PROCEEDINGS OF SCIENCE

Measurement of J/ψ production cross-section in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ at LHCb

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The production of J/ψ mesons in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$ is studied with the LHCb detector. Cross-section measurements are performed as a function of the transverse momentum p_{T} and the rapidity y of the J/ψ meson in the region $p_{\mathrm{T}} < 14\,\mathrm{GeV}/c$ and $2.0 < y < 4.5$, for both prompt J/ψ mesons and J/ψ mesons from b-hadron decays. The production cross-sections integrated over the kinematic coverage are $15.30 \pm 0.03 \pm 0.86\,\mu\mathrm{b}$ for prompt J/ψ and $2.34 \pm 0.01 \pm 0.13\,\mu\mathrm{b}$ for J/ψ from b-hadron decays, assuming zero polarization of the J/ψ meson. The first uncertainties are statistical and the second systematic. The ratios of the cross-sections with respect to $\sqrt{s} = 8\,\mathrm{TeV}$ are also determined.

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1. Introduction

Heavy quarkonium in pp collisions is produced in two stages. The first stage is the production of a heavy $Q\overline{Q}$ pair and this process is well-described perturbatively. At the second stage, the heavy $Q\overline{Q}$ pair hadronizes to a quarkonium state. Two main approaches to the description of the J/ψ production are the color-singlet model (CSM) [1] and the non-relativistic QCD (NRQCD) [2]. The color singlet model assumes the intermediate $Q\overline{Q}$ state to be colorless, whereas NRQCD allows it to have all allowed quantum numbers. NRQCD calcularions require experimental inputs, namely the long-distance matrix elements (LDME) [3] to calculate the probability of the transformation of a $Q\overline{Q}$ state with the specific configuration of quantum numbers to the final quarkonium state. Both NRQCD and CSM predictions are in agreement with previous cross-section measurements [4–6], but they give contradictory estimations of the J/ψ polarization at high transverse momentum, p_{T}, [7] which are not confirmed by experimental results [8].

Together with J/ψ mesons produced directly in hard collisions of partons or through the feed-down of excited quarkonium states, which are referred in this text as prompt J/ψ, high energy pp collisions also produce J/ψ mesons as the decay products of b-hadrons. In this document such mesons are referred to as "J/ψ-from-b". The production cross-section of J/ψ-from-b and its dependence on p_{T} are described with the Fixed Order plus Next-to-Leading Logarithms (FONLL) formalism [9].

Under the assumption of zero J/ψ polarization, the following quantities are measured: the double differential cross-sections of prompt J/ψ and J/ψ-from-b as function of p_{T} and y; the integrated production cross-sections for prompt J/ψ and J/ψ-from-b; the $b\overline{b}$ production cross-section; and the ratio of the cross-sections with respect to the J/ψ cross-sections in pp collisions at $\sqrt{s} = 8$ TeV previously measured by the LHCb [10].

This paper is an abridged version of Ref. [11] by the LHCb collaboration, which contains a full description of the analysis.

2. New trigger scheme

This analysis benefits from a new scheme for the LHCb software trigger introduced for LHC Run 2. The alignment and the calibration are performed in nearly real-time [12] and updated alignment constants are made available for the trigger. The same alignment and calibration information is propagated to the offline reconstruction, to ensure consistent and high-quality particle identification information for the trigger and offline reconstruction. The larger time budget available in the trigger with respect to the LHCb Run 1 also results in the convergence of the online and offline track reconstructions, such that the offline performance is achieved in the trigger. The identical performance of the online and offline reconstruction achieved in this way offers the opportunity to perform physics analyses directly using candidates reconstructed in the trigger [13]. The storage of only the triggered candidates enables a reduction in the event size by an order of magnitude. The analysis described in this document uses the online reconstruction for the first time in LHCb, and is checked against the standard offline reconstruction chain.

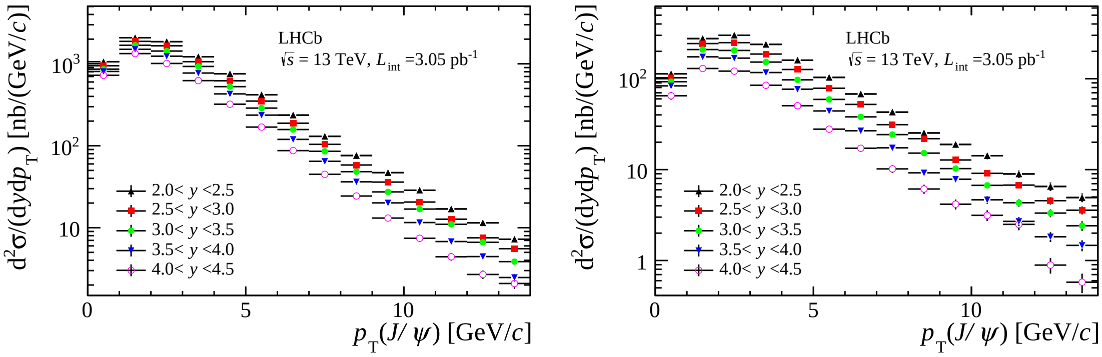

Figure 1: Double differential cross-sections for prompt J/ψ (left) and J/ψ-from-b (right) mesons as functions of p_{T} in bins of y. Statistical and systematic uncertainties are added in quadrature.

3. Cross-section determination

The data used in this analysis come from pp collisions at $\sqrt{s} = 13\,\text{TeV}$, collected by the LHCb detector [14] in July 2015, with an average of 1.1 visible interactions per bunch crossing and corresponding to an integrated luminosity of $3.05 \pm 0.12\,\text{pb}^{-1}$.

The online event selection consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which performs the J/ψ candidate reconstruction. In this analysis the J/ψ candidates are reconstructed from the two opposite-charged muons. The main selection criteria are based on the kinematics of the muons and on the quality of the primary vertex (PV) and the two-track vertex of the J/ψ candidate.

The double differential J/ψ production cross-section in each kinematic bin of p_{T} and y is defined as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}} = \frac{N(J/\psi \to \mu^+\mu^-)}{L_{\mathrm{int}} \times \varepsilon_{\mathrm{tot}} \times \mathscr{B}(J/\psi \to \mu^+\mu^-) \times \Delta y \times \Delta p_{\mathrm{T}}}, \tag{3.1}$$

where $N(J/\psi \to \mu^+\mu^-)$ is the yield of prompt J/ψ or J/ψ-from-b signals in the given kinematic bin, $\varepsilon_{\mathrm{tot}}$ is the total detection efficiency in the given kinematic bin, L_{int} is the integrated luminosity, $\mathscr{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$ [15] is the branching ratio of the decay $J/\psi \to \mu^+\mu^-$ and $\Delta p_{\mathrm{T}} = 1\,\text{GeV}/c$ and $\Delta y = 0.5$ are the bin widths. The yield of J/ψ signal events, both from prompt J/ψ and J/ψ-from-b, is determined from a two-dimensional unbinned maximum likelihood fit to the invariant mass and pseudo proper time of the candidates, performed independently for each (p_{T}, y) bin. The pseudo proper time is defined as

$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \times M_{J/\psi}}{p_z}, \tag{3.2}$$

where $z_{J/\psi} - z_{\mathrm{PV}}$ is the difference of the positions along the beam axis between the J/ψ decay vertex and the PV, p_z is the z-component of the J/ψ momentum, and $M_{J/\psi}$ the known J/ψ mass [15]. The reconstructed vertex of the J/ψ meson originating from b-hadron decays tends to be separated from the PVs, and thus it can be distinguished from prompt J/ψ mesons from the fit to the pseudo proper time.

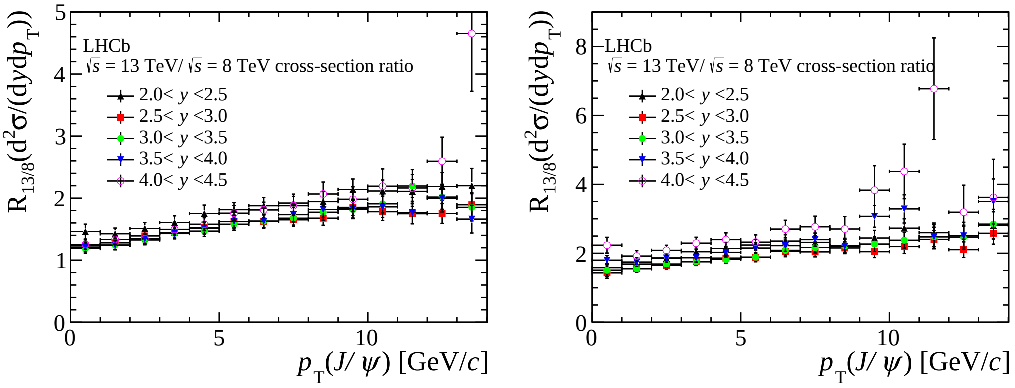

Figure 2: Ratios of differential cross-sections between measurements at $\sqrt{s} = 13\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$ as functions of p_{T} in bins of y for (left) prompt J/ψ mesons and (right) J/ψ-from-b mesons.

4. Results

The measured double differential cross-sections for prompt J/ψ and J/ψ-from-b mesons, assuming no polarization, are shown in Fig. 1, whereas the cross-sections integrated over all (p_{T}, y) bins in the kinematic range $p_{\text{T}} < 14\,\text{GeV}/c$ and $2.0 < y < 4.5$ are:

$$\begin{aligned}
\sigma(\text{prompt } J/\psi\,, p_{\text{T}} < 14\,\text{GeV}/c, 2.0 < y < 4.5) &= 15.30 \pm 0.03 \pm 0.86\,\mu\text{b},\\
\sigma(J/\psi\text{-from-}b, p_{\text{T}} < 14\,\text{GeV}/c, 2.0 < y < 4.5) &= \;\; 2.34 \pm 0.01 \pm 0.13\,\mu\text{b},
\end{aligned}$$

where the first uncertainties are statistical and the second systematic.

In addition to absolute values, the double differential production cross-sections of prompt and J/ψ-from-b mesons in pp collisions at the center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$ were measured relatively to that of $\sqrt{s} = 8\,\text{TeV}$ ($R_{13/8}$) and are presented in Fig. 2.

The calculation of the ratio of the two measurements allows to reduce some correlated uncertainties. In particular, significant improvement was achieved for the systematical uncertainty coming from the luminosity, the tracking and trigger efficiencies. Some of the uncertainties in the theoretical predictions were also canceled. For example, the leading uncertainty of the NRQCD prediction, caused by LDME, canceled almost completely and no theoretical uncertainty is given for this prediction.

The calculation of the ratio also allows to improve the FONLL predictions. Since the scale choice made at the two energies (8 TeV and 13 TeV) is correlated, uncertainties of this type are partially canceled. Other parameters such as the heavy quark mass, the fragmentation fractions to specific hadrons, the fragmentation functions and the decay branching ratios are also fully correlated at different energies and lead to negligible systematic uncertainties in the cross-section ratios [16]. Thus, the main sources of the remaining uncertainty of FONLL predictions for the cross-section ratios are the scale dependence, the choice of the heavy quark mass and the parton distribution functions (PDF). The cancelation of correlated theoretical uncertainties makes it possible to distinguish the predictions based on different PDFs, which leads to possibly useful constraints on parton density functions.

The measured ratios of the differential production cross-section as functions of p_T and y, together with available theoretical predictions are presented in Fig. 3.

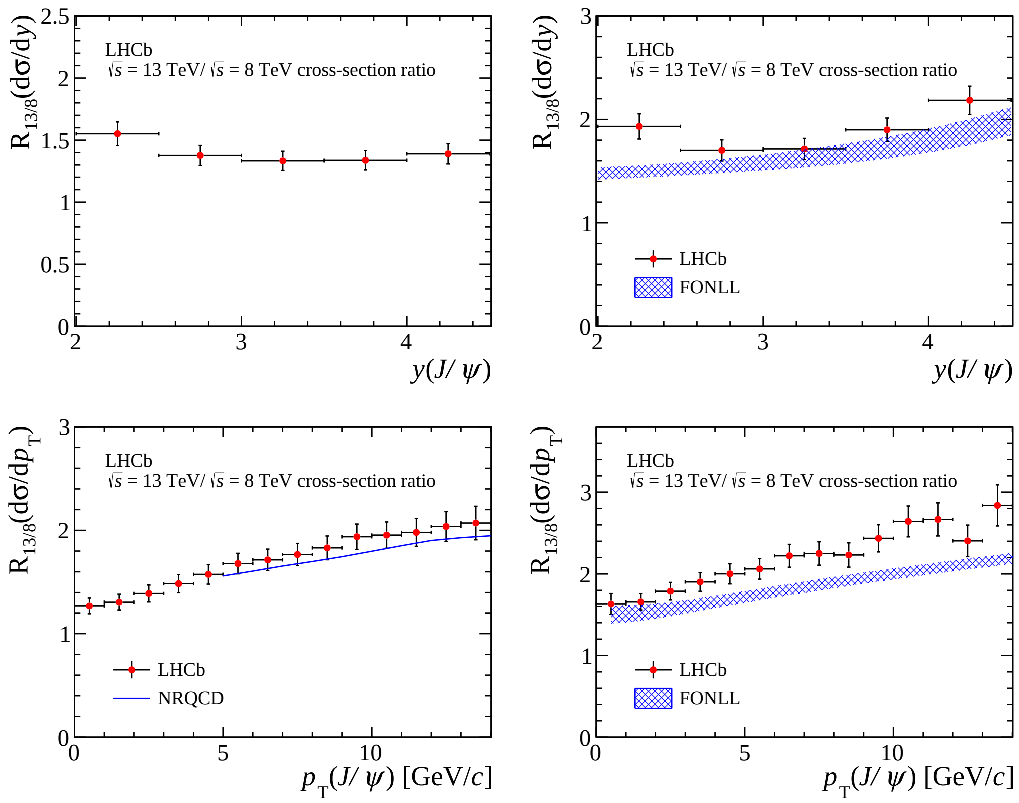

Figure 3: Ratios of differential cross-sections between measurements at $\sqrt{s} = 13\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$ as functions of y integrated over p_T (top row) and as functions of p_T integrated over y (bottom row) for prompt J/ψ (left column) and J/ψ-from-b mesons (right column). Calculations of NRQCD [17] and FONLL [16] are compared to prompt J/ψ mesons and J/ψ-from-b mesons, respectively.

5. Conclusions

A new LHCb trigger scheme is used for the first time to collect data for this analysis. These data allowed to measure the differential J/ψ production cross-sections in pp collisions at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$ for prompt and J/ψ-from-b mesons and the ratios to those at $\sqrt{s} = 8\,\text{TeV}$ in bins of transverse momentum and rapidity in the range of $p_T < 14\,\text{GeV}/c$ and $2.0 < y < 4.5$. The calculation of a ratio of the production cross-sections allowed to decrease the uncertainties both for the measures and the predicted values, which leads to a more stringent test of the theory.

The theoretical predictions based on NRQCD accurately describe the p_T dependence of the ratio of the production cross-section measurements at $\sqrt{s} = 13\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$ for a prompt J/ψ mesons. The theoretical prediction based on FONLL undershoot the p_T dependence of the ratio for J/ψ-from-b, but is in agreement with the rapidity dependence of the ratio fo the production cross-section measurements at $\sqrt{s} = 13\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$.

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