Tapprogge,[80]
D. Tardif,[157] S. Tarem,[151] F. Tarrade,[28] G. F. Tartarelli,[88a] P. Tas,[125] M. Tasevsky,[124] E. Tassi,[36a,36b]
M. Tatarkhanov,[14] Y. Tayalati,[134d] C. Taylor,[76] F. E. Taylor,[91] G. N. Taylor,[85] W. Taylor,[158b] M. Teinturier,[114]
M. Teixeira Dias Castanheira,[74] P. Teixeira-Dias,[75] K. K. Temming,[47] H. Ten Kate,[29] P. K. Teng,[150] S. Terada,[65]
K. Terashi,[154] J. Terron,[79] M. Terwort,[41,o] M. Testa,[46] R. J. Teuscher,[157,j] J. Thadome,[173] J. Therhaag,[20]
T. Theveneaux-Pelzer,[77] M. Thioye,[174] S. Thoma,[47] J. P. Thomas,[17] E. N. Thompson,[34] P. D. Thompson,[17]
P. D. Thompson,[157] A. S. Thompson,[52] E. Thomson,[119] M. Thomson,[27] R. P. Thun,[86] F. Tian,[34] T. Tic,[124]
V. O. Tikhomirov,[93] Y. A. Tikhonov,[106] P. Tipton,[174] F. J. Tique Aires Viegas,[29] S. Tisserant,[82] J. Tobias,[47]
B. Toczek,[37] T. Todorov,[4] S. Todorova-Nova,[160] B. Toggerson,[162] J. Tojo,[65] S. Tokár,[143a] K. Tokunaga,[66]
K. Tokushuku,[65] K. Tollefson,[87] M. Tomoto,[100] L. Tompkins,[30] K. Toms,[102] G. Tong,[32a] A. Tonoyan,[13]
C. Topfel,[16] N. D. Topilin,[64] I. Torchiani,[29] E. Torrence,[113] H. Torres,[77] E. Torró Pastor,[166] J. Toth,[82,x]
F. Touchard,[82] D. R. Tovey,[138] D. Traynor,[74] T. Trefzger,[172] L. Tremblet,[29] A. Tricoli,[29] I. M. Trigger,[158a]
S. Trincaz-Duvoid,[77] T. N. Trinh,[77] M. F. Tripiana,[69] W. Trischuk,[157] A. Trivedi,[24,w] B. Trocmé,[54] C. Troncon,[88a]
M. Trottier-McDonald,[141] M. Trzebinski,[38] A. Trzupek,[38] C. Tsarouchas,[29] J. C-L. Tseng,[117] M. Tsiakiris,[104]
P. V. Tsiareshka,[89] D. Tsionou,[4] G. Tsipolitis,[9] V. Tsiskaridze,[47] E. G. Tskhadadze,[50a] I. I. Tsukerman,[94]
V. Tsulaia,[14] J.-W. Tsung,[20] S. Tsuno,[65] D. Tsybychev,[147] A. Tua,[138] A. Tudorache,[25a] V. Tudorache,[25a]
J. M. Tuggle,[30] M. Turala,[38] D. Turecek,[126] I. Turk Cakir,[3e] E. Turlay,[104] R. Turra,[88a,88b] P. M. Tuts,[34]
A. Tykhonov,[73] M. Tylmad,[145a,145b] M. Tyndel,[128] H. Tyrvainen,[29] G. Tzanakos,[8] K. Uchida,[20] I. Ueda,[154]
R. Ueno,[28] M. Ugland,[13] M. Uhlenbrock,[20] M. Uhrmacher,[53] F. Ukegawa,[159] G. Unal,[29] D. G. Underwood,[5]
A. Undrus,[24] G. Unel,[162] Y. Unno,[65] D. Urbaniec,[34] E. Urkovsky,[152] G. Usai,[7] M. Uslenghi,[118a,118b]
L. Vacavant,[82] V. Vacek,[126] B. Vachon,[84] S. Vahsen,[14] J. Valenta,[124] P. Valente,[131a] S. Valentinetti,[19a,19b]
S. Valkar,[125] E. Valladolid Gallego,[166] S. Vallecorsa,[151] J. A. Valls Ferrer,[166] H. van der Graaf,[104]
E. van der Kraaij,[104] R. Van Der Leeuw,[104] E. van der Poel,[104] D. van der Ster,[29] N. van Eldik,[83]
P. van Gemmeren,[5] Z. van Kesteren,[104] I. van Vulpen,[104] M. Vanadia,[98] W. Vandelli,[29] G. Vandoni,[29]
A. Vaniachine,[5] P. Vankov,[41] F. Vannucci,[77] F. Varela Rodriguez,[29] R. Vari,[131a] D. Varouchas,[14] A. Vartapetian,[7]
K. E. Varvell,[149] V. I. Vassilakopoulos,[55] F. Vazeille,[33] G. Vegni,[88a,88b] J. J. Veillet,[114] C. Vellidis,[8] F. Veloso,[123a]
R. Veness,[29] S. Veneziano,[131a] A. Ventura,[71a,71b] D. Ventura,[137] M. Venturi,[47] N. Venturi,[16] V. Vercesi,[118a]
M. Verducci,[137] W. Verkerke,[104] J. C. Vermeulen,[104] A. Vest,[43] M. C. Vetterli,[141,e] I. Vichou,[164] T. Vickey,[144b,aa]
O. E. Vickey Boeriu,[144b] G. H. A. Viehhauser,[117] S. Viel,[167] M. Villa,[19a,19b] M. Villaplana Perez,[166] E. Vilucchi,[46]
M. G. Vincter,[28] E. Vinek,[29] V. B. Vinogradov,[64] M. Virchaux,[135,a] J. Virzi,[14] O. Vitells,[170] M. Viti,[41]
I. Vivarelli,[47] F. Vives Vaque,[2] S. Vlachos,[9] D. Vladoiu,[97] M. Vlasak,[126] N. Vlasov,[20] A. Vogel,[20] P. Vokac,[126]
G. Volpi,[46] M. Volpi,[85] G. Volpini,[88a] H. von der Schmitt,[98] J. von Loeben,[98] H. von Radziewski,[47]
E. von Toerne,[20] V. Vorobel,[125] A. P. Vorobiev,[127] V. Vorwerk,[11] M. Vos,[166] R. Voss,[29] T. T. Voss,[173]
J. H. Vossebeld,[72] N. Vranjes,[12a] M. Vranjes Milosavljevic,[104] V. Vrba,[124] M. Vreeswijk,[104] T. Vu Anh,[80]
R. Vuillermet,[29] I. Vukotic,[114] W. Wagner,[173] P. Wagner,[119] H. Wahlen,[173] J. Wakabayashi,[100] J. Walbersloh,[42]

S. Walch,[86] J. Walder,[70] R. Walker,[97] W. Walkowiak,[140] R. Wall,[174] P. Waller,[72] C. Wang,[44] H. Wang,[171] H. Wang,[32b,bb] J. Wang,[150] J. Wang,[54] J. C. Wang,[137] R. Wang,[102] S. M. Wang,[150] A. Warburton,[84] C. P. Ward,[27] M. Warsinsky,[47] P. M. Watkins,[17] A. T. Watson,[17] M. F. Watson,[17] G. Watts,[137] S. Watts,[81] A. T. Waugh,[149] B. M. Waugh,[76] J. Weber,[42] M. Weber,[128] M. S. Weber,[16] P. Weber,[53] A. R. Weidberg,[117] P. Weigell,[98] J. Weingarten,[53] C. Weiser,[47] H. Wellenstein,[22] P. S. Wells,[29] M. Wen,[46] T. Wenaus,[24] S. Wendler,[122] Z. Weng,[150,r] T. Wengler,[29] S. Wenig,[29] N. Wermes,[20] M. Werner,[47] P. Werner,[29] M. Werth,[162] M. Wessels,[57a] C. Weydert,[54] K. Whalen,[28] S. J. Wheeler-Ellis,[162] S. P. Whitaker,[21] A. White,[7] M. J. White,[85] S. R. Whitehead,[117] D. Whiteson,[162] D. Whittington,[60] D. Wicke,[173] F. J. Wickens,[128] W. Wiedenmann,[171] M. Wielers,[128] P. Wienemann,[20] C. Wiglesworth,[74] L. A. M. Wiik,[47] P. A. Wijeratne,[76] A. Wildauer,[166] M. A. Wildt,[41,o] I. Wilhelm,[125] H. G. Wilkens,[29] J. Z. Will,[97] E. Williams,[34] H. H. Williams,[119] W. Willis,[34] S. Willocq,[83] J. A. Wilson,[17] M. G. Wilson,[142] A. Wilson,[86] I. Wingerter-Seez,[4] S. Winkelmann,[47] F. Winklmeier,[29] M. Wittgen,[142] M. W. Wolter,[38] H. Wolters,[123a,h] W. C. Wong,[40] G. Wooden,[86] B. K. Wosiek,[38] J. Wotschack,[29] M. J. Woudstra,[83] K. W. Wozniak,[38] K. Wraight,[52] C. Wright,[52] M. Wright,[52] B. Wrona,[72] S. L. Wu,[171] X. Wu,[48] Y. Wu,[32b,cc] E. Wulf,[34] R. Wunstorf,[42] B. M. Wynne,[45] S. Xella,[35] M. Xiao,[135] S. Xie,[47] Y. Xie,[32a] C. Xu,[32b,dd] D. Xu,[138] G. Xu,[32a] B. Yabsley,[149] S. Yacoob,[144b] M. Yamada,[65] H. Yamaguchi,[154] A. Yamamoto,[65] K. Yamamoto,[63] S. Yamamoto,[154] T. Yamamura,[154] T. Yamanaka,[154] J. Yamaoka,[44] T. Yamazaki,[154] Y. Yamazaki,[66] Z. Yan,[21] H. Yang,[86] U. K. Yang,[81] Y. Yang,[60] Y. Yang,[32a] Z. Yang,[145a,145b] S. Yanush,[90] Y. Yasu,[65] G. V. Ybeles Smit,[129] J. Ye,[39] S. Ye,[24] M. Yilmaz,[3c] R. Yoosoofmiya,[122] K. Yorita,[169] R. Yoshida,[5] C. Young,[142] S. Youssef,[21] D. Yu,[24] J. Yu,[7] J. Yu,[111] L. Yuan,[32a,ee] A. Yurkewicz,[105] V. G. Zaets,[127] R. Zaidan,[62] A. M. Zaitsev,[127] Z. Zajacova,[29] Yo. K. Zalite,[120] L. Zanello,[131a,131b] P. Zarzhitsky,[39] A. Zaytsev,[106] C. Zeitnitz,[173] M. Zeller,[174] M. Zeman,[124] A. Zemla,[38] C. Zendler,[20] O. Zenin,[127] T. Ženiš,[143a] Z. Zenonos,[121a,121b] S. Zenz,[14] D. Zerwas,[114] G. Zevi della Porta,[56] Z. Zhan,[32d] D. Zhang,[32b,bb] H. Zhang,[87] J. Zhang,[5] X. Zhang,[32d] Z. Zhang,[114] L. Zhao,[107] T. Zhao,[137] Z. Zhao,[32b] A. Zhemchugov,[64] S. Zheng,[32a] J. Zhong,[117] B. Zhou,[86] N. Zhou,[162] Y. Zhou,[150] C. G. Zhu,[32d] H. Zhu,[41] J. Zhu,[86] Y. Zhu,[32b] X. Zhuang,[97] V. Zhuravlov,[98] D. Zieminska,[60] R. Zimmermann,[20] S. Zimmermann,[20] S. Zimmermann,[47] M. Ziolkowski,[140] R. Zitoun,[4] L. Živković,[34] V. V. Zmouchko,[127,a] G. Zobernig,[171] A. Zoccoli,[19a,19b] Y. Zolnierowski,[4] A. Zsenei,[29] M. zur Nedden,[15] V. Zutshi,[105] and L. Zwalinski[29]

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