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, Aléjandro; 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 $f_s/f_d$ in $pp$ Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

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With an integrated luminosity of 2.47 fb$^{-1}$ recorded by the ATLAS experiment at the LHC, the exclusive decays $B_s^0 \to J/\psi K^0$ and $B_d^0 \to J/\psi K^0$ 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 $B_s^0 \to J/\psi K^0$ and $B_d^0 \to J/\psi K^0$ yields, the quantity $(f_s/f_d)[B(B_s^0 \to J/\psi K^0)/B(B_d^0 \to J/\psi K^0)]$ is measured to be $0.199 \pm 0.004$(stat)$\pm 0.008$(syst). Using a recent theory prediction for $[B(B_s^0 \to J/\psi K^0)/B(B_d^0 \to J/\psi K^0)]$ yields $(f_s/f_d) = 0.240 \pm 0.004$(stat)$\pm 0.010$(syst)$\pm 0.017$(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 $B_s^0$ ($B_d^0$) 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 $B_s^0$ ($B_d^0$) 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 $B_s^0 \to \mu^+\mu^-$ [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 $B_s^0 \to J/\psi K^0$ and $B_d^0 \to J/\psi K^0$ decays.

The ratio of fragmentation fractions $f_s/f_d$ is extracted from the measured $B_s^0 \to J/\psi K^0$ and $B_d^0 \to J/\psi K^0$ signal yields, $N_{B_s^0}$ and $N_{B_d^0}$. These are converted into $B_s^0$ and $B_d^0$ 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:

$$\frac{f_s}{f_d} = \frac{N_{B_s^0} B(B_s^0 \to J/\psi K^0) B(K^0 \to K^+\pi^-)}{N_{B_d^0} B(B_d^0 \to J/\psi K^0) B(\phi \to K^-K^+)} \mathcal{R}_{\text{eff}},$$

(1)

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 $B_s^0 \to J/\psi K^0$ and $B_d^0 \to J/\psi K^0$ 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

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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 $B^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^{*0}$ 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 $B^0$ 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 $p_T(B^0) > 8$ 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 $B^0 \to J/\psi\phi$ produces a peaking background in $B^0 \to J/\psi K^{*0}$ 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 $B^0 \to J/\psi\phi$ and $B^0_d \to J/\psi K^{*0}$ 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, $\sum_i p_T^2$, yields the highest value. The $\chi^2$/dof, $L_{xy}$ and $\alpha$ selection criteria are optimized using simulated $B^0_d \to J/\psi\phi$ and $B^0 \to J/\psi K^{*0}$ 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 $B^0 \to J/\psi\phi$ ($B^0_d \to J/\psi K^{*0}$) $p_T$ 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:

$$W_{ij}(p_T, \eta) = \frac{n_{i}^{\text{data/MC}(p_T)}}{n_{i}^{\text{MC}(p_T)}} \frac{n_{j}^{\text{data}(\eta)}}{n_{j}^{\text{MC}(\eta)}},$$

where $n_{i}^{\text{data/MC}(p_T)}$ is the normalized number of entries in the $p_T$ bin $i$ and $n_{j}^{\text{data/MC}(\eta)}$ 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 $B^0 \to (B^0_d)^*$ 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 $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K^+\pi^-$ contribute to $B^0 \to J/\psi \phi$, while $B^0 \to J/\psi K^+\pi^-$ also contributes to $B^0 \to J/\psi K^{*0}$.

To reduce these backgrounds, the $\chi^2$/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 $B^0 (B^0')$ mode, the optimization yields $\chi^2$/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 $\chi^2$/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 $N_{B^0}$ and $N_{B^0'}$ are extracted from unbinned extended maximum-likelihood fits to the $J/\psi K^+K^-$ and $J/\psi K^+\pi^-$ invariant-mass spectra, respectively. The $B^0$ 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 $B^0$ 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 $B^0$ 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 $B^0 \to J/\psi K^+\pi^-$ yield with respect to that of the $B^0 \to J/\psi K^{*0}$ 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 $N_{B^0} = 6640 \pm 100$ $B^0 \to J/\psi \phi$ and $N_{B^0'} = 36290 \pm 320$ $B^0 \to J/\psi K^{*0}$ signal events. The $\chi^2$/dof values of the fits are 0.959 for $B^0$ and 0.945 for $B^0'$, indicating that both fits describe the data well.

The additive systematic uncertainties result from the $B^0 \to J/\psi \phi$ and $B^0 \to J/\psi K^{*0}$ 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 $B^0$ and with a second-order polynomial plus an error function for the $B^0'$. The difference in signal yield with respect to the nominal fit is taken as a systematic error. For peaking backgrounds, the

FIG. 1 (color online). The invariant-mass spectra of $B^0 \to J/\psi \phi$ (left panel) and $B^0 \to J/\psi K^{*0}$ decays (right panel) for data (points with error bars), total fit (solid line), signal (dashed line), residual background (yellow shaded), partially reconstructed events (magenta shaded) and peaking background (blue shaded).
fixed parameters are varied by ±1σ, and the difference with respect to the nominal yield is taken as a systematic error. In addition, since S-wave contributions from \( B^0 \rightarrow J/\psi K^+ K^- \) and \( B^0_s \rightarrow J/\psi f_0(980) \) decays to \( B^0_s \rightarrow J/\psi \phi \) and \( B^0_d \rightarrow J/\psi K^{*0} \) are neglected in the fits, an uncertainty is derived using the ATLAS measured contribution of 2.4% [22] for \( B^0 \rightarrow J/\psi \phi \), and the contribution of 1% for \( B^0_s \rightarrow J/\psi K^{*0} \) derived from the MC simulation. All additive systematic errors are added in quadrature, yielding total additive uncertainties of 220 \( N_{B^0} \) and 650 \( N_{B^0} \) 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 ±1σ 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 \( \chi^2 / \text{dof}, L_{xy} \) 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

\[
\frac{f_s}{f_d} \frac{\mathcal{B}(B^0_s \rightarrow J/\psi \phi)}{\mathcal{B}(B^0_d \rightarrow J/\psi K^{*0})} = 0.199 \pm 0.004(\text{stat}) \pm 0.008(\text{syst}) .
\]

A perturbative QCD prediction [23] yields

\[
\frac{\mathcal{B}(B^0_s \rightarrow J/\psi \phi)}{\mathcal{B}(B^0_d \rightarrow J/\psi K^{*0})} = 0.83^{+0.03} \omega_B^{+0.01} f_M^{+0.02} a_1^{+0.01} (m_c),
\]

where the uncertainties result from the shape parameter \( \omega_B \) of the \( B \) meson wave function, meson decay constants \( f_M \), Gegenbauer moments \( a_1 \) 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

\[
\frac{f_s}{f_d} = 0.240 \pm 0.004(\text{stat}) \pm 0.010(\text{syst}) \pm 0.017(\text{th}).
\]

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

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<th>Observable</th>
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<tr>
<td>( N_{B^0} )</td>
<td>6640 ± 100 ± 220</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>( N_{B^0} )</td>
<td>36290 ± 320 ± 650</td>
<td>1.8%</td>
<td></td>
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<tr>
<td>( \mathcal{R}_{\text{eff}} )</td>
<td>0.799 ± 0.001 ± 0.010</td>
<td>1.3%</td>
<td></td>
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<tr>
<td>( \mathcal{B}(\phi \rightarrow K^+ K^-) )</td>
<td>0.489 ± 0.005</td>
<td>1.0%</td>
<td>[15]</td>
</tr>
<tr>
<td>( \mathcal{B}(K^{*0} \rightarrow 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>
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FIG. 2 (color online). (Left panel) Measurements of \( f_s / f_d \) versus \( B \) meson \( p_T \) for CDF [7], LHCb [8], and ATLAS, where the ATLAS data points are plotted at the average \( p_T \) of the events in each bin. The error bars show statistical and systematic errors added in quadrature. The LEP ratio, taken from Ref. [6], is plotted at an average \( p_T \) value in \( Z \) decays. (Right panel) Measurements of \( f_s / f_d \) (black and blue points with error bars) from LEP [6], CDF [6], LHCb [8,9], and ATLAS. The total experimental error (thin black line) is added linearly to the theory error (thick red line). The green-shaded region shows the HFAG average obtained using the blue points.
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 $8 \text{ GeV} < p_T < 50 \text{ GeV}$ 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 $B_S^0 \rightarrow J/\psi \phi$ and $B_d^0 \rightarrow J/\psi K^{*0}$ 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 $pp$ collisions at $\sqrt{s} = 7 \text{ TeV}$ 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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[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.

[22] ATLAS Collaboration, Flavour tagged time-dependent angular analysis of the $B^0_s \rightarrow J/\psi \phi$ decay and extraction of $\Delta \Gamma$, and the weak phase $\phi_3$ in ATLAS, Phys. Rev. D 90, 052007 (2014).

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<thead>
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<th>Institution</th>
<th>Location</th>
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<tbody>
<tr>
<td>1. Department of Physics, University of Adelaide, Adelaide, Australia</td>
<td>Adelaide, Australia</td>
</tr>
<tr>
<td>2. Physics Department, SUNY Albany, Albany, New York, USA</td>
<td></td>
</tr>
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<td>8. High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA</td>
<td>Argonne, Illinois, USA</td>
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<td>9. Department of Physics, University of Arizona, Tucson, Arizona, USA</td>
<td>Tucson, Arizona, USA</td>
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<td>10. Division of Physics, The University of Texas at Arlington, Arlington, Texas, USA</td>
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<td>11. Physics Department, University of Athens, Athens, Greece</td>
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<td>12. Physics Department, National Technical University of Athens, Zografou, Greece</td>
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<td>13. Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan</td>
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<td>14. University of Belgrade, Belgrade, Serbia</td>
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<td>15. Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA</td>
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<td>16. Department of Physics and Technology, University of Bergen, Bergen, Norway</td>
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<td>17. Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland</td>
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<td>18. School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom</td>
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<td>19. Bogazici University, Istanbul, Turkey</td>
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<td>20. Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey</td>
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<td>21. Department of Physics, Dogus University, Istanbul, Turkey</td>
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<td>24. Physikalisches Institut, University of Bonn, Bonn, Germany</td>
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<td>25. Department of Physics, Boston University, Boston, Massachusetts, USA</td>
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<td>28. Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil</td>
<td>Juiz de Fora, Brazil</td>
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<td>29. Federal University of Sao Joao del Rei (UFJ), Sao Joao del Rei, Brazil</td>
<td>Sao Joao del Rei, Brazil</td>
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<td>30. Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil</td>
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<td>31. Physics Department, Brookhaven National Laboratory, Upton, New York, USA</td>
<td>Upton, New York, USA</td>
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<td>32. National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj Napoca, Romania</td>
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<td>33. University Politehnica Bucharest, Bucharest, Romania</td>
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<td>34. West University in Timisoara, Timisoara, Romania</td>
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<td>35. Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina</td>
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<td>36. Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom</td>
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<td>37. Department of Physics, Carleton University, Ottawa, Ontario, Canada</td>
<td>Ottawa, Ontario, Canada</td>
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<td>38. CERN, Geneva, Switzerland</td>
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<td>39. Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA</td>
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<td>40. Pontificia Universidad Católica de Chile, Santiago, Chile</td>
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<td>41. Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile</td>
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<tr>
<td>42. Institute of Modern Physics, Chinese Academy of Sciences, Beijing, China</td>
<td>Beijing, China</td>
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<tr>
<td>43. Department of Physics, Nanjing University, Jiangsu, China</td>
<td>Jiangsu, China</td>
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<td>44. School of Physics, Shandong University, Shandong, China</td>
<td>Shandong, China</td>
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<tr>
<td>45. Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China</td>
<td>Shanghai, China</td>
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<tr>
<td>46. Physics Department, Tsinghua University, Beijing 100084, China</td>
<td>Beijing, China</td>
</tr>
<tr>
<td>47. Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France</td>
<td>Clermont-Ferrand, France</td>
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<td>48. Nevis Laboratory, Columbia University, Irvington, New York, USA</td>
<td>Irvington, New York, USA</td>
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<tr>
<td>49. Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark</td>
<td>Copenhagen, Denmark</td>
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<tr>
<td>50. INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy</td>
<td>Frascati, Italy</td>
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<tr>
<td>51. Dipartimento di Fisica, Università della Calabria, Rende, Italy</td>
<td>Rende, Italy</td>
</tr>
<tr>
<td>52. AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland</td>
<td>Krakow, Poland</td>
</tr>
<tr>
<td>53. Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland</td>
<td>Krakow, Poland</td>
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</tbody>
</table>

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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
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Department of Physics, University of Texas at Dallas, Richardson, Texas, USA
Physics Department, Southern Methodist University, Dallas, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Physik, Universität Leipzig, Leipzig, Germany
INFN Sezione di Genova, Genova, Italy
Department of Physics, The 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
Department of Physics, Leopold-Franzens-Universität Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyushu University, Fukuoka, 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
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, Lunds universitet, 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
Also at Department of Physics, California State University, Fresno CA, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
Also at Tomsk State University, Tomsk, Russia.
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at Universita di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Louisiana Tech University, Ruston LA, USA.
Also at Institucio Catalana de Recerca i Estudis Avancats, ICRAE, Barcelona, Spain.
Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Department of Physics, National Tsing Hua University, Taiwan.
Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Georgian Technical University (GTU), Tbilisi, Georgia.
Also at Manhattan College, New York NY, USA.
Also at Hellenic Open University, Patras, Greece.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at School of Physics, Shandong University, Shandong, China.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at International School for Advanced Studies (SISSA), Trieste, Italy.
Also at School of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Department of Physics, Stanford University, Stanford CA, USA.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.