Quarkonia in dimuon final states and exclusive dimuon decays at LHCb

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Quarkonia cross-sections in hadron collisions are fundamental observables for understanding the production mechanisms. Exploiting the dimuon decay mode, the cross-sections for J/ψ, double J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ production have been measured at LHCb [1] with pp collisions at $\sqrt{s} = 7$ TeV. Moreover exclusive dimuon production, both resonant and non-resonant, has been studied and the cross-sections have been measured.

1 Introduction

Quarkonium production mechanisms in hadronic collisions are still subject of large interest and debate. It is well known that the Leading Order Color Singlet Model (CSM), leads to predictions of the cross-sections which are in disagreement with measurements [2], [3]. In recent years other models have been introduced like, for example, the Color Octet Model (COM), which in the framework of Non-Relativistic QCD (NRQCD) allows a better description of the observed cross-sections. The measurement of J/ψ, $\psi(2S)$ and Y production cross-sections at LHC energies is crucial for the understanding of the relative contributions of CSM and COM. Further hints can be given from double J/ψ production cross-section where higher order corrections are suppressed. Moreover measurements of exclusive dimuon events allow the behaviour of other states predicted by QCD, such as the pomeron and (so far unobserved) odderon, to be studied in a clean environment.

2 J/ψ cross-section

The J/ψ production cross-section has been measured at LHCb [4] with an integrated luminosity of 5.2 pb^{-1} in the fiducial region $2 < y < 4.5$ and $0 < p_{\text{T}} < 14$ GeV/c. The

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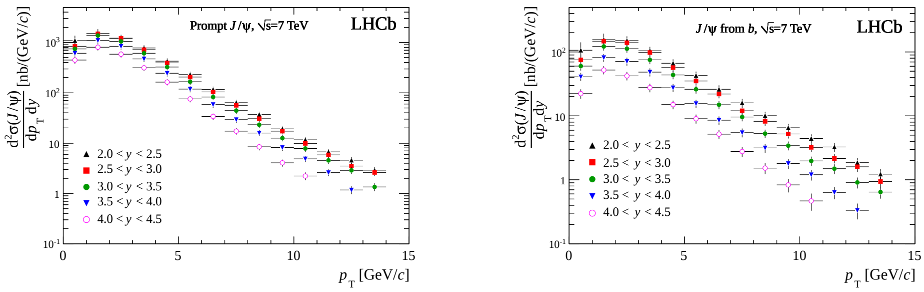


(a) **(b)**

Figure 1: Double differential cross-section in bins of p_{T} and y for promptly produced J/ψ (a) and for J/ψ from b-hadrons (b). Prompt J/ψ are assumed to be unpolarized.

J/ψ candidates have been reconstructed in the dimuon decay mode by fitting two tracks, identified as muons, to a common vertex. Prompt J/ψ, produced either directly in pp collisions or via feed-down from higher charmonium states, are separated from those produced in the decays of b-hadrons using the pseudo-propertime variable defined as $t_z = (z_{J/\psi} - z_{PV})M_{J/\psi}/p_z$, where the subscript $_{PV}$ stands for Primary Vertex, z is the coordinate along the beam axis and p_z is the component of the J/ψ momentum along the z direction. The cross-section has been measured in 14 bins of p_{T} and 5 bins of y. In each bin a simultaneous fit to the dimuon invariant mass and pseudo-propertime distributions has been performed in order to determine the number of prompt and non-prompt signal events. The number of events has then been corrected by the efficiency factors calculated from LHCb Monte Carlo simulation. The results are quoted in three different polarization scenarios: longitudinally polarized J/ψ, transversally polarized J/ψ and unpolarized J/ψ. Figure 1 shows the cross-section measured as a function of transverse momentum and rapidity. The cross-section integrated over the fiducial region is $\sigma = 10.52 \pm 0.04(\text{stat}) \pm 1.40(\text{syst})^{+1.64}_{-2.20}\ \mu\text{b}$ for prompt J/ψ and $\sigma = 1.14 \pm 0.01(\text{stat}) \pm 0.16(\text{syst})\ \mu\text{b}$ for J/ψ from b-hadrons. The asymmetric error on the prompt cross-section is due to the unknown polarization. Good agreement is found between data and theory predictions in particular with NLO NRQCD for prompt J/ψ and with FONLL model for J/ψ from b-hadrons.

3 Double J/ψ cross-section

Studies of double J/ψ production also allow the production mechanisms to be probed. Such production can be affected by the existence of charm tetra-quark states. At LHCb the double J/ψ production cross-section has been measured in the fiducial region $2 < y < 4.5$ and $0 < p_{\mathrm{T}} < 10$ GeV$/c$ exploiting the dimuon decay mode [5]. The data sample used to perform the measurement corresponds to an integrated luminosity of 35.2 pb^{-1}. The strategy consists in reconstructing two muon pairs $(\mu^+,\mu^-)_1$ and $(\mu^+,\mu^-)_2$ in the same event.

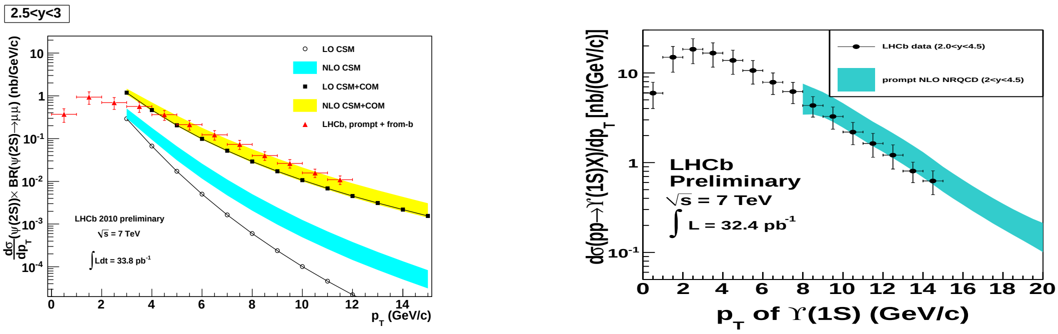
In selecting candidates, particular care has been used to minimize the effect of duplicate tracks created by the reconstruction, while the pile-up effect (two J/ψ from consecutive collisions wrongly assigned to the same collision) has been demonstrated to be negligible. The distribution of $(\mu^+,\mu^-)_1$ invariant mass is fitted in bins of $(\mu^+,\mu^-)_2$ invariant mass in order to extract the total number of double J/ψ. The number of signal events is corrected by the efficiency factor to take into account the detector and selection effect. The cross-section measured is $\sigma_{J/\psi J/\psi} = 5.6 \pm 1.1 \pm 1.2$ nb where the first uncertainty is statistical and the second is systematic. The result can be compared with a LO QCD calculation [6] which predicts a value of 4.34 nb (4.15 nb) with (without) initial state gluon radiations.

4 $\psi(2S)$ cross-section

The $\psi(2S)$ meson, unlike J/ψ, has not appreciable feed-down from higher mass charmonium states, therefore the prompt cross-section is easier to interpret and it can be directly compared with the theory predictions. The inclusive $\psi(2S)$ cross-section has been measured at LHCb [7] with an integrated luminosity of 33.8 pb^{-1} exploiting the dimuon decay mode. The measurement has been performed in bins of p_{T} and y, in the fiducial region $0 < p_{\mathrm{T}} < 12$ GeV$/c$ and $2 < y < 4.5$. The selection is similar to the $J/\psi \to \mu^+\mu^-$ one but with a harder cut on the muon p_{T}: $p_{\mathrm{T}} > 1.2$ GeV$/c$ instead of $p_{\mathrm{T}} > 0.7$ GeV$/c$. No division into prompt and non-prompt components has yet been performed: the fraction of $\psi(2S)$ from b is expected to be of the order of 10% at low p_{T} and 40% at large p_{T}. Figure 2 (a) shows a comparison between the inclusive cross-section measured at LHCb and the predictions for prompt cross-section by different theoretical models [8]. The cross-section measured, integrated over the fiducial region, is $\sigma = 1.88 \pm 0.02(\mathrm{stat}) \pm 0.31(\mathrm{syst})^{+0.25}_{-0.48}$ μb, where the last asymmetric error is due to the unknown polarization.

5 $\Upsilon(1S)$ cross-section

At LHCb, the $\Upsilon(1S)$ production cross-section has been measured [9] with a data sample of 32.4 pb^{-1}. The measurement has been performed in bins of p_{T} and y, in the fiducial region $0 < p_{\mathrm{T}} < 15$ GeV$/c$ and $2 < y < 4.5$. Thanks to the experimental resolution of about 50 MeV$/c^2$ it has been possible to separate fully the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ invariant mass peaks. The strategy for the cross-section measurement is the same already discussed above. The cross-section integrated over the fiducial region, assuming unpolarized $\Upsilon(1S)$, results to be $\sigma = 108.3 \pm 0.7^{+30.9}_{-25.8}$ nb, where the first uncertainty is statistical and the second is systematic. Figure 2 (b) shows a comparison between the cross-section measured and a theoretical prediction from NLO NRQCD.



(a) **(b)**

Figure 2: (a) Differential cross-section in bins of p_{T} in the range $2.5 < y < 3$ for inclusive $\psi(2S)$ production. The predictions from theoretical models are made for prompt $\psi(2S)$ production. (b) Comparison between $\Upsilon(1S)$ cross-section measured at LHCb and NLO NRQCD predictions.

6 Exclusive dimuon production

Exclusive dimuon events, $pp \rightarrow p\mu^+\mu^-p$, are collisions in which an elastic interaction occurs between the two protons: they proceed undetected in the beam pipe and the event is characterized exclusively by only two muons. The two muons can be non-resonant, or resonant through intermediate production of a J/ψ, $\psi(2S)$ or χ_c state. Exclusive dimuon events allow to understand QCD in a clean environment, as they are unambiguous evidence for pomeron existence and allow to search for the odderon.

The selection requires no backward tracks (the Vertex Locator of LHCb allows some coverage for negative pseudorapidity: $-4 < \eta < -1.5$) and only two forward muons with $p_{\mathrm{T}}(\mu\mu) < 900$ MeV$/c$ to reduce the contamination from inelastic production. Moreover for χ_c, precisely one photon is required in addition. The measurement has been performed at LHCb with 36 pb^{-1} [10]. Table 1 reports the cross-sections measured for different dimuon productions. Theory predictions in this sector are rather uncertain and vary significantly. For example for exclusive J/ψ production there are predictions from 292 pb (Starlight), 330 pb (SuperChic) up to 710 pb [11].

7 Conclusions

Quarkonia production cross-section measurements, exploiting the dimuon decay mode, have been presented. The cross-sections are generally in good agreement with theory. Moreover a detailed study of the exclusive dimuon events has allowed the measurement of

Dimuon process	cross-section (pb)
$J/\psi \to \mu^+\mu^-$	$\sigma = 474 \pm 12 \pm 51 \pm 92$
$\psi(2S) \to \mu^+\mu^-$	$\sigma = 12.2 \pm 1.8 \pm 1.3 \pm 2.4$
$\chi_{c0} \to J/\psi(\mu^+\mu^-)\gamma$	$\sigma = 9.3 \pm 2.2 \pm 3.5 \pm 1.8$
$\chi_{c1} \to J/\psi(\mu^+\mu^-)\gamma$	$\sigma = 16.4 \pm 5.3 \pm 5.8 \pm 3.2$
$\chi_{c2} \to J/\psi(\mu^+\mu^-)\gamma$	$\sigma = 28.0 \pm 5.4 \pm 9.7 \pm 5.4$
non-resonant $\mu^+\mu^-$	$\sigma = 67 \pm 10 \pm 7 \pm 15$

Table 1: Cross-sections measured at LHCb for exclusive dimuon production. The pseudo-rapidity $\eta_\mu, \eta_\gamma \in [2, 4.5]$ and $m_{\mu^+\mu^-} > 2.5\,\text{GeV}/c^2$ for the non-resonant cross-section.

the cross-sections for resonant and non-resonant production, providing important input for comparisons with theory.

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