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# *b*-quark and quarkonium production and polarisation

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**Abstract.** An overview is given of recent measurements of open beauty and heavy quarkonium production and quarkonium polarisation, made by the ATLAS, CMS and LHCb collaborations at the Large Hadron Collider.

## 1 Introduction

Almost forty years after the discovery of $J/\psi$, the investigation of open and hidden heavy flavour production processes in hadronic collisions still presents significant challenges to both theory and experiment. Large amounts of LHC data have now become available, thus opening a new energy frontier and a new chapter in such studies.

This note is an overview of recent results on open beauty and quarkonium production and polarisation from the ATLAS [1], CMS [2] and LHCb [3] collaborations.

## 2 Open beauty production

All three collaborations have provided competitive measurements of the properties of the $\Lambda_b$ baryon, observed as a peak in its $\Lambda + J/\psi$ decay mode [4–6]. CMS [5] and LHCb [7] have also measured its differential cross section. The distribution from CMS [5] is shown in fig. 1 alongside earlier similar results for other beauty hadrons. When compared to theoretical expectations, the measured $\Lambda_b$ distribution is noticeably steeper [5]; moreover, it looks as if the more massive the *B*-hadron, the steeper is its $p_{\mathrm{T}}$ distribution.

The $p_{\mathrm{T}}$ distribution of the charged *B* mesons in their $J/\psi K^{\pm}$ decay mode, measured by the LHCb collaboration [8], is shown in fig. 2. FONLL model predictions [9] describe the data well, but with the theoretical uncertainties of the model exceeding the experimental errors in this case. ATLAS [10] have measured the $p_{\mathrm{T}}$ dependence of *B* hadron production in partially reconstructed final states $D^{*+}\mu X$ (fig. 3). Several theoretical models reproduce the shapes of the data distributions reasonably well, however, the overall normalisation is slightly higher in the data.

Similar conclusions are drawn from the studies of inclusive muons originating from heavy flavour decays, performed by CMS [11] and ATLAS [12] (as well as ALICE [13]). While at lower $p_{\mathrm{T}}$ both NLO and FONLL perturbative QCD calculations show reasonable agreement with the data, at higher $p_{\mathrm{T}}$ (up to 100 GeV, as reached by ATLAS) FONLL seems to do a better job (fig. 4).

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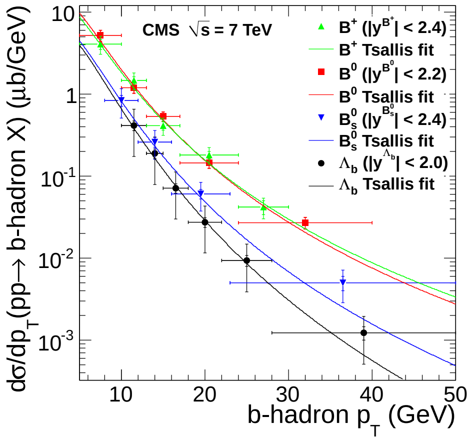


**Figure 1.** Transverse momentum distributions of various B hadrons from [5].

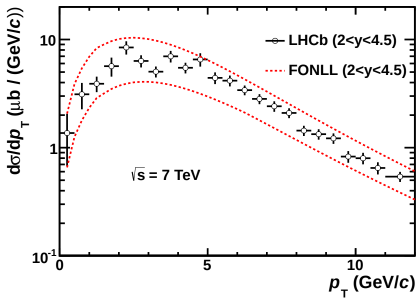


**Figure 2.** Transverse momentum distributions of $B^{\pm}$ from [8].

ATLAS [14], CMS [15] and LHCb [16] have all observed prominent peaks from $B_c \equiv (\bar{b}c)$ in the $J/\psi\pi$ decay mode. LHCb [17] and CMS [15] have also seen it in the $J/\psi 3\pi$ mode, while LHCb [16] have measured the ratio of production cross sections

$$R_{c/u} \equiv \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$$

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to be (0.68 ± 0.10(stat) ± 0.03(syst) ± 0.05(lifetime))% in the kinematic range $p_T > 4$ GeV, $2.5 < \eta < 4.5$, which should provide a valuable input for theoretical models.

## 3 Charmonium production

All the LHC experiments have accumulated huge statistics of $J/\psi, \psi(2S) \rightarrow \mu\mu$ candidates, and the number of published measurements of charmonium production properties is growing fast.

In hadronic collisions, both $J/\psi$ and $\psi(2S)$ can be produced either from *prompt* short-lived QCD sources, or from *non-prompt*, long-lived $B$ hadron decays (with both of these including *direct* production as well as feeddown from excited charmonium state decays). The measured decay length of the dimuon is used by all LHC collaborations to separate prompt and non-prompt contributions, and hence measure the fraction of non-prompt $J/\psi$ and $\psi(2S)$ in various bins of dimuon $p_{\rm T}$ and rapidity $y$ [18–21], some of which are shown in fig. 5. These results are

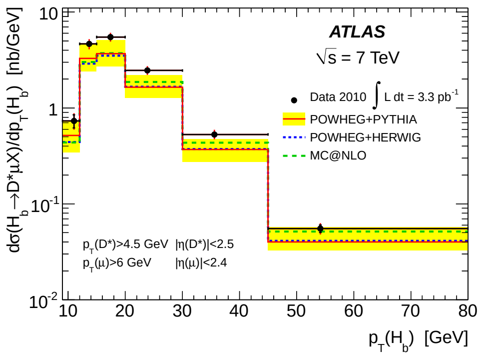


**Figure 3.** Transverse momentum distributions of partially reconstructed $B$ hadrons from [10].

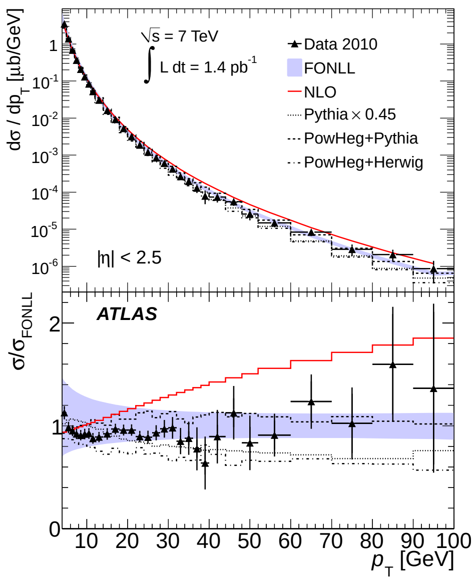


**Figure 4.** Transverse momentum distribution of muons from heavy flavour decays, from [12].

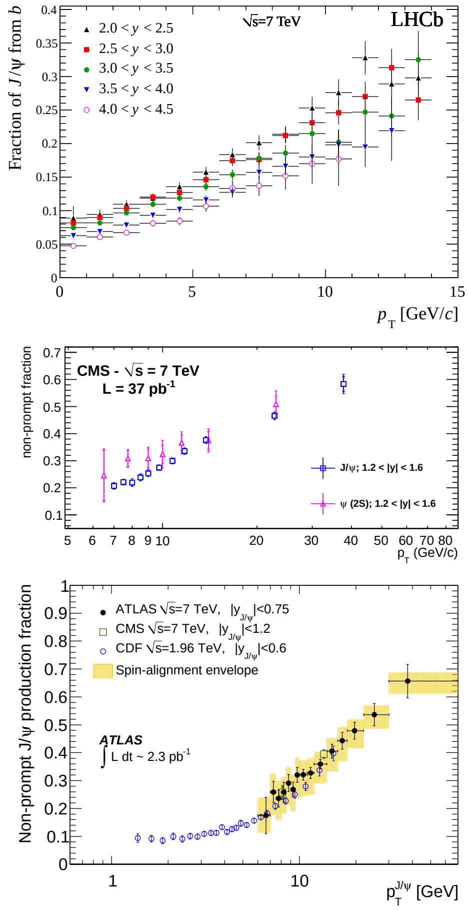


**Figure 5.** Fraction of non-prompt charmonium. Top: $J/\psi$ in the forward region from LHCb [21]; middle: $J/\psi$ and $\psi(2S)$ at intermediate rapidities from CMS [20]; bottom: $J/\psi$ at central rapidities from ATLAS [19], CMS [20] and CDF [22].

in good agreement with each other, complementing each other to provide a detailed and consistent picture in a two-dimensional $(p_T, y)$ space for a wide range of the variables, while a comparison with CDF results shows little dependence on collider energy. The non-prompt fraction of $J/\psi$ starts at about 0.1 at low $p_{\rm T}$ and central rapidity, and smoothly increases to a plateau at high $p_{\rm T}$, with the height of that plateau decreasing with increasing rapidity. For $\psi(2S)$ the picture is similar, but the low-$p_{\rm T}$, central rapidity value is larger at about 0.3.

The published results on prompt and non-prompt $J/\psi$ and $\psi(2S)$ production can be combined to cover a wide kinematic range $|y| < 4.5, 0 < pT < 70$ GeV, with different measurements made in overlapping kinematic areas generally consistent with each other. Production of *non-prompt* $J/\psi$ and $\psi(2S)$ is, within uncertainties, in agreement with FONLL calculations with essentially no free parameters. On the other hand, neither of the various models that aim to describe *prompt* charmonium production is free of difficulties (fig. 6). NLO calculations in Colour Singlet Model (CSM) underestimate the data by a large factor. Inclusion of NNLO contributions (which do not take into account the feeddown from $\chi_c$ states [23]) improves things quite

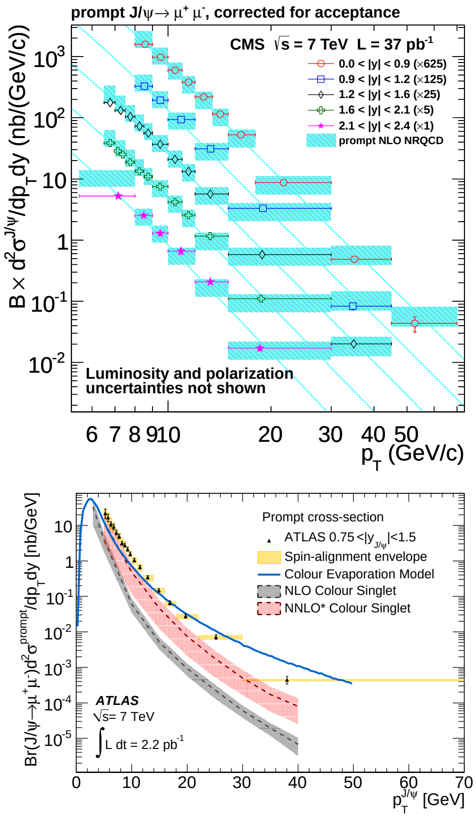


**Figure 6.** Transverse momentum distributions for prompt $J/\psi$ production measured by CMS [20] (top) and ATLAS [19] (bottom), in comparison to various theoretical models [23–25].

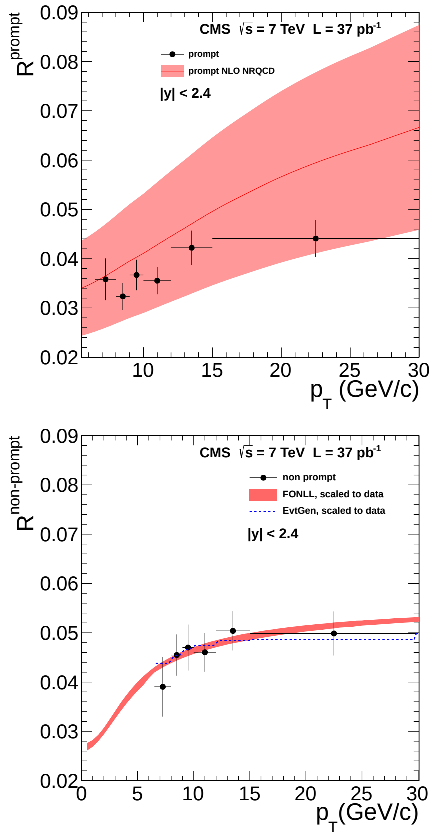


**Figure 7.** Ratio of $\psi(2S)$ to $J/\psi$ production cross sections as a function of transverse momentum, separately for prompt (top) and non-prompt (bottom) contributions [20].

significantly, but the $p_{\rm T}$ dependence is still steeper than in data. The opposite is true for the Colour Evaporation Model (CEM) [24]. Note that neither of the above models has any free parameters. On the other hand, different variations of the Colour Octet Model (COM) [25] use the data to constrain the multitude of parameters of the model and hence can describe the measured $p_{\rm T}$ and $y$ distributions reasonably well, but require other observables to judge the degree of their success and of the insight they provide.

The production dynamics of $\psi(2S)$ is largely similar to $J/\psi$, but without any significant feeddown from excited states. Fig. 7 shows the $p_{\rm T}$-dependence of the cross section ratio $R = [\mathcal{B}^{\psi(2S)}_{\mu\mu}\sigma(\psi(2S))]/[\mathcal{B}^{J/\psi}_{\mu\mu}\sigma(J/\psi)]$, separately for prompt and non-prompt cases, measured by CMS [20]. Similar results are published by LHCb [21], covering the range $0 < p_T < 12$ GeV and forward rapidities. While in the non-prompt sector the predictions of FONLL [9] are fairly precise and describe the data very well, the predictions of COM [25] in the prompt sector, although consistent with data, have very large uncertainties.

With increased $J/\psi$ statistics have come new opportunities to measure the production of $\chi_c$ states. Results for the ratio of $\chi_{c2}$ to $\chi_{c1}$ cross sections, measured by CMS [26] and LHCb [27], agree with each other where they overlap, and between the two cover a wide range of $p_{\rm T}$ (fig. 8). The falling $p_{\rm T}$ dependence is in qualitative agreement with the naïve perturbative expectations. LHCb have also measured the fraction of prompt $J/\psi$ produced from $\chi_c$ decays (fig. 9 [28]). Here COM [25] describes data well, but perturbative CSM-style calculations are in contrast with both, and so the overall picture is less than clear.

## 4 Bottomonium studies

Recent ATLAS results on the $p_{\rm T}$ and rapidity dependence of the production cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ [29] are in agreement with existing data from CMS [30] and LHCb [31], but extend the $p_{\rm T}$ range up to 70 GeV. The rapidity distributions remain flat within $|y| < 2$, but decrease at the higher $y$ values covered by LHCb. The measured cross section ratios $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$, presented in fig. 10, show a non-trivial $p_{\rm T}$ dependence which confirms the existence of multiple production mechanisms, and hints on their evolution with transverse momentum. A comparison with theoretical models, some of which are shown in fig. 11 alongside ATLAS data, yields conclusions similar to the charmonium case (see sect. 3).

The production of orbitally excited bottomonium states $\chi_b$ has also been observed at LHC. After the discovery of $\chi_b(3P)$ by ATLAS [32] (subsequently confirmed by D0 [33] and LHCb [34]) it became clear that all three $\Upsilon$ states are subject to feeddown from $\chi_b$ states. LHCb have

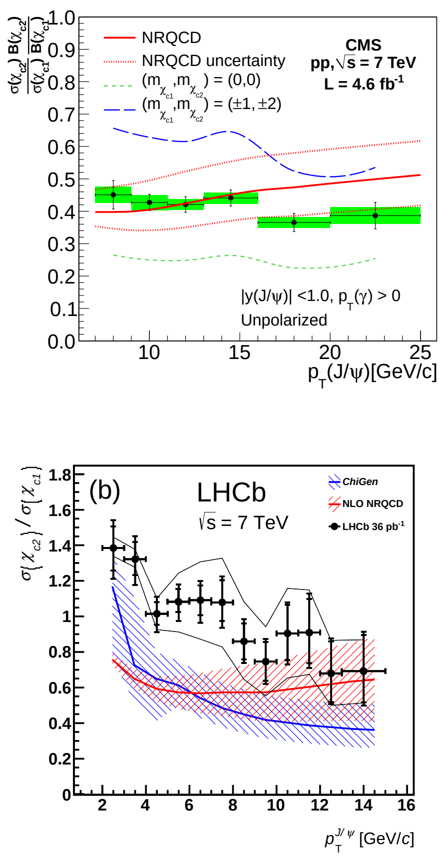


**Figure 8.** Ratio of $\chi_{c2}$ to $\chi_{c1}$ production cross sections as a function of $J/\psi$ $p_T$, from CMS [26] (top) and LHCb [27] (bottom).

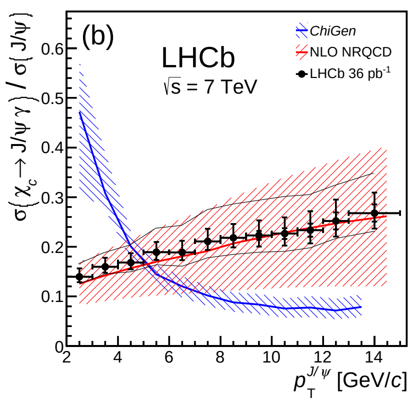


**Figure 9.** Fraction of $J/\psi$ produced from $\chi_c$ decays, as a function of $J/\psi$ transverse momentum from [28].

measured the intensity of one such feeddown: at forward rapidities, $(20.7 \pm 5.7(\text{stat}) \pm 2.1(\text{syst})^{+2.7}_{-5.4}(\text{pol}))\%$ of $\Upsilon(1S)$ come from radiative decays of $\chi_b(1P)$ states [35].

CMS have achieved an important milestone in studying the dynamics of quarkonium production at LHC by applying the full two-angle formalism [36] to measure the polarisation of all three $\Upsilon$ states, in two rapidity bins, and three different reference frames, as a function of $\Upsilon$ transverse momentum [37]. In particular, it was found that spin alignment for $\Upsilon(1S)$ is not strong, if present at all. There are possible hints of a slightly increasing transverse polarisation when moving from $\Upsilon(1S)$ to $\Upsilon(2S)$ to $\Upsilon(3S)$, but still well below the level predicted by some theoretical models (see fig. 12). Note that the model curves in fig. 12 were made before the observation of $\chi_b(3P)$, under the assumption that $\Upsilon(3S)$ is only produced directly.

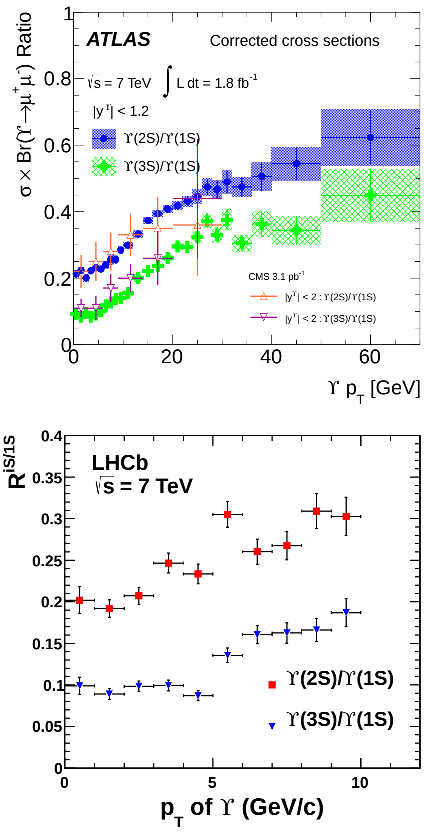


**Figure 10.** Ratios of production cross sections of $\Upsilon(2S)$ to $\Upsilon(3S)$, and $\Upsilon(3S)$ to $\Upsilon(1S)$, measured by CMS [30], ATLAS [29] (top) and LHCb [31] (bottom).

## 5 Summary and outlook

Many different measurements on open heavy flavour production have become available from all LHC experiments. All of them are so far described reasonably well by models based on perturbative QCD, with FONLL leading the way. $B_c$ – "open-charm-open-beauty charged heavy quarkonium" – is now appearing in numbers large enough to study its production characteristics, which may help understand some aspects of $J/\psi$ and $\Upsilon$ production.

The prompt production of charmonium states $J/\psi, \psi(2S), \chi_{cJ}$ is being studied in detail, with a huge range of $p_T$ and $y$ covered in some cases, and the LHC experiments nicely complementing each other. These measurements provide a great deal of input for theorists, and plenty of questions, but no clear answers yet. The same is true about the $\Upsilon$ states, with a possible hint that perturbative QCD may be doing slightly better here.

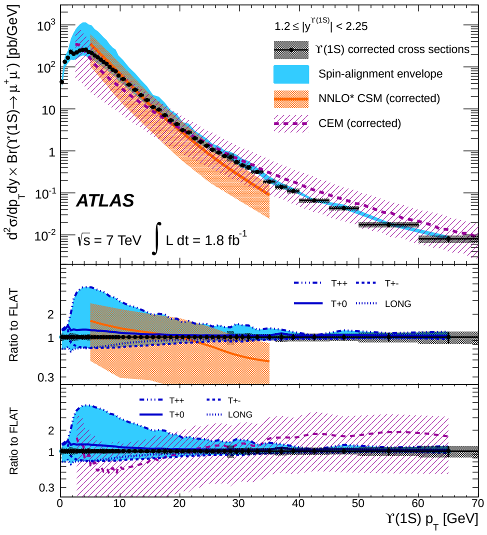


**Figure 11.** $\Upsilon(1S)$ production cross section from [29], compared to theoretical predictions from [23, 24].

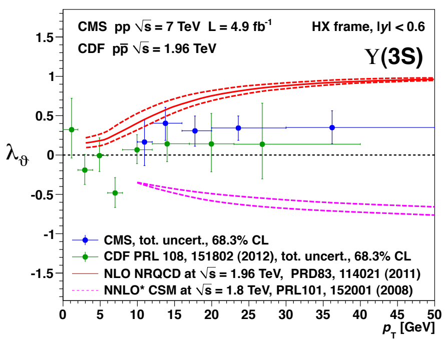


**Figure 12.** Polarisation of $\Upsilon(3S)$ at central rapidity in the helicity frame, compared to various predictions (see [37] for details).

The first "two-angle" measurements of vector quarkonium spin alignment show no signs of strong polarisation, against the expectations of leading models, suggesting that differential cross section and polarisation measurements may not be enough, and additional "new observables" may be needed to understand properly the dynamics of hadronic production of quarkonia. The first such measurements have become available: studies of quarkonium associations with other quarkonia [38], open heavy flavours [39] and underlying event characteristics [40]. Many more are still to come, providing new opportunities and challenges for both theory and experiment.

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