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LHCb results on production, polarisation and production asymmetries

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The LHCb experiment is producing many interesting results in heavy flavour physics sector. Some recent results are presented and discussed here. In particular we present the measurement of the J/ψ and $\Upsilon(nS)$ production cross-sections at $\sqrt{s} = 8$ TeV, the $\Lambda_b^0 \to J/\psi\Lambda$ decay amplitudes and polarisation, and the forward-central $b\bar{b}$ production asymmetry. Comparisons with the theoretical predictions are also showed.

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1. Introduction

Heavy quarkonium production at hadron machines is still an open problem in QCD. In the framework of non-relativistic QCD (NRQCD) [1,2], the production of heavy quarkonium factorises into two steps: the heavy quark-antiquark pair initially created at short distances subsequently evolves non-perturbatively into quarkonium. NRQCD, which is based on the colour-singlet (CS) and colour-octet (CO) matrix elements, allows to resolve the discrepancy observed between the J/ψ cross-section measured at the Tevatron [3] and the cross-section estimated through the CS model [4, 5]. More recent higher-order calculations [6–9] close the gap between the CS model predictions and the experimental data [10], reducing the need for large CO contributions. After the measurements of J/ψ and $\Upsilon(nS)$ production cross-sections at lower energies ($\sqrt{s} = 7$ TeV [11,12], $\sqrt{s} = 2.76$ TeV [13]), LHCb has performed the first measurements of quarkonium production at $\sqrt{s} = 8$ TeV [14] providing a new hint for the theory.

Hadro-production mechanisms are not yet fully understood not only for quarkonium, but also for the production of barions: Λ_b^0 produced in pp collisions are expected to be polarised transversally according to the Heavy Quark Effective Theory (HQET), which predicts that a large fraction of the b-quark transverse polarisation is retained after hadronisation [15,16]. LHCb has performed the first measurement ever, at hadron machines, of the $\Lambda_b^0 \to J/\psi\Lambda$ decay amplitudes and Λ_b^0 polarisation [17].

Another interesting result that is discussed here is the forward-central $b\overline{b}$ production asymmetry, which provides useful constraints to any models attempting to explain the intriguing Tevatron results [18] on the forward-backward $t\overline{t}$ production asymmetry.

2. J/ψ and $\Upsilon(nS)$ production at $\sqrt{s} = 8$ TeV

In this analysis, $\Upsilon(nS)$ $(n = 1,2,3)$ and J/ψ are reconstructed in the dimuon decay channel. Data analysed have been collected by LHCb during April 2012 and correspond to an integrated luminosity of 51 pb^{-1} for $\Upsilon(nS)$ and 18 pb^{-1} for J/ψ. Transverse momentum (p_{T}) and rapidity (y) of the selected mesons are limited to the fiducial region $p_{\mathrm{T}} < 14$ GeV/c ($p_{\mathrm{T}} < 15$ GeV/c for $\Upsilon(nS)$) and $2.0 < y < 4.5$. In the selection two oppositely charged particles, identified as muons and with good quality track fit, are required to originate from a common vertex. Prompt J/ψ mesons are separated from those from b-hadron decays by exploiting the pseudo-decaytime variable defined as $t_z = (z_{J/\psi} - z_{\mathrm{PV}})M_{J/\psi}/p_z$, where $z_{J/\psi}$ and z_{PV} are the positions along the beam axis z of the J/ψ decay vertex and of the primary vertex, p_z is the z-component of the measured momentum and $M_{J/\psi}$ is the J/ψ nominal mass [19]. The differential cross-section for the production of a vector meson V in a bin of (p_{T}, y), decaying into a muon pair, is

$$\frac{d^2\sigma}{dp_{\mathrm{T}}dy}(pp \to VX) = \frac{N(V \to \mu^+\mu^-)}{\mathscr{L} \times \varepsilon_{\mathrm{tot}} \times \mathscr{B}(V \to \mu^+\mu^-) \times \Delta y \times \Delta p_{\mathrm{T}}} \tag{2.1}$$

where $N(V \to \mu^+\mu^-)$ and $\varepsilon_{\mathrm{tot}}$ are the number of observed events and the total detection efficiency respectively in the given bin, $\mathscr{L}$ is the integrated luminosity, $\mathscr{B}(V \to \mu^+\mu^-)$ is the dimuon branching fraction of the vector meson V [19], and Δy and Δp_{T} are the bin sizes. The efficiency has been determined from Monte Carlo simulation and has been extensively validated with data.

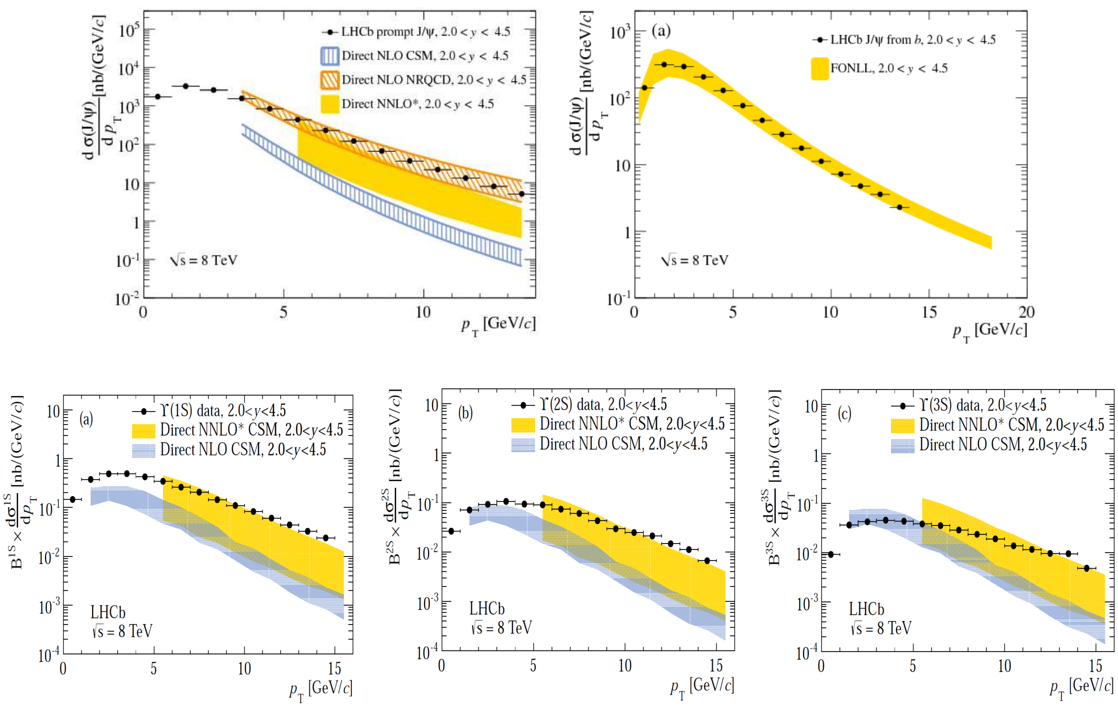

Figure 1: Differential cross-section (under the assumption of zero polarisation) as a function of p_{T} for the production of prompt J/ψ mesons (top-left), J/ψ from b-hadron decays (top-right), $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ (bottom, from left to right). Theoretical predictions are drawn for comparison.

Among the systematic uncertainties, a major contribution comes from the trigger efficiency (4%) and from the luminosity determination (5%). The cross-sections are given here in the hypothesis of unpolarised mesons. Figure 1 shows the measured cross-sections, under the assumption of zero polarisation, as a function of p_{T}, for prompt J/ψ mesons, J/ψ from b-hadron decays, for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. Theoretical predictions are also shown for comparison with data. The measured cross-sections integrated over p_{T} and y are:

$$\sigma(\text{prompt } J/\psi) = 10.94 \pm 0.02 \pm 0.79\ \mu\text{b} \tag{2.2}$$

$$\sigma(J/\psi \text{ from } b) = 1.28 \pm 0.01 \pm 0.11\ \mu\text{b} \tag{2.3}$$

$$\sigma(\Upsilon(1S)) \times \mathscr{B}(\Upsilon(1S) \to \mu^+\mu^-) = 3.241 \pm 0.018 \pm 0.231 \text{ nb} \tag{2.4}$$

$$\sigma(\Upsilon(2S)) \times \mathscr{B}(\Upsilon(2S) \to \mu^+\mu^-) = 0.761 \pm 0.008 \pm 0.055 \text{ nb} \tag{2.5}$$

$$\sigma(\Upsilon(3S)) \times \mathscr{B}(\Upsilon(3S) \to \mu^+\mu^-) = 0.369 \pm 0.005 \pm 0.027 \text{ nb} \tag{2.6}$$

where the first uncertainty is statistical and the second systematic.

3. $\Lambda_b^0 \to J/\psi\Lambda$ decay amplitudes and Λ_b^0 polarisation

The Λ_b^0 spin has not yet measured but the quark model prediction is spin $\frac{1}{2}$. Thus $\Lambda_b^0 \to J/\psi\Lambda$ is a decay of a spin $\frac{1}{2}$ particle into a spin 1 and a spin $\frac{1}{2}$ particle. The $\Lambda_b^0 \to J/\psi\Lambda$ decay dynamics

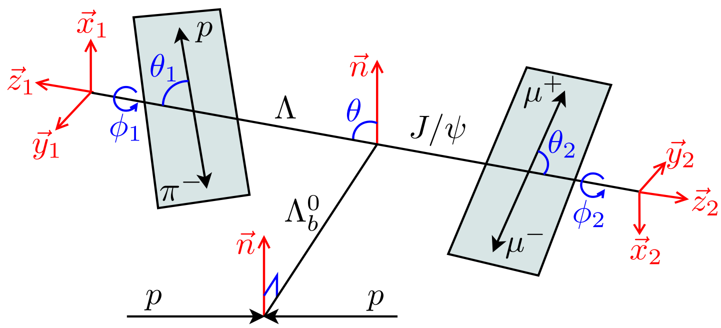

Figure 2: Definition of the five angles used to describe the $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ decay.

can be probed looking at five angles as shown in Fig. 2, where $\vec{n}$ is the normal to the production plane, θ is the angle between $\vec{n}$ and the Λ momentum in the Λ_b^0 rest-frame, (θ_1, ϕ_1) are the polar and azimuthal angles of the proton momentum in the Λ rest-frame, and (θ_2, ϕ_2) are the polar and azimuthal angles of the μ^+ momentum in the J/ψ rest-frame. Integrating over the two azimuthal angles ϕ_1 and ϕ_2, in the helicity amplitudes formalism the decay distribution can be written as:

$$\frac{d\Gamma}{d\Omega_3} = \frac{1}{16\pi}\sum_{i=0}^{7} = f_i(a_+, a_-, b_+, b_-) g_i(P_b, \alpha_\Lambda) h_i(\cos\theta, \cos\theta_1, \cos\theta_2) \tag{3.1}$$

where $a_+ = \mathscr{M}_{+\frac{1}{2},0}$, $a_- = \mathscr{M}_{-\frac{1}{2},0}$, $b_+ = \mathscr{M}_{-\frac{1}{2},-1}$ and $b_- = \mathscr{M}_{+\frac{1}{2},+1}$ are the helicity amplitudes, P_b is the Λ_b^0 transverse polarisation parameter and α_Λ is the Λ asymmetry parameter. The functions f_i, g_i and h_i are defined in detail in [17]. The analysis is based on 1 fb^{-1} of data collected in 2011 at $\sqrt{s} = 7$ TeV. Due to the different levels of background, the events are classified into two categories and are analysed separately: Λ decays outside the Vertex Locator (downstream events, see Fig. 3-left); Λ decays inside the Vertex Locator (long events, see Fig. 3-right).

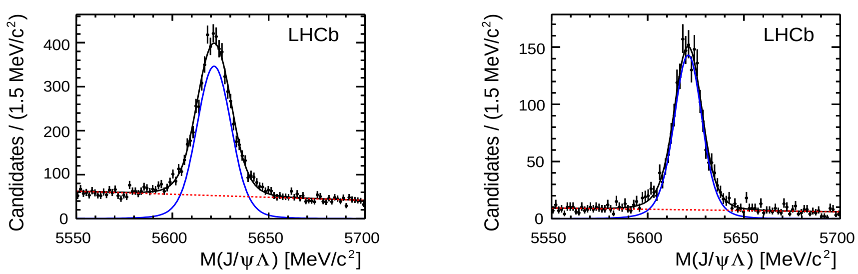

Figure 3: $J/\psi\Lambda$ invariant mass distribution for downstream events (left) and for long events (right). For the definitions of downstream and long events see text.

From the mass distribution fits, w_{mass} weights are obtained to subtract the background in the $(\cos\theta, \cos\theta_1, \cos\theta_2)$ angular distribution. Moreover, simulated events are used to determine w_{acc} weights to correct for the acceptance. Finally each event is weighted by the product $w_{\text{mass}} w_{\text{acc}}$ and the resulting angular distribution is fitted with the function 3.1. In order to understand its reliability, the fit procedure has been checked with Monte Carlo simulations: the mass has been generated according to the yields and shape observed in data, while the angular distribution has been generated using the expectations for P_b and α_b. The bias from the fit has been included in the systematic error calculation.

The measured transverse polarisation parameter is $P_b = 0.06 \pm 0.07 \pm 0.02$ and the parity violating asymmetry parameter is $\alpha_b = 0.05 \pm 0.17 \pm 0.07$, where the first uncertainty is statistical and the second is systematic. The main contributions to the systematic uncertainty are due to the determination of the acceptance function from simulation, and to the fit bias. The measurements reported here cannot exclude a transverse polarisation for Λ_b^0 of the order of 10% [20] and a parity violating parameter of about 15% as predicted by many theoretical models.

4. Forward-central $b\bar{b}$ production asymmetry

Forward-backward $t\bar{t}$ production asymmetry measured at the Tevatron [18] suggests an asymmetry larger than the value predicted by the Standard Model. The forward-central $b\bar{b}$ production asymmetry at the LHC, defined as $A_{\rm FC}^{b\bar{b}} = [N(\Delta y > 0) - N(\Delta y < 0)]/[N(\Delta y > 0) + N(\Delta y < 0)]$, where $\Delta y = |y_b| - |y_{\bar{b}}|$ is the difference of the b-quarks rapidity, is a related observable which provides useful constraints to any models attempting to explain the results from the Tevatron [21]. The analysis reported here is based on an integrated luminosity of 1 fb^{-1} collected by LHCb at $\sqrt{s} = 7$ TeV [22]. In the selection, two high $p_{\rm T}$ ($p_{\rm T} > 15$ GeV/c) back-to-back ($\Delta\phi > 2.5$ rad) b-tagged jets from a common primary vertex are reconstructed. A dedicated trigger algorithm is used to select jets containing a b-hadron. The tagging of the b-flavour is obtained by the charge of the hardest track in the jet which has been identified as a muon: under the assumption of a semileptonic b-decay the muon charge is related to the b-flavour. The tagging purity determined from data is (70.7 ± 0.4)% and is in good agreement with the tagging purity estimated from Monte Carlo simulations, (73 ± 2)%. Out of acceptance particles and the detector response make needed a jet energy correction between 20%-30%, while an additional energy correction of 10%-20% is needed to account for missing neutrinos. Figure 4 shows the Δy distribution for all events (left) and for events for which the invariant mass $M_{b\bar{b}} > 100$ GeV/c (right). The resolution on the di-jet mass ranges between 15%-20%.

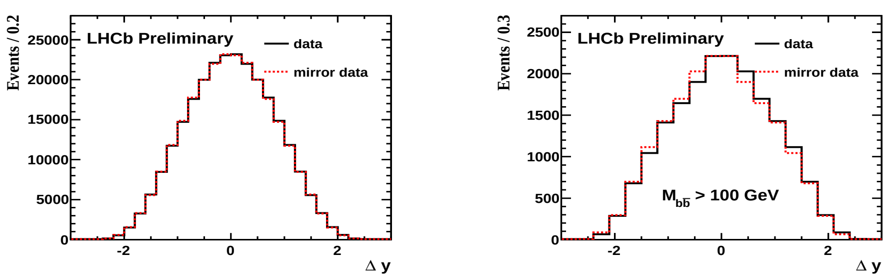

Figure 4: Δy distribution for all events (left) and for events for which the invariant mass $M_{b\bar{b}} > 100$ GeV/c (right). The dashed distribution (mirror data) corresponds to the inversion $\Delta y \to -\Delta y$.

The raw asymmetries obtained are

$$A_{\rm FC}^{\rm raw} = (0.2 \pm 0.2({\rm stat}))\% \tag{4.1}$$

$$A_{\rm FC}^{\rm raw}(M_{b\bar{b}} > 100\ {\rm GeV}/c) = (1.8 \pm 0.7({\rm stat}))\%. \tag{4.2}$$

The dilution due to b-tagging impurities or to the Δy resolution can be neglected. Correcting the raw asymmetry by the dilution factor $1-2\omega$, where $\omega = 0.293 \pm 0.004$ is the mis-flavor tag rate, we finally get

$$A_{\mathrm{FC}}^{b\bar{b}} = (0.5 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst}))\% \tag{4.3}$$

$$A_{\mathrm{FC}}^{b\bar{b}}(M_{b\bar{b}} > 100\ \mathrm{GeV}/c) = (4.3 \pm 1.7(\mathrm{stat}) \pm 2.4(\mathrm{syst}))\%. \tag{4.4}$$

Though no significant forward-central $b\bar{b}$ production asymmetry is observed, a percent level asymmetry for large $M_{b\bar{b}}$ would be in agreement with the Standard Model expectations.

5. Conclusions

We have presented a selection of the LHCb most recent analyses in the heavy flavour physics sector. The J/ψ and $\Upsilon(nS)$ production cross-sections at $\sqrt{s} = 8$ TeV provide a further hint to the theorists attempting to resolve the quarkonium hadro-production mechanism puzzle.

For the first time at a hadron machine, LHCb has measured the $\Lambda_b^0 \to J/\psi\Lambda$ decay amplitudes and the Λ_b^0 polarisation. The results presented, though have still large errors, give strong indications about the respective theoretical models.

Finally, an analysis performed on b-tagged jets has allowed to measure the forward-central $b\bar{b}$ production asymmetry: no significant asymmetry is observed using the full mass range or using only di-jet events with large $b\bar{b}$ invariant masses. This is in agreement with the SM expectations.

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