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

The ATLAS Collaboration

Abstract

With an integrated luminosity of 2.47 fb$^{-1}$ recorded by the ATLAS experiment at the LHC, the exclusive decays $B^0_s \to J/\psi \phi$ and $B^0_d \to J/\psi K^{*0}$ 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 $B^0_s \to J/\psi \phi$ and $B^0_d \to J/\psi K^{*0}$ yields, the quantity $\frac{f_s}{f_d} \frac{B(B^0_s \to J/\psi \phi)}{B(B^0_d \to J/\psi K^{*0})}$ is measured to be $0.199 \pm 0.004({\text{stat}}) \pm 0.008({\text{sys}})$. Using a recent theory prediction for $\frac{B(B^0_s \to J/\psi \phi)}{B(B^0_d \to J/\psi K^{*0})}$ yields $\frac{f_s}{f_d} = 0.240 \pm 0.004({\text{stat}}) \pm 0.010({\text{sys}}) \pm 0.017({\text{th}})$. This result is based on a new approach that provides a significant improvement of the world average.
The production rate of $B_s^0$ ($B_d^0$) mesons is a product of the $b\bar{b}$ 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, $B_c$ mesons and $b$-baryons are produced at the LHC with respective fragmentation fractions $f_{u\bar{u}}, f_c$ and $f_{b\text{baryon}}$. 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 $f_u + f_d + f_s + f_c + f_{b\text{baryon}} = 1$. 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 $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ decays.

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

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

where the $J/\psi$, $\phi$ and $K^{*0}$ are reconstructed in their $s\bar{s}$ ($d\bar{d}$) 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 $2.47 \pm 0.04$ 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 $B_s^0 \to J/\psi\phi$ 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 vertex fit chi-square per degree of freedom (dof) is required to be $\chi^2/\text{dof} < 10$. 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 endcaps ($1.05 < |\eta| < 2.5$) 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 endcap and one barrel muon (EB), and two endcap muons (EE). The parameters describing the dimuon mass distribution in the $J/\psi$ signal region for the three pseudorapidity classes in data and in $B_d^0 \rightarrow J/\psi\phi$ and $B_d^0 \rightarrow J/\psi K^{*0}$ MC signal samples are extracted from maximum-likelihood fits. Signal events are selected requiring mass windows of ±3σ 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 $B_s^0$ 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 $p_T(B_s^0) > 8$ GeV, $\chi^2/\text{dof} < 3$ for the vertex fit and the $K^+K^-$ invariant mass lies in the range determined by ±3 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 $B_d^0$ 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 $B_d^0 \rightarrow J/\psi\phi$ produces a peaking background in $B_d^0 \rightarrow J/\psi K^{*0}$ 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 $B_s^0 \rightarrow J/\psi\phi$ and $B_d^0 \rightarrow J/\psi K^{*0}$ decays are optimized using three variables with high background suppression power: the $\chi^2/\text{dof}$ 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 $\chi^2/\text{dof}$, $L_{xy}$ and $\alpha$ selection criteria are optimized using simulated $B_d^0 \rightarrow J/\psi\phi$ and $B_d^0 \rightarrow J/\psi K^{*0}$ 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 $B_d^0 \rightarrow J/\psi\phi$ ($B_d^0 \rightarrow J/\psi K^{*0}$) $p_T$ 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:

\[
W_{i,j}(p_T, \eta) = \frac{n_{i,j}^{\text{data}(p_T)}}{n_{i,j}^{\text{MC}(p_T)}} \times \frac{n_{i,j}^{\text{data}(\eta)}}{n_{i,j}^{\text{MC}(\eta)}},
\]

where \( n_{i,j}^{\text{data}(p_T)} \) is the normalized number of entries in the \( p_T \) bin \( i \) and \( n_{i,j}^{\text{data}(\eta)} \) 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 \( \chi^2/\text{dof}, L_{xy} \) and \( \alpha \) are determined that are in good agreement with those measured in the data. The correlation between \( p_T \) and \( \eta \) 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 \( B_s^0 (B_d^0) \) 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 \( B \rightarrow J/\psi X \) 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 \( \phi (K^{0\ast}) \) decay are replaced with random hadrons is negligible. In addition, peaking backgrounds from \( B_s^0 \rightarrow J/\psi K^{0\ast} \) and \( B_d^0 \rightarrow J/\psi K^+ \pi^- \) contribute to \( B_s^0 \rightarrow J/\psi \phi \) while \( B_s^0 \rightarrow J/\psi K^+ \pi^- \) also contributes to \( B_d^0 \rightarrow J/\psi K^0\).

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 \( N_{B_d^0} \) and \( N_{B_s^0} \) are extracted from unbinned extended maximum-likelihood fits to the \( J/\psi K^+ K^- \) and \( J/\psi K^+ \pi^- \) invariant-mass spectra, respectively. The \( B_s^0 \) 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 \( 652 \pm 93 \) 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 \( B_d^0 \rightarrow J/\psi K^+ \pi^- \) 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 parameterization 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 $N_{B^0_{J/\psi \phi}} = 6640 \pm 100$ $B^0_{J/\psi \phi}$ and $N_{B^0_{J/\psi K^{*0}}} = 36290 \pm 320$ $B^0_{J/\psi K^{*0}}$ signal events. The $\chi^2$/dof values of the fits are 0.959 for $B^0_{J/\psi \phi}$ and 0.945 for $B^0_{J/\psi K^{*0}}$ indicating that both fits describe the data well.

The additive systematic uncertainties result from the $B^0_{J/\psi \phi}$ and $B^0_{J/\psi K^{*0}}$ signal and background parameterizations. The contribution from the signal shape parameterization is calculated by varying the five fixed parameters within $\pm 1\sigma$ in a multivariate Gaussian function that takes into account all correlations. For non-peaking backgrounds, the exponential function is replaced with a second-order polynomial for the $B^0_{J/\psi \phi}$ and with a second-order polynomial plus an error function for the $B^0_{J/\psi K^{*0}}$. The difference in signal yield with respect to the nominal fit is taken as a systematic error. For peaking backgrounds, the fixed parameters are varied by $\pm 1\sigma$ and the difference with respect to the nominal yield is taken as a systematic error. In addition, since S-wave contributions from $B^0_{J/\psi \phi}$ and $B^0_{J/\psi K^{*0}}$ decays to $B^0_{J/\psi \phi}$ and $B^0_{J/\psi K^{*0}}$ are neglected in the fits, an uncertainty is derived using the ATLAS measured contribution of $2.4\%$ [22] for $B^0_{J/\psi \phi}$ and the contribution of $1\%$ for $B^0_{J/\psi K^{*0}}$ derived from the MC simulation. All additive systematic errors are added in quadrature, yielding total additive uncertainties of 220 $N_{B^0_{J/\psi \phi}}$ and 650 $N_{B^0_{J/\psi K^{*0}}}$ 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 $\pm 1\sigma$ and adding all contributions in quadrature. Other uncertainties from the $J/\psi$ selection (0.2%), reweighting (0.4%), $B^0_{J/\psi \phi}$ and $B^0_{J/\psi K^{*0}}$ 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 1 summarizes the contributions of the additive and multiplicative systematic errors.
Table 1: Measured $B_s^0$ and $B_d^0$ 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 $f_s$, $\frac{B(B_s^0 \to J/\psi \phi)}{B(B_d^0 \to J/\psi K^{*0})}$.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value</th>
<th>$\sigma$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{B_s^0}$</td>
<td>6640 ± 100 ± 220</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>$N_{B_d^0}$</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% [15]</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(K^{*0} \to K^+ \pi^-)$</td>
<td>0.66503 ± 0.00014</td>
<td>0.02% [15]</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

$$\frac{f_s}{f_d} \frac{\mathcal{B}(B_s^0 \to J/\psi \phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.199 \pm 0.004(\text{stat}) \pm 0.008(\text{sys}). \quad (3)$$

A perturbative QCD prediction [23] yields

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

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

$$\frac{f_s}{f_d} = 0.240 \pm 0.004(\text{stat}) \pm 0.010(\text{sys}) \pm 0.017(\text{th}). \quad (4)$$

Figure 2 (right) 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) shows the $p_T$ dependence of $f_s/f_d$ for ATLAS and that of other experiments. To investigate the $p_T$ and $\eta$ dependences 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 $B_s^0 \to J/\psi \phi$ and $B_d^0 \to J/\psi K^{*0}$ 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 $\sqrt{s} = 7 \text{ TeV}$ 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.
Figure 2: (Left) 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) 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) is added linearly to the theory error (thick red). The green-shaded region shows the HFAG average obtained using the blue points.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.
References


[10] Charge conjugation is implied unless stated otherwise.


ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre 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 \(\eta = -\ln \tan(\theta/2)\).

T. Skwarnicki,

The PV is the parton interaction vertex: the one of interest is that where the B meson is produced.

ATLAS Collaboration, Measurement of the differential cross-sections of inclusive, prompt and non-prompt \(J/\psi\) production in proton-proton collisions at \(\sqrt{s} = 7\) TeV, 

ATLAS Collaboration, Flavour tagged time-dependent angular analysis of the \(B_s^0 \to J/\psi \phi\) decay and extraction of \(\Delta \Gamma_s\) and the weak phase \(\phi_s\) in ATLAS, Phys. Rev. D 90 (2014) 052007, arXiv:1407.1796 [hep-ex].

X. Liu, W. Wang and Y. Xie, Penguin Pollution in \(B_s^0 \to J/\psi V\) Decays and Impact on the Extraction of the \(B_s^0\) – \(\bar{B}_s^0\) mixing phase. arXiv:1309.0313v2 [hep-ph] for this version, 
The ATLAS Collaboration

Department of Physics, University of Arizona, Tucson AZ, United States of America
Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
Physics Department, University of Athens, Athens, Greece
Physics Department, National Technical University of Athens, Zografou, Greece
Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
Institute of Physics, University of Belgrade, Belgrade, Serbia
Department for Physics and Technology, University of Bergen, Bergen, Norway
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
Department of Physics, Humboldt University, 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
(a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Dogus University, Istanbul, Turkey
INFIN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Boston University, Boston MA, United States of America
Department of Physics, Brandeis University, Waltham MA, United States of America
(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa ON, Canada
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington NY, United States of America
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Department of Physics, Kyushu University, Fukuoka, Japan
71 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
72 Physics Department, Lancaster University, Lancaster, United Kingdom
73 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
75 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
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
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 Fisica 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 MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
INFN Sezione di Milano; 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 MA, United States of America
Group of Particle Physics, University of Montreal, Montreal QC, 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; Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
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 IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK,
| 114 | United States of America Department of Physics, Oklahoma State University, Stillwater OK, United States of America |
| 115 | Czech Republic Palacký University, RCPTM, Olomouc, Czech Republic |
| 116 | United States of America Center for High Energy Physics, University of Oregon, Eugene OR, United States of America |
| 117 | France LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France |
| 118 | Japan Graduate School of Science, Osaka University, Osaka, Japan |
| 119 | Norway Department of Physics, University of Oslo, Oslo, Norway |
| 120 | United Kingdom Department of Physics, Oxford University, Oxford, United Kingdom |
| 121 | Italy INFN Sezione di Pavia; Dipartimento di Fisica, Università di Pavia, Pavia, Italy |
| 122 | United States of America Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America |
| 123 | Russia National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia |
| 124 | Italy INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy |
| 125 | United States of America Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America |
| 126 | Portugal Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; Faculdade de Ciências, Universidade de Lisboa, Lisboa; Department of Physics, University of Coimbra, Coimbra; Centro de Física Nuclear da Universidade de Lisboa, Lisboa; Departamento de Física, Universidade do Minho, Braga; Departamento de Física Teorica y del Cosmos and CAPE, Universidad de Granada, Granada (Spain); Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal |
| 127 | Czech Republic Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic |
| 128 | Czech Republic Czech Technical University in Prague, Prague, Czech Republic |
| 129 | Czech Republic Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic |
| 130 | Russia State Research Center Institute for High Energy Physics, Protvino, Russia |
| 131 | United Kingdom Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom |
| 132 | Italy INFN Sezione di Roma; Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy |
| 133 | Italy INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy |
| 134 | Italy INFN Sezione di Roma Tre; Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy |
| 135 | Morocco Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; Centre National de l’Énergie des Sciences Techniques Nucleaires, Rabat; Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco |
| 136 | France DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Énergie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France |
| 137 | United States of America Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America |
| 138 | United States of America Department of Physics, University of Washington, Seattle WA, United States of America |
| 139 | United Kingdom Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom |
| 140 | Japan Department of Physics, Shinshu University, Nagano, Japan |
| 141 | Germany Fachbereich Physik, Universität Siegen, Siegen, Germany |
| 142 | Canada Department of Physics, Simon Fraser University, Burnaby BC, Canada |
| 143 | United States of America SLAC National Accelerator Laboratory, Stanford CA, United States of America |
| 144 | Slovakia Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; Department of Mathematics, Physics & Informatics, Comenius University, Bratislava |
of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

145 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

147 Physics Department, Royal Institute of Technology, Stockholm, Sweden

148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

150 School of Physics, University of Sydney, Sydney, Australia

151 Institute of Physics, Academia Sinica, Taipei, Taiwan

152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

158 Department of Physics, University of Toronto, Toronto ON, Canada

159 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

160 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

161 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

164 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

165 Department of Physics, University of Illinois, Urbana IL, United States of America

166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMM), University of Valencia and CSIC, Valencia, Spain

168 Department of Physics, University of British Columbia, Vancouver BC, Canada

169 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

170 Department of Physics, University of Warwick, Coventry, United Kingdom

171 Waseda University, Tokyo, Japan

172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

173 Department of Physics, University of Wisconsin, Madison WI, United States of America

174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

175 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

176 Department of Physics, Yale University, New Haven CT, United States of America

177 Yerevan Physics Institute, Yerevan, Armenia

178 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

24