Quarkonium results from LHCb

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During 2010 and 2011 the LHCb experiment [1] has collected a dataset corresponding to an integrated luminosity of 1 fb^{-1} in p-p collisions at $\sqrt{s} = 7$ TeV. We present results of the quarkonium production studies recently performed at LHCb. The experimental findings are compared with the theoretical predictions and with measurements from other experiments. A good agreement is found with the theory predictions.

1 Introduction

The mechanism for the production of quarkonia in hadronic collisions is not yet completely understood. It is well known that the LO Colour Singlet Model (CSM) leads to predictions of the cross-sections which are in disagreement with the observations at high p_{T}. New theoretical approaches have been proposed in recent years. For example, the Non-Relativistic QCD factorisation formalism, in which Colour Octet diagrams are introduced. Another approach consists in extending the computation of the cross-sections in Colour Singlet Model up to the NNLO. In the Colour Evaporation Model (CEM) instead, the probability of forming a specific quarkonium state is assumed to be independent of the color of the $Q\bar{Q}$ pair. The debate is still open and experimental confirmations from the LHC experiments are needed to determine the reliability of the proposed models.

Open charm can be produced in p-p collisions in association to a J/ψ meson or in association to another open charm hadron. Predictions for the production cross-sections exist and are given by the LO perturbative QCD, where calculations are made for the processes gg $\rightarrow$J/ψJ/ψ [2], gg $\rightarrow$J/$\psi c\bar{c}$ and gg $\rightarrow c\bar{c}c\bar{c}$ [3, 4]. These predictions are affected by uncertainties that can amount to a factor of two due to the selection of the α_s scale. In p-p collisions contributions from other mechanisms are possible, such as Double Parton Scattering (DPS) in which the factorisation of the two PDF is assumed [5, 6], or the intrinsic charm content of the proton (IC) [7]. Since such theories lead to different predictions for double charm(onium) cross-sections, experimental results from the LHC can give helpful hints and strong indications.

2 $\psi(2S)$, χ_c and $\Upsilon(nS)$ production cross-sections

Promptly produced $\psi(2S)$ mesons have not appreciable feed-down from higher mass charmonium states. This facilitates the comparison between the measured cross-section and the theory prediction. $\psi(2S)$ cross-section has been measured at LHCb [8] with an integrated luminosity of 36 pb^{-1}, exploiting the decay channels $\psi(2S) \rightarrow \mu^+\mu^-$ and $\psi(2S) \rightarrow$J/$\psi(\mu^+\mu^-)\pi^+\pi^-$.

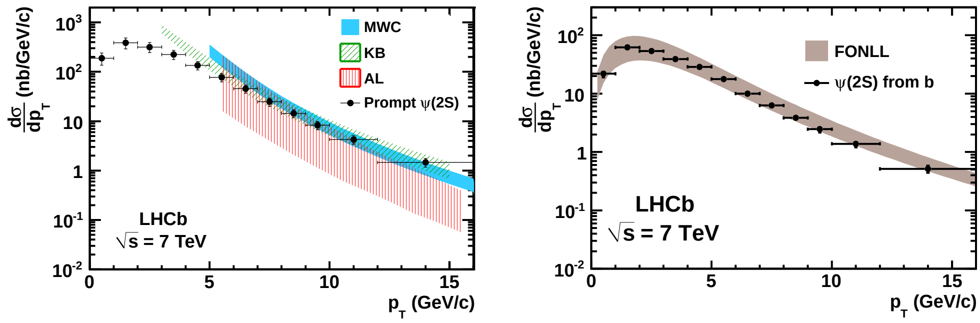

Figure 1: $\psi(2S)$ cross-section as a function of the transverse momentum for prompt mesons (left) and for $\psi(2S)$ originating from b-hadron decays (right) in the rapidity range $2 < y(\psi(2S)) < 4.5$. Experimental results are compared to theoretical predictions (see text).

Figure 1 (left) shows the measured cross-section for prompt $\psi(2S)$ as a function of the transverse momentum in the rapidity range $2 < y(\psi(2S)) < 4.5$. Since the polarisation state of the $\psi(2S)$ mesons is not measured yet, a systematic uncertainty is quoted and assigned to the cross-section. For comparison some theoretical predictions are also plotted: MWC [9] and KB [10] are NLO calculations including Colour Singlet and Colour Octet contributions. AL [11, 12] is a Colour Singlet model including the dominant NNLO terms. $\psi(2S)$ are also produced from b-hadron decays. They can be distinguished from promptly produced $\psi(2S)$ exploiting their finite decay time. Figure 1 (right) shows the measured cross-section for $\psi(2S)$ from b-hadrons as a function of the transverse momentum in the rapidity range $2 < y(\psi(2S)) < 4.5$. The shaded band is the prediction from a FONLL calculation [13, 14]. Combining these results with the LHCb J/ψ measurements given in Ref. [15] we determined the inclusive branching fraction $\mathcal{B}(b \to \psi(2S)X) = (2.73 \pm 0.06(\text{stat}) \pm 0.16(\text{syst}) \pm 0.24(\text{bf})) \times 10^{-3}$, where the last uncertainty originates from the uncertainties of the branching fractions involved in the measurement.
Feed-down from χ_c states provide a substantial contribution to prompt J/ψ through the decay $\chi_c \to$J/ψ γ, thus affecting the J/ψ cross-section and polarisation measurements. $\chi_{c1,2}$ have been selected at LHCb combining J/$\psi \to \mu^+\mu^-$ and $\gamma \to e^+e^-$ with converted photons in the tracking system [16]. Using a data sample corresponding to 370 pb^{-1}, the cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ has been measured as a function of the J/ψ transverse momentum and a good agreement with the NLO NRQCD predictions has been found for $p_{\rm T}$ above 8 GeV/c. Moreover LHCb has measured the prompt cross-section ratio $\sigma(\chi_c \to$J/ψ $\gamma)/\sigma($J/$\psi)$ with a data sample of 36 pb^{-1} [17]. In this case, good agreement with the NLO NRQCD predictions is found.
The bottomonium states $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ are abundantly produced in p-p collisions. Their production cross-sections have been measured at LHCb [18] with a data sample of 25 pb^{-1} in the fiducial region $2 < y(\Upsilon) < 4.5$ and $p_{\rm T}(\Upsilon) < 15$ GeV/c. The signal yields obtained from the mass fits are 26410±212 for $\Upsilon(1S) \to \mu^+\mu^-$, 6726±142 for $\Upsilon(2S) \to \mu^+\mu^-$ and 3260±112 for $\Upsilon(3S) \to \mu^+\mu^-$. Figure 2 (left) shows the ratios $\Upsilon(2S) \to \mu^+\mu^-$ and $\Upsilon(3S) \to \mu^+\mu^-$ with respect to $\Upsilon(1S) \to \mu^+\mu^-$ as a function of the Υ $p_{\rm T}$. Since the polarisation state of the Υ mesons is not measured yet, a systematic error is quoted and assigned to the cross-sections.

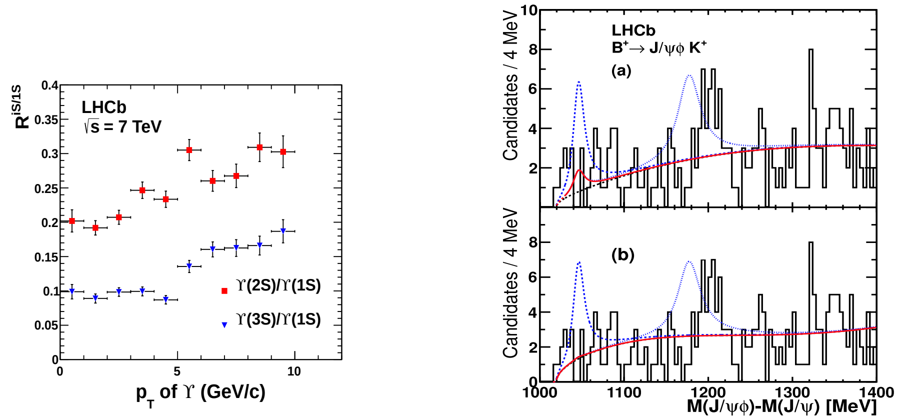

Figure 2: (Left) $\Upsilon(2S) \to \mu^+\mu^-$ and $\Upsilon(3S) \to \mu^+\mu^-$ to $\Upsilon(1S) \to \mu^+\mu^-$ production ratio as a function of the Υ transverse momentum. (Right) invariant mass difference $m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ for selected events at LHCb. The solid red line is the fitted curve while the dotted blue lines illustrate the expected X(4140) and X(4274) signal yields from the CDF measurement. The top and bottom plots differ by the background function definition.

3 Double charm production

As mentioned in the introduction, there is large theoretical interest in double charm production involving open charm. At LHCb, the J/ψC, CC and C$\bar{\text{C}}$ production cross-sections have been measured [19] in the fiducial region $3 < p_{\text{T}}(\text{C}) < 12$ GeV/c, $p_{\text{T}}(\text{J}/\psi) < 12$ GeV/c and $2 < y(\text{J}/\psi)$, $y(\text{C}) < 4$, where C=D^0,D^+,D_s^+,Λ_c^+. The analysis is based on a data sample of 355 pb^{-1}. Reconstructed and selected charmed hadrons are then required to be consistent with the same primary vertex. The pile-up has been accurately checked both with simulation and real data methods and it has been demonstrated to be negligible. Table 1 lists the measured cross-sections: the first uncertainty is statistical, the second is systematic. The dominant contribution to the systematic error comes from the hadron track reconstruction, with 2% error

Table 1: Double charm production cross-sections. The first uncertainty is statistical and the second is systematic.

Mode	σ [nb]	Mode	σ [nb]
$\text{J}/\psi\text{D}^0$	$161.0 \pm 3.7 \pm 12.2$	D^0D_s^+	$270 \pm 50 \pm 40$
$\text{J}/\psi\text{D}^+$	$56.6 \pm 1.7 \pm 5.9$	D^0D_s^-	$1680 \pm 110 \pm 240$
$\text{J}/\psi\text{D}_s^+$	$30.5 \pm 2.6 \pm 3.4$	D^+D^+	$80 \pm 10 \pm 10$
$\text{J}/\psi\Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$	D^+D^-	$780 \pm 40 \pm 130$
D^0D^0	$690 \pm 40 \pm 70$	D^+D_s^+	$70 \pm 15 \pm 10$
$\text{D}^0\bar{\text{D}}^0$	$6230 \pm 120 \pm 630$	D^+D_s^-	$550 \pm 60 \pm 90$
D^0D^+	$520 \pm 80 \pm 70$	$\text{D}^+\Lambda_c^+$	$60 \pm 30 \pm 20$
D^0D^-	$3990 \pm 90 \pm 500$	$\text{D}^+\bar{\Lambda}_c^-$	$530 \pm 130 \pm 170$
$\text{D}^0\bar{\Lambda}_c^-$	$2010 \pm 280 \pm 600$		

per track. The predictions from gluon-gluon fusion, when available, are significantly smaller than the measured cross-sections, while better agreement is found with the DPS model.

4 X(3872), X(4140) and X(4274) production studies

X(3872) have been reconstructed at LHCb in the decay channel X(3872)$\to$J/$\psi(\mu^+\mu^-)\pi^+\pi^-$ with a data sample corresponding to 35 pb^{-1} [20]. With a signal yield of 570 candidates, the production cross-section and the mass of the X(3872) have been measured. The obtained values are respectively $\sigma_{\mathrm{X}(3872)}\mathcal{B}_{J/\psi\pi^+\pi^-} = 4.7 \pm 1.1(\mathrm{stat}) \pm 0.7(\mathrm{syst})$ nb and $M_{\mathrm{X}(3872)} = 3871.95 \pm 0.48(\mathrm{stat}) \pm 0.12(\mathrm{syst})$ MeV$/c^2$. The dominant contributions to the systematic uncertainty on the mass measurement come from the momentum calibration scale ($\Delta m = 0.10$ MeV$/c^2$) and from the energy loss correction ($\Delta m = 0.05$ MeV$/c^2$). The mass value is a crucial input for the theory as it can help to understand the nature of the X(3872).

The CDF experiment has observed two narrow resonances in the J/$\psi\varphi$ system of the decay B$^\pm$ $\to$J/$\psi\varphi$ K$^\pm$ [21]. Such resonances, generally referred to as X(4140) and X(4274), are very close to the J/$\psi\varphi$ kinematic threshold and their physical nature is not understood. LHCb searched for such resonances in the decay B$^+$ $\to$J/$\psi\varphi$ K$^+$ and did not find evidence for the X(4140) nor for the X(4274) [22]. Figure 2 (right) shows the invariant mass difference $m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ for selected events at LHCb. The solid red line is the fitted curve while the dotted blue lines illustrate the expected X(4140) and X(4274) signal yields from the CDF measurement. The top and bottom plots differ by the background function definition. The following upper limits for the branching fraction ratios have been determined:

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\varphi)}{\mathcal{B}(B^+ \to J/\psi\varphi K^+)} < 0.07$$

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\varphi)}{\mathcal{B}(B^+ \to J/\psi\varphi K^+)} < 0.08$$

with 90% confidence level.

5 Conclusions

Quarkonia production studies performed at LHCb have been presented. The $\psi(2S)$, χ_c and $\Upsilon(nS)$ cross-sections are in good agreement with the theory predictions. Moreover LHCb has measured for the first time at a hadron collider, the charmed hadron pair production giving helpful hints to the theoretical models. Finally, the production of the exotic states X(3872), X(4140) and X(4274) has been studied: while the cross-section and the mass of the X(3872) have been measured with high precision, LHCb does not confirm the existence of the states X(4140) and X(4274) previously claimed by the CDF experiment.

References

[1] The LHCb collaboration, A. Augusto Alves Jr. *et al.*, *The LHCb Detector at the LHC*, JINST 3 (2008) S08005.

[2] A. V. Berezhnoy, A. K. Likhoded, A. V. Luchinsky and A. A. Novoselov, *Double J/ψ meson Production at LHC and 4c-tetraquark state*, Phys. Rev. D84 (2011) 094023, arXiv:1101.5881.

[3] A. V. Berezhnoy, V. V. Kiselev, A. K. Likhoded and A. I. Onishchenko, *Doubly charmed baryon production in hadronic experiments*, Phys. Rev. D57 (1998) 4385, arXiv:hep-ph/9710339.

[4] S. P. Baranov, *Topics in associated $J/\psi + c\bar{c}$ production at modern colliders*, Phys. Rev. D73 (2006) 074021.

[5] C. H. Kom, A. Kulesza, and W. J. Stirling, *Pair production of J/ψ as a probe of double parton scattering at LHCb*, Phys. Rev. Lett. 107 (2011) 082002, arXiv:1105.4186.

[6] S. P. Baranov, A. M. Snigirev, and N. P. Zotov, *Double heavy meson production through double parton scattering in hadronic collisions*, Phys. Lett. B705 (2011) 116, arXiv:1105.6276.

[7] S. Brodsky et al., *The intrinsic charm of the proton*, Phys. Lett. B93 (1980) 451.

[8] The LHCb collaboration, R. Aaij *et al.*, *Measurement of $\psi(2S)$ meson production in pp collisions at $\sqrt{s} = 7$ TeV*, LHCb-PAPER-2011-045, CERN-PH-EP-2012-094, arXiv:1204.1258v1 [hep-ex].

[9] Y.-Q. Ma, K. Wang and K.-T. Chao, *A complete NLO calculation of the J/ψ and ψ' production at hadron colliders*, arXiv:hep-ph/1012.1030.

[10] B. Kniehl and M. Butenschön, *Reconciling J/ψ production at HERA, RHIC, Tevatron, and LHC with nonrelativistic QCD factorization at next-to-leading order*, Phys. Rev. Lett. 106 (2011) 022003, and private communication.

[11] P. Artoisenet *et al.*, *Υ production at Fermilab Tevatron and LHC energies*, Phys. Rev. Lett. 101 (2008) 152001.

[12] J.-P. Lansberg, *On the mechanisms of heavy-quarkonium hadroproduction*, Eur. Phys. J. C61 (2009) 693.

[13] M. Cacciari, M. Greco, P. Nason, *The p_T spectrum in heavy-flavour hadroproduction*, JHEP 9805 (1998) 007.

[14] M. Cacciari, S. Frixione, M. Mangano, P. Nason and G. Ridolfi, *QCD analysis of first b cross-section data at 1.96 TeV*, JHEP 0407 (2004) 033.

[15] The LHCb collaboration, R. Aaij *et al.*, *Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C71 (2011) 1645.

[16] The LHCb collaboration, R. Aaij *et al.*, *Measurement of the cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ for prompt χ_c production at $\sqrt{s} = 7$ TeV*, arXiv:1202.1080, LHCB-PAPER-2011-019, CERN-PH-EP-2011-227.

[17] The LHCb collaboration, R. Aaij *et al.*, *Measurement of the ratio of prompt χ_c to J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV*, arXiv:1204.1462, CERN-PH-EP-2012-068, LHCB-PAPER-2011-030.

[18] The LHCb collaboration, R. Aaij *et al.*, *Measurement of Υ production in pp collisions at $\sqrt{s} = 7$ TeV*, arXiv:1202.6579, CERN-PH-EP-2012-051, LHCB-PAPER-2011-036.

[19] The LHCb collaboration, R. Aaij *et al.*, *Observation of double charm production involving open charm in pp collisions at $\sqrt{s} = 7$ TeV*, arXiv:1205.0975, CERN-PH-EP-2012-109, LHCB-PAPER-2012-003.

[20] The LHCb collaboration, R. Aaij *et al.*, *Observation of X(3872) production in pp collisions at $\sqrt{s} = 7$ TeV*, arXiv:1112.5310, LHCB-PAPER-2011-034, CERN-PH-EP-2011-216.

[21] CDF collaboration, T. Aaltonen *et al.*, *Observation of the Y(4140) structure in the $J/\psi\varphi$ mass spectrum in $B^{\pm} \to J/\psi\varphi K$ decays*, arXiv:1101.6058.

[22] The LHCb collaboration, R. Aaij *et al.*, *Search for the X(4140) state in $B^+ \to J/\psi\varphi K^+$ decays*, arXiv:1202.5087, CERN-PH-EP-2012-004, LHCB-PAPER-2011-033.