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Heavy flavor production in the forward acceptance at the LHC

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In this report the most recent results on heavy flavor production studies at the LHCb experiment are covered. The measurements of production cross-sections of the χ_{bJ}(mP), η_c(1S) and B_c^+ states in proton-proton collisions at center of mass energies $\sqrt{s}$ =7 and 8 TeV are presented.

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1. Introduction

Heavy flavor and quarkonia production is a long standing puzzle of QCD. Its various aspects have been successfully described by several theoretical approaches (color-octet and color-singlet mechanisms, etc. [1, 2, 3, 4]). However, the relative role of these proposed mechanisms is poorly understood. The discrepancies between data and theory predictions tend to become more visible in the region of small transverse momenta and large rapidities. At the LHC, the LHCb experiment [5] stands in this region having a coverage of $2 < \eta < 5$ and therefore providing an unique possibility for stringent test of the theory. The previous studies of the heavy flavor production at the LHCb experiment have covered the following topics: charmonium (J/ψ, $\psi(2S)$, $\chi_{c0,1,2}$ and $X(3872)$) and bottomonium ($\Upsilon(\mathrm{nS})$, $\chi_b(1P)$) production in pp- and pPb-collisions, b-hadron ($B^{+/0}$, B_s^0, B_c^+ and Λ_b^0) production and also double charm production ($J/\psi J/\psi$, $J/\psi D$ and DD, where D is $D^{+/0}$, D_s^+ or Λ_c^+). In this report, the recent results of these studies are presented.

2. Production of $\chi_{bJ}(\mathrm{mP})$ states

Investigation of $\chi_{bJ}(\mathrm{mP})$ states is performed using $\chi_{bJ}(\mathrm{mP}) \to \Upsilon(\mathrm{nS})\gamma$ decays where the photon is reconstructed either in the electromagnetic calorimeter [6] or through its conversion into e^+e^- pair in the detector [7]. The $\Upsilon(\mathrm{nS})$ mesons are reconstructed via their dimuon decays and selected by requiring two tracks identified as muons, having large transverse momentum and common vertex compatible with the primary pp-interaction vertex. The events with dimuon invariant mass compatible with $\Upsilon(1,2,3\mathrm{S})$ states are then combined with photon candidates having transverse momentum larger than 0.6 GeV/c to form $\chi_{bJ}(\mathrm{mP})$ candidates. When reconstructing a photon through its conversion to e^+e^-, invariant mass of the dielectron pair is required to be less than 50 MeV/c^2.

Invariant mass distributions of selected $\Upsilon(\mathrm{nS})\gamma$ candidates with photon reconstructed in electromagnetic calorimeter are presented in Fig. 1 showing various $\chi_{bJ}(\mathrm{mP}) \to \Upsilon(\mathrm{nS})\gamma$ transitions. Based on these signals the fractions of $\Upsilon(\mathrm{nS})$ from feed-down

$$R^{\chi_b(\mathrm{mP})}_{\Upsilon(\mathrm{nS})} \equiv \frac{\sigma(pp \to \chi_{b1}(\mathrm{mP})X)}{\sigma(pp \to \Upsilon(\mathrm{nS})X)} \times \mathscr{B}_1 + \frac{\sigma(pp \to \chi_{b2}(\mathrm{mP})X)}{\sigma(pp \to \Upsilon(\mathrm{nS})X)} \times \mathscr{B}_2 \,,$$

are measured, where $\mathscr{B}_{1,2}$ are the $\chi_{b1,2}(\mathrm{mP}) \to \Upsilon(\mathrm{nS})\gamma$ branching fractions. The feed-down is found to be of order of 30% and show no dependence on pp-collision energy. The fraction $R^{\chi_b(3\mathrm{P})}_{\Upsilon(3\mathrm{S})}$ is measured for the first time and found to be unexpectedly large. In addition, using the

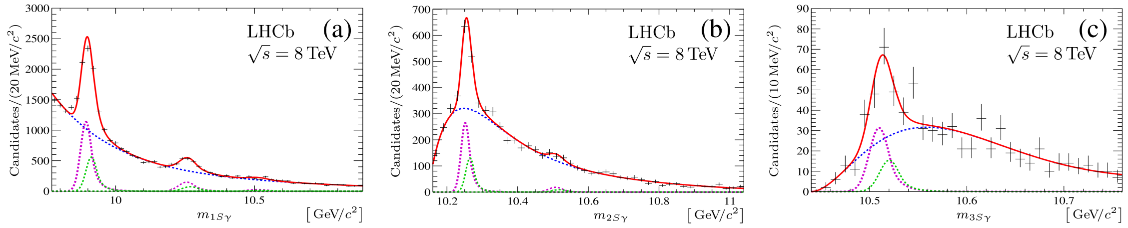

Figure 1: Invariant mass distributions of (a) $\Upsilon(1\mathrm{S})\gamma$, (b) $\Upsilon(2\mathrm{S})\gamma$ and (c) $\Upsilon(3\mathrm{S})\gamma$ candidates with photon reconstructed in electromagnetic calorimeter. The data collected at energy of $\sqrt{s} = 8$ TeV are shown.

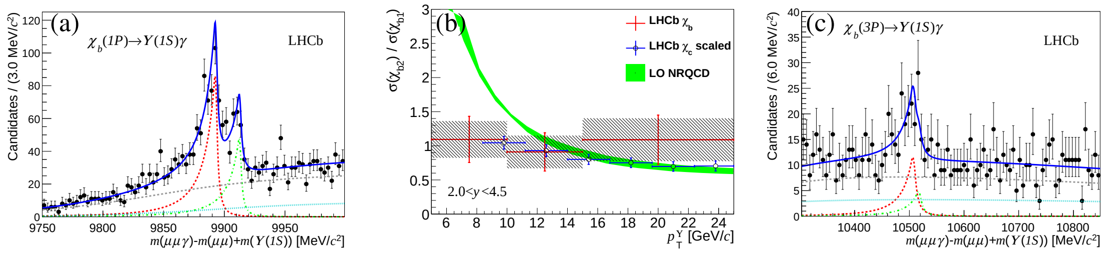

Figure 2: (a) Invariant mass distribution of $\chi_b(1\text{P}) \to \Upsilon(1\text{S})\gamma$ candidates with photon reconstructed through conversion to dielectron pair. (b) Relative production cross-sections of $\chi_{b1}(1\text{P})$ and $\chi_{b2}(1\text{P})$ mesons as function of p_{T}^{Υ}. (c) Invariant mass distribution of $\chi_b(3\text{P}) \to \Upsilon(1\text{S})\gamma$ candidates with photon reconstructed through conversion to dielectron pair.

$\chi_{bJ}(3\text{P}) \to \Upsilon(3\text{S})\gamma$ decay the mass of the $\chi_{b1}(3\text{P})$ state is measured to be $m_{\chi_{b1}(3\text{P})} = 10511.3 \pm 1.7(\text{stat}) \pm 2.5(\text{syst})\ \text{MeV/c}^2$. This result is compatible and more precise than the measurements reported previously by the ATLAS [8] and D0 [9] experiments.

Owing to the good energy resolution obtained with converted photons, the $\chi_{b1}(m\text{P})$ and $\chi_{b2}(m\text{P})$ states could be resolved as shown in Fig. 2(a). Thus, the production cross section of $\chi_{b2}(1\text{P})$ relative to $\chi_{b1}(1\text{P})$ is measured for the first time. Its p_{T} dependency is shown in the Fig. 2(b). The results agree with LO NRQCD predictions [10], theory expectation based on LHCb χ_c measurements [11] and also with CMS results [12]. The $\chi_{bJ}(3\text{P}) \to \Upsilon(1\text{S})\gamma$ and $\chi_{bJ}(3\text{P}) \to \Upsilon(2\text{S})\gamma$ decays are also observed (see Fig. 2(c)) and used to measure the mass of the $\chi_{b1}(3\text{P})$ state to be $m_{\chi_{b1}(3\text{P})} = 10515.7^{+2.2}_{-3.9}(\text{stat})^{+1.5}_{-2.1}(\text{syst})\ \text{MeV/c}^2$.

3. Production of $\eta_c(1\text{S})$ state

Investigation of $\eta_c(1\text{S})$ states complements the previous studies of J/ψ, $\psi(2\text{S})$ and $\chi_{c0,1,2}(1\text{P})$ production performed at LHCb. Measurement of its production cross-section, in particular in the low p_{T} region, can have important implications. It allows to test heavy-quark spin-symmetry relation between the $\eta_c(1\text{S})$ and J/ψ matrix elements as the NLO NRQCD calculations predict different p_{T} dependence of the production rates for spin singlet ($\eta_c(1\text{S})$, $h_c(1\text{P})$) and spin triplet (J/ψ, $\chi_{c0,1,2}(1\text{P})$) states [13, 14, 15].

In the analysis performed by the LHCb experiment [16] the $\eta_c(1\text{S})$ and J/ψ states are reconstructed via their decays to $p\overline{p}$ pair, which could be done thanks to excellent proton identification provided by the LHCb detector. The pseudo-proper decay time defined as $t_z = \Delta z M/p_z$ (where M and p_z are invariant mass and longitudinal momentum of the $p\overline{p}$ pair respectively) is used to separate prompt $\eta_c(1\text{S})$ production from production in b-decays. Invariant mass distribution of $p\overline{p}$ candidates produced in b-decays is shown in Fig. 3(a). In the figure, the peaks corresponding to $\eta_c(1\text{S})$ and J/ψ states are clearly seen. The fit of this distribution gives the following $\eta_c(1\text{S})$ and J/ψ events yields: $N^b_{\eta_c(1\text{S})} = 2020 \pm 230$ and $N^b_{J/\psi} = 6110 \pm 116$. The efficiencies for $\eta_c(1\text{S})$ and J/ψ modes are the same within 0.5%. Therefore, neglecting the bias due to requirement on $p_{\text{T}}(p\overline{p}) > 6.5$ GeV/c, the ratio of yields can be easily transformed into the following ratio of branching fractions:

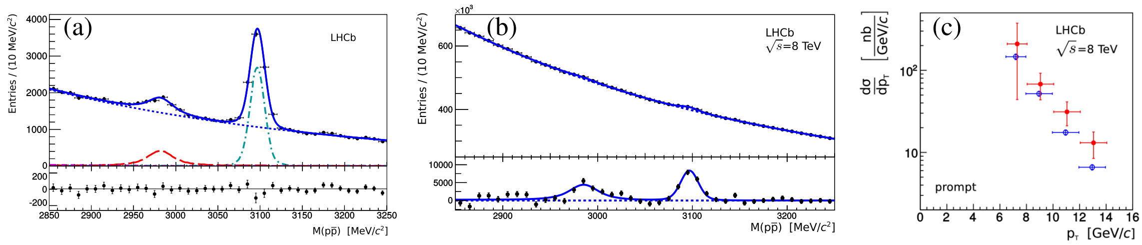

Figure 3: Invariant mass distribution of $p\overline{p}$ candidates produced in (a) b-decays and (b) in primary pp-collisions. (c) Prompt production spectra of $\eta_c(1\mathrm{S})$ mesons (red filled circles) in comparison with spectra of J/ψ mesons.

$$\frac{\mathscr{B}(b\to\eta_c(1\mathrm{S})X)}{\mathscr{B}(b\to J/\psi X)}=\frac{N^b_{\eta_c(1\mathrm{S})}}{N^b_{J/\psi}}\times\frac{\mathscr{B}(J/\psi\to p\overline{p})}{\mathscr{B}(\eta_c(1\mathrm{S})\to p\overline{p})}=0.421\pm0.055(\mathrm{stat})\pm0.025(\mathrm{syst})\pm0.045(\mathscr{B})\,.$$

This is the first measurement of the branching fraction of inclusive b-decays to $\eta_c(1\mathrm{S})$ and it agrees with upper limit of $\mathscr{B}(B^-,\overline{B}^0\to\eta_c(1\mathrm{S})X)<9\times10^{-3}$ at 90% previously reported by the CLEO collaboration [17].

The parameters of $\eta_c(1\mathrm{S})$ and J/ψ peaks, determined from the fit with candidates from b-decays, are used in the fit of invariant mass distributions of $p\overline{p}$ candidates produced in primary pp-collisions (see Fig. 3(b)). The fits yields are 13370 ± 2260 $\eta_c(1\mathrm{S})$ and 11052 ± 1004 J/ψ signal decays for the data taken at $\sqrt{s}=7$ TeV, and 22416 ± 4072 $\eta_c(1\mathrm{S})$ and 20217 ± 1403 J/ψ signal decays for the $\sqrt{s}=8$ TeV data. Based on these yields, the prompt production cross-sections of $\eta_c(1\mathrm{S})$ state in kinematic region of $2<y<4.5$ and $p_\mathrm{T}>6.5$ GeV/c at $\sqrt{s}=7$ and 8 TeV are determined relatively to J/ψ:

$$(\sigma_{\eta_c(1\mathrm{S})}/\sigma_{J/\psi})_{\sqrt{s}=7\ \mathrm{TeV}}=1.74\pm0.29(\mathrm{stat})\pm0.28(\mathrm{syst})\pm0.18(\mathscr{B})\,,$$
$$(\sigma_{\eta_c(1\mathrm{S})}/\sigma_{J/\psi})_{\sqrt{s}=8\ \mathrm{TeV}}=1.60\pm0.29(\mathrm{stat})\pm0.25(\mathrm{syst})\pm0.17(\mathscr{B})\,.$$

Using previously measured production cross-sections of J/ψ as a reference, the $\eta_c(1\mathrm{S})$ production cross-sections are determined to be

$$(\sigma_{\eta_c(1\mathrm{S})})_{\sqrt{s}=7\ \mathrm{TeV}}=0.52\pm0.09(\mathrm{stat})\pm0.08(\mathrm{syst})\pm0.06(\sigma_{J/\psi},\mathscr{B})\,,$$
$$(\sigma_{\eta_c(1\mathrm{S})})_{\sqrt{s}=8\ \mathrm{TeV}}=0.59\pm0.11(\mathrm{stat})\pm0.09(\mathrm{syst})\pm0.08(\sigma_{J/\psi},\mathscr{B})\,.$$

This is the first measurement of $\eta_c(1\mathrm{S})$ prompt production in pp-collisions. The results are consistent with predictions of color singlet leading order calculations [18]. The $\eta_c(1\mathrm{S})$ differential cross-section as a function of p_T is also measured (see Fig. 3(c)). In contrast to NLO NRQCD expectations no difference in p_T dependence between $\eta_c(1\mathrm{S})$ and J/ψ is observed.

4. Production of B_c^+ meson

The B_c^+ meson is a unique quarkonium system being composed of two heavy quarks or different flavor ($\overline{b}$ and c). Besides of having similarities with both charmonium and bottomonium systems it has its own specific features. At the LHC, the B_c^+ mesons are mainly produced through

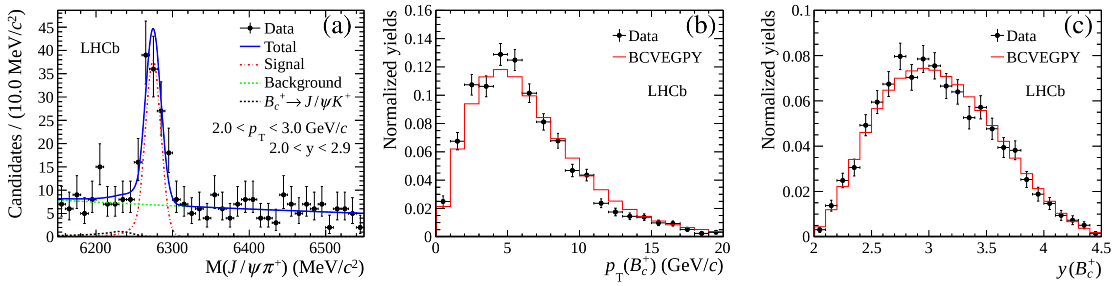

Figure 4: (a) Invariant mass distribution of B_c^+ candidates in one of the kinematic regions. Background-subtracted (b) p_T and (c) y distributions of B_c^+ mesons. The red line represents the spectra obtained with the simulation.

gluon-gluon fusion $gg \to (b\bar{b})(c\bar{c}) \to B_c^+ + b + c$ with leading contribution of order of α_s^4 [19] giving three order suppression with respect to $B^{+/0}$ mesons. The main contribution to the B_c^+ production comes from two competitive mechanisms: fragmentation and recombination, having different impact on p_T spectra (also different from spectra of $B^{+/0}$ mesons). Therefore it is particularly important to extend the previous measurements by LHCb and CMS experiments of the ratio $R_{c/u}$ defined as

$$R_{c/u} = \frac{\sigma(B_c^+)\mathscr{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathscr{B}(B^+ \to J/\psi K^+)}$$

to a measurement of its kinematic dependence.

In the recent analysis performed by the LHCb experiment [20] with data collected at energy $\sqrt{s} = 8$ TeV the decays $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ with similar kinematics and topology are used. The B_c^+ and B^+ mesons are reconstructed in $2 < y < 4.5$ and $0 < p_\mathrm{T} < 20$ GeV/c kinematic region and selected with help of the boost decision trees (BDT) method. The invariant mass of the selected B_c^+ candidates in a reduced kinematic region is shown in Fig. 4(a). Based on the fits to invariant mass distributions in various kinematic regions approximately 3100 B_c^+ mesons are observed and their background-subtracted p_T and y spectra are determined (see Fig. 4(b,c)). The figure shows the remarkable fact that the simulation, based on BCVEGPY generator [21], provides a good description of p_T and y distributions of B_c^+ mesons in data. The ratio $R_{c/u}$ integrated over the whole $2 < y < 4.5$ and $0 < p_\mathrm{T} < 20$ GeV/c kinematic region is measured to be

$$R_{c/u} = (0.683 \pm 0.018(\mathrm{stat}) \pm 0.009(\mathrm{syst}))\% ,$$

which is consistent with the previous measurement at $\sqrt{s} = 7$ TeV. For the first time the double-differential production cross-section of B_c^+ meson is measured with respect to B^+. The dependence of this ratio $R_{c/u}$ on kinematics is observed as shown in Fig. 5. These results will provide useful information on the B_c^+ production mechanism, help to understand the quarkonium production and therefore deepen our understanding of QCD.

5. Summary

The LHCb experiment provides unique input for investigation of QCD by exploiting heavy flavor production in the forward region at the LHC. The production cross-sections of χ_b(mP),

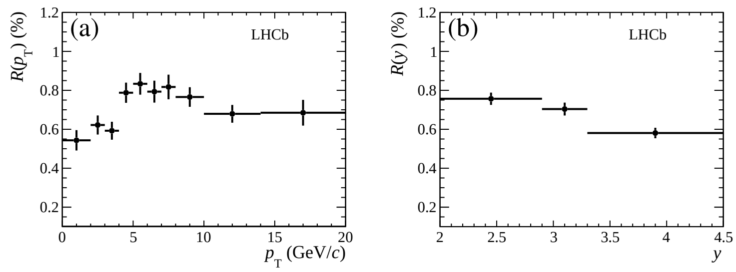

Figure 5: Ratio $R_{c/u}$ as a function (a) of p_T integrated over y in the region $2 < y < 4.5$ and (b) of y integrated over p_T in the region $0 < p_T < 20$ GeV/c.

$\eta_c(1S)$ and B_c^+ states are recently measured providing new tests for the theory. This measurements show a great potential of the LHCb experiment to obtain even more exciting results with future data at energy $\sqrt{s} = 13$ TeV.

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