Quarkonium Production at LHCb

Giacomo Graziani
on behalf of the LHCb collaboration
INFN, Sezione di Firenze, Italy

1 Introduction

The LHCb detector [1] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Its excellent performance in reconstructing decays of heavy hadrons allows to study the production of quarkonia states both in a unique rapidity range and at the new energy frontier brought by the LHC. As an example, the combined performance of the vertexing, tracking and muon identification detectors allow to reconstruct $J/\psi \to \mu^+\mu^-$ decays with a mass resolution of about 15 MeV/c^2 and a background contamination at the per cent level. Moreover, the trigger of the experiment is able to effectively select high–mass dimuons and single muons with relatively low ($\sim$ 1.5 GeV/c) transverse momentum threshold, and about one half of the trigger bandwidth, reaching 5 kHz in 2012, is devoted to muon and dimuon lines.

The first data sample collected during the 2010 run, corresponding to a 37 pb^{-1} integrated luminosity of pp collisions at $\sqrt{s} = 7$ TeV, allowed for the first production studies. Processes more statistically limited are studied using the 2011 data sample, corresponding to 1.1 fb^{-1}. The experiment is actually running at $\sqrt{s} = 8$ TeV, aiming at collecting 1.5 fb^{-1} by the end of 2012.

2 Production of charmonium and bottomonium

The production cross-sections for J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ (n=1,2,3) are studied using the dimuon decay mode. Such measurements provide a testbench for QCD production models, notably to probe for possible color octet (CO) contributions beside the predictions obtained in the framework of the the color singlet exchange model (CSM). For the charmonium states, the prompt component is cleanly separated from the delayed component due to b decays using the excellent proper time resolution of the detector. Already with the 2010 data sample, the systematic error, notably from the unknown state polarization, dominates the total uncertainty.

The measured cross-sections as a function of the transverse momentum p_{T} are compared to theoretical predictions, bearing in mind that most calculations only predict the direct component (excluding feed–down from higher states) and often do not cover the lowest p_{T} region. A few of these comparisons [2, 3, 4] are shown in Fig. 1. An excess by two order of magnitudes of the observed charmonium production with respect to leading order CSM predictions at high p_{T} is observed, confirming the Tevatron findings. Recently available NLO and NNLO calculations based on CSM seem to explain the gap, yet with large uncertainty. When available, non–perturbative calculations including CO contributions seem to reproduce the experimental observations more accurately. The production of J/ψ and $\psi(2S)$ from b decays agree remarkably well with the prediction in the FONLL approach [5].

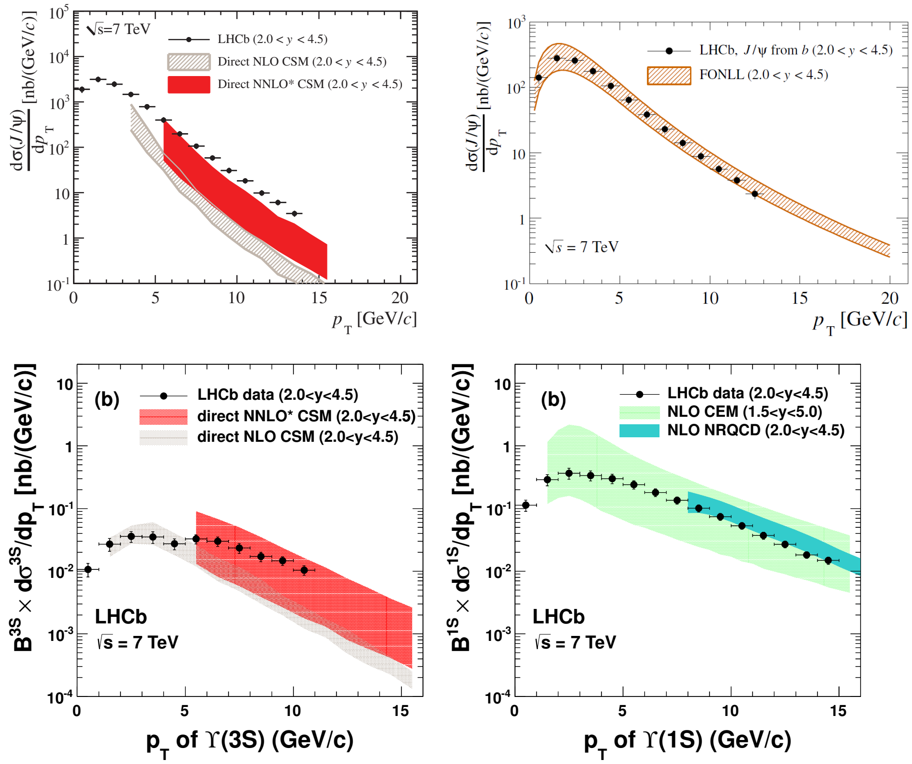

Figure 1: The upper plots show the p_{T} dependence of the J/ψ production cross section for the prompt (left) and delayed (right) components. The lower plots show the results for two of the bottomonium states. The results for $\Upsilon(3S)$, free from feed–down due to higher states, and for prompt J/ψ are compared with NLO and NNLO predictions based on CSM perturbative calculations [6]. The result for $\Upsilon(1S)$ is compared with effective models including CO contributions: NRQCD [8] and CEM [7].

The production of χ_c mesons has been studied using the radiative decay to J/ψ [9]. Despite the low photon energy and the harsh hadronic environment, a clean sample of χ_c was obtained using converted and unconverted photons. The LO CSM calculations are unable to reproduce the p_{T} spectrum shape, as opposite to the NLO NRQCD predictions. The ratio of χ_{c2} to χ_{c1} production cross–sections seems larger than any prediction [10, 11].

All results assume unpolarized quarkonia states. The polarization can be measured via an angular analysis in order to reduce the main uncertainty on cross sections, but also to provide a crucial test of production models. Acceptance effects strongly affect the angular distributions, introducing potentially severe systematic effects. Results for the J/ψ polarization are expected in the near future.

3 The B_c^+ meson

As the only meson consisting of two heavy quarks with different flavour, the B_c^+ provides another important testbench for hadronic models and has a rich spectroscopy to be explored. Only the ground state was observed so far at the Tevatron [12]. Using 2010 data, LHCb provided an accurate mass measurement using the $J/\psi\ \pi^+$ decay mode. A preliminary result was also obtained[13] for the B_c^+ production, normalized to the B^+, for $p_{\mathrm{T}} > 4$ GeV/c, $2.5 < \eta < 4.5$:

$$\frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \to J/\psi\,K^+)} = (2.2 \pm 0.8_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}})\%.$$

Using the 2011 data sample, both the statistical and systematic uncertainties, the latter being dominated by the uncertainty on the B_c^+ lifetime, will be improved. Other B_c^+ decay modes are expected to be discovered, the first of which being $B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+$, for which LHCb measures[14]

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)} = 2.41 \pm 0.30_{\mathrm{stat}} \pm 0.33_{\mathrm{syst}},$$

in good agreement with the theoretical predictions, ranging from 1.5 to 2.3.

4 Double $c\bar{c}$ production

The energy and luminosity of the LHC also provides the possibility to study the production of multiple pairs of heavy quarks. Double $c\bar{c}$ production can be expected in single parton collisions via high order gluon-gluon diagrams, with strong sensitivity to possible CO contributions, but could also be enhanced by double parton scattering (DPS) and by the charm content of the proton. A simple, maybe naive, model for DPS consists in assuming the two simultaneous parton collisions (labeled 1 and 2) to occur independently:

$$\frac{\sigma_{C_1}\sigma_{C_2}}{\sigma_{C_1C_2}} = \sigma_{eff}^{DPS} \tag{1}$$

where the constant σ_{eff}^{DPS} was determined, in this hypothesis, to be about 15 mb according to studies on multi–jet events performed at the Tevatron[17].

Double J/ψ production is observed already from the 2010 sample, from which 116 ± 16 events are selected, corresponding to a production cross section[15] $\sigma(J/\psi\, J/\psi) = 5.1 \pm 1.0_{\rm stat} \pm 1.1_{\rm syst}$ nb. The result agrees with the LO CSM prediction, while the predicted 50% enhancement from DPS can not be excluded within the experimental and theoretical uncertainties.

The simultaneous production of a J/ψ meson and an open charm state C was also studied, with C= $D^0(\to K^-\pi^+)$, $D^+(\to K^-\pi^+\pi^+)$, $D_s^+(\to \phi\pi^+)$ or $\Lambda_c^+(\to pK^-\pi^+)$, using 355 pb^{-1}.

Due to the highest production cross section of open charm modes [16], these modes are much more sensitive to DPS, whose contribution, according to eq. 1, exceeds by one order of magnitude the available LO CSM predictions for single collisions. The production of these four modes, together with six of the CC modes, was established with a significance of more than 3σ [18]. As shown in Fig. 2, the results for the J/ψ C modes agree nicely with the naive DPS prediction, though this is not the case for the CC modes, whose observed yields are lower by a factor 2 to 3 with respect to the same model.

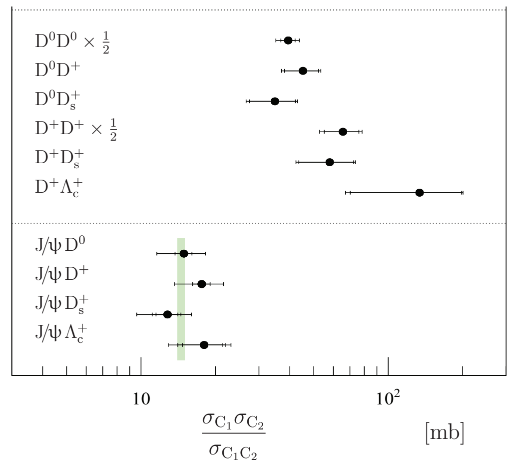

Figure 2: Results for double charm production involving open charm. The ratio of equation 1 is compared with the value σ_{eff}^{DPS} predicted by the simple DPS interpretation (shaded line) for the different observed modes .

5 Conclusions and outlook

Unique measurements of the production of quarkonia and quarkonia–like states have been obtained with the LHCb experiment. These studies provide valuable input to improve the accuracy of theoretical models. These studies are being repeated for the higher energy of the 2012 run, and extended to other states as the χ_b. New decay modes for the relatively unexplored B_c^+ are also expected to be observed, and the uncertainty on its lifetime will be reduced using the 2011 data. More exotic states as the recently reported X, Y, Z states, as well as tetra and pentaquark states, are also being actively searched for [19, 20].

References

[1] A. A. Alves, Jr. *et al.* [LHCb collaboration], JINST **3** (2008) S08005.

[2] R. Aaij *et al.* [LHCb collaboration], Eur. Phys. J. C **71** (2011) 1645

[3] R. Aaij *et al.* [LHCb collaboration], Eur. Phys. J. C **72** (2012) 2100

[4] R. Aaij *et al.* [LHCb collaboration], Eur. Phys. J. C **72** (2012) 2025

[5] M. Cacciari, S. Frixione and P. Nason, JHEP **0103** (2001) 006

[6] J. P. Lansberg, Eur. Phys. J. C **61** (2009) 693

[7] A. D. Frawley, T. Ullrich and R. Vogt, Phys. Rept. **462** (2008) 125

[8] Y. -Q. Ma, K. Wang and K. -T. Chao, Phys. Rev. Lett. **106** (2011) 042002

[9] R.Aaij *et al.* [LHCb collaboration],

[10] R. Aaij *et al.* [LHCb collaboration], Phys. Lett. B **714** (2012) 215

[11] R. Aaij *et al.* [LHCb collaboration], LHCb-CONF-2012-062

[12] F. Abe *et al.* [CDF collaboration], Phys. Rev. Lett. **81** (1998) 2432

[13] R. Aaij *et al.* [LHCb collaboration], LHCb-CONF-2011-017

[14] R. Aaij *et al.* [LHCb collaboration], Phys. Rev. Lett. **108** (2012) 251802

[15] R. Aaij *et al.* [LHCb collaboration], Phys. Lett. B **707** (2012) 52

[16] R. Aaij *et al.* [LHCb collaboration], LHCb-CONF-2010-013

[17] F. Abe *et al.* [CDF collaboration], Phys. Rev. D **56** (1997) 3811.

[18] R. Aaij *et al.* [LHCb collaboration], JHEP **1206** (2012) 141

[19] R. Aaij *et al.* [LHCb collaboration], Eur. Phys. J. C **72** (2012) 1972

[20] R. Aaij *et al.* [LHCb collaboration], Phys. Rev. D **85** (2012) 091103