Determination of the Ratio of b-Quark Fragmentation Fractions \( f(s)/f(d) \) in pp Collisions at root \( s=7 \) TeV with the ATLAS Detector

Aad, G.; Abbott, B.; Abdallah, J.; Abdinov, O.; Aben, R.; Abolins, M.; AbouZeid, O.S.; Abramowicz, H.; Abreu, H.; Abreu, R.; Dam, Mogens; Hansen, Jørn Dines; Hansen, Jørgen Beck; Xella, Stefania; Hansen, Peter Henrik; Petersen, Troels Christian; Thomsen, Lotte Ansgaard; Mehlhase, Sascha; Jørgensen, Morten Dam; Pingel, Almut Maria; Løvschall-Jensen, Ask Emil; Alonso Diaz, Alêjandro; Monk, James William; Pedersen, Lars Egholm; Wiglesworth, Graig; Galster, Gorm Aske Gram Krohn

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Determination of the Ratio of $b$-Quark Fragmentation Fractions $f_s/f_d$

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G. Aad et al. (*)

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With an integrated luminosity of 2.47 fb$^{-1}$ recorded by the ATLAS experiment at the LHC, the exclusive decays $B^0_s \rightarrow J/\psi \phi$ and $B^0_d \rightarrow J/\psi K^{*0}$ of $B$ mesons produced in $pp$ collisions at $\sqrt{s} = 7$ TeV are used to determine the ratio of fragmentation fractions $f_s/f_d$. From the observed $B^0_s \rightarrow J/\psi \phi$ and $B^0_s \rightarrow J/\psi K^{*0}$ yields, the quantity $(f_s/f_d) [\mathcal{B}(B^0_s \rightarrow J/\psi \phi)/\mathcal{B}(B^0_s \rightarrow J/\psi K^{*0})]$ is measured to be $0.199\pm 0.004(\text{stat})\pm 0.008(\text{syst})$. Using a recent theory prediction for $[\mathcal{B}(B^0_s \rightarrow J/\psi \phi)/\mathcal{B}(B^0_d \rightarrow J/\psi K^{*0})]$ yields $(f_s/f_d) = 0.240\pm 0.004(\text{stat})\pm 0.010(\text{syst})\pm 0.017(\text{th})$. This result is based on a new approach that provides a significant improvement of the world average.

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The production rate of $B^0_s$ ($B^0_d$) mesons is a product of the $bb$ cross section, the instantaneous luminosity and the probability that the $b$ quark is bound to an $s$ ($d$) quark. The latter, denoted by the fragmentation fraction $f_s$ ($f_d$), depends on the probability that in pQCD-inspired calculations [1,2], a soft gluon splits into $s\bar{s}$ ($d\bar{d}$) and that the overlap of the $b$ and $s(d)$ wave functions is sufficiently large to produce a $B^0_s$ ($B^0_d$) bound state. In a similar fashion, $B^+$ mesons, $B_s$ mesons, and $b$ baryons are produced at the LHC with respective fragmentation fractions $f_u$, $f_c$, and $f_{\text{baryon}}$. The fragmentation fractions are about 40% each for $u$ and $d$ quarks, 10% for $s$ quarks, at the percent level for $c$ quarks, and ~8% for baryon production satisfying the constraint $f_u + f_d + f_s + f_c + f_{\text{baryon}} = 1$. Precise knowledge of the fragmentation fractions is essential for measuring $b$-hadron cross sections and branching fractions at the LHC. In particular, for rare decays, such as the branching fraction measurement of $B^0_s \rightarrow \mu^+\mu^-$ [3–5], a precise knowledge of $f_s/f_d$ is important since it improves the sensitivity of searches for new physics processes beyond the standard model (SM). The fragmentation ratio $f_s/f_d$ is a universal quantity that was measured by LEP experiments [6], CDF [7], and LHCb [8,9]. This Letter presents a measurement of $f_s/f_d$ using $B^0_s \rightarrow J/\psi \phi$ and $B^0_d \rightarrow J/\psi K^{*0}$ decays.

The ratio of fragmentation fractions $f_s/f_d$ is extracted from the measured $B^0_s \rightarrow J/\psi \phi$ and $B^0_d \rightarrow J/\psi K^{*0}$ signal yields, $N_{B^0_s}$ and $N_{B^0_d}$. These are converted into $B^0_s$ and $B^0_d$ meson yields after dividing by the branching fractions of the relevant decays and correcting for the relative efficiency $\mathcal{R}_{\text{eff}}$ that is expressed as a product of acceptance and selection efficiency ratios for the two modes and is determined from Monte Carlo (MC) simulations:

$$\frac{f_s}{f_d} = \frac{N_{B^0_s}}{N_{B^0_d}} \frac{\mathcal{B}(B^0_s \rightarrow J/\psi K^{*0})}{\mathcal{B}(B^0_d \rightarrow J/\psi \phi)} \frac{\mathcal{B}(J/\psi \phi)}{\mathcal{B}(J/\psi K^{*0})} \mathcal{R}_{\text{eff}},$$

where the $J/\psi$, $\phi$, and $K^{*0}$ are reconstructed in their $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$, and $K^{*0} \to K^+\pi^-$ final states [10], respectively. The data sample consists of $pp$ collisions collected with the ATLAS detector at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 2.47 ± 0.04 fb$^{-1}$. The ATLAS multipurpose detector is described in detail in Ref. [11].

The PYTHIA 6 and 8 [12,13] MC generators with parameters tuned to reproduce ATLAS data [14] are used to simulate background and signal events, respectively. For the signal channels, the angular distributions are produced with the measured polarization parameters [15]. The detector response for the generated events is simulated with GEANT4 [16,17].

The $B^0_s \rightarrow J/\psi \phi$ and $B^0_d \rightarrow J/\psi K^{*0}$ signal candidates consist of two muons and two hadrons originating from a common secondary vertex. The $J/\psi$ candidates are selected from the dimuon trigger sample requiring two oppositely charged muon candidates, each having a transverse momentum of $p_T > 4$ GeV. Reconstructed muon candidates are categorized either as combined or segment-tagged muons. A combined muon consists of an inner detector (ID) track combined with a muon spectrometer (MS) track using tight matching criteria, while a segment-tagged muon requires an ID track and track segments in the MS that are not reconstructed as an MS track [11]. The two muons, of which at least one must be a combined muon, are fitted to originate from the same two-track vertex. The
vertex fit chi-square per degree of freedom (dof) is required to be $\chi^2$/dof < 10. To improve the sample purity, each muon track must have at least one hit in the pixel detector, more than five hits in the silicon strip detector and at least one hit in the transition radiation tracker that reduces the pseudorapidity coverage to $|\eta| < 2.0$ [18].

Since the dimuon mass resolution is different for muons reconstructed in the end caps (1.05 < $|\eta|$ < 2.5) and for muons reconstructed in the barrel (|$\eta$| < 1.05), all accepted $J/\psi$ candidates are divided into three classes: two barrel muons (BB), one end-cap and one barrel muon (EB), and two end-cap muons (EE). The parameters describing the dimuon mass distribution in the $J/\psi$ signal region for the three pseudorapidity classes in data and in $B^0_s \rightarrow J/\psi \phi$ and $B^0_s \rightarrow J/\psi K^{*0}$ MC signal samples are extracted from maximum-likelihood fits. Signal events are selected requiring mass windows of $\pm 3\sigma$ around the $J/\psi$ peak in data and simulations. For data, the selected signal regions are 2.991–3.197 GeV for BB, 2.955–3.235 GeV for EB, and 2.914–3.275 GeV for EE classes, while in simulations they are slightly smaller.

The $B^0_s$ candidates are reconstructed from a $J/\psi$ candidate plus two oppositely charged hadrons with a kaon mass hypothesis assigned. The dimuon mass is constrained to the $J/\psi$ mass [15], and the $J/\psi$ and two kaons have to originate from the same vertex. All combinations are accepted if $p_T(B^0_s) > 8$ GeV, $\chi^2$/dof < 3 for the vertex fit and the $K^+K^-$ invariant mass lies in the range determined by $\pm 2$ natural widths ($\Gamma_\phi$) around the $\phi$ mass peak, 1011 < $m_{K^+K^-} <$ 1028 MeV. The $m_{K^+K^-}$ distribution is modeled with a Breit-Wigner line shape convolved with a Crystal Ball function [19]. The selected mass window retains 85% of signal events.

The $B^0_d$ candidates are reconstructed in a similar way. Here, one track of the $K^{*0}$ decay is assigned a kaon mass hypothesis and the other track a pion mass hypothesis. Since ATLAS has limited kaon-pion separation capability in the momentum range relevant for this analysis, both $K\pi$ mass assignment combinations are tested. That with mass closest to the nominal $K^{*0}$ mass is chosen, yielding the correct $K\pi$ selection for 86% of all $K^{*0}$ candidates. The probability density function (PDF) for the invariant mass of correctly selected $K\pi$ candidates is modeled with a relativistic Breit-Wigner line shape convolved with a Crystal Ball function, while that where the $K$ and $\pi$ are swapped is modeled with a Gaussian function. The decay $B^0_d \rightarrow J/\psi \phi$ produces a peaking background in $B^0_s \rightarrow J/\psi K^{*0}$ that appears in the low $K^{*0}$ mass region. To remove this contribution, the selected $K^{*0}$ region is constrained to one $K^{*0}$ decay width around the $K^{*0}$ mass peak, corresponding to 847 < $m_{K\pi} <$ 942 MeV for data. Since the $K^{*0}$ line shape is narrower in the MC simulations than in data, the $K\pi$ mass selection needs to be adjusted in simulations to produce identical efficiencies in data and simulations. For the $K^+K^-$ mass selection, a similar procedure is used.

The signal-to-background ratios for $B^0_s \rightarrow J/\psi \phi$ and $B^0_s \rightarrow J/\psi K^{*0}$ decays are optimized using three variables with high background suppression power: the $\chi^2$/dof of the $B$ vertex fit, the transverse decay length $L_{xy}$ defined as the length of the vector from the primary vertex (PV) [20] to the $B$ decay vertex in the transverse plane, and the pointing angle $\alpha$ defined as the angle between the $B$ meson transverse momentum and $L_{xy}$. If more than one $PV$ candidate exists, the one is selected for which the sum of squared transverse momenta of all tracks originating from the vertex, $\sum p_T^2$, yields the highest value. The $\chi^2$/dof, $L_{xy}$ and $\alpha$ selection criteria are optimized using simulated $B^0_s \rightarrow J/\psi \phi$ and $B^0_s \rightarrow J/\psi K^{*0}$ events for signal and data sidebands for background.

To produce similar $p_T$ and $\eta$ distributions in data and MC, data-driven weights are obtained by the following procedure. Sideband-subtracted $B^0_s \rightarrow J/\psi \phi (B^0_s \rightarrow J/\psi K^{*0})$ $p_T$ and $\eta$ distributions from data are compared with corresponding distributions in simulation in the signal region. 5.32 < $m_{J/\psi\phi} <$ 5.42 (5.21 < $m_{J/\psi K^{*0}} <$ 5.35) GeV. The upper and lower sidebands 5.20 < $m_{J/\psi\phi} <$ 5.25 (5.09 < $m_{J/\psi K^{*0}} <$ 5.16) GeV and 5.48 < $m_{J/\psi\phi} <$ 5.53 (5.40 < $m_{J/\psi K^{*0}} <$ 5.47) GeV are selected such that their summed yields represent the expected backgrounds in the signal region for the data. The weights are obtained by dividing the yield in each $p_T$ and $\eta$ bin in data by the corresponding yield of the MC sample using only events with odd event numbers. Thus, for each bin (i) and (j) of the $p_T$ and $\eta$ distributions, a weight is determined as a product of a $p_T$-dependent and $\eta$-dependent weights:

$$W_{ij}(p_T, \eta) = \frac{n_{data}(p_T)}{n_{MC}(p_T)} \frac{n_{data}(\eta)}{n_{MC}(\eta)},$$

where $n_{i}^{data/MC}(p_T)$ is the normalized number of entries in the $p_T$ bin $i$ and $n_{j}^{data/MC}(\eta)$ is that in the $\eta$ bin $j$. To obtain good agreement between data and simulation, the procedure is repeated twice. The two sets of weights are multiplied and are used to correct the $p_T$ and $\eta$ distributions of the MC sample with even event numbers. From the corrected MC samples, distributions for $\chi^2$/dof, $L_{xy}$, and $\alpha$ are determined, which are in good agreement with those measured in the data. The correlation between $p_T$ and $\eta$ is small and is accounted for in the systematic error.

For both modes, the dominant background originates from a $J/\psi$ produced at the PV plus two oppositely charged hadrons (direct $J/\psi$) [21]. Since the hadrons are not associated with any $B^0_s (B^0_d)$ decay, the $J/\psi K^+ K^- (J/\psi K^+ \pi^-)$ invariant-mass spectrum does not peak but decreases with mass. Another large background consists of two random low-momentum, oppositely
charged muons combined with two random charged hadrons. Here, the dimuon mass distribution does not peak at the $J/\psi$ nor does the four-particle mass show any peaking structure. Inclusive decays $B \to J/\psi X$, where $X$ is a single hadron or a collection of hadrons, provide a source of background that is very similar to the signal. If $X$ consists of exactly two charged-particle tracks (without any $\pi^0$), the mode is topologically indistinguishable from the signal mode. Self-cross-feed, in which one or both hadrons from the $\phi(K^0)$ decay are replaced with random hadrons, is negligible. In addition, peaking backgrounds from $B_{d}^{0} \to J/\psi K^{-}\pi^{0}$ and $B_{d}^{0} \to J/\psi K^{+}\pi^{-}$ contribute to $B_{s}^{0} \to J/\psi \phi$ while $B_{d}^{0} \to J/\psi K^{+}\pi^{-}$ also contributes to $B_{d}^{0} \to J/\psi K^{0}$. To reduce these backgrounds, the $\chi^{2}/\text{dof}$, $L_{xy}$, and $\alpha$ selections are optimized for each mode separately by determining the maximum value of $S/\sqrt{S+B}$ as a function of selected values for the observable to be optimized, where $S$ represents the signal yield obtained from simulation and $B$ is the background extracted from data sidebands. For the $B_{s}^{0}$ ($B_{d}^{0}$) mode, the optimization yields $\chi^{2}/\text{dof} < 2.4$ ($2.6$), $L_{xy} > 0.26$ (0.30) mm, and $\alpha < 0.14$ (0.12) rad. In combination with the $J/\psi$ mass requirement, the $\chi^{2}/\text{dof}$ selection reduces the combinatorial background significantly, while the $L_{xy}$ and $\alpha$ selections remove most of the direct $J/\psi$ background.

In the final sample, the signal yields $N_{B_{s}^{0}}$ and $N_{B_{d}^{0}}$ are extracted from unbinned extended maximum-likelihood fits to the $J/\psi K^{+}\pi^{-}$ and $J/\psi K^{+}\pi^{-}$ invariant-mass spectra, respectively. The $B_{s}^{0}$ signal PDF is modeled with three Gaussian functions with common mean that is determined from the fit, while widths and fractions are fixed to the values obtained from MC simulations. To account for possible width differences in the two narrowest Gaussian functions between data and simulation, an additional scale factor is introduced, which is left free in the fit. The peaking background PDF is modeled with a Crystal Ball function with parameters fixed to the values obtained in simulations.

The peaking background yield of 652 ± 93 events is calculated from the $B_{d}^{0}$ signal yield. The selection efficiencies of both peaking background modes are determined from simulation and are fixed in the fit to data. The remaining residual backgrounds are modeled with an exponential function leaving fraction and exponent free in the fit to data.

The $B_{d}^{0}$ signal PDF is parametrized with three Gaussian functions that describe both the correctly reconstructed and swapped $K^{+}\pi^{-}$ events. The PDF of the peaking background is modeled with a sum of Crystal Ball and Gaussian functions for which the relative $B_{d}^{0} \to J/\psi K^{+}\pi^{-}$ yield with respect to that of the $B_{d}^{0} \to J/\psi K^{0}$ signal is determined from the corresponding branching fractions and selection efficiencies, yielding $(4.7 \pm 2.4)\%$. Most of the residual background is modeled with an exponential function, while partially reconstructed $B \to J/\psi X$ decays require parametrization with a complementary error function. All parameters of the residual background PDFs are left free in the fit.

Figure 1 shows the measured $J/\psi \phi$ and $J/\psi K^{0}$ invariant-mass spectra with fits overlaid. The fits yield $N_{B_{s}^{0}} = 6640 \pm 100$ $B_{s}^{0} \to J/\psi \phi$ and $N_{B_{d}^{0}} = 36290 \pm 320$ $B_{d}^{0} \to J/\psi K^{0}$ signal events. The $\chi^{2}/\text{dof}$ values of the fits are 0.959 for $B_{s}^{0}$ and 0.945 for $B_{d}^{0}$, indicating that both fits describe the data well.

The additive systematic uncertainties result from the $B_{s}^{0} \to J/\psi \phi$ and $B_{d}^{0} \to J/\psi K^{0}$ signal and background parametrizations. The contribution from the signal shape parametrization is calculated by varying the five fixed parameters within $\pm 1\sigma$ in a multivariate Gaussian function that takes into account all correlations. For nonpeaking backgrounds, the exponential function is replaced with a second-order polynomial for the $B_{s}^{0}$ and with a second-order polynomial plus an error function for the $B_{d}^{0}$. The difference in signal yield with respect to the nominal fit is taken as a systematic error. For peaking backgrounds, the
TABLE I. Measured $B^0_s$ and $B^0_d$ signal yields, the efficiency ratio $R_{\text{eff}}$ extracted from simulations, world averages for $\phi$ and $K^{*0}$ decay branching fractions, as well as corresponding systematic uncertainties $\sigma$ on $(f_s/f_d)[B(B_s^0 \to J/\psi \phi)/B(B_d^0 \to J/\psi K^{*0})]$.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value</th>
<th>$\sigma$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{B^0_s}$</td>
<td>6640 ± 100 ± 220</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>$N_{B^0_d}$</td>
<td>36290 ± 320 ± 650</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>$R_{\text{eff}}$</td>
<td>0.799 ± 0.001 ± 0.010</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\phi \to K^+ K^-)$</td>
<td>0.489 ± 0.005</td>
<td>1.0%</td>
<td>[15]</td>
</tr>
<tr>
<td>$\mathcal{B}(K^{*0} \to K^+ \pi^-)$</td>
<td>0.66503 ± 0.00014</td>
<td>0.02%</td>
<td>[15]</td>
</tr>
<tr>
<td>Total</td>
<td>4.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

fixed parameters are varied by ±1 $\sigma$, and the difference with respect to the nominal yield is taken as a systematic error. In addition, since S-wave contributions from $B^0_s \to J/\psi K^+ K^-$ and $B^0_s \to J/\psi f_0(980)$ decays to $B_s^0 \to J/\psi \phi$ and $B_d^0 \to J/\psi K^{*0}$ are neglected in the fits, an uncertainty is derived using the ATLAS measured contribution of 2.4% [22] for $B^0_s \to J/\psi \phi$, and the contribution of 1% for $B_d^0 \to J/\psi K^{*0}$ derived from the MC simulation. All additive systematic errors are added in quadrature, yielding total additive uncertainties of 220 $N_{B^0_s}$ and 650 $N_{B^0_d}$ events.

The multiplicative systematic uncertainty includes contributions from the relative efficiency and the branching fractions of the $\phi$ and $K^{*0}$ decays. The uncertainty on the relative efficiency is dominated by the uncertainty on the $\phi/K^{*0}$ selection (1.2%), which is obtained by varying the fixed fit parameters in the $\phi$ and $K^{*0}$ fits by ±1 $\sigma$ and adding all contributions in quadrature. Other uncertainties from the $J/\psi$ selection (0.2%), reweighting (0.4%), $B^0_s$ and $B^0_d$ lifetimes (0.002%), and the contribution due to uncertainties in the polarization parameters (0.01%) are negligible. Varying the selection criteria of $\chi^2$/dof, $L_{xy}$ and $\alpha$ gives negligible contributions. Table I summarizes the contributions of the additive and multiplicative systematic errors.

From the ratio $N_{B^0_s}/N_{B^0_d}$ after efficiency correction and division by $\phi$ and $K^{*0}$ decay branching fractions, ATLAS measures

$$f_s/B(s^0)/B(d^0) = 0.199 ± 0.004(\text{stat}) ± 0.008(\text{syst}).$$

A perturbative QCD prediction [23] yields

$$\frac{f_s}{f_d} = \frac{\mathcal{B}(B_s^0 \to J/\psi \phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.83^{+0.03}_{-0.02} (\omega_B)^{+0.01}_{-0.00} (f_M)^{+0.01}_{-0.02} (a_i)^{+0.01}_{-0.02} (m_c),$$

where the uncertainties result from the shape parameter $\omega_B$ of the $B$ meson wave function, meson decay constants $f_M$, Gegenbauer moments $a_i$ in the wave functions of the light vector mesons and the $c$-quark mass. Adding all contributions linearly yields a 7.1% theory error. Using this prediction, the ratio of fragmentation fractions is measured to be

$$f_s/f_d = 0.240 ± 0.004(\text{stat}) ± 0.010(\text{syst}) ± 0.017(\text{th}).$$

Figure 2 (right panel) shows the ATLAS $f_s/f_d$ measurement in comparison with results from LEP [6], CDF [6,7], and LHCb [8,9]. The ratio $f_s/f_d$ may depend on $p_T$ and $\eta$ of the $B$ meson; e.g., LHCb observes a $p_T$ but no $\eta$ dependence of $f_s/f_d$ [8]. Figure 2 (left panel) shows the $p_T$ dependence of $f_s/f_d$ for ATLAS and that of other...
experiments. To investigate the $p_T$ and $\eta$ dependence of $f_s/f_d$, the data sample is divided into six $p_T$ bins in the range 8 GeV < $p_T$ < 50 GeV and into four $\eta$ bins for $|\eta| < 2.5$ such that the number of events in each bin is approximately equal. The $f_s/f_d$ distributions as a function of $p_T$ and $\eta$ have been fitted with a uniform (first-order polynomial) distribution yielding fit $p$ values 0.54 (0.66) and 0.66 (0.49), respectively. No significant $f_s/f_d$ dependence on $p_T$ and $|\eta|$ is seen at the present level of accuracy.

In summary, this Letter reports on the first ATLAS measurement of the ratio of $B^0_s \rightarrow J/\psi f$ and $B^0 \rightarrow J/\psi K^{*0}$ branching fractions multiplied by the ratio of fragmentation fractions $f_s/f_d$ from which $f_s/f_d$ is determined. The data were produced at the LHC in $p p$ collisions at $\sqrt{s} = 7$ TeV and correspond to an integrated luminosity of 2.47 fb$^{-1}$. This $f_s/f_d$ measurement, obtained with a new approach, agrees with the LHCb [8,9] results, improving the world average considerably. A comparison with the CDF [6,7] measurement and the LEP [6] average confirms the universality of $f_s/f_d$. The ATLAS data show no dependence on $p_T$ nor on $|\eta|$ within the kinematic range tested.

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[5] CMS Collaboration, Measurement of the $B^0_s \rightarrow \mu^+\mu^-$ Branching Fraction and Search for $B^0 \rightarrow \mu^+\mu^-$ with the CMS Experiment, Phys. Rev. Lett. 111, 101804 (2013).


[7] T. Aaltonen et al. (CDF Collaboration), BR($B^0_s \rightarrow J/\psi f$) measurement and extraction of the fragmentation fractions, Public CDF Note No. 10795, 2012.


[10] Charge conjugation is implied unless stated otherwise.


[18] 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 pipe. 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 beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln(\tan(\theta/2))$.


[20] The PV is the parton interaction vertex. The one of interest is that where the $B$ meson is produced.

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Ženiš,13 G. Zobernig,173 A. Zoccoli,20a,20b M. zur Nedden,16 G. Zurzolo,104a,104b and L. Zwalinski30 (ATLAS Collaboration)

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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 Alberta, Canada
4a Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4b Istanbul Aydin University, Istanbul, Turkey
4c Istanbul Aydin University, Istanbul, Turkey
5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, 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, The University of Texas at Arlington, Arlington, Texas, USA
9 Physics Department, University of Athens, Athens, Greece
10 Institute of Physics, National Technical University of Athens, Zografou, Greece
11 Instituto de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
12 Physics Department, University of Belgrade, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
15 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
16 Department of Physics, Bogazici University, Istanbul, Turkey
17 Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
18 Department of Physics, Dogus University, Istanbul, Turkey
19 INFN Sezione di Bologna, Bologna, Italy
20 Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
23 Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
24 Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
25 Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
26 Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
28 National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj Napoca, Romania
29 West University in Timisoara, Timisoara, Romania
30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
32 Department of Physics, Carleton University, Ottawa, Ontario, Canada
33 Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
34 INFN, Geneva, Switzerland
35 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
36 Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
37 Instituto de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
38 Institute of Modern Physics, Chinese Academy of Sciences, Beijing, China
39 Department of Modern Physics, University of Science and Technology of China, Anhui, China
40 Department of Physics, Nanjing University, Jiangsu, China
41 School of Physics, Shandong University, Shandong, China
42 Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China
43 Physics Department, Tsinghua University, Beijing 100084, China
44 Laboratoire de Physique Corpusculaire, Clermont Université
45 and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
46 Nevis Laboratory, Columbia University, Irvington, New York, USA
47 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
48 INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy
49 Dipartimento di Fisica, Università della Calabria, Rende, Italy
50 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
51 Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

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Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut 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
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
DESY, Hamburg and Zeuthen, Germany
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Department of Physics, The University of Hong Kong, Hong Kong, China
Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, Indiana University, Bloomington, Indiana, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
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
INFN Sezione di Lecce, Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jožef Stefan Institute and 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, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston LA, United States of America
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lund unversitet, Lund, Sweden
Departamento de Física Teorica C-15, Universidad Autonoma 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 and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal, Québec, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
INFN Sezione di Milano, Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Group of Particle Physics, University of Montreal, Montreal, Québec, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), 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

INFN Sezione di Napoli, Napoli, Italy

Dipartimento di Fisica, Università di Napoli, Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

Department of Physics, Northern Illinois University, DeKalb, Ilioninois, USA

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

Department of Physics, New York University, New York, New York, USA

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, RCPTM, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA

LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

Graduate School of Science, Osaka University, Osaka, Japan

Department of Physics, University of Oslo, Oslo, Norway

Department of Physics, Oxford University, Oxford, United Kingdom

INFN Sezione di Pavia, Pavia, Italy

Dipartimento di Fisica, Università di Pavia, Pavia, Italy

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia

INFN Sezione di Pisa, Pisa, Italy

Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal

Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

Department of Physics, University of Coimbra, Coimbra, Portugal

Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

Departamento de Física, Universidade do Minho, Braga, Portugal

Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain), Portugal

Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

Czech Technical University in Prague, Praha, Czech Republic

Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic

State Research Center Institute for High Energy Physics, Protvino, Russia

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

INFN Sezione di Roma, Roma, Italy

Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy

INFN Sezione di Roma Tor Vergata, Roma, Italy

Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

INFN Sezione di Roma Tre, Roma, Italy

Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco

Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco

Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco