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Heavy flavour and quarkonium production at the LHC

M. Bona on behalf of the ATLAS, CMS and LHCb Collaborations
Queen Mary University of London - London, UK

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Summary. — This document presents a review of recent results for quarkonium production at the LHC from ATLAS, CMS, and LHCb. Production cross sections for J/ψ, $\psi(2S)$, and $\Upsilon(mS)$, and production ratios for $\chi_{c,bJ}$ are found to be in good agreement with predictions from non-relativistic QCD. In contrast, spin-alignment (polarisation) measurements seem to disagree with all theoretical predictions. Some other production channels useful for investigating quarkonium hadroproduction mechanisms are also considered.

PACS `14.40.Pq` – Heavy quarkonia.
PACS `12.38.-t` – Quantum chromodynamics.

1. – Introduction

Quarkonium is the bound state of heavy quarks ($c\bar{c}$ and $b\bar{b}$). It is a generally well-understood system, with many successful predictions for masses, widths, decay modes, and production rates for an entire family of particles.

The production of heavy flavours (HF) at hadron colliders provides particular opportunity to study the theory of Quantum Chromodynamics (QCD), in particular the boundary of the perturbative and non-perturbative regimes. At LHC, due to the high energy available $\sqrt{s} = 7$–$8\,\mathrm{TeV}$, it is possible to explore new kinematic regions (*e.g.*, high p_T up to $10^2\,\mathrm{GeV}$) to test the predictions of various theoretical models for both quarkonium and open state production.

The two leading models to describe quarkonium hadroproduction are the colour singlet model (CSM) and non-relativistic QCD (NRQCD) (also referred to as the colour octet model). In the CSM, the heavy quark pair is produced in a colour singlet state and evolves into the final state quarkonium with the same quantum numbers. In NRQCD, colour octet states can also be produced, which then evolve to the singlet final state via soft gluon emission. Matrix elements for the various colour octet contributions are determined from a fit to the data.

In most cases, corrections over the leading order (LO) are available (*e.g.*, next-to-leading (NLO), next-to-leading-log (NLL)) and an accurate quantitative comparison of data with QCD predictions can be performed to discriminate among various quarkonium production models, *e.g.* CS [1] and NRQCD [2].

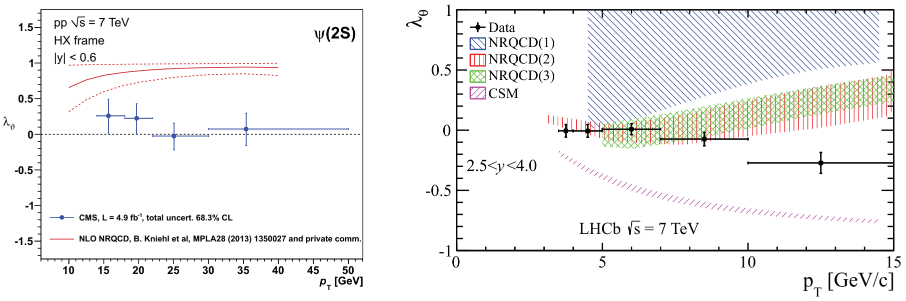

Fig. 1. – Polarisation for the $\psi(2S)$ from CMS [4] (left) and LHCb [6] (right).

For spin-1 quarkonia (J/ψ, $\psi(2S)$, and $\Upsilon(1S, 2S, 3S)$), the spin alignment of the produced quarkonium is quantified by the relative importance of the spin-1 eigenstates, determined by measuring the angular distribution of the leptonic pair decay (*e.g.* $J/\psi \to \mu^+\mu^-$). The most general description of the system requires two angles (θ and ϕ) measured relative to an arbitrary quantisation axis, and three polarisation parameters (λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$). The CSM and NRQCD have considerably different theoretical predictions for the spin alignment, making this observable an important discriminant between these two leading quarkonium hadroproduction theories.

2. – Spin alignment

CMS and LHCb have recently published several results on quarkonium spin alignment (polarisation) [3-6]. These two experiments offer a complementary range of p_T and rapidity coverage. In all analyses, all three polarisation parameters are measured in multiple frames of reference. For J/ψ production, CMS [4] and LHCb [5] find very little to no polarisation. Neither the CSM nor the NRQCD predictions of direct J/ψ agree with these experimental results. However, because these measurements are of inclusive J/ψ, there is the possibility that $\psi(2S)$ and $\chi_{cJ}(1P)$ feed-down effects may be *washing out* polarisation effects. $\psi(2S)$ decays would be free from this possible source of contamination. Still, neither CMS [4] nor LHCb [6] observe polarisation in this system. Figure 1 shows the measured polarisation parameters versus p_T for $\psi(2S)$ for both CMS and LHCb in the helicity (HX) polarisation frame.

The predictions from the theoretical calculations are shown in comparison to both experimental results and the disagreement is clearly evident. Bottomonium, $\Upsilon(1S, 2S, 3S)$, again shows similar results. CMS analysed the production of all three states and find small or no polarisation [3]. It should be noted that this system is not free from feed-down effects from higher quarkonia ($\Upsilon(nS)$ and $\chi_{bJ}(nP)$ states ranging up to $n = 3$). Nonetheless, measurable polarisation effects were predicted by all theoretical models, and are conspicuously absent for all types of quarkonium production and in all frames of reference considered at the LHC thus far.

3. – Production cross sections

All quarkonium hadroproduction measurements at the LHC generally follow a similar analysis strategy. The spin-1 quarkonia are reconstructed via their decays to two muons

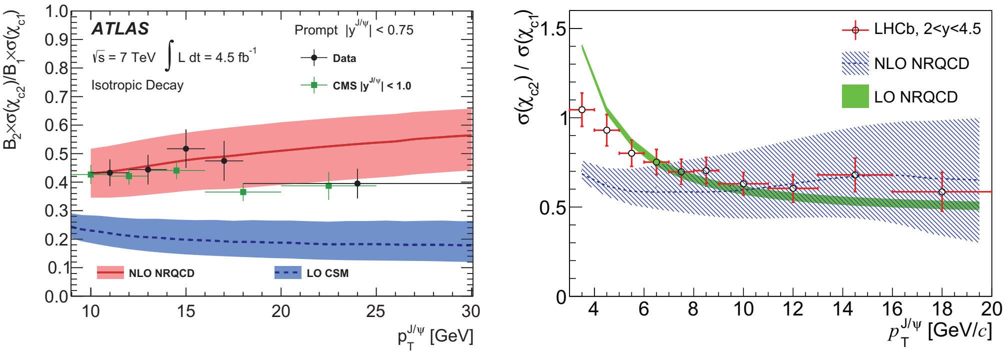

Fig. 2. – The production cross-section of prompt χ_{c2} relative to prompt χ_{c1} measured as a function of $p_T^{J/\psi}$ in ATLAS [9] (left) and in LHCb [11]. For the ATLAS plot, the measurements are compared to the predictions of NLO NRQCD, LO CSM and to the measurement from CMS [10]. For the LHCb plot, results are compared with the NLO NRQCD calculation from ref. [12] (blue shading) and the LO NRQCD calculation of ref. [13] (solid green).

(due to triggering/background, decays to electrons are not typically considered), requiring an accurate understanding of detector muon acceptance. Signal events are determined from the $m_{\mu^+\mu}$ distribution, with backgrounds extrapolated from the side-bands. $\chi_{c,bJ}$ quarkonia are reconstructed via radiative decays (*e.g.*, $\chi_{cJ} \to \gamma J/\psi$). Photon energy resolution sufficient to distinguish between the different J states is achieved by identifying photons converting into e^+e^- pairs in detector material. Non-prompt quarkonia (*i.e.*, $B \to c\bar{c}X$) are separated from prompt production by vertex-related variables taking advantage of the measurable flight distance of the secondary decay from the primary vertex. Measurements of the production rate are then performed in bins of, for example, p_T, $|y|$, $\cos\theta$, and ϕ. In essentially all cases, the NRQCD predictions are a better fit to the data than those from the CSM or others, though the CSM with next-to-next-to-leading order corrections [1] remains competitive. This can be seen in the recent measurements of the J/ψ and $\psi(2S)$ production cross sections presented by LHCb [7]. ATLAS reports measurements of $\psi(2S)$ production [8] reconstructing $\psi(2S) \to \pi^+\pi^- J/\psi$ rather than $\psi(2S) \to \mu^+\mu^-$: this analysis shows agreement with the other results and the theoretical predictions. However, at the highest p_T values there is evidence for a departure from the theoretical predictions for prompt, and particularly non-prompt, production. This disagreement is a subject for future understanding.

For the P-wave states, ATLAS [9], CMS [10], and LHCb [11] have performed measurements of $\chi_{cJ}(1P)$ production. The ATLAS result is the most recent, and the first at the LHC to measure absolute production rates. This requires a detailed knowledge of the conversion photon characteristics in the ATLAS detector. Figure 2 shows the ATLAS and the LHCb measurements compared to theoretical calculations. In all cases, the results are well-described by the NRQCD predictions.

To date, the only measurement in the bottomonium sector comes from CMS [14]. Analogously to the $\chi_{cJ}(1P)$ analyses, radiative decays $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ are reconstructed and the improved resolution of converted photons is used to separate the $J = 1, 2$ peaks. This measurement is more difficult than for $\chi_{cJ}(1P)$ due to the smaller $\sim 20\,\mathrm{MeV}$ energy splitting, and the CMS result is the first at the LHC to be able to resolve the $\chi_{b1,2}$ peaks.

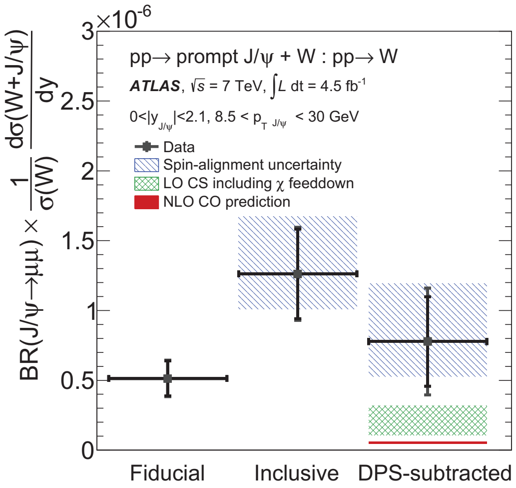

Fig. 3. – The $W^{\pm}$ + prompt J/ψ in ATLAS [15]: W production differential cross section ratio in the J/ψ fiducial region (Fiducial), after correction for J/ψ acceptance (Inclusive), and after subtraction of the double parton scattering component (DPS-subtracted). The LO colour-singlet (CS) and NLO colour-octet (CO) predictions for SPS production are shown for comparison.

4. – Other tests of quarkonium production

This section covers two selected recent results that test other aspects of quarkonium productions.

In a recent result, ATLAS has measured the production cross section of prompt J/ψ mesons in association with a $W^{\pm}$ boson [15], obtaining a 5.1σ significance for this first observation. Figure 3 shows the W production differential cross-section ratio of $W^{\pm}$ + prompt J/ψ production relative to inclusive $W^{\pm}$ boson production in the same phase space. In the case of prompt J/ψ production in association with a $W^{\pm}$ boson, the relative

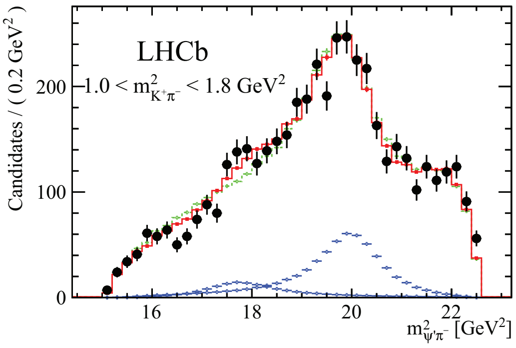

Fig. 4. – Observation of the resonant character of the $Z(4430)^{-}$ state by LHCb [22]. Distribution of $m^2_{\psi'\pi^-}$ in the data (black points) for $1.0 < m^2_{K^+\pi^-} < 1.8\,\mathrm{GeV}^2$ ($K^*(892)$, $K_2^*(1430)$ veto region) compared with the fit with two, 0^- and 1^+ (solid-line red histogram) and only one 1^+ (dashed-line green histogram) Z^- resonances. Individual Z^- terms (blue points) are shown for the fit with two Z^- resonances.

contributions of CS and CO processes differ from the inclusive process. Some theoretical studies [16] suggest $W^{\pm}$ + prompt J/ψ production should be dominated by colour-octet processes, and thus be a distinctive test of the NRQCD framework. In contrast, recent work [17] suggests that in 7 TeV pp collisions, CO and CS (in particular, electromagnetic $W^{\pm}\gamma \rightarrow W^{\pm}J/\psi$) contributions to the $W^{\pm}$ + prompt J/ψ cross section are comparable. Measurements of the production cross sections can help distinguish between these models.

The ATLAS analysis reconstructed $J/\psi \rightarrow \mu^{+}\mu^{-}$ and $W \rightarrow \mu\nu$, and performed a fit to the invariant mass of the lepton pair and the pseudo-proper time. The contribution from double parton scattering was also estimated and subtracted, resulting in a prompt $W+J/\psi$ production rate about an order of magnitude larger than expected. Nonetheless, large uncertainties on the result imply that current predictions for single parton scattering production are compatible with the measurement at the 2σ level.

Charged charmonium-like states have been investigated widely since the Belle collaboration discovered the $X(3872)$: CMS [18] and LHCb [19,20] have recently reported new measurements of the $X(3872)$ production cross section, the determination of its quantum numbers (1^{++}), and evidence for the radiative decay $X(3872) \rightarrow \psi(2S)\gamma$. Another state known as the $Z(4430)^{-}$ was seen by the Belle experiment [21] and it has been now confirmed by LHCb [22] as shown in fig. 4. The measurement is based on four-dimension amplitude fit to the $B^{0} \rightarrow \psi' K^{+}\pi^{-}$ decays providing the confirmation of the existence of the $Z(4430)^{-}$ resonance and establishing its spin-parity to be 1^{+}, both with very high significance. The measured mass, $4475 \pm 7^{+15}_{-25}$ MeV, and width, $172 \pm 13^{+37}_{-34}$ MeV are consistent with the Belle results.

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