Measurement of the relative $B_c^\pm/B^\pm$ production cross section with the ATLAS detector at $\sqrt{s}=8$ TeV

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

(Received 6 December 2019; accepted 21 June 2021; published 26 July 2021)

The total cross section and differential cross sections for the production of $B_c^\pm$ mesons, times their branching fraction to $J/\psi\pi^\pm$, are measured relative to those for the production of $B^\pm$ mesons, times their branching fraction to $J/\psi K^\pm$. The data used for this study correspond to an integrated luminosity of 20.3 fb^{-1} of pp collisions recorded by the ATLAS detector at the Large Hadron Collider in 2012 at a center-of-mass energy of $\sqrt{s}=8$ TeV. The measurement is performed differentially in bins of transverse momentum p_T for 13 GeV $< p_T(B_c^\pm) <$ 22 GeV and $p_T(B_c^\pm) >$ 22 GeV and in bins of rapidity y for $|y| < 0.75$ and $0.75 < |y| < 2.3$. The relative cross section times branching fraction for the full range $p_T >$ 13 GeV and $|y| < 2.3$ is $(0.34 \pm 0.04_{\text{stat}}\,{}^{+0.06}_{-0.02}{}_{\text{sys}} \pm 0.01_{\text{lifetime}})\%$. The differential measurements suggest that the production cross section of the $B_c^\pm$ decreases faster with p_T than the production cross section of the $B^\pm$, while no significant dependence on rapidity is observed.

DOI: 10.1103/PhysRevD.104.012010

I. INTRODUCTION

The $B_c^\pm$ meson is a bound state of the two heaviest distinct quarks able to form a stable state, c and $\bar{b}$ for B_c^+ or $\bar{c}$ and b for B_c^-. Measurements of its production can provide unique insight into heavy-quark hadronization: unlike lighter B-states, production of a $B_c^\pm$ meson requires collinear production of two distinct heavy quarks.

A measurement of the production cross section times branching fraction for $B_c^\pm \to J/\psi\pi^\pm$, relative to that for $B^\pm \to J/\psi K^\pm$, at $\sqrt{s}=8$ TeV of pp collisions and differential in transverse momentum p_T and in rapidity[1] y, has not yet been reported for the fiducial region considered in this article and defined below, although measurements of the individual cross sections have been published. At $\sqrt{s}=7$ TeV, the LHCb Collaboration reported [1] a relative cross section times branching fraction of $(0.68 \pm 0.10_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.05_{\text{lifetime}})\%$ for $p_T(B_c^\pm) > 4$ GeV in the pseudorapidity[2] range $2.5 < \eta < 4.5$. LHCb reported [2] for the same differential relative B_c^+ cross section at $\sqrt{s}=8$ TeV a measurement of $(0.683 \pm 0.018_{\text{stat}} \pm 0.009_{\text{syst}})\%$ in the rapidity range $2.0 < y < 4.5$ for the interval $0 < p_T(B_c^+) <$ 20 GeV. The measurement [2] by the LHCb Collaboration at $\sqrt{s}=8$ TeV has a very slight overlap with the fiducial region (defined below) of this one. In the fiducial region $13 < p_T(B) < 20$ GeV and $2.0 < y(B) < 2.3$, where the two experiments are both sensitive, the LHCb data show no trend in the ratio as a function of p_T. However, the LHCb dataset is dominated by B_c candidates with p_T lower than those in this ATLAS analysis. The CMS Collaboration measured the same quantity in the rapidity range $|y| < 1.6$ for $p_T(B_c^\pm) > 15$ GeV to be $(0.48 \pm 0.05_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.05_{\text{lifetime}})\%$ [3] at $\sqrt{s}=7$ TeV. The values reported here by ATLAS are smaller than those obtained by the other experiments at different energies and with different fiducial volumes, and evidence of dependence of this relative production cross section on transverse momentum is shown here for the first time.

Theoretical predictions for the hadronic $B_c^\pm$ production cross section have been reported by several authors [4–10] and this study is motivated by the range of predicted values. Theoretical calculations predict that the total production cross section σ_{B_c} is in the range of 1 nb to 31.5 nb at $\sqrt{s}=1.8$ TeV and 44 nb to 190 nb at $\sqrt{s}=14$ TeV, but no published calculation for the relative cross section at $\sqrt{s}=8$ TeV is available at this time. These calculations depend on the square of the decay constant $f_{B_c^\pm}$ [4,11,12], which in the nonrelativistic approach is proportional to the absolute value of the wave function at the origin.

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

[1]The rapidity y is defined as $(1/2)\times\ln[(E+p_z)/(E-p_z)]$, where E is the energy of a particle and p_z is its component of momentum along the beam axis.

[2]The pseudorapidity η is defined as $-\ln[\tan(\theta/2)]$, where θ is the angle between the particle momentum and the positive direction of the beam axis.

In this measurement of the cross section times branching fraction for $B_c^\pm \to J/\psi\pi^\pm$ relative to that for $B^\pm \to J/\psi K^\pm$, the J/ψ mesons are reconstructed from their decays into $\mu^+\mu^-$. The relative cross section measurement is differential in two bins of the transverse momentum p_T of the $B_c^\pm$, 13 GeV $< p_T(B_c^\pm) <$ 22 GeV and $p_T(B^\pm) >$ 22 GeV, for rapidity $|y| < 2.3$, and in two bins of rapidity y of the $B_c^\pm$, $|y| < 0.75$ and $0.75 < |y| < 2.3$, for $p_T(B_c^\pm) > 13$ GeV.

The relative cross section is also measured for the inclusive dataset with $p_T > 13$ GeV and $|y| < 2.3$. The fiducial volume is defined by the requirements on $p_T(B_c^\pm)$ and $y(B_c^\pm)$. The bins are selected to equalize yields of the $B_c^\pm$. The same bin sizes are used for the $B_c^\pm$ and the $B^\pm$. The data were recorded in 2012 by the ATLAS [13] experiment at a center-of-mass energy of $\sqrt{s} = 8$ TeV.

The article is organized as follows. After this introduction, Sec. II provides an overview of the ATLAS detector including the trigger system and the objects used. Section III describes the simulation, reconstruction, and event selection. Section IV shows the relative cross-section calculation. Section V presents the fits to the mass distributions. Section VI describes the calculation of the efficiency and acceptance ratios. Section VII reports the systematic uncertainties. Section VIII presents the results of the measurements. Conclusions are drawn in Sec. IX.

II. THE ATLAS DETECTOR, TRIGGER, AND BASIC TRACK SELECTIONS

ATLAS is a general-purpose particle detector [13] consisting of several subsystems including the inner detector (ID), the electromagnetic and hadronic calorimeters, and the muon spectrometer (MS). Muons pass through the calorimeters and reach the MS if their momentum is above approximately 3 GeV. The ID features a three-component tracking system, consisting of two silicon-based detectors, the pixel detector and the microstrip semiconductor tracker (SCT), and the transition radiation tracker (TRT).

ID tracks are reconstructed if their transverse momentum is greater than 400 MeV and if the magnitude of their pseudorapidity, $|\eta|$, is less than 2.5. Muon candidates are either formed from a stand-alone MS track that is matched to an ID track (so-called combined muons) or from an ID track extrapolated to the MS and matched to track segments in the MS (so-called tagged muons) [14]. The ID and MS subsystems are of particular importance to this study. Only the data taken when both of these subsystems were properly operational and when LHC beams were stable are used, corresponding to an integrated luminosity of 20.3 fb^{-1}. Although both the ID and the MS provide momentum measurements, in the p_T range relevant to this analysis, the MS momentum resolution is worse than that of the ID due to energy loss in the calorimeters. Therefore, the MS is used only to identify muons, and the p_T measurement is taken from the ID. The muon candidates are required to have the number of pixel hits plus the number of crossed dead pixel sensors greater than zero, the number of SCT hits plus the number of crossed dead SCT sensors greater than four, and the number of pixel holes[3] plus the number of SCT holes on the track less than three.

ID tracks from charged hadrons are required to have at least two pixel hits and at least six hits in the SCT (eight hits in total). If a track crosses a dead sensor, it is not counted as a hit in the corresponding subdetector; the number of pixel + SCT holes is required to be less than three. For tracks with $0.1 < |\eta| < 1.9$ it is required that $n > 5$ and $n_{\mathrm{TRT}}^{\mathrm{out}} < 0.9n$, where $n = n_{\mathrm{TRT}} + n_{\mathrm{TRT}}^{\mathrm{out}}$, and $n_{\mathrm{TRT}}(n_{\mathrm{TRT}}^{\mathrm{out}})$ stands for the number of TRT hits (outliers [14]) on the track.

The trigger system [15] for data collected up to and including 2012 comprises three levels: the hardware-based first-level (L1) trigger and the high-level triggers (HLT), consisting of the second-level trigger and the event filter. The L1 trigger uses resistive plate chambers and thin gap chambers to trigger on muons in the pseudorapidity ranges of $|\eta| < 1.05$ and $1.05 < |\eta| < 2.5$, respectively. One or more regions-of-interest (RoI), identified by the L1 muon trigger, seed the HLT muon reconstruction algorithms, where the tracks from both the ID and the MS are combined. For this analysis the HLT selection of the J/ψ requires two oppositely charged muons, originating at a common vertex, with the invariant mass of the muon pair lying between 2.5 GeV and 4.3 GeV. The individual muon p_T thresholds are both 4 GeV. The pseudorapidity range of the muon selection is $|\eta| < 2.5$.

III. SIMULATION, RECONSTRUCTION, AND EVENT SELECTION

Samples for the signal ($B_c^\pm \to J/\psi\pi^\pm$ and $B^\pm \to J/\psi K^\pm$) were generated with the PYTHIA Monte Carlo (MC) generator [16,17]. For the generation of the $B_c^\pm$ meson a dedicated PYTHIA extension was used, based on theoretical input [5,9]. The parameters of the MC simulation are described in Sec. VI. The response of the ATLAS detector was simulated with the ATLFAST2 procedure [18] using the GEANT4 package [19], and the events are reconstructed with the same software as is used to process the data from the detector. The effect of multiple proton-proton collisions per beam crossing, also known as pileup, is included.

The J/ψ candidates are reconstructed from pairs of oppositely charged muon candidates. To allow the most accurate corrections for trigger efficiencies, each reconstructed muon candidate is required to match a

[3]In this context, a hole is counted when a hit is expected in an active sensor located on the track trajectory between the first and the last hit associated with this track, but no such hit is found. If the corresponding sensor is known to be inactive and therefore not expected to provide a hit, no hole is counted.

trigger-identified muon candidate within a cone[4] of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.01$. The efficiency of matching the reconstructed muon candidates to the trigger muon candidates is comparable for the two B-meson species according to MC simulation. The muon pair is fitted to a common vertex with the requirement that at least one of the muons is a combined muon. The procedure is described in Ref. [20]. The following requirements are applied to choose a J/ψ candidate:

(i) The p_{T} of each of the two muon candidates must be above 4 GeV.

(ii) The vertex fit quality $\chi^2/(N_{\mathrm{d.o.f.}} = 1)$ must be below 15. This soft requirement is chosen to remove highly unlikely muon combinations.

(iii) The invariant mass $m(\mu^+\mu^-)$ calculated from the refitted track parameters must lie in a mass window that depends on the pseudorapidity of the muons. The η ranges are determined from the resolution of the muon detectors. Three mass windows are defined for the J/ψ around the world average value of 3096.916 MeV [21], as follows. If the $|\eta|$ of both muons is less than (greater than) 1.05, the mass window is ± 120 MeV (± 270 MeV). If the $|\eta|$ of one muon is less than 1.05 and the $|\eta|$ of the other muon is between 1.05 and 2.5, the mass window is ± 180 MeV.

The muon mass is assigned to each track in the J/ψ reconstruction. The refitted track parameters are derived from the vertex fit.

The B candidates (where B represents $B_c^{\pm}$ or $B^{\pm}$) are reconstructed by fitting the tracks of the two muons from the J/ψ candidate, together with a charged-hadron track, to a common vertex. For the $B^{\pm}$ candidates the kaon mass is assigned to the hadron track while for the $B_c^{\pm}$ candidates the pion mass is assigned to the hadron track. The mass of the J/ψ meson is constrained in the fit to its world average value.

The primary pp interaction vertex is found by extrapolating the flight direction of the reconstructed B candidate to the z-axis and then selecting the closest vertex in the z direction [22]. The selected vertex is refitted with the three signal tracks (two muonic and one hadronic) removed.

A significant part of the combinatorial background consists of J/ψ mesons that combine with light hadrons that are not associated with the decay. This background can be reduced by applying a minimum value for the significance of the impact parameter of the hadron track relative to the primary vertex in the transverse plane, $d_{xy}^0/\sigma(d_{xy}^0)$, where d_{xy}^0 is the projection of the impact parameter onto the transverse plane and $\sigma(d_{xy}^0)$ is the uncertainty of d_{xy}^0.

Another significant source of background which is especially important for the $B_c^{\pm}$ is the partially reconstructed semileptonic decays of the $B_c^{\pm}$ such as $B_c^{\pm} \to J/\psi\mu^{\pm}\nu_{\mu}$. This background is reduced by removing combinations in which one of the hadronic candidates is identified as a muon by the MS.

Reconstructed B candidates are required to satisfy the following selection criteria:

(i) The $\chi^2/(N_{\mathrm{d.o.f.}} = 4)$ of the fit of the B vertex must be below 1.8.

(ii) The rapidity $|y(B)|$ must be less than 2.3.

(iii) The p_{T} of the hadron candidate must be above 2.0 GeV.

(iv) To suppress combinatorial background due to prompt[5] J/ψ candidates, the impact parameter significance $d_{xy}^0/\sigma(d_{xy}^0)$ of the hadron candidate must exceed 1.2. MC studies demonstrated that this criterion is more efficient for the $B_c^{\pm}$ candidate selection than a requirement on the lifetime.

In events with multiple B candidates, the candidate with the best χ^2 from the vertex fits is used. The fraction of multiple-candidate events is negligible for this analysis, as observed in data and confirmed by MC studies. This analysis uses all the ground-state B candidates including those produced directly and those produced from the cascade decay of excited states.

IV. RELATIVE CROSS SECTION CALCULATION

The relative cross section times branching fraction is given by:

$$\frac{\sigma(B_c^{\pm}) \cdot \mathcal{B}(B_c^{\pm} \to J/\psi\pi^{\pm}) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\sigma(B^{\pm}) \cdot \mathcal{B}(B^{\pm} \to J/\psi K^{\pm}) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)} = \frac{N^{\mathrm{reco}}(B_c^{\pm})}{N^{\mathrm{reco}}(B^{\pm})} \cdot \frac{\epsilon(B^{\pm})}{\epsilon(B_c^{\pm})}. \quad (1)$$

The notation $N^{\mathrm{reco}}(X)$ refers to the number of reconstructed collision data events, where X is either $B_c^{\pm}$ or $B^{\pm}$. The $\epsilon(B^{\pm})$ and $\epsilon(B_c^{\pm})$ are the efficiencies of $B^{\pm}$ and $B_c^{\pm}$ reconstruction that correct the numbers $N^{\mathrm{reco}}(B_c^{\pm})$ and $N^{\mathrm{reco}}(B^{\pm})$ for detector effects, selection criteria, differences between interactions of $K^{\pm}$ and $\pi^{\pm}$ with the detector material, as well as efficiencies associated with the trigger.

[4]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam line. The x-axis points from the IP to the center 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 z-axis and r the distance from the IP in the transverse plane.

[5]"Prompt" here refer to states that are produced directly by short-lived QCD sources, i.e., those not produced in the beauty hadron decays.

V. FIT TO THE MASS DISTRIBUTIONS

Extended unbinned maximum-likelihood fits to the mass distributions of the $B_c^\pm$ and the $B^\pm$ are performed to extract $N^{\rm reco}(B_c^\pm)$ and $N^{\rm reco}(B^\pm)$ from the data in each bin in $p_{\rm T}$ and $|y|$. This involves calculating the parameters that maximize the likelihood function, defined as

$$\mathcal{L} = \frac{e^{-N_{\rm sig}-N_{\rm bkg}}}{N!}\prod_{i=1}^{N}[N_{\rm sig}\mathcal{F}_{\rm signal}(m^i_{J/\psi X_h}, \delta m^i_{J/\psi X_h}) + N_{\rm bkg}\mathcal{F}_{\rm bkg}(m^i_{J/\psi X_h})]$$

where N is the total number of $J/\psi X_h$ candidates, X_h represents the corresponding hadron, $N_{\rm sig}$ is the total number of signal events, and $N_{\rm bkg}$ is the total number of background events. The contribution from the signal $\mathcal{F}_{\rm signal}$ is modeled by a Gaussian probability density function with event-by-event errors. It is given for the $B_c^\pm$ by

$$\mathcal{F}_{\rm signal}(m^i_{J/\psi\pi}, \delta m^i_{J/\psi\pi}) \propto \exp\left(-\frac{(m^i_{J/\psi\pi^\pm} - m_{B_c^\pm})^2}{2(s_1\delta m^i_{J/\psi\pi^\pm})^2}\right)$$

and for the $B^\pm$ by

$$\mathcal{F}_{\rm signal}(m^i_{J/\psi K^\pm}, \delta m^i_{J/\psi K^\pm}) \propto \exp\left(-\frac{(m^i_{J/\psi K^\pm} - m_{B^\pm})^2}{2(s_2\delta m^i_{J/\psi K^\pm})^2}\right)$$

where $m_{B^\pm}$ and $m_{B_c^\pm}$ are the masses of the $B^\pm$ and $B_c^\pm$, respectively. The variables $m_{B^\pm}$ and $m_{B_c^\pm}$ are taken as free parameters in the fit. The widths $s_1\delta m^i_{J/\psi\pi^\pm}$ and $s_2\delta m^i_{J/\psi K^\pm}$ are the products of the corresponding scale factors s_1 and s_2 and the event-by-event mass resolution. The event-by-event mass uncertainty is calculated from the tracking covariance matrices by error propagation. The scale factors are free parameters of the fit which account for imperfection in estimates of the mass errors. Ideally the value of $s_{1,2}$ is one. The mass resolution σ_m is obtained from the fits and appears in the relevant tables below. It is defined as the half-width of the region of the J/ψ mass distribution for which the integral of the sum of $\mathcal{F}_{\rm signal}(m_{J/\psi X_h}, \delta m_{J/\psi X_h})$ over all candidates contains 68.27% of $N_{\rm sig}$.

The background to $B_c^\pm$ production is modeled with an exponential function plus a constant term,

$$\mathcal{F}_{\rm bkg} \propto \exp(a\cdot m^i_{J/\psi\pi^\pm}) + b.$$

In the $B^\pm$ mass region, partially reconstructed b-hadron decays populate the lower part of the $B^\pm$ mass spectrum. Their contributions are estimated with a complementary error function

$$\mathcal{F}^{(1)}_{\rm bkg}(m^i_{J/\psi K^\pm}) \propto 1 - {\rm erf}\left(\frac{m^i_{J/\psi K^\pm} - m_0}{s_0}\right) = 1 - \frac{2}{\sqrt{\pi}}\int_0^A e^{-t^2}dt$$

where $A = \frac{m^i_{J/\psi K^\pm} - m_0}{s_0}$, and m_0 and s_0 determine the position and the slope of the error function, respectively.

The Cabibbo-suppressed decay $B^\pm \to J/\psi\pi^\pm$ populates the high part of the $B^\pm$ mass spectrum. It is modeled by a Gaussian function

$$\mathcal{F}^{(2)}_{\rm bkg}(m^i_{J/\psi K^\pm}) \propto \exp\left(-\frac{(m^i_{J/\psi K^\pm} - m_{B^\pm,\pi^\pm})^2}{2(s_3\delta m^i_{J/\psi K^\pm})^2}\right),$$

where s_3 is the corresponding scale factor. The variable $m_{B^\pm,\pi^\pm}$ is the median of the mass distribution in the data for $B^\pm \to J/\psi\pi^\pm$ events when the kaon mass instead of the pion mass is assumed for the charged-hadron track.

The remaining background is mostly due to production of J/ψ mesons from decays of b-hadrons other than the $B^\pm$, which are combined with a random hadron track. They are described with an exponential function

$$\mathcal{F}^{(3)}_{\rm bkg}(m^i_{J/\psi K^\pm}) \propto \exp(d\cdot m^i_{J/\psi K^\pm}), \quad (2)$$

where d is a constant.

The models for the background contributions are combined with different fractions, which are fitted to the data. The relative fractions are left free in the fit, as $(a\times\mathcal{F}^{(1)}_{\rm bkg} + b\times\mathcal{F}^{(2)}_{\rm bkg} + (1-(a+b))\times\mathcal{F}^{(3)}_{\rm bkg})$, where a and b are free parameters of the fit.

The projections of the results of the invariant-mass fits of the $B^\pm$ and the $B_c^\pm$ for the various $p_{\rm T}$ and y bins considered in this measurement are given in Figs. 1–6. The inset below each plot shows the bin-by-bin difference between each data point and the value obtained from the fit function divided by the quadrature sum of the statistical uncertainty and the systematic uncertainties obtained from varying the fit model and discussed in Sec. VII. Tables I and II show a summary of the main parameters of the fits.

VI. DETERMINATION OF THE $B_c/B^\pm$ EFFICIENCY AND ACCEPTANCE RATIO

In order to correct the MC distributions to match the observed data, a sPlot-based MC reweighting technique [23] is exploited. This procedure is applied separately to the $B_c^\pm$ and $B^\pm$ candidates. The following MC variables are reweighted: $p_{\rm T}$ of the B candidate, y of the B candidate, χ^2 of the secondary vertex, and the transverse impact parameter significance $d^0_{xy}/\sigma(d^0_{xy})$.

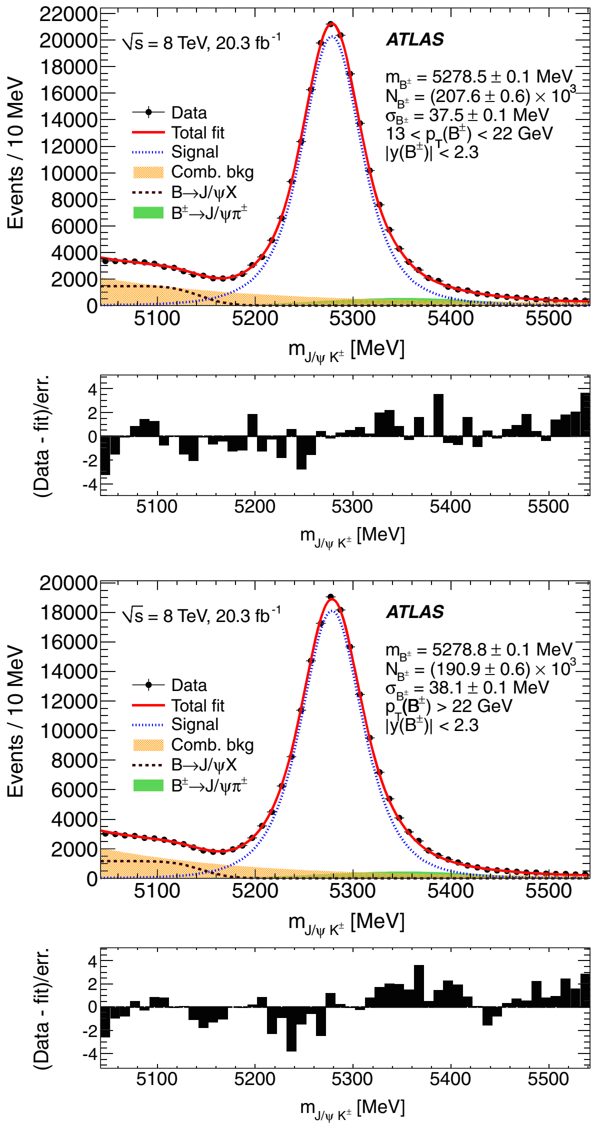

FIG. 1. The projection of the fit of the invariant mass distribution for the $B^{\pm}$ meson. "Signal" stands for the signal component of the fit, "Comb. bkg" stands for the combinatorial background component of the fit, and "Total fit" stands for the fit to the sum of the signal and all background components. The fit for the low transverse momentum bin ($13\ \mathrm{GeV} < p_{\mathrm{T}}(B^{\pm}) < 22\ \mathrm{GeV}$) is shown at the top, and that for the high transverse momentum bin ($p_{\mathrm{T}}(B^{\pm}) > 22\ \mathrm{GeV}$) is shown at the bottom. The rapidity requirement is $|y(B^{\pm})| < 2.3$. The fits are used to extract $N^{\mathrm{reco}}(B^{+}) + N^{\mathrm{reco}}(B^{-})$ and its uncertainty in each bin. The inset below each plot shows the bin-by-bin difference between the data point and the value obtained from the fit function divided by the quadrature sum of the statistical uncertainty and the systematic uncertainties obtained from varying the fit model.

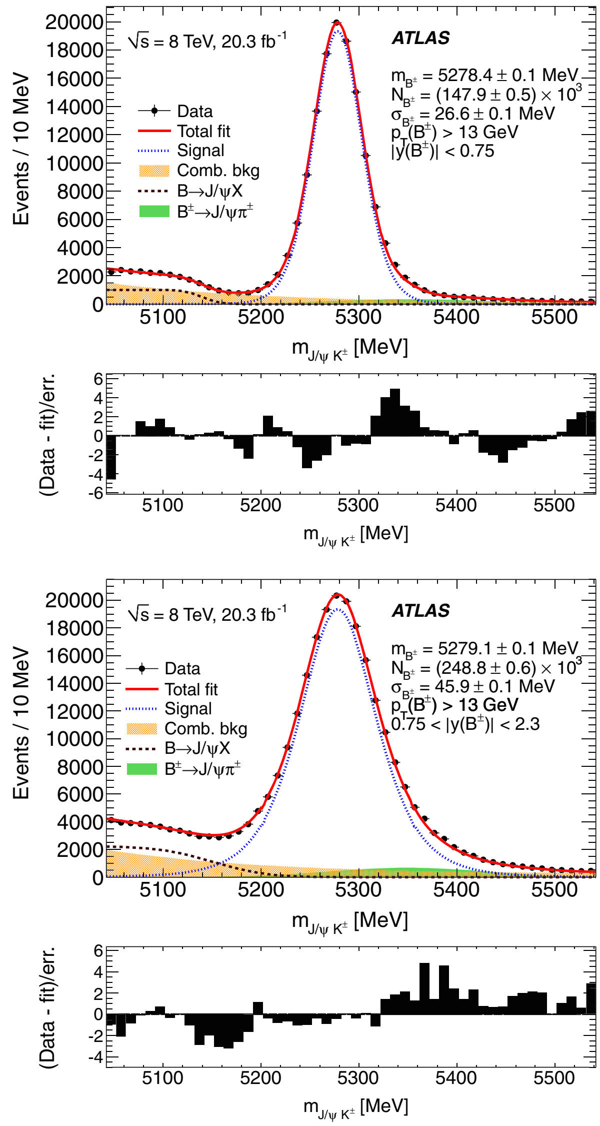

FIG. 2. The projection of the fit of the invariant mass distribution for the $B^{\pm}$ meson. "Signal" stands for the signal component of the fit, "Comb. bkg" stands for the combinatorial background component of the fit, and "Total fit" stands for the fit to the sum of the signal and all background components. The fit for the inner rapidity bin ($|y(B^{\pm})| < 0.75$) is shown at the top, and that for the outer rapidity bin ($0.75 < |y(B^{\pm})| < 2.3$) is shown at the bottom. The p_{T} requirement is $p_{\mathrm{T}}(B^{\pm}) > 13\ \mathrm{GeV}$. The fits are used to extract $N^{\mathrm{reco}}(B^{+}) + N^{\mathrm{reco}}(B^{-})$ and its uncertainty in each bin. The inset below each plot shows the bin-by-bin difference between the data point and the value obtained from the fit function divided by the quadrature sum of the statistical uncertainty and the systematic uncertainties obtained from varying the fit model.

The reconstruction efficiencies are determined using the MC samples for the $B_c^{\pm}$ and $B^{\pm}$ signals. The efficiencies are averaged over each bin in p_{T} and each bin in $|y|$. They are calculated from the ratio of the number of reconstructed MC events $N_{\mathrm{MC}}^{\mathrm{reco}}$ to the number of generated MC events $N_{\mathrm{MC}}^{\mathrm{gen}}$ in the associated bins in the fiducial region. Bin-to-bin migration is included and found to be less than 0.1%, and the associated systematic uncertainties are significantly smaller than uncertainties from other sources.

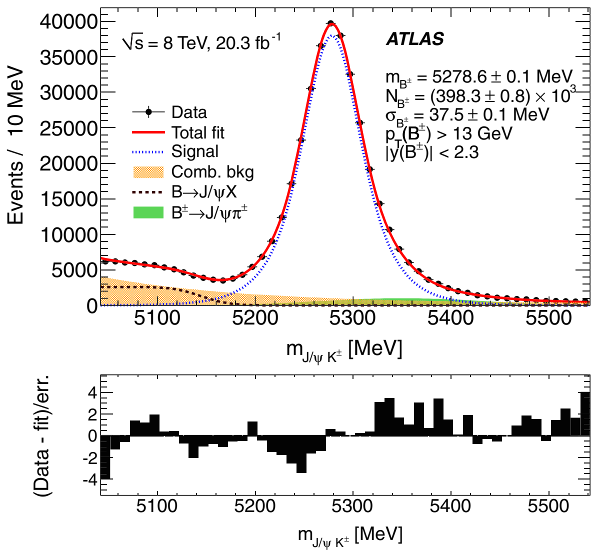

FIG. 3. The projection of the fit of the invariant mass distribution for the $B^\pm$ meson using the complete dataset ($p_T(B^\pm) > 13$ GeV, $|y(B^\pm)| < 2.3$). "Signal" stands for the signal component of the fit, "Comb. bkg" stands for the combinatorial background component of the fit, and "Total fit" stands for the fit to the sum of the signal and all background components. The fit is used to extract $N^{\rm reco}(B^+) + N^{\rm reco}(B^-)$ and its uncertainty in each bin. The inset below each plot shows the bin-by-bin difference between the data point and the value obtained from the fit function divided by the quadrature sum of the statistical uncertainty and the systematic uncertainties obtained from varying the fit model.

The efficiencies can be factorized into the product of the efficiency of the J/ψ trigger $\epsilon^{\rm trigger}$, the efficiency of the muon spectrometer $\epsilon^{\rm MS}$, the efficiency of the inner detector $\epsilon^{\rm ID}$, the efficiency of fitting the muon and hadron tracks to a common decay vertex $\epsilon^{\rm vertex}$, and the efficiency of the selection criteria $\epsilon^{\rm selection}$ [24]:

$$\epsilon = \epsilon^{\rm trigger} \cdot \epsilon^{\rm MS}(\mu^+) \cdot \epsilon^{\rm MS}(\mu^-) \cdot (\epsilon^{\rm ID}(\mu^\pm))^2 \cdot \epsilon^{\rm ID}(X_h) \cdot \epsilon^{\rm vertex}(B) \cdot \epsilon^{\rm selection}(B),$$

where $\epsilon(X_h)$ is the $K^\pm$ efficiency in the $B^\pm$ channel and $\pi^\pm$ efficiency in the $B_c^\pm$ channel, while B stands for the $B^\pm$ and $B_c^\pm$ candidates. Muon trigger efficiencies are calculated using the method outlined in Ref. [25], which can be briefly summarized as follows. The single-muon trigger efficiency is determined from a tag-and-probe study of the J/ψ and Υ dimuon decays in Ref. [26]. The efficiency map is calculated as a function of $p_T(\mu)$ and $q \times \eta(\mu)$, where $q = \pm 1$ is the electric charge of the $\mu^\pm$, expressed in units of e.

Besides the product of two single-muon terms, the trigger efficiency includes components that account for reductions in efficiency due to closely spaced muons firing only a single RoI, for vertex quality and opposite-sign charge requirements.

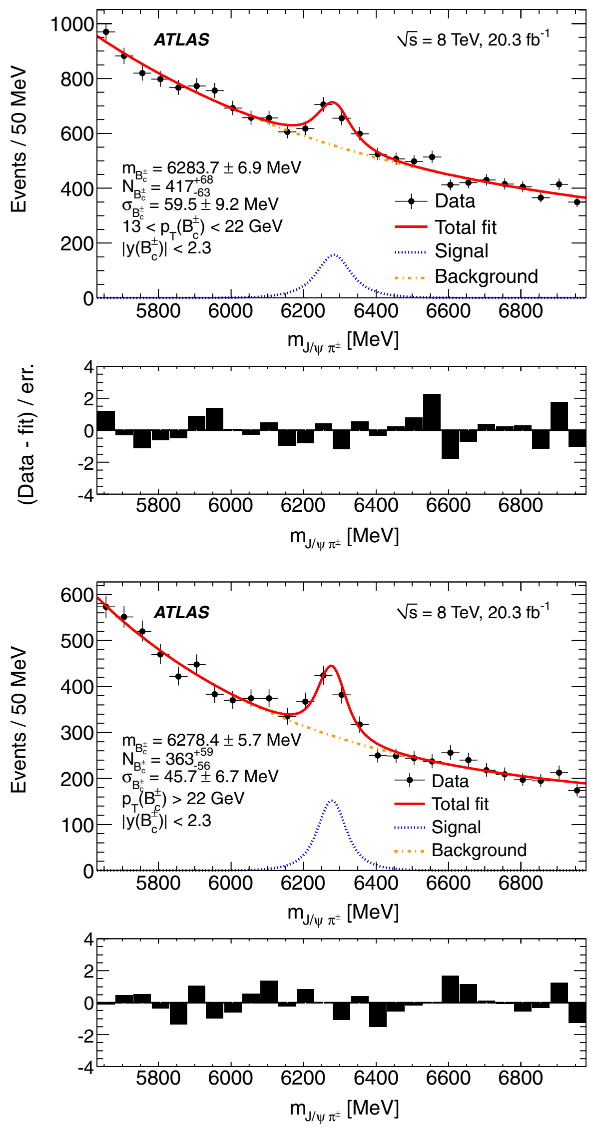

FIG. 4. The projection of the fit of the invariant mass distribution for the $B_c^\pm$ meson. "Signal" stands for the signal component of the fit, "Background" stands for the combinatorial background component of the fit, and "Total fit" stands for the fit to the sum of the signal and background components. The fit for the low transverse momentum bin (13 GeV $< p_T(B_c^\pm) <$ 22 GeV) is shown at the top, and that for the high transverse momentum bin ($p_T(B_c^\pm) > 22$ GeV) at the bottom. The rapidity requirement is $|y(B_c^\pm)| < 2.3$. The fits are used to extract $N^{\rm reco}(B_c^+) + N^{\rm reco}(B_c^-)$ and its uncertainty in each bin. The inset below each plot shows the bin-by-bin difference between the data point and the value obtained from the fit function divided by the quadrature sum of the statistical uncertainty and the systematic uncertainties obtained from varying the fit model.

For the calculation of $\epsilon^{\rm MS}(\mu^\pm)$, the muon reconstruction maps [27] are used. These maps are based on a sample of about two million $J/\psi \to \mu^+\mu^-$ events collected with unbiased triggers (single muonic and "muon + track"). The efficiency is measured in bins of p_T and η using the

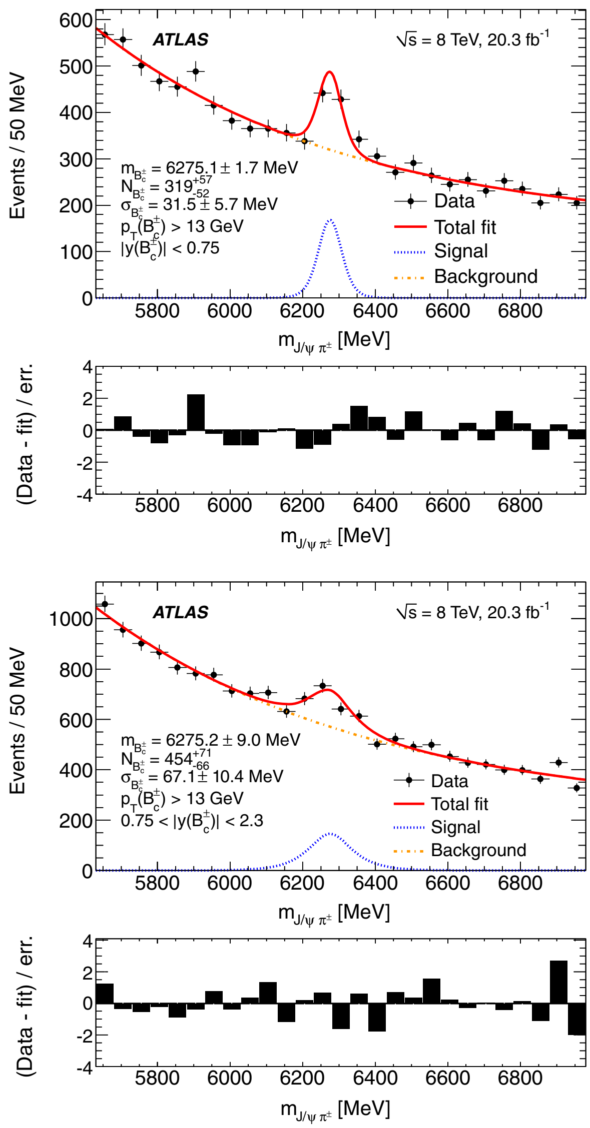

FIG. 5. The projection of the fit of the invariant mass distribution for the $B_c^\pm$ meson. "Signal" stands for the signal component of the fit, "Background" stands for the combinatorial background component of the fit, and "Total fit" stands for the fit to the sum of the signal and background components. The fit for the inner rapidity bin ($|y(B_c^\pm)| < 0.75$) is shown at the top, and that for the outer rapidity bin ($0.75 < |y(B_c^\pm)| < 2.3$) at the bottom. The p_T requirement is $p_T(B_c^\pm) > 13$ GeV. The fits are used to extract $N^{\rm reco}(B_c^+) + N^{\rm reco}(B_c^-)$ and its uncertainty in each bin. The inset below each plot shows the bin-by-bin difference between the data point and the value obtained from the fit function divided by the quadrature sum of the statistical uncertainty and the systematic uncertainties obtained from varying the fit model.

same tag-and-probe method. Combined muons are used as the tag muons and the ID tracks with the standard quality requirements are used as probes. The efficiency $\epsilon^{\rm ID}(\mu^\pm)$ of the muon track reconstruction with the ID is conservatively taken to be $(99 \pm 1)\%$ [28,29].

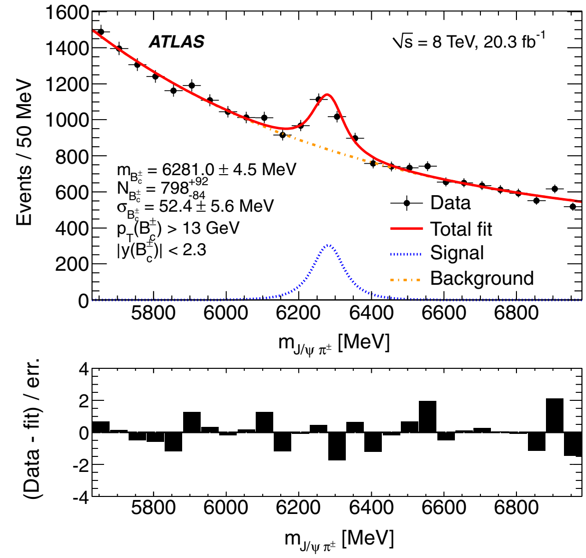

FIG. 6. The projection of the fit of the invariant mass distribution for the $B_c^\pm$ meson using the complete dataset ($p_T(B_c^\pm) > 13$ GeV, $|y(B_c^\pm)| < 2.3$). "Signal" stands for the signal component of the fit, "Background" stands for the combinatorial background component of the fit, and "Total fit" stands for the fit to the sum of the signal and background components. The fit is used to extract $N^{\rm reco}(B_c^+) + N^{\rm reco}(B_c^-)$ and its uncertainty in each bin. The inset below each plot shows the bin-by-bin difference between the data point and the value obtained from the fit function divided by the quadrature sum of the statistical uncertainty and the systematic uncertainties obtained from varying the fit model.

The vertexing efficiency $\epsilon^{\rm vertex}$ is estimated with data and MC simulation for the $B^\pm$ and the $B_c^\pm$. The efficiency ratio $\epsilon^{\rm vertex}(B^\pm)/\epsilon^{\rm vertex}(B_c^\pm)$ is found to be $1.01 \pm 0.01_{\rm stat}$.

The MC samples ($B_c^\pm \to J/\psi\pi^\pm$ and $B^\pm \to J/\psi K^\pm$) were generated with requirements on the hadron of $p_T > 500$ MeV and $|\eta| < 2.5$. The requirements on muons were $p_T > 2.5$ GeV and $|\eta| < 2.7$. These are called the minimal selection criteria (MSC). To determine corrections to the efficiencies due to MSC, a dedicated MC sample was produced for each channel with no selection on pion, kaon, and muon momenta and with a requirement that their absolute rapidity be less than 10. The MC samples are corrected to take into account the MSC, and these correction factors are propagated to the analysis results. The following values are computed: $f_{\rm cor}(B_c^\pm) = N(B_c^\pm)_{\rm MSC}/N(B_c^\pm)_{\rm no\ MSC}$, and $f_{\rm cor}(B^\pm) = N(B^\pm)_{\rm MSC}/N(B^\pm)_{\rm no\ MSC}$, where $N(B)_{\rm no\ MSC}$ and $N(B)_{\rm MSC}$ stand for the numbers of B decays before and after applying the MSC, respectively, in the p_T and $|y|$ bins used in the analysis. These correction factors range from 8% to 22% depending on the p_T and $|y|$ of the B candidates. The value of the ratio $f_{\rm cor}(B_c^\pm)/f_{\rm cor}(B^\pm)$ is propagated as a correction factor to the relative $B_c^\pm/B^\pm$ cross section. The corrections obtained, along with their uncertainties, are

TABLE I. Summary of the main parameters of the $B^\pm$ fits. The uncertainties quoted are statistical.

Analysis bin	Fitted mass of the $B^\pm$ [MeV]	Number of the $B^\pm$ candidates	σ_m of the $B^\pm$ [MeV]
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	5278.6 ± 0.1	$(398.3 \pm 0.8) \times 10^3$	37.5 ± 0.1
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert < 2.3$	5278.5 ± 0.1	$(207.6 \pm 0.6) \times 10^3$	37.5 ± 0.1
$p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$	5278.8 ± 0.1	$(190.9 \pm 0.6) \times 10^3$	38.1 ± 0.1
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$	5278.4 ± 0.1	$(147.9 \pm 0.5) \times 10^3$	26.6 ± 0.1
$p_T(B) > 13$ GeV, $0.75 < \lvert y(B)\rvert < 2.3$	5279.1 ± 0.1	$(248.8 \pm 0.6) \times 10^3$	45.9 ± 0.1

TABLE II. Summary of the main parameters of the $B_c^\pm$ fits. The uncertainties quoted are statistical.

Analysis bin	Fitted mass of the $B_c^\pm$ [MeV]	Number of the $B_c^\pm$ candidates	σ_m of the $B_c^\pm$ [MeV]
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	6281.0 ± 4.5	798^{+92}_{-84}	52.4 ± 5.6
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert < 2.3$	6283.7 ± 6.9	417^{+68}_{-63}	59.5 ± 9.2
$p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$	6278.4 ± 5.7	363^{+59}_{-56}	45.7 ± 6.7
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$	6275.1 ± 1.7	319^{+57}_{-52}	31.5 ± 5.7
$p_T(B) > 13$ GeV, $0.75 < \lvert y(B)\rvert < 2.3$	6275.2 ± 9.0	454^{+71}_{-66}	67.1 ± 10.4

TABLE III. Summary of corrections due to the minimal selection criteria in the MC simulation. The first uncertainty is statistical, the second one is systematic.

Analysis bin	Correction to the $B_c^\pm$	Correction to the $B^\pm$	Ratio of the corrections
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	$0.0969 \pm 0.0004 \pm 0.0024$	$0.0929 \pm 0.0004 \pm 0.0022$	$0.959 \pm 0.006 \pm 0.024$
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert < 2.3$	$0.0829 \pm 0.0004 \pm 0.0031$	$0.0826 \pm 0.0004 \pm 0.0029$	$0.996 \pm 0.007 \pm 0.039$
$p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$	$0.2164 \pm 0.0014 \pm 0.0018$	$0.2213 \pm 0.0013 \pm 0.0017$	$1.023 \pm 0.009 \pm 0.009$
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$	$0.0984 \pm 0.0007 \pm 0.0033$	$0.0996 \pm 0.0007 \pm 0.0035$	$1.012 \pm 0.010 \pm 0.035$
$p_T(B) > 13$ GeV, $0.75 < \lvert y(B)\rvert < 2.3$	$0.0952 \pm 0.0005 \pm 0.0014$	$0.0859 \pm 0.0005 \pm 0.0016$	$0.902 \pm 0.007 \pm 0.014$

summarized in Table III. Each entry in the rightmost column in Table III is then multiplied by the corresponding value of the ratio of efficiencies $\epsilon(B^\pm)/\epsilon(B_c^\pm)$. The systematic uncertainty on the MSC procedure is estimated as the difference between the raw MC prediction and the one reweighted using the sPlot-based technique. The uncertainties in these corrections and each of the uncertainties contributing to the final efficiency ratios are added in quadrature.

The efficiency of the analysis selection criteria, $\epsilon^{\text{selection}}$, derived from MC simulation, is incorporated into the final efficiency ratios given below. The efficiency ratios $\epsilon(B^\pm)/\epsilon(B_c^\pm)$, excluding the MSC corrections, are found to be 2.19 ± 0.05 for 13 GeV $< p_T <$ 22 GeV, 1.22 ± 0.03 for $p_T >$ 22 GeV, 1.75 ± 0.03 for $p_T >$ 13 GeV, 1.74 ± 0.05 for $|y| < 0.75$, and 1.76 ± 0.04 for $0.75 < |y| < 2.3$ (see Section VII). Here and below, when the range of a single variable is specified, it is implicitly understood that the full range is selected for the other variable, namely $p_T >$ 13 GeV and $|y| < 2.3$. The reason for the efficiency ratios being larger than one is primarily that the $B^\pm$ has a longer lifetime than the $B_c^\pm$. Due to the shorter $B_c^\pm$ lifetime, the combination of the $d_{xy}^0/\sigma(d_{xy}^0)$ and p_T (hadron) selections criteria affects the $B_c^\pm$ more than the $B^\pm$, this fact explains the factor two difference in the relative analysis efficiency between the p_T bins.

TABLE IV. Summary of the absolute values of systematic uncertainties for the analysis efficiency ratios.

Source of uncertainty	Absolute value of the uncertainty in the efficiency ratio				
	$p_T >$ 13 GeV	$13 < p_T <$ 22 GeV	$p_T >$ 22 GeV	$\lvert y\rvert < 0.75$	$0.75 < \lvert y\rvert < 2.3$
Size of the MC samples and the event counting	0.03	0.05	0.03	0.05	0.04
sPlot-based MC reweighting procedure	0.04	0.03	0.03	0.05	0.06
Minimal selection criteria	0.04	0.09	0.02	0.06	0.03
Tracking uncertainty	0.01	0.01	0.01	0.01	0.01

TABLE V. Summary of all systematic uncertainties for the number of signal events in the two p_{T} bins.

	Uncertainty value			
	$B_c^{\pm}$		$B^{\pm}$	
Source of uncertainty	13 GeV < p_{T} < 22 GeV	p_{T} > 22 GeV	13 GeV < p_{T} < 22 GeV	p_{T} > 22 GeV
Signal model of the fit	2.4%	1.1%	0.1%	0.2%
CS and PRD components	$^{+19.3\%}_{-2.4\%}$	$^{+19.9\%}_{-2.4\%}$	0.5%	0.5%
Background model of the fit	1.7%	1.2%	0.2%	0.2%
Trigger and reconstruction effects	0.9%	0.8%	1.2%	1.2%
B-meson lifetime uncertainty	1.1%	0.9%	<0.1%	<0.1%

TABLE VI. Summary of all systematic uncertainties for the number of signal events in the two $|y|$ bins.

	Uncertainty value			
	$B_c^{\pm}$		$B^{\pm}$	
Source of uncertainty	$\|y\| < 0.75$	$0.75 < \|y\| < 2.3$	$\|y\| < 0.75$	$0.75 < \|y\| < 2.3$
Signal model of the fit	2.5%	2.8%	0.1%	0.2%
CS and PRD components	$^{+11.2\%}_{-2.4\%}$	$^{+23.2\%}_{-2.4\%}$	0.5%	0.5%
Background model of the fit	2.8%	1.3%	0.2%	0.2%
Trigger effects and reconstruction effects	1.1%	1.0%	1.2%	1.1%
B-meson lifetime uncertainty	1.0%	0.9%	<0.1%	<0.1%

VII. SYSTEMATIC UNCERTAINTIES

A summary of all sources of uncertainty that contribute to the analysis efficiency values is given in Table IV. These are absolute values, not percentages. The absolute values for the efficiency ratios are presented in Sec. VI. They propagate directly to the final results via Eq. (1). The uncertainty in the ratio of efficiencies of detecting a kaon versus a pion is shown in Table IV in the row titled "Tracking uncertainty". Tables V–VII contain the systematic uncertainties related to the number of signal events.

The systematic uncertainties of the efficiency ratios are primarily given by the systematic uncertainties of $\epsilon^{\mathrm{ID}}(X_h)$. They are dominated by the material description in the simulation of the detector [30]. The material density affects the $K^{\pm}$ and $\pi^{\pm}$ detection in different ways.

TABLE VII. Summary of all systematic uncertainties for the number of signal events in the combined bin ($p_{\mathrm{T}} > 13$ GeV, $|y| < 2.3$).

	Uncertainty value	
Source of uncertainty	$B_c^{\pm}$	$B^{\pm}$
Signal model of the fit	2.4%	0.1%
CS and PRD components	$^{+17.4\%}_{-2.4\%}$	0.5%
Background model of the fit	2.9%	0.1%
Trigger effects and reconstruction effects	0.9%	0.9%
B-meson lifetime uncertainty	0.7%	<0.1%

The uncertainty in the efficiencies is due to the size of the MC sample and systematic uncertainties in the event counting. The precision of the efficiencies due to the size of the MC sample is calculated according to Bernoulli statistics. The uncertainty in the probability of generated events to fall into a specific bin in p_{T} or $|y|$ and the uncertainty in the probability of reconstructing these events are added in quadrature.

The sPlot-based MC reweighting procedure produces an additional systematic uncertainty that is estimated by varying the reweighted distributions while preserving agreement with the data at the 1σ level. The maximum deviation for the analysis efficiency is taken as the systematic uncertainty of the analysis efficiency derived from the sPlot-based MC reweighting procedure. The uncertainties in the efficiency ratios are found to be 0.03 for $13\,\mathrm{GeV} < p_{\mathrm{T}} < 22\,\mathrm{GeV}$, 0.03 for $p_{\mathrm{T}} > 22\,\mathrm{GeV}$, 0.04 for $p_{\mathrm{T}} > 13$ GeV, 0.05 for $|y| < 0.75$, and 0.06 for $0.75 < |y| < 2.3$.

The systematic uncertainties of the fitting procedure (which influence the number of signal events) involve the choice of signal model and the choice of background model. They are estimated by fitting the invariant mass distributions of the $B_c^{\pm}$ and $B^{\pm}$ using alternative models for the signal and background shapes and varying the mass range of the fit. The sources of uncertainty are treated as uncorrelated. The maximum deviations from the nominal values when performing alternative fits for each of the sources are added in quadrature to form the systematic uncertainty of the fitted number of events.

The influence of the choice of signal model on the $B_c^\pm$ signal yield is estimated by replacing the Gaussian function by a Crystal Ball function [31,32]

$$\mathcal{F}_{\rm signal}^{\rm Crystal\ Ball}(m_{J/\psi\pi^\pm}) \propto \begin{cases} \exp\left[-(m_{J/\psi\pi^\pm} - m_{B_c^\pm})^2/(2\sigma_{\rm CB}^2)\right], & \text{for } m_{J/\psi\pi^\pm} > m_{B_c^\pm} - \alpha\sigma_{\rm CB} \\ \frac{(n/\alpha)^n \exp(-\alpha^2/2)}{[(m_{B_c^\pm} - m_{J/\psi\pi^\pm})/\sigma_{\rm CB} + (n/\alpha) - \alpha]^n}, & \text{for } m_{J/\psi\pi^\pm} < m_{B_c^\pm} - \alpha\sigma_{\rm CB} \end{cases},$$

convolved with a Gaussian function. All the parameters in the convolution are free and their values are obtained from the fit itself. The resulting uncertainty in $N^{\rm reco}(B_c^+) + N^{\rm reco}(B_c^-)$ is 2.4% for 13 GeV $< p_{\rm T}(B_c^\pm) <$ 22 GeV, 1.1% for $p_{\rm T}(B_c^\pm) >$ 22 GeV, 2.5% for $|y| < 0.75$, 2.8% for $0.75 < |y| < 2.3$, and 2.4% for the combined bin $p_{\rm T}(B_c^\pm) >$ 13 GeV. This comes solely from changing the signal model; the effect of changing the background model is described next.

The uncertainty due to the choice of background model is estimated as the maximum deviation from the nominal signal yield $N^{\rm reco}(B_c^\pm)$ when the default model is replaced by fourth-order Chebychev polynomials of the second kind. The result is 1.7% for 13 GeV $< p_{\rm T}(B_c^\pm) <$ 22 GeV, 1.2% for $p_{\rm T}(B_c^\pm) >$ 22 GeV, 2.8% for $|y| < 0.75$, 1.3% for $0.75 < |y| < 2.3$, and 2.9% for the inclusive bin $p_{\rm T}(B_c^\pm) >$ 13 GeV.

To estimate the effect of neglecting the contributions of the Cabibbo-suppressed (CS) decays $B_c^\pm \to J/\psi K^\pm$, the nominal fit model is adapted to include a CS contribution and the difference with respect to the nominal result is taken as a systematic uncertainty. In addition, to estimate the effect of neglecting both the CS contribution and the partially reconstructed $B_c^\pm$ decays (PRD), MC pseudo-experiments have been used. They are generated starting from the default yield results of the fits and adding CS and PRD components. The CS component is estimated based on its branching fraction and efficiency ratio to be 8.6% of the signal yield [21], while a conservative estimation of the PRD component is obtained from a fit to the data. The generated samples are then fit both with the default configuration (no CS and no PRD) and with a fit including the CS and PRD components and the differences on the signal yields are recorded.

The uncertainty in the number of reconstructed $B^\pm$ events due to the choice of signal model, estimated in the same way as for the $B_c^\pm$, is found to be 0.1% for 13 GeV $< p_{\rm T}(B^\pm) <$ 22 GeV, 0.2% for $p_{\rm T}(B^\pm) >$ 22 GeV, 0.1% for $|y| < 0.75$, 0.2% for $0.75 < |y| < 2.3$, and 0.1% for the combined bin $p_{\rm T}(B^\pm) >$ 13 GeV. The total systematic uncertainty of the $B^\pm$ fit is calculated by adding the uncertainties associated with the mass range, the signal model, and the background model in quadrature.

To determine the systematic uncertainty due to the choice of background model for the $B^\pm$ fit, the exponential function in Eq. (2) is replaced by fourth-order Chebychev polynomials of the second kind. The result is 0.2% for 13 GeV $< p_{\rm T}(B^\pm) <$ 22 GeV, 0.2% for $p_{\rm T}(B^\pm) >$ 22 GeV, 0.2% for $|y| < 0.75$, 0.2% for $0.75 < |y| < 2.3$, and 0.1% for the inclusive bin $p_{\rm T}(B^\pm) >$ 13 GeV. All these contributions are summarized in Tables V, VI, and VII in the row labeled "Background model of the fit."

The CS contribution to the $B^\pm$ fit is estimated by considering two extreme scenarios: no contribution and one that is twice the nominal fraction obtained from the fit. The difference between these scenarios is taken as the uncertainty in the number of candidates. As a cross-check, the functional form of the $B^\pm \to J/\psi\pi^\pm$ component is varied to the sum of a Gaussian and an asymmetric Johnson function [33,34] and the resulting effects are found to be covered by the quoted systematic uncertainty.

Dimuon trigger efficiencies are calculated for both decay modes, and relative trigger efficiencies for both channels considered are identical within the systematic uncertainty. The residual minor uncertainty is propagated to the final combined uncertainty of the result.

The current world average uncertainty in the $B_c^\pm$ lifetime of 0.507 ps is 0.009 ps [21], which corresponds to about 2%, while the uncertainty in the $B^\pm$ lifetime is four times smaller. To analytically estimate the upper limit on the uncertainty due to the lifetime, the d_{xy}^0 significance is studied and treated as 100% correlated with the lifetime. Using the limiting value for the selection criterion, which is $d_{xy}^0/\sigma(d_{xy}^0) = 1.2$, the uncertainty is obtained by multiplying 1.2 by 2% to yield 0.024. Applying ± 0.024 to the d_{xy}^0 significance, the resulting change in the number of $B_c^\pm$ signal events is taken as the uncertainty due to the lifetime. The absolute values of this uncertainty are shown in Tables V–VII. As a cross-check, the $B_c^\pm$ MC exclusive signal sample is reweighted in order to reflect the $\pm 2\%$ lifetime uncertainty mentioned above. The analysis efficiencies are recalculated and the maximum deviations are found to have smaller impact than those from the main method, so the largest deviations obtained from the main method are used as an estimator of the uncertainty.

The central values of the integrated luminosity for the two B-meson datasets are exactly the same, so the integrated luminosity cancels out completely in the ratio and the luminosity uncertainty does not contribute to the uncertainty of this measurement. Removing combinations in which one of the hadronic candidates is identified as a muon contributes an uncertainty that is very small

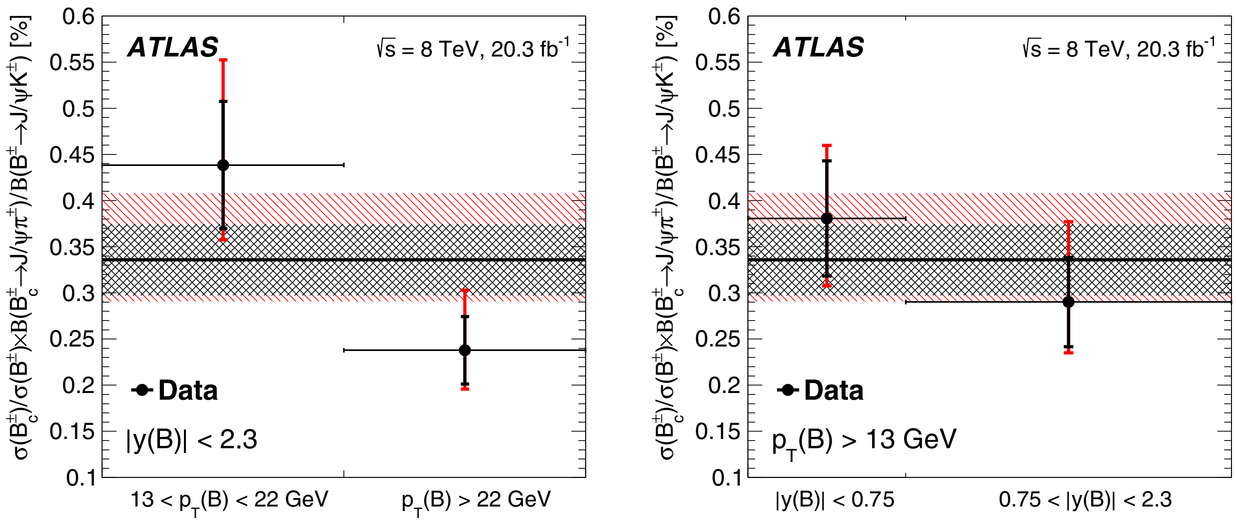

FIG. 7. Summary of the cross-section measurement presented in this article. The left figure shows the production cross section for the $B_c^\pm$ relative to the $B^\pm$ (times the corresponding branching fractions) for two bins in p_T (black data points) and for the inclusive bin (horizontal band). The right figure shows the measurement binned in rapidity (black data points). On each point the horizontal bar indicates the bin width. The vertical inner error bars on the data points indicate the statistical uncertainty. The outer error bars indicate the size of the quadrature sum of uncertainties from all sources: statistical, systematic, and lifetime. The double hatched error band indicates statistical uncertainty, while the single hatched bands indicate the quadrature sum of uncertainties from all sources.

compared with the total systematic uncertainty and is consequently neglected.

A summary of all sources of systematic uncertainties that contribute to the number of signal events is given in Tables V–VII. The different components of the systematic uncertainty are added in quadrature. The components of uncertainties correlated between the $B_c^\pm$ and the $B^\pm$ are subtracted for the relative production cross section times branching fractions presented in Sec. VIII.

VIII. RESULTS

The yields $N^{\mathrm{reco}}(B_c^\pm)$ and $N^{\mathrm{reco}}(B^\pm)$, and their statistical uncertainties are extracted from the maximum-likelihood fits of the respective invariant mass distributions. The differential relative production cross sections times branching fractions are calculated according to Eq. (1) for all bins in p_T and $|y|$.

The differential relative production cross section for the inclusive selection containing all events in the range $p_T > 13$ GeV and $|y| < 2.3$ is

$$\frac{\sigma(B_c^\pm)\cdot\mathcal{B}(B_c^\pm\to J/\psi\pi^\pm)}{\sigma(B^\pm)\cdot\mathcal{B}(B^\pm\to J/\psi K^\pm)} = (0.34\pm 0.04_{\mathrm{stat}}\,{}^{+0.06}_{-0.02}\,{}_{\mathrm{syst}}\pm 0.01_{\mathrm{lifetime}})\%,$$

(i) for 13 GeV $< p_T <$ 22 GeV, $|y| < 2.3$ is $(0.44\pm 0.07_{\mathrm{stat}}\,{}^{+0.09}_{-0.04}\,{}_{\mathrm{syst}}\pm 0.01_{\mathrm{lifetime}})\%$,
(ii) for $p_T > 22$ GeV, $|y| < 2.3$ is $(0.24\pm 0.04_{\mathrm{stat}}\,{}^{+0.05}_{-0.01}\,{}_{\mathrm{syst}}\pm 0.01_{\mathrm{lifetime}})\%$,
(iii) for $p_T > 13$ GeV, $|y| < 0.75$ is $(0.38\pm 0.06_{\mathrm{stat}}\,{}^{+0.05}_{-0.04}\,{}_{\mathrm{syst}}\pm 0.01_{\mathrm{lifetime}})\%$,
(iv) and for $p_T > 13$ GeV, $0.75 < |y| < 2.3$ is $(0.29\pm 0.05_{\mathrm{stat}}\,{}^{+0.07}_{-0.02}\,{}_{\mathrm{syst}}\pm 0.01_{\mathrm{lifetime}})\%$.

Figure 7 summarizes the results of the measurement for the $p_T(B)$ and $|y(B)|$ bins as well as for the inclusive bin.

The differential measurement suggests a dependence on the transverse momentum: the production cross section of the $B_c^\pm$ decreases faster with p_T than the production cross section of the $B^\pm$. No significant dependence on rapidity is observed.

IX. CONCLUSION

The production cross section of the $B_c^\pm$ meson relative to the production cross section of the $B^\pm$ meson is measured using $B_c^\pm\to J/\psi\pi^\pm$ and $B^\pm\to J/\psi K^\pm$ decays reconstructed by the ATLAS detector analyzing pp collisions at $\sqrt{s}=8$ TeV delivered by the LHC in 2012. The data used for this study correspond to an integrated luminosity of 20.3 fb^{-1}. The relative cross section times branching fraction for the full range $p_T > 13$ GeV and $|y| < 2.3$ is $(0.34\pm 0.04_{\mathrm{stat}}\,{}^{+0.06}_{-0.02\,\mathrm{sys}}\pm 0.01_{\mathrm{lifetime}})\%$. The ratio of the B_c to $B^\pm$ cross sections is measured in two intervals of transverse momentum and rapidity of the B-meson candidates. The differential measurement suggests a dependence on the transverse momentum: the production cross section of the $B_c^\pm$ meson decreases faster with p_T than the production cross section of the $B^\pm$ meson. No significant dependence on rapidity is observed.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRT, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; JINR; MES of Russia and NRC KI, Russian Federation; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada, CRC and IVADO, Canada; Beijing Municipal Science & Technology Commission, China; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [35].

[1] R. Aaij*et al.* LHCb Collaboration, Measurements of B_c^+ Production and Mass with the $B_c^+ \to J/\psi\pi^+$ Decay, Phys. Rev. Lett. **109**, 232001 (2012).

[2] I. Bediaga*et al.* LHCb Collaboration, Measurement of B_c^+ Production in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. Lett. **114**, 132001 (2015).

[3] V. Khachatryan*et al.* CMS Collaboration, Measurement of the ratio of the production cross sections times branching fractions of $B_c^\pm \to J/\psi\pi^\pm$ and $B^\pm \to J/\psi K^\pm$ and $\mathfrak{B}(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)/\mathfrak{B}(B_c^\pm \to J/\psi\pi^\pm)$ at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 01 (2015) 063.

[4] M. Masetti and F. Sartogo, Perturbative predictions for B_c meson production in hadronic collisions, Phys. Lett. B **357**, 659 (1995).

[5] A. Berezhnoy, A. Likhoded, and M. Shelyagin, Hadronic production of Bc mesons, Phys. At. Nucl. **58**, 672 (1995).

[6] C. Chang, Y. Chen, G. Han, and H. Jiang, On hadronic production of the Bc meson, Phys. Rev. D **48**, 4086 (1993).

[7] I. P. Gouz, V. V. Kiselev, A. K. Likhoded, V. I. Romanovsky, and O. P. Yushchenko, Prospects for the Bc studies at LHCb, Phys. At. Nucl. **67**, 1559 (2004).

[8] S. Slabospitsky, B_c-meson production in hadron-hadron collisions, Phys. At. Nucl. **58**, 988 (1995).

[9] A. Berezhnoy, A. Likhoded, and O. Yushchenko, Some features of the hadronic $B_c^{(*)}$-meson production at large p_T, Phys. At. Nucl. **59**, 709 (1996).

[10] C. Chang, Y. Chen, and R. Oakes, Comparative study of the hadronic production of B_c mesons, Phys. Rev. D **54**, 4344 (1996).

[11] C. McNeile, C. T. H. Davies, E. Follana, K. Hornbostel, and G. P. Lepage, Heavy meson masses and decay constants from relativistic heavy quarks in full lattice QCD, Phys. Rev. D **86**, 074503 (2012).

[12] B. Colquhoun, C. T. H. Davies, J. Kettle, J. Koponen, A. T. Lytle, R. J. Dowdall, and G. P. Lepage, B-meson decay constants: A more complete picture from full lattice QCD, Phys. Rev. D **91**, 114509 (2015).

[13] G. Aad *et al.* ATLAS Collaboration, The ATLAS Experiment at the CERN large hadron collider, J. Instrum. **3**, S08003 (2008).

[14] G. Aad *et al.* ATLAS Collaboration, Muon reconstruction efficiency and momentum resolution of the ATLAS experiment in proton-proton collisions at $\sqrt{s} = 7$ TeV in 2010, Eur. Phys. J. C **74**, 3034 (2014).

[15] V. Mitsou *et al.* ATLAS Collaboration, Performance of the ATLAS trigger system in 2010, Eur. Phys. J. C **72**, 1849 (2012).

[16] T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.

[17] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. **178**, 852 (2008).

[18] G. Aad *et al.* ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C **70**, 823 (2010).

[19] S. Agostinelli *et al.*, GEANT4—A simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[20] V. Kostyukhin ATLAS Collaboration, VKalVrt—Package for vertex reconstruction in ATLAS, ATLAS Note, ATL-PHYS-2003-031 (2003), http://inspirehep.net/record/1195847.
[21] M. Tanabashi *et al.* (Particle Data Group), Review of particle physics, Phys. Rev. D **98**, 030001 (2018).
[22] M. Aabou *et al.* ATLAS Collaboration, Reconstruction of primary vertices at the ATLAS experiment in Run 1 proton–proton collisions at the LHC, Eur. Phys. J. C **77**, 332 (2017).
[23] M. Pivk and F. R. Le Diberder, sPlot: A statistical tool to unfold data distributions, Nucl. Instrum. Methods Phys. Res., Sect. A **555**, 356 (2005).
[24] G. Aad *et al.* ATLAS Collaboration, Measurement of the differential cross-section of B^+ meson production in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS, J. High Energy Phys. 10 (2013) 042.
[25] G. Aad *et al.* ATLAS Collaboration, Measurement of the differential cross-sections of prompt and nonprompt production of J/ψ and $\psi(2S)$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector, Eur. Phys. J. C **76**, 283 (2016).
[26] G. Aad *et al.* ATLAS Collaboration, Observation and measurements of the production of prompt and nonprompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Eur. Phys. J. C **75**, 229 (2015).
[27] G. Aad *et al.* ATLAS Collaboration, Measurement of the muon reconstruction performance of the ATLAS detector using 2011 and 2012 LHC proton-proton collision data, Eur. Phys. J. C **74**, 3130 (2014).
[28] G. Aad *et al.* ATLAS Collaboration, Measurement of the production cross-section of $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS, J. High Energy Phys. 09 (2014) 079.
[29] G. Aad *et al.* ATLAS Collaboration, Measurement of Upsilon production in 7 TeV pp collisions at ATLAS, Phys. Rev. D **87**, 052004 (2013).
[30] G. Aad *et al.* ATLAS Collaboration, Charged-particle multiplicities in pp interactions measured with the ATLAS detector at LHC, New J. Phys. **13**, 053033 (2011).
[31] J. Gaiser, Ph.D. thesis, SLAC-255, 1982, Stanford, https://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-255.pdf.
[32] R. Lee, Ph.D. thesis, SLAC-282, 1985, Stanford, http://www.slac.stanford.edu/pubs/slacreports/reports06/slac-r-282.pdf.
[33] N. L. Johnson, Systems of frequency curves generated by methods of translation, Biometrika **36**, 149 (1949).
[34] M. C. Jones and A. Pewsey, Sinh-arcsinh distributions, Biometrika **96**, 761 (2009).
[35] ATLAS Collaboration, ATLAS Computing Acknowledgements, ATL-SOFT-PUB-2020-001, https://cds.cern.ch/record/2717821.

M. Aaboud,[35e] G. Aad,[102] B. Abbott,[129] D. C. Abbott,[103] O. Abdinov,[13,a] A. Abed Abud,[71a,71b] D. K. Abhayasinghe,[94] S. H. Abidi,[168] O. S. AbouZeid,[40] N. L. Abraham,[157] H. Abramowicz,[162] H. Abreu,[161] Y. Abulaiti,[6] B. S. Acharya,[67a,67b,b] S. Adachi,[164] L. Adam,[100] C. Adam Bourdarios,[65] L. Adamczyk,[84a] L. Adamek,[168] J. Adelman,[121] M. Adersberger,[114] A. Adiguzel,[12c,c] S. Adorni,[54] T. Adye,[144] A. A. Affolder,[146] Y. Afik,[161] C. Agapopoulou,[65] M. N. Agaras,[38] A. Aggarwal,[119] C. Agheorghiesei,[27c] J. A. Aguilar-Saavedra,[140f,140a,d] F. Ahmadov,[80] G. Aielli,[74a,74b] S. Akatsuka,[86] T. P. A. Åkesson,[97] E. Akilli,[54] A. V. Akimov,[111] K. Al Khoury,[65] G. L. Alberghi,[23b,23a] J. Albert,[177] M. J. Alconada Verzini,[162] S. Alderweireldt,[119] M. Aleksa,[36] I. N. Aleksandrov,[80] C. Alexa,[27b] D. Alexandre,[19] T. Alexopoulos,[10] A. Alfonsi,[120] M. Alhroob,[129] B. Ali,[142] G. Alimonti,[69a] J. Alison,[37] S. P. Alkire,[149] C. Allaire,[65] B. M. M. Allbrooke,[157] B. W. Allen,[132] P. P. Allport,[21] A. Aloisio,[70a,70b] A. Alonso,[40] F. Alonso,[89] C. Alpigiani,[149] A. A. Alshehri,[57] M. I. Alstaty,[102] M. Alvarez Estevez,[99] B. Alvarez Gonzalez,[36] D. Álvarez Piqueras,[175] M. G. Alviggi,[70a,70b] Y. Amaral Coutinho,[81b] A. Ambler,[104] L. Ambroz,[135] C. Amelung,[26] D. Amidei,[106] S. P. Amor Dos Santos,[140a,140c] S. Amoroso,[46] C. S. Amrouche,[54] F. An,[79] C. Anastopoulos,[150] N. Andari,[145] T. Andeen,[11] C. F. Anders,[61b] J. K. Anders,[20] A. Andreazza,[69a,69b] V. Andrei,[61a] C. R. Anelli,[177] S. Angelidakis,[38] I. Angelozzi,[120] A. Angerami,[39] A. V. Anisenkov,[122b,122a] A. Annovi,[72a] C. Antel,[61a] M. T. Anthony,[150] M. Antonelli,[51] D. J. A. Antrim,[172] F. Anulli,[73a] M. Aoki,[82] J. A. Aparisi Pozo,[175] L. Aperio Bella,[36] G. Arabidze,[107] J. P. Araque,[140a] V. Araujo Ferraz,[81b] R. Araujo Pereira,[81b] A. T. H. Arce,[49] F. A. Arduh,[89] J-F. Arguin,[110] S. Argyropoulos,[78] J.-H. Arling,[46] A. J. Armbruster,[36] L. J. Armitage,[93] A. Armstrong,[172] O. Arnaez,[168] H. Arnold,[120] A. Artamonov,[124,a] G. Artoni,[135] S. Artz,[100] S. Asai,[164] N. A. Asbah,[59] E. M. Asimakopoulou,[173] L. Asquith,[157] K. Assamagan,[29] R. Astalos,[28a] R. J. Atkin,[33a] M. Atkinson,[174] N. B. Atlay,[152] H. Atmani,[65] K. Augsten,[142] G. Avolio,[36] R. Avramidou,[60a] M. K. Ayoub,[15a] A. M. Azoulay,[169b] G. Azuelos,[110,e] A. E. Baas,[61a] M. J. Baca,[21] H. Bachacou,[145] K. Bachas,[68a,68b] M. Backes,[135] F. Backman,[45a,45b] P. Bagnaia,[73a,73b] H. Bahrasemani,[153] A. J. Bailey,[175] V. R. Bailey,[174] J. T. Baines,[144] M. Bajic,[40] C. Bakalis,[10] O. K. Baker,[184] P. J. Bakker,[120] D. Bakshi Gupta,[8] S. Balaji,[158] E. M. Baldin,[122b,122a] P. Balek,[181] F. Balli,[145] W. K. Balunas,[135] J. Balz,[100] E. Banas,[85] A. Bandyopadhyay,[24] Sw. Banerjee,[182,f] A. A. E. Bannoura,[183] L. Barak,[162] W. M. Barbe,[38] E. L. Barberio,[105] D. Barberis,[55b,55a] M. Barbero,[102] T. Barillari,[115] M-S. Barisits,[36] J. Barkeloo,[132] T. Barklow,[154] R. Barnea,[161] S. L. Barnes,[60c] B. M. Barnett,[144] R. M. Barnett,[18]

Z. Barnovska-Blenessy,[60a] A. Baroncelli,[60a] G. Barone,[29] A. J. Barr,[135] L. Barranco Navarro,[175] F. Barreiro,[99] J. Barreiro Guimarães da Costa,[15a] R. Bartoldus,[154] G. Bartolini,[102] A. E. Barton,[90] P. Bartos,[28a] A. Basalaev,[46] A. Bassalat,[65,g] R. L. Bates,[57] S. J. Batista,[168] S. Batlamous,[35f] J. R. Batley,[32] B. Batool,[152] M. Battaglia,[146] M. Bauce,[73a,73b] F. Bauer,[145,a] K. T. Bauer,[172] H. S. Bawa,[31,h] J. B. Beacham,[49] T. Beau,[136] P. H. Beauchemin,[171] P. Bechtle,[24] H. C. Beck,[53] H. P. Beck,[20,i] K. Becker,[52] M. Becker,[100] C. Becot,[46] A. Beddall,[12d] A. J. Beddall,[12a] V. A. Bednyakov,[80] M. Bedognetti,[120] C. P. Bee,[156] T. A. Beermann,[77] M. Begalli,[81b] M. Begel,[29] A. Behera,[156] J. K. Behr,[46] F. Beisiegel,[24] A. S. Bell,[95] G. Bella,[162] L. Bellagamba,[23b] A. Bellerive,[34] P. Bellos,[9] K. Beloborodov,[122b,122a] K. Belotskiy,[112] N. L. Belyaev,[112] O. Benary,[162,a] D. Benchekroun,[35a] N. Benekos,[10] Y. Benhammou,[162] D. P. Benjamin,[6] M. Benoit,[54] J. R. Bensinger,[26] S. Bentvelsen,[120] L. Beresford,[135] M. Beretta,[51] D. Berge,[46] E. Bergeaas Kuutmann,[173] N. Berger,[5] B. Bergmann,[142] L. J. Bergsten,[26] J. Beringer,[18] S. Berlendis,[7] N. R. Bernard,[103] G. Bernardi,[136] C. Bernius,[154] F. U. Bernlochner,[24] T. Berry,[94] P. Berta,[100] C. Bertella,[15a] G. Bertoli,[45a,45b] I. A. Bertram,[90] G. J. Besjes,[40] O. Bessidskaia Bylund,[183] N. Besson,[145] A. Bethani,[101] S. Bethke,[115] A. Betti,[24] A. J. Bevan,[93] J. Beyer,[115] R. Bi,[139] R. M. Bianchi,[139] O. Biebel,[114] D. Biedermann,[19] R. Bielski,[36] K. Bierwagen,[100] N. V. Biesuz,[72a,72b] M. Biglietti,[75a] T. R. V. Billoud,[110] M. Bindi,[53] A. Bingul,[12d] C. Bini,[73a,73b] S. Biondi,[23b,23a] M. Birman,[181] T. Bisanz,[53] J. P. Biswal,[162] A. Bitadze,[101] C. Bittrich,[48] D. M. Bjergaard,[49] J. E. Black,[154] K. M. Black,[25] T. Blazek,[28a] I. Bloch,[46] C. Blocker,[26] A. Blue,[57] U. Blumenschein,[93] G. J. Bobbink,[120] V. S. Bobrovnikov,[122b,122a] S. S. Bocchetta,[97] A. Bocci,[49] D. Bogavac,[114] A. G. Bogdanchikov,[122b,122a] C. Bohm,[45a] V. Boisvert,[94] P. Bokan,[53] T. Bold,[84a] A. S. Boldyrev,[113] A. E. Bolz,[61b] M. Bomben,[136] M. Bona,[93] J. S. Bonilla,[132] M. Boonekamp,[145] H. M. Borecka-Bielska,[91] A. Borisov,[123] G. Borissov,[90] J. Bortfeldt,[36] D. Bortoletto,[135] V. Bortolotto,[74a,74b] D. Boscherini,[23b] M. Bosman,[14] J. D. Bossio Sola,[30] K. Bouaouda,[35a] J. Boudreau,[139] E. V. Bouhova-Thacker,[90] D. Boumediene,[38] S. K. Boutle,[57] A. Boveia,[127] J. Boyd,[36] D. Boye,[33c] I. R. Boyko,[80] A. J. Bozson,[94] J. Bracinik,[21] N. Brahimi,[102] G. Brandt,[183] O. Brandt,[61a] F. Braren,[46] U. Bratzler,[165] B. Brau,[103] J. E. Brau,[132] W. D. Breaden Madden,[57] K. Brendlinger,[46] L. Brenner,[46] R. Brenner,[173] S. Bressler,[181] B. Brickwedde,[100] D. L. Briglin,[21] D. Britton,[57] D. Britzger,[115] I. Brock,[24] R. Brock,[107] G. Brooijmans,[39] T. Brooks,[94] W. K. Brooks,[147d] E. Brost,[121] J. H Broughton,[21] P. A. Bruckman de Renstrom,[85] D. Bruncko,[28b] A. Bruni,[23b] G. Bruni,[23b] L. S. Bruni,[120] S. Bruno,[74a,74b] B. H. Brunt,[32] M. Bruschi,[23b] N. Bruscino,[139] P. Bryant,[37] L. Bryngemark,[97] T. Buanes,[17] Q. Buat,[36] P. Buchholz,[152] A. G. Buckley,[57] I. A. Budagov,[80] M. K. Bugge,[134] F. Bührer,[52] O. Bulekov,[112] T. J. Burch,[121] S. Burdin,[91] C. D. Burgard,[120] A. M. Burger,[130] B. Burghgrave,[8] J. T. P. Burr,[46] V. Büscher,[100] E. Buschmann,[53] P. J. Bussey,[57] J. M. Butler,[25] C. M. Buttar,[57] J. M. Butterworth,[95] P. Butti,[36] W. Buttinger,[36] A. Buzatu,[159] A. R. Buzykaev,[122b,122a] G. Cabras,[23b,23a] S. Cabrera Urbán,[175] D. Caforio,[142] H. Cai,[174] V. M. M. Cairo,[154] O. Cakir,[4a] N. Calace,[36] P. Calafiura,[18] A. Calandri,[102] G. Calderini,[136] P. Calfayan,[66] G. Callea,[57] L. P. Caloba,[81b] S. Calvente Lopez,[99] D. Calvet,[38] S. Calvet,[38] T. P. Calvet,[156] M. Calvetti,[72a,72b] R. Camacho Toro,[136] S. Camarda,[36] D. Camarero Munoz,[99] P. Camarri,[74a,74b] D. Cameron,[134] R. Caminal Armadans,[103] C. Camincher,[36] S. Campana,[36] M. Campanelli,[95] A. Camplani,[40] A. Campoverde,[152] V. Canale,[70a,70b] A. Canesse,[104] M. Cano Bret,[60c] J. Cantero,[130] T. Cao,[162] Y. Cao,[174] M. D. M. Capeans Garrido,[36] M. Capua,[41b,41a] R. Cardarelli,[74a] F. Cardillo,[150] I. Carli,[143] T. Carli,[36] G. Carlino,[70a] B. T. Carlson,[139] L. Carminati,[69a,69b] R. M. D. Carney,[45a,45b] S. Caron,[119] E. Carquin,[147d] S. Carrá,[69a,69b] J. W. S. Carter,[168] M. P. Casado,[14,j] A. F. Casha,[168] D. W. Casper,[172] R. Castelijn,[120] F. L. Castillo,[175] V. Castillo Gimenez,[175] N. F. Castro,[140a,140e] A. Catinaccio,[36] J. R. Catmore,[134] A. Cattai,[36] J. Caudron,[24] V. Cavaliere,[29] E. Cavallaro,[14] D. Cavalli,[69a] M. Cavalli-Sforza,[14] V. Cavasinni,[72a,72b] E. Celebi,[12b] F. Ceradini,[75a,75b] L. Cerda Alberich,[175] A. S. Cerqueira,[81a] A. Cerri,[157] L. Cerrito,[74a,74b] F. Cerutti,[18] A. Cervelli,[23b,23a] S. A. Cetin,[12b] A. Chafaq,[35a] D. Chakraborty,[121] S. K. Chan,[59] W. S. Chan,[120] W. Y. Chan,[91] J. D. Chapman,[32] B. Chargeishvili,[160b] D. G. Charlton,[21] C. C. Chau,[34] C. A. Chavez Barajas,[157] S. Che,[127] A. Chegwidden,[107] S. Chekanov,[6] S. V. Chekulaev,[169a] G. A. Chelkov,[80] M. A. Chelstowska,[36] B. Chen,[79] C. Chen,[60a] C. H. Chen,[79] H. Chen,[29] J. Chen,[60a] J. Chen,[39] S. Chen,[137] S. J. Chen,[15c] X. Chen,[15b,k] Y. Chen,[83] Y-H. Chen,[46] H. C. Cheng,[63a] H. J. Cheng,[15a] A. Cheplakov,[80] E. Cheremushkina,[123] R. Cherkaoui El Moursli,[35f] E. Cheu,[7] K. Cheung,[64] T. J. A. Chevalérias,[145] L. Chevalier,[145] V. Chiarella,[51] G. Chiarelli,[72a] G. Chiodini,[68a] A. S. Chisholm,[36,21] A. Chitan,[27b] I. Chiu,[164] Y. H. Chiu,[177] M. V. Chizhov,[80] K. Choi,[66] A. R. Chomont,[65] S. Chouridou,[163] Y. S. Chow,[120] M. C. Chu,[63a] J. Chudoba,[141] A. J. Chuinard,[104] J. J. Chwastowski,[85] L. Chytka,[131] D. Cinca,[47] V. Cindro,[92] I. A. Cioară,[27b] A. Ciocio,[18] F. Cirotto,[70a,70b] Z. H. Citron,[181,l] M. Citterio,[69a] B. M. Ciungu,[168] A. Clark,[54] M. R. Clark,[39] P. J. Clark,[50] C. Clement,[45a,45b] Y. Coadou,[102] M. Cobal,[67a,67c] A. Coccaro,[55b] J. Cochran,[79] H. Cohen,[162] A. E. C. Coimbra,[181] L. Colasurdo,[119] B. Cole,[39] A. P. Colijn,[120] J. Collot,[58] P. Conde Muiño,[140a,m] E. Coniavitis,[52] S. H. Connell,[33c] I. A. Connelly,[57] S. Constantinescu,[27b]

F. Conventi,[70a,n] A. M. Cooper-Sarkar,[135] F. Cormier,[176] K. J. R. Cormier,[168] L. D. Corpe,[95] M. Corradi,[73a,73b] E. E. Corrigan,[97] F. Corriveau,[104,o] M. J. Costa,[175] F. Costanza,[5] D. Costanzo,[150] G. Cowan,[94] J. W. Cowley,[32] J. Crane,[101] K. Cranmer,[125] S. J. Crawley,[57] R. A. Creager,[137] S. Crépé-Renaudin,[58] F. Crescioli,[136] M. Cristinziani,[24] V. Croft,[120] G. Crosetti,[41b,41a] A. Cueto,[5] T. Cuhadar Donszelmann,[150] A. R. Cukierman,[154] S. Czekierda,[85] P. Czodrowski,[36] M. J. Da Cunha Sargedas De Sousa,[60b] J. V. Da Fonseca Pinto,[81b] C. Da Via,[101] W. Dabrowski,[84a] T. Dado,[28a] S. Dahbi,[35f] T. Dai,[106] C. Dallapiccola,[103] M. Dam,[40] G. D'amen,[23b,23a] J. Damp,[100] J. R. Dandoy,[137] M. F. Daneri,[30] N. P. Dang,[182,f] N. S. Dann,[101] M. Danninger,[176] V. Dao,[36] G. Darbo,[55b] O. Dartsi,[5] A. Dattagupta,[132] T. Daubney,[46] S. D'Auria,[69a,69b] W. Davey,[24] C. David,[46] T. Davidek,[143] D. R. Davis,[49] E. Dawe,[105] I. Dawson,[150] K. De,[8] R. De Asmundis,[70a] A. De Benedetti,[129] M. De Beurs,[120] S. De Castro,[23b,23a] S. De Cecco,[73a,73b] N. De Groot,[119] P. de Jong,[120] H. De la Torre,[107] A. De Maria,[15c] D. De Pedis,[73a] A. De Salvo,[73a] U. De Sanctis,[74a,74b] M. De Santis,[74a,74b] A. De Santo,[157] K. De Vasconcelos Corga,[102] J. B. De Vivie De Regie,[65] C. Debenedetti,[146] D. V. Dedovich,[80] A. M. Deiana,[42] M. Del Gaudio,[41b,41a] J. Del Peso,[99] Y. Delabat Diaz,[46] D. Delgove,[65] F. Deliot,[145] C. M. Delitzsch,[7] M. Della Pietra,[70a,70b] D. Della Volpe,[54] A. Dell'Acqua,[36] L. Dell'Asta,[25] M. Delmastro,[5] C. Delporte,[65] P. A. Delsart,[58] D. A. DeMarco,[168] S. Demers,[184] M. Demichev,[80] G. Demontigny,[110] S. P. Denisov,[123] D. Denysiuk,[120] L. D'Eramo,[136] D. Derendarz,[85] J. E. Derkaoui,[35e] F. Derue,[136] P. Dervan,[91] K. Desch,[24] C. Deterre,[46] K. Dette,[168] M. R. Devesa,[30] P. O. Deviveiros,[36] A. Dewhurst,[144] S. Dhaliwal,[26] F. A. Di Bello,[54] A. Di Ciaccio,[74a,74b] L. Di Ciaccio,[5] W. K. Di Clemente,[137] C. Di Donato,[70a,70b] A. Di Girolamo,[36] G. Di Gregorio,[72a,72b] B. Di Micco,[75a,75b] R. Di Nardo,[103] K. F. Di Petrillo,[59] R. Di Sipio,[168] D. Di Valentino,[34] C. Diaconu,[102] F. A. Dias,[40] T. Dias Do Vale,[140a,140e] M. A. Diaz,[147a] J. Dickinson,[18] E. B. Diehl,[106] J. Dietrich,[19] S. Díez Cornell,[46] A. Dimitrievska,[18] W. Ding,[15b] J. Dingfelder,[24] F. Dittus,[36] F. Djama,[102] T. Djobava,[160b] J. I. Djuvsland,[17] M. A. B. Do Vale,[148] M. Dobre,[27b] D. Dodsworth,[26] C. Doglioni,[97] J. Dolejsi,[143] Z. Dolezal,[143] M. Donadelli,[81c] J. Donini,[38] A. D'onofrio,[93] M. D'Onofrio,[91] J. Dopke,[144] A. Doria,[70a] M. T. Dova,[89] A. T. Doyle,[57] E. Drechsler,[153] E. Dreyer,[153] T. Dreyer,[53] Y. Du,[60b] Y. Duan,[60b] F. Dubinin,[111] M. Dubovsky,[28a] A. Dubreuil,[54] E. Duchovni,[181] G. Duckeck,[114] A. Ducourthial,[136] O. A. Ducu,[110,p] D. Duda,[115] A. Dudarev,[36] A. C. Dudder,[100] E. M. Duffield,[18] L. Duflot,[65] M. Dührssen,[36] C. Dülsen,[183] M. Dumancic,[181] A. E. Dumitriu,[27b] A. K. Duncan,[57] M. Dunford,[61a] A. Duperrin,[102] H. Duran Yildiz,[4a] M. Düren,[56] A. Durglishvili,[160b] D. Duschinger,[48] B. Dutta,[46] D. Duvnjak,[1] G. I. Dyckes,[137] M. Dyndal,[46] S. Dysch,[101] B. S. Dziedzic,[85] K. M. Ecker,[115] R. C. Edgar,[106] T. Eifert,[36] G. Eigen,[17] K. Einsweiler,[18] T. Ekelof,[173] M. El Kacimi,[35c] R. El Kosseifi,[102] V. Ellajosyula,[173] M. Ellert,[173] F. Ellinghaus,[183] A. A. Elliot,[93] N. Ellis,[36] J. Elmsheuser,[29] M. Elsing,[36] D. Emeliyanov,[144] A. Emerman,[39] Y. Enari,[164] J. S. Ennis,[179] M. B. Epland,[49] J. Erdmann,[47] A. Ereditato,[20] M. Escalier,[65] C. Escobar,[175] O. Estrada Pastor,[175] A. I. Etienvre,[145] E. Etzion,[162] H. Evans,[66] A. Ezhilov,[138] M. Ezzi,[35f] F. Fabbri,[57] L. Fabbri,[23b,23a] V. Fabiani,[119] G. Facini,[95] R. M. Faisca Rodrigues Pereira,[140a] R. M. Fakhrutdinov,[123] S. Falciano,[73a] P. J. Falke,[5] S. Falke,[5] J. Faltova,[143] Y. Fang,[15a] Y. Fang,[15a] G. Fanourakis,[44] M. Fanti,[69a,69b] A. Farbin,[8] A. Farilla,[75a] E. M. Farina,[71a,71b] T. Farooque,[107] S. Farrell,[18] S. M. Farrington,[179] P. Farthouat,[36] F. Fassi,[35f] P. Fassnacht,[36] D. Fassouliotis,[9] M. Faucci Giannelli,[50] W. J. Fawcett,[32] L. Fayard,[65] O. L. Fedin,[138,q] W. Fedorko,[176] M. Feickert,[42] S. Feigl,[134] L. Feligioni,[102] A. Fell,[150] C. Feng,[60b] E. J. Feng,[36] M. Feng,[49] M. J. Fenton,[57] A. B. Fenyuk,[123] J. Ferrando,[46] A. Ferrari,[173] P. Ferrari,[120] R. Ferrari,[71a] D. E. Ferreira de Lima,[61b] A. Ferrer,[175] D. Ferrere,[54] C. Ferretti,[106] F. Fiedler,[100] A. Filipčič,[92] F. Filthaut,[119] K. D. Finelli,[25] M. C. N. Fiolhais,[140a,140c,r] L. Fiorini,[175] C. Fischer,[14] F. Fischer,[114] W. C. Fisher,[107] I. Fleck,[152] P. Fleischmann,[106] R. R. M. Fletcher,[137] T. Flick,[183] B. M. Flierl,[114] L. Flores,[137] L. R. Flores Castillo,[63a] F. M. Follega,[76a,76b] N. Fomin,[17] G. T. Forcolin,[76a,76b] A. Formica,[145] F. A. Förster,[14] A. C. Forti,[101] A. G. Foster,[21] D. Fournier,[65] H. Fox,[90] S. Fracchia,[150] P. Francavilla,[72a,72b] M. Franchini,[23b,23a] S. Franchino,[61a] D. Francis,[36] L. Franconi,[20] M. Franklin,[59] M. Frate,[172] A. N. Fray,[93] B. Freund,[110] W. S. Freund,[81b] E. M. Freundlich,[47] D. C. Frizzell,[129] D. Froidevaux,[36] J. A. Frost,[135] C. Fukunaga,[165] E. Fullana Torregrosa,[175] E. Fumagalli,[55b,55a] T. Fusayasu,[116] J. Fuster,[175] A. Gabrielli,[23b,23a] A. Gabrielli,[18] G. P. Gach,[84a] S. Gadatsch,[54] P. Gadow,[115] G. Gagliardi,[55b,55a] L. G. Gagnon,[110] C. Galea,[27b] B. Galhardo,[140a,140c] E. J. Gallas,[135] B. J. Gallop,[144] P. Gallus,[142] G. Galster,[40] R. Gamboa Goni,[93] K. K. Gan,[127] S. Ganguly,[181] J. Gao,[60a] Y. Gao,[91] Y. S. Gao,[31,h] C. García,[175] J. E. García Navarro,[175] J. A. García Pascual,[15a] C. Garcia-Argos,[52] M. Garcia-Sciveres,[18] R. W. Gardner,[37] N. Garelli,[154] S. Gargiulo,[52] V. Garonne,[134] A. Gaudiello,[55b,55a] G. Gaudio,[71a] I. L. Gavrilenko,[111] A. Gavrilyuk,[124] C. Gay,[176] G. Gaycken,[24] E. N. Gazis,[10] C. N. P. Gee,[144] J. Geisen,[53] M. Geisen,[100] M. P. Geisler,[61a] C. Gemme,[55b] M. H. Genest,[58] C. Geng,[106] S. Gentile,[73a,73b] S. George,[94] T. Geralis,[44] D. Gerbaudo,[14] L. O. Gerlach,[53] G. Gessner,[47] S. Ghasemi,[152] M. Ghasemi Bostanabad,[177] A. Ghosh,[78] B. Giacobbe,[23b] S. Giagu,[73a,73b] N. Giangiacomi,[23b,23a] P. Giannetti,[72a]

A. Giannini,[70a,70b] S. M. Gibson,[94] M. Gignac,[146] D. Gillberg,[34] G. Gilles,[183] D. M. Gingrich,[3,e] M. P. Giordani,[67a,67c] F. M. Giorgi,[23b] P. F. Giraud,[145] G. Giugliarelli,[67a,67c] D. Giugni,[69a] F. Giuli,[135] M. Giulini,[61b] S. Gkaitatzis,[163] I. Gkialas,[9,s] E. L. Gkougkousis,[14] P. Gkountoumis,[10] L. K. Gladilin,[113] C. Glasman,[99] J. Glatzer,[14] P. C. F. Glaysher,[46] A. Glazov,[46] M. Goblirsch-Kolb,[26] S. Goldfarb,[105] T. Golling,[54] D. Golubkov,[123] A. Gomes,[140a,140b] R. Goncalves Gama,[53] R. Gonçalo,[140a] G. Gonella,[52] L. Gonella,[21] A. Gongadze,[80] F. Gonnella,[21] J. L. Gonski,[59] S. González de la Hoz,[175] S. Gonzalez-Sevilla,[54] G. R. Gonzalvo Rodriguez,[175] L. Goossens,[36] P. A. Gorbounov,[124] H. A. Gordon,[29] B. Gorini,[36] E. Gorini,[68a,68b] A. Gorišek,[92] A. T. Goshaw,[49] M. I. Gostkin,[80] C. A. Gottardo,[24] C. R. Goudet,[65] M. Gouighri,[35b] D. Goujdami,[35c] A. G. Goussiou,[149] N. Govender,[33c,t] C. Goy,[5] E. Gozani,[161] I. Grabowska-Bold,[84a] P. O. J. Gradin,[173] E. C. Graham,[91] J. Gramling,[172] E. Gramstad,[134] S. Grancagnolo,[19] M. Grandi,[157] V. Gratchev,[138] P. M. Gravila,[27f] F. G. Gravili,[68a,68b] C. Gray,[57] H. M. Gray,[18] C. Grefe,[24] K. Gregersen,[97] I. M. Gregor,[46] P. Grenier,[154] K. Grevtsov,[46] N. A. Grieser,[129] J. Griffiths,[8] A. A. Grillo,[146] K. Grimm,[31,u] S. Grinstein,[14,v] J.-F. Grivaz,[65] S. Groh,[100] E. Gross,[181] J. Grosse-Knetter,[53] Z. J. Grout,[95] C. Grud,[106] A. Grummer,[118] L. Guan,[106] W. Guan,[182] J. Guenther,[36] A. Guerguichon,[65] F. Guescini,[169a] D. Guest,[172] R. Gugel,[52] B. Gui,[127] T. Guillemin,[5] S. Guindon,[36] U. Gul,[57] J. Guo,[60c] W. Guo,[106] Y. Guo,[60a,w] Z. Guo,[102] R. Gupta,[46] S. Gurbuz,[12c] G. Gustavino,[129] P. Gutierrez,[129] C. Gutschow,[95] C. Guyot,[145] M. P. Guzik,[84a] C. Gwenlan,[135] C. B. Gwilliam,[91] A. Haas,[125] C. Haber,[18] H. K. Hadavand,[8] N. Haddad,[35f] A. Hadef,[60a] S. Hageböck,[36] M. Hagihara,[170] M. Haleem,[178] J. Haley,[130] G. Halladjian,[107] G. D. Hallewell,[102] K. Hamacher,[183] P. Hamal,[131] K. Hamano,[177] H. Hamdaoui,[35f] G. N. Hamity,[150] K. Han,[60a,x] L. Han,[60a] S. Han,[15a] K. Hanagaki,[82,y] M. Hance,[146] D. M. Handl,[114] B. Haney,[137] R. Hankache,[136] E. Hansen,[97] J. B. Hansen,[40] J. D. Hansen,[40] M. C. Hansen,[24] P. H. Hansen,[40] E. C. Hanson,[101] K. Hara,[170] A. S. Hard,[182] T. Harenberg,[183] S. Harkusha,[108] P. F. Harrison,[179] N. M. Hartmann,[114] Y. Hasegawa,[151] A. Hasib,[50] S. Hassani,[145] S. Haug,[20] R. Hauser,[107] L. Hauswald,[48] L. B. Havener,[39] M. Havranek,[142] C. M. Hawkes,[21] R. J. Hawkings,[36] D. Hayden,[107] C. Hayes,[156] R. L. Hayes,[176] C. P. Hays,[135] J. M. Hays,[93] H. S. Hayward,[91] S. J. Haywood,[144] F. He,[60a] M. P. Heath,[50] V. Hedberg,[97] L. Heelan,[8] S. Heer,[24] K. K. Heidegger,[52] J. Heilman,[34] S. Heim,[46] T. Heim,[18] B. Heinemann,[46,z] J. J. Heinrich,[132] L. Heinrich,[36] C. Heinz,[56] J. Hejbal,[141] L. Helary,[61b] A. Held,[176] S. Hellesund,[134] C. M. Helling,[146] S. Hellman,[45a,45b] C. Helsens,[36] R. C. W. Henderson,[90] Y. Heng,[182] S. Henkelmann,[176] A. M. Henriques Correia,[36] G. H. Herbert,[19] H. Herde,[26] V. Herget,[178] Y. Hernández Jiménez,[33f] H. Herr,[100] M. G. Herrmann,[114] T. Herrmann,[48] G. Herten,[52] R. Hertenberger,[114] L. Hervas,[36] T. C. Herwig,[137] G. G. Hesketh,[95] N. P. Hessey,[169a] A. Higashida,[164] S. Higashino,[82] E. Higón-Rodriguez,[175] K. Hildebrand,[37] E. Hill,[177] J. C. Hill,[32] K. K. Hill,[29] K. H. Hiller,[46] S. J. Hillier,[21] M. Hils,[48] I. Hinchliffe,[18] F. Hinterkeuser,[24] M. Hirose,[133] S. Hirose,[52] D. Hirschbuehl,[183] B. Hiti,[92] O. Hladik,[141] D. R. Hlaluku,[33f] X. Hoad,[50] J. Hobbs,[156] N. Hod,[181] M. C. Hodgkinson,[150] A. Hoecker,[36] F. Hoenig,[114] D. Hohn,[52] D. Hohov,[65] T. R. Holmes,[37] M. Holzbock,[114] L. B. A. H. Hommels,[32] S. Honda,[170] T. Honda,[82] T. M. Hong,[139] A. Hönle,[115] B. H. Hooberman,[174] W. H. Hopkins,[6] Y. Horii,[117] P. Horn,[48] A. J. Horton,[153] L. A. Horyn,[37] J-Y. Hostachy,[58] A. Hostiuc,[149] S. Hou,[159] A. Hoummada,[35a] J. Howarth,[101] J. Hoya,[89] M. Hrabovsky,[131] J. Hrdinka,[77] I. Hristova,[19] J. Hrivnac,[65] A. Hrynevich,[109] T. Hryn'ova,[5] P. J. Hsu,[64] S.-C. Hsu,[149] Q. Hu,[29] S. Hu,[60c] Y. Huang,[15a] Z. Hubacek,[142] F. Hubaut,[102] M. Huebner,[24] F. Huegging,[24] T. B. Huffman,[135] M. Huhtinen,[36] R. F. H. Hunter,[34] P. Huo,[156] A. M. Hupe,[34] N. Huseynov,[80,aa] J. Huston,[107] J. Huth,[59] R. Hyneman,[106] S. Hyrych,[28a] G. Iacobucci,[54] G. Iakovidis,[29] I. Ibragimov,[152] L. Iconomidou-Fayard,[65] Z. Idrissi,[35f] P. Iengo,[36] R. Ignazzi,[40] O. Igonkina,[120,a,bb] R. Iguchi,[164] T. Iizawa,[54] Y. Ikegami,[82] M. Ikeno,[82] D. Iliadis,[163] N. Ilic,[119] F. Iltzsche,[48] G. Introzzi,[71a,71b] M. Iodice,[75a] K. Iordanidou,[39] V. Ippolito,[73a,73b] M. F. Isacson,[173] N. Ishijima,[133] M. Ishino,[164] M. Ishitsuka,[166] W. Islam,[130] C. Issever,[135] S. Istin,[161] F. Ito,[170] J. M. Iturbe Ponce,[63a] R. Iuppa,[76a,76b] A. Ivina,[181] H. Iwasaki,[82] J. M. Izen,[43] V. Izzo,[70a] P. Jacka,[141] P. Jackson,[1] R. M. Jacobs,[24] V. Jain,[2] G. Jäkel,[183] K. B. Jakobi,[100] K. Jakobs,[52] S. Jakobsen,[77] T. Jakoubek,[141] J. Jamieson,[57] D. O. Jamin,[130] R. Jansky,[54] J. Janssen,[24] M. Janus,[53] P. A. Janus,[84a] G. Jarlskog,[97] N. Javadov,[80,aa] T. Javůrek,[36] M. Javurkova,[52] F. Jeanneau,[145] L. Jeanty,[132] J. Jejelava,[160a,cc] A. Jelinskas,[179] P. Jenni,[52,dd] J. Jeong,[46] N. Jeong,[46] S. Jézéquel,[5] H. Ji,[182] J. Jia,[156] H. Jiang,[79] Y. Jiang,[60a] Z. Jiang,[154,ee] S. Jiggins,[52] F. A. Jimenez Morales,[38] J. Jimenez Pena,[175] S. Jin,[15c] A. Jinaru,[27b] O. Jinnouchi,[166] H. Jivan,[33f] P. Johansson,[150] K. A. Johns,[7] C. A. Johnson,[66] K. Jon-And,[45a,45b] R. W. L. Jones,[90] S. D. Jones,[157] S. Jones,[7] T. J. Jones,[91] J. Jongmanns,[61a] P. M. Jorge,[140a,140b] J. Jovicevic,[169a] X. Ju,[18] J. J. Junggeburth,[115] A. Juste Rozas,[14,v] A. Kaczmarska,[85] M. Kado,[65] H. Kagan,[127] M. Kagan,[154] T. Kaji,[180] E. Kajomovitz,[161] C. W. Kalderon,[97] A. Kaluza,[100] A. Kamenshchikov,[123] L. Kanjir,[92] Y. Kano,[164] V. A. Kantserov,[112] J. Kanzaki,[82] L. S. Kaplan,[182] D. Kar,[33f] M. J. Kareem,[169b] S. N. Karpov,[80] Z. M. Karpova,[80] V. Kartvelishvili,[90] A. N. Karyukhin,[123] L. Kashif,[182] R. D. Kass,[127] A. Kastanas,[45a,45b] Y. Kataoka,[164] C. Kato,[60d,60c]

J. Katzy,[46] K. Kawade,[83] K. Kawagoe,[88] T. Kawaguchi,[117] T. Kawamoto,[164] G. Kawamura,[53] E. F. Kay,[177] V. F. Kazanin,[122b,122a] R. Keeler,[177] R. Kehoe,[42] J. S. Keller,[34] E. Kellermann,[97] J. J. Kempster,[21] J. Kendrick,[21] O. Kepka,[141] S. Kersten,[183] B. P. Kerševan,[92] S. Ketabchi Haghighat,[168] R. A. Keyes,[104] M. Khader,[174] F. Khalil-Zada,[13] A. Khanov,[130] A. G. Kharlamov,[122b,122a] T. Kharlamova,[122b,122a] E. E. Khoda,[176] A. Khodinov,[167] T. J. Khoo,[54] E. Khramov,[80] J. Khubua,[160b] S. Kido,[83] M. Kiehn,[54] C. R. Kilby,[94] Y. K. Kim,[37] N. Kimura,[67a,67c] O. M. Kind,[19] B. T. King,[91,a] D. Kirchmeier,[48] J. Kirk,[144] A. E. Kiryunin,[115] T. Kishimoto,[164] V. Kitali,[46] O. Kivernyk,[5] E. Kladiva,[28b,a] T. Klapdor-Kleingrothaus,[52] M. H. Klein,[106] M. Klein,[91] U. Klein,[91] K. Kleinknecht,[100] P. Klimek,[121] A. Klimentov,[29] T. Klingl,[24] T. Klioutchnikova,[36] F. F. Klitzner,[114] P. Kluit,[120] S. Kluth,[115] E. Kneringer,[77] E. B. F. G. Knoops,[102] A. Knue,[52] D. Kobayashi,[88] T. Kobayashi,[164] M. Kobel,[48] M. Kocian,[154] P. Kodys,[143] P. T. Koenig,[24] T. Koffas,[34] N. M. Köhler,[115] T. Koi,[154] M. Kolb,[61b] I. Koletsou,[5] T. Kondo,[82] N. Kondrashova,[60c] K. Köneke,[52] A. C. König,[119] T. Kono,[126] R. Konoplich,[125,ff] V. Konstantinides,[95] N. Konstantinidis,[95] B. Konya,[97] R. Kopeliansky,[66] S. Koperny,[84a] K. Korcyl,[85] K. Kordas,[163] G. Koren,[162] A. Korn,[95] I. Korolkov,[14] E. V. Korolkova,[150] N. Korotkova,[113] O. Kortner,[115] S. Kortner,[115] T. Kosek,[143] V. V. Kostyukhin,[24] A. Kotwal,[49] A. Koulouris,[10] A. Kourkoumeli-Charalampidi,[71a,71b] C. Kourkoumelis,[9] E. Kourlitis,[150] V. Kouskoura,[29] A. B. Kowalewska,[85] R. Kowalewski,[177] C. Kozakai,[164] W. Kozanecki,[145] A. S. Kozhin,[123] V. A. Kramarenko,[113] G. Kramberger,[92] D. Krasnopevtsev,[60a] M. W. Krasny,[136] A. Krasznahorkay,[36] D. Krauss,[115] J. A. Kremer,[84a] J. Kretzschmar,[91] P. Krieger,[168] A. Krishnan,[61b] K. Krizka,[18] K. Kroeninger,[47] H. Kroha,[115] J. Kroll,[141] J. Kroll,[137] J. Krstic,[16] U. Kruchonak,[80] H. Krüger,[24] N. Krumnack,[79] M. C. Kruse,[49] T. Kubota,[105] S. Kuday,[4b] D. Kuechler,[46] J. T. Kuechler,[46] S. Kuehn,[36] A. Kugel,[61a] T. Kuhl,[46] V. Kukhtin,[80] R. Kukla,[102] Y. Kulchitsky,[108,gg] S. Kuleshov,[147d] Y. P. Kulinich,[174] M. Kuna,[58] T. Kunigo,[86] A. Kupco,[141] T. Kupfer,[47] O. Kuprash,[52] H. Kurashige,[83] L. L. Kurchaninov,[169a] Y. A. Kurochkin,[108] A. Kurova,[112] M. G. Kurth,[15a,15d] E. S. Kuwertz,[36] M. Kuze,[166] A. K. Kvam,[149] J. Kvita,[131] T. Kwan,[104] A. La Rosa,[115] J. L. La Rosa Navarro,[81c] L. La Rotonda,[41b,41a] F. La Ruffa,[41b,41a] C. Lacasta,[175] F. Lacava,[73a,73b] D. P. J. Lack,[101] H. Lacker,[19] D. Lacour,[136] E. Ladygin,[80] R. Lafaye,[5] B. Laforge,[136] T. Lagouri,[33f] S. Lai,[53] S. Lammers,[66] W. Lampl,[7] E. Lançon,[29] U. Landgraf,[52] M. P. J. Landon,[93] M. C. Lanfermann,[54] V. S. Lang,[46] J. C. Lange,[53] R. J. Langenberg,[36] A. J. Lankford,[172] F. Lanni,[29] K. Lantzsch,[24] A. Lanza,[71a] A. Lapertosa,[55b,55a] S. Laplace,[136] J. F. Laporte,[145] T. Lari,[69a] F. Lasagni Manghi,[23b,23a] M. Lassnig,[36] T. S. Lau,[63a] A. Laudrain,[65] A. Laurier,[34] M. Lavorgna,[70a,70b] M. Lazzaroni,[69a,69b] B. Le,[105] O. Le Dortz,[136] E. Le Guirriec,[102] M. LeBlanc,[7] T. LeCompte,[6] F. Ledroit-Guillon,[58] C. A. Lee,[29] G. R. Lee,[147a] L. Lee,[59] S. C. Lee,[159] S. J. Lee,[34] B. Lefebvre,[169a] M. Lefebvre,[177] F. Legger,[114] C. Leggett,[18] K. Lehmann,[153] N. Lehmann,[183] G. Lehmann Miotto,[36] W. A. Leight,[46] A. Leisos,[163,hh] M. A. L. Leite,[81c] R. Leitner,[143] D. Lellouch,[181,a] K. J. C. Leney,[42] T. Lenz,[24] B. Lenzi,[36] R. Leone,[7] S. Leone,[72a] C. Leonidopoulos,[50] A. Leopold,[136] G. Lerner,[157] C. Leroy,[110] R. Les,[168] C. G. Lester,[32] M. Levchenko,[138] J. Levêque,[5] D. Levin,[106] L. J. Levinson,[181] D. J. Lewis,[21] B. Li,[15b] B. Li,[106] C-Q. Li,[60a,ii] F. Li,[60c] H. Li,[60a] H. Li,[60b] J. Li,[60c] K. Li,[154] L. Li,[60c] M. Li,[15a,15d] Q. Li,[15a,15d] Q. Y. Li,[60a] S. Li,[60d,60c] X. Li,[46] Y. Li,[46] Z. Liang,[15a] B. Liberti,[74a] A. Liblong,[168] K. Lie,[63c] S. Liem,[120] C. Y. Lin,[32] K. Lin,[107] T. H. Lin,[100] R. A. Linck,[66] J. H. Lindon,[21] A. L. Lionti,[54] E. Lipeles,[137] A. Lipniacka,[17] M. Lisovyi,[61b] T. M. Liss,[174,jj] A. Lister,[176] A. M. Litke,[146] J. D. Little,[8] B. Liu,[79] B. X. Liu,[6] H. B. Liu,[29] H. Liu,[106] J. B. Liu,[60a] J. K. K. Liu,[135] K. Liu,[136] M. Liu,[60a] P. Liu,[18] Y. Liu,[15a,15d] Y. L. Liu,[106] Y. W. Liu,[60a] M. Livan,[71a,71b] A. Lleres,[58] J. Llorente Merino,[15a] S. L. Lloyd,[93] C. Y. Lo,[63b] F. Lo Sterzo,[42] E. M. Lobodzinska,[46] P. Loch,[7] S. Loffredo,[74a,74b] T. Lohse,[19] K. Lohwasser,[150] M. Lokajicek,[141] J. D. Long,[174] R. E. Long,[90] L. Longo,[36] K. A. Looper,[127] J. A. Lopez,[147d] I. Lopez Paz,[101] A. Lopez Solis,[150] J. Lorenz,[114] N. Lorenzo Martinez,[5] M. Losada,[22a] P. J. Lösel,[114] A. Lösle,[52] X. Lou,[46] X. Lou,[15a] A. Lounis,[65] J. Love,[6] P. A. Love,[90] J. J. Lozano Bahilo,[175] H. Lu,[63a] M. Lu,[60a] Y. J. Lu,[64] H. J. Lubatti,[149] C. Luci,[73a,73b] A. Lucotte,[58] C. Luedtke,[52] F. Luehring,[66] I. Luise,[136] L. Luminari,[73a] B. Lund-Jensen,[155] M. S. Lutz,[103] D. Lynn,[29] R. Lysak,[141] E. Lytken,[97] F. Lyu,[15a] V. Lyubushkin,[80] T. Lyubushkina,[80] H. Ma,[29] L. L. Ma,[60b] Y. Ma,[60b] G. Maccarrone,[51] A. Macchiolo,[115] C. M. Macdonald,[150] J. Machado Miguens,[137,140b] D. Madaffari,[175] R. Madar,[38] W. F. Mader,[48] N. Madysa,[48] J. Maeda,[83] K. Maekawa,[164] S. Maeland,[17] T. Maeno,[29] M. Maerker,[48] A. S. Maevskiy,[113] V. Magerl,[52] N. Magini,[79] D. J. Mahon,[39] C. Maidantchik,[81b] T. Maier,[114] A. Maio,[140a,140b,140d] K. Maj,[85] O. Majersky,[28a] S. Majewski,[132] Y. Makida,[82] N. Makovec,[65] B. Malaescu,[136] Pa. Malecki,[85] V. P. Maleev,[138] F. Malek,[58] U. Mallik,[78] D. Malon,[6] C. Malone,[32] S. Maltezos,[10] S. Malyukov,[80] J. Mamuzic,[175] G. Mancini,[51] I. Mandić,[92] L. Manhaes de Andrade Filho,[81a] I. M. Maniatis,[163] J. Manjarres Ramos,[48] K. H. Mankinen,[97] A. Mann,[114] A. Manousos,[77] B. Mansoulie,[145] I. Manthos,[163] S. Manzoni,[120] A. Marantis,[163,hh] G. Marceca,[30] L. Marchese,[135] G. Marchiori,[136] M. Marcisovsky,[141] C. Marcon,[97] C. A. Marin Tobon,[36] M. Marjanovic,[38] Z. Marshall,[18] M. U. F. Martensson,[173]

S. Marti-Garcia,[175] C. B. Martin,[127] T. A. Martin,[179] V. J. Martin,[50] B. Martin dit Latour,[17] M. Martinez,[14,v] V. I. Martinez Outschoorn,[103] S. Martin-Haugh,[144] V. S. Martoiu,[27b] A. C. Martyniuk,[95] A. Marzin,[36] L. Masetti,[100] T. Mashimo,[164] R. Mashinistov,[111] J. Masik,[101] A. L. Maslennikov,[122b,122a] L. H. Mason,[105] L. Massa,[74a,74b] P. Massarotti,[70a,70b] P. Mastrandrea,[72a,72b] A. Mastroberardino,[41b,41a] T. Masubuchi,[164] A. Matic,[114] P. Mättig,[24] J. Maurer,[27b] B. Maček,[92] D. A. Maximov,[122b,122a] R. Mazini,[159] I. Maznas,[163] S. M. Mazza,[146] S. P. Mc Kee,[106] T. G. McCarthy,[115] L. I. McClymont,[95] W. P. McCormack,[18] E. F. McDonald,[105] J. A. Mcfayden,[36] M. A. McKay,[42] K. D. McLean,[177] S. J. McMahon,[144] P. C. McNamara,[105] C. J. McNicol,[179] R. A. McPherson,[177,o] J. E. Mdhluli,[33f] Z. A. Meadows,[103] S. Meehan,[149] T. Megy,[52] S. Mehlhase,[114] A. Mehta,[91] T. Meideck,[58] B. Meirose,[43] D. Melini,[175] B. R. Mellado Garcia,[33f] J. D. Mellenthin,[53] M. Melo,[28a] F. Meloni,[46] A. Melzer,[24] S. B. Menary,[101] E. D. Mendes Gouveia,[140a,140e] L. Meng,[36] X. T. Meng,[106] S. Menke,[115] E. Meoni,[41b,41a] S. Mergelmeyer,[19] S. A. M. Merkt,[139] C. Merlassino,[20] P. Mermod,[54,a] L. Merola,[70a,70b] C. Meroni,[69a] O. Meshkov,[113] J. K. R. Meshreki,[152] A. Messina,[73a,73b] J. Metcalfe,[6] A. S. Mete,[172] C. Meyer,[66] J. Meyer,[161] J-P. Meyer,[145] H. Meyer Zu Theenhausen,[61a] F. Miano,[157] R. P. Middleton,[144] L. Mijović,[50] G. Mikenberg,[181] M. Mikestikova,[141] M. Mikuž,[92] H. Mildner,[150] M. Milesi,[105] A. Milic,[168] D. A. Millar,[93] D. W. Miller,[37] A. Milov,[181] D. A. Milstead,[45a,45b] R. A. Mina,[154,ee] A. A. Minaenko,[123] M. Miñano Moya,[175] I. A. Minashvili,[160b] A. I. Mincer,[125] B. Mindur,[84a] M. Mineev,[80] Y. Minegishi,[164] Y. Ming,[182] L. M. Mir,[14] A. Mirto,[68a,68b] K. P. Mistry,[137] T. Mitani,[180] J. Mitrevski,[114] V. A. Mitsou,[175] M. Mittal,[60c] A. Miucci,[20] P. S. Miyagawa,[150] A. Mizukami,[82] J. U. Mjörnmark,[97] T. Mkrtchyan,[185] M. Mlynarikova,[143] T. Moa,[45a,45b] K. Mochizuki,[110] P. Mogg,[52] S. Mohapatra,[39] R. Moles-Valls,[24] M. C. Mondragon,[107] K. Mönig,[46] J. Monk,[40] E. Monnier,[102] A. Montalbano,[153] J. Montejo Berlingen,[36] M. Montella,[95] F. Monticelli,[89] S. Monzani,[69a] N. Morange,[65] D. Moreno,[22a] M. Moreno Llácer,[36] P. Morettini,[55b] M. Morgenstern,[120] S. Morgenstern,[48] D. Mori,[153] M. Morii,[59] M. Morinaga,[180] V. Morisbak,[134] A. K. Morley,[36] G. Mornacchi,[36] A. P. Morris,[95] L. Morvaj,[156] P. Moschovakos,[10] B. Moser,[120] M. Mosidze,[160b] H. J. Moss,[150] J. Moss,[31,kk] K. Motohashi,[166] E. Mountricha,[36] E. J. W. Moyse,[103] S. Muanza,[102] F. Mueller,[115] J. Mueller,[139] R. S. P. Mueller,[114] D. Muenstermann,[90] G. A. Mullier,[97] J. L. Munoz Martinez,[14] F. J. Munoz Sanchez,[101] P. Murin,[28b] W. J. Murray,[179,144] A. Murrone,[69a,69b] M. Muškinja,[18] C. Mwewa,[33a] A. G. Myagkov,[123,ll] J. Myers,[132] M. Myska,[142] B. P. Nachman,[18] O. Nackenhorst,[47] A. Nag Nag,[48] K. Nagai,[135] K. Nagano,[82] Y. Nagasaka,[62] M. Nagel,[52] E. Nagy,[102] A. M. Nairz,[36] Y. Nakahama,[117] K. Nakamura,[82] T. Nakamura,[164] I. Nakano,[128] H. Nanjo,[133] F. Napolitano,[61a] R. F. Naranjo Garcia,[46] R. Narayan,[11] D. I. Narrias Villar,[61a] I. Naryshkin,[138] T. Naumann,[46] G. Navarro,[22a] H. A. Neal,[106,a] P. Y. Nechaeva,[111] F. Nechansky,[46] T. J. Neep,[145] A. Negri,[71a,71b] M. Negrini,[23b] S. Nektarijevic,[119] C. Nellist,[53] M. E. Nelson,[135] S. Nemecek,[141] P. Nemethy,[125] M. Nessi,[36,mm] M. S. Neubauer,[174] M. Neumann,[183] P. R. Newman,[21] T. Y. Ng,[63c] Y. S. Ng,[19] Y. W. Y. Ng,[172] H. D. N. Nguyen,[102] T. Nguyen Manh,[110] E. Nibigira,[38] R. B. Nickerson,[135] R. Nicolaidou,[145] D. S. Nielsen,[40] J. Nielsen,[146] N. Nikiforou,[11] V. Nikolaenko,[123,ll] I. Nikolic-Audit,[136] K. Nikolopoulos,[21] P. Nilsson,[29] H. R. Nindhito,[54] Y. Ninomiya,[82] A. Nisati,[73a] N. Nishu,[60c] R. Nisius,[115] I. Nitsche,[47] T. Nitta,[180] T. Nobe,[164] Y. Noguchi,[86] M. Nomachi,[133] I. Nomidis,[136] M. A. Nomura,[29] M. Nordberg,[36] N. Norjoharuddeen,[135] T. Novak,[92] O. Novgorodova,[48] R. Novotny,[142] L. Nozka,[131] K. Ntekas,[172] E. Nurse,[95] F. Nuti,[105] F. G. Oakham,[34,e] H. Oberlack,[115] J. Ocariz,[136] A. Ochi,[83] I. Ochoa,[39] J. P. Ochoa-Ricoux,[147a] K. O'Connor,[26] S. Oda,[88] S. Odaka,[82] S. Oerdek,[53] A. Ogrodnik,[84a] A. Oh,[101] S. H. Oh,[49] C. C. Ohm,[155] H. Oide,[55b,55a] M. L. Ojeda,[168] H. Okawa,[170] Y. Okazaki,[86] Y. Okumura,[164] T. Okuyama,[82] A. Olariu,[27b] L. F. Oleiro Seabra,[140a] S. A. Olivares Pino,[147a] D. Oliveira Damazio,[29] J. L. Oliver,[1] M. J. R. Olsson,[172] A. Olszewski,[85] J. Olszowska,[85] D. C. O'Neil,[153] A. Onofre,[140a,140e] K. Onogi,[117] P. U. E. Onyisi,[11] H. Oppen,[134] M. J. Oreglia,[37] G. E. Orellana,[89] D. Orestano,[75a,75b] N. Orlando,[14] R. S. Orr,[168] B. Osculati,[55b,55a,a] V. O'Shea,[57] R. Ospanov,[60a] G. Otero y Garzon,[30] H. Otono,[88] M. Ouchrif,[35e] F. Ould-Saada,[134] A. Ouraou,[145,a] Q. Ouyang,[15a] M. Owen,[57] R. E. Owen,[21] V. E. Ozcan,[12c] N. Ozturk,[8] J. Pacalt,[131] H. A. Pacey,[32] K. Pachal,[49] A. Pacheco Pages,[14] C. Padilla Aranda,[14] S. Pagan Griso,[18] M. Paganini,[184] G. Palacino,[66] S. Palazzo,[50] S. Palestini,[36] M. Palka,[84b] D. Pallin,[38] I. Panagoulias,[10] C. E. Pandini,[36] J. G. Panduro Vazquez,[94] P. Pani,[46] G. Panizzo,[67a,67c] L. Paolozzi,[54] C. Papadatos,[110] K. Papageorgiou,[9,s] A. Paramonov,[6] D. Paredes Hernandez,[63b] S. R. Paredes Saenz,[135] B. Parida,[167] T. H. Park,[168] A. J. Parker,[90] M. A. Parker,[32] F. Parodi,[55b,55a] E. W. Parrish,[121] J. A. Parsons,[39] U. Parzefall,[52] L. Pascual Dominguez,[136] V. R. Pascuzzi,[168] J. M. P. Pasner,[146] E. Pasqualucci,[73a] S. Passaggio,[55b] F. Pastore,[94] P. Pasuwan,[45a,45b] S. Pataraia,[100] J. R. Pater,[101] A. Pathak,[182] T. Pauly,[36] B. Pearson,[115] M. Pedersen,[134] L. Pedraza Diaz,[119] R. Pedro,[140a,140b] S. V. Peleganchuk,[122b,122a] O. Penc,[141] C. Peng,[15a] H. Peng,[60a] B. S. Peralva,[81a] M. M. Perego,[65] A. P. Pereira Peixoto,[140a,140e] D. V. Perepelitsa,[29] F. Peri,[19] L. Perini,[69a,69b] H. Pernegger,[36] S. Perrella,[70a,70b] V. D. Peshekhonov,[80,a] K. Peters,[46] R. F. Y. Peters,[101]

B. A. Petersen,[36] T. C. Petersen,[40] E. Petit,[58] A. Petridis,[1] C. Petridou,[163] M. Petrov,[135] F. Petrucci,[75a,75b] M. Pettee,[184] N. E. Pettersson,[103] K. Petukhova,[143] A. Peyaud,[145] R. Pezoa,[147d] T. Pham,[105] F. H. Phillips,[107] P. W. Phillips,[144] M. W. Phipps,[174] G. Piacquadio,[156] E. Pianori,[18] A. Picazio,[103] R. H. Pickles,[101] R. Piegaia,[30] D. Pietreanu,[27b] J. E. Pilcher,[37] A. D. Pilkington,[101] M. Pinamonti,[74a,74b] J. L. Pinfold,[3] M. Pitt,[181] L. Pizzimento,[74a,74b] M.-A. Pleier,[29] V. Pleskot,[143] E. Plotnikova,[80] D. Pluth,[79] P. Podberezko,[122b,122a] R. Poettgen,[97] R. Poggi,[54] L. Poggioli,[65] I. Pogrebnyak,[107] D. Pohl,[24] I. Pokharel,[53] G. Polesello,[71a] A. Poley,[18] A. Policicchio,[73a,73b] R. Polifka,[36] A. Polini,[23b] C. S. Pollard,[46] V. Polychronakos,[29] D. Ponomarenko,[112] L. Pontecorvo,[36] S. Popa,[27a] G. A. Popeneciu,[27d] D. M. Portillo Quintero,[136] S. Pospisil,[142] K. Potamianos,[46] I. N. Potrap,[80] C. J. Potter,[32] H. Potti,[11] T. Poulsen,[97] J. Poveda,[36] T. D. Powell,[150] G. Pownall,[46] M. E. Pozo Astigarraga,[36] P. Pralavorio,[102] S. Prell,[79] D. Price,[101] M. Primavera,[68a] S. Prince,[104] M. L. Proffitt,[149] N. Proklova,[112] K. Prokofiev,[63c] F. Prokoshin,[147d] S. Protopopescu,[29] J. Proudfoot,[6] M. Przybycien,[84a] A. Puri,[174] P. Puzo,[65] J. Qian,[106] Y. Qin,[101] A. Quadt,[53] M. Queitsch-Maitland,[46] A. Qureshi,[1] P. Rados,[105] F. Ragusa,[69a,69b] G. Rahal,[98] J. A. Raine,[54] S. Rajagopalan,[29] A. Ramirez Morales,[93] K. Ran,[15a,15d] T. Rashid,[65] S. Raspopov,[5] M. G. Ratti,[69a,69b] D. M. Rauch,[46] F. Rauscher,[114] S. Rave,[100] B. Ravina,[150] I. Ravinovich,[181] J. H. Rawling,[101] M. Raymond,[36] A. L. Read,[134] N. P. Readioff,[58] M. Reale,[68a,68b] D. M. Rebuzzi,[71a,71b] A. Redelbach,[178] G. Redlinger,[29] R. G. Reed,[33f] K. Reeves,[43] L. Rehnisch,[19] J. Reichert,[137] D. Reikher,[162] A. Reiss,[100] A. Rej,[152] C. Rembser,[36] H. Ren,[15a] M. Rescigno,[73a] S. Resconi,[69a] E. D. Resseguie,[137] S. Rettie,[176] E. Reynolds,[21] O. L. Rezanova,[122b,122a] P. Reznicek,[143] E. Ricci,[76a,76b] R. Richter,[115] S. Richter,[46] E. Richter-Was,[84b] O. Ricken,[24] M. Ridel,[136] P. Rieck,[115] C. J. Riegel,[183] O. Rifki,[46] M. Rijssenbeek,[156] A. Rimoldi,[71a,71b] M. Rimoldi,[20] L. Rinaldi,[23b] G. Ripellino,[155] B. Ristić,[90] E. Ritsch,[36] I. Riu,[14] J. C. Rivera Vergara,[147a] F. Rizatdinova,[130] E. Rizvi,[93] C. Rizzi,[36] R. T. Roberts,[101] S. H. Robertson,[104,o] M. Robin,[46] D. Robinson,[32] J. E. M. Robinson,[46] A. Robson,[57] E. Rocco,[100] C. Roda,[72a,72b] Y. Rodina,[102] S. Rodriguez Bosca,[175] A. Rodriguez Perez,[14] D. Rodriguez Rodriguez,[175] A. M. Rodríguez Vera,[169b] S. Roe,[36] O. Røhne,[134] R. Röhrig,[115] C. P. A. Roland,[66] J. Roloff,[59] A. Romaniouk,[112] M. Romano,[23b,23a] N. Rompotis,[91] M. Ronzani,[125] L. Roos,[136] S. Rosati,[73a] K. Rosbach,[52] N-A. Rosien,[53] G. Rosin,[103] B. J. Rosser,[137] E. Rossi,[46] E. Rossi,[75a,75b] E. Rossi,[70a,70b] L. P. Rossi,[55b] L. Rossini,[69a,69b] J. H. N. Rosten,[32] R. Rosten,[14] M. Rotaru,[27b] J. Rothberg,[149,a] D. Rousseau,[65] D. Roy,[33f] A. Rozanov,[102] Y. Rozen,[161] X. Ruan,[33f] F. Rubbo,[154] F. Rühr,[52] A. Ruiz-Martinez,[175] A. Rummler,[36] Z. Rurikova,[52] N. A. Rusakovich,[80] H. L. Russell,[104] L. Rustige,[38,47] J. P. Rutherfoord,[7] E. M. Rüttinger,[46,nn] Y. F. Ryabov,[138,a] M. Rybar,[39] G. Rybkin,[65] A. Ryzhov,[123] G. F. Rzehorz,[53] P. Sabatini,[53] G. Sabato,[120] S. Sacerdoti,[65] H. F-W. Sadrozinski,[146] R. Sadykov,[80] F. Safai Tehrani,[73a] P. Saha,[121] S. Saha,[104] M. Sahinsoy,[61a] A. Sahu,[183] M. Saimpert,[46] M. Saito,[164] T. Saito,[164] H. Sakamoto,[164] A. Sakharov,[125,ff] D. Salamani,[54] G. Salamanna,[75a,75b] J. E. Salazar Loyola,[147d] P. H. Sales De Bruin,[173] D. Salihagic,[115,a] A. Salnikov,[154] J. Salt,[175] D. Salvatore,[41b,41a] F. Salvatore,[157] A. Salvucci,[63a,63b,63c] A. Salzburger,[36] J. Samarati,[36] D. Sammel,[52] D. Sampsonidis,[163] D. Sampsonidou,[163] J. Sánchez,[175] A. Sanchez Pineda,[67a,67c] H. Sandaker,[134] C. O. Sander,[46] M. Sandhoff,[183] C. Sandoval,[22a] D. P. C. Sankey,[144] M. Sannino,[55b,55a] Y. Sano,[117] A. Sansoni,[51] C. Santoni,[38] H. Santos,[140a,140b] S. N. Santpur,[18] A. Santra,[175] A. Sapronov,[80] J. G. Saraiva,[140a,140d] O. Sasaki,[82] K. Sato,[170] E. Sauvan,[5] P. Savard,[168,e] N. Savic,[115] R. Sawada,[164] C. Sawyer,[144] L. Sawyer,[96,oo] C. Sbarra,[23b] A. Sbrizzi,[23a] T. Scanlon,[95] J. Schaarschmidt,[149] P. Schacht,[115] B. M. Schachtner,[114] D. Schaefer,[37] L. Schaefer,[137] J. Schaeffer,[100] S. Schaepe,[36] U. Schäfer,[100] A. C. Schaffer,[65] D. Schaile,[114] R. D. Schamberger,[156] N. Scharmberg,[101] V. A. Schegelsky,[138] D. Scheirich,[143] F. Schenck,[19] M. Schernau,[172] C. Schiavi,[55b,55a] S. Schier,[146] L. K. Schildgen,[24] Z. M. Schillaci,[26] E. J. Schioppa,[36] M. Schioppa,[41b,41a] K. E. Schleicher,[52] S. Schlenker,[36] K. R. Schmidt-Sommerfeld,[115] K. Schmieden,[36] C. Schmitt,[100] S. Schmitt,[46] S. Schmitz,[100] J. C. Schmoeckel,[46] U. Schnoor,[52] L. Schoeffel,[145] A. Schoening,[61b] E. Schopf,[135] M. Schott,[100] J. F. P. Schouwenberg,[119] J. Schovancova,[36] S. Schramm,[54] A. Schulte,[100] H-C. Schultz-Coulon,[61a] M. Schumacher,[52] B. A. Schumm,[146] Ph. Schune,[145] A. Schwartzman,[154] T. A. Schwarz,[106] Ph. Schwemling,[145] R. Schwienhorst,[107] A. Sciandra,[24] G. Sciolla,[26] M. Scornajenghi,[41b,41a] F. Scuri,[72a] F. Scutti,[105] L. M. Scyboz,[115] C. D. Sebastiani,[73a,73b] P. Seema,[19] S. C. Seidel,[118] A. Seiden,[146] T. Seiss,[37] J. M. Seixas,[81b] G. Sekhniaidze,[70a] K. Sekhon,[106] S. J. Sekula,[42] N. Semprini-Cesari,[23b,23a] S. Sen,[49] S. Senkin,[38] C. Serfon,[77] L. Serin,[65] L. Serkin,[67a,67b] M. Sessa,[60a] H. Severini,[129] T. Šfiligoj,[92] F. Sforza,[171] A. Sfyrla,[54] E. Shabalina,[53] J. D. Shahinian,[146] N. W. Shaikh,[45a,45b] D. Shaked Renous,[181] L. Y. Shan,[15a] R. Shang,[174] J. T. Shank,[25] M. Shapiro,[18] A. Sharma,[135] A. S. Sharma,[1] P. B. Shatalov,[124] K. Shaw,[157] S. M. Shaw,[101] A. Shcherbakova,[138] Y. Shen,[129] N. Sherafati,[34] A. D. Sherman,[25] P. Sherwood,[95] L. Shi,[159,pp] S. Shimizu,[82] C. O. Shimmin,[184] Y. Shimogama,[180] M. Shimojima,[116] I. P. J. Shipsey,[135] S. Shirabe,[88] M. Shiyakova,[80,qq] J. Shlomi,[181] A. Shmeleva,[111] M. J. Shochet,[37] J. Shojaii,[105] D. R. Shope,[129] S. Shrestha,[127] E. Shulga,[181] P. Sicho,[141] A. M. Sickles,[174] P. E. Sidebo,[155]

E. Sideras Haddad,[33f] O. Sidiropoulou,[36] A. Sidoti,[23b,23a] F. Siegert,[48] Dj. Sijacki,[16] M. Silva Jr.,[182] M. V. Silva Oliveira,[81a] S. B. Silverstein,[45a] S. Simion,[65] E. Simioni,[100] M. Simon,[100] R. Simoniello,[100] P. Sinervo,[168] N. B. Sinev,[132] M. Sioli,[23b,23a] I. Siral,[106] S. Yu. Sivoklokov,[113] J. Sjölin,[45a,45b] E. Skorda,[97] P. Skubic,[129] M. Slawinska,[85] K. Sliwa,[171] R. Slovak,[143] V. Smakhtin,[181] B. H. Smart,[144] J. Smiesko,[28a] N. Smirnov,[112] S. Yu. Smirnov,[112] Y. Smirnov,[112] L. N. Smirnova,[113,rr] O. Smirnova,[97] J. W. Smith,[53] M. Smizanska,[90] K. Smolek,[142] A. Smykiewicz,[85] A. A. Snesarev,[111] I. M. Snyder,[132] S. Snyder,[29] R. Sobie,[177,o] A. M. Soffa,[172] A. Soffer,[162] A. Søgaard,[50] F. Sohns,[53] G. Sokhrannyi,[92] C. A. Solans Sanchez,[36] E. Yu. Soldatov,[112] U. Soldevila,[175] A. A. Solodkov,[123] A. Soloshenko,[80] O. V. Solovyanov,[123] V. Solovyev,[138] P. Sommer,[150] H. Son,[171] W. Song,[144] W. Y. Song,[169b] A. Sopczak,[142] F. Sopkova,[28b] C. L. Sotiropoulou,[72a,72b] S. Sottocornola,[71a,71b] R. Soualah,[67a,67c,ss] A. M. Soukharev,[122b,122a] D. South,[46] S. Spagnolo,[68a,68b] M. Spalla,[115] M. Spangenberg,[179] F. Spanò,[94] D. Sperlich,[19] T. M. Spieker,[61a] R. Spighi,[23b] G. Spigo,[36] L. A. Spiller,[105] M. Spina,[157] D. P. Spiteri,[57] M. Spousta,[143] A. Stabile,[69a,69b] B. L. Stamas,[121] R. Stamen,[61a] M. Stamenkovic,[120] S. Stamm,[19] E. Stanecka,[85] R. W. Stanek,[6] B. Stanislaus,[135] M. M. Stanitzki,[46] M. Stankaityte,[135] B. Stapf,[120] E. A. Starchenko,[123] G. H. Stark,[146] J. Stark,[58] S. H. Stark,[40] P. Staroba,[141] P. Starovoitov,[61a] S. Stärz,[104] R. Staszewski,[85] G. Stavropoulos,[44] M. Stegler,[46] P. Steinberg,[29] B. Stelzer,[153] H. J. Stelzer,[36] O. Stelzer-Chilton,[169a] H. Stenzel,[56] T. J. Stevenson,[157] G. A. Stewart,[36] M. C. Stockton,[36] G. Stoicea,[27b] M. Stolarski,[140a] P. Stolte,[53] S. Stonjek,[115] A. Straessner,[48] J. Strandberg,[155] S. Strandberg,[45a,45b] M. Strauss,[129] P. Strizenec,[28b] R. Ströhmer,[178] D. M. Strom,[132] R. Stroynowski,[42] A. Strubig,[50] S. A. Stucci,[29] B. Stugu,[17] J. Stupak,[129] N. A. Styles,[46] D. Su,[154] S. Suchek,[61a] Y. Sugaya,[133] V. V. Sulin,[111] M. J. Sullivan,[91] D. M. S. Sultan,[54] S. Sultansoy,[4c] T. Sumida,[86] S. Sun,[106] X. Sun,[3] K. Suruliz,[157] C. J. E. Suster,[158] M. R. Sutton,[157] S. Suzuki,[82] M. Svatos,[141] M. Swiatlowski,[37] S. P. Swift,[2] A. Sydorenko,[100] I. Sykora,[28a] M. Sykora,[143] T. Sykora,[143] D. Ta,[100] K. Tackmann,[46,tt] J. Taenzer,[162] A. Taffard,[172] R. Tafirout,[169a] E. Tahirovic,[93] H. Takai,[29] R. Takashima,[87] K. Takeda,[83] T. Takeshita,[151] E. P. Takeva,[50] Y. Takubo,[82] M. Talby,[102] A. A. Talyshev,[122b,122a] N. M. Tamir,[162] J. Tanaka,[164] M. Tanaka,[166] R. Tanaka,[65] B. B. Tannenwald,[127] S. Tapia Araya,[174] S. Tapprogge,[100] A. Tarek Abouelfadl Mohamed,[136] S. Tarem,[161] G. Tarna,[27b,uu] G. F. Tartarelli,[69a] P. Tas,[143] M. Tasevsky,[141] T. Tashiro,[86] E. Tassi,[41b,41a] A. Tavares Delgado,[140a,140b] Y. Tayalati,[35f] A. J. Taylor,[50] G. N. Taylor,[105] P. T. E. Taylor,[105] W. Taylor,[169b] A. S. Tee,[90] R. Teixeira De Lima,[154] P. Teixeira-Dias,[94] H. Ten Kate,[36] J. J. Teoh,[120] S. Terada,[82] K. Terashi,[164] J. Terron,[99] S. Terzo,[14] M. Testa,[51] R. J. Teuscher,[168,o] S. J. Thais,[184] T. Theveneaux-Pelzer,[46] F. Thiele,[40] D. W. Thomas,[94] J. O. Thomas,[42] J. P. Thomas,[21] A. S. Thompson,[57] P. D. Thompson,[21] L. A. Thomsen,[184] E. Thomson,[137] Y. Tian,[39] R. E. Ticse Torres,[53] V. O. Tikhomirov,[111,vv] Yu. A. Tikhonov,[122b,122a] S. Timoshenko,[112] P. Tipton,[184] S. Tisserant,[102] K. Todome,[23b,23a] S. Todorova-Nova,[5] S. Todt,[48] J. Tojo,[88] S. Tokár,[28a] K. Tokushuku,[82] E. Tolley,[127] K. G. Tomiwa,[33f] M. Tomoto,[117] L. Tompkins,[154,ee] K. Toms,[118] B. Tong,[59] P. Tornambe,[103] E. Torrence,[132] H. Torres,[48] E. Torró Pastor,[149] C. Tosciri,[135] J. Toth,[102,ww] D. R. Tovey,[150] C. J. Treado,[125] T. Trefzger,[178] F. Tresoldi,[157] A. Tricoli,[29] I. M. Trigger,[169a] S. Trincaz-Duvoid,[136] W. Trischuk,[168] B. Trocmé,[58] A. Trofymov,[65] C. Troncon,[69a] M. Trovatelli,[177] F. Trovato,[157] L. Truong,[33c] M. Trzebinski,[85] A. Trzupek,[85] F. Tsai,[46] J. C-L. Tseng,[135] P. V. Tsiareshka,[108,gg] A. Tsirigotis,[163] N. Tsirintanis,[9] V. Tsiskaridze,[156] E. G. Tskhadadze,[160a] M. Tsopoulou,[163] I. I. Tsukerman,[124] V. Tsulaia,[18] S. Tsuno,[82] D. Tsybychev,[156] Y. Tu,[63b] A. Tudorache,[27b] V. Tudorache,[27b] T. T. Tulbure,[27a] A. N. Tuna,[59] S. Turchikhin,[80] D. Turgeman,[181] I. Turk Cakir,[4b,xx] R. J. Turner,[21] R. Turra,[69a] P. M. Tuts,[39] S. Tzamarias,[163] E. Tzovara,[100] G. Ucchielli,[47] I. Ueda,[82] M. Ughetto,[45a,45b] F. Ukegawa,[170] G. Unal,[36] A. Undrus,[29] G. Unel,[172] F. C. Ungaro,[105] Y. Unno,[82] K. Uno,[164] J. Urban,[28b] P. Urquijo,[105] G. Usai,[8] J. Usui,[82] L. Vacavant,[102] V. Vacek,[142] B. Vachon,[104] K. O. H. Vadla,[134] A. Vaidya,[95] C. Valderanis,[114] E. Valdes Santurio,[45a,45b] M. Valente,[54] S. Valentinetti,[23b,23a] A. Valero,[175] L. Valéry,[46] R. A. Vallance,[21] A. Vallier,[36] J. A. Valls Ferrer,[175] T. R. Van Daalen,[14] P. Van Gemmeren,[6] I. Van Vulpen,[120] M. Vanadia,[74a,74b] W. Vandelli,[36] A. Vaniachine,[167] R. Vari,[73a] E. W. Varnes,[7] C. Varni,[55b,55a] T. Varol,[42] D. Varouchas,[65] K. E. Varvell,[158] M. E. Vasile,[27b] G. A. Vasquez,[177] J. G. Vasquez,[184] F. Vazeille,[38] D. Vazquez Furelos,[14] T. Vazquez Schroeder,[36] J. Veatch,[53] V. Vecchio,[75a,75b] L. M. Veloce,[168] F. Veloso,[140a,140c] S. Veneziano,[73a] A. Ventura,[68a,68b] N. Venturi,[36] A. Verbytskyi,[115] V. Vercesi,[71a] M. Verducci,[75a,75b] C. M. Vergel Infante,[79] C. Vergis,[24] W. Verkerke,[120] A. T. Vermeulen,[120] J. C. Vermeulen,[120] M. C. Vetterli,[153,e] N. Viaux Maira,[147d] M. Vicente Barreto Pinto,[54] I. Vichou,[174,a] T. Vickey,[150] O. E. Vickey Boeriu,[150] G. H. A. Viehhauser,[135] L. Vigani,[135] M. Villa,[23b,23a] M. Villaplana Perez,[69a,69b] E. Vilucchi,[51] M. G. Vincter,[34] V. B. Vinogradov,[80] A. Vishwakarma,[46] C. Vittori,[23b,23a] I. Vivarelli,[157] M. Vogel,[183] P. Vokac,[142] G. Volpi,[14] S. E. von Buddenbrock,[33f] E. Von Toerne,[24] V. Vorobel,[143] K. Vorobev,[112] M. Vos,[175] J. H. Vossebeld,[91] N. Vranjes,[16] M. Vranjes Milosavljevic,[16] V. Vrba,[142,a] M. Vreeswijk,[120] R. Vuillermet,[36] I. Vukotic,[37] P. Wagner,[24] W. Wagner,[183] J. Wagner-Kuhr,[114] H. Wahlberg,[89] S. Wahrmund,[48] K. Wakamiya,[83] V. M. Walbrecht,[115]

J. Walder,[90] R. Walker,[114] S. D. Walker,[94] W. Walkowiak,[152] V. Wallangen,[45a,45b] A. M. Wang,[59] C. Wang,[60b] F. Wang,[182] H. Wang,[18] H. Wang,[3] J. Wang,[158] J. Wang,[61b] P. Wang,[42] Q. Wang,[129] R.-J. Wang,[136] R. Wang,[60a] R. Wang,[6] S. M. Wang,[159] W. T. Wang,[60a] W. Wang,[15c,yy] W. X. Wang,[60a,yy] Y. Wang,[60a,ii] Z. Wang,[60c] C. Wanotayaroj,[46] A. Warburton,[104] C. P. Ward,[32] D. R. Wardrope,[95] A. Washbrook,[50] A. T. Watson,[21] M. F. Watson,[21] G. Watts,[149] B. M. Waugh,[95] A. F. Webb,[11] S. Webb,[100] C. Weber,[184] M. S. Weber,[20] S. A. Weber,[34] S. M. Weber,[61a] A. R. Weidberg,[135] J. Weingarten,[47] M. Weirich,[100] C. Weiser,[52] P. S. Wells,[36] T. Wenaus,[29] T. Wengler,[36] S. Wenig,[36] N. Wermes,[24] M. D. Werner,[79] P. Werner,[36] M. Wessels,[61a] T. D. Weston,[20] K. Whalen,[132] N. L. Whallon,[149] A. M. Wharton,[90] A. S. White,[106] A. White,[8] M. J. White,[1] R. White,[147d] D. Whiteson,[172] B. W. Whitmore,[90] F. J. Wickens,[144] W. Wiedenmann,[182] M. Wielers,[144] C. Wiglesworth,[40] L. A. M. Wiik-Fuchs,[52] F. Wilk,[101] H. G. Wilkens,[36] L. J. Wilkins,[94] H. H. Williams,[137] S. Williams,[32] C. Willis,[107] S. Willocq,[103] J. A. Wilson,[21] I. Wingerter-Seez,[5] E. Winkels,[157] F. Winklmeier,[132] O. J. Winston,[157] B. T. Winter,[52] M. Wittgen,[154] M. Wobisch,[96] A. Wolf,[100] T. M. H. Wolf,[120] R. Wolff,[102] R. Wölker,[135] J. Wollrath,[52] M. W. Wolter,[85] H. Wolters,[140a,140c] V. W. S. Wong,[176] N. L. Woods,[146] S. D. Worm,[21] B. K. Wosiek,[85] K. W. Woźniak,[85] K. Wraight,[57] S. L. Wu,[182] X. Wu,[54] Y. Wu,[60a] T. R. Wyatt,[101] B. M. Wynne,[50] S. Xella,[40] Z. Xi,[106] D. Xu,[15a] H. Xu,[60a,uu] L. Xu,[29] T. Xu,[145] W. Xu,[106] Z. Xu,[60b] Z. Xu,[154] B. Yabsley,[158] S. Yacoob,[33a] K. Yajima,[133] D. P. Yallup,[95] D. Yamaguchi,[166] Y. Yamaguchi,[166] A. Yamamoto,[82] T. Yamanaka,[164] F. Yamane,[83] M. Yamatani,[164] T. Yamazaki,[164] Y. Yamazaki,[83] Z. Yan,[25] H. J. Yang,[60c,60d] H. T. Yang,[18] S. Yang,[78] X. Yang,[60b,58] Y. Yang,[164] Z. Yang,[17] W-M. Yao,[18] Y. C. Yap,[46] Y. Yasu,[82] E. Yatsenko,[60c,60d] J. Ye,[42] S. Ye,[29] I. Yeletskikh,[80] E. Yigitbasi,[25] E. Yildirim,[100] K. Yorita,[180] K. Yoshihara,[137] C. J. S. Young,[36] C. Young,[154] J. Yu,[79] X. Yue,[61a] S. P. Y. Yuen,[24] B. Zabinski,[85] G. Zacharis,[10] E. Zaffaroni,[54] J. Zahreddine,[136] R. Zaidan,[14] A. M. Zaitsev,[123,ll] T. Zakareishvili,[160b] N. Zakharchuk,[34] S. Zambito,[59] D. Zanzi,[36] D. R. Zaripovas,[57] S. V. Zeißner,[47] C. Zeitnitz,[183] G. Zemaityte,[135] J. C. Zeng,[174] O. Zenin,[123] T. Ženiš,[28a] D. Zerwas,[65] M. Zgubič,[135] D. F. Zhang,[15b] F. Zhang,[182] G. Zhang,[60a] G. Zhang,[15b] H. Zhang,[15c] J. Zhang,[6] L. Zhang,[15c] L. Zhang,[60a] M. Zhang,[174] R. Zhang,[60a] R. Zhang,[24] X. Zhang,[60b] Y. Zhang,[15a,15d] Z. Zhang,[63a] Z. Zhang,[65] P. Zhao,[49] Y. Zhao,[60b] Z. Zhao,[60a] A. Zhemchugov,[80] Z. Zheng,[106] D. Zhong,[174] B. Zhou,[106] C. Zhou,[182] M. S. Zhou,[15a,15d] M. Zhou,[156] N. Zhou,[60c] Y. Zhou,[7] C. G. Zhu,[60b] H. L. Zhu,[60a] H. Zhu,[15a] J. Zhu,[106] Y. Zhu,[60a] X. Zhuang,[15a] K. Zhukov,[111] V. Zhulanov,[122b,122a] D. Zieminska,[66] N. I. Zimine,[80] S. Zimmermann,[52,a] Z. Zinonos,[115] M. Ziolkowski,[152] L. Živković,[16] G. Zobernig,[182] A. Zoccoli,[23b,23a] K. Zoch,[53] T. G. Zorbas,[150] R. Zou,[37] and L. Zwalinski[36]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany, New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton AB, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey*
[4c]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[5]*LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
[12a]*Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
[12b]*Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
[12c]*Department of Physics, Bogazici University, Istanbul, Turkey*
[12d]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[13]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[14]*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
[15a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[15b]*Physics Department, Tsinghua University, Beijing, China*
[15c]*Department of Physics, Nanjing University, Nanjing, China*
[15d]*University of Chinese Academy of Science (UCAS), Beijing, China*
[16]*Institute of Physics, University of Belgrade, Belgrade, Serbia*

[17]Department for Physics and Technology, University of Bergen, Bergen, Norway
[18]Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[21]School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[22a]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia
[22b]Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, Colombia
[23a]INFN Bologna and Universita' di Bologna, Dipartimento di Fisica, Italy
[23b]INFN Sezione di Bologna, Italy
[24]Physikalisches Institut, Universität Bonn, Bonn, Germany
[25]Department of Physics, Boston University, Boston, Massachusetts, USA
[26]Department of Physics, Brandeis University, Waltham, Massachusetts, USA
[27a]Transilvania University of Brasov, Brasov, Romania
[27b]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[27c]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
[27d]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
[27e]University Politehnica Bucharest, Bucharest, Romania
[27f]West University in Timisoara, Timisoara, Romania
[28a]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
[28b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[29]Physics Department, Brookhaven National Laboratory, Upton New York, USA
[30]Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[31]California State University, California, USA
[32]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[33a]Department of Physics, University of Cape Town, Cape Town, South Africa
[33b]iThemba Labs, Western Cape, South Africa
[33c]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
[33d]National Institute of Physics, University of the Philippines Diliman, Philippines
[33e]University of South Africa, Department of Physics, Pretoria, South Africa
[33f]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[34]Department of Physics, Carleton University, Ottawa ON, Canada
[35a]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
[35b]Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
[35c]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
[35d]Moroccan Foundation for Advanced Science Innovation and Research (MAScIR), Rabat, Morocco
[35e]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco
[35f]Faculté des sciences, Université Mohammed V, Rabat, Morocco
[36]CERN, Geneva, Switzerland
[37]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[38]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
[39]Nevis Laboratory, Columbia University, Irvington, New York, USA
[40]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[41a]Dipartimento di Fisica, Università della Calabria, Rende, Italy
[41b]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
[42]Physics Department, Southern Methodist University, Dallas, Texas, USA
[43]Physics Department, University of Texas at Dallas, Richardson, Texas, USA
[44]National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece
[45a]Department of Physics, Stockholm University, Sweden
[45b]Oskar Klein Centre, Stockholm, Sweden
[46]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
[47]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[48]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[49]Department of Physics, Duke University, Durham, North Carolina, USA
[50]SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

[51]INFN e Laboratori Nazionali di Frascati, Frascati, Italy
[52]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
[53]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[54]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[55a]Dipartimento di Fisica, Università di Genova, Genova, Italy
[55b]INFN Sezione di Genova, Italy
[56]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[57]SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[58]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[59]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[60a]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[60b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[60c]School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
[60d]Tsung-Dao Lee Institute, Shanghai, China
[61a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[61b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[62]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[63a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[63b]Department of Physics, University of Hong Kong, Hong Kong, China
[63c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[64]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[65]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
[66]Department of Physics, Indiana University, Bloomington, Indiana, USA
[67a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
[67b]ICTP, Trieste, Italy
[67c]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
[68a]INFN Sezione di Lecce, Italy
[68b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[69a]INFN Sezione di Milano, Italy
[69b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[70a]INFN Sezione di Napoli, Italy
[70b]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[71a]INFN Sezione di Pavia, Italy
[71b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[72a]INFN Sezione di Pisa, Italy
[72b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[73a]INFN Sezione di Roma, Italy
[73b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[74a]INFN Sezione di Roma Tor Vergata, Italy
[74b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[75a]INFN Sezione di Roma Tre, Italy
[75b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[76a]INFN-TIFPA, Italy
[76b]Università degli Studi di Trento, Trento, Italy
[77]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[78]University of Iowa, Iowa City, Iowa, USA
[79]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[80]Joint Institute for Nuclear Research, Dubna, Russia
[81a]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
[81b]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
[81c]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[82]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[83]Graduate School of Science, Kobe University, Kobe, Japan
[84a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

[84b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[85]Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[86]Faculty of Science, Kyoto University, Kyoto, Japan
[87]Kyoto University of Education, Kyoto, Japan
[88]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
[89]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[90]Physics Department, Lancaster University, Lancaster, United Kingdom
[91]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[92]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
[93]School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[94]Department of Physics, Royal Holloway University of London, Egham, United Kingdom
[95]Department of Physics and Astronomy, University College London, London, United Kingdom
[96]Louisiana Tech University, Ruston, Louisiana, USA
[97]Fysiska institutionen, Lunds universitet, Lund, Sweden
[98]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
[99]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
[100]Institut für Physik, Universität Mainz, Mainz, Germany
[101]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[102]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[103]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[104]Department of Physics, McGill University, Montreal QC, Canada
[105]School of Physics, University of Melbourne, Victoria, Australia
[106]Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
[107]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[108]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
[109]Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
[110]Group of Particle Physics, University of Montreal, Montreal QC, Canada
[111]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
[112]National Research Nuclear University MEPhI, Moscow, Russia
[113]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[114]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[115]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[116]Nagasaki Institute of Applied Science, Nagasaki, Japan
[117]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[118]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[119]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
[120]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[121]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[122a]Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia
[122b]Novosibirsk State University Novosibirsk, Russia
[123]Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
[124]Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow, Russia
[125]Department of Physics, New York University, New York, New York, USA
[126]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
[127]Ohio State University, Columbus, Ohio, USA
[128]Faculty of Science, Okayama University, Okayama, Japan
[129]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[130]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[131]Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
[132]Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
[133]Graduate School of Science, Osaka University, Osaka, Japan
[134]Department of Physics, University of Oslo, Oslo, Norway
[135]Department of Physics, Oxford University, Oxford, United Kingdom

[136]LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France
[137]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
[138]Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
[139]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[140a]Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
[140b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[140c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[140d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[140e]Departamento de Física, Universidade do Minho, Braga, Portugal
[140f]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
[140g]Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[140h]Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[141]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[142]Czech Technical University in Prague, Prague, Czech Republic
[143]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[144]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[145]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[146]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[147a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[147b]Universidad Andres Bello, Department of Physics, Santiago, Chile
[147c]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
[147d]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[148]Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil
[149]Department of Physics, University of Washington, Seattle, Washington, USA
[150]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[151]Department of Physics, Shinshu University, Nagano, Japan
[152]Department Physik, Universität Siegen, Siegen, Germany
[153]Department of Physics, Simon Fraser University, Burnaby BC, Canada
[154]SLAC National Accelerator Laboratory, Stanford, California, USA
[155]Department of Physics, Royal Institute of Technology, Stockholm, Sweden
[156]Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[157]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[158]School of Physics, University of Sydney, Sydney, Australia
[159]Institute of Physics, Academia Sinica, Taipei, Taiwan
[160a]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
[160b]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[161]Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
[162]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[163]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[164]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
[165]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[166]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[167]Tomsk State University, Tomsk, Russia
[168]Department of Physics, University of Toronto, Toronto ON, Canada
[169a]TRIUMF, Vancouver BC, Canada
[169b]Department of Physics and Astronomy, York University, Toronto ON, Canada
[170]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[171]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
[172]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
[173]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[174]Department of Physics, University of Illinois, Urbana, Illinois, USA
[175]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain
[176]Department of Physics, University of British Columbia, Vancouver BC, Canada
[177]Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[178]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany

[179]Department of Physics, University of Warwick, Coventry, United Kingdom
[180]Waseda University, Tokyo, Japan
[181]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
[182]Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
[183]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[184]Department of Physics, Yale University, New Haven, Connecticut, USA
[185]Yerevan Physics Institute, Yerevan, Armenia

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
[d]Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.
[e]Also at TRIUMF, Vancouver BC, Canada.
[f]Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
[g]Also at Physics Department, An-Najah National University, Nablus, Palestinian Authority.
[h]Also at Department of Physics, California State University, Fresno, USA.
[i]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[j]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[k]Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[l]Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
[m]Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.
[n]Also at Universita di Napoli Parthenope, Napoli, Italy.
[o]Also at Institute of Particle Physics (IPP), Canada.
[p]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
[q]Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[r]Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[s]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[t]Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
[u]Also at Department of Physics, California State University, East Bay, USA.
[v]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[w]Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
[x]Also at IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France.
[y]Also at Graduate School of Science, Osaka University, Osaka, Japan.
[z]Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
[aa]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[bb]Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands.
[cc]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[dd]Also at CERN, Geneva, Switzerland.
[ee]Also at Department of Physics, Stanford University, Stanford, California, USA.
[ff]Also at Manhattan College, New York, New York, USA.
[gg]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[hh]Also at Hellenic Open University, Patras, Greece.
[ii]Also at LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France.
[jj]Also at The City College of New York, New York, New York, USA.
[kk]Also at Department of Physics, California State University, Sacramento, USA.
[ll]Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[mm]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[nn]Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[oo]Also at Louisiana Tech University, Ruston, Louisiana, USA.
[pp]Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
[qq]Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[rr]Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
[ss]Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
[tt]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[uu]Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
[vv]Also at National Research Nuclear University MEPhI, Moscow, Russia.
[ww]Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[xx]Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
[yy]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.