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Aaboud, M.; ATLAS Collaboration; Stapf, B.

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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)

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The total cross section and differential cross sections for the production of $B^\pm$ mesons, times their branching fraction to $J/\psi \pi^\pm$, are measured relative to those for the production of $B_c^\pm$ 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 $(0.34 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$. 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.

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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 $B_c^\pm \rightarrow J/\psi \pi^\pm$, relative to that for $B^\pm \rightarrow J/\psi K^\pm$, at $\sqrt{s}=8$ TeV of $pp$ collisions and differential in transverse momentum $p_T$ and in rapidity $y$, 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 $2.5 < \eta < 4.5$. LHCb reported [2] for the same differential relative $B_c^\pm$ 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 $0 < p_T(B_c^\pm) < 20$ 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 $13 < p_T(B_c^\pm) < 20$ GeV and $2.0 < y(B_c^\pm) < 2.3$, 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 $\sigma_{B_c}$ 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 $f_{B_c}$ [4,11,12], which in the nonrelativistic approach is proportional to the absolute value of the wave function at the origin.

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In this measurement of the cross section times branching fraction for \( B^\pm \to J/\psi \pi^\pm \) relative to that for \( B^\pm \to J/\psi K^\pm \), the \( J/\psi \) 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 \( B^\pm \), 13 GeV < \( p_T(B^\pm) < 22 \) GeV and \( p_T(B^\pm) > 22 \) GeV, for rapidity \( |y| < 2.3 \), and in two bins of rapidity \( y \) of the \( B^\pm \), \( |y| < 0.75 \) and 0.75 < \( |y| < 2.3 \), for \( p_T(B^\pm) > 13 \) 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 \( p_T(B^\pm_\mu) \) and \( y(B^\pm) \). The bins are selected to equalize yields of the \( B^\pm_\mu \). The same bin sizes are used for the \( B^\pm_\mu \) 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 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 efficiency and acceptance ratios. Section VII reports 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 \( n_{\text{out}}^\text{TRT} < 0.9n \), where \( n = n_{\text{TRT}} + n_{\text{out}}^\text{TRT} \), and \( p_{\text{TRT}}(n_{\text{out}}^\text{TRT}) \) 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 \( J/\psi \) 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 \( (B^\pm \to J/\psi \pi^\pm \) and \( B^\pm \to J/\psi K^\pm \)) were generated with the PYTHIA Monte Carlo (MC) generator [16,17]. For the generation of the \( B^\pm \) 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 \( J/\psi \) 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 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 $J/\psi$ candidate:

(i) The $p_T$ of each of the two muon candidates must be above 4 GeV.

(ii) The vertex fit quality $\chi^2/(N_{d.o.f.} = 1)$ 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 $\eta$ ranges are determined from the resolution of the muon detectors. Three mass windows are defined for the $J/\psi$ 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 $\pm120$ MeV ($\pm270$ 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 $\pm180$ MeV.

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

The $B$ candidates (where $B$ represents $B^+_c$ or $B^-$) are reconstructed by fitting the tracks of the two muons from the $J/\psi$ candidate, together with a charged-hadron track, to a common vertex. For the $B^-$ candidates the kaon mass is assigned to the hadron track while for the $B^+_c$ candidates the pion mass is assigned to the hadron track. The mass of the $J/\psi$ 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 $J/\psi$ 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, $d_{SV}/\sigma(d_{SV})$, where $d_{SV}$ is the projection of the impact parameter onto the transverse plane and $\sigma(d_{SV})$ is the uncertainty of $d_{SV}$.

Another significant source of background which is especially important for the $B^+_c$ is the partially reconstructed semileptonic decays of the $B^+_c$ such as $B^+_c \rightarrow J/\psi \mu^+\mu^-$. 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 $\chi^2/(N_{d.o.f.} = 4)$ 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 $J/\psi$ candidates, the impact parameter significance $d_{SV}/\sigma(d_{SV})$ of the hadron candidate must exceed 1.2. MC studies demonstrated that this criterion is more efficient for the $B^+_c$ candidate selection than a requirement on the lifetime.

In events with multiple $B$ candidates, the candidate with the best $\chi^2$ 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:

$$\frac{\sigma(B^+_c) \cdot B(B^+_c \rightarrow J/\psi \pi^+) \cdot B(J/\psi \rightarrow \mu^+\mu^-)}{\sigma(B^-) \cdot B(B^- \rightarrow J/\psi K^+) \cdot B(J/\psi \rightarrow \mu^+\mu^-)} = \frac{N_{\text{reco}}(B^+_c)}{N_{\text{reco}}(B^-)} \cdot \frac{e(B^+_c)}{e(B^-)}. \quad (1)$$

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

4ATLAS 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 $(r, \phi)$ are used in the transverse plane, $\phi$ 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 $N_{\text{reco}}(B_c^\pm)$ and $N_{\text{reco}}(B^\pm)$ from the data in each bin in $p_T$ and $|y|$. This involves calculating the parameters that maximize the likelihood function, defined as

$$L = e^{-N_{\text{sig}} - N_{\text{bkg}}} \prod_{i=1}^{N} [N_{\text{sig}} f_{\text{signal}}(m_{j_{/\psi K^\pm}}, \delta m_{j_{/\psi K^\pm}}) + N_{\text{bkg}} f_{\text{bkg}}(m_{j_{/\psi K^\pm}})]$$

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

$$f_{\text{signal}}(m_{j_{/\psi K^\pm}}, \delta m_{j_{/\psi K^\pm}}) \propto \exp \left( -\frac{(m_{j_{/\psi K^\pm}} - m_{B_c^\pm})^2}{2(s_1 \delta m_{j_{/\psi K^\pm}})^2} \right)$$

and for the $B^\pm$ by

$$f_{\text{signal}}(m_{j_{/\psi K^\pm}}, \delta m_{j_{/\psi K^\pm}}) \propto \exp \left( -\frac{(m_{j_{/\psi K^\pm}} - m_{B^\pm})^2}{2(s_2 \delta m_{j_{/\psi K^\pm}})^2} \right)$$

where $m_{B_c^\pm}$ and $m_{B^\pm}$ are the masses of the $B_c^\pm$ and $B^\pm$, respectively. The variables $m_{B_c^\pm}$ and $m_{B^\pm}$ are taken as free parameters in the fit. The widths $s_1 \delta m_{j_{/\psi K^\pm}}$ and $s_2 \delta m_{j_{/\psi K^\pm}}$ 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 $\sigma_m$ is obtained from the fits and appears in the relevant tables below. It is defined as the half-width of the region of the $J/\psi$ mass distribution for which the integral of the sum of $f_{\text{signal}}(m_{j_{/\psi K^\pm}}, \delta m_{j_{/\psi K^\pm}})$ over all candidates contains 68.27% of $N_{\text{sig}}$.

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

$$f_{\text{bkg}} \propto \exp(a \cdot m_{j_{/\psi K^\pm}}) + b.$$  

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

$$f_{\text{bkg}}(m_{j_{/\psi K^\pm}}) \propto 1 - \frac{m_{j_{/\psi K^\pm}} - m_0}{s_0} \cdot \text{erf} \left( \frac{m_{j_{/\psi K^\pm}} - m_0}{s_0} \right)$$

where $A = \frac{m_{j_{/\psi K^\pm}} - m_0}{s_0}$, 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

$$f_{\text{bkg}}^{(2)}(m_{j_{/\psi K^\pm}}) \propto \exp \left( -\frac{(m_{j_{/\psi K^\pm}} - m_{B^\pm K^\pm})^2}{2(s_3 \delta m_{j_{/\psi K^\pm}})^2} \right)$$

where $s_3$ is the corresponding scale factor. The variable $m_{B^\pm K^\pm}$ 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 $J/\psi$ 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

$$f_{\text{bkg}}^{(3)}(m_{j_{/\psi K^\pm}}) \propto \exp(d \cdot m_{j_{/\psi K^\pm}})$$

(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 $(a \times f_{\text{bkg}}^{(1)} + b \times f_{\text{bkg}}^{(2)} + (1 - (a + b)) \times f_{\text{bkg}}^{(3)})$, 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 $p_T$ 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 $B_c^\pm$ 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: $p_T$ of the $B$ candidate, $y$ of the $B$ candidate, $\chi^2$ of the secondary vertex, and the transverse impact parameter significance $d^{0}_y/\sigma(d^{0}_y)$. 

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The reconstruction efficiencies are determined using the MC samples for the $B^\pm_2$ and $B^\mp_2$ 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 $N_{MC}^{\text{reco}}$ to the number of generated MC events $N_{MC}^{\text{gen}}$ 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.

MC events $N_{MC}^{\text{reco}}$ to the number of generated MC events $N_{MC}^{\text{gen}}$ 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.
The fit is used to extract the fit to the sum of the signal and all background components. The fit for the common decay vertex $\epsilon_B$ and $\epsilon_B^{\text{meson}}$ is shown at the top, and that for the high transverse momentum bin ($p_T^{(B^\pm)} < 22$ GeV) at the bottom. The rapidity requirement is $\eta(B^\pm) > 2.3$. The fits are used to extract $N_{\text{rec}}(B^+) + N_{\text{rec}}(B^-)$ 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 $J/\psi$ trigger $\epsilon^\text{trigger}$, the efficiency of the muon spectrometer $\epsilon^\text{MS}$, the efficiency of the inner detector $\epsilon^\text{ID}$, the efficiency of fitting the muon and hadron tracks to a common decay vertex $\epsilon^\text{vertex}$, and the efficiency of the selection criteria $\epsilon^\text{selection}$ [24]:

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

where $\epsilon(X)$ is the $K^\pm$ efficiency in the $B^\pm$ channel and $\pi^\pm$ efficiency in the $B^\mp$ channel, while $B$ stands for the $B^\pm$ and $B^\mp$ 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 $J/\psi$ and $\Upsilon$ 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.

For the calculation of $\epsilon^\text{MS}(\mu^\pm)$, the muon reconstruction maps [27] are used. These maps are based on a sample of about two million $J/\psi \rightarrow \mu^+\mu^-$ events collected with unbiased triggers (single muonic and “muon + track”). The efficiency is measured in bins of $p_T$ and $\eta$ using the
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 \( \epsilon_{\text{ID}}(p_T) \) of the muon track reconstruction with the ID is conservatively taken to be \((99 \pm 1)\% \) [28,29].

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

The MC samples \( (B^\pm \rightarrow J/\psi \pi^\pm \text{ and } B^\pm \rightarrow J/\psi K^\pm) \) were generated with requirements on the hadron of \( p_T > 500 \text{ MeV and } |y| < 2.5 \). The requirements on muons were \( p_T > 2.5 \text{ GeV and } |y| < 2.7 \). 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: \( f_{\text{cor}}(B_c^\pm) = N(B_c^\pm)_{\text{MSC}}/N(B_c^\pm)_{\text{no MSC}} \), and \( f_{\text{cor}}(B^\pm) = N(B^\pm)_{\text{MSC}}/N(B^\pm)_{\text{no MSC}} \), where \( N(B^\pm)_{\text{no MSC}} \) and \( N(B)_{\text{MSC}} \) 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 \( f_{\text{cor}}(B_c^\pm)/f_{\text{cor}}(B^\pm) \) is propagated as a correction factor to the relative \( B_c^\pm/B^\pm \) cross section. The corrections obtained, along with their uncertainties, are

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 (\(|y| < 0.75\)) is shown at the top, and that for the outer rapidity bin (\(0.75 < |y| < 2.3\)) at the bottom. The \( p_T \) requirement is \( p_T(B_c^\pm) > 13 \text{ GeV} \). The fits are used to extract \( N^{\text{rec}}(B_c^\pm) \) and \( N^{\text{rec}}(B_c^-) \) 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.
SUMMARY OF THE MAIN PARAMETERS OF THE $B^\pm$ FITS. THE UNCERTAINTIES QUOTED ARE STATISTICAL.

<table>
<thead>
<tr>
<th>Analysis bin</th>
<th>Fitted mass of the $B^\pm$ [MeV]</th>
<th>Number of the $B^\pm$ candidates</th>
<th>$\sigma_m$ of the $B^\pm$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B) &gt; 13$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>5278.6 ± 0.1</td>
</tr>
<tr>
<td>$13 &lt; p_T(B) &lt; 22$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>5278.5 ± 0.1</td>
</tr>
<tr>
<td>$p_T(B) &gt; 22$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>5278.8 ± 0.1</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 0.75$</td>
<td>5278.4 ± 0.1</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13$ GeV, $0.75 &lt;</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>5279.1 ± 0.1</td>
</tr>
</tbody>
</table>

SUMMARY OF CORRECTIONS DUE TO THE MINIMAL SELECTION CRITERIA IN THE MC SIMULATION. THE FIRST UNCERTAINTY IS STATISTICAL, THE SECOND ONE IS SYSTEMATIC.

<table>
<thead>
<tr>
<th>Analysis bin</th>
<th>Correction to the $B^\pm$</th>
<th>Correction to the $B^\pm$</th>
<th>Ratio of the corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B) &gt; 13$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>0.0969 ± 0.0004 ± 0.0024</td>
</tr>
<tr>
<td>$13 &lt; p_T(B) &lt; 22$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>0.0829 ± 0.0004 ± 0.0031</td>
</tr>
<tr>
<td>$p_T(B) &gt; 22$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>0.2164 ± 0.0014 ± 0.0018</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13$ GeV, $</td>
<td>y(B)</td>
<td>&lt; 0.75$</td>
<td>0.0984 ± 0.0007 ± 0.0033</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13$ GeV, $0.75 &lt;</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
<td>0.0952 ± 0.0005 ± 0.0014</td>
</tr>
</tbody>
</table>

SUMMARY OF THE ABSOLUTE VALUES OF SYSTEMATIC UNCERTAINTIES FOR THE ANALYSIS EFFICIENCY RATIOS.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Absolute value of the uncertainty in the efficiency ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_T &gt; 13$ GeV</td>
</tr>
<tr>
<td>Size of the MC samples and the event counting</td>
<td>0.03</td>
</tr>
<tr>
<td>sPlot-based MC reweighting procedure</td>
<td>0.04</td>
</tr>
<tr>
<td>Minimal selection criteria</td>
<td>0.04</td>
</tr>
<tr>
<td>Tracking uncertainty</td>
<td>0.01</td>
</tr>
</tbody>
</table>
TABLE V. Summary of all systematic uncertainties for the number of signal events in the two $p_T$ bins.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$B^\pm$</th>
<th>$B^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$13 \text{ GeV} &lt; p_T &lt; 22 \text{ GeV}$</td>
<td>$p_T &gt; 22 \text{ GeV}$</td>
</tr>
<tr>
<td>Signal model of the fit</td>
<td>2.4%</td>
<td>1.1%</td>
</tr>
<tr>
<td>CS and PRD components</td>
<td>$^{+19.3}%$</td>
<td>$^{+19.9}%$</td>
</tr>
<tr>
<td>Background model of the fit</td>
<td>1.7%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Trigger and reconstruction effects</td>
<td>0.9%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$B$-meson lifetime uncertainty</td>
<td>1.1%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$B^\pm$</th>
<th>$B^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$</td>
<td>y</td>
</tr>
<tr>
<td>Signal model of the fit</td>
<td>2.5%</td>
<td>2.8%</td>
</tr>
<tr>
<td>CS and PRD components</td>
<td>$^{+11.2}%$</td>
<td>$^{+23.2}%$</td>
</tr>
<tr>
<td>Background model of the fit</td>
<td>2.8%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Trigger effects and reconstruction effects</td>
<td>1.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$B$-meson lifetime uncertainty</td>
<td>1.0%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

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 $x^\text{ID}(X_b)$. 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 ($p_T > 13 \text{ GeV}$, $|y| < 2.3$).

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$B^\pm$</th>
<th>$B^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal model of the fit</td>
<td>2.4%</td>
<td>0.1%</td>
</tr>
<tr>
<td>CS and PRD components</td>
<td>$^{+17.4}%$</td>
<td>0.5%</td>
</tr>
<tr>
<td>Background model of the fit</td>
<td>$^{+2.4}%$</td>
<td>0.5%</td>
</tr>
<tr>
<td>Trigger effects and reconstruction effects</td>
<td>2.9%</td>
<td>0.1%</td>
</tr>
<tr>
<td>$B$-meson lifetime uncertainty</td>
<td>0.7%</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>

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 1$\sigma$ 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 $13 \text{ GeV} < p_T < 22 \text{ GeV}$, 0.04 for $p_T > 13 \text{ GeV}$, 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 $B^\pm$ and $B^+$ 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 $B^{±}$ signal yield is estimated by replacing the Gaussian function by a Crystal Ball function \[31,32]\n
\[\mathcal{X}_{\text{Crystal Ball}}(m_{j/\psi K^{∓}}) \propto \left\{ \begin{array}{ll}
\exp \left[-(m_{j/\psi K^{∓}} - m_{B^{±}}^c)^2/(2\sigma_{CB}^2)\right], & \text{for } m_{j/\psi K^{∓}} > m_{B^{±}}^c - \alpha\sigma_{CB} \\
\frac{(n/a)^n \exp(-a^2/2)}{[m_{B^{±}}^c - m_{j/\psi K^{∓}}]/\sigma_{CB} + (n/a) - a],} & \text{for } m_{j/\psi K^{∓}} < m_{B^{±}}^c - \alpha\sigma_{CB}
\end{array} \right.\]

polynomials of the second kind. The result is 0.2% for 13 GeV < $p_T(B^{±})$ < 22 GeV, 0.2% for $p_T(B^{±})$ > 22 GeV, 0.2% for $|y| < 0.75$, 0.2% for 0.75 < $|y| < 2.3$, and 0.1% for the inclusive bin $p_T(B^{±}) > 13$ 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 $B^{±}$ 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 $B^{±} \rightarrow J/\psi \pi^{±}$ 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 $B^{±}$ lifetime of 0.507 ps is 0.009 ps \[21\], which corresponds to about 2%, while the uncertainty in the $B^{±}$ lifetime is four times smaller. To analytically estimate the upper limit on the uncertainty due to the lifetime, the $d_{xy}$ significance is studied and treated as 100% correlated with the lifetime. Using the limiting value for the selection criterion, which is $d_{xy}/\sigma(d_{xy}) = 1.2$, the uncertainty is obtained by multiplying 1.2 by 2% to yield 0.024. Applying ±0.024 to the $d_{xy}$ significance, the resulting change in the number of $B^{±}$ 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 $B^{±}$ MC exclusive signal sample is reweighted in order to reflect the ±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.
The yields $N_{\text{reco}}(B^\pm_\text{c})$ and $N_{\text{reco}}(B^\pm)$, 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

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

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

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 $B^\pm_\text{c}$ decreases faster with $p_T$ than the production cross section of the $B^\pm$. No significant dependence on rapidity is observed.

**VIII. RESULTS**

The production cross section of the $B^\pm_\text{c}$ meson relative to the production cross section of the $B^\pm$ meson is measured using $B^\pm_\text{c} \to J/\psi \pi^\mp$ 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 $(0.34 \pm 0.04_{\text{stat}}^{+0.06}_{-0.02 \text{ syst}} \pm 0.01_{\text{lifetime}})\%$. The ratio of the $B^\pm_\text{c}$ 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 $B^\pm_\text{c}$ meson decreases faster with $p_T$ than the production cross section of the $B^\pm$ meson. No significant dependence on rapidity is observed.

**IX. CONCLUSION**

The production cross section of the $B^\pm_\text{c}$ meson relative to the production cross section of the $B^\pm$ meson is measured using $B^\pm_\text{c} \to J/\psi \pi^\mp$ 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 $(0.34 \pm 0.04_{\text{stat}}^{+0.06}_{-0.02 \text{ syst}} \pm 0.01_{\text{lifetime}})\%$. The ratio of the $B^\pm_\text{c}$ 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 $B^\pm_\text{c}$ meson decreases faster with $p_T$ than the production cross section of the $B^\pm$ meson. No significant dependence on rapidity is observed.
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[3] V. Khachatryan et al. CMS Collaboration, Measurement of the ratio of the cross sections times branching fractions of $B^0 \rightarrow J/\psi \pi^+ \pi^-$ and $B^+ \rightarrow J/\psi K^+$ and $\Phi(B^0 \rightarrow J/\psi \pi^+ \pi^-) / \Phi(B^+ \rightarrow J/\psi \pi^+)$ at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 01 (2015) 063.
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MEASUREMENT OF THE RELATIVE $B^0_c / B^0 \ldots$
MEASUREMENT OF THE RELATIVE $B_s^0/B^\pm$ ...

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

012010-22
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, 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 JICLAb, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
66 Department of Physics, Indiana University, Bloomington, Indiana, USA
66a INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
66b ICTP, Trieste, Italy
67a Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
67b INFN Sezione di Lecce, Italy
68a INFN Sezione di Milano, Italy
68b Dipartimento di Fisica, Università del Salento, Lecce, Italy
69a INFN Sezione di Pavia, 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
Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Egham, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston, Louisiana, USA
Fysiska institutionen, Lunds universitet, Lund, Sweden
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia
Novosibirsk State University Novosibirsk, Russia
Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre “Kurchatov Institute”, Moscow, Russia
Department of Physics, New York University, New York, New York, USA
Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
Deceased.
1 Also at Department of Physics, King’s College London, London, United Kingdom.
2 Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
3 Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.
4 Also at TRIUMF, Vancouver BC, Canada.
5 Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
6 Also at Physics Department, An-Najah National University, Nablus, Palestinian Authority.
7 Also at Department of Physics, California State University, Fresno, USA.
8 Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
9 Also at Departament de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain.
10 Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
11 Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
12 Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.
13 Also at Universita di Napoli Parthenope, Napoli, Italy.
14 Also at Institute of Particle Physics (IPP), Canada.
15 Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
16 Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
17 Also at Borough of Manhattan Community College, City University of New York, New York, USA.
18 Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
19 Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
20 Also at Department of Physics, California State University, East Bay, USA.
21 Also at Institutu Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
22 Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
23 Also at IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91-405, Orsay, France.
24 Also at Graduate School of Science, Osaka University, Osaka, Japan.
25 Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
26 Also at CERN, Geneva, Switzerland.
27 Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
28 Also at Department of Physics, Stanford University, Stanford, California, USA.
29 Also at Department of Physics, University of Wisconsin, Madison, Wisconsin, USA.
30 Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
31 Also at Department of Physics, University of Sharjah, Sharjah, United Arab Emirates.
32 Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
33 Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
34 Also at National Research Nuclear University MEPhI, Moscow, Russia.
35 Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
36 Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
37 Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.