Measurement of prompt $J/\psi$ and beauty hadron production cross sections at mid-rapidity in pp collisions at $s=7$ TeV

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The ALICE Collaboration

Abstract

The ALICE experiment at the LHC has studied $J/\psi$ production at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV through its electron pair decay on a data sample corresponding to an integrated luminosity $L_{\text{int}} = 5.6 \text{nb}^{-1}$. The fraction of $J/\psi$ from the decay of long-lived beauty hadrons was determined for $J/\psi$ candidates with transverse momentum $p_t > 1.3 \text{ GeV}/c$ and rapidity $|y| < 0.9$. The cross section for prompt $J/\psi$ mesons, i.e. directly produced $J/\psi$ and prompt decays of heavier charmonium states such as the $\psi(2S)$ and $\chi_c$ resonances, is $\sigma_{\text{prompt } J/\psi} (p_t > 1.3 \text{ GeV}/c, |y| < 0.9) = 8.3 \pm 0.8 \text{ (stat.)} \pm 1.5 \text{ (syst.)} \mu\text{b}$. The cross section for the production of b-hadrons decaying to $J/\psi$ with $p_t > 1.3 \text{ GeV}/c$ and $|y| < 0.9$ is $\sigma_{J/\psi \rightarrow h_b} (p_t > 1.3 \text{ GeV}/c, |y| < 0.9) = 1.46 \pm 0.38 \text{ (stat.)} \pm 0.26 \text{ (syst.)} \mu\text{b}$. The results are compared to QCD model predictions. The shape of the $p_t$ and $y$ distributions of b-quarks predicted by perturbative QCD model calculations are used to extrapolate the measured cross section to derive the $b\bar{b}$ pair total cross section and $d\sigma/dy$ at mid-rapidity.

*See Appendix A for the list of collaboration members*
Prompt $J/\psi$ and beauty hadron production at mid-rapidity in pp collisions at $\sqrt{s}=7$ TeV

1 Introduction

The production of both charmonium mesons and beauty-flavoured hadrons, referred to as b-hadrons or $h_B$ in this paper, in hadronic interactions represents a challenging testing ground for models based on Quantum ChromoDynamics (QCD).

The mechanisms of $J/\psi$ production operate at the boundary of the perturbative and non-perturbative regimes of QCD. At hadron colliders, $J/\psi$ production was extensively studied at the Tevatron [1-3] and RHIC [5]. Measurements in the new energy domain of the Large Hadron Collider (LHC) can contribute to a deeper understanding of the physics of the hadroproduction processes. The first LHC experimental results on the $J/\psi$ transverse momentum ($p_t$) differential cross sections [6-10] are well described by various theoretical approaches [11-13]. Among those results, the ALICE Collaboration reported the measurement of the rapidity ($y$) and transverse momentum dependence of inclusive $J/\psi$ production in proton–proton (pp) collisions at $\sqrt{s}=7$ TeV [9]. The inclusive $J/\psi$ yield is composed of three contributions: prompt $J/\psi$ produced directly in the proton-proton collision, prompt $J/\psi$ produced indirectly (via the decay of heavier charmonium states such as $\chi_c$ and $\psi(2S)$), and non-prompt $J/\psi$ from the decay of b-hadrons. Other LHC experiments have separated the prompt and non-prompt $J/\psi$ component [6-8,10]. However, at mid-rapidity, only the high-$p_t$ part of the differential $d\sigma_{J/\psi}/dp_t$ distribution was measured ($p_t > 6.5$ GeV/$c$), i.e. a small fraction (few percent) of the $p_t$-integrated cross section.

The measurement of the production of b-hadrons in pp collisions at the LHC provides a way to test, in a new energy domain, calculations of QCD processes based on the factorization approach. In this scheme, the cross sections are computed as a convolution of the parton distribution functions of the incoming protons, the partonic hard scattering cross sections, and the fragmentation functions. Measurements of cross sections for beauty quark production in high-energy hadronic interactions have been done in the past at pp colliders at center-of-mass energies from 630 GeV [15-16] to 1.96 TeV [2,17-19] and in p-nucleus collisions with beam energies from 800 to 920 GeV [20]. The LHC experiments have reported measurements of b-hadron production in pp collisions at $\sqrt{s}=7$ TeV by studying either exclusive decays of B mesons [21-23] or semi-inclusive decays of b-hadrons [6-8,10,24,25]. At mid-rapidity, the measurements are available only for $p_t$ of the b-hadrons larger than $\approx 5$ GeV/$c$, whereas the low $p_t$ region of the differential b-hadron cross sections, where the bulk of the b-hadrons is produced, has not been studied.

In this paper, the measurement of the fraction of $J/\psi$ from the decay of b-hadrons in pp collisions at $\sqrt{s}=7$ TeV for $J/\psi$ in the ranges $1.3 < p_t < 10$ GeV/$c$ and $|y| < 0.9$ is determined. This information is combined with the previous inclusive $J/\psi$ cross section measurement reported by ALICE [9]. Prompt $J/\psi$ and b-hadron cross sections are thus determined at mid-rapidity down to the lowest $p_t$ reach at the LHC energy.

2 Experiment and data analysis

The ALICE experiment [26] consists of a central barrel, covering the pseudorapidity region $|\eta|<0.9$, and a muon spectrometer with $-4 < \eta < -2.5$ coverage. The results presented in this paper were obtained with the central barrel tracking detectors, in particular the Inner Tracking System (ITS) [26,27] and the Time Projection Chamber (TPC) [28]. The ITS, which consists of two innermost Silicon Pixel Detector (SPD), two Silicon Drift Detector (SDD), and two outer Silicon Strip Detector (SSD) layers, provides up to six space points (hits) for each track. The TPC is a large cylindrical drift detector with an active volume that extends over the ranges $85 < r < 247$ cm and $-250 < z < 250$ cm in the radial and longitudinal (beam) directions, respectively. The TPC provides up to 159 space points per track and charged particle identification via specific energy loss ($dE/dx$) measurement.

The event sample, corresponding to $3.5 \times 10^8$ minimum bias events and an integrated luminosity $L_{int}=$
A detailed description of the track and vertex reconstruction procedures can be found in \cite{29}. The primary vertex was determined via an analytic \( \chi^2 \) minimization method in which tracks are approximated as straight lines after propagation to their common point of closest approach. The vertex fit was constrained in the transverse plane using the information on the position and spread of the luminous region. The latter was determined from the distribution of primary vertices reconstructed over the run. Typically, the transverse position of the vertex has a resolution that ranges from 40 \( \mu \)m in low-multiplicity events with less than 10 charged particles per unit of rapidity to about 10 \( \mu \)m in events with a multiplicity of about 40. For each \( J/\psi \) candidate a specific primary vertex was also calculated by excluding the \( J/\psi \) decay tracks, in order to estimate a systematic uncertainty related to the evaluation of the primary vertex in the case of events with non-prompt \( J/\psi \), as discussed in section 3. The decay vertex of the \( J/\psi \) candidate was computed with the same analytic \( \chi^2 \) minimization as for the primary vertex, using the two decay tracks only and without the constraint of the luminous region.

The measurement of the fraction of the \( J/\psi \) yield coming from b-hadron decays, \( f_B \), relies on the discrimination of \( J/\psi \) mesons produced at a distance from the pp collision vertex. The signed projection of the \( J/\psi \) flight distance onto its transverse momentum vector, \( \vec{p}_{J/\psi} \), was constructed according to the formula

\[
L_{xy} = \vec{L} \cdot \frac{\vec{p}_{J/\psi}}{p_{J/\psi}},
\]

where \( \vec{L} \) is the vector from the primary vertex to the \( J/\psi \) decay vertex. The variable \( x \), referred to as “pseudoproper decay length” in the following, was introduced to separate prompt \( J/\psi \) from those produced by the decay of b-hadron.

\[
x = \frac{c \cdot L_{xy} \cdot m_{J/\psi}}{p_{J/\psi}},
\]

where \( m_{J/\psi} \) is the (world average) \( J/\psi \) mass \cite{30}.

For events with very low \( J/\psi \) \( p_t \), the non-negligible amount of \( J/\psi \) with large opening angle between its flight direction and that of the b-hadron impairs the separation ability. Monte Carlo simulation shows shows

\[1 \text{ The variable } x, \text{ which was introduced in } [1], \text{ mimics a similar variable used for b-hadron lifetime measurements where b-hadrons are reconstructed exclusively and therefore the mass and } p_t \text{ of the b-hadron can be used in place of those of the } J/\psi, \text{ to get } c \tau = \frac{L_{xy}}{p_7} - \frac{cL_{xy}}{\langle p_t \rangle_{b-hadron}}.\]
that the detector resolution allows the determination of the fraction of J/ψ from the decay of b-hadrons for events with J/ψ \( p_t \) greater than 1.3 GeV/c.

An unbinned 2-dimensional likelihood fit was used to determine the ratio of the non-prompt to inclusive J/ψ production and the ratio of J/ψ signal candidates (the sum of both prompt and non-prompt components) to the total number of candidates, \( f_{\text{Sig}} \), by maximizing the quantity

\[
\ln L = \sum_{i=1}^{N} \ln F(x, m_{e^+e^-}),
\]

where \( m_{e^+e^-} \) is the invariant mass of the electron pair and \( N \) is the total number of candidates in the range \( 2.4 < m_{e^+e^-} < 4.0 \text{ GeV}/c^2 \). The expression for \( F(x, m_{e^+e^-}) \) is

\[
F(x, m_{e^+e^-}) = f_{\text{Sig}} \cdot F_{\text{Sig}}(x) \cdot M_{\text{Sig}}(m_{e^+e^-}) + (1 - f_{\text{Sig}}) \cdot F_{\text{Bkg}}(x) \cdot M_{\text{Bkg}}(m_{e^+e^-}),
\]

where \( F_{\text{Sig}}(x) \) and \( F_{\text{Bkg}}(x) \) are Probability Density Functions (PDFs) describing the pseudoprop decay length distribution for signal and background candidates, respectively. \( M_{\text{Sig}}(m_{e^+e^-}) \) and \( M_{\text{Bkg}}(m_{e^+e^-}) \) are the PDFs describing the dielectron invariant mass distributions for the signal and background, respectively. A Crystal Ball function [31] is used for the former and an exponential function for the latter. The signal PDF is given by

\[
F_{\text{Sig}}(x) = f_{B} \cdot F_{B}(x) + (1 - f_{B}) \cdot F_{\text{prompt}}(x),
\]

where \( F_{\text{prompt}}(x) \) and \( F_{B}(x) \) are the PDFs for prompt and non-prompt J/ψ, respectively, and \( f_{B} \) is the fraction of reconstructed non-prompt J/ψ.

\[
f_{B} = \frac{N_{J/\psi \rightarrow h_{\ell\ell}}}{N_{J/\psi \rightarrow h_{\ell\ell}} + N_{\text{prompt}J/\psi}},
\]

which can differ (see below) from \( f_{B} \) due to different acceptance and reconstruction efficiency of prompt and non-prompt J/ψ. The distribution of non-prompt J/ψ is the convolution of the \( x \) distribution of J/ψ from b-hadron events, \( \chi_{B}(x) \), and the experimental resolution on \( x \), \( R_{\text{type}}(x) \), which depends on the type of candidate (FF or FS),

\[
F_{B}(x) = \chi_{B}(x') \otimes R_{\text{type}}(x' - x).
\]

Promptly produced J/ψ mesons decay at the primary vertex, and their pseudoprop decay length distribution is thus simply described by \( R_{\text{type}}(x) \):

\[
F_{\text{prompt}}(x) = \delta(x') \otimes R_{\text{type}}(x' - x) = R_{\text{type}}(x).
\]

The resolution function is described by the sum of two Gaussians and a power law function reflected about \( x = 0 \) and was determined, as a function of the \( p_t \) of the J/ψ, with a Monte Carlo simulation study. In this simulation, which utilizes GEANT3 [32] and incorporates a detailed description of the detector material, geometry, and response, prompt J/ψ were generated with a \( p_t \) distribution extrapolated from CDF measurements [11] and a \( y \) distribution parameterization taken from Color Evaporation Model (CEM) calculations [33]. These J/ψ were individually injected into proton–proton collisions simulated using the PYTHIA 6.4.21 event generator [34],[35], and reconstructed as for J/ψ candidates in data. A data-driven method (discussed in section 3) was also developed and used to estimate the systematic uncertainty related to this procedure. The Monte Carlo \( x \) distribution of J/ψ from the decay of b-hadrons produced in proton–proton collisions simulated using the PYTHIA 6.4.21 event generator [34],[35] with Perugia-0 tuning [36] was taken as the template for the \( x \) distribution of b-hadron events in data, \( \chi_{B}(x) \). A second template, used to estimate the systematic uncertainty, was obtained by decaying the simulated b-hadrons using the EvtGen package [37], and describing the final state radiation (“internal” bremsstrahlung) using PHOTOS [38],[39].
The value of the fit parameter are shown with superimposed projections of the maximum likelihood fit result. In figure 1 the distributions of the invariant mass and the pseudoproper decay length, the latter restricted mis-reconstructed tracks which contribute both to positive and negative $x$ of charm and beauty hadrons, which tend to produce positive because the background consists also of random combinations of electrons from semi-leptonic decays.

For the background $x$ distribution, $F_{\text{Bkg}}(x)$, the functional form employed by CDF \cite{11} was used:

$$F_{\text{Bkg}}(x) = (1 - f_+ - f_- - f_{\text{sym}}) R_{\text{type}}(x) + \frac{f_+}{\lambda_+} e^{-x'/\lambda_+} \theta(x') + \frac{f_-}{\lambda_-} e^{-x'/\lambda_-} \theta(-x') + \frac{f_{\text{sym}}}{2\lambda_{\text{sym}}} e^{-|x'|/\lambda_{\text{sym}}} \right] \otimes R_{\text{type}}(x' - x),$$

where $\theta(x)$ is the step function, $f_+$, $f_-$ and $f_{\text{sym}}$ are the fractions of three components with positive, negative and symmetric decay length exponential distributions, respectively. The effective parameters $\lambda_+$, $\lambda_-$ and $\lambda_{\text{sym}}$, and optionally also the corresponding fractions, were determined, prior to the likelihood fit maximization, with a fit to the $x$ distribution in the sidebands of the dielectron invariant mass distribution, defined as the regions 1.8–2.6 and 3.2–5.0 GeV/$c^2$. The introduction of these components is needed because the background consists also of random combinations of electrons from semi-leptonic decays of charm and beauty hadrons, which tend to produce positive $x$ values, as well as of other secondary or mis-reconstructed tracks which contribute both to positive and negative $x$ values. The first term in eq. \cite{9} proportional to $R_{\text{type}}(x)$, describes the residual combinatorics of primary particles.

In figure\cite{11} the distributions of the invariant mass and the pseudoproper decay length, the latter restricted to candidates with $2.92 < m_{e^+e^-} < 3.16$ GeV/$c^2$, for opposite-sign electron pairs with $p_t > 1.3$ GeV/$c$ are shown with superimposed projections of the maximum likelihood fit result.

The value of the fit parameter $f_B$ provides the fraction of non-prompt $J/\psi$ which were reconstructed. In principle prompt and non-prompt $J/\psi$ can have different acceptance times efficiency ($A \times \varepsilon$) values. This can happen because of two effects: (i) the $A \times \varepsilon$ depends on the $p_t$ of the $J/\psi$ and prompt and non-prompt $J/\psi$ have different $p_t$ distributions within the considered $p_t$ range; (ii) at a given $p_t$, prompt and non-prompt $J/\psi$ can have different polarization and, therefore, a different acceptance. The fraction of non-prompt $J/\psi$, corrected for these effects, was obtained as

$$f_B = \left( 1 + \frac{1 - f_B}{f_B} \frac{\langle A \times \varepsilon \rangle_B}{\langle A \times \varepsilon \rangle_{\text{prompt}}} \right)^{-1},$$

where $\langle A \times \varepsilon \rangle_B$ and $\langle A \times \varepsilon \rangle_{\text{prompt}}$ are the average acceptance times efficiency values, in the considered $p_t$ range and for the assumed polarization state, of non-prompt and prompt $J/\psi$, respectively. The acceptance times efficiency ($A \times \varepsilon$) varies very smoothly with $p_t$ and, for unpolarized $J/\psi$ in the $p_t$ range from 1.3 to 10 GeV/$c$, has a minimum of 8% at 2 GeV/$c$ and a broad maximum of 12% at 7 GeV/$c$ \cite{9}. As a consequence, the $\langle A \times \varepsilon \rangle$ values of prompt and non-prompt $J/\psi$ differ by about 3% only in this integrated $p_t$ range.
The central values of the resulting cross sections are quoted assuming both prompt and non-prompt J/ψ to be unpolarized and the variations due to different assumptions are estimated as a separate systematic uncertainty. The polarization of J/ψ from b-hadron decays is expected to be much smaller than for prompt J/ψ due to the averaging effect caused by the admixture of various exclusive B → J/ψ + X decay channels. In fact, the sizeable polarization, which is observed when the polarization axis refers to the B-meson direction [40], is strongly smeared when calculated with respect to the direction of the daughter J/ψ [7], as indeed observed by CDF [2]. Therefore, these variations will be calculated in the two cases of prompt J/ψ with fully transverse (λ = 1) or longitudinal (λ = −1) polarization, in the Collins-Soper (CS) and helicity (HE) reference frames 2, the non-prompt component being left unpolarized.

Despite the small J/ψ candidate yield, amounting to about 400 counts, the data sample could be divided into four pt bins (1.3–3, 3–5, 5–7 and 7–10 GeV/c), and the fraction fB was evaluated in each of them with the same technique. At low pt the statistics is higher, but the resolution is worse and the signal over background, S/B, is smaller (i.e. fSig is smaller). At high pt the statistics is smaller, but the resolution improves and the background becomes negligible. In figure 2 the distributions of the invariant mass and of the pseudoproper decay length are shown in different pt bins with superimposed results of the fits.

3 Systematic uncertainties

The different contributions to the systematic uncertainties affecting the measurement of the fraction of J/ψ from the decay of b-hadrons are discussed in the following, referring to the integrated pt range, and summarized in table 1.

- **Resolution function.** The resolution function was determined from a Monte Carlo simulation, as discussed above. The fits were repeated by artificially modifying the resolution function, according to the formula
  \[ R'_{\text{type}}(x) = \frac{1}{1 + \delta} R_{\text{type}} \left( \frac{x}{1 + \delta} \right), \]
  where δ is a constant representing the desired relative variation of the RMS of the resolution function. Studies on track distance of closest approach to the primary interaction vertex in the bending plane (d0) show that the pt dependence of the d0 resolution as measured in the data is reproduced within about 10% by the Monte Carlo simulation [29], but with a systematically worse resolution in data. For the x variable a similar direct comparison to data is not straightforward, however, the residual discrepancy is not expected to be larger than that observed for d0.

  The variations of fB obtained in the likelihood fit results by varying δ from −5% to +10% are +8% and −15%, respectively, and they were assumed as the systematic uncertainty due to this contribution.

  An alternative, data-driven, approach was also considered. The x distribution of the signal, composed of prompt and non-prompt J/ψ, was obtained by subtracting the x distribution of the background, measured in the sidebands of the invariant mass distribution. This distribution is then fitted by fixing the ratio of prompt to non-prompt J/ψ to that obtained from the likelihood fit and leaving free the parameters of the resolution function. The RMS of the fitted resolution function is found to be 8% larger than the one determined using the Monte Carlo simulation, hence within the range of variation assumed for δ.

- **Pseudoproper decay length distribution of background.** The shape of the combinatorial background was determined from a fit to the x distribution of candidates in the sidebands of the invariant mass distribution. By varying the fit parameters within their errors an envelope of distributions was

\[ \frac{dN}{d\cos \theta} = 1 + \lambda \cos^2 \theta. \]

2The polar angle distribution of the J/ψ decay leptons is given by dN/dcos θ = 1 + λ cos^2 θ.
obtained, whose extremes were used in the likelihood fit in place of the most probable distribution. The variations in the result of the fit were determined and adopted as systematic uncertainties. Also, it was verified that the $x$ distribution obtained for like-sign (LS) candidates, with invariant mass in the range from 2.92 to 3.16 GeV/$c^2$ complementary to the sidebands, is best fitted by a distribution which falls within the envelope of the OS distributions. Finally, the likelihood fit was repeated by relaxing, one at a time, the parameters of the functional form (eq. $9$) and it was found that the values of $f_B$ were within the estimated uncertainties. The estimated systematic uncertainty is 6%.

- **Pseudoproper decay length distribution of b-hadrons.** The fits were also done using as template for the $x$ distribution of b-hadrons, $\chi_B(x)$, that obtained by the EvtGen package [37], and describing the final state radiation using PHOTOS [38,39]. The central values of the fits differ by a few percent at most and the resulting systematic uncertainty is 3%.

- **Invariant mass distributions.** The likelihood method was used in this analysis to fit simultaneously the invariant mass distribution, which is sensitive to the ratio of signal to all candidates ($f_{SS}$), and the $x$ distribution, which determines the ratio of non-prompt to signal candidates ($f_B$). The statistical uncertainties on these quantities were therefore evaluated together, including the
effects of correlations. However, the choice of the function describing the invariant mass distribution, as well as the procedure, can introduce systematic uncertainties in the evaluation of $f_B$. Different approaches were therefore considered: (i) the functional form describing the background was changed into an exponential plus a constant and the fit repeated; (ii) the background was described using the LS distribution and the signal was obtained by subtracting the LS from the OS distributions. The signal and the background shapes were determined with $\chi^2$ minimizations. Both functional forms, exponential and exponential plus a constant, were considered for the background. The likelihood fit was then performed again to determine $f_B$ (and $f_{\text{Sig}}$); (iii) the same procedure as in (ii) was used, but additionally $f_{\text{Sig}}$ was estimated a priori using a bin counting method \[9\] instead of the integrals of the best fit functions. The maximum likelihood fit was performed with $f_{\text{Sig}}$ fixed to this new value; (iv) and (v) the same procedures as in (ii) and (iii) were used but with the background described by a track rotation (TR) method \[9\].

Half of the difference between the maximum and minimum $f_B$ values obtained with the different methods was assumed as systematic uncertainty. It amounts to about 6%.

- **Primary vertex.** The effect of excluding the decay tracks of the $J/\psi$ candidate in the computation of the primary vertex was studied with the Monte Carlo simulation: on the one hand, for the prompt $J/\psi$, the $x$ resolution function is degraded, due to the fact that two prompt tracks are not used in the computation of the vertex, which is thus determined with less accuracy. The effect on the resolution is $p_t$ dependent, with the RMS of the $x$ distribution of prompt $J/\psi$ increasing by 15% at low $p_t$ and by 7% at high $p_t$. On the other hand, for non-prompt $J/\psi$ a bias on the $x$ determination should be reduced. The bias consists in an average shift of the primary vertex towards the secondary decay vertex of the $b$-hadrons, which is reflected in a shift of the mean of the $x$ distribution by about $4 \mu m$ for the $p_t$-integrated distribution. However, the shift is $p_t$ and “type” dependent. In some cases the bias is observed in the opposite direction and is enhanced by removing the decay tracks of the candidate. This can happen since $b$-quarks are always produced in pairs. If a charged track from the fragmentation of the second $b$-quark also enters the acceptance, it can pull the primary vertex position towards the opposite direction. In the end, therefore, the primary vertex was computed without removing the decay tracks of the candidates. To estimate the systematic uncertainty, the analysis was repeated by either (i) removing the decay tracks in the computation of the primary vertex and using the corresponding worse resolution function in the fit or (ii) keeping those tracks and introducing an ad hoc shift in the distribution of the $\chi^2_{B}(x)$, equal to that observed in the Monte Carlo simulation for non-prompt $J/\psi$. The contribution to the systematic uncertainty is about 5%.

- **MC $p_t$ spectrum.** The ratio $\frac{A\times f_B}{A\times f_{\text{prompt}}}$ in eq. \[10\] was computed using MC simulations: prompt $J/\psi$ were generated with the $p_t$ distribution extrapolated from CDF measurements \[11\] and the $y$ distribution parameterized from CEM \[33\]; $b$-hadrons were generated using the PYTHIA 6.4.21 \[34,35\] event generator with Perugia-0 tuning \[36\]. By varying the average $p_t$ of the $J/\psi$ distributions within a factor 2, a 1.5% variation in the acceptance was obtained both for prompt and non-prompt $J/\psi$. Such a small value is a consequence of the weak $p_t$ dependence of the acceptance. For the measurement integrated over $p_t$ ($p_t > 1.3$ GeV/$c$), the $A \times \epsilon$ values of prompt and non-prompt $J/\psi$ differ by about 3% only. The uncertainty due to Monte Carlo $p_t$ distributions is thus estimated to be 1%. When estimating $f_B$ in $p_t$ bins, this uncertainty is negligible.

- **Polarization.** The variations of $f_B$ obtained assuming different polarization scenarios for the prompt component only were evaluated, as discussed in section \[2\] and are reported in table \[1\]. The maximum variations are quoted as separate errors.

The study of systematic uncertainties was repeated as a function of $p_t$. In table \[1\] the results are summarized for the integrated $p_t$ range ($p_t > 1.3$ GeV/$c$) and for the lowest (1.3–3 GeV/$c$) and highest
Table 1: Systematic uncertainties (in percent) on the measurement of the fraction of J/ψ from the decay of b-hadrons, \( f_B \). The variations of \( f_B \) are also reported, with respect to the case of both prompt and non-prompt J/ψ unpolarized, when assuming the prompt component with given polarization.

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty (%)</th>
<th>( p_t ) integrated</th>
<th>lowest ( p_t ) bin</th>
<th>highest ( p_t ) bin</th>
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</thead>
<tbody>
<tr>
<td>Resolution function</td>
<td>+8, −15</td>
<td>+15, −25</td>
<td>+2, −3</td>
<td></td>
</tr>
<tr>
<td>( x ) distribution of background</td>
<td>±3</td>
<td>±3</td>
<td>±2</td>
<td></td>
</tr>
<tr>
<td>( x ) distribution of b-hadrons</td>
<td>±6</td>
<td>±13</td>
<td>±1</td>
<td></td>
</tr>
<tr>
<td>( m_{e^+e^-} ) distributions</td>
<td>±3</td>
<td>±3</td>
<td>±2</td>
<td></td>
</tr>
<tr>
<td>Primary vertex</td>
<td>+4, −5</td>
<td>±4</td>
<td>+4, −8</td>
<td></td>
</tr>
<tr>
<td>MC ( p_t ) spectrum</td>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>+12, −18</td>
<td>+23, −30</td>
<td>+6, −9</td>
<td></td>
</tr>
</tbody>
</table>

The values are given for the integrated \( p_t \) bins. All systematic uncertainties increase with decreasing \( p_t \), except the one related to the primary vertex measurement.

4 Results

4.1 Fraction of \( J/\psi \) from the decay of \( b \)-hadrons

The fraction of \( J/\psi \) from the decay of \( b \)-hadrons in the experimentally accessible kinematic range, \( p_t > 1.3 \text{ GeV}/c \) and \( |y| < 0.9 \), which is referred to as “measured region” in the following, is

\[
f_B = 0.149 \pm 0.037 \text{ (stat.)} +0.018^{+0.025}_{-0.027} \text{ (syst.)} \text{ (syst.pol.).}
\]

The fractions measured in the \( p_t \) bins are reported in table 2 and shown in figure 3. In the figure, the data symbols are placed at the average value of the \( p_t \) distribution of each bin. The average was computed using the above mentioned Monte Carlo distributions: the one based on the CDF extrapolation \([33]\) and that using PYTHIA \([34,35]\) with Perugia-0 tuning \([36]\) for prompt and non-prompt \( J/\psi \), respectively, weighted by the measured \( f_B \). In figure 3 the results of the ATLAS \([8]\) and CMS \([10]\) experiments measured at mid-rapidity for the same colliding system are also shown. The ALICE results extend the mid-rapidity measurements down to low \( p_t \).

4.2 Prompt \( J/\psi \) production

By combining the measurement of the inclusive \( J/\psi \) cross section, which was determined as described in \([9]\), and the \( f_B \) value, the prompt \( J/\psi \) cross section was obtained:

\[
\sigma_{\text{prompt } J/\psi} = (1 - f_B) \cdot \sigma_{J/\psi}.
\]

The numerical values of the inclusive \( J/\psi \) cross section in the \( p_t \) ranges used for this analysis are summarized in table 2. In the measured region the integrated cross section is \( \sigma_{\text{prompt } J/\psi} (|y| < 0.9, p_t > 1.3 \text{ GeV}/c) = 8.3 \pm 0.8 \text{ (stat.)} +1.1\text{ (syst.)} \text{ (HE } \lambda = -1) \text{ (HE } \lambda = 1) \text{ fb}. The systematic uncertainties related to the unknown polarization are quoted for the reference frame where they are the largest.

The differential distribution \( d^2 \sigma_{\text{prompt } J/\psi}/dp_t dy \) is shown as a function of \( p_t \) in figure 4 and \( d\sigma_{\text{prompt } J/\psi}/dy \) is plotted in figure 5. The numerical values are summarized in table 2. In figure 4 the statistical and all systematic
Fig. 3: The fraction of $J/\psi$ from the decay of $b$-hadrons as a function of $p_t$ of $J/\psi$ compared with results from ATLAS [8] and CMS [10] in pp collisions at $\sqrt{s}=7$ TeV.

Errors are added in quadrature for better visibility, while in figure 5 the error bar shows the quadratic sum of statistical and systematic errors, except for the 3.5% systematic uncertainty on luminosity and the 1% on the branching ratio (BR), which are added in quadrature and shown as box. The results shown in figures 4 and 5 assume unpolarized $J/\psi$ production. Systematic uncertainties due to the unknown $J/\psi$ polarization are not shown. Results by the CMS [6,10], LHCb [7] and ATLAS [8] Collaborations are shown for comparison. Also for these data the uncertainties due to luminosity and to the BR are shown separately (boxes) in figure 5, while the error bars represent the statistical and the other sources of systematic uncertainties added in quadrature.

The ALICE $\frac{d\sigma}{dp_t}^{J/\psi}$ measurement at mid-rapidity (left panel of figure 4) is complementary to the data of CMS, available for $|y|<0.9$ and $p_t > 8$ GeV/c, and ATLAS, which covers the region $|y|<0.75$ and $p_t > 7$ GeV/c. In the right panel of figure 4 the ALICE results are compared to next-to-leading order (NLO) non-relativistic QCD (NRQCD) theoretical calculations by M. Butenschön and B.A. Kniehl [12] and Y.-Q. Ma et al. [13]. Both calculations include color-singlet (CS), color-octet (CO), and heavier charmonium feed-down contributions. For one of the two models (M. Butenschön and B.A. Kniehl) the partial results with only the CS contribution are also shown. The comparison suggests that the CO processes are indispensable to describe the data also at low $p_t$. The results are also compared to the model of V.A. Saleev et al. [14], which includes the contribution of partonic sub-processes involving t-channel parton exchanges and provides a prediction down to $p_t = 0$.

The ALICE result for $\frac{d\sigma}{dp_t}^{\text{prompt} J/\psi}$ (figure 5), which equals

$$\frac{d\sigma}{dy}^{\text{prompt} J/\psi} = 5.89 \pm 0.60 \text{(stat.)}^{+0.88}_{-0.90} \text{(syst.)}^{+0.03}_{-0.01} \text{(extr.)}^{+1.01}_{-0.99} \mu\text{b},$$

was obtained by subtracting from the inclusive $J/\psi$ cross section measured for $p_t > 0$ that of $J/\psi$ coming from $b$-hadron decays. The latter was determined, as discussed in the next section, by extrapolating the cross section from the measured region down to $p_t > 0$ using an implementation of pQCD calculations at fixed order with next-to leading-log resummation (FONLL) [41]. The extrapolation uncertainty is negligible with respect to the other systematic uncertainties. In figure 5 the CMS and LHCb results for
Table 2: The fraction of $J/\psi$ from the decay of b-hadrons and cross sections. Some of the contributions to the systematic uncertainty do not depend on $p_t$, thus affecting only the overall normalization, and they are separately quoted (correl.). The contributions which depend on $p_t$, even when they are correlated bin by bin, were included among the non-correlated systematic errors. The values of $\langle p_t \rangle$ were computed using Monte Carlo distributions (see text for details).

<table>
<thead>
<tr>
<th>$p_t$ (GeV/c)</th>
<th>$\langle p_t \rangle$ (GeV/c)</th>
<th>Measured quantity</th>
<th>Systematic uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$f_B$ (%)</td>
</tr>
<tr>
<td>1.3–3.0</td>
<td>2.02</td>
<td>9.2 ± 7.4</td>
<td>0</td>
</tr>
<tr>
<td>3.0–5.0</td>
<td>3.65</td>
<td>13.8 ± 3.8</td>
<td>0</td>
</tr>
<tr>
<td>5.0–7.0</td>
<td>5.75</td>
<td>23.2 ± 7.2</td>
<td>0</td>
</tr>
<tr>
<td>7.0–10.0</td>
<td>8.06</td>
<td>30.7 ± 13.8</td>
<td>0</td>
</tr>
<tr>
<td>$p_t &gt; 1.3$</td>
<td>2.85</td>
<td>14.9 ± 3.7</td>
<td>0</td>
</tr>
<tr>
<td>$p_t &gt; 0$</td>
<td>2.41</td>
<td>14.3 ± 3.6</td>
<td>0</td>
</tr>
</tbody>
</table>

the rapidity bins where the $p_t$ coverage extends down to zero were selected. For CMS, the value for $1.6 < |y| < 2.4$ was obtained by integrating the published $d^2\sigma_{prompt J/\psi}/dy dp_t$ data [6]. The ALICE data point at mid-rapidity complements the other LHC measurements of prompt $J/\psi$ production cross section as a function of rapidity. It is worth noting that the uncertainties of the data sets of the three experiments are uncorrelated, except for that (negligible) of the $BR$, while within the same experiment most of the systematic uncertainties are correlated. The prediction of the model by V.A. Saleev et al. [14] at mid-rapidity provides $d^2\sigma_{prompt J/\psi}/dy = 7.8_{-4.5}^{+9.7}$ µb, which, within the large band of theoretical uncertainties, is in agreement with our measurement.

4.3 Beauty hadron production

The cross section of $J/\psi$ from b-hadrons decay was obtained as $\sigma_{J/\psi-b} = f_B \cdot \sigma_{J/\psi}$. In the measured region it is

$$\sigma_{J/\psi-b}(p_t > 1.3\text{GeV}/c, |y| < 0.9) = 1.46 \pm 0.38_{\text{stat.}} \pm 0.26_{\text{syst.}} \text{µb}.$$ 

This measurement can be compared to theoretical calculations based on the factorization approach. In particular, the prediction of the FONLL [41], which describes well the beauty production at Tevatron energy, provides $1.33 \pm 0.48$ µb, in good agreement with the measurement. For this calculation CTEQ6.6 parton distribution functions [43] were used and the theoretical uncertainty was obtained by varying the factorization and renormalization scales, $\mu_F$ and $\mu_R$, independently in the ranges $0.5 < \mu_F/m_t < 2$,
The same FONLL calculations were used to extrapolate the cross section of non-prompt $J/\psi$ down to $p_t$ equal to zero. The extrapolation factor, which is equal to $1.212^{+0.016}_{-0.038}$, was computed as the ratio of the cross section for $p_t^{1/\psi} > 0$ and $|y_{1/\psi}| < 0.9$ to that in the measured region ($p_t^{1/\psi} > 1.3$ GeV/c and $|y_{1/\psi}| < 0.9$). Using the PYTHIA event generator with Perugia-0 tuning instead of FONLL provides an extrapolation factor of 1.156. The measured cross section corresponds thus to about 80% of the $p_t$-integrated cross section at mid-rapidity. Dividing by the rapidity range $\Delta y = 1.8$ one obtains

$$\frac{d\sigma_{J/\psi-h_b}}{dy} = 0.98 \pm 0.26 \text{ (stat.)}^{+0.18}_{-0.22} \text{ (syst.)}^{+0.01}_{-0.03} \text{ (extr.)} \mu b.$$ 

In figure 5 this measurement is plotted together with the LHCb [7] and CMS [6] data at forward rapidity. For CMS the values for $1.2 < |y| < 1.6$ and $1.6 < |y| < 2.4$ were obtained by integrating the published $d^2\sigma_{J/\psi-h_b}/dp_t dy$ data [4], the value for $1.2 < |y| < 1.6$ was also extrapolated from $p_t^{\text{min}} = 2.0$ GeV/c to $p_t = 0$, with the approach based on the FONLL calculations as previously described. The extrapolation uncertainties are shown in figure 5 as the slashed areas. The central FONLL prediction and its uncertainty band are also shown. A good agreement between data and theory is observed.

A similar procedure was used to derive the $b\bar{b}$ quark-pair production cross section

$$\frac{d\sigma_{b\bar{b}}}{dy} = \frac{d\sigma_{b\bar{b}}^{\text{theory}}}{dy} \times \sigma_{J/\psi-h_b}(p_t^{1/\psi} > 1.3 \text{ GeV/c}, |y_{1/\psi}| < 0.9)\sigma_{J/\psi-h_b}(p_t^{1/\psi} > 1.3 \text{ GeV/c}, |y_{1/\psi}| < 0.9),$$

where the average branching fraction of inclusive b-hadron decays to $J/\psi$ measured at LEP [44,46], $BR(h_b \rightarrow J/\psi + X) = (1.16 \pm 0.10)\%$, was used in the computation of $\sigma_{b\bar{b}}^{\text{theory}}$. The extrapolation with the FONLL calculations provides

$$\frac{d\sigma_{b\bar{b}}}{dy} = 43 \pm 11 \text{ (stat.)}^{+9}_{-10} \text{ (syst.)}^{+0.6}_{-1.5} \text{ (extr.)} \mu b.$$
Fig. 5: $d\sigma_{\text{prompt } J/\psi}/dy$ as a function of $y$. The error bars represent the quadratic sum of the statistical and systematic errors, while the systematic uncertainties on luminosity and branching ratio are shown as boxes around the data points. The symbols are plotted at the center of each bin. The CMS value was obtained by integrating the published $d^2\sigma_{\text{prompt } J/\psi}/dp_Tdy$ data measured for $1.6 < |y| < 2.4$ [6]. The results obtained by LHCb [7] and CMS are reflected with respect to $y = 0$ (open symbols).

Using the PYTHIA event generator with Perugia-0 tuning (with the EvtGen package to describe the particle decays) instead of FONLL results in a central value of 40.4 (40.9) $\mu$b. A compilation of measurements of $d\sigma_{b\bar{b}}/dy$ at mid-rapidity is plotted in figure 7 as a function of $\sqrt{s}$, with superimposed FONLL predictions.

Finally, the total $b\bar{b}$ cross section was obtained as

$$\sigma(pp \rightarrow b\bar{b} + X) = \alpha_{4\pi} \frac{\sigma_{J/\psi \rightarrow b\bar{b}}(p_T^{J/\psi} > 1.3 \text{ GeV}/c, |y_{J/\psi}| < 0.9) \cdot BR(b\rightarrow J/\psi + X)}{2 \cdot BR(h_b \rightarrow J/\psi + X)}$$

(13)

where $\alpha_{4\pi}$ is the ratio between the yield of $J/\psi$ mesons (from the decay of $b$-hadrons) in the full phase space and the yield in the measured region $|y_{J/\psi}| < 0.9$ and $p_T^{J/\psi} > 1.3$ GeV/c. The FONLL calculations provide $\alpha_{4\pi} = 4.49^{+0.12}_{-0.06}$, which produces $\sigma(pp \rightarrow b\bar{b} + X) = 282 \pm 74(\text{stat.})^{+58}_{-68}(\text{syst.})^{+5}_{-8}(\text{extr.})$ $\mu$b. The extrapolation factor $\alpha_{4\pi}$ was also estimated using PYTHIA with Perugia-0 tuning and found to be $\alpha_{4\pi}^{\text{PYTHIA}} = 4.20$. This measurement is in good agreement with those of the LHCb experiment, namely $288 \pm 4(\text{stat.}) \pm 48(\text{syst.}) \mu$b and $284 \pm 20(\text{stat.}) \pm 49(\text{syst.}) \mu$b, which were based on the measured cross sections determined in the forward rapidity range from $b$-hadron decays into $J/\psi X$ and $D^0 \mu \nu X$, respectively [7,24].

5 Summary

Results on the production cross section of prompt $J/\psi$ and $J/\psi$ from the decay of $b$-hadrons at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV have been presented. The measured cross sections have been compared to theoretical predictions based on QCD and results from other experiments. Prompt $J/\psi$ production is well described by NLO NRQCD models that include color-octet processes. The cross
Prompt $J/ \psi$ and beauty hadron production at mid-rapidity in pp collisions at $\sqrt{s}=7$ TeV

Fig. 6: $\frac{d\sigma}{dy}$ from b-hadron decays as a function of $y$. The error bars represent the quadratic sum of the statistical and systematic errors, while the systematic uncertainties on luminosity and branching ratio are shown as boxes. The systematic uncertainties on the extrapolation to $p_t = 0$ are indicated by the slashed areas. The CMS values were obtained by integrating the published $d^2\sigma/dp_t dy$ data measured for $1.2 < |y| < 1.6$ and $1.6 < |y| < 2.4$. The results obtained in the forward region by LHCb [7] are reflected with respect to $y=0$ (open symbols). The FONLL calculation [41, 42] (and its uncertainty) is represented by solid (dashed) lines.

section of $J/\psi$ from b-hadron decays is in good agreement with the FONLL prediction, based on perturbative QCD. The ALICE results at mid-rapidity, covering a lower $p_t$ region down to $p_t = 1.3$ GeV/$c$, are complementary to those of the ATLAS and CMS experiments, which are available for $J/\psi$ $p_t$ above 6.5 GeV/$c$. Using the shape of the $p_t$ and $y$ distributions of b-quarks predicted by FONLL calculations, the mid-rapidity $d\sigma/dy$ and the total production cross section of $b\bar{b}$ pairs were determined.

References
$b$-meson production in $\bar{b}$ at mid rapidity as a function of $\sqrt{s}$ in $p\bar{p}$ (PHENIX [47] and ALICE results) and $pp$ (UA1 [16] and CDF [17] results) collisions. The FONLL calculation [41, 42] (and its uncertainty) is represented by solid (dashed) lines.


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Prompt J/ψ and beauty hadron production at mid-rapidity in pp collisions at √s = 7 TeV

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Prompt $J/\psi$ and beauty hadron production at mid-rapidity in pp collisions at $\sqrt{s}=7$ TeV
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