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Measurement of the differential cross-section of B⁺ meson production in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS

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Measurement of the differential cross-section of B^+ meson production in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS



The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: The production cross-section of B^+ mesons is measured as a function of transverse momentum p_T and rapidity y in proton-proton collisions at centre-of-mass energy $\sqrt{s} = 7$ TeV, using 2.4fb^{-1} of data recorded with the ATLAS detector at the Large Hadron Collider. The differential production cross-sections, determined in the range $9\text{ GeV} < p_T < 120\text{ GeV}$ and $|y| < 2.25$, are compared to next-to-leading-order theoretical predictions.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

The b -hadron production cross-section has been predicted with next-to-leading-order (NLO) accuracy for more than twenty years [1, 2] and more recently it has been predicted with fixed order plus next-to-leading-logarithms (FONLL) calculations [3, 4]. Several measurements were performed with proton-antiproton collisions by the UA1 collaboration at the $S\bar{p}\bar{p}S$ collider (CERN) at a centre-of-mass energy of $\sqrt{s} = 630$ GeV [5, 6] and by the CDF and D0 collaborations at the Tevatron collider (Fermilab) at $\sqrt{s} = 630$ GeV, 1.8 TeV and 1.96 TeV [7–16]. These measurements made a significant contribution to the understanding of heavy-quark production in hadronic collisions [17]. However, the dependence of the theoretical predictions for b -quark production on the factorisation and renormalisation scales and the b -quark mass m_b [2] results in theoretical uncertainties of up to 40% and, therefore, it is important to perform precise measurements of b -hadron production cross-sections. In addition, measurements of b -hadron production cross-sections are of theoretical interest at higher \sqrt{s} [18] and for B mesons of higher transverse momentum (p_T) [19].

Measurements of the b -hadron production cross-section in proton-proton collisions at the Large Hadron Collider (LHC) provide further tests of QCD calculations for heavy-quark production at higher centre-of-mass energies and in wider transverse momentum (p_T) and rapidity (y) ranges, thanks to the extended coverage and excellent performance of the LHC detectors. Recently the LHCb collaboration measured b -hadron production cross-sections using $B^\pm \rightarrow J/\psi K^\pm$, $b \rightarrow J/\psi X$ and semileptonic b -hadron decays in the forward

rapidity region at $\sqrt{s} = 7$ TeV [20–22]. The CMS collaboration measured the production cross-sections for B^+ , B^0 , B_s mesons, Λ_b baryons, and inclusive b -hadron production using $b \rightarrow J/\psi X$ decays, semileptonic decays, and b -hadron jets at $\sqrt{s} = 7$ TeV [23–30]. ATLAS has measured b -hadron production cross-sections using semileptonic decays [31, 32], $b \rightarrow J/\psi X$ decays [33] and b -hadron jets [34].

This paper presents a measurement of the B^+ production cross-section using the decay channel $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ in pp collisions at $\sqrt{s} = 7$ TeV, as a function of B^+ transverse momentum and rapidity. The ATLAS and CMS detectors provide coverage in the central rapidity region, so their measurements are complementary to the LHCb measurements. With 2.4 fb^{-1} of data collected by the ATLAS detector, this analysis extends the measurement of the B^+ cross-section up to p_T of about 100 GeV, allowing comparisons with NLO predictions in four rapidity regions in the range $|\eta| < 2.25$ to be made. The results are reported for B^+ meson production, but are derived from both charged states, under the assumption that in the phase space accessible by this measurement the B^+ and B^- production cross-sections are equal. This assumption is in agreement with the predictions of NLO Monte Carlo generators and is also valid within the precision of the measurement.

2 The ATLAS detector

The ATLAS experiment [35] uses a general-purpose detector¹ consisting of an inner tracker, a calorimeter and a muon spectrometer. A brief outline of the components that are most relevant for this analysis is given below. The inner detector (ID) directly surrounds the interaction point; it includes a silicon pixel detector (Pixel), a silicon microstrip detector (SCT) and a transition radiation tracker (TRT), and is embedded in an axial 2 T magnetic field. The ID covers the range $|\eta| < 2.5$ and is enclosed by a calorimeter system containing electromagnetic and hadronic sections. The calorimeter is surrounded by a large muon spectrometer (MS) inside an air-core toroidal magnet system that contains a combination of monitored drift tubes (MDTs) and cathode strip chambers (CSCs), designed to provide precise position measurements in the bending plane in the range $|\eta| < 2.7$. In addition, resistive plate chambers (RPCs) and thin gap chambers (TGCs) with a coarse position resolution but a fast response time are used primarily to trigger muons in the ranges $|\eta| < 1.05$ and $1.05 < |\eta| < 2.4$, respectively. RPCs and TGCs are also used to provide position measurements in the non-bending plane and to improve pattern recognition and track reconstruction. Momentum measurements in the MS are based on track segments formed in at least two of the three stations of the MDTs and the CSCs.

The ATLAS trigger system [36] has three levels: the hardware-based Level-1 trigger and the two-stage High Level Trigger (HLT), comprising the Level-2 trigger and Event Filter (EF). At Level-1, the muon trigger searches for patterns of hits satisfying different p_T

¹ATLAS uses a right-handed coordinate system (x, y, z) with its origin at the nominal interaction point. The z -axis is along the beam pipe, the x -axis points to the centre of the LHC ring and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle.

thresholds using the RPCs and TGCs. The region-of-interest (RoI) around these Level-1 hit patterns then serves as a seed for the HLT muon reconstruction, in which dedicated algorithms are used to incorporate information from both the MS and the ID, achieving a position and momentum resolution close to that provided by the offline muon reconstruction.

3 Data and Monte Carlo samples

The analysis is based on data collected at the LHC during the proton-proton running period in the early 2011 (April-August) with a dimuon trigger that required the presence of at least two muon candidates with $p_T > 4$ GeV. Later run periods are not considered because this trigger was prescaled. Selected events are required to have occurred during stable LHC beam conditions and the ID, as well as the MS, must have been fully operational. The collected data correspond to an integrated luminosity of 2.4 fb^{-1} with an uncertainty of 1.8% [37].

In the analysis two Monte Carlo (MC) samples are used. The first sample simulates the signal $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$, while the second simulates $b\bar{b}$ production, with $b\bar{b} \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X$, including the signal and also the backgrounds which are relevant for the analysis. Both samples were generated with PYTHIA 6 [38] using the 2011 ATLAS tune [39]. The response of the ATLAS detector was simulated [40] using GEANT4 [41]. Additional pp interactions in the same and nearby bunch crossings (pile-up) were included in the simulation.

The MC samples are used in several parts of the analysis. The first is the extraction of the fit models for signal and background. The second is the construction of efficiency maps for the muon trigger and reconstruction. The third is the estimation of the signal reconstruction efficiency and the kinematic acceptance of the selection criteria applied to the final-state particles in each p_T and rapidity interval used in the analysis. In the MC samples generated with PYTHIA, the decay $J/\psi \rightarrow \mu^+ \mu^-$ is isotropic. In order to take into account that the J/ψ meson is produced with zero helicity in the B^\pm rest frame, in the analysis a weight proportional to $\sin^2 \theta^*$ is applied to each event, where θ^* is the μ^+ angle relative to the B^\pm direction in the J/ψ rest frame.

To compare the cross-section measurements with theoretical predictions, NLO QCD calculations matched with a leading-logarithmic parton shower MC simulation are used. Predictions for $b\bar{b}$ production are evaluated with two packages: POWHEG-HVQ (POWHEG-BOX 1.0) [42, 43] and MC@NLO 4.01 [44, 45]. For the hadronisation process, POWHEG is matched with PYTHIA, which uses the Lund string model [46] with the Bowler modification [47] of the Lund symmetric fragmentation function [48]. MC@NLO is matched with HERWIG [49], which uses a cluster model for hadronisation [50]. The b -quark production cross-section is also calculated in the FONLL theoretical framework [19], permitting direct comparison with the data assuming the world average of the hadronisation fraction $f_{\bar{b} \rightarrow B^+} = 0.401 \pm 0.008$ [51]. The theoretical uncertainties associated with the POWHEG, MC@NLO and FONLL predictions are discussed in section 7 where the comparisons to the measured cross-sections are made.

4 Event selection and reconstruction

Events for the analysis were selected with a trigger that requires two muon RoIs at Level-1. A full track reconstruction of dimuon candidates was performed by the HLT where both muons are required to have $p_T > 4$ GeV and fulfill additional requirements, loosely selecting events compatible with J/ψ meson decays into a muon pair.

Events selected by the trigger are required to have at least one reconstructed primary vertex with a minimum of three associated tracks. Tracks reconstructed in the ID which are matched to tracks reconstructed in the MS are selected as muon candidates. Muon candidates are required to have sufficient numbers of hits in the Pixel, SCT and TRT detectors to ensure accurate ID measurements. The same selection criteria are applied to tracks selected as potential K^\pm candidates.

Events are required to contain at least one pair of reconstructed oppositely signed muons that fit successfully to a common vertex, using a vertexing algorithm [52]. The momenta of the muons and the dimuon invariant mass are calculated from the refitted track parameters returned by the vertexing algorithm. Muon pairs with a common vertex are considered as $J/\psi \rightarrow \mu^+\mu^-$ candidates if their invariant mass lies in the mass range 2.7–3.5 GeV. Because of the trigger requirements on muons, the reconstructed J/ψ candidate must have rapidity $|y| < 2.25$ and the reconstructed muons $p_T > 4$ GeV and $|\eta| < 2.3$. To ensure that the muon pair from the J/ψ candidate is the one that triggered the event, an (η, ϕ) match between the trigger muons and those of the J/ψ candidate is required. If multiple J/ψ candidates are found in the event, all are considered in the formation of B^\pm candidates.

The muon tracks of the selected J/ψ candidates are again fitted to a common vertex with an additional third track with p_T greater than 1 GeV. The three-track vertex fit is performed by constraining the muon tracks to the J/ψ mass [51]. The K^\pm mass is assigned to the third track and the $\mu^+\mu^-K^\pm$ invariant mass is calculated from the refitted track parameters returned by the vertexing algorithm. Regarding the quality of the three-track vertex fit, the χ^2 per degree of freedom must be $\chi^2/N_{\text{d.o.f.}} < 6$, which is found to select about 99% of signal events while rejecting background events. We retain B^+ and B^- candidates with $p_T > 9$ GeV and $|y| < 2.25$ in the mass range 5.040–5.800 GeV. After this selection, the average candidate multiplicity is 1.3. The multiple B^\pm candidates result mainly from random combinations of tracks with selected J/ψ mesons produced promptly in pp collisions. Such combinations result in non-resonant background and do not affect the estimation of the signal yield.

5 Cross-section determination

The differential cross-section for B^+ meson production in pp collisions times branching ratio to the final state is given by

$$\frac{d^2\sigma(pp \rightarrow B^+X)}{dp_T dy} \cdot \mathcal{B} = \frac{N^{B^+}}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}, \quad (5.1)$$

where \mathcal{B} is the total branching ratio of the signal decay, which is $(6.03 \pm 0.21) \times 10^{-5}$, obtained by combining the world-average values of the branching ratios for $B^+ \rightarrow J/\psi K^+$ and $J/\psi \rightarrow \mu^+ \mu^-$ [51], N^{B^+} is the number of $B^+ \rightarrow J/\psi K^+$ signal decays produced, \mathcal{L} is the integrated luminosity of the data sample and Δp_T , Δy are the widths of p_T and y intervals. Assuming that B^+ and B^- mesons are produced in equal numbers, N^{B^+} is derived from the average yield of the two reconstructed charged states in a (p_T, y) interval, after correcting for detector effects and acceptance,

$$N^{B^+} = \frac{1}{A} \frac{N_{\text{reco}}^{B^+}}{\varepsilon^{B^+}} = \frac{1}{A} \frac{N_{\text{reco}}^{B^-}}{\varepsilon^{B^-}} = \frac{1}{A} \frac{N_{\text{reco}}^{B^\pm}}{\varepsilon^{B^+} + \varepsilon^{B^-}}, \quad (5.2)$$

where $N_{\text{reco}}^{B^\pm}$ is the number of reconstructed signal events, obtained from data with a fit to the invariant mass distribution of B^\pm candidates, A is the acceptance of the kinematic selection of the final-state particles of the signal decay, obtained from MC simulation, and ε^{B^+} , ε^{B^-} are the reconstruction efficiencies for the B^\pm signal decays. Separate efficiency is needed for B^+ and B^- signal decays, because the different interaction cross-sections of K^+ and K^- with the detector material result in different reconstruction efficiencies for the two charged mesons. The reconstruction efficiencies for B^+ and B^- are obtained from MC simulation. In the following, ε^{B^-} is implicitly referred to, together with ε^{B^+} . The efficiency for B^+ events is defined as the product of trigger, muon reconstruction (ID and MS), kaon reconstruction and vertexing efficiencies,

$$\varepsilon^{B^+} = \varepsilon_{\text{trigger}}^{J/\psi} \cdot \varepsilon^{\mu^+} \cdot \varepsilon^{\mu^-} \cdot \varepsilon_{\text{ID}}^{K^+} \cdot \varepsilon_{\text{vertex}}^{\mu\mu K} = \varepsilon_{\text{trigger}}^{J/\psi} \cdot \varepsilon_{\text{MS}}^{\mu^+} \cdot \varepsilon_{\text{MS}}^{\mu^-} \cdot (\varepsilon_{\text{ID}}^{\mu})^2 \cdot \varepsilon_{\text{ID}}^{K^+} \cdot \varepsilon_{\text{vertex}}^{\mu\mu K}.$$

In the above equation, $\varepsilon_{\text{MS}}^{\mu^+}$ and $\varepsilon_{\text{MS}}^{\mu^-}$ are the efficiencies for reconstructing μ^+ and μ^- in the MS, which differ for muons of low p_T and large $|\eta|$ because of the bending of tracks in the toroidal magnetic field. This effect is to large extent symmetric for a simultaneous change of sign in the muon charge and in η . The trigger efficiency, $\varepsilon_{\text{trigger}}^{J/\psi}$, depends on the ability of the trigger to identify muons of given p_T and η as decay products of a J/ψ meson. The trigger efficiency includes independent and correlated terms between the two muons [53]. The efficiency ε^{B^+} for a given (p_T, y) interval is obtained from MC-simulated signal events from the fraction

$$\varepsilon^{B^+} = \frac{N_{\text{MC, reco}}^{B^+}}{N_{\text{MC, gen}}^{B^+}}, \quad (5.3)$$

where the denominator is the number of signal events generated in a given interval of the generated p_T and y and the numerator is the number of signal events that pass the trigger and the offline selection requirements in the same (p_T, y) interval of the reconstructed variables. Bin-to-bin migration effects are included in the efficiency definition of eq. (5.3). The trigger and muon reconstruction efficiencies are measured in the data using auxiliary single muon and dimuon triggers and tag-and-probe methods [53] and the simulation is corrected with per-event weights to reproduce the efficiencies measured with data. The derived weights, $w_{\text{MS}}^{\mu^+}$, $w_{\text{MS}}^{\mu^-}$, $w_{\text{trigger}}^{J/\psi}$, are applied in each reconstructed MC-simulated signal

event, so that $N_{\text{MC, reco}}^{B^+}$ in eq. (5.3) is now defined as

$$N_{\text{MC, reco}}^{B^+} = \sum_{i=1}^{N_{\text{MC}}^{\text{events}}} (w_{\text{MS}}^{\mu^+})_i \cdot (w_{\text{MS}}^{\mu^-})_i \cdot (w_{\text{trigger}}^{J/\psi})_i, \quad (5.4)$$

where $N_{\text{MC}}^{\text{events}}$ is the number of reconstructed MC-simulated signal events before applying the weights derived from data. The efficiency for reconstructing muons in the ID, $\varepsilon_{\text{ID}}^{\mu}$, and the vertexing efficiency, $\varepsilon_{\text{vertex}}^{\mu\mu K}$, are found to be equal to 99% and are well reproduced by the MC simulation. The reconstruction efficiency for hadrons in the ID was verified in ref. [54] for data and simulation; for the kaons used in this analysis, the efficiency is obtained from simulation.

The number of reconstructed B^{\pm} mesons is obtained using a binned maximum likelihood fit to the invariant mass distribution of the selected candidates. The probability density function (pdf) for the signal is defined as the sum of two Gaussians of relative fraction f_1 and corresponding widths σ_1, σ_2 , both centred at the reconstructed B^{\pm} mass. The pdf for the background consists of three components to model the following three sources of background:

- $B^{\pm} \rightarrow J/\psi \pi^{\pm}$, where the kaon mass is wrongly assigned to the pion; this decay is Cabibbo suppressed with a relative fraction of 4.9% [51] with respect to the signal decay; it produces a resonant structure in the signal region that is modelled with a Crystal Ball function (see appendix E of ref. [55]).
- $B^{\pm/0} \rightarrow J/\psi K^{*\pm/0} \rightarrow J/\psi (K\pi)^{\pm/0}$ and $B^{\pm/0} \rightarrow J/\psi (K\pi)^{\pm/0}$, where the final-state pion is not associated to the decay vertex, creating a resonant structure displaced from the B^{\pm} mass by about m_{π} , where m_{π} is the mass of the pion; these partially reconstructed B -decays are modelled with a complementary error function.
- Combinatorial background from random combinations of J/ψ (produced promptly in pp collisions or in feed-down from B -decays) with a track; it is modelled with an exponential function. The background from muon pairs not originating from J/ψ decays is negligible after the full B^{\pm} candidate selection.

The extraction of the signal yield is done in two steps. First, the shapes of the signal and the resonant background pdfs, which depend on the p_{T} and y of the B^{\pm} meson candidate, are obtained by fitting the invariant mass distribution of signal and background events from MC samples in each (p_{T}, y) interval. Then the invariant mass distribution of the data is fitted in the same (p_{T}, y) interval. The parameters for the shape of the signal pdf (σ_1, σ_2 and f_1) and the resonant backgrounds are fixed to the results of the fits to MC event samples. The relative normalisation of the $B^{\pm} \rightarrow J/\psi \pi^{\pm}$ decay to the signal is fixed to the fraction of the world-average values for their branching ratios, and is corrected for the difference in acceptance for the two decay modes. The reconstructed mass $m_{B^{\pm}}$ is obtained from data for the full p_{T} range in a rapidity interval by fitting the invariant mass distribution of the selected candidates, and is fixed throughout the fits in p_{T} intervals. Therefore, when fitting the data in each (p_{T}, y) interval, the free parameters are the

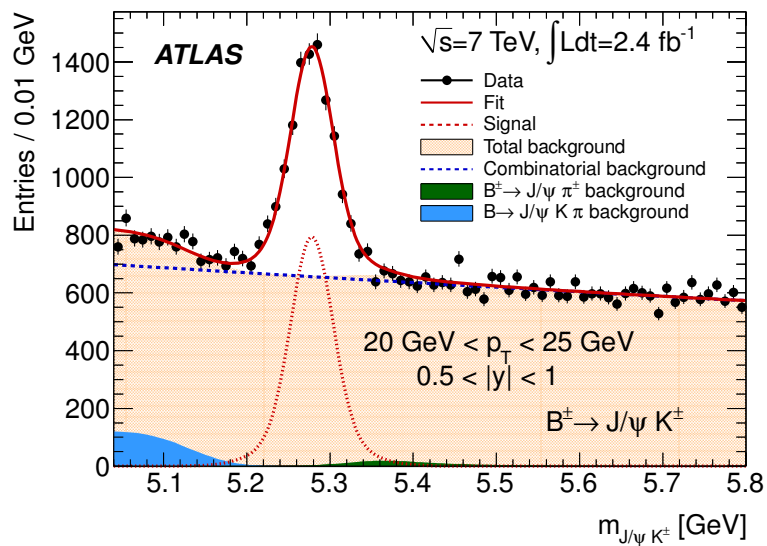


Figure 1. The observed invariant mass distribution of B^\pm candidates, $m_{J/\psi K^\pm}$, with transverse momentum and rapidity in the range $20 \text{ GeV} < p_T < 25 \text{ GeV}$, $0.5 < |y| < 1$ (dots), compared to the binned maximum likelihood fit (solid line). The error bars represent the statistical uncertainty. Also shown are the components of the fit as described in the legend.

normalisation of the signal, the normalisation of the partially reconstructed B -decays, and the slope of the combinatorial background. The results of the fits to the invariant mass distributions of the selected B^\pm candidates from data are exemplified in figure 1 for an interval of intermediate p_T and central rapidity. The stability of the fit was tested with simulated samples of signal and background with statistical size similar to our data and no evidence of bias in the fit was found.

The total number of signal B^\pm events observed in data in the full p_T and y range covered by the analysis, $9 \text{ GeV} < p_T < 120 \text{ GeV}$ and $|y| < 2.25$, before acceptance and efficiency corrections, is about 125600. These events populate four intervals in $|y|$ and eight intervals in p_T for the differential cross-section measurement. The acceptance correction, A , has a small dependence on y and ranges from 4% to 85% from the low to the high p_T intervals. The efficiency ε^{B^+} has a dependence on both y and p_T and ranges from 25% to 40%. The relative difference between the efficiencies for reconstructing B^+ and B^- mesons, $(\varepsilon^{B^+} - \varepsilon^{B^-})/\varepsilon^{B^+}$, has a dependence on p_T and ranges from 5% to 2%.

The assumption of equal B^+ and B^- production is tested by fitting the invariant mass distribution of B^+ and B^- candidates separately. The resulting yields, before applying efficiency corrections, are 63530 ± 840 and 62090 ± 840 respectively, where the quoted uncertainties are statistical. Taking into account the different efficiencies for reconstructing B^+ and B^- mesons, the ratio of B^+/B^- is found to be consistent with unity, within the statistical precision of this test.

6 Systematic uncertainties

Various sources of systematic uncertainty on the measurement of the B^+ production cross-section are considered and discussed below:

1. *Trigger.* The trigger efficiency is obtained from data in bins of p_T and $q \cdot \eta$ of the muon, where q is the muon charge, using a tag-and-probe method [53]. Then, the correction weights for the trigger efficiency $w_{\text{trigger}}^{J/\psi}$ (see eq. (5.4)) are obtained from the fraction of the measured efficiency from data over the expectation from simulation in each $(p_T, q \cdot \eta)$ bin. As the statistical components of the uncertainty associated with the weights for the trigger efficiency are dominant, the uncertainties on the cross-section are derived from a series of pseudo-experiments by allowing the weights to fluctuate randomly under a Gaussian assumption, according to their assigned uncertainty.
2. *Fit.* For the fit method, three sources of systematic uncertainty are identified and considered to be uncorrelated. These are the shape of the signal pdf, the reconstructed B^\pm mass and the shape of the background pdf. Below, the procedure to estimate the systematic uncertainty from each source is described, and the resulting uncertainties are added quadratically to obtain the total systematic uncertainty from the fit method in each (p_T, y) interval.
 - (a) *Uncertainty on shape of the signal pdf.* This uncertainty is estimated with variations of the fit model, where the values of the signal pdf parameters σ_1 , σ_2 , f_1 are varied independently within their uncertainties derived from the fit to signal events from MC simulation. From these variations of the fit model, the largest absolute value of the signal yield variation is taken as the systematic uncertainty from the signal pdf shape, in order to account for the large correlations of these parameters. Two alternative pdfs were considered (three Gaussians, two Crystal Ball + Gaussian) and no significant differences in the signal yield were observed. Among the various sources of systematic uncertainty considered for the fit method, the signal pdf is dominant and its contribution ranges from 1% to 8%.
 - (b) *Uncertainty on the B^\pm mass value.* The reconstructed mass m_{B^\pm} is obtained from data by fitting the invariant mass distribution of all candidates with $p_T > 9$ GeV in each of the four rapidity intervals. The resulting values are used to fix this parameter when performing the fits in the various (p_T, y) intervals and their statistical uncertainties (0.4–1.0 MeV) are used to estimate the systematic uncertainty on the signal yield. The fits in the various (p_T, y) intervals are repeated varying the value of m_{B^\pm} within its statistical uncertainty. The observed difference in the signal yield is smaller than 1%.
 - (c) *Uncertainty on the shape of the background pdf.* The fit includes three components for the description of the background (see below), and each contributes as a possible source of uncertainty. In order to account for the large correlations between the three components, the systematic uncertainty assigned to the

background modelling for each (p_T, y) interval is obtained after varying each component independently, and taking the largest observed difference in the signal yield.

- i. Combinatorial background: with a polynomial instead of exponential shape for the combinatorial background; the observed relative difference in the signal yield ranges from 0.1% to 4%, where the larger change is observed for higher values of y and p_T .
 - ii. $B^\pm \rightarrow J/\psi \pi^\pm$: for the resonant background from $B^\pm \rightarrow J/\psi \pi^\pm$, the dominant uncertainty comes from the relative branching fraction of this decay with respect to the signal, which has an uncertainty of 10% [51]. Varying this fraction in the fit within its uncertainty was found to have a small effect on the signal yield ($\sim 1\%$).
 - iii. Partially reconstructed B -decays: the resonant background from partially reconstructed B -decays is modelled with a complementary error function. When varying its parameters within their uncertainties from the fits to background events from MC simulation, the observed difference in the signal yield is smaller than 1%.
3. *Kaon track reconstruction.* The efficiency of hadron reconstruction is determined from MC simulation and validated with data [54], with the uncertainty dominated by the material description. The uncertainty ranges with increasing rapidity from 2% to 4% for the kaons used in this analysis.
 4. *Acceptance.* The acceptance in each (p_T, y) interval has a relative uncertainty ranging from 1% to 4%, due to the size of the MC sample, which is assigned as systematic uncertainty.
 5. *Muon reconstruction.* The muon reconstruction efficiency is obtained from data in bins of p_T and $q \cdot \eta$ of the muon, using a tag-and-probe method [53]. Then, the correction weights w_{MS}^μ (see eq. (5.4)) are obtained from the fraction of the measured efficiency from data over the expectation from simulation in each $(p_T, q \cdot \eta)$ bin. The uncertainties associated with the weights for the muon reconstruction efficiency are mainly statistical, so the same procedure as for the trigger efficiency is used to estimate the systematic uncertainty on the cross-section. In addition, there is also an uncertainty coming from the efficiency for reconstructing a muon in the ID with the selection criteria used in this analysis. This efficiency is found to be 99% with a systematic uncertainty of 0.5% for each muon.
 6. B^\pm *vertex-finding efficiency.* The vertex quality requirement has an efficiency of $\sim 99\%$ and is fairly independent of p_T and y . It was estimated with data by comparing the signal yields in four rapidity intervals before and after applying this requirement and is found to be consistent with the expectation from MC simulation. A systematic uncertainty of 2% is assigned to the cross-section, as the maximum difference observed between the estimate from data and the expectation from MC simulation for this efficiency.

7. *Branching ratio.* The total branching ratio of the selected decay, obtained by combining the branching ratios of the decays $B^\pm \rightarrow J/\psi K^\pm$ and $J/\psi \rightarrow \mu^+ \mu^-$, has an uncertainty of 3.4% [51].
8. *Luminosity.* The luminosity calibration is based on data from van der Meer scans and has an uncertainty of 1.8% [37].
9. *Signal efficiency.* The efficiency correction factor for B^\pm signal events is obtained from MC simulation (eq. (5.3)). The systematic uncertainty assigned to this factor has two components, which are added in quadrature:
 - (a) *Uncertainty from the size of the MC sample.* The sample used for the estimation of the efficiency correction factor corresponds to a luminosity similar to that of the data sample. Due to the size of this sample, the efficiency estimation has an uncertainty that is small ($\sim 1\%$) in most intervals and becomes significant in the high- p_T interval 70–120 GeV ($\sim 10\%$). It is added quadratically to the rest of the sources of uncertainty.
 - (b) *Uncertainty from K^+/K^- efficiency asymmetry.* The efficiencies for reconstructing K^+ and K^- mesons are obtained from simulation and their relative difference is found to be $\sim 3.5\%$. This difference is verified with data and the statistical uncertainty of the estimate from data is used to assign a systematic uncertainty of 1%, which propagates to the cross-section through the sum of efficiencies ($\varepsilon^{B^+} + \varepsilon^{B^-}$) in eq. (5.2).

The range of these uncertainties is summarised in table 1. Their breakdown in (p_T, y) intervals is given in figure 2. In the same figure, the total systematic uncertainty, including the uncertainties from the luminosity and branching ratio, is compared to the statistical precision of the measurement. In most intervals, the systematic uncertainty dominates.

Additional sources of systematic uncertainty were examined, but were found to be less significant and were neglected. Residual effects related to final-state radiation have been determined to be smaller than 1% and are neglected. Differences in the underlying kinematic distributions modelled by the PYTHIA and NLO generators, including parton distribution functions, were considered. The impact on the acceptance and the signal efficiency was estimated by reweighting the kinematic distributions of PYTHIA to those of POWHEG and MC@NLO. The largest effect is seen in the high-rapidity intervals ($1.5 < |y| < 2.25$), where the maximum relative difference observed is 1%, with a statistical uncertainty of the same order, while in most (p_T, y) intervals the effect is very small ($\sim 0.1\%$). Bin-to-bin migration of signal events due to finite detector resolution is studied with MC simulation. It is found to be a small effect ($< 0.5\%$), which is included in the definition of signal efficiency (eq. (5.3)). Potential effects in the calculation of the signal efficiency due to the difference between the momentum scales in data and MC simulation are expected to be larger in the lower p_T intervals used in this analysis, where they were estimated to be smaller than 0.5%.

Source	Relative uncertainty [%]			
	$ y < 0.5$	$0.5 < y < 1$	$1 < y < 1.5$	$1.5 < y < 2.25$
Statistical uncertainty	2.2–14	2.5–17	3.2–22	3.8–24
Total systematic uncertainty	6.7–14	6.5–13	6.9–16	7.6–18
1. Trigger	3.8–7.4	3.2–6.2	3.4–7.0	3.6–8.8
2. Invariant mass fit	1.8–3.4	1.7–5.3	2.4–8.9	2.6–7.6
3. Kaon reconstruction	2.2	2.2–2.4	2.5–2.9	3.5–4.0
4. Acceptance	0.9–3.5	0.9–3.6	1.0–4.2	1.0–5.8
5. Muon reconstruction	0.5–1.3	0.5–1.7	0.5–2.1	0.6–5.4
6. B^\pm vertexing	2.0	2.0	2.0	2.0
7. Branching ratio	3.4	3.4	3.4	3.4
8. Luminosity	1.8	1.8	1.8	1.8
9. Signal efficiency	1.3–10	1.3–9.1	1.3–9.5	1.2–12

Table 1. The statistical and total systematic uncertainties on the cross-section measurement in different ranges of rapidity y . The contributions from the various sources of systematic uncertainty are also given. The range of values quoted for some of the uncertainties represent the lower and upper limit of the uncertainty over the p_T range in a given rapidity range.

7 Cross-section results

Using eq. (5.1), the differential cross-section for B^+ production times the product of branching ratios \mathcal{B} is obtained as a function of p_T and y of the B^+ meson and the results are shown in tables 2 and 3, averaged over each (p_T, y) interval. The double-differential cross-section is integrated over p_T to obtain the differential cross-section $d\sigma/dy$, or over rapidity to obtain $d\sigma/dp_T$, and results are reported in tables 4 and 5. When summing over the intervals in p_T or rapidity, the systematic uncertainty from each source is calculated from the linear sum of the contributions from each interval, as they are correlated. Tabulated results of the measurements presented in this paper are available in HEPDATA [56].

Using the world-average values for the branching ratio \mathcal{B} , the differential cross-sections obtained are compared to predictions of POWHEG (+PYTHIA) and MC@NLO (+HERWIG) and the FONLL approximations. For POWHEG and MC@NLO the CT10 [57] parameterisation for the parton distribution function of the proton is used, while for FONLL calculations the CTEQ6.6 [58] parameterisation is used. In all cases, a b -quark mass of 4.75 ± 0.25 GeV is used, with the renormalisation and factorisation scales, μ_r, μ_f , set to $\mu_r = \mu_f = \mu$, where μ has different definitions for the POWHEG, MC@NLO and FONLL predictions.² The predictions are quoted with uncertainties due to the b -quark mass and

²For POWHEG: $\mu^2 = m_Q^2 + (m_{Q\bar{Q}}^2/4 - m_Q^2) \sin^2 \theta_Q$, where $m_{Q\bar{Q}}$ is the invariant mass of the $Q\bar{Q}$ system and θ_Q is the polar angle of the heavy quark in the $Q\bar{Q}$ rest frame. For MC@NLO: $\mu^2 = m_Q^2 + (p_{T,Q} + p_{T,\bar{Q}})^2/4$, where $p_{T,Q}$ and $p_{T,\bar{Q}}$ are the transverse momenta of the produced heavy quark and antiquark respectively, and m_Q is the heavy-quark mass. For FONLL: $\mu = \sqrt{m_Q^2 + p_{T,Q}^2}$.

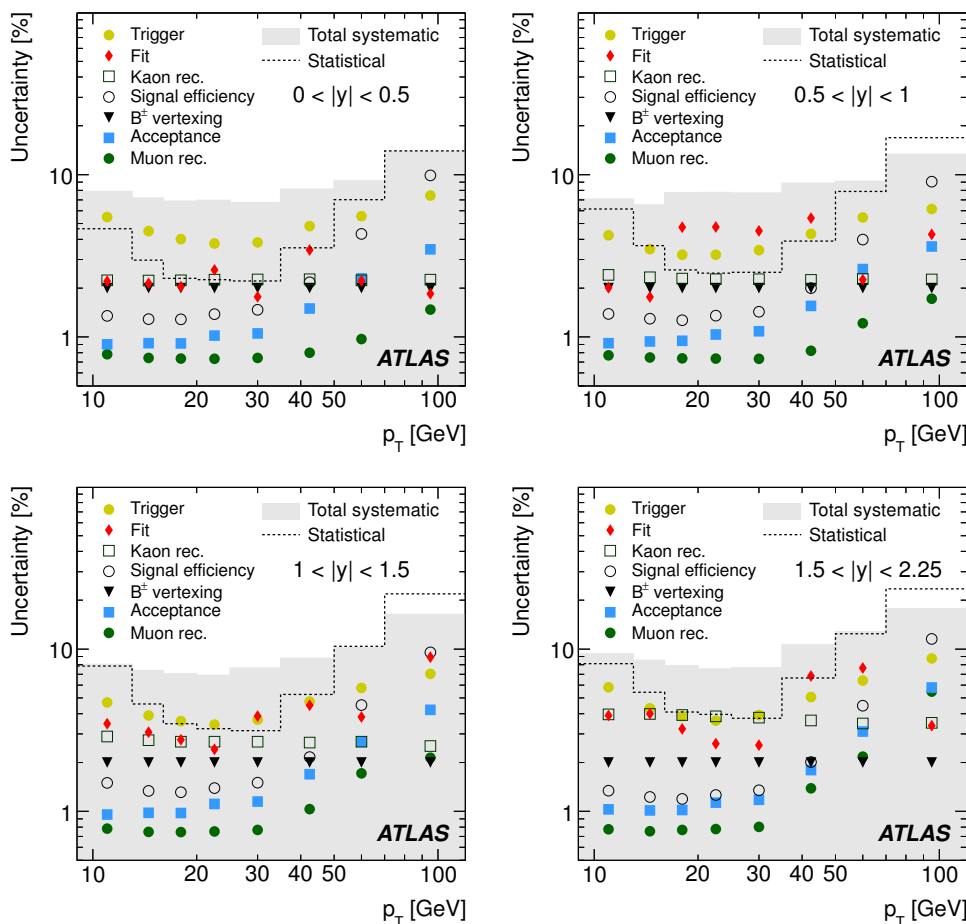


Figure 2. Relative systematic uncertainties on the cross-section determination as a function of p_T for different rapidity ranges. The total systematic uncertainty (solid area), including uncertainties from luminosity (1.8%) and branching ratio (3.4%), is compared to the statistical uncertainty (dashed line).

renormalisation and factorisation scales. Uncertainties from factorisation and renormalisation scales are estimated by varying them independently up and down by a factor of two [19].

POWHEG and MC@NLO predictions are compared with the double-differential cross-section measurement in figure 3. To allow a better comparison between the measured cross-sections and the NLO predictions, figure 4 shows their ratio for each rapidity range separately for POWHEG and MC@NLO. The data are in good agreement with POWHEG in all rapidity intervals. MC@NLO, however, predicts a lower production cross-section at low p_T and a p_T spectrum that is softer than the data for $|y| < 1$ and harder than the data for $|y| > 1$. In the integration of the four rapidity intervals, this effect averages out and the prediction of the cross-section $d\sigma/dp_T$ is compatible with data.

The FONLL prediction is compared with the measured differential cross-section $d\sigma/dp_T$ in figure 5. In this figure, the results from CMS [23] for B^+ meson production as a function of p_T , covering the rapidity range $|y| < 2.4$, are shown for comparison. The

p_T interval [GeV]	$\frac{d^2\sigma}{dp_T dy} \cdot \mathcal{B}(B^+ \rightarrow J/\psi K^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$ [pb/GeV]					
	$0 < y < 0.5$			$0.5 < y < 1$		
9–13	24.5	± 1.1	± 1.7	21.7	± 1.3	± 1.4
13–16	8.7	± 0.3	± 0.6	8.5	± 0.3	± 0.5
16–20	3.76	± 0.09	± 0.22	3.9	± 0.10	± 0.27
20–25	1.54	± 0.04	± 0.09	1.57	± 0.04	± 0.11
25–35	0.467	± 0.010	± 0.027	0.468	± 0.012	± 0.033
35–50	0.097	± 0.003	± 0.007	0.095	± 0.004	± 0.008
50–70	0.0165	± 0.0012	± 0.0014	0.0178	± 0.0014	± 0.0015
70–120	0.00188	± 0.00026	± 0.00025	0.00202	± 0.00034	± 0.00026

Table 2. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each (p_T, y) interval in the rapidity range $|y| < 0.5$ and $0.5 < |y| < 1$. The first quoted uncertainty is statistical, the second uncertainty is systematic.

p_T interval [GeV]	$\frac{d^2\sigma}{dp_T dy} \cdot \mathcal{B}(B^+ \rightarrow J/\psi K^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$ [pb/GeV]					
	$1 < y < 1.5$			$1.5 < y < 2.25$		
9–13	23.6	± 1.9	± 1.7	22.3	± 1.8	± 1.9
13–16	8.0	± 0.4	± 0.5	7.1	± 0.4	± 0.6
16–20	3.29	± 0.11	± 0.20	2.90	± 0.12	± 0.21
20–25	1.32	± 0.04	± 0.08	1.08	± 0.04	± 0.07
25–35	0.408	± 0.013	± 0.028	0.312	± 0.012	± 0.022
35–50	0.073	± 0.004	± 0.006	0.055	± 0.004	± 0.006
50–70	0.0135	± 0.0014	± 0.0013	0.0097	± 0.0012	± 0.0012
70–120	0.00095	± 0.00021	± 0.00015	0.00083	± 0.00019	± 0.00014

Table 3. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each (p_T, y) interval in the rapidity range $1 < |y| < 1.5$ and $1.5 < |y| < 2.25$. The first quoted uncertainty is statistical, the second uncertainty is systematic.

FONLL prediction is in good agreement with the data concerning the behaviour in rapidity and p_T , within the theoretical uncertainties.

All available predictions for $d\sigma/dy$ are compared with data in figure 6. The measured cross-section has a small rapidity dependence and is in agreement with the predictions within their uncertainties. The theoretical uncertainties in all cases are large ($\sim 30\%$) and are similar for the POWHEG, MC@NLO and FONLL predictions.

p_T interval [GeV]	$\frac{d\sigma}{dp_T} \cdot \mathcal{B}(B^+ \rightarrow J/\psi K^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$ [pb/GeV] $ y < 2.25$
9–13	$103 \pm 4 \pm 8$
13–16	$36.0 \pm 0.8 \pm 2.3$
16–20	$15.3 \pm 0.3 \pm 1.0$
20–25	$6.1 \pm 0.1 \pm 0.4$
25–35	$1.81 \pm 0.03 \pm 0.12$
35–50	$0.348 \pm 0.008 \pm 0.028$
50–70	$0.062 \pm 0.003 \pm 0.005$
70–120	$0.0061 \pm 0.0006 \pm 0.0007$

Table 4. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each p_T interval in the rapidity range $|y| < 2.25$. The first quoted uncertainty is statistical, the second uncertainty is systematic.

$ y $ interval	$\frac{d\sigma}{dy} \cdot \mathcal{B}(B^+ \rightarrow J/\psi K^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$ [pb] $9 \text{ GeV} < p_T < 120 \text{ GeV}$
0.0–0.5	$154 \pm 5 \pm 10$
0.5–1.0	$143 \pm 6 \pm 9$
1.0–1.5	$144 \pm 8 \pm 10$
1.5–2.25	$132 \pm 7 \pm 11$

Table 5. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each y interval in the p_T range $9 \text{ GeV} < p_T < 120 \text{ GeV}$. The first quoted uncertainty is statistical, the second uncertainty is systematic.

The integrated B^+ production cross-section in the kinematic range $9 \text{ GeV} < p_T < 120 \text{ GeV}$ and $|y| < 2.25$ is:

$$\sigma(pp \rightarrow B^+ X) = 10.6 \pm 0.3 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \pm 0.2 \text{ (lumi.)} \pm 0.4 \text{ (}\mathcal{B}\text{)} \mu\text{b}.$$

The FONLL prediction, with its theoretical uncertainty from the renormalisation and factorisation scale and the b -quark mass, is:

$$\sigma(pp \rightarrow bX) \cdot f_{\bar{b} \rightarrow B^+} = 8.6_{-1.9}^{+3.0} \text{ (scale)} \pm 0.6 \text{ (}m_b\text{)} \mu\text{b},$$

where $f_{\bar{b} \rightarrow B^+} = (40.1 \pm 0.8)\%$ [51] is the world-average value for the hadronisation fraction. The corresponding predictions of POWHEG and MC@NLO are $9.4 \mu\text{b}$ and $8.8 \mu\text{b}$, respectively, with theoretical uncertainties similar to those of the FONLL prediction.

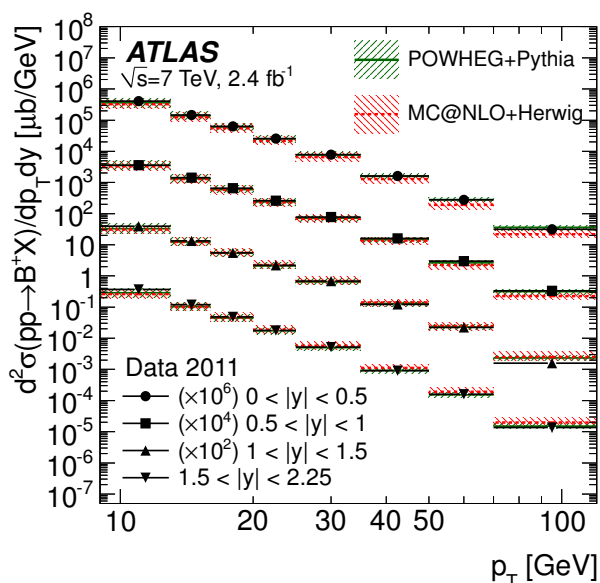


Figure 3. Double-differential cross-section of B^+ production as a function of p_T and y , averaged over each (p_T, y) interval and quoted at its centre. The data points are compared to NLO predictions from POWHEG and MC@NLO. The shaded areas around the theoretical predictions reflect the uncertainty from renormalisation and factorisation scales and the b -quark mass.

8 Conclusions

The differential cross-section for B^+ meson production has been studied with 2.4 fb^{-1} of pp collision data at $\sqrt{s} = 7 \text{ TeV}$, recorded in 2011 with the ATLAS detector at the LHC. The cross-section was measured as a function of transverse momentum and rapidity in the range $9 \text{ GeV} < p_T < 120 \text{ GeV}$ and $|y| < 2.25$, and quoted with a total uncertainty of 7%–30% with the main source of uncertainty being systematic. The next-to-leading-order QCD calculation is compatible with the measured differential cross-section. The predictions are obtained within the POWHEG and MC@NLO frameworks and are quoted with an uncertainty from renormalisation and factorisation scales and b -quark mass of the order of 20%–40%. Within these uncertainties, POWHEG+PYTHIA is in agreement with the measured integrated cross-sections and with the dependence on p_T and y . At low $|y|$, MC@NLO+HERWIG predicts a lower production cross-section and a softer p_T spectrum than the one observed in data, while for $|y| > 1$ the predicted p_T spectrum becomes harder than observed in data. The FONLL calculation for $\sigma(pp \rightarrow bX)$ is compared to the data, assuming a hadronisation fraction $f_{b \rightarrow B^+}$ of $(40.1 \pm 0.8)\%$ [51], and is in good agreement with the measured differential cross-section $d\sigma/dp_T$, within the theoretical uncertainty.

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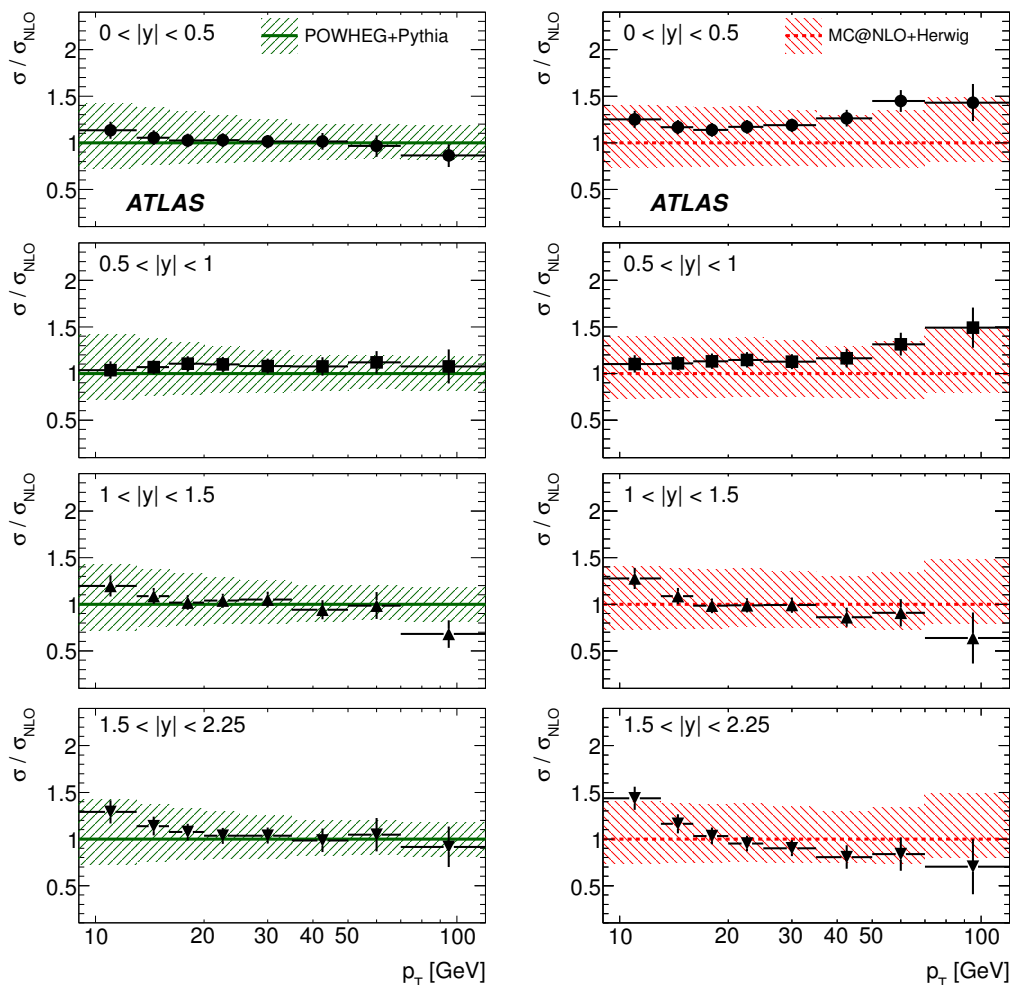


Figure 4. Ratio of the measured cross-section to the theoretical predictions ($\sigma/\sigma_{\text{NLO}}$) of POWHEG (left) and MC@NLO (right) in eight p_T intervals in four rapidity ranges. The points with error bars correspond to data with their associated uncertainty, which is the combination of the statistical and systematic uncertainty. The shaded areas around the theoretical predictions reflect the uncertainty from renormalisation and factorisation scales and the b -quark mass.

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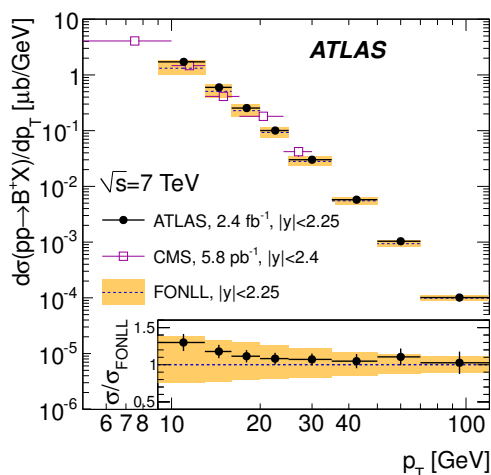


Figure 5. Differential cross-section of B^+ production vs p_T , integrated over rapidity. The solid circle points with error bars correspond to the differential cross-section measurement of ATLAS with total uncertainty (statistical and systematic) in the rapidity range $|y| < 2.25$, averaged over each p_T interval and quoted at its centre. For comparison, data points from CMS are also shown, for a measurement covering $p_T < 30$ GeV and $|y| < 2.4$ [23]. Predictions of the FONLL calculation [19] for b -quark production are also compared with the data, assuming a hadronisation fraction of $f_{\bar{b} \rightarrow B^+}$ of $(40.1 \pm 0.8)\%$ [51] to fix the overall scale. Also shown is the ratio of the measured cross-section to the predictions of the FONLL calculation ($\sigma/\sigma_{\text{FONLL}}$). The upper and lower uncertainty limits on the prediction were obtained considering scale and b -quark mass variations.

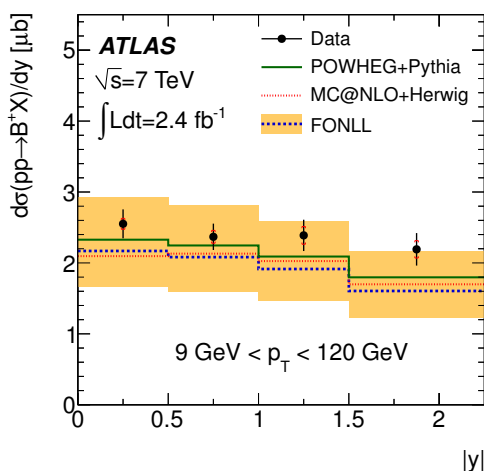


Figure 6. Differential cross-section of B^+ production vs rapidity, integrated over p_T . Points with error bars correspond to the differential cross-section measurement with total uncertainty (lines on the error bars indicate the statistical component) in the p_T range $9 \text{ GeV} < p_T < 120 \text{ GeV}$, averaged over each rapidity interval and quoted at its centre. POWHEG, MC@NLO and FONLL predictions are also given for comparison. The FONLL prediction is quoted with upper and lower uncertainty limits, which were obtained considering scale and b -quark mass variations. The relevant uncertainties of the predictions of POWHEG and MC@NLO are of the same order and are not shown.

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G. Aad⁴⁸, T. Abajyan²¹, B. Abbott¹¹², J. Abdallah¹², S. Abdel Khalek¹¹⁶, A.A. Abdelalim⁴⁹, O. Abidinov¹¹, R. Aben¹⁰⁶, B. Abi¹¹³, M. Abolins⁸⁹, O.S. AbouZeid¹⁵⁹, H. Abramowicz¹⁵⁴, H. Abreu¹³⁷, Y. Abulaiti^{147a,147b}, B.S. Acharya^{165a,165b,a}, L. Adamczyk^{38a}, D.L. Adams²⁵, T.N. Addy⁵⁶, J. Adelman¹⁷⁷, S. Adomeit⁹⁹, T. Adye¹³⁰, S. Aefsky²³, J.A. Aguilar-Saavedra^{125b,b}, M. Agustoni¹⁷, S.P. Ahlen²², F. Ahles⁴⁸, A. Ahmad¹⁴⁹, M. Ahsan⁴¹, G. Aielli^{134a,134b}, T.P.A. Åkesson⁸⁰, G. Akimoto¹⁵⁶, A.V. Akimov⁹⁵, M.A. Alam⁷⁶, J. Albert¹⁷⁰, S. Albrand⁵⁵, M.J. Alconada Verzini⁷⁰, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, F. Alessandria^{90a}, C. Alexa^{26a}, G. Alexander¹⁵⁴, G. Alexandre⁴⁹, T. Alexopoulos¹⁰, M. Alhroob^{165a,165c}, M. Aliev¹⁶, G. Alimonti^{90a}, J. Alison³¹, B.M.M. Allbrooke¹⁸, L.J. Allison⁷¹, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸³, A. Aloisio^{103a,103b}, R. Alon¹⁷³, A. Alonso³⁶, F. Alonso⁷⁰, A. Altheimer³⁵, B. Alvarez Gonzalez⁸⁹, M.G. Alviggi^{103a,103b}, K. Amako⁶⁵, Y. Amaral Coutinho^{24a}, C. Amelung²³, V.V. Ammosov^{129,*}, S.P. Amor Dos Santos^{125a}, A. Amorim^{125a,c}, S. Amoroso⁴⁸, N. Amram¹⁵⁴, C. Anastopoulos³⁰, L.S. Ancu¹⁷, N. Andari³⁰, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders^{58a}, K.J. Anderson³¹, A. Andreazza^{90a,90b}, V. Andrei^{58a}, X.S. Anduaga⁷⁰, S. Angelidakis⁹, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A.V. Anisenkov¹⁰⁸, N. Anjos^{125a}, A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁷, J. Antos^{145b}, F. Anulli^{133a}, M. Aoki¹⁰², L. Aperio Bella¹⁸, R. Apolle^{119,d}, G. Arabidze⁸⁹, I. Aracena¹⁴⁴, Y. Arai⁶⁵, A.T.H. Arce⁴⁵, S. Arfaoui¹⁴⁹, J-F. Arguin⁹⁴, S. Argyropoulos⁴², E. Arik^{19a,*}, M. Arik^{19a}, A.J. Armbruster⁸⁸, O. Arnaez⁸², V. Arnal⁸¹, A. Artamonov⁹⁶, G. Artoni^{133a,133b}, D. Arutinov²¹, S. Asai¹⁵⁶, N. Asbah⁹⁴, S. Ask²⁸, B. Åsman^{147a,147b}, L. Asquith⁶, K. Assamagan²⁵, R. Astalos^{145a}, A. Astbury¹⁷⁰, M. Atkinson¹⁶⁶, B. Auerbach⁶, E. Auge¹¹⁶, K. Augsten¹²⁷, M. Aurousseau^{146b}, G. Avolio³⁰, D. Axen¹⁶⁹, G. Azuelos^{94,e}, Y. Azuma¹⁵⁶, M.A. Baak³⁰, C. Bacci^{135a,135b}, A.M. Bach¹⁵, H. Bachacou¹³⁷, K. Bachas¹⁵⁵, M. Backes⁴⁹, M. Backhaus²¹, J. Backus Mayes¹⁴⁴, E. Badescu^{26a}, P. Bagiachi^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{33a}, D.C. Bailey¹⁵⁹, T. Bain³⁵, J.T. Baines¹³⁰, O.K. Baker¹⁷⁷, S. Baker⁷⁷, P. Balek¹²⁸, F. Balli¹³⁷, E. Banas³⁹, P. Banerjee⁹⁴, Sw. Banerjee¹⁷⁴, D. Banfi³⁰, A. Bangert¹⁵¹, V. Bansal¹⁷⁰, H.S. Bansil¹⁸, L. Barak¹⁷³, S.P. Baranov⁹⁵, T. Barber⁴⁸, E.L. Barberio⁸⁷, D. Barberis^{50a,50b}, M. Barbero⁸⁴, D.Y. Bardin⁶⁴, T. Barillari¹⁰⁰, M. Barisonzi¹⁷⁶, T. Barklow¹⁴⁴, N. Barlow²⁸, B.M. Barnett¹³⁰, R.M. Barnett¹⁵, A. Baroncelli^{135a}, G. Barone⁴⁹, A.J. Barr¹¹⁹, F. Barreiro⁸¹, J. Barreiro Guimarães da Costa⁵⁷, R. Bartoldus¹⁴⁴, A.E. Barton⁷¹, V. Bartsch¹⁵⁰, A. Basye¹⁶⁶, R.L. Bates⁵³, L. Batkova^{145a}, J.R. Batley²⁸, A. Battaglia¹⁷, M. Battistin³⁰, F. Bauer¹³⁷, H.S. Bawa^{144,f}, S. Beale⁹⁹, T. Beau⁷⁹, P.H. Beauchemin¹⁶², R. Beccherle^{50a}, P. Bechtel²¹, H.P. Beck¹⁷, K. Becker¹⁷⁶, S. Becker⁹⁹, M. Beckingham¹³⁹, K.H. Becks¹⁷⁶, A.J. Beddall^{19c}, A. Beddall^{19c}, S. Bedikian¹⁷⁷, V.A. Bednyakov⁶⁴, C.P. Bee⁸⁴, L.J. Beamster¹⁰⁶, T.A. Beermann¹⁷⁶, M. Begel²⁵, C. Belanger-Champagne⁸⁶, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵⁴, L. Bellagamba^{20a}, A. Bellerive²⁹, M. Bellomo³⁰, A. Belloni⁵⁷, O.L. Beloborodova^{108,g}, K. Belotskiy⁹⁷, O. Beltramello³⁰, O. Benary¹⁵⁴, D. Benchekroun^{136a}, K. Bendtz^{147a,147b}, N. Benekos¹⁶⁶, Y. Benhammou¹⁵⁴, E. Benhar Nocchioli⁴⁹, J.A. Benitez Garcia^{160b}, D.P. Benjamin⁴⁵, J.R. Bensinger²³, K. Benslama¹³¹, S. Bentvelsen¹⁰⁶, D. Berge³⁰, E. Bergeas Kuutmann¹⁶, N. Berger⁵, F. Berghaus¹⁷⁰, E. Berglund¹⁰⁶, J. Beringer¹⁵, P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius⁷⁸, F.U. Bernlochner¹⁷⁰, T. Berry⁷⁶, C. Bertella⁸⁴, F. Bertolucci^{123a,123b}, M.I. Besana^{90a,90b}, G.J. Besjes¹⁰⁵, N. Besson¹³⁷, S. Bethke¹⁰⁰, W. Bhimji⁴⁶, R.M. Bianchi¹²⁴, L. Bianchini²³, M. Bianco^{72a,72b}, O. Biebel⁹⁹, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁵, M. Biglietti^{135a}, H. Bilokon⁴⁷, M. Bindi^{20a,20b}, S. Binet¹¹⁶, A. Bingul^{19c}, C. Bini^{133a,133b}, B. Bittner¹⁰⁰, C.W. Black¹⁵¹, J.E. Black¹⁴⁴, K.M. Black²², D. Blackburn¹³⁹, R.E. Blair⁶, J.-B. Blanchard¹³⁷, T. Blazek^{145a}, I. Bloch⁴², C. Blocker²³, J. Blocki³⁹, W. Blum⁸², U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁶, V.S. Bobrovnikov¹⁰⁸, S.S. Bocchetta⁸⁰, A. Bocchi⁴⁵, C.R. Boddy¹¹⁹, M. Boehler⁴⁸, J. Boek¹⁷⁶, T.T. Boek¹⁷⁶, N. Boelaert³⁶, J.A. Bogaerts³⁰, A.G. Bogdanchikov¹⁰⁸, A. Bogouch^{91,*}, C. Boehm^{147a}, J. Boehm¹²⁶, V. Boisvert⁷⁶, T. Bold^{38a}, V. Boldea^{26a}, N.M. Bolnet¹³⁷, M. Bomben⁷⁹, M. Bona⁷⁵, M. Boonekamp¹³⁷, S. Bordon⁷⁹, C. Borer¹⁷, A. Borisov¹²⁹, G. Borissov⁷¹, M. Borri⁸³, S. Borroni⁴², J. Bortfeldt⁹⁹,

V. Bortolotto^{135a,135b}, K. Bos¹⁰⁶, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁶, J. Bouchami⁹⁴, J. Boudreau¹²⁴, E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁶, N. Bousson⁸⁴, S. Boutouil^{136d}, A. Boveia³¹, J. Boyd³⁰, I.R. Boyko⁶⁴, I. Bozovic-Jelisavcic^{13b}, J. Bracinik¹⁸, P. Branchini^{135a}, A. Brandt⁸, G. Brandt¹⁵, O. Brandt⁵⁴, U. Bratzler¹⁵⁷, B. Brau⁸⁵, J.E. Brau¹¹⁵, H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelrier¹⁵⁹, J. Bremer³⁰, K. Brendlinger¹²¹, R. Brenner¹⁶⁷, S. Bressler¹⁷³, T.M. Bristow^{146c}, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁸⁹, F. Broggi^{90a}, C. Bromberg⁸⁹, J. Bronner¹⁰⁰, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, E. Brost¹¹⁵, G. Brown⁸³, P.A. Bruckman de Renstrom³⁹, D. Bruncko^{145b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, L. Bryngemark⁸⁰, T. Buanes¹⁴, Q. Buat⁵⁵, F. Bucci⁴⁹, J. Buchanan¹¹⁹, P. Buchholz¹⁴², R.M. Buckingham¹¹⁹, A.G. Buckley⁴⁶, S.I. Buda^{26a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁹, L. Bugge¹¹⁸, O. Bulekov⁹⁷, A.C. Bundock⁷³, M. Bunse⁴³, T. Buran^{118,*}, H. Burckhart³⁰, S. Burdin⁷³, T. Burgess¹⁴, S. Burke¹³⁰, E. Busato³⁴, V. Büscher⁸², P. Bussey⁵³, C.P. Buszello¹⁶⁷, B. Butler⁵⁷, J.M. Butler²², C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁸, M. Byszewski¹⁰, S. Cabrera Urbán¹⁶⁸, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, G. Calderini⁷⁹, P. Calfayan⁹⁹, R. Calkins¹⁰⁷, L.P. Caloba^{24a}, R. Caloi^{133a,133b}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro⁴⁹, P. Camarri^{134a,134b}, D. Cameron¹¹⁸, L.M. Caminada¹⁵, R. Caminal Armadans¹², S. Campana³⁰, M. Campanelli⁷⁷, V. Canale^{103a,103b}, F. Canelli³¹, A. Canepa^{160a}, J. Cantero⁸¹, R. Cantrill⁷⁶, T. Cao⁴⁰, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}, D. Capriotti¹⁰⁰, M. Capua^{37a,37b}, R. Caputo⁸², R. Cardarelli^{134a}, T. Carli³⁰, G. Carlino^{103a}, L. Carminati^{90a,90b}, S. Caron¹⁰⁵, E. Carquin^{32b}, G.D. Carrillo-Montoya^{146c}, A.A. Carter⁷⁵, J.R. Carter²⁸, J. Carvalho^{125a,h}, D. Casadei¹⁰⁹, M.P. Casado¹², M. Cascella^{123a,123b}, C. Caso^{50a,50b,*}, E. Castaneda-Miranda¹⁷⁴, A. Castelli¹⁰⁶, V. Castillo Gimenez¹⁶⁸, N.F. Castro^{125a}, G. Cataldi^{72a}, P. Catastini⁵⁷, A. Catinaccio³⁰, J.R. Catmore³⁰, A. Cattai³⁰, G. Cattani^{134a,134b}, S. Caughron⁸⁹, V. Cavaliere¹⁶⁶, D. Cavalli^{90a}, M. Cavalli-Sforza¹², V. Cavalchini^{123a,123b}, F. Ceradini^{135a,135b}, B. Cerio⁴⁵, A.S. Cerqueira^{24b}, A. Cerri¹⁵, L. Cerrito⁷⁵, F. Cerutti¹⁵, A. Cervelli¹⁷, S.A. Cetin^{19b}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁷, I. Chalupkova¹²⁸, K. Chan³, P. Chang¹⁶⁶, B. Chapleau⁸⁶, J.D. Chapman²⁸, J.W. Chapman⁸⁸, D.G. Charlton¹⁸, V. Chavda⁸³, C.A. Chavez Barajas³⁰, S. Cheatham⁸⁶, S. Chekanov⁶, S.V. Chekulaev^{160a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰⁵, C. Chen⁶³, H. Chen²⁵, S. Chen^{33c}, X. Chen¹⁷⁴, Y. Chen³⁵, Y. Cheng³¹, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{136e}, V. Chernyatin²⁵, E. Cheu⁷, S.L. Cheung¹⁵⁹, L. Chevalier¹³⁷, V. Chiarella⁴⁷, G. Chiefari^{103a,103b}, J.T. Childers³⁰, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷, A. Chitan^{26a}, M.V. Chizhov⁶⁴, G. Choudalakis³¹, S. Chouridou⁹, B.K.B. Chow⁹⁹, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart³⁰, M.L. Chu¹⁵², J. Chudoba¹²⁶, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca⁶², V. Cindro⁷⁴, A. Ciocio¹⁵, M. Cirilli⁸⁸, P. Cirkovic^{13b}, Z.H. Citron¹⁷³, M. Citterio^{90a}, M. Ciubancan^{26a}, A. Clark⁴⁹, P.J. Clark⁴⁶, R.N. Clarke¹⁵, J.C. Clemens⁸⁴, B. Clement⁵⁵, C. Clement^{147a,147b}, Y. Coadou⁸⁴, M. Cobal^{165a,165c}, A. Coccaro¹³⁹, J. Cochran⁶³, S. Coelli^{90a}, L. Coffey²³, J.G. Cogan¹⁴⁴, J. Coggeshall¹⁶⁶, J. Colas⁵, S. Cole¹⁰⁷, A.P. Colijn¹⁰⁶, N.J. Collins¹⁸, C. Collins-Tooth⁵³, J. Collot⁵⁵, T. Colombo^{120a,120b}, G. Colon⁸⁵, G. Compostella¹⁰⁰, P. Conde Muiño^{125a}, E. Coniavitis¹⁶⁷, M.C. Conidi¹², S.M. Consonni^{90a,90b}, V. Consorti⁴⁸, S. Constantinescu^{26a}, C. Conta^{120a,120b}, G. Conti⁵⁷, F. Conventi^{103a,i}, M. Cooke¹⁵, B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁹, N.J. Cooper-Smith⁷⁶, K. Copic¹⁵, T. Cornelissen¹⁷⁶, M. Corradi^{20a}, F. Corriveau^{86,j}, A. Corso-Radu¹⁶⁴, A. Cortes-Gonzalez¹⁶⁶, G. Cortiana¹⁰⁰, G. Costa^{90a}, M.J. Costa¹⁶⁸, D. Costanzo¹⁴⁰, D. Côté³⁰, G. Cottin^{32a}, L. Courneyea¹⁷⁰, G. Cowan⁷⁶, B.E. Cox⁸³, K. Cranmer¹⁰⁹, S. Crépe-Renaudin⁵⁵, F. Crescioli⁷⁹, M. Cristinziani²¹, G. Crosetti^{37a,37b}, C.-M. Cuciuc^{26a}, C. Cuenca Almenar¹⁷⁷, T. Cuhadar Donszelmann¹⁴⁰, J. Cummings¹⁷⁷, M. Curatolo⁴⁷, C.J. Curtis¹⁸, C. Cuthbert¹⁵¹, H. Czirr¹⁴², P. Czodrowski⁴⁴, Z. Czyczula¹⁷⁷, S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio^{133a,133b}, M.J. Da Cunha Sargedas De Sousa^{125a}, C. Da Via⁸³, W. Dabrowski^{38a}, A. Dafinca¹¹⁹, T. Dai⁸⁸, F. Dallaire⁹⁴, C. Dallapiccola⁸⁵, M. Dam³⁶, D.S. Damiani¹³⁸, A.C. Daniells¹⁸, H.O. Danielsson³⁰, V. Dao¹⁰⁵, G. Darbo^{50a}, G.L. Darlea^{26c}, S. Darmora⁸, J.A. Dassoulas⁴², W. Davey²¹,

T. Davidek¹²⁸, N. Davidson⁸⁷, E. Davies^{119,d}, M. Davies⁹⁴, O. Davignon⁷⁹, A.R. Davison⁷⁷,
 Y. Davygora^{58a}, E. Dawe¹⁴³, I. Dawson¹⁴⁰, R.K. Daya-Ishmukhametova²³, K. De⁸,
 R. de Asmundis^{103a}, S. De Castro^{20a,20b}, S. De Cecco⁷⁹, J. de Graat⁹⁹, N. De Groot¹⁰⁵,
 P. de Jong¹⁰⁶, C. De La Taille¹¹⁶, H. De la Torre⁸¹, F. De Lorenzi⁶³, L. De Nooij¹⁰⁶,
 D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis^{165a,165c}, A. De Santo¹⁵⁰,
 J.B. De Vivie De Regie¹¹⁶, G. De Zorzi^{133a,133b}, W.J. Dearnaley⁷¹, R. Debbé²⁵, C. Debenedetti⁴⁶,
 B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹²¹, J. Del Peso⁸¹, T. Del Prete^{123a,123b},
 T. Delemontex⁵⁵, M. Deliyergiyev⁷⁴, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Della Pietra^{103a,i},
 D. della Volpe^{103a,103b}, M. Delmastro⁵, P.A. Delsart⁵⁵, C. Deluca¹⁰⁶, S. Demers¹⁷⁷,
 M. Demichev⁶⁴, A. Demilly⁷⁹, B. Demirköz^{12,k}, S.P. Denisov¹²⁹, D. Derendarz³⁹,
 J.E. Derkaoui^{136d}, F. Derue⁷⁹, P. Dervan⁷³, K. Desch²¹, P.O. Deviveiros¹⁰⁶, A. Dewhurst¹³⁰,
 B. DeWilde¹⁴⁹, S. Dhaliwal¹⁰⁶, R. Dhullipudi^{78,l}, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵,
 C. Di Donato^{103a,103b}, A. Di Girolamo³⁰, B. Di Girolamo³⁰, S. Di Luise^{135a,135b}, A. Di Mattia¹⁵³,
 B. Di Micco^{135a,135b}, R. Di Nardo⁴⁷, A. Di Simone^{134a,134b}, R. Di Sipio^{20a,20b}, M.A. Diaz^{32a},
 E.B. Diehl⁸⁸, J. Dietrich⁴², T.A. Dietzsch^{58a}, S. Diglio⁸⁷, K. Dindar Yagci⁴⁰, J. Dingfelder²¹,
 F. Dinut^{26a}, C. Dionisi^{133a,133b}, P. Dita^{26a}, S. Dita^{26a}, F. Dittus³⁰, F. Djama⁸⁴, T. Djobava^{51b},
 M.A.B. do Vale^{24c}, A. Do Valle Wemans^{125a,m}, T.K.O. Doan⁵, D. Dobos³⁰, E. Dobson⁷⁷,
 J. Dodd³⁵, C. Doglioni⁴⁹, T. Doherty⁵³, T. Dohmae¹⁵⁶, Y. Doi^{65,*}, J. Dolejsi¹²⁸, Z. Dolezal¹²⁸,
 B.A. Dolgoshein^{97,*}, M. Donadelli^{24d}, J. Donini³⁴, J. Dopke³⁰, A. Doria^{103a}, A. Dos Anjos¹⁷⁴,
 A. Dotti^{123a,123b}, M.T. Dova⁷⁰, A.T. Doyle⁵³, M. Dris¹⁰, J. Dubbert⁸⁸, S. Dube¹⁵, E. Dubreuil³⁴,
 E. Duchovni¹⁷³, G. Duckeck⁹⁹, D. Duda¹⁷⁶, A. Dudarev³⁰, F. Dudziak⁶³, L. Dufflot¹¹⁶,
 M-A. Dufour⁸⁶, L. Duguid⁷⁶, M. Dührssen³⁰, M. Dunford^{58a}, H. Duran Yildiz^{4a}, M. Düren⁵²,
 M. Dwuznik^{38a}, J. Ebke⁹⁹, S. Eckweiler⁸², W. Edson², C.A. Edwards⁷⁶, N.C. Edwards⁵³,
 W. Ehrenfeld²¹, T. Eifert¹⁴⁴, G. Eigen¹⁴, K. Einsweiler¹⁵, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁷,
 M. El Kacimi^{136c}, M. Ellert¹⁶⁷, S. Elles⁵, F. Ellinghaus⁸², K. Ellis⁷⁵, N. Ellis³⁰, J. Elmsheuser⁹⁹,
 M. Elsing³⁰, D. Emeliyanov¹³⁰, Y. Enari¹⁵⁶, O.C. Endner⁸², R. Engelmann¹⁴⁹, A. Engl⁹⁹,
 J. Erdmann¹⁷⁷, A. Ereditato¹⁷, D. Eriksson^{147a}, J. Ernst², M. Ernst²⁵, J. Ernwein¹³⁷,
 D. Errede¹⁶⁶, S. Errede¹⁶⁶, E. Ertel⁸², M. Escalier¹¹⁶, H. Esch⁴³, C. Escobar¹²⁴,
 X. Espinal Curull¹², B. Esposito⁴⁷, F. Etienne⁸⁴, A.I. Etienvre¹³⁷, E. Etzion¹⁵⁴,
 D. Evangelakou⁵⁴, H. Evans⁶⁰, L. Fabbri^{20a,20b}, C. Fabre³⁰, G. Facini³⁰, R.M. Fakhruddinov¹²⁹,
 S. Falciano^{133a}, Y. Fang^{33a}, M. Fanti^{90a,90b}, A. Farbin⁸, A. Farilla^{135a}, T. Farooque¹⁵⁹,
 S. Farrell¹⁶⁴, S.M. Farrington¹⁷¹, P. Farthouat³⁰, F. Fassi¹⁶⁸, P. Fassnacht³⁰, D. Fassouliotis⁹,
 B. Fathollahzadeh¹⁵⁹, A. Favareto^{90a,90b}, L. Fayard¹¹⁶, P. Federic^{145a}, O.L. Fedin¹²²,
 W. Fedorko¹⁶⁹, M. Fehling-Kaschek⁴⁸, L. Felgioni⁸⁴, C. Feng^{33d}, E.J. Feng⁶, H. Feng⁸⁸,
 A.B. Fenyuk¹²⁹, J. Ferencei^{145b}, W. Fernando⁶, S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴²,
 A. Ferrari¹⁶⁷, P. Ferrari¹⁰⁶, R. Ferrari^{120a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁸, D. Ferrere⁴⁹,
 C. Ferretti⁸⁸, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³¹, F. Fiedler⁸², A. Filipčič⁷⁴, F. Filthaut¹⁰⁵,
 M. Fincke-Keeler¹⁷⁰, K.D. Finelli⁴⁵, M.C.N. Fiolhais^{125a,h}, L. Fiorini¹⁶⁸, A. Firan⁴⁰, J. Fischer¹⁷⁶,
 M.J. Fisher¹¹⁰, E.A. Fitzgerald²³, M. Flechl⁴⁸, I. Fleck¹⁴², P. Fleischmann¹⁷⁵, S. Fleischmann¹⁷⁶,
 G.T. Fletcher¹⁴⁰, G. Fletcher⁷⁵, T. Flick¹⁷⁶, A. Floderus⁸⁰, L.R. Flores Castillo¹⁷⁴,
 A.C. Florez Bustos^{160b}, M.J. Flowerdew¹⁰⁰, T. Fonseca Martin¹⁷, A. Formica¹³⁷, A. Forti⁸³,
 D. Fortin^{160a}, D. Fournier¹¹⁶, H. Fox⁷¹, P. Francavilla¹², M. Franchini^{20a,20b}, S. Franchino³⁰,
 D. Francis³⁰, M. Franklin⁵⁷, S. Franz³⁰, M. Fraternali^{120a,120b}, S. Fratina¹²¹, S.T. French²⁸,
 C. Friedrich⁴², F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁷,
 E. Fullana Torregrosa¹²⁸, B.G. Fulson¹⁴⁴, J. Fuster¹⁶⁸, C. Gabaldon³⁰, O. Gabizon¹⁷³,
 A. Gabrielli^{20a,20b}, A. Gabrielli^{133a,133b}, S. Gadatsch¹⁰⁶, T. Gadfort²⁵, S. Gadomski⁴⁹,
 G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁹, B. Galhardo^{125a}, E.J. Gallas¹¹⁹, V. Gallo¹⁷,
 B.J. Gallop¹³⁰, P. Gallus¹²⁷, K.K. Gan¹¹⁰, R.P. Gandrajula⁶², Y.S. Gao^{144,f}, A. Gaponenko¹⁵,
 F.M. Garay Walls⁴⁶, F. Garbersson¹⁷⁷, C. García¹⁶⁸, J.E. García Navarro¹⁶⁸, M. Garcia-Sciveres¹⁵,
 R.W. Gardner³¹, N. Garelli¹⁴⁴, V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{120a}, B. Gaur¹⁴²,
 L. Gauthier⁹⁴, P. Gauzzi^{133a,133b}, I.L. Gavrilenko⁹⁵, C. Gay¹⁶⁹, G. Gaycken²¹, E.N. Gazis¹⁰,
 P. Ge^{33d,n}, Z. Gece¹⁶⁹, C.N.P. Gee¹³⁰, D.A.A. Geerts¹⁰⁶, Ch. Geich-Gimbel²¹,

K. Gellerstedt^{147a,147b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{133a,133b},
 M. George⁵⁴, S. George⁷⁶, D. Gerbaudo¹⁶⁴, A. Gershon¹⁵⁴, H. Ghazlane^{136b}, N. Ghodbane³⁴,
 B. Giacobbe^{20a}, S. Giagu^{133a,133b}, V.angiobbe¹², P. Giannetti^{123a,123b}, F. Gianotti³⁰,
 B. Gibbard²⁵, A. Gibson¹⁵⁹, S.M. Gibson⁷⁶, M. Gilchriese¹⁵, T.P.S. Gillam²⁸, D. Gillberg³⁰,
 A.R. Gillman¹³⁰, D.M. Gingrich^{3,e}, N. Giokaris⁹, M.P. Giordani^{165c}, R. Giordano^{103a,103b},
 F.M. Giorgi¹⁶, P. Giovannini¹⁰⁰, P.F. Giraud¹³⁷, D. Giugni^{90a}, C. Giuliani⁴⁸, M. Giunta⁹⁴,
 B.K. Gjelsten¹¹⁸, I. Gkialas^{155,o}, L.K. Gladilin⁹⁸, C. Glasman⁸¹, J. Glatzer²¹, A. Glazov⁴²,
 G.L. Glonti⁶⁴, M. Goblirsch-Kolb¹⁰⁰, J.R. Goddard⁷⁵, J. Godfrey¹⁴³, J. Godlewski³⁰,
 M. Goebel⁴², C. Goeringer⁸², S. Goldfarb⁸⁸, T. Golling¹⁷⁷, D. Golubkov¹²⁹, A. Gomes^{125a,c},
 L.S. Gomez Fajardo⁴², R. Gonalo⁷⁶, J. Goncalves Pinto Firmino Da Costa⁴², L. Gonella²¹,
 S. Gonzalez de la Hoz¹⁶⁸, G. Gonzalez Parra¹², M.L. Gonzalez Silva²⁷, S. Gonzalez-Sevilla⁴⁹,
 J.J. Goodson¹⁴⁹, L. Goossens³⁰, P.A. Gorbounov⁹⁶, H.A. Gordon²⁵, I. Gorelov¹⁰⁴, G. Gorfine¹⁷⁶,
 B. Gorini³⁰, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁹, A.T. Goshaw⁶, C. Gossling⁴³,
 M.I. Gostkin⁶⁴, I. Gough Eschrich¹⁶⁴, M. Gouighri^{136a}, D. Goujdami^{136c}, M.P. Goulette⁴⁹,
 A.G. Goussiou¹³⁹, C. Goy⁵, S. Gozpinar²³, L. Graber⁵⁴, I. Grabowska-Bold^{38a},
 P. Grafstrom^{20a,20b}, K-J. Grahm⁴², E. Gramstad¹¹⁸, F. Grancagnolo^{72a}, S. Grancagnolo¹⁶,
 V. Grassi¹⁴⁹, V. Gratchev¹²², H.M. Gray³⁰, J.A. Gray¹⁴⁹, E. Graziani^{135a}, O.G. Grebenyuk¹²²,
 T. Greenshaw⁷³, Z.D. Greenwood^{78,l}, K. Gregersen³⁶, I.M. Gregor⁴², P. Grenier¹⁴⁴, J. Griffiths⁸,
 N. Grigalashvili⁶⁴, A.A. Grillo¹³⁸, K. Grimm⁷¹, S. Grinstein^{12,p}, Ph. Gris³⁴, Y.V. Grishkevich⁹⁸,
 J.-F. Grivaz¹¹⁶, J.P. Grohs⁴⁴, A. Grohsjean⁴², E. Gross¹⁷³, J. Grosse-Knetter⁵⁴,
 J. Groth-Jensen¹⁷³, K. Grybel¹⁴², F. Guescini⁴⁹, D. Guest¹⁷⁷, O. Gueta¹⁵⁴, C. Guicheney³⁴,
 E. Guido^{50a,50b}, T. Guillemin¹¹⁶, S. Guindon², U. Gul⁵³, J. Gunther¹²⁷, J. Guo³⁵, P. Gutierrez¹¹²,
 N. Guttman¹⁵⁴, O. Gutzwiller¹⁷⁴, C. Guyot¹³⁷, C. Gwenlan¹¹⁹, C.B. Gwilliam⁷³, A. Haas¹⁰⁹,
 S. Haas³⁰, C. Haber¹⁵, H.K. Hadavand⁸, P. Haefner²¹, Z. Hajduk³⁹, H. Hakobyan¹⁷⁸, D. Hall¹¹⁹,
 G. Halladjian⁶², K. Hamacher¹⁷⁶, P. Hamal¹¹⁴, K. Hamano⁸⁷, M. Hamer⁵⁴, A. Hamilton^{146a,q},
 S. Hamilton¹⁶², L. Han^{33b}, K. Hanagaki¹¹⁷, K. Hanawa¹⁶¹, M. Hance¹⁵, C. Handel⁸², P. Hanke^{58a},
 J.R. Hansen³⁶, J.B. Hansen³⁶, J.D. Hansen³⁶, P.H. Hansen³⁶, P. Hansson¹⁴⁴, K. Hara¹⁶¹,
 A.S. Hard¹⁷⁴, T. Harenberg¹⁷⁶, S. Harkusha⁹¹, D. Harper⁸⁸, R.D. Harrington⁴⁶, O.M. Harris¹³⁹,
 J. Hartert⁴⁸, F. Hartjes¹⁰⁶, T. Haruyama⁶⁵, A. Harvey⁵⁶, S. Hasegawa¹⁰², Y. Hasegawa¹⁴¹,
 S. Hassani¹³⁷, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁸⁹, M. Havranek²¹, C.M. Hawkes¹⁸,
 R.J. Hawkings³⁰, A.D. Hawkins⁸⁰, T. Hayakawa⁶⁶, T. Hayashi¹⁶¹, D. Hayden⁷⁶, C.P. Hays¹¹⁹,
 H.S. Hayward⁷³, S.J. Haywood¹³⁰, S.J. Head¹⁸, T. Heck⁸², V. Hedberg⁸⁰, L. Heelan⁸, S. Heim¹²¹,
 B. Heinemann¹⁵, S. Heisterkamp³⁶, J. Hejbal¹²⁶, L. Helary²², C. Heller⁹⁹, M. Heller³⁰,
 S. Hellman^{147a,147b}, D. Hellmich²¹, C. Helsens³⁰, J. Henderson¹¹⁹, R.C.W. Henderson⁷¹,
 M. Henke^{58a}, A. Henrichs¹⁷⁷, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁶, C. Hensel⁵⁴,
 G.H. Herbert¹⁶, C.M. Hernandez⁸, Y. Hernandez Jimenez¹⁶⁸, R. Herrberg-Schubert¹⁶,
 G. Herten⁴⁸, R. Hertenberger⁹⁹, L. Hervas³⁰, G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁶, R. Hickling⁷⁵,
 E. Higon-Rodriguez¹⁶⁸, J.C. Hill²⁸, K.H. Hiller⁴², S. Hillert²¹, S.J. Hillier¹⁸, I. Hinchliffe¹⁵,
 E. Hines¹²¹, M. Hirose¹¹⁷, D. Hirschbuehl¹⁷⁶, J. Hobbs¹⁴⁹, N. Hod¹⁰⁶, M.C. Hodgkinson¹⁴⁰,
 P. Hodgson¹⁴⁰, A. Hoecker³⁰, M.R. Hoferkamp¹⁰⁴, J. Hoffman⁴⁰, D. Hoffmann⁸⁴,
 J.I. Hofmann^{58a}, M. Hohlfeld⁸², S.O. Holmgren^{147a}, J.L. Holzbauer⁸⁹, T.M. Hong¹²¹,
 L. Hooft van Huysduynen¹⁰⁹, J.-Y. Hostachy⁵⁵, S. Hou¹⁵², A. Hoummada^{136a}, J. Howard¹¹⁹,
 J. Howarth⁸³, M. Hrabovsky¹¹⁴, I. Hristova¹⁶, J. Hrivnac¹¹⁶, T. Hryn'ova⁵, P.J. Hsu⁸²,
 S.-C. Hsu¹³⁹, D. Hu³⁵, X. Hu²⁵, Z. Hubacek³⁰, F. Hubaut⁸⁴, F. Huegging²¹, A. Huettmann⁴²,
 T.B. Huffman¹¹⁹, E.W. Hughes³⁵, G. Hughes⁷¹, M. Huhtinen³⁰, T.A. Hulsing⁸², M. Hurwitz¹⁵,
 N. Huseynov^{64,r}, J. Huston⁸⁹, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, I. Ibragimov¹⁴²,
 L. Iconomidou-Fayard¹¹⁶, J. Idarraga¹¹⁶, P. Iengo^{103a}, O. Igonkina¹⁰⁶, Y. Ikegami⁶⁵,
 K. Ikematsu¹⁴², M. Ikeno⁶⁵, D. Iliadis¹⁵⁵, N. Ilic¹⁵⁹, T. Ince¹⁰⁰, P. Ioannou⁹, M. Iodice^{135a},
 K. Iordanidou⁹, V. Ippolito^{133a,133b}, A. Irls Quiles¹⁶⁸, C. Isaksson¹⁶⁷, M. Ishino⁶⁷,
 M. Ishitsuka¹⁵⁸, R. Ishmukhametov¹¹⁰, C. Issever¹¹⁹, S. Istin^{19a}, A.V. Ivashin¹²⁹, W. Iwanski³⁹,
 H. Iwasaki⁶⁵, J.M. Izen⁴¹, V. Izzo^{103a}, B. Jackson¹²¹, J.N. Jackson⁷³, P. Jackson¹, M.R. Jaekel³⁰,
 V. Jain², K. Jakobs⁴⁸, S. Jakobsen³⁶, T. Jakoubek¹²⁶, J. Jakubek¹²⁷, D.O. Jamin¹⁵²,

D.K. Jana¹¹², E. Jansen⁷⁷, H. Jansen³⁰, J. Janssen²¹, A. Jantsch¹⁰⁰, M. Janus⁴⁸, R.C. Jared¹⁷⁴,
 G. Jarlskog⁸⁰, L. Jeanty⁵⁷, G.-Y. Jeng¹⁵¹, I. Jen-La Plante³¹, D. Jennens⁸⁷, P. Jenni³⁰,
 J. Jentsch⁴³, C. Jeske¹⁷¹, P. Jež³⁶, S. Jézéquel⁵, M.K. Jha^{20a}, H. Ji¹⁷⁴, W. Ji⁸², J. Jia¹⁴⁹,
 Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, O. Jinnouchi¹⁵⁸, M.D. Joergensen³⁶, D. Joffe⁴⁰,
 M. Johansen^{147a,147b}, K.E. Johansson^{147a}, P. Johansson¹⁴⁰, S. Johnert⁴², K.A. Johns⁷,
 K. Jon-And^{147a,147b}, G. Jones¹⁷¹, R.W.L. Jones⁷¹, T.J. Jones⁷³, P.M. Jorge^{125a}, K.D. Joshi⁸³,
 J. Jovicevic¹⁴⁸, T. Agatonovic-Jovin^{13b}, X. Ju¹⁷⁴, C.A. Jung⁴³, R.M. Jungst³⁰, P. Jussel⁶¹,
 A. Juste Rozas^{12,p}, S. Kabana¹⁷, M. Kaci¹⁶⁸, A. Kaczmarska³⁹, P. Kadlecik³⁶, M. Kado¹¹⁶,
 H. Kagan¹¹⁰, M. Kagan⁵⁷, E. Kajomovitz¹⁵³, S. Kalinin¹⁷⁶, S. Kama⁴⁰, N. Kanaya¹⁵⁶,
 M. Kaneda³⁰, S. Kaneti²⁸, T. Kanno¹⁵⁸, V.A. Kantserov⁹⁷, J. Kanzaki⁶⁵, B. Kaplan¹⁰⁹,
 A. Kapliy³¹, D. Kar⁵³, K. Karakostas¹⁰, M. Karnevskiy⁸², V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁹,
 L. Kashif¹⁷⁴, G. Kasieczka^{58b}, R.D. Kass¹¹⁰, A. Kastanas¹⁴, Y. Kataoka¹⁵⁶, J. Katzy⁴²,
 V. Kaushik⁷, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁶, G. Kawamura⁵⁴, S. Kazama¹⁵⁶, V.F. Kazanin¹⁰⁸,
 M.Y. Kazarinov⁶⁴, R. Keeler¹⁷⁰, P.T. Keener¹²¹, R. Kehoe⁴⁰, M. Keil⁵⁴, J.S. Keller¹³⁹,
 H. Keoshkerian⁵, O. Kepka¹²⁶, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁶, K. Kessoku¹⁵⁶, J. Keung¹⁵⁹,
 F. Khalil-zada¹¹, H. Khandanyan^{147a,147b}, A. Khanov¹¹³, D. Kharchenko⁶⁴, A. Khodinov⁹⁷,
 A. Khomich^{58a}, T.J. Khoo²⁸, G. Khoraiuli²¹, A. Khoroshilov¹⁷⁶, V. Khovanskii⁹⁶, E. Khramov⁶⁴,
 J. Khubua^{51b}, H. Kim^{147a,147b}, S.H. Kim¹⁶¹, N. Kimura¹⁷², O. Kind¹⁶, B.T. King⁷³, M. King⁶⁶,
 R.S.B. King¹¹⁹, S.B. King¹⁶⁹, J. Kirk¹³⁰, A.E. Kiryunin¹⁰⁰, T. Kishimoto⁶⁶, D. Kisielewska^{38a},
 T. Kitamura⁶⁶, T. Kittelmann¹²⁴, K. Kiuchi¹⁶¹, E. Kladiva^{145b}, M. Klein⁷³, U. Klein⁷³,
 K. Kleinknecht⁸², M. Klemetti⁸⁶, A. Klier¹⁷³, P. Klimek^{147a,147b}, A. Klimentov²⁵,
 R. Klingenberg⁴³, J.A. Klinger⁸³, E.B. Klinkby³⁶, T. Klioutchnikova³⁰, P.F. Klok¹⁰⁵,
 E.-E. Kluge^{58a}, P. Kluit¹⁰⁶, S. Kluth¹⁰⁰, E. Kneringer⁶¹, E.B.F.G. Knoops⁸⁴, A. Knue⁵⁴,
 B.R. Ko⁴⁵, T. Kobayashi¹⁵⁶, M. Kobel⁴⁴, M. Kocian¹⁴⁴, P. Kodys¹²⁸, S. Koenig⁸²,
 F. Koetsveld¹⁰⁵, P. Koesesarki²¹, T. Koffas²⁹, E. Koffeman¹⁰⁶, L.A. Kogan¹¹⁹, S. Kohlmann¹⁷⁶,
 F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴⁴, H. Kolanoski¹⁶, I. Koletsou^{90a}, J. Koll⁸⁹,
 A.A. Komar⁹⁵, Y. Komori¹⁵⁶, T. Kondo⁶⁵, K. Köneke³⁰, A.C. König¹⁰⁵, T. Kono^{42,s},
 A.I. Kononov⁴⁸, R. Konoplich^{109,t}, N. Konstantinidis⁷⁷, R. Kopeliansky¹⁵³, S. Koperny^{38a},
 L. Köpke⁸², A.K. Kopp⁴⁸, K. Korcyl³⁹, K. Kordas¹⁵⁵, A. Korn⁴⁶, A.A. Korol¹⁰⁸, I. Korolkov¹²,
 E.V. Korolkova¹⁴⁰, V.A. Korotkov¹²⁹, O. Kortner¹⁰⁰, S. Kortner¹⁰⁰, V.V. Kostyukhin²¹,
 S. Kotov¹⁰⁰, V.M. Kotov⁶⁴, A. Kotwal⁴⁵, C. Kourkoumelis⁹, V. Kouskoura¹⁵⁵, A. Koutsman^{160a},
 R. Kowalewski¹⁷⁰, T.Z. Kowalski^{38a}, W. Kozanecki¹³⁷, A.S. Kozhin¹²⁹, V. Kral¹²⁷,
 V.A. Kramarenko⁹⁸, G. Kramberger⁷⁴, M.W. Krasny⁷⁹, A. Krasznahorkay¹⁰⁹, J.K. Kraus²¹,
 A. Kravchenko²⁵, S. Kreiss¹⁰⁹, J. Kretzschmar⁷³, K. Kreutzfeldt⁵², N. Krieger⁵⁴, P. Krieger¹⁵⁹,
 K. Kroeninger⁵⁴, H. Kroha¹⁰⁰, J. Kroll¹²¹, J. Kroseberg²¹, J. Krstic^{13a}, U. Kruchonak⁶⁴,
 H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruse¹⁷⁴, M.K. Kruse⁴⁵,
 M. Kruskal²², T. Kubota⁸⁷, S. Kuday^{4a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴², V. Kukhtin⁶⁴,
 Y. Kulchitsky⁹¹, S. Kuleshov^{32b}, M. Kuna⁷⁹, J. Kunkle¹²¹, A. Kupco¹²⁶, H. Kurashige⁶⁶,
 M. Kurata¹⁶¹, Y.A. Kurochkin⁹¹, V. Kus¹²⁶, E.S. Kuwertz¹⁴⁸, M. Kuze¹⁵⁸, J. Kvita¹⁴³,
 R. Kwee¹⁶, A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, L. Labarga⁸¹, S. Lablak^{136a}, C. Lacasta¹⁶⁸,
 F. Lacava^{133a,133b}, J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁷⁹, V.R. Lacuesta¹⁶⁸, E. Ladygin⁶⁴,
 R. Lafaye⁵, B. Laforge⁷⁹, T. Lagouri¹⁷⁷, S. Lai⁴⁸, H. Laier^{58a}, E. Laisne⁵⁵, L. Lambourne⁷⁷,
 C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, V.S. Lang^{58a},
 C. Lange⁴², A.J. Lankford¹⁶⁴, F. Lanni²⁵, K. Lantzosch³⁰, A. Lanza^{120a}, S. Laplace⁷⁹,
 C. Lapoire²¹, J.F. Laporte¹³⁷, T. Lari^{90a}, A. Lerner¹¹⁹, M. Lassnig³⁰, P. Laurelli⁴⁷,
 V. Lavorini^{37a,37b}, W. Lavrijsen¹⁵, P. Laycock⁷³, O. Le Dortz⁷⁹, E. Le Guirrec⁸⁴,
 E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁶, J.S.H. Lee¹¹⁷, S.C. Lee¹⁵²,
 L. Lee¹⁷⁷, G. Lefebvre⁷⁹, M. Lefebvre¹⁷⁰, M. Legendre¹³⁷, F. Legger⁹⁹, C. Leggett¹⁵,
 M. Lehmacher²¹, G. Lehmann Miotto³⁰, A.G. Leister¹⁷⁷, M.A.L. Leite^{24d}, R. Leitner¹²⁸,
 D. Lellouch¹⁷³, B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{146c}, T. Lenz¹⁰⁶, G. Lenzen¹⁷⁶,
 B. Lenzi³⁰, K. Leonhardt⁴⁴, S. Leontsinis¹⁰, F. Lepold^{58a}, C. Leroy⁹⁴, J.-R. Lessard¹⁷⁰,
 C.G. Lester²⁸, C.M. Lester¹²¹, J. Levêque⁵, D. Levin⁸⁸, L.J. Levinson¹⁷³, A. Lewis¹¹⁹,

G.H. Lewis¹⁰⁹, A.M. Leyko²¹, M. Leyton¹⁶, B. Li^{33b,u}, B. Li⁸⁴, H. Li¹⁴⁹, H.L. Li³¹, S. Li^{33b,v}, X. Li⁸⁸, Z. Liang^{119,w}, H. Liao³⁴, B. Liberti^{134a}, P. Lichard³⁰, K. Lie¹⁶⁶, J. Liebal²¹, W. Liebig¹⁴, C. Limbach²¹, A. Limosani⁸⁷, M. Limper⁶², S.C. Lin^{152,x}, F. Linde¹⁰⁶, B.E. Lindquist¹⁴⁹, J.T. Linnemann⁸⁹, E. Lipeles¹²¹, A. Lipniacka¹⁴, M. Lisovyi⁴², T.M. Liss¹⁶⁶, D. Lissauer²⁵, A. Lister¹⁶⁹, A.M. Litke¹³⁸, D. Liu¹⁵², J.B. Liu^{33b}, K. Liu^{33b,y}, L. Liu⁸⁸, M. Liu⁴⁵, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{120a,120b}, S.S.A. Livermore¹¹⁹, A. Lleres⁵⁵, J. Llorente Merino⁸¹, S.L. Lloyd⁷⁵, F. Lo Sterzo^{133a,133b}, E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁸, T. Loddenkoetter²¹, F.K. Loebinger⁸³, A.E. Loevschall-Jensen³⁶, A. Loginov¹⁷⁷, C.W. Loh¹⁶⁹, T. Lohse¹⁶, K. Lohwasser⁴⁸, M. Lokajicek¹²⁶, V.P. Lombardo⁵, R.E. Long⁷¹, L. Lopes^{125a}, D. Lopez Mateos⁵⁷, J. Lorenz⁹⁹, N. Lorenzo Martinez¹¹⁶, M. Losada¹⁶³, P. Loscutoff¹⁵, M.J. Losty^{160a,*}, X. Lou⁴¹, A. Lounis¹¹⁶, K.F. Loureiro¹⁶³, J. Love⁶, P.A. Love⁷¹, A.J. Lowe^{144,f}, F. Lu^{33a}, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁵, D. Ludwig⁴², I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰, W. Lukas⁶¹, L. Luminari^{133a}, E. Lund¹¹⁸, J. Lundberg^{147a,147b}, O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸, J. Lundquist³⁶, M. Lungwitz⁸², D. Lynn²⁵, R. Lysak¹²⁶, E. Lytken⁸⁰, H. Ma²⁵, L.L. Ma¹⁷⁴, G. Maccarrone⁴⁷, A. Macchiolo¹⁰⁰, B. Maček⁷⁴, J. Machado Miguens^{125a}, D. Macina³⁰, R. Mackeprang³⁶, R. Madar⁴⁸, R.J. Madaras¹⁵, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, A. Madsen¹⁶⁷, M. Maeno⁵, T. Maeno²⁵, L. Magnoni¹⁶⁴, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁶, S. Mahmoud⁷³, G. Mahout¹⁸, C. Maiani¹³⁷, C. Maidantchik^{24a}, A. Maio^{125a,c}, S. Majewski¹¹⁵, Y. Makida⁶⁵, N. Makovec¹¹⁶, P. Mal^{137,z}, B. Malaescu⁷⁹, Pa. Malecki³⁹, P. Malecki³⁹, V.P. Maleev¹²², F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶, C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁸, S. Malyukov³⁰, J. Mamuzic^{13b}, L. Mandelli^{90a}, I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{125a}, A. Manfredini¹⁰⁰, L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos¹³⁷, A. Mann⁹⁹, P.M. Manning¹³⁸, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁷, R. Mantifel⁸⁶, L. Mapelli³⁰, L. March¹⁶⁸, J.F. Marchand²⁹, F. Marchese^{134a,134b}, G. Marchiori⁷⁹, M. Marcisovsky¹²⁶, C.P. Marino¹⁷⁰, C.N. Marques^{125a}, F. Marroquim^{24a}, Z. Marshall¹²¹, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁸, B. Martin³⁰, B. Martin⁸⁹, J.P. Martin⁹⁴, T.A. Martin¹⁷¹, V.J. Martin⁴⁶, B. Martin dit Latour⁴⁹, H. Martinez¹³⁷, M. Martinez^{12,p}, S. Martin-Haugh¹⁵⁰, A.C. Martyniuk¹⁷⁰, M. Marx⁸³, F. Marzano^{133a}, A. Marzin¹¹², L. Masetti⁸², T. Mashimo¹⁵⁶, R. Mashinistov⁹⁵, J. Masik⁸³, A.L. Maslennikov¹⁰⁸, I. Massa^{20a,20b}, N. Massol⁵, P. Mastrandrea¹⁴⁹, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁶, H. Matsunaga¹⁵⁶, T. Matsushita⁶⁶, P. Mättig¹⁷⁶, S. Mättig⁴², C. Mattraversi^{119,d}, J. Maurer⁸⁴, S.J. Maxfield⁷³, D.A. Maximov^{108,g}, R. Mazini¹⁵², M. Mazur²¹, L. Mazzaferro^{134a,134b}, M. Mazzanti^{90a}, S.P. Mc Kee⁸⁸, A. McCarn¹⁶⁶, R.L. McCarthy¹⁴⁹, T.G. McCarthy²⁹, N.A. McCubbin¹³⁰, K.W. McFarlane^{56,*}, J.A. McFayden¹⁴⁰, G. Mchedlize^{51b}, T. McLaughlan¹⁸, S.J. McMahon¹³⁰, R.A. McPherson^{170,j}, A. Meade⁸⁵, J. Mechnich¹⁰⁶, M. Mechtel¹⁷⁶, M. Medinnis⁴², S. Meehan³¹, R. Meera-Lebbai¹¹², T. Meguro¹¹⁷, S. Mehlhase³⁶, A. Mehta⁷³, K. Meier^{58a}, C. Meineck⁹⁹, B. Meirose⁸⁰, C. Melachrinou³¹, B.R. Mellado Garcia^{146c}, F. Meloni^{90a,90b}, L. Mendoza Navas¹⁶³, A. Mengarelli^{20a,20b}, S. Menke¹⁰⁰, E. Meoni¹⁶², K.M. Mercurio⁵⁷, N. Meric¹³⁷, P. Mermod⁴⁹, L. Merola^{103a,103b}, C. Meroni^{90a}, F.S. Merritt³¹, H. Merritt¹¹⁰, A. Messina^{30,aa}, J. Metcalfe²⁵, A.S. Mete¹⁶⁴, C. Meyer⁸², C. Meyer³¹, J-P. Meyer¹³⁷, J. Meyer³⁰, J. Meyer⁵⁴, S. Michal³⁰, R.P. Middleton¹³⁰, S. Migas⁷³, L. Mijović¹³⁷, G. Mikenberg¹⁷³, M. Mikestikova¹²⁶, M. Mikuž⁷⁴, D.W. Miller³¹, W.J. Mills¹⁶⁹, C. Mills⁵⁷, A. Milov¹⁷³, D.A. Milstead^{147a,147b}, D. Milstein¹⁷³, A.A. Minaenko¹²⁹, M. Miñano Moya¹⁶⁸, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁹, B. Mindur^{38a}, M. Mineev⁶⁴, Y. Ming¹⁷⁴, L.M. Mir¹², G. Mirabelli^{133a}, J. Mitrevski¹³⁸, V.A. Mitsou¹⁶⁸, S. Mitsui⁶⁵, P.S. Miyagawa¹⁴⁰, J.U. Mjörnmark⁸⁰, T. Moe^{147a,147b}, V. Moeller²⁸, S. Mohapatra¹⁴⁹, W. Mohr⁴⁸, R. Moles-Valls¹⁶⁸, A. Molfetas³⁰, K. Mönig⁴², C. Monini⁵⁵, J. Monk³⁶, E. Monnier⁸⁴, J. Montejo Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{20a,20b}, R.W. Moore³, C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange⁶², J. Morel⁵⁴, D. Moreno⁸², M. Moreno Llácer¹⁶⁸, P. Morettini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁷, S. Moritz⁸², A.K. Morley³⁰, G. Mornacchi³⁰, J.D. Morris⁷⁵, L. Morvaj¹⁰², N. Möser²¹, H.G. Moser¹⁰⁰, M. Mosidze^{51b}, J. Moss¹¹⁰, R. Mount¹⁴⁴, E. Mountricha^{10,ab}, S.V. Mouraviev^{95,*}, E.J.W. Moyse⁸⁵, R.D. Mudd¹⁸, F. Mueller^{58a}, J. Mueller¹²⁴, K. Mueller²¹, T. Mueller²⁸, T. Mueller⁸², D. Muenstermann³⁰, Y. Munwes¹⁵⁴,

J.A. Murillo Quijada¹⁸, W.J. Murray¹³⁰, I. Mussche¹⁰⁶, E. Musto¹⁵³, A.G. Myagkov^{129,ac}, M. Myska¹²⁶, O. Nackenhorst⁵⁴, J. Nadal¹², K. Nagai¹⁶¹, R. Nagai¹⁵⁸, Y. Nagai⁸⁴, K. Nagano⁶⁵, A. Nagarkar¹¹⁰, Y. Nagasaka⁵⁹, M. Nagel¹⁰⁰, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura⁶⁵, T. Nakamura¹⁵⁶, I. Nakano¹¹¹, H. Namasivayam⁴¹, G. Nanava²¹, A. Napier¹⁶², R. Narayan^{58b}, M. Nash^{77,d}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶³, H.A. Neal⁸⁸, P.Yu. Nechaeva⁹⁵, T.J. Neep⁸³, A. Negri^{120a,120b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, A. Nelson¹⁶⁴, T.K. Nelson¹⁴⁴, S. Nemecek¹²⁶, P. Nemethy¹⁰⁹, A.A. Nepomuceno^{24a}, M. Nessi^{30,ad}, M.S. Neubauer¹⁶⁶, M. Neumann¹⁷⁶, A. Neusiedl⁸², R.M. Neves¹⁰⁹, P. Nevski²⁵, F.M. Newcomer¹²¹, P.R. Newman¹⁸, D.H. Nguyen⁶, V. Nguyen Thi Hong¹³⁷, R.B. Nickerson¹¹⁹, R. Nicolaidou¹³⁷, B. Niquevert³⁰, F. Niedercorn¹¹⁶, J. Nielsen¹³⁸, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko^{129,ac}, I. Nikolic-Audit⁷⁹, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, P. Nilsson⁸, Y. Ninomiya¹⁵⁶, A. Nisati^{133a}, R. Nisius¹⁰⁰, T. Nobe¹⁵⁸, L. Nodulman⁶, M. Nomachi¹¹⁷, I. Nomidis¹⁵⁵, S. Norberg¹¹², M. Nordberg³⁰, J. Novakova¹²⁸, M. Nozaki⁶⁵, L. Nozka¹¹⁴, A.-E. Nuncio-Quiroz²¹, G. Nunes Hanninger⁸⁷, T. Nunnemann⁹⁹, E. Nurse⁷⁷, B.J. O'Brien⁴⁶, D.C. O'Neil¹⁴³, V. O'Shea⁵³, L.B. Oakes⁹⁹, F.G. Oakham^{29,e}, H. Oberlack¹⁰⁰, J. Ocariz⁷⁹, A. Ochi⁶⁶, M.I. Ochoa⁷⁷, S. Oda⁶⁹, S. Odaka⁶⁵, J. Odier⁸⁴, H. Ogren⁶⁰, A. Oh⁸³, S.H. Oh⁴⁵, C.C. Ohm³⁰, T. Ohshima¹⁰², W. Okamura¹¹⁷, H. Okawa²⁵, Y. Okumura³¹, T. Okuyama¹⁵⁶, A. Olariu^{26a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino⁴⁶, M. Oliveira^{125a,h}, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁸, D. Olivito¹²¹, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{125a,ae}, P.U.E. Onyisi^{31,af}, C.J. Oram^{160a}, M.J. Oreglia³¹, Y. Oren¹⁵⁴, D. Orestano^{135a,135b}, N. Orlando^{72a,72b}, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁹, B. Osculati^{50a,50b}, R. Ospanov¹²¹, G. Otero y Garzon²⁷, J.P. Ottersbach¹⁰⁶, M. Ouchrif^{136d}, E.A. Ouellette¹⁷⁰, F. Ould-Saada¹¹⁸, A. Ouraou¹³⁷, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸³, S. Owen¹⁴⁰, V.E. Ozcan^{19a}, N. Ozturk⁸, A. Pacheco Pages¹², C. Padilla Aranda¹², S. Pagan Griso¹⁵, E. Paganis¹⁴⁰, C. Pahl¹⁰⁰, F. Paige²⁵, P. Pais⁸⁵, K. Pajchel¹¹⁸, G. Palacino^{160b}, C.P. Paleri⁷, S. Palestini³⁰, D. Pallin³⁴, A. Palma^{125a}, J.D. Palmer¹⁸, Y.B. Pan¹⁷⁴, E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁶, P. Pani¹⁰⁶, N. Panikashvili⁸⁸, S. Panitkin²⁵, D. Pantea^{26a}, A. Papadelis^{147a}, Th.D. Papadopoulou¹⁰, K. Papageorgiou^{155,o}, A. Paramonov⁶, D. Paredes Hernandez³⁴, W. Park^{25,ag}, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, S. Pashapour⁵⁴, E. Pasqualucci^{133a}, S. Passaggio^{50a}, A. Passeri^{135a}, F. Pastore^{135a,135b,*}, Fr. Pastore⁷⁶, G. Pásztor^{49,ah}, S. Pataria¹⁷⁶, N.D. Patel¹⁵¹, J.R. Pater⁸³, S. Patricelli^{103a,103b}, T. Pauly³⁰, J. Pearce¹⁷⁰, M. Pedersen¹¹⁸, S. Pedraza Lopez¹⁶⁸, M.I. Pedraza Morales¹⁷⁴, S.V. Peleganchuk¹⁰⁸, D. Pelikan¹⁶⁷, H. Peng^{33b}, B. Penning³¹, A. Penson³⁵, J. Penwell⁶⁰, T. Perez Cavalcanti⁴², E. Perez Codina^{160a}, M.T. Pérez García-Estañ¹⁶⁸, V. Perez Reale³⁵, L. Perini^{90a,90b}, H. Pernegger³⁰, R. Perrino^{72a}, P. Perrodo⁵, V.D. Peshekhonov⁶⁴, K. Peters³⁰, R.F.Y. Peters^{54,ai}, B.A. Petersen³⁰, J. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁵, A. Petridis^{147a,147b}, C. Petridou¹⁵⁵, E. Petrolu^{133a}, F. Petrucci^{135a,135b}, D. Petschull⁴², M. Petteni¹⁴³, R. Pezoa^{32b}, A. Phan⁸⁷, P.W. Phillips¹³⁰, G. Piacquadio¹⁴⁴, E. Pianori¹⁷¹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, S.M. Piec⁴², R. Piegai²⁷, D.T. Pignotti¹¹⁰, J.E. Pilcher³¹, A.D. Pilkington⁷⁷, J. Pina^{125a,c}, M. Pinamonti^{165a,165c,aj}, A. Pinder¹¹⁹, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{125a}, C. Pizio^{90a,90b}, M.-A. Pleier²⁵, V. Pleskot¹²⁸, E. Plotnikova⁶⁴, P. Plucinski^{147a,147b}, S. Poddar^{58a}, F. Podlyski³⁴, R. Poettgen⁸², L. Poggioli¹¹⁶, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{120a}, A. Policicchio^{37a,37b}, R. Polifka¹⁵⁹, A. Polini^{20a}, V. Polychronakos²⁵, D. Pomeroy²³, K. Pommès³⁰, L. Pontecorvo^{133a}, B.G. Pope⁸⁹, G.A. Popeneciu^{26b}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso¹², G.E. Pospelov¹⁰⁰, S. Pospisil¹²⁷, I.N. Potrap⁶⁴, C.J. Potter¹⁵⁰, C.T. Potter¹¹⁵, G. Poulard³⁰, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, R. Prabhu⁷⁷, P. Pralavorio⁸⁴, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan²⁵, S. Prell⁶³, K. Pretzl¹⁷, D. Price⁶⁰, J. Price⁷³, L.E. Price⁶, D. Prieur¹²⁴, M. Primavera^{72a}, M. Proissl⁴⁶, K. Prokofiev¹⁰⁹, F. Prokoshin^{32b}, E. Protopapadaki¹³⁷, S. Protopopescu²⁵, J. Proudfoot⁶, X. Prudent⁴⁴, M. Przybycien^{38a}, H. Przysiezniak⁵, S. Psoroulas²¹, E. Ptacek¹¹⁵, E. Pueschel⁸⁵, D. Poldon¹⁴⁹, M. Purohit^{25,ag}, P. Puzo¹¹⁶, Y. Pylypchenko⁶², J. Qian⁸⁸, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle¹⁷⁴, D. Quilty⁵³, M. Raas¹⁰⁵, V. Radeka²⁵, V. Radescu⁴², P. Radloff¹¹⁵, F. Ragusa^{90a,90b}, G. Rahal¹⁷⁹,

S. Rajagopalan²⁵, M. Rammensee⁴⁸, M. Rammes¹⁴², A.S. Randle-Conde⁴⁰, K. Randrianarivony²⁹,
 C. Rangel-Smith⁷⁹, K. Rao¹⁶⁴, F. Rauscher⁹⁹, T.C. Rave⁴⁸, T. Ravenscroft⁵³, M. Raymond³⁰,
 A.L. Read¹¹⁸, D.M. Rebuffi^{120a,120b}, A. Redelbach¹⁷⁵, G. Redlinger²⁵, R. Reece¹²¹, K. Reeves⁴¹,
 A. Reinsch¹¹⁵, I. Reisinger⁴³, M. Relich¹⁶⁴, C. Rembser³⁰, Z.L. Ren¹⁵², A. Renaud¹¹⁶,
 M. Rescigno^{133a}, S. Resconi^{90a}, B. Resende¹³⁷, P. Reznicek⁹⁹, R. Rezvani⁹⁴, R. Richter¹⁰⁰,
 E. Richter-Was^{38b}, M. Ridel⁷⁹, P. Rieck¹⁶, M. Rijssenbeek¹⁴⁹, A. Rimoldi^{120a,120b}, L. Rinaldi^{20a},
 R.R. Rios⁴⁰, E. Ritsch⁶¹, I. Riu¹², G. Rivoltella^{90a,90b}, F. Rizatdinova¹¹³, E. Rizvi⁷⁵,
 S.H. Robertson^{86,j}, A. Robichaud-Veronneau¹¹⁹, D. Robinson²⁸, J.E.M. Robinson⁸³, A. Robson⁵³,
 J.G. Rocha de Lima¹⁰⁷, C. Roda^{123a,123b}, D. Roda Dos Santos³⁰, A. Roe⁵⁴, S. Roe³⁰,
 O. Röhne¹¹⁸, S. Rolli¹⁶², A. Romaniouk⁹⁷, M. Romano^{20a,20b}, G. Romeo²⁷, E. Romero Adam¹⁶⁸,
 N. Rompotis¹³⁹, L. Roos⁷⁹, E. Ros¹⁶⁸, S. Rosati^{133a}, K. Rosbach⁴⁹, A. Rose¹⁵⁰, M. Rose⁷⁶,
 G.A. Rosenbaum¹⁵⁹, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴², V. Rossetti¹², E. Rossi^{133a,133b},
 L.P. Rossi^{50a}, M. Rotaru^{26a}, I. Roth¹⁷³, J. Rothberg¹³⁹, D. Rousseau¹¹⁶, C.R. Royon¹³⁷,
 A. Rozanov⁸⁴, Y. Rozen¹⁵³, X. Ruan^{146c}, F. Rubbo¹², I. Rubinskiy⁴², N. Ruckstuhl¹⁰⁶,
 V.I. Rud⁹⁸, C. Rudolph⁴⁴, M.S. Rudolph¹⁵⁹, F. Rühr⁷, A. Ruiz-Martinez⁶³, L. Rumyantsev⁶⁴,
 Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, A. Ruschke⁹⁹, J.P. Rutherford⁷, N. Ruthmann⁴⁸,
 P. Ruzicka¹²⁶, Y.F. Ryabov¹²², M. Rybar¹²⁸, G. Rybkin¹¹⁶, N.C. Ryder¹¹⁹, A.F. Saavedra¹⁵¹,
 A. Saddique³, I. Sadeh¹⁵⁴, H.F.W. Sadrozinski¹³⁸, R. Sadykov⁶⁴, F. Safai Tehrani^{133a},
 H. Sakamoto¹⁵⁶, G. Salamanna⁷⁵, A. Salamon^{134a}, M. Saleem¹¹², D. Salek³⁰, D. Salihagic¹⁰⁰,
 A. Salnikov¹⁴⁴, J. Salt¹⁶⁸, B.M. Salvachua Ferrando⁶, D. Salvatore^{37a,37b}, F. Salvatore¹⁵⁰,
 A. Salvucci¹⁰⁵, A. Salzburger³⁰, D. Sampsonidis¹⁵⁵, A. Sanchez^{103a,103b}, J. Sánchez¹⁶⁸,
 V. Sanchez Martinez¹⁶⁸, H. Sandaker¹⁴, H.G. Sander⁸², M.P. Sanders⁹⁹, M. Sandhoff¹⁷⁶,
 T. Sandoval²⁸, C. Sandoval¹⁶³, R. Sandstroem¹⁰⁰, D.P.C. Sankey¹³⁰, A. Sansoni⁴⁷, C. Santoni³⁴,
 R. Santonico^{134a,134b}, H. Santos^{125a}, I. Santoyo Castillo¹⁵⁰, K. Sapp¹²⁴, J.G. Saraiva^{125a},
 T. Sarangi¹⁷⁴, E. Sarkisyan-Grinbaum⁸, B. Sarrazin²¹, F. Sarri^{123a,123b}, G. Sartisohn¹⁷⁶,
 O. Sasaki⁶⁵, Y. Sasaki¹⁵⁶, N. Sasao⁶⁷, I. Satsounkevitch⁹¹, G. Sauvage^{5,*}, E. Sauvan⁵,
 J.B. Sauvan¹¹⁶, P. Savard^{159,e}, V. Savinov¹²⁴, D.O. Savu³⁰, C. Sawyer¹¹⁹, L. Sawyer^{78,l},
 D.H. Saxon⁵³, J. Saxon¹²¹, C. Sbarra^{20a}, A. Sbrizzi³, D.A. Scannicchio¹⁶⁴, M. Scarcella¹⁵¹,
 J. Schaarschmidt¹¹⁶, P. Schacht¹⁰⁰, D. Schaefer¹²¹, A. Schaelicke⁴⁶, S. Schaepe²¹, S. Schaetzel^{58b},
 U. Schäfer⁸², A.C. Schaffer¹¹⁶, D. Schaile⁹⁹, R.D. Schamberger¹⁴⁹, V. Scharf^{58a},
 V.A. Schegelsky¹²², D. Scheirich⁸⁸, M. Schernau¹⁶⁴, M.I. Scherzer³⁵, C. Schiavi^{50a,50b},
 J. Schieck⁹⁹, C. Schillo⁴⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden²¹,
 C. Schmitt⁸², C. Schmitt⁹⁹, S. Schmitt^{58b}, B. Schneider¹⁷, Y.J. Schnellbach⁷³, U. Schnoor⁴⁴,
 L. Schoeffel¹³⁷, A. Schoening^{58b}, A.L.S. Schorlemmer⁵⁴, M. Schott⁸², D. Schouten^{160a},
 J. Schovancova¹²⁶, M. Schram⁸⁶, C. Schroeder⁸², N. Schroer^{58c}, M.J. Schultens²¹,
 H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁸, Ph. Schune¹³⁷,
 A. Schwartzman¹⁴⁴, Ph. Schwegler¹⁰⁰, Ph. Schwemling¹³⁷, R. Schwienhorst⁸⁹, J. Schwindling¹³⁷,
 T. Schwindt²¹, M. Schwoerer⁵, F.G. Sciacca¹⁷, E. Scifo¹¹⁶, G. Sciolla²³, W.G. Scott¹³⁰,
 F. Scutti²¹, J. Searcy⁸⁸, G. Sedov⁴², E. Sedykh¹²², S.C. Seidel¹⁰⁴, A. Seiden¹³⁸, F. Seifert⁴⁴,
 J.M. Seixas^{24a}, G. Sekhniaidze^{103a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov¹²²,
 G. Sellers⁷³, M. Seman^{145b}, N. Semprini-Cesari^{20a,20b}, C. Serfon³⁰, L. Serin¹¹⁶, L. Serkin⁵⁴,
 T. Serre⁸⁴, R. Seuster^{160a}, H. Severini¹¹², A. Sfyrila³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁵,
 L.Y. Shan^{33a}, J.T. Shank²², Q.T. Shao⁸⁷, M. Shapiro¹⁵, P.B. Shatalov⁹⁶, K. Shaw^{165a,165c},
 P. Sherwood⁷⁷, S. Shimizu¹⁰², M. Shimojima¹⁰¹, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁵,
 M.J. Shochet³¹, D. Short¹¹⁹, S. Shrestha⁶³, E. Shulga⁹⁷, M.A. Shupe⁷, P. Sicho¹²⁶, A. Sidoti^{133a},
 F. Siegert⁴⁸, Dj. Sijacki^{13a}, O. Silbert¹⁷³, J. Silva^{125a}, Y. Silver¹⁵⁴, D. Silverstein¹⁴⁴,
 S.B. Silverstein^{147a}, V. Simak¹²⁷, O. Simard⁵, Lj. Simic^{13a}, S. Simion¹¹⁶, E. Simioni⁸²,
 B. Simmons⁷⁷, R. Simoniello^{90a,90b}, M. Simonyan³⁶, P. Sinervo¹⁵⁹, N.B. Sinev¹¹⁵, V. Sipica¹⁴²,
 G. Siragusa¹⁷⁵, A. Sircar⁷⁸, A.N. Sisakyan^{64,*}, S.Yu. Sivoklokov⁹⁸, J. Sjölin^{147a,147b},
 T.B. Sjurson¹⁴, L.A. Skinnari¹⁵, H.P. Skottowe⁵⁷, K.Yu. Skovpen¹⁰⁸, P. Skubic¹¹², M. Slater¹⁸,
 T. Slavicek¹²⁷, K. Sliwa¹⁶², V. Smakhtin¹⁷³, B.H. Smart⁴⁶, L. Smestad¹¹⁸, S.Yu. Smirnov⁹⁷,
 Y. Smirnov⁹⁷, L.N. Smirnova^{98,ak}, O. Smirnova⁸⁰, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷,

A.A. Snesarev⁹⁵, G. Snidero⁷⁵, J. Snow¹¹², S. Snyder²⁵, R. Sobie^{170,j}, J. Sodomka¹²⁷, A. Soffer¹⁵⁴,
 D.A. Soh^{152,w}, C.A. Solans³⁰, M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁷, U. Soldevila¹⁶⁸,
 E. Solfaroli Camillocci^{133a,133b}, A.A. Solodkov¹²⁹, O.V. Solovyanov¹²⁹, V. Solovyev¹²², N. Soni¹,
 A. Sood¹⁵, V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sosebee⁸, R. Soualah^{165a,165c}, P. Soueid⁹⁴,
 A.M. Soukharev¹⁰⁸, D. South⁴², S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, R. Spighi^{20a}, G. Spigo³⁰,
 R. Spiwoks³⁰, M. Spousta^{128,al}, T. Spreitzer¹⁵⁹, B. Spurlock⁸, R.D. St. Denis⁵³, J. Stahlman¹²¹,
 R. Stamen^{58a}, E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{135a}, M. Stanescu-Bellu⁴²,
 M.M. Stanitzki⁴², S. Stapnes¹¹⁸, E.A. Starchenko¹²⁹, J. Stark⁵⁵, P. Staroba¹²⁶, P. Starovoitov⁴²,
 R. Staszewski³⁹, A. Staude⁹⁹, P. Stavina^{145a,*}, G. Steele⁵³, P. Steinbach⁴⁴, P. Steinberg²⁵,
 I. Stekl¹²⁷, B. Stelzer¹⁴³, H.J. Stelzer⁸⁹, O. Stelzer-Chilton^{160a}, H. Stenzel⁵², S. Stern¹⁰⁰,
 G.A. Stewart³⁰, J.A. Stillings²¹, M.C. Stockton⁸⁶, M. Stoebe⁸⁶, K. Stoerig⁴⁸, G. Stoicea^{26a},
 S. Stonjek¹⁰⁰, A.R. Stradling⁸, A. Straessner⁴⁴, J. Strandberg¹⁴⁸, S. Strandberg^{147a,147b},
 A. Strandlie¹¹⁸, M. Strang¹¹⁰, E. Strauss¹⁴⁴, M. Strauss¹¹², P. Strizenc^{145b}, R. Ströhmer¹⁷⁵,
 D.M. Strom¹¹⁵, J.A. Strong^{76,*}, R. Stroynowski⁴⁰, B. Stugu¹⁴, I. Stumer^{25,*}, J. Stupak¹⁴⁹,
 P. Sturm¹⁷⁶, N.A. Styles⁴², D. Su¹⁴⁴, HS. Subramania³, R. Subramaniam⁷⁸, A. Succurro¹²,
 Y. Sugaya¹¹⁷, C. Suhr¹⁰⁷, M. Suk¹²⁷, V.V. Sulim⁹⁵, S. Sultansoy^{4c}, T. Sumida⁶⁷, X. Sun⁵⁵,
 J.E. Sundermann⁴⁸, K. Suruliz¹⁴⁰, G. Susinno^{37a,37b}, M.R. Sutton¹⁵⁰, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶,
 M. Svatos¹²⁶, S. Swedish¹⁶⁹, M. Swiatlowski¹⁴⁴, I. Sykora^{145a}, T. Sykora¹²⁸, D. Ta¹⁰⁶,
 K. Tackmann⁴², A. Taffard¹⁶⁴, R. Tafirout^{160a}, N. Taiblum¹⁵⁴, Y. Takahashi¹⁰², H. Takai²⁵,
 R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴¹, Y. Takubo⁶⁵, M. Talby⁸⁴, A.A. Talyshev^{108,g},
 J.Y.C. Tam¹⁷⁵, M.C. Tamssett^{78,am}, K.G. Tan⁸⁷, J. Tanaka¹⁵⁶, R. Tanaka¹¹⁶, S. Tanaka¹³²,
 S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴³, K. Tani⁶⁶, N. Tannoury⁸⁴, S. Tapprogge⁸², S. Tarem¹⁵³,
 F. Tarrade²⁹, G.F. Tartarelli^{90a}, P. Tas¹²⁸, M. Tasevsky¹²⁶, T. Tashiro⁶⁷, E. Tassi^{37a,37b},
 Y. Tayalati^{136d}, C. Taylor⁷⁷, F.E. Taylor⁹³, G.N. Taylor⁸⁷, W. Taylor^{160b}, M. Teinturier¹¹⁶,
 F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸,
 H. Ten Kate³⁰, P.K. Teng¹⁵², S. Terada⁶⁵, K. Terashi¹⁵⁶, J. Terron⁸¹, M. Testa⁴⁷,
 R.J. Teuscher^{159,j}, J. Therhaag²¹, T. Theveneaux-Pelzer³⁴, S. Thoma⁴⁸, J.P. Thomas¹⁸,
 E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁹, A.S. Thompson⁵³, L.A. Thomsen³⁶,
 E. Thomson¹²¹, M. Thomson²⁸, W.M. Thong⁸⁷, R.P. Thun^{88,*}, F. Tian³⁵, M.J. Tibbetts¹⁵,
 T. Tic¹²⁶, V.O. Tikhomirov⁹⁵, Yu.A. Tikhonov^{108,g}, S. Timoshenko⁹⁷, E. Tiouchichine⁸⁴,
 P. Tipton¹⁷⁷, S. Tisserant⁸⁴, T. Todorov⁵, S. Todorova-Nova¹⁶², B. Toggerson¹⁶⁴, J. Tojo⁶⁹,
 S. Tokár^{145a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁹, L. Tomlinson⁸³, M. Tomoto¹⁰², L. Tompkins³¹,
 K. Toms¹⁰⁴, A. Tonoyan¹⁴, C. Topfel¹⁷, N.D. Topilin⁶⁴, E. Torrence¹¹⁵, H. Torres⁷⁹,
 E. Torró Pastor¹⁶⁸, J. Toth^{84,ah}, F. Touchard⁸⁴, D.R. Tovey¹⁴⁰, H.L. Tran¹¹⁶, T. Trefzger¹⁷⁵,
 L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{160a}, S. Trincz-Duvoid⁷⁹, M.F. Tripiana⁷⁰, N. Triplett²⁵,
 W. Trischuk¹⁵⁹, B. Trocme⁵⁵, C. Troncon^{90a}, M. Trottier-McDonald¹⁴³, M. Trovatelli^{135a,135b},
 P. True⁸⁹, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C-L. Tseng¹¹⁹, M. Tsiakiris¹⁰⁶,
 P.V. Tsiarehka⁹¹, D. Tsionou¹³⁷, G. Tsipolitis¹⁰, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸,
 E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁶, V. Tsulaia¹⁵, J.-W. Tsung²¹, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁹,
 A. Tua¹⁴⁰, A. Tudorache^{26a}, V. Tudorache^{26a}, J.M. Tuggle³¹, A.N. Tuna¹²¹, M. Turala³⁹,
 D. Turecek¹²⁷, I. Turk Cakir^{4d}, R. Turra^{90a,90b}, P.M. Tuts³⁵, A. Tykhonov⁷⁴, M. Tylmad^{147a,147b},
 M. Tyndel¹³⁰, K. Uchida²¹, I. Ueda¹⁵⁶, R. Ueno²⁹, M. Ughetto⁸⁴, M. Ugländ¹⁴, M. Uhlenbrock²¹,
 F. Ukegawa¹⁶¹, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶⁴, F.C. Ungaro⁴⁸, Y. Unno⁶⁵, D. Urbaniec³⁵,
 P. Urquijo²¹, G. Usai⁸, L. Vacavant⁸⁴, V. Vacek¹²⁷, B. Vachon⁸⁶, S. Vahsen¹⁵, N. Valencic¹⁰⁶,
 S. Valentineti^{20a,20b}, A. Valero¹⁶⁸, L. Valery³⁴, S. Valkar¹²⁸, E. Valladolid Gallego¹⁶⁸,
 S. Vallecorsa¹⁵³, J.A. Valls Ferrer¹⁶⁸, R. Van Berg¹²¹, P.C. Van Der Deijl¹⁰⁶, R. van der Geer¹⁰⁶,
 H. van der Graaf¹⁰⁶, R. Van Der Leeuw¹⁰⁶, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶,
 J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁶, M. Vanadia¹⁰⁰, W. Vandelli³⁰, A. Vaniachine⁶,
 P. Vankov⁴², F. Vannucci⁷⁹, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁸⁵, D. Varouchas¹⁵,
 A. Vartapetian⁸, K.E. Varvell¹⁵¹, V.I. Vassilakopoulos⁵⁶, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴,
 F. Veloso^{125a}, S. Veneziano^{133a}, A. Ventura^{72a,72b}, D. Ventura⁸⁵, M. Venturi⁴⁸, N. Venturi¹⁵⁹,
 V. Vercesi^{120a}, M. Verducci¹³⁹, W. Verkerke¹⁰⁶, J.C. Vermeulen¹⁰⁶, A. Vest⁴⁴, M.C. Vetterli^{143,e},

I. Vichou¹⁶⁶, T. Vickey^{146c,an}, O.E. Vickey Boeriu^{146c}, G.H.A. Viehhauser¹¹⁹, S. Viel¹⁶⁹,
M. Villa^{20a,20b}, M. Villaplana Perez¹⁶⁸, E. Vilucchi⁴⁷, M.G. Vincter²⁹, V.B. Vinogradov⁶⁴,
J. Virzi¹⁵, O. Vitells¹⁷³, M. Viti⁴², I. Vivarelli⁴⁸, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁹,
M. Vlasak¹²⁷, A. Vogel²¹, P. Vokac¹²⁷, G. Volpi⁴⁷, M. Volpi⁸⁷, G. Volpini^{90a},
H. von der Schmitt¹⁰⁰, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁸, M. Vos¹⁶⁸, R. Voss³⁰,
J.H. Vosseveld⁷³, N. Vranjes¹³⁷, M. Vranjes Milosavljevic¹⁰⁶, V. Vrba¹²⁶, M. Vreeswijk¹⁰⁶,
T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁷, W. Wagner¹⁷⁶, P. Wagner²¹,
S. Wahrmund⁴⁴, J. Wakabayashi¹⁰², S. Walch⁸⁸, J. Walder⁷¹, R. Walker⁹⁹, W. Walkowiak¹⁴²,
R. Wall¹⁷⁷, P. Waller⁷³, B. Walsh¹⁷⁷, C. Wang⁴⁵, H. Wang¹⁷⁴, H. Wang⁴⁰, J. Wang¹⁵²,
J. Wang^{33a}, K. Wang⁸⁶, R. Wang¹⁰⁴, S.M. Wang¹⁵², T. Wang²¹, X. Wang¹⁷⁷, A. Warburton⁸⁶,
C.P. Ward²⁸, D.R. Wardrop⁷⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², I. Watanabe⁶⁶,
P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵¹, M.F. Watson¹⁸, G. Watts¹³⁹, S. Watts⁸³,
A.T. Waugh¹⁵¹, B.M. Waugh⁷⁷, M.S. Weber¹⁷, J.S. Webster³¹, A.R. Weidberg¹¹⁹, P. Weigell¹⁰⁰,
J. Weingarten⁵⁴, C. Weiser⁴⁸, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{152,w},
T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Werth¹⁶⁴, M. Wessels^{58a},
J. Wetter¹⁶², K. Whalen²⁹, A. White⁸, M.J. White⁸⁷, R. White^{32b}, S. White^{123a,123b},
S.R. Whitehead¹¹⁹, D. Whiteson¹⁶⁴, D. Whittington⁶⁰, D. Wicke¹⁷⁶, F.J. Wickens¹³⁰,
W. Wiedenmann¹⁷⁴, M. Wielers^{80,d}, P. Wienemann²¹, C. Wiglesworth³⁶, L.A.M. Wiik-Fuchs²¹,
P.A. Wijeratne⁷⁷, A. Wildauer¹⁰⁰, M.A. Wildt^{42,s}, I. Wilhelm¹²⁸, H.G. Wilkens³⁰, J.Z. Will⁹⁹,
E. Williams³⁵, H.H. Williams¹²¹, S. Williams²⁸, W. Willis^{35,*}, S. Willocq⁸⁵, J.A. Wilson¹⁸,
A. Wilson⁸⁸, I. Wingerter-Seez⁵, S. Winkelmann⁴⁸, F. Winklmeier³⁰, M. Wittgen¹⁴⁴, T. Wittig⁴³,
J. Wittkowski⁹⁹, S.J. Wollstadt⁸², M.W. Wolter³⁹, H. Wolters^{125a,h}, W.C. Wong⁴¹, G. Wooden⁸⁸,
B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸³, K.W. Wozniak³⁹, K. Wraight⁵³, M. Wright⁵³,
B. Wrona⁷³, S.L. Wu¹⁷⁴, X. Wu⁴⁹, Y. Wu⁸⁸, E. Wulf³⁵, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁷,
S. Xie⁴⁸, C. Xu^{33b,ab}, D. Xu^{33a}, L. Xu^{33b,ao}, B. Yabsley¹⁵¹, S. Yacoub^{146b,ap}, M. Yamada⁶⁵,
H. Yamaguchi¹⁵⁶, Y. Yamaguchi¹⁵⁶, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁶,
T. Yamamura¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰², T. Yamazaki¹⁵⁶, Y. Yamazaki⁶⁶, Z. Yan²²,
H. Yang^{33e}, H. Yang¹⁷⁴, U.K. Yang⁸³, Y. Yang¹¹⁰, Z. Yang^{147a,147b}, S. Yanush⁹², L. Yao^{33a},
Y. Yasu⁶⁵, E. Yatsenko⁴², K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵, A.L. Yen⁵⁷, E. Yildirim⁴²,
M. Yilmaz^{4b}, R. Yoosoofmiya¹²⁴, K. Yorita¹⁷², R. Yoshida⁶, K. Yoshihara¹⁵⁶, C. Young¹⁴⁴,
C.J.S. Young¹¹⁹, S. Youssef²², D. Yu²⁵, D.R. Yu¹⁵, J. Yu⁸, J. Yu¹¹³, L. Yuan⁶⁶, A. Yurkewicz¹⁰⁷,
B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev^{129,ac}, S. Zambito²³, L. Zanello^{133a,133b}, D. Zanzi¹⁰⁰,
A. Zaytsev²⁵, C. Zeitnitz¹⁷⁶, M. Zeman¹²⁷, A. Zemla³⁹, O. Zenin¹²⁹, T. Ženiš^{145a}, D. Zerwas¹¹⁶,
G. Zevi della Porta⁵⁷, D. Zhang⁸⁸, H. Zhang⁸⁹, J. Zhang⁶, L. Zhang¹⁵², X. Zhang^{33d}, Z. Zhang¹¹⁶,
Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁹, B. Zhou⁸⁸, N. Zhou¹⁶⁴, Y. Zhou¹⁵², C.G. Zhu^{33d},
H. Zhu⁴², J. Zhu⁸⁸, Y. Zhu^{33b}, X. Zhuang^{33a}, A. Zibell⁹⁹, D. Zieminska⁶⁰, N.I. Zimin⁶⁴,
C. Zimmermann⁸², R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, Z. Zinonos^{123a,123b},
M. Ziolkowski¹⁴², R. Zitoun⁵, L. Živković³⁵, V.V. Zmouchko^{129,*}, G. Zobernig¹⁷⁴,
A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, V. Zutshi¹⁰⁷, L. Zwalinski³⁰

¹ School of Chemistry and Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany NY, United States of America

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

⁴ ^(a) Department of Physics, Ankara University, Ankara; ^(b) Department of Physics, Gazi University, Ankara; ^(c) Division of Physics, TOBB University of Economics and Technology, Ankara; ^(d) Turkish Atomic Energy Authority, Ankara, Turkey

⁵ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

⁷ Department of Physics, University of Arizona, Tucson AZ, United States of America

⁸ Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

⁹ Physics Department, University of Athens, Athens, Greece

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

- ¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹² Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- ¹³ ^(a) Institute of Physics, University of Belgrade, Belgrade; ^(b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
- ¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
- ¹⁶ Department of Physics, Humboldt University, Berlin, Germany
- ¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ¹⁹ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics, Dogus University, Istanbul; ^(c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- ²⁰ ^(a) INFN Sezione di Bologna; ^(b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- ²¹ Physikalisches Institut, University of Bonn, Bonn, Germany
- ²² Department of Physics, Boston University, Boston MA, United States of America
- ²³ Department of Physics, Brandeis University, Waltham MA, United States of America
- ²⁴ ^(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; ^(c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁵ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- ²⁶ ^(a) National Institute of Physics and Nuclear Engineering, Bucharest; ^(b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; ^(c) University Politehnica Bucharest, Bucharest; ^(d) West University in Timisoara, Timisoara, Romania
- ²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ²⁹ Department of Physics, Carleton University, Ottawa ON, Canada
- ³⁰ CERN, Geneva, Switzerland
- ³¹ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- ³² ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³³ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Department of Modern Physics, University of Science and Technology of China, Anhui; ^(c) Department of Physics, Nanjing University, Jiangsu; ^(d) School of Physics, Shandong University, Shandong; ^(e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
- ³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵ Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ³⁶ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁷ ^(a) INFN Gruppo Collegato di Cosenza; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸ ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas TX, United States of America
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴² DESY, Hamburg and Zeuthen, Germany

- 43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- 44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- 45 Department of Physics, Duke University, Durham NC, United States of America
- 46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- 47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
- 48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- 49 Section de Physique, Université de Genève, Geneva, Switzerland
- 50 ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- 51 ^(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- 52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- 53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- 54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- 55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- 56 Department of Physics, Hampton University, Hampton VA, United States of America
- 57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- 58 ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- 59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 60 Department of Physics, Indiana University, Bloomington IN, United States of America
- 61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 62 University of Iowa, Iowa City IA, United States of America
- 63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- 64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 66 Graduate School of Science, Kobe University, Kobe, Japan
- 67 Faculty of Science, Kyoto University, Kyoto, Japan
- 68 Kyoto University of Education, Kyoto, Japan
- 69 Department of Physics, Kyushu University, Fukuoka, Japan
- 70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 71 Physics Department, Lancaster University, Lancaster, United Kingdom
- 72 ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 77 Department of Physics and Astronomy, University College London, London, United Kingdom
- 78 Louisiana Tech University, Ruston LA, United States of America
- 79 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 80 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 81 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 82 Institut für Physik, Universität Mainz, Mainz, Germany
- 83 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 84 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 85 Department of Physics, University of Massachusetts, Amherst MA, United States of America
- 86 Department of Physics, McGill University, Montreal QC, Canada
- 87 School of Physics, University of Melbourne, Victoria, Australia

- 88 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
 89 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States
 of America
 90 ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
 91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of
 Belarus
 92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic
 of Belarus
 93 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of
 America
 94 Group of Particle Physics, University of Montreal, Montreal QC, Canada
 95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
 96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
 97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
 98 D.V.Skobeltzyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow,
 Russia
 99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
 100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
 101 Nagasaki Institute of Applied Science, Nagasaki, Japan
 102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
 103 ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
 104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States
 of America
 105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University
 Nijmegen/Nikhef, Nijmegen, Netherlands
 106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam,
 Netherlands
 107 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
 108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
 109 Department of Physics, New York University, New York NY, United States of America
 110 Ohio State University, Columbus OH, United States of America
 111 Faculty of Science, Okayama University, Okayama, Japan
 112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK,
 United States of America
 113 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
 114 Palacký University, RCPTM, Olomouc, Czech Republic
 115 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
 116 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
 117 Graduate School of Science, Osaka University, Osaka, Japan
 118 Department of Physics, University of Oslo, Oslo, Norway
 119 Department of Physics, Oxford University, Oxford, United Kingdom
 120 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
 121 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
 122 Petersburg Nuclear Physics Institute, Gatchina, Russia
 123 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
 124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of
 America
 125 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal; ^(b)
 Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada,
 Spain
 126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
 127 Czech Technical University in Prague, Praha, Czech Republic

- 128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
 129 State Research Center Institute for High Energy Physics, Protvino, Russia
 130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
 131 Physics Department, University of Regina, Regina SK, Canada
 132 Ritsumeikan University, Kusatsu, Shiga, Japan
 133 ^(a) INFN Sezione di Roma I; ^(b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
 134 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
 135 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
 136 ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
 137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
 138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
 139 Department of Physics, University of Washington, Seattle WA, United States of America
 140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
 141 Department of Physics, Shinshu University, Nagano, Japan
 142 Fachbereich Physik, Universität Siegen, Siegen, Germany
 143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
 144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
 145 ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
 146 ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
 147 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
 148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
 149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
 150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
 151 School of Physics, University of Sydney, Sydney, Australia
 152 Institute of Physics, Academia Sinica, Taipei, Taiwan
 153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
 154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
 155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
 156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
 157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
 158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
 159 Department of Physics, University of Toronto, Toronto ON, Canada
 160 ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON, Canada
 161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
 162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
 163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

- ¹⁶⁴ Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- ¹⁶⁵ ^(a) INFN Gruppo Collegato di Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁶ Department of Physics, University of Illinois, Urbana IL, United States of America
- ¹⁶⁷ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁸ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁶⁹ Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁷⁰ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁷¹ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷² Waseda University, Tokyo, Japan
- ¹⁷³ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷⁴ Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁵ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁶ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁷ Department of Physics, Yale University, New Haven CT, United States of America
- ¹⁷⁸ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ^a Also at Department of Physics, King's College London, London, United Kingdom
- ^b Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- ^c Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- ^d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ^e Also at TRIUMF, Vancouver BC, Canada
- ^f Also at Department of Physics, California State University, Fresno CA, United States of America
- ^g Also at Novosibirsk State University, Novosibirsk, Russia
- ^h Also at Department of Physics, University of Coimbra, Coimbra, Portugal
- ⁱ Also at Università di Napoli Parthenope, Napoli, Italy
- ^j Also at Institute of Particle Physics (IPP), Canada
- ^k Also at Department of Physics, Middle East Technical University, Ankara, Turkey
- ^l Also at Louisiana Tech University, Ruston LA, United States of America
- ^m Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ⁿ Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ^o Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
- ^p Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- ^q Also at Department of Physics, University of Cape Town, Cape Town, South Africa
- ^r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^s Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^t Also at Manhattan College, New York NY, United States of America
- ^u Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^v Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ^w Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- ^x Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^y Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ^z Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India

- ^{aa} Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- ^{ab} Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- ^{ac} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ^{ad} Also at section de Physique, Université de Genève, Geneva, Switzerland
- ^{ae} Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
- ^{af} Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- ^{ag} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- ^{ah} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ^{ai} Also at DESY, Hamburg and Zeuthen, Germany
- ^{aj} Also at International School for Advanced Studies (SISSA), Trieste, Italy
- ^{ak} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ^{al} Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ^{am} Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- ^{an} Also at Department of Physics, Oxford University, Oxford, United Kingdom
- ^{ao} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ^{ap} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
- * Deceased