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J/ψ and $B_c^{\pm}$ production at LHCb

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Measurements of the J/ψ and B_c^+ production cross-sections at $\sqrt{s} = 7$ TeV with the LHCb detector are presented.
The analysis of J/ψ production is based on an integrated luminosity of 5.2 pb^{-1} of data. The double differential cross-section of both prompt J/ψ and J/ψ from b is measured, as a function of the J/ψ transverse momentum p_{T} and of the rapidity y in the fiducial region $p_{\mathrm{T}} \in [0, 14]$ GeV/c and $y \in [2.0, 4.5]$. The integrated cross-section for prompt J/ψ production in this fiducial region is measured to be $\sigma(\text{prompt } J/\psi, p_{\mathrm{T}} < 14\ \text{GeV}/c, 2.0 < y < 4.5) = 10.52 \pm 0.04(\text{stat.}) \pm 1.40(\text{syst.})^{+1.64}_{-2.20}(\text{polarisation})\ \mu\text{b}$. The integrated cross-section for the production of J/ψ from b in the same fiducial region is measured to be $\sigma(J/\psi \text{ from } b, p_{\mathrm{T}} < 14\ \text{GeV}/c, 2.0 < y < 4.5) = 1.14 \pm 0.01(\text{stat.}) \pm 0.16(\text{syst.})\ \mu\text{b}$.
The B_c^+ production measurement is based on an integrated luminosity of 32 pb^{-1}. We present a preliminary measurement of the ratio of production cross-section times branching ratio for $B_c^+ \to J/\psi\pi^+$ relative to that of $B^+ \to J/\psi K^+$, $\frac{\sigma(B_c^+)\times BR(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\times BR(B^+\to J/\psi K^+)} = (2.2 \pm 0.8(\text{stat.}) \pm 0.2(\text{syst.}))\,\%$.

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1. Introduction

The LHCb detector, as described in Ref. [1], is a single-arm forward spectrometer dedicated to precise measurements of CP violation and rare decays at the LHC. It has a unique geometrical acceptance, $1.9 < \eta < 4.9$ and excellent trigger, tracking and particle identification performances, which make it an ideal experiment to perform precise measurements of hadroproduction of particles.

This paper presents the measurements of J/ψ and B_c^+ production (charge conjugates are implied throughout this paper) in pp collisions at $\sqrt{s} = 7$ TeV with the data taken by the LHCb detector in 2010.

2. Measurement of J/ψ production

The double differential cross-section of prompt J/ψ and of J/ψ from b has been measured with 5.2 pb^{-1} of data [2], as a function of the J/ψ transverse momentum $p_{\rm T}$ and of the rapidity y in the fiducial region $p_{\rm T} \in [0, 14]$ GeV/c and $y \in [2.0, 4.5]$. The prompt J/ψ includes directly produced J/ψ, and J/ψ from feed-down from directly produced heavier charmonium states. The double differential cross-section in a given $(p_{\rm T}, y)$ bin is defined as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\,\mathrm{d}p_{\rm T}} = \frac{N\left(J/\psi \to \mu^+\mu^-\right)}{\mathcal{L} \times \varepsilon_{\rm tot} \times \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right) \times \Delta y \times \Delta p_{\rm T}}, \tag{2.1}$$

where $N\left(J/\psi \to \mu^+\mu^-\right)$ is the number of observed $J/\psi \to \mu^+\mu^-$ in bin ($p_{\rm T}$,y), $\varepsilon_{\rm tot}$ is the J/ψ total efficiency in bin $(p_{\rm T}, y)$, including the geometrical acceptance, the trigger, detection, reconstruction and selection efficiencies, $\mathcal{L}$ is the integrated luminosity, $\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$ is the branching fraction of the $J/\psi \to \mu^+\mu^-$ decay ($(5.93 \pm 0.06) \times 10^{-2}$ [3]), and $\Delta y = 0.5$ and $\Delta p_{\rm T} = 1\,\mathrm{GeV}/c$ are the y and $p_{\rm T}$ bin sizes, respectively. The transverse momentum is defined as $p_{\rm T} = \sqrt{p_x^2 + p_y^2}$ and the rapidity is defined as $y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$ where $(E, \mathbf{p})$ is the J/ψ four-momentum in the centre-of-mass frame of the colliding protons.

2.1 J/ψ selection

J/ψ candidates are formed from pairs of tracks with opposite charge. Each track is required to have a good track fit quality, $p_{\rm T} > 0.7$ GeV/c, and be identified as muon. The muon pair are required to originate from a common vertex with good vertex fit probability (>0.5%). J/ψ candidates triggered by lifetime-unbiased single muon or di-muon triggers are used in this analysis.

Only events with at least one reconstructed primary vertex are kept. To separate prompt J/ψ from those of b decays, we define the pseudo-proper time t_z as

$$t_z = \frac{\left(z_{J/\psi} - z_{\rm PV}\right) \times M_{J/\psi}}{p_z}, \tag{2.2}$$

where $z_{J/\psi}$ and $z_{\rm PV}$ are the positions along the z-axis (defined along the beam axis, and oriented from the VELO to the MUON) of the J/ψ decay vertex and of the primary vertex, respectively; p_z is the z component of the measured J/ψ momentum and $M_{J/\psi}$ is the nominal J/ψ mass.

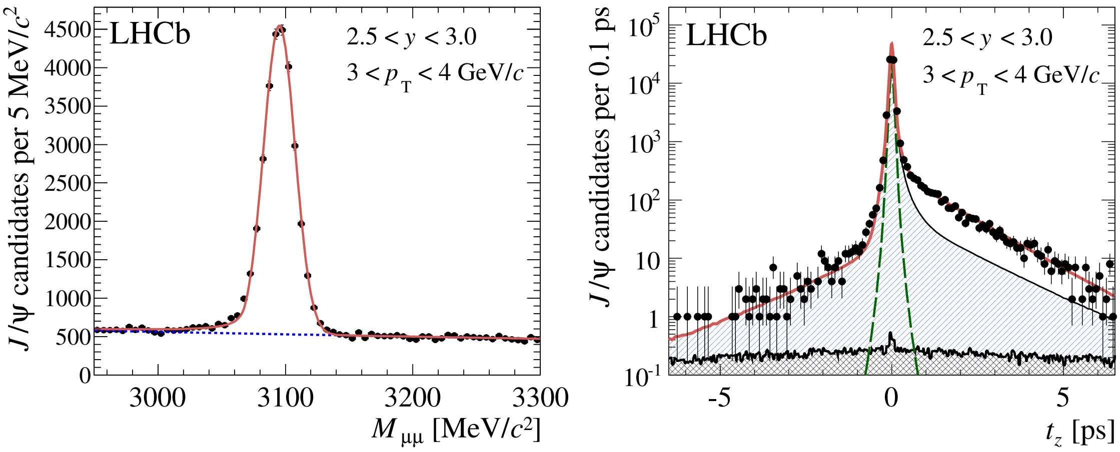

Figure 1: Dimuon mass distribution (left) and t_z distribution (right), with fit results superimposed, for one bin ($3 < p_{\rm T} < 4\,{\rm GeV}/c, 2.5 < y < 3.0$). For the t_z distribution, the solid red line is the total fit function, the green dashed line is the prompt J/ψ contribution, the single-hatched area is the background component and the cross-hatched area is the tail contribution.

2.2 Extraction of signal yields

In each $(p_{\rm T}, y)$ bin, the number of J/ψ of all sources is extracted from an extended unbinned maximum likelihood fit to the J/ψ invariant mass distribution. The mass distribution of the signal component is described by a Crystal Ball function and that of the combinatorial background by an exponential function. The numbers of prompt J/ψ and J/ψ from b are extracted from a fit to the t_z distribution. The t_z distribution of the prompt J/ψ is described by a delta function convolved with a resolution function (double Gaussian), and that of the J/ψ from b by an exponential function convolved with the resolution function. The shape of the t_z distribution for the background is taken from J/ψ mass sidebands. In addition, there is a long tail arising from the association of the J/ψ candidate with the wrong primary vertex, this contribution is measured using the J/ψ in the current event and the primary vertex in the next triggered event, which is uncorrelated to the first.

As an example, the J/ψ mass and t_z distributions, together with the fit results for one bin ($3 < p_{\rm T} < 4\,{\rm GeV}/c,\ 2.5 < y < 3.0$) are shown in Fig. 1. A total signal yield of 565 000 events is obtained by summing over all $(p_{\rm T}, y)$ bins.

2.3 Efficiency

The total efficiency $\varepsilon_{\rm tot}$ is estimated using a simulated sample of inclusive, unpolarised J/ψ mesons and checked with data. Since neither the trigger nor the offline selection makes use of the lifetime information, the efficiencies of prompt J/ψ and J/ψ from b in a given $(p_{\rm T}, y)$ bin are assumed to be equal. This assumption has been confirmed with Monte-Carlo studies.

2.4 Systematics

From Eq. 2.1, one can see that the J/ψ production measurement is affected by the systematic uncertainties on the determination of signal yields, the efficiencies, branching fraction (1%) and luminosity (10%). The uncertainty of the signal yield arises from the fit functions (1.0% for mass

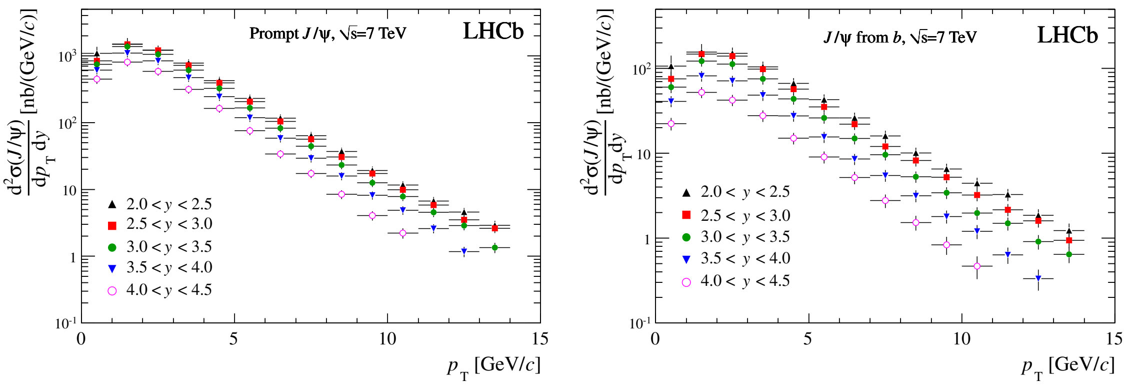

Figure 2: Differential production cross-section for prompt J/ψ (left) and J/ψ from b (right), as a function of $p_{\rm T}$ in bins of y , assuming that prompt J/ψ are produced unpolarised. The errors are the quadratic sums of the statistical and systematic uncertainties.

fits, and 3.6% for t_z fits). The uncertainties on the efficiencies arise from the trigger (1.7-4.5%), muon identification (1.1%), tracking (8.0%), vertex fit (0.8%), final states radiation (1.0%), and J/ψ polarisation (3-30%). In the extrapolation to obtain the $b\bar{b}$ cross section in the full polar angle, an uncertainty of 2% is assigned, due to the dependence of the branching fraction of inclusive $b \to J/\psi X$ on the b hadronisation fractions, which is measured to be different at LEP [4] and Tevatron [5, 6].

2.5 Results

Fig. 2 shows the measured double-differential cross-sections for prompt J/ψ and J/ψ from b in the various $(p_{\rm T}, y)$ bins, after all corrections and assuming J/ψ is not polarised.

The integrated cross-section for prompt J/ψ production in the defined fiducial region, summing over all $(p_{\rm T}, y)$ bins, is

$$\begin{aligned} &\sigma\,(\text{prompt } J/\psi, p_{\rm T} < 14\text{ GeV}/c, 2.0 < y < 4.5) \\ &= 10.52 \pm 0.04(\text{stat.}) \pm 1.40(\text{syst.})^{+1.64}_{-2.20}(\text{polarisation})\ \mu\text{b}. \end{aligned} \tag{2.3}$$

The integrated cross-section for the production of J/ψ from b in the same fiducial region is

$$\sigma\,(J/\psi \text{ from } b,\, p_{\rm T} < 14\text{ GeV}/c, 2.0 < y < 4.5) = 1.14 \pm 0.01(\text{stat.}) \pm 0.16(\text{syst.})\ \mu\text{b}. \tag{2.4}$$

Using the LHCb Monte Carlo simulation based on PYTHIA 6.4 [7] and EvtGen [8], and the average branching fraction of inclusive b-hadron decays to J/ψ measured at LEP [4] $\mathscr{B}(b \to J/\psi X) = (1.16 \pm 0.10)\%$, the result quoted in Eq. 2.4 is extrapolated to the full polar angle range:

$$\sigma(pp \to b\bar{b}X) = 288 \pm 4(\text{stat.}) \pm 48(\text{syst.})\ \mu\text{b}, \tag{2.5}$$

where the systematic uncertainty includes the uncertainties on the b fractions (2%) and on $\mathscr{B}(b \to J/\psi X)$ (9%). No uncertainty on the extrapolation factor is included in this result. This result is in agreement with the previous LHCb measurement using $b \to D^0 \mu \nu X$ decays [9], $\sigma(pp \to b\bar{b}X) = 284 \pm 20(\text{stat.}) \pm 49(\text{syst.})\ \mu\text{b}$.

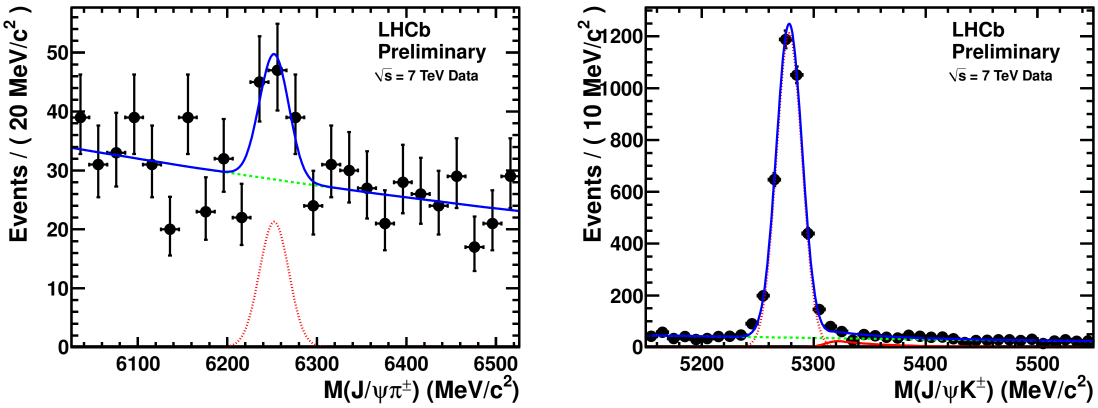

Figure 3: Invariant mass distribution for $B_c^+ \to J/\psi\pi^+$ (left) and $B^+ \to J/\psi K^+$ (right) candidates.

3. Measurement of B_c^+ production

The ratio R_{c+} of production cross-section times branching ratio for $B_c^+ \to J/\psi\pi^+$ relative to that of $B^+ \to J/\psi K^+$, for $p_T(B) > 4$ GeV/c and $\eta \in [2.5, 4.5]$ has been measured with 32 pb^{-1} of data [10]. The ratio R_{c+} is defined as

$$\mathscr{R}_{c+} = \frac{\sigma(B_c^+) \times BR(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times BR(B^+ \to J/\psi K^+)} = \varepsilon_{\rm rel} \times \frac{N(B_c^+)}{N(B^+)}, \tag{3.1}$$

where $N(B_c^+)$ and $N(B^+)$ are the numbers of B_c^+ and B^+ signal events respectively, $\varepsilon_{\rm rel}$ is the relative total efficiency.

The $B^+ \to J/\psi K^+$ and $B_c^+ \to J/\psi\pi^+$ are selected with as similar requirements as possible. J/ψ candidates are selected in the same way as described in Section 2.1, except that the $p_T(\mu)$ minimum value requirement is increased to 900 MeV/c, and the vertex fit quality requirement tightened to $\chi^2/\text{ndf} < 9$ to get a purer J/ψ sample. J/ψ candidates with an invariant mass in $[3.04, 3.14]$ GeV/c^2 and a p_T above 1.5 GeV/c are combined with a charged track with a p_T above 1.5 GeV/c and a good track fit quality to form B_c^+ and B^+ candidates. No particle identification requirement is imposed on the π^+ and K^+. A J/ψ mass constrained vertex fit is applied to improve the reconstructed B mass resolution, and only the B candidates with a vertex fit quality ($\chi^2/\text{ndf} < 9$) are kept. B candidates with a p_T larger than 4 GeV/c, a proper time larger than 0.3 ps and $2.5 < \eta < 4.5$ are used in the production rate measurement. This fiducial region is chosen to be sufficiently far away from the detector acceptance limits, in order to have a large efficiency over the full acceptance. Fig. 3 shows the invariant mass distributions of the $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ candidates obtained with the selection described above.

The numbers of B_c^+ and B^+ signal events are extracted from an extended unbinned maximum likelihood fit to the B_c^+ and B^+ invariant mass distributions respectively. The mass distribution of signal is described by a Gaussian function and the combinatorial background by an exponential function. For the B^+, the contamination from Cabibbo-suppressed $B^+ \to J/\psi\pi^+$ is also considered. This background contribution is modeled from the invariant mass shape observed on a $B^+ \to J/\psi\pi^+$ simulated sample, reconstructed as $B^+ \to J/\psi K^+$. The fit yields 43 ± 13 and 3476 ± 62 signal candidates in the case of the B_c^+ and B^+ respectively.

The relative total efficiencies are obtained using $B^+ \to J/\psi K^+$ and $B_c^+ \to J/\psi\pi^+$ simulation samples and checked with data.

Since the two decay modes have a similar topology, most of the systematic uncertainties cancel in the ratio R_{c+}. The main uncertainty is due to the selection requirement on the proper time of the B meson ($t(B) > 0.3\,\text{ps}$) because the B_c^+ lifetime is only known to a precision of 10%, $\tau(B_c^+) = 0.453 \pm 0.041\text{ps}$ [3]. The uncertainty will be reduced by performing a more precise measurement of the B_c^+ lifetime.

The preliminary measurement of ratio R_{c+} is:

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

4. Summary

The measurement of the double differential cross-section of prompt J/ψ and J/ψ from b is presented. The main systematics due to J/ψ polarisation will be largely reduced after a J/ψ polarisation measurement. A preliminary measurement of the ratio of production cross-section times branching ratio for $B_c^+ \to J/\psi\pi^+$ relative to that of $B^+ \to J/\psi K^+$ is also discussed.

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