ATLAS Results with Beauty Mesons

Ann-Kathrin Perrevoort[1]⋆, on behalf of the ATLAS Collaboration

1 Nikhef, Amsterdam, The Netherlands
* ann-kathrin.perrevoort@cern.ch

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Abstract

A broad range of measurements involving B mesons are performed with the ATLAS experiment at the Large Hadron Collider, of which a selection is discussed in this note. This includes a measurement of the relative $B_c^\pm$ to $B^\pm$ production cross section in pp collisions at a centre-of-mass energy $\sqrt{s}$ of 8 TeV, as well as the latest results on the branching ratios of the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ using pp collisions recorded at $\sqrt{s} = 7$, 8 and 13 TeV. Furthermore, accurate measurements of mixing and CP violation in $B_s^0 \to J/\psi\,\phi$ decays are performed. The latest results on the CP violating phase ϕ_s and other parameters describing the decay obtained at $\sqrt{s} = 7$, 8 and 13 TeV are reported.

1 Introduction

In measurements of the production and decay of b-hadrons, predictions of the Standard Model (SM), for example on hadronization or CP violation, can be tested with high precision and contributions of physics beyond the SM can be investigated. The ATLAS experiment [1] at the Large Hadron Collider (LHC) [2] conducts a rich B physics program. In the following, measurements of the relative $B_c^\pm/B^\pm$ production cross section, the branching ratio of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ and the CP violating phase in $B_s^0 \to J/\psi\,\phi$ decays are presented.

2 Relative production cross sections of $B_c^\pm$ and $B^\pm$ mesons

The $B_c^\pm$ meson is a bound state of a c- and a b-quark, the two heaviest quarks that can form a stable state. With measurements of the production of $B_c^\pm$ mesons, heavy-quark hadronisation can be studied. In ATLAS, the total and differential cross section times branching ratio of $B_c^\pm \to J/\psi\,\pi^\pm$ relative to $B^\pm \to J/\psi\,K^\pm$ is measured using 20.3 fb^{-1} of pp collision data recorded in 2012 at a centre-of-mass energy of 8 TeV [3].

Events are selected with di-muon triggers for $J/\psi \to \mu^+\mu^-$ decays. At first, J/ψ candidates are reconstructed by means of a vertex fit of opposite-charge muon pairs. $B_c^\pm$ ($B^\pm$) candidates are then reconstructed in a vertex fit of the J/ψ candidate and a charged hadron track in which the mass of the J/ψ candidate is constrained to the world average value and the $\pi^\pm$ ($K^\pm$) mass is assigned to the hadron track. The hadron track is required to have a transverse momentum

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Table 1: Summary of the measured production cross section times branching ratio for $B_c^\pm \to J/\psi\,\pi^\pm$ relative to $B^\pm \to J/\psi\,K^\pm$ in the respective analysis bins [3].

Analysis bin		$\sigma(B_c^\pm)/\sigma(B^\pm) \cdot \mathcal{B}(B_c^\pm \to J/\psi\,\pi^\pm)/\mathcal{B}(B^\pm \to J/\psi\,K^\pm)$
$p_{\mathrm{T}}\left(B_{(c)}^\pm\right) > 13\,\mathrm{GeV}$	$\left\|y\left(B_{(c)}^\pm\right)\right\| < 2.3$	$(0.34 \pm 0.04_{\,\mathrm{stat}}\,{}^{+0.06}_{-0.02}\,{}_{\mathrm{syst}} \pm 0.01_{\mathrm{lifetime}})\%$
$13\,\mathrm{GeV} < p_{\mathrm{T}}\left(B_{(c)}^\pm\right) < 22\,\mathrm{GeV}$	$\left\|y\left(B_{(c)}^\pm\right)\right\| < 2.3$	$(0.44 \pm 0.07_{\,\mathrm{stat}}\,{}^{+0.09}_{-0.04}\,{}_{\mathrm{syst}} \pm 0.01_{\mathrm{lifetime}})\%$
$p_{\mathrm{T}}\left(B_{(c)}^\pm\right) > 22\,\mathrm{GeV}$	$\left\|y\left(B_{(c)}^\pm\right)\right\| < 2.3$	$(0.24 \pm 0.04_{\,\mathrm{stat}}\,{}^{+0.05}_{-0.01}\,{}_{\mathrm{syst}} \pm 0.01_{\mathrm{lifetime}})\%$
$p_{\mathrm{T}}\left(B_{(c)}^\pm\right) > 13\,\mathrm{GeV}$	$\left\|y\left(B_{(c)}^\pm\right)\right\| < 0.75$	$(0.38 \pm 0.06_{\,\mathrm{stat}}\,{}^{+0.05}_{-0.04}\,{}_{\mathrm{syst}} \pm 0.01_{\mathrm{lifetime}})\%$
$p_{\mathrm{T}}\left(B_{(c)}^\pm\right) > 13\,\mathrm{GeV}$	$0.75 < \left\|y\left(B_{(c)}^\pm\right)\right\| < 2.3$	$(0.29 \pm 0.05_{\,\mathrm{stat}}\,{}^{+0.07}_{-0.02}\,{}_{\mathrm{syst}} \pm 0.01_{\mathrm{lifetime}})\%$

of $p_{\mathrm{T}} > 2\,\mathrm{GeV}$ and to not be identified as a muon in the muon spectrometer. Events with a $\chi^2/\mathrm{ndf} < 1.8$ of the $B_{(c)}^\pm$ vertex fit are considered. If multiple $B_{(c)}^\pm$ candidates are reconstructed in an event, the one with the best χ^2 is selected.

Backgrounds arise from combinations of J/ψ decays with light hadrons not associated with the $B_{(c)}^\pm$ decay, as well as partially reconstructed semi-leptonic b-hadron decays, for example $B_c^\pm \to J/\psi\,\mu^\pm\nu_\mu$, as well as the Cabibbo-suppressed $B^\pm \to J/\psi\,\pi^\pm$ decay. The former is suppressed by requiring the significance of the impact parameter of the hadron track relative to the primary vertex in the transverse plane to exceed 1.2.

The relative production ratio times branching ratio is measured double-differentially in two bins of the transverse momentum $p_{\mathrm{T}}(B_{(c)}^\pm)$ and two bins of rapidity $y(B_{(c)}^\pm)$ of the reconstructed $B_{(c)}^\pm$ in a fiducial volume constrained by $p_{\mathrm{T}}(B_{(c)}^\pm) > 13\,\mathrm{GeV}$ and $|y(B_{(c)}^\pm)| < 2.3$:

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

The number N^{reco} of reconstructed $B_{(c)}^\pm$ is extracted in an extended unbinned maximum-likelihood fit to the invariant $B_{(c)}^\pm$ mass distributions after selection. The likelihood function comprises contributions from signal and background from partially reconstructed b-hadron decays, combinatorial background and $B^\pm \to J/\psi\,\pi^\pm$ decays. The efficiency terms ϵ are correcting for the efficiencies of the detector and trigger, the vertex reconstruction and the selection differences that arise from having a $\pi^\pm$ or a $K^\pm$ in the final state.

Besides statistical uncertainties, uncertainties on the $B_{(c)}^\pm$ lifetime and systematic uncertainties arising from detector effects, triggering and reconstruction, simulation sample sizes and reweighting, minimal selection criteria, and modelling of signal and backgrounds are considered in the fit.

The results are shown in Figure 1 and summarized in Table 1 for the differential and inclusive measurement in the full fiducial volume. The differential measurement suggests that the production cross section of $B_c^\pm$ is falling more rapidly with increasing p_{T} than the production cross section of $B^\pm$ while no significant dependence on the rapidity is observed.

3   Measurement of the branching ratios of $B_{(s)}^0 \to \mu^+\mu^-$

In the SM, the flavour-changing neutral current processes $b \to s\mu^+\mu^-$ are mediated via loop or box diagrams and thus occur at low rates. Rare B meson decays could however also receive contributions from potential physics beyond the SM, leading for example to modifications of the branching ratios.

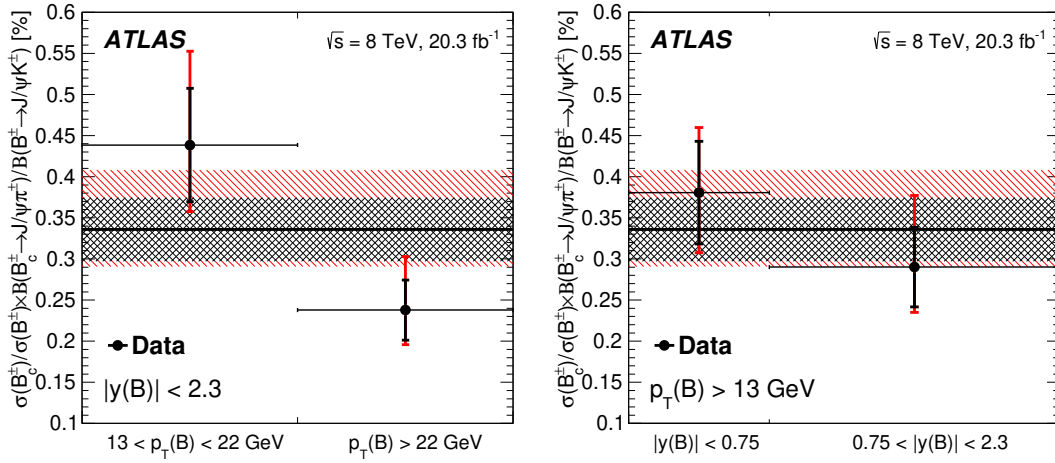The ATLAS experiment has performed a measurement of the branching ratios of $B^0 \to \mu^+\mu^-$

Figure 1: Measured production cross section times branching ratio for $B_c^\pm \to J/\psi\, \pi^\pm$ relative to $B^\pm \to J/\psi\, K^\pm$ [3]: (left) for two bins in $p_{\mathrm{T}}(B_{(c)}^\pm)$ (data points), and (right) two bins in rapidity $|y(B_{(c)}^\pm)|$ (data points). The inclusive bin is shown as horizontal band in both figures. The horizontal error bar on the data points indicates the bin width. The vertical inner error bars on the data points and the double hatched error band indicate the statistical uncertainty. The outer error bars and the single hatched error band indicate the size of the quadrature sum from all sources (statistical, systematic, lifetime).

and $B_s^0 \to \mu^+\mu^-$ using $36.2\,\mathrm{fb}^{-1}$ of pp collision data at $\sqrt{s} = 13\,\mathrm{TeV}$ collected in 2015 and 2016 [4]. The results are combined with a previous ATLAS measurement based on $25\,\mathrm{fb}^{-1}$ data at a $\sqrt{s}$ of 7 TeV and 8 TeV [5].

The data is collected using a di-muon trigger requiring a di-muon invariant mass $m_{\mu\mu}$ between 4 GeV and 8.5 GeV. Events are selected based on the quality of the reconstructed muons and the reconstructed $B_{(s)} \to \mu^+\mu^-$ vertex, and only considered in the analysis if the reconstructed invariant di-muon mass lies within 4.766 GeV and 5.966 GeV. The range of $m_{\mu\mu}$ between 5.166 GeV and 5.526 GeV is defined as signal region.

Backgrounds arise from partially reconstructed $b \to \mu^+\mu^-X$ decays, $B_{(s)}$ decays to hadrons mis-identified as muons, and continuum combinatorial background from muons of uncorrelated hadron decays. The latter is reduced with a boosted decision tree (BDT) that takes 15 variables into account and is trained and tested on data sidebands and simulated signal events. The $B_{(s)}^0 \to \mu^+\mu^-$ branching ratios are measured relative to the abundant and well-measured reference channel $B^\pm \to J/\psi(\to \mu^+\mu^-)K^\pm$. The yield in the reference channel is determined in an unbinned maximum likelihood fit to the invariant mass $m_{J/\psi K^\pm}$ of the $\mu^+\mu^-K^\pm$ system, while the efficiency relative to the signal decay $B_{(s)}^0 \to \mu^+\mu^-$ is taken from MC simulations.

An unbinned maximum likelihood fit to the $m_{\mu\mu}$ distribution is performed in four BDT intervals of constant signal efficiency to extract the signal yield. Due to the limited mass resolution, the peaks of $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ overlap and are statistically separated in the fit.

The results are combined with a previous ATLAS measurement based on $25\,\mathrm{fb}^{-1}$ data at $\sqrt{s}$ of 7 TeV and 8 TeV [5]. The branching ratio of the $B_s^0 \to \mu^+\mu^-$ decay is measured to be $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$, and an upper limit on the branching ratio of $B^0 \to \mu^+\mu^-$ decays is set at $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \cdot 10^{-10}$ at 95% CL. The likelihood contours are shown in the left plot in Figure 2. The results are combined with results obtained by the CMS and LHCb experiments with data collected between 2011 and 2016 [6]. The likelihood contours
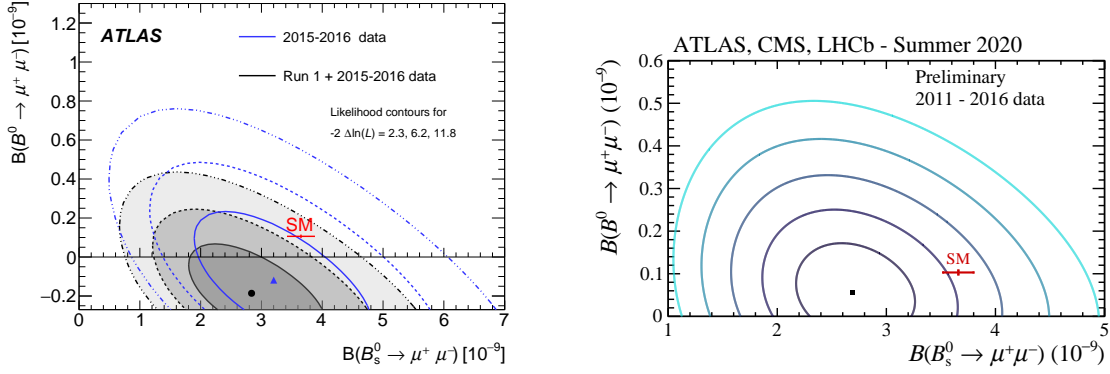
Figure 2: Likelihood contours for the results of the measurement of $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$. (Left) Contours of the ATLAS measurement for values of $-2\Delta\ln(\mathcal{L})$ equal to 2.3, 6.2, 11.8 [4]. (Right) Contours of the combination of the ATLAS, CMS, and LHCb results for values of $-2\Delta\ln(\mathcal{L})$ =2.3, 6.2, 11.8, 19.3, and 30.2 [6].

of the combination are shown in the right plot in Figure 2. The branching ratio of $B^0_s \to \mu^+\mu^-$ is measured to $\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$, and an upper limit on the $B^0 \to \mu^+\mu^-$ branching ratio is set at $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 1.9\cdot 10^{-10}$ at 95% CL.

4 Measurements of CP violation in $B^0_s \to J/\psi\,\phi$

The violation of the charge-parity symmetry (CPV) arises in $B^0_s \to J/\psi\,\phi$ decays through the interference of direct decays and decays with $B^0_s - \overline{B^0_s}$ mixing. The CP-violating phase ϕ_s is the weak phase difference between the $B^0_s - \overline{B^0_s}$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. In the SM, ϕ_s is determined by the elements of the quark mixing matrix and is predicted to be $\phi_s = -36.5^{+1.3}_{-1.2}$ mrad [7]. The size of CPV can be enhanced by physics beyond the SM. The $B^0_s - \overline{B^0_s}$ mixing is further characterized by the average decay width $\Gamma_s = \frac{1}{2}\left(\Gamma^s_L + \Gamma^s_H\right)$ and the width difference $\Delta\Gamma_s = \Gamma^s_L - \Gamma^s_H$ between the light (B_L) and heavy (B_H) mass eigenstates. The ATLAS experiment has performed a measurement of the decay parameters of the decay $B^0_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ using 80.5 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV recorded in 2015-2017 [8]. The results are combined with a previous ATLAS measurement based on 19.2 fb^{-1} of pp collision data recorded at $\sqrt{s}$ of 7 TeV and 8 TeV [9].

Events are selected with di-muon triggers for the $J/\psi \to \mu^+\mu^-$ signature. J/ψ candidates are reconstructed in a vertex fit of oppositely charged muon pairs. They need to have a $\chi^2/\text{ndf} < 10$ of the vertex fit and pass $|\eta(\mu)|$ dependent invariant mass cuts to ensure they are compatible with a $J/\psi \to \mu^+\mu^-$ decay. Similarly, a vertex fit is performed of oppositely charged track pairs with $p_T >1$ GeV and $|\eta| < 2.5$ that are not identified as muons in the muon spectrometer to reconstruct $\phi \to K^+K^-$ decays. These two pairs are fitted to a common B^0_s decay vertex with the di-muon invariant mass being constrained to the J/ψ mass and the $K^\pm$ mass being assigned to the hadron tracks. Events need to have a $\chi^2/\text{ndf} < 3$ of the B^0_s vertex fit and pass selections on the reconstructed invariant ϕ mass ($|m(K^+K^-)-m_{PDG}(\phi)| < 11$ MeV) and B^0_s mass (5.15 GeV $< m(B^0_s) < 5.65$ GeV) to be considered in the analysis. In the case of multiple B^0_s candidates in an event, the one with the best χ^2 is selected.

Since b-quarks are only produced in $b\bar{b}$ pairs, the initial flavour of the B^0_s candidate, i.e. B^0_s or $\overline{B^0_s}$, can be extracted from semi-leptonic decays of the other b-hadron in the event. A tagging probability is derived based on the p_T-weighted sum of the charge of tracks from the other
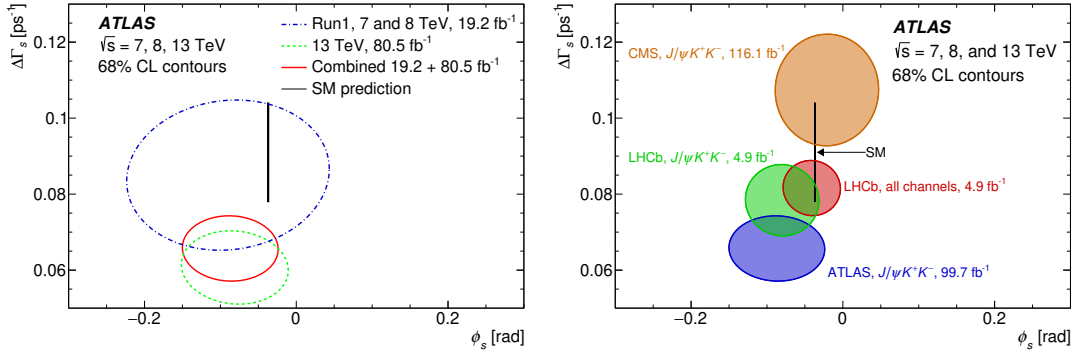
Figure 3: Contours of the 68% confidence level in the $\phi_s - \Delta\Gamma_s$ plane [8]. (Left) Comparison of the ATLAS results obtained with 7 TeV and 8 TeV data (blue dashed-dotted curve), 13 TeV data (green dashed curve), and their combination (red solid line). (Right) Comparison of the combined ATLAS results (blue) to results from CMS (red) and LHCb (green). In both figures, the SM prediction is shown as a black rectangle [7, 10]. In all contours, the statistical and systematic uncertainties are combined in quadrature taking into account correlations.

b-hadron decay, the cone charge

$$Q_x = \frac{\sum_i^{N_{\text{tracks}}} q^i (p_{\text{T}}^i)^\kappa}{\sum_i^{N_{\text{tracks}}} (p_{\text{T}}^i)^\kappa} , \qquad (2)$$

in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5$ around the particle used in the respective tagging method $x = \{\mu, e, \text{jet}\}$. $\Delta\eta$ and $\Delta\phi$ denote the difference in pseudorapidity and azimuthal angle around the beam axis, respectively. The coefficient κ is optimized for each tagging method. The method is calibrated with the self-tagging decay channel $B^\pm \rightarrow J/\psi K^\pm$.

The decay parameters of the $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay are extracted in an unbinned maximum likelihood fit to the reconstructed invariant B_s^0 mass, the proper decay time and three transversity angles. Probability density functions for the signal decay including a non-resonant S-wave state, for background from mis-reconstructed b-hadron decays and for combinatorial background are used. The systematic uncertainties cover uncertainties arising from detector effects and triggering, flavour tagging, selections, background modelling, and the choice of the fit model.

The results are found to be compatible with a previous ATLAS measurement on $19.2\,\text{fb}^{-1}$ of pp collision data recorded at $\sqrt{s}$ of 7 TeV and 8 TeV [9]. The combination of the two measurements yields the following results:

$$
\begin{aligned}
\phi_s &= -0.087 \pm 0.036 \ (\text{stat.}) \pm 0.021 \ (\text{syst.}) \ \text{rad} \\
\Delta\Gamma_s &= 0.0657 \pm 0.0043 \ (\text{stat.}) \pm 0.0037 \ (\text{syst.}) \ \text{ps}^{-1} \\
\Gamma_s &= 0.6703 \pm 0.0014 \ (\text{stat.}) \pm 0.0018 \ (\text{syst.}) \ \text{ps}^{-1} .
\end{aligned}
$$

In the combined results, the precision has improved by a factor of two with respect to the previous measurement. In Figure 3, the measured values of ϕ_s and $\Delta\Gamma_s$ are shown in comparison to the previous measurement and measurements by the CMS and LHCb experiments.

5 Conclusion

The ATLAS experiment at the LHC has a rich B-physics program. Selected measurements on the relative $B_c^{\pm}/B^{\pm}$ production cross section, the branching ratio of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ and the CP violating phase in $B_s^0 \to J/\psi\,\phi$ decays are presented above. All these results are found to be consistent with SM predictions. The precision of these measurements will further improve with the analysis of the full Run 2 dataset ($139\,\mathrm{fb}^{-1}$ of pp data at $\sqrt{s}$ of 13 TeV recorded in 2015-2018) and future data.

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