ATLAS measurements of production, decays and spectroscopy of heavy flavour hadrons

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Abstract. Recent results from the ATLAS experiment on production, decays and spectroscopy of heavy flavour hadrons are presented. The latest results on CP-violation in $B_s \rightarrow J/\psi \phi$ decays are discussed. Measurements of the inclusive and associated charmonium production are also reported. In addition, searches for pentaquarks with hidden charm and recent results on $B_c$ meson production and decays are highlighted.

1. Introduction
The ATLAS experiment [1] has a very rich heavy flavour research program focusing on the measurement of production, decays and spectroscopy of heavy flavour hadrons, providing opportunity for precise tests of the Quantum Chromodynamics (QCD) calculations. An overview of the latest results published by the ATLAS experiment is presented. This includes a precise measurement of the CP-violation phase $\phi_s$ in $B_s \rightarrow J/\psi \phi$ decay, an inclusive and associated $J/\psi$ production cross section measurement, a $J/\psi p$ resonances measurement in $\Lambda_b \rightarrow J/\psi p K^-$ decays, and a measurement of the relative $B_s^0/B_s^\pm$ production cross section.

2. Measurement of the CP-violating phase $\phi_s$ in $B_s^0 \rightarrow J/\psi \phi$ decay
The $B_s^0 \rightarrow J/\psi \phi$ channel is used to measure the CP-violation phase $\phi_s$ which is potentially sensitive to New Physics (NP). In the $B_s^0 \rightarrow J/\psi \phi$ channel, CP-violation occurs due to interference between a direct decay and a decay with $B_s^0 - B_s^\pm$ mixing. In the Standard Model (SM), $\phi_s$ is related to the CKM elements and is predicted with high precision to be $\phi_s \approx 2 \text{arg}[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = -0.0363^{+0.0016}_{-0.0015}$ rad [2]. The NP processes could introduce additional contributions to the box diagrams describing the $B_s^0$ mixing and change the predicted $\phi_s$ value. Although large NP enhancements of the mixing amplitude have been excluded by the precise measurement of the oscillation frequency, there is still some room on the order of statistical uncertainty.

Other measured quantities in $B_s^0$ mixing are $\Delta \Gamma_s = \Gamma_s^L - \Gamma_s^H$, where $\Gamma_s^L$ and $\Gamma_s^H$ are the decay widths of the different mass eigenstates and $\Gamma_s = (\Gamma_s^L + \Gamma_s^H)/2$ their average. The $\Delta \Gamma_s$ and $\Gamma_s$ are not sensitive to NP; however, the measurement is interesting for testing the SM prediction.

The final states describing resonant $B_s \rightarrow J/\psi \phi$ and non-resonant $S$-wave decays can be distinguished through flavour-tagged time-dependent angular analysis. In order to extract physics parameters, a simultaneous unbinned maximum-likelihood fit was performed. The presented analysis introduces the measurement of the $B_s^0 \rightarrow J/\psi \phi$ decay parameters using
80.5 fb$^{-1}$ of $pp$ data collected by the ATLAS detector during 2015–2017 at a centre-of-mass energy $\sqrt{s} = 13$ TeV [3]. The measured values are then statistically combined with those from 19.2 fb$^{-1}$ of 7 TeV and 8 TeV data [4]. The combined values are consistent with Standard Model predictions as well as with other LHC measurements. The comparison can be seen in the two dimensional contours in the $\phi_s - \Delta \Gamma_s$ plane in figure 1.

![Figure 1](image.png)

**Figure 1.** Contours of 68% confidence level in the $\phi_s - \Delta \Gamma_s$ plane, including results from CMS (orange) and LHCb (green) using the $B_s^0 \to J/\psi K^+ K^-$ decay only and LHCb (red) for all the channels. The Standard Model prediction is shown as a very thin black rectangle. In all contours the statistical and systematic uncertainties are combined in quadrature. Taken from ref. [3].

3. $J/\psi$ and $\psi(2S)$ production cross section

Differential cross section measurements of quarkonia states provide unique insight into the nature of QCD near the boundary of the perturbative and non-perturbative regimes. The results presented in the article are based on $pp$ collisions data at 13 TeV accumulated by the ATLAS detector in the period between 2015 and 2018 with integrated luminosity of 139 fb$^{-1}$ [5]. In that period, ATLAS collected a huge sample of $J/\psi \to \mu^+ \mu^-$ and $\psi(2S) \to \mu^+ \mu^-$ decays, allowing for a thorough test of QCD calculation predictions in bins of $\eta$ and $p_T$, and reaching very high $p_T$ regions, up to 360 GeV.

In high energy hadronic collisions, charmonium states can be produced either from short-lived QCD sources (referred to as “prompt” production), or from long-lived sources such as decays of beauty hadrons (referred to as “non-prompt” production). These can be separated experimentally by measuring the distance between the production and decay vertices of the quarkonium state. FONLL calculations within the framework of perturbative QCD have been reasonably successful in describing the non-prompt contributions; however, for the prompt contribution, methods within a non-relativistic QCD (NRQCD) approach were developed.

The double-differential cross sections of prompt and non-prompt components were measured for both the $J/\psi$ and the $\psi(2S)$ states. The non-prompt fraction for each state is also measured, as well as the production ratios of $\psi(2S)$ to $J/\psi$. In addition, the non-prompt cross section was compared with the predictions of the FONLL model with a default set of parameters. The overlaid distributions can be seen in figure 2. The comparison shows good agreement at the lower $p_T$ regions; however, the FONLL model predicts higher cross sections in high-$p_T$ regions.
Figure 2. The non-prompt differential cross section overlaid with FONLL predictions is shown for (a) $J/\psi$ mesons, and (b) $\psi(2S)$ mesons, where the horizontal position of each point represents the mean of the weighted $p_T$ distribution for that bin. The data are shown after all relevant corrections are applied, including corrections for acceptance under an isotropic assumption. The green shaded bands represent the range of theoretical uncertainty associated with the variations of the scales. The symbols for the data are centred at unity and the vertical error bars represent the relative uncertainties of the data. Taken from ref. [5].

4. Measurement of $J/\psi$ production in association with a $W^\pm$ boson

The associated production of prompt $J/\psi$ mesons with $W^\pm$ bosons provides a powerful probe of the charmonium production mechanism in hadronic collisions, in particular the effect of the color singlet (CS) and color octet (CO) process contributions. The requirement of an associated object (e.g., $W^\pm$, $Z^0$, $J/\psi$) filters the possible number of CS and CO diagrams contributing to the final state. The result presented in the article highlight a new ATLAS measurement of the ratio of the cross section for associated production of prompt $J/\psi + W^\pm$ to the inclusive $W^\pm$ production cross section with $W^\pm \rightarrow \mu\nu$ and $J/\psi \rightarrow \mu^+\mu^-$ at a centre-of-mass energy of 8 TeV and integrated luminosity of 20.3 fb$^{-1}$ [6]. These cross section ratios are presented for $J/\psi$ transverse momenta in the range $8.5 < p_T < 150$ GeV and rapidities satisfying $|y_{J/\psi}| < 2.1$.

This measurement includes contributions from Single Parton Scattering (SPS) and Double Parton Scattering (DPS) processes. The DPS contribution can be estimated using the effective cross section ($\sigma_{\text{eff}}$) measured by the ATLAS collaboration. Since $\sigma_{\text{eff}}$ may not be process-independent, it is unclear which value of $\sigma_{\text{eff}}$ to use for prompt $J/\psi + W^\pm$ production, so two different values are considered: $\sigma_{\text{eff}} = 15 \pm 3$(stat.)$^{+5}_{-3}$(sys.) mb from $W^\pm + 2$-jet [7] events and $\sigma_{\text{eff}} = 6.3 \pm 1.6$(stat.)$ \pm 1.0$(sys.) mb from prompt $J/\psi$ pair production [8]. These two values of $\sigma_{\text{eff}}$ are chosen since they are the two ATLAS measurements closest to the $J/\psi + W^\pm$ final state.

The SPS and DPS contributions can be distinguished in the azimuthal opening angle $\Delta\phi(J/\psi, W^\pm)$ between the directions of the $J/\psi$ and the $W^\pm$. The DPS component should not have a preferred $\Delta\phi$ value, while the SPS events are expected to peak at $\Delta\phi \approx \pi$ due to momentum conservation. The cross section ratio for SPS is obtained after subtracting the estimated DPS fraction. The comparison of the SPS theoretical values provided by the CO model in conjunction with the estimated DPS contribution is shown in figure 3. The models underestimate the measurement for both $\sigma_{\text{eff}}$ values especially in the higher $p_T$ intervals, possibly because CS processes are not included in the prediction.

5. Study of $J/\psi p$ resonances in $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays

An experimental observation of pentaquark signals was reported by the LHCb collaboration in 2015. Two resonances were found in the $J/\psi p$ mass spectrum of $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays, and
Figure 3. The inclusive (SPS+DPS) differential cross section ratio measurements and theory predictions presented in six $p_{T,J/\psi}$ regions for $|y_{J/\psi}| < 2.1$. NLO colour-octet SPS predictions are shown, with long-distance matrix elements model extracted from the differential cross section and spin alignment of prompt $J/\psi$ mesons at the Tevatron [9]. The DPS contribution is estimated using (a) $\sigma_{\text{eff}} = 15^{+5.8}_{-4.2}$ mb and (b) $\sigma_{\text{eff}} = 6.3 \pm 1.9$ mb and the method discussed in the text. The data points are identical in the two plots. Taken from ref. [6].

interpreted as the pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$ [10]. Later LHCb resolved the $P_c(4450)^+$ into two states ($P_c(4440)^+$ and $P_c(4457)^+$) and discovered a new $P_c(4312)^+$ [11].

The ATLAS experiment performed a study of $J/\psi p$ resonances in the $\Lambda^0_b \rightarrow J/\psi pK^-$ decays in $pp$ collisions at 7 and 8 TeV data with integrated luminosities of 4.9 fb$^{-1}$ and 20.6 fb$^{-1}$ [12], in order to seek confirmation of their observations.

Due to the absence of particle identification in the ATLAS detector, the $\Lambda^0_b$ decays are reconstructed together with the decays $B^0 \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^+$, and $B^0 \rightarrow J/\psi K^+$. The distribution $m(J/\psi p)$ is analyzed in the signal region, 5.59 GeV < $m(J/\psi p, h_1 = p, h_2 = K) < 6.55$ GeV. A $\chi^2$ fit was performed to the $m(J/\psi p)$ distribution for the hypothesis with two pentaquarks with spin-parity $3/2^-$ for lighter pentaquark candidates and $5/2^+$ for heavier pentaquark candidates, resulting in $\chi^2/N_{\text{dof}} = 37.1/39$. The narrow pentaquarks reported recently by LHCb cannot be distinguished due to the smaller number of signal candidates and lower resolution. The fit projection and parameters derived from the signal fit to the data using this two-pentaquark hypothesis are shown in figure 4.

To verify the four-pentaquark hypothesis, a fit with fixed masses, widths and relative yields of the narrow pentaquarks to LHCb values is performed, resulting in $\chi^2/N_{\text{dof}} = 37.1/42$. A $\chi^2$ fit using the hypothesis without pentaquarks with the default $\Lambda^+$ model was performed as well. The fit yields to $\chi^2/N_{\text{dof}} = 69.2/37$, corresponding to a p-value of $1.0 \times 10^{-3}$.

All systematic tests relevant to the hypothesis without pentaquarks were repeated. The systematic test using the extended $\Lambda^0_b \rightarrow J/\psi \Lambda^0$ decay model provides the best description of the data, with $\chi^2/N_{\text{dof}} = 42.0/23$, which corresponds to a p-value of $9.1 \times 10^{-3}$. Although the data prefer the model with two or more pentaquark states, consistent with previous LHCb measurements, the model without pentaquarks is not excluded.

6. Measurement of the relative $B_c^\pm / B^\pm$ production cross section

The $B_c^\pm$ meson is a bound state of the two heaviest distinct quarks able to form a stable state. Measurements of its production can provide unique insight into heavy quark hadronization and probe heavy quark dynamics. The ATLAS experiment performed a measurement of the production cross section times branching fraction for $B_c^\pm \rightarrow J/\psi \pi^\pm$ relative to that for
Figure 4. Parameters of the $\Lambda_b^0 \rightarrow P_c^+ K^-$ decays derived from the fit for the hypothesis with two pentaquarks (a) and the projection of the $\chi^2$ fit of the $m(J/\psi p)$ distribution (b). The pentaquark yields under the assumption of no interference effects ($N(P_{c1})$ and $N(P_{c2})$), the yield of a sum of two pentaquarks ($N(P_{c1} + P_{c2})$), the relative phase between pentaquark amplitudes ($\Delta \phi$), and the pentaquark masses and widths are reported. Taken from ref. [12].

$B^\pm \rightarrow J/\psi K^\pm$ using pp collisions at 8 TeV with an integrated luminosity of 20.3 fb$^{-1}$ [13].

The relative cross section measurement was performed in two bins of the transverse momentum $p_T$ of the $B_c^\pm$, 13 GeV < $p_T(B_c^\pm)$ < 22 GeV and $p_T(B_c^\pm)$ > 22 GeV, for rapidity $|y| < 2.3$, and in two bins of absolute rapidity $|y|$ of the $B_c^\pm$, $|y| < 0.75$ and $0.75 < |y| < 2.3$, for $p_T(B_c^\pm)$ > 13 GeV. The relative cross section is also measured for the inclusive dataset with $p_T > 13$ GeV and $|y| < 2.3$.

The relative production cross section for the inclusive range $p_T > 13$ GeV and $|y| < 2.3$ is $(0.34 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$. The results of the differential measurements in the $p_T$ and $y$ bins are shown in figure 5.

Figure 5. The production cross section for the $B_c^\pm$ relative to the $B^\pm$ (times the corresponding branching fractions) for two bins in $p_T$ (a) and two bins in absolute rapidity (b). The data are represented by black points and the inclusive bin by the horizontal band. On each point the horizontal bar indicates the bin width. The vertical inner error bars on the data points indicate the statistical uncertainty. The outer error bars indicate the size of the quadrature sum of uncertainties from all sources: statistical, systematic, and lifetime. The double hatched error band indicates statistical uncertainty, while the single hatched bands indicate the quadrature sum of uncertainties from all sources. Taken from ref. [13].
They suggest a dependence on the transverse momentum: the production cross section of the $B^\pm_{cc}$ decreases faster with $p_T$ than the production cross section of the $B^\pm$, and there is no significant dependence on rapidity.

7. Summary

The recent ATLAS measurement of CP violation parameters in the $B^0_s \to J/\psi \phi$ channel provides competitive results consistent with other LHC experiments as well as the SM prediction. The results of a measurement of the double-differential production cross section of $J/\psi$ and $\psi(2S)$ together with the measurement of $J/\psi$ production in association with a $W^\pm$ boson provide a thorough test of QCD calculations. The results of a study of $J/\psi p$ resonances in $\Lambda^0_b \to J/\psi p K^-$ decays are consistent with a two-pentaquark hypothesis; however, the model without pentaquarks is not excluded. The production cross section of the $B^\pm_{cc}$ meson relative to the production cross section of the $B^\pm$ meson provides unique insight into heavy quark hadronization dynamics.

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