PROCEEDINGS OF SCIENCE

ATLAS results on charmonium production and B_c^+ meson production and decays

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Recent results from the proton-proton collision data taken by the ATLAS experiment on the charmonium production and on the B_c^+ meson production and decays are presented. The measurement of J/ψ meson and $\psi(2S)$ meson differential cross sections is reported. New results on the B_c^+ meson decays to $J/\psi D_s^{(*)}$ final states are included. Both studies are based on pp collision data collected at $\sqrt{s} = 13$ TeV during the LHC Run 2, corresponding to an integrated luminosity of $139\,\text{fb}^{-1}$. The measurement of the differential ratios of the B_c^+ and B^+ mesons production cross sections at $\sqrt{s} = 8$ TeV with an integrated luminosity of $20.3\,\text{fb}^{-1}$ is also discussed.

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1. Introduction

ATLAS is a multi-purpose detector [1], designed to study a variety of phenomena at the Large Hadron Collider (LHC). Its physics program includes heavy flavour studies mainly focusing on final states with two muons. Heavy quarkonium states decaying to muon pairs represent a good method for studying heavy quark dynamics. An overview of the latest results published by the ATLAS experiment is presented here. This includes a high transverse momenta (p_T) J/ψ and $\psi(2S)$ mesons production measurement, a measurement of the relative B_c^+/B^+ production cross section ratio and a study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays.

2. High-p_T J/ψ and $\psi(2S)$ mesons production measurement

Differential cross-section measurements of quarkonia states provide unique insight into the nature of QCD near the boundary of the perturbative and non-perturbative modes.

In high energy hadron 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. The FONLL model calculations [2] within the framework of perturbative QCD have been reasonably successful in describing the non-prompt contributions, however, a satisfactory understanding of the prompt production mechanisms is still to be achieved. The double-differential cross sections of prompt and non-prompt components are measured by ATLAS for both the J/ψ and the $\psi(2S)$ states in the range of high-p_T (from 60 to 360 GeV for J/ψ meson and 60–140 GeV for $\psi(2S)$ meson) [3]. The non-prompt fraction for each state is also measured, as well as the production ratios of $\psi(2S)$ meson relative to J/ψ meson. In addition, the non-prompt cross section is compared with the predictions of the FONLL model with a default set of parameters. The overlaid distributions can be seen in Figure 1. The comparison shows good agreement at the lower p_T regions; however, the FONLL model predicts higher cross sections in high-p_T regions.

3. Relative B_c^+/B^+ production measurement

The B_c^+ meson is a bound state of the two heaviest distinct quarks able to form a stable state. Measurements of its production can provide important information about heavy-quark hadronization. The ATLAS experiment has already performed a measurement of the production cross section times branching fraction for $B_c^+ \to J/\psi\pi^+$ decay relative to that for $B^+ \to J/\psi K^+$ decay [4]. The relative cross section measurement was performed in two bins of the transverse momentum p_T of the B_c^+ meson, 13 GeV $< p_T(B_c^+) <$ 22 GeV and $p_T(B_c^+) >$ 22 GeV, for rapidity $|y| < 2.3$, and in two bins of absolute rapidity $|y|$ of the B_c^+ meson, $|y| < 0.75$ and $0.75 < |y| < 2.3$, for $p_T(B_c^+) >$ 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 $(0.34 \pm 0.04(\text{stat.})^{+0.06}_{-0.02}(\text{syst.}) \pm 0.01(\text{lifetime}))\%$. The results of the differential measurements in the p_T and y bins are shown in Figure 2. The production cross section of the B_c^+ meson decreases faster with p_T than the production cross section of the B^+ meson, and there is no significant dependence on rapidity.

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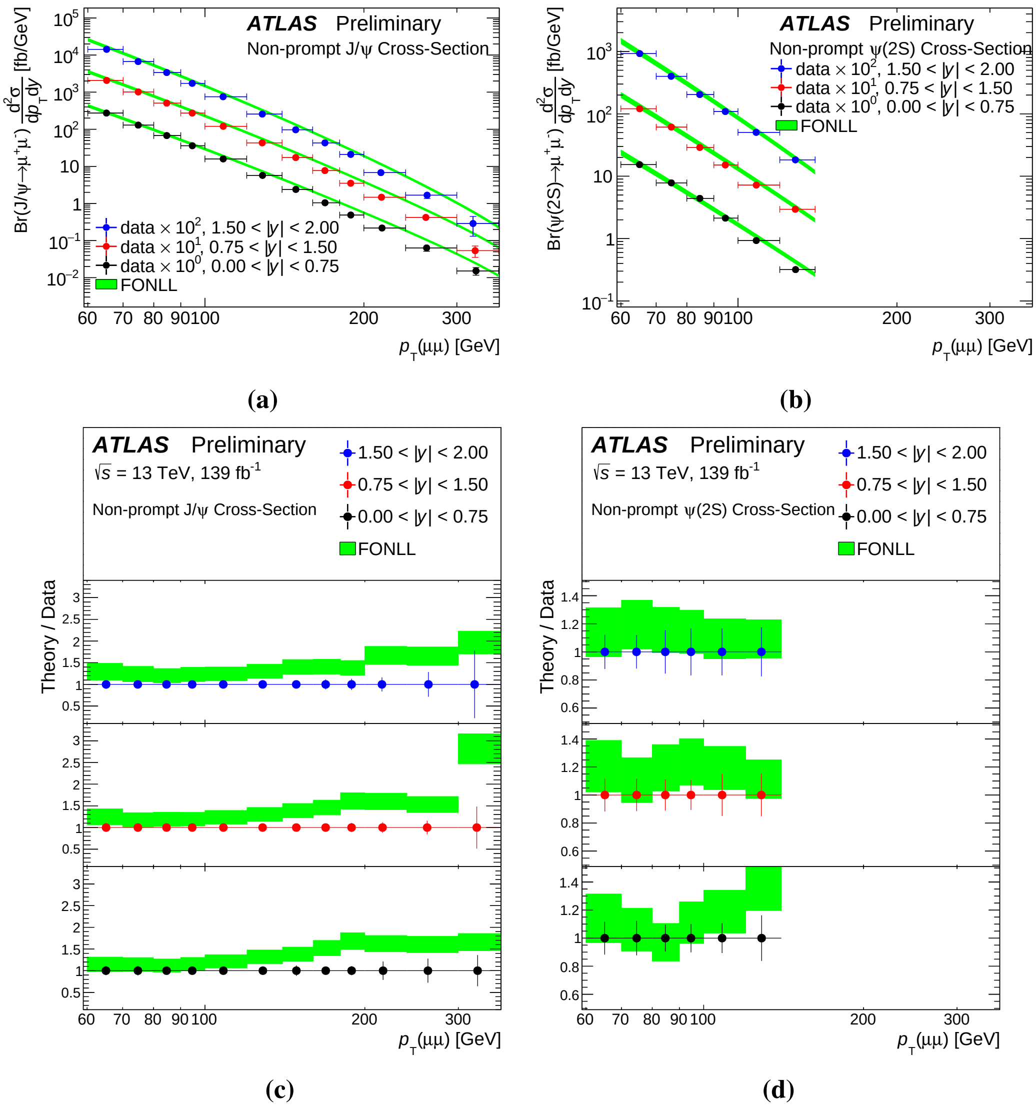
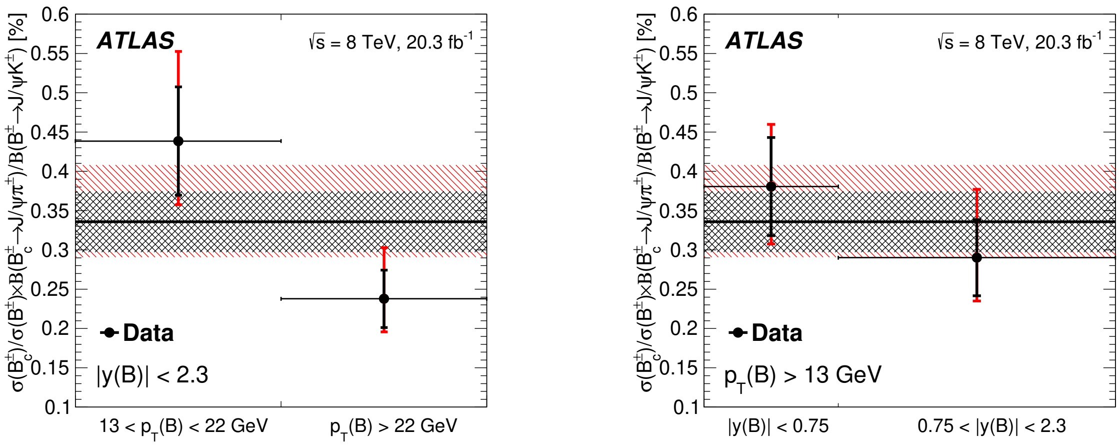


Figure 1: The non-prompt differential cross-section overlaid with FONLL predictions for J/ψ mesons (a), and $\psi(2S)$ mesons (b).The data are shown after all relevant corrections applied, including corrections for acceptance under an isotropic assumption. Ratios of the the FONLL model prediction to the measured differential cross sections for J/ψ meson (c) and $\psi(2S)$ meson (d) [3].

4. Study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays

Decays of B_c^+ meson to final states with J/ψ meson involve the $\bar{b}$ quark transition with the c quark being a spectator; contribution from an annihilation diagram is also included. A new study of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays with the ATLAS detector is performed. The purpose of the current study is to improve the precision of measured properties of these decays by using a larger data sample and new analysis methods. The $B_c^+ \to J/\psi D_s^{(*)+}$ decay candidates are built by combining the selected J/ψ meson and D_s^+ mesons candidates. The J/ψ meson decays instantly at the same point as the B_c^+ meson does (secondary vertex) while the D_s^+ meson lives long enough to



(a) **(b)**

Figure 2: The production cross section for the B_c^+ meson relative to the B^+ meson (times the corresponding branching fractions) for two bins in p_T (a) and two bins in absolute rapidity (b) [4].

form a displaced tertiary vertex.

The D_s^+ meson is reconstructed via the $D_s^+ \to \phi\pi^+$ decay with the ϕ meson decaying into a pair of charged kaons. The D_s^{*+} meson decays into a D_s^+ meson and a soft photon or π^0 meson which are not reconstructed in the analysis. However, the mass difference between the D_s^{*+} and D_s^+ mesons is sufficient for the two decay signals to be resolved as two distinct structures in the distribution of reconstructed mass of $J/\psi D_s^+$ system. The J/ψ meson is reconstructed via its decay into a muon pair. The $B_c^+ \to J/\psi\pi^+$ decay is used as a reference to measure the branching fractions.

The following ratios are measured: the ratios between the branching fractions for $B_c^+ \to J/\psi D_s^{(*)+}$ and $B_c^+ \to J/\psi\pi^+$ decays

$$R_{D_s^+/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+), \tag{1}$$
$$R_{D_s^{*+}/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi\pi^+), \tag{2}$$

and the ratio between the branching fractions for $B_c^+ \to J/\psi D_s^{*+}$ and $B_c^+ \to J/\psi D_s^+$ decays

$$R_{D_s^{*+}/D_s^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi D_s^+). \tag{3}$$

The $B_c^+ \to J/\psi D_s^{*+}$ decay, being a transition of a pseudoscalar meson into two vector states, can be described in terms of three helicity amplitudes: A_{++}, A_{00} and A_{--}, where indices correspond to the helicities of the J/ψ and D_s^{*+} mesons. The contribution of the A_{++} and A_{--} amplitudes, referred to as the $A_{\pm\pm}$ component, corresponds to the J/ψ and D_s^{*+} transverse polarisation. Its fraction, $\Gamma_{\pm\pm}/\Gamma$, is also measured.

The ratios between the branching fractions for $B_c^+ \to J/\psi D_s^{(*)+}$ and $B_c^+ \to J/\psi\pi^+$ decays are found to be

$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.16(D_s)^{1}, \tag{4}$$

[1] The uncertainty on the branching fraction of $D_s^+ \to \phi(K^+K^-)\pi^+$ decay

$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61(\text{stat.}) \pm 0.67(\text{syst.}) \pm 0.32(D_s). \tag{5}$$

The ratio between the branching fractions for $B_c^+ \to J/\psi D_s^{*+}$ and $B_c^+ \to J/\psi D_s^+$ decays is found to be

$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24(\text{stat.}) \pm 0.10(\text{syst.}). \tag{6}$$

The fraction of transverse polarisation in $B_c^+ \to J/\psi D_s^{*+}$ decay is found to be

$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.}). \tag{7}$$

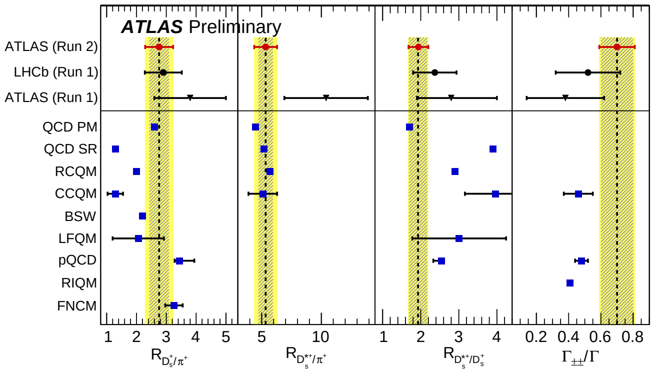


Figure 3: Comparison of the results of this measurement with those of ATLAS Run 1, LHCb and theoretical predictions based on a QCD relativistic potential model (QCD PM) [8], QCD sum rules (QCD SR) [9] , relativistic constituent quark model (RCQM) [10], covariant confined quark model (CCQM) [11], BSW relativistic quark model [12], light-front quark model (LFQM) [13], perturbative QCD (pQCD) [14], relativistic independent quark model (RIQM) [15], and calculations in QCD factorization approach (FNCM) [16]. Hatched areas show the statistical uncertainties of this measurement and yellow bands correspond to the total uncertainties [5].

These results (ATLAS Run 2) are compared with those of LHCb [6] and ATLAS Run 1[7] measurements and to the expectations from various theoretical calculations in Figure 3. All results are consistent with the previous measurements. The precision of the measurement exceeds that of all previous studies of these decays.

5. Summary

The recent ATLAS results in heavy flavour physics, including studies of charmonium production and B_c^+ production and decay were highlighted in this contribution. They are obtained with the data collected by LHC during Run 1 and Run 2, corresponding to integrated luminosities of 20.3 fb^{-1} and 139 fb^{-1} respectively. These results are compared to theoretical predictions and can serve as probes for the available models.

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