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Quarkonium results at the LHC

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Summary. — We will discuss selected results from the four LHC experiments in the field of quarkonium production. These include the production cross sections of $J/\psi, \psi(2S), \chi_c, \Upsilon$ and X as well as the first measurement of the J/ψ polarisation and the observation of the new $\chi_b(3P)$ state.

PACS `14.40.Lb` – Charmed mesons.
PACS `14.40.Pq` – Heavy quarkonia.
PACS `13.25.Gv` – Decays of J/ψ, Υ, and other quarkonia.
PACS `13.60.Le` – Meson production.

1. – Introduction

Despite the fact the first observation of quarkonium states like J/ψ dates back to almost forty years ago, the mechanism of hadro-production is still unclear. Several models exist, but so far none of them is able to correctly reproduce both the measured production cross sections and the polarisation. At the centre-of-mass energy of 7 TeVreached at the Large Hadron Collider (LHC) the ALICE, ATLAS, CMS and LHCb experiments have the potential to elucidate the model of quarkonium production as well as probe the existence of new states recently observed.

The experiments started operations in late 2009, and collected up to $5\,\text{fb}^{-1}$ of pp collisions by the end of 2011. All experiments were fully operational during the data-taking periods considered here, with efficiencies close to or above 90%. The two central experiments, ATLAS and CMS, cover a rapidity range of approximately $|y| < 2$ for the analyses considered here, while ALICE and LHCb have a more asymmetric muon coverage extending in the region of $2.5 < y < 4$ and $2 < y < 4.5$ respectively. In this paper first studies of J/ψ, $\psi(2S)$ and Υ are presented. The first results on χ_c, χ_b and $X(3872)$ are also briefly discussed.

2. – J/ψ production and polarisation

Three sources of J/ψ production in pp collisions need to be considered when comparing experimental observables and theoretical calculations: direct, feed-down from the decay

TABLE I. – *Summary of the J/ψ cross section from the four LHC experiments. The first uncertainty is statistical, the second systematic (the polarisation uncertainty is not included in the CMS measurement). Here $\mathcal{B}_{\mu\mu} = \mathcal{B}(J/\psi \to \mu\mu)$.*

	p_T(GeV/c), y	$\sigma^{J/\psi}_{inclusive} \times \mathcal{B}_{\mu\mu}$	$\sigma^{J/\psi}_{prompt} \times \mathcal{B}_{\mu\mu}$	$\sigma^{J/\psi}_{from\ b} \times \mathcal{B}_{\mu\mu}$
ALICE ($13.3\,\mathrm{nb}^{-1}$)	0-12, $2.5 < y < 4.0$	$(6.31 \pm 0.25^{+1.2}_{-2.1}\mu\mathrm{b}) \times \mathcal{B}_{\mu\mu}$		
ATLAS ($2.3\,\mathrm{pb}^{-1}$)	> 7, $\lvert y\rvert < 2.4$	$81 \pm 1^{+27}_{-23}\,\mathrm{nb}$	$59 \pm 1^{+12}_{-10}\,\mathrm{nb}$	$23.0 \pm 0.6 \pm 2.9\,\mathrm{nb}$
CMS ($37\,\mathrm{pb}^{-1}$)	5.5-70, $\lvert y\rvert < 2.4$		$54.5 \pm 0.3 \pm 3.2\,\mathrm{nb}$	$20.2 \pm 0.2 \pm 1.1\,\mathrm{nb}$
LHCb ($5.2\,\mathrm{pb}^{-1}$)	0-14, $2.0 < y < 4.5$		$(10.52 \pm 0.04^{+2.2}_{-2.6}\,\mu\mathrm{b})$ $\times\mathcal{B}_{\mu\mu}$	$(1.14 \pm 0.01 \pm 0.16\,\mu\mathrm{b})$ $\times\mathcal{B}_{\mu\mu}$

of other prompt charmonium states, and J/ψ from b-hadron decay chains. The sum of the first two sources will be called "*prompt* J/ψ", the third "J/ψ *from* b". The measurement of the differential production cross section of both *prompt* J/ψ and J/ψ *from* b as a function of the $J/\psi\, p_T$ and rapidity (y) is discussed for the four LHC experiments [1-5]. The *prompt* component is separated from the *from* b one using the pseudo proper time variable t_z defined as $t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$, where $z_{J/\psi}$ and z_{PV} are the positions along the z-axis of the J/ψ decay vertex and of the primary vertex, p_z is the measured J/ψ momentum in the z direction, and $M_{J/\psi}$ the nominal J/ψ mass. The details of the measurements are summarised in table I.

The cross sections are obtained assuming no J/ψ polarisation and un uncertainty is associated to this [1, 2]. Figure 1 shows the J/ψ inclusive cross section as a function of $J/\psi\, p_T$ for the four experiments, and the fraction of J/ψ *from* b for the ATLAS and LHCb experiments [6]. The results agree given the different p_T and y ranges. The fraction *from* b agrees at low p_T and shows a saturation at larger p_T values.

ALICE has been the first of the LHC experiments to measure the polarisation of the J/ψ [7]. The measurement is performed in the dimuon channel in the range $2.5 < y < 4.0$ and using an inclusive J/ψ sample of roughly $100\,\mathrm{nb}^{-1}$. The J/ψ angular distribution

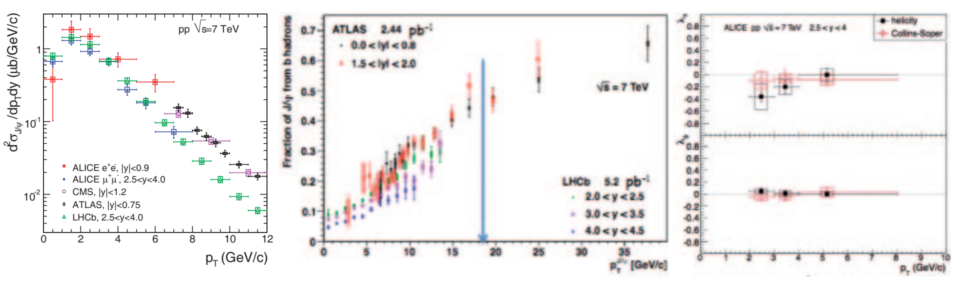

Fig. 1. – Left: Inclusive J/ψ cross section as a function of $J/\psi\, p_T$ for the four LHC experiments (the CMS measurement is an earlier one performed with $0.314\,\mathrm{pb}^{-1}$). Middle: Fraction of J/ψ *from* b as a function of $J/\psi\, p_T$ measured by ATLAS and LHCb. Right: Polarisation measured in the inclusive J/ψ sample by ALICE as a function of $J/\psi\, p_T$. Both λ_θ (top) and λ_ϕ (bottom) are shown in the plot.

TABLE II. – *Summary of the $\psi(2S)$ results from CMS and LHCb. The first uncertainty is statistical, the second systematic and the third due to the luminosity for CMS and the unknown J/ψ polarisation for LHCb. The LHCb measurement is the average of the results in the two decay modes $\psi(2S) \to \mu\mu$ and $\psi(2S) \to J/\psi(\to \mu\mu)\pi^+\pi^-$. Here $\mathcal{B}_{\mu\mu} = \mathcal{B}(\psi(2S) \to \mu\mu)$.*

	p_{T}(GeV/c), y	$\sigma^{\psi(2S)}_{prompt} \times \mathcal{B}_{\mu\mu}$	$\sigma^{\psi(2S)}_{from\,b} \times \mathcal{B}_{\mu\mu}$	$\mathcal{B}(B \to \psi(2S)X)$
CMS (37,pb^{-1})	5.5-70,$\lvert y\rvert$ <2.4	$410 \pm 9 \pm 23 \pm 16\,\mathrm{pb}$	$235 \pm 6 \pm 13 \pm 9\,\mathrm{pb}$	$(3.08 \pm 0.46) \times 10^{-3}$
LHCb (36 pb^{-1})	0-16,$2.0 < y < 4.5$	$(1.44 \pm 0.01 \pm 0.12^{+0.20}_{-0.40}\,\mu\mathrm{b})$ $\times\mathcal{B}_{\mu\mu}$	$(0.25 \pm 0.01 \pm 0.02\,\mu\mathrm{b})$ $\times\mathcal{B}_{\mu\mu}$	$(2.73 \pm 0.29) \times 10^{-3}$

is described by $W(\cos\theta, \phi) \sim 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$, where the λ parameters determine the size of the polarisation. λ_θ and λ_ϕ are shown in fig. 1 in different reference frames as a function of the $J/\psi\, p_{\mathrm{T}}$ and are found to be consistent with zero. More confirmations are expected by the other LHC experiments soon.

3. – $\psi(2S)$ and Υ production

CMS [4] and LHCb [8] recently measured the *prompt* and *from b* production cross section of the $\psi(2S)$ meson. The results are reported in table II for the two experiments and are in agreement with the theory predictions [9]. LHCb has also measured the ratio of the J/ψ to $\psi(2S)$ cross sections as a function of the $J/\psi\, p_{\mathrm{T}}$, and both experiments have also extracted the inclusive branching fraction $\mathcal{B}(B \to \psi(2S)X)$.

Three of the bottomonium Υ states can be reconstructed in their dimuon decay channel, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. Due to the larger momentum, the background is lower than for the J/ψ and the Υ states can be cleanly identified at all four experiments. CMS [10] and LHCb [11] have presented measurements of the Υ cross sections as a function of the $\Upsilon\, p_{\mathrm{T}}$ and y, as reported in table III. The $\Upsilon(1S)$ cross section integrated over p_{T} as a function of y and the ratio of the cross sections of the $\Upsilon(2S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ are shown in fig. 2 for both experiments. Although there is no overlapping region in rapidity, the measurements show the same trend and are both consistent with

TABLE III. – *Summary of the Υ results from the CMS and LHCb experiments. The first uncertainty is statistical, the second systematic and the third due to the unknown Υ polarisation for LHCb and the luminosity for CMS.*

		$\int \mathcal{L}$ (pb^{-1})	p_{T} range (GeV/c)	y range	$\sigma^{\Upsilon} \times \mathcal{B}(\Upsilon \to \mu\mu)$ (nb)
LHCb	$\Upsilon(1S)$	25.0	0–15	$2.0 < y < 4.5$	$2.29 \pm 0.01 \pm 0.10^{+0.19}_{-0.37}$
	$\Upsilon(2S)$	25.0	0–15	$2.0 < y < 4.5$	$0.562 \pm 0.007 \pm 0.023^{+0.048}_{-0.092}$
	$\Upsilon(3S)$	25.0	0–15	$2.0 < y < 4.5$	$0.283 \pm 0.005 \pm 0.012^{+0.025}_{-0.048}$
CMS	$\Upsilon(1S)$	3.1	6.5–30	$\lvert y\rvert < 2.0$	$7.37 \pm 0.13^{+0.61}_{-0.42} \pm 0.81$
	$\Upsilon(2S)$	3.1	6.5–30	$\lvert y\rvert < 2.0$	$1.90 \pm 0.09^{+0.20}_{-0.14} \pm 0.24$
	$\Upsilon(3S)$	3.1	6.5–30	$\lvert y\rvert < 2.0$	$1.02 \pm 0.07^{+0.11}_{-0.08} \pm 0.11$

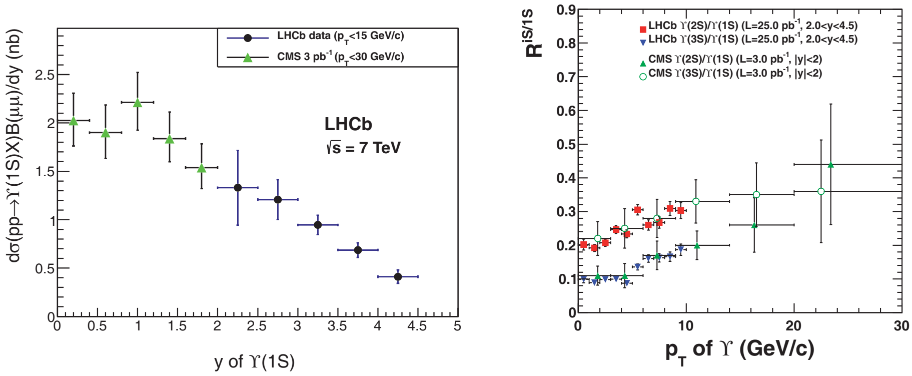

Fig. 2. – Left: $\Upsilon(1S)$ cross section integrated over p_{T} as a function of y for the CMS and LHCb experiments. Right: Ratio of the $\Upsilon(2S)$ and $\Upsilon(3S)$ to the $\Upsilon(1S)$ cross section, integrated over y as a function of p_{T}.

the theory models examined. The agreement of the measurement of the ratios shows that this quantity does not depend on the rapidity range. ATLAS has also measured the $\Upsilon(1S)$ cross section finding consistent results [12].

4. – χ_c and χ_b studies

The χ_c is a P-wave charmonium state which appears as a spin triplet $\chi_c^i, i = 0, 1, 2$, and can be identified through its decay into $J/\psi\gamma$. The low p_{T} of the γ involved makes its reconstruction challenging. LHCb, ATLAS and CMS have observed this state in a dataset varying between 0.035 and $1\,\mathrm{fb}^{-1}$ reconstructing the photon through its conversions into electrons, identified in the tracking systems. LHCb and CMS can clearly separate the three spin states. LHCb has measured the ratio of the cross sections of χ_{c2} to χ_{c1} and of χ_{c1} to J/ψ, using both photons reconstructed in the calorimeter and in the tracker. The ratio is measured as a function of the p_{T} of the J/ψ and it is consistent among the three measurements and with the theory expectations. The analogous P-wave bottomonium states $\chi_b(1P)$ and $\chi_b(2P)$ have also been observed by ATLAS and LHCb in their decay into $\Upsilon\gamma$. ATLAS has also recently claimed the first observation of the new $\chi_b(3P)$ state [13], confirmed by D0 very shortly afterwards [14]. More studies of this state are expected in the future.

5. – X(3872) mass and production

The intriguing X(3872) state decays into $J/\psi\pi^+\pi^-$ similarly to the $\psi(2S)$. CMS has identified 548 ± 104 X(3872) signal events and measured the production cross section of the X(3872) into $J/\psi\pi\pi$, relative to the $\psi(2S)$ cross section [15], finding

$$R = \frac{\sigma_X \times \mathcal{B}(X \to J/\psi\pi\pi)}{\sigma_{\psi(2S)} \times \mathcal{B}(\psi(2S) \to J/\psi\pi\pi)} = 0.087 \pm 0.017(\mathrm{stat}) \pm 0.009(\mathrm{syst})$$

in $40\,\mathrm{pb}^{-1}$. With 585 ± 74 events in $35\,\mathrm{pb}^{-1}$, LHCb has measured the X(3872) mass [16], finding the value of $\mathrm{M(X(3872))} = 3871.95 \pm 0.48\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst})\ \mathrm{MeV}/c^2$, in excellent agreement with the previous measurements. In the same sample LHCb has also measured the X(3872) production cross section [16], finding the value of $\sigma(pp \to X(3872)+\text{anything})\times\mathcal{B}(X(3872) \to \mu^+\mu^-\pi^+\pi^-) = 5.4\pm1.3(\text{stat})\pm0.8(\text{syst})\,\text{nb}$.

6. – Conclusions and outlook

We reviewed selected results from the four LHC experiments in the field of quarkonium production. The production cross sections of $J/\psi, \psi(2S), \chi_c, \Upsilon$ and X have been measured and agree well with the theoretical models considered. A first measurement of the J/ψ polarisation has been performed, and more are expected by the end of the year, with a better knowledge of the detectors and larger data samples.

A new state has been observed, which opens the route to an exciting era of discoveries. All these different components will be crucial in identifying the underlying model of quarkonium production.

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