Measurement of the cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ for prompt $\chi_c$ production at $\sqrt{s} = 7$ TeV

**LHCb Collaboration**

**Abstract**

The prompt production of the charmonium $\chi_{c1}$ and $\chi_{c2}$ mesons has been studied in proton–proton (pp) collisions at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. The $\chi_c$ mesons are identified through their decays $\chi_c \rightarrow J/\psi \gamma$ with $J/\psi \rightarrow \mu^+ \mu^-$ using 36 pb$^{-1}$ of data collected by the LHCb detector in 2010. The ratio of the prompt production cross-sections for the two $\chi_c$ spin states, $\sigma(\chi_{c2})/\sigma(\chi_{c1})$, has been determined as a function of the $J/\psi$ transverse momentum, $p_T^{J/\psi}$, in the range from 2 to 15 GeV/c. The results are in agreement with the next-to-leading order non-relativistic QCD model at high $p_T^{J/\psi}$ and lie consistently above the pure leading-order colour-singlet prediction.

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1. Introduction

Explaining heavy quarkonium production remains a challenging problem for Quantum Chromodynamics (QCD). At the energies of the proton–proton (pp) collisions at the Large Hadron Collider, $c\bar{c}$ pairs are expected to be produced predominantly via Leading Order (LO) gluon–gluon interactions, followed by the formation of the bound charmonium states. While the former can be calculated using perturbative QCD, the latter is described by non-perturbative models. Other, more recent, approaches make use of non-relativistic QCD factorisation (NRQCD) which assumes a combination of the colour-singlet (CS) and colour-octet (CO) $c\bar{c}$ and soft gluon exchange for the production of the final bound state [1]. To describe previous experimental data, it was found to be necessary to include Next-to-Leading Order (NLO) QCD corrections for the description of charmonium production [2,3].

The study of the production of $P$-wave charmonia $\chi_{cJ}(1P)$, with $J = 0, 1, 2$, is important, since these resonances give substantial feed-down contributions to the prompt $J/\psi$ production through their radiative decays $\chi_c \rightarrow J/\psi \gamma$ and can have significant impact on the measurement of the $J/\psi$ polarisation. Furthermore, the ratio of the production rate of $\chi_c$ to that of $\chi_{c1}$ is interesting because it is sensitive to the CS and CO production mechanisms.

Measurements of $\chi_c$ production and the relative amounts of the $\chi_{c1}$ and $\chi_{c2}$ spin states, have previously been made using different particle beams and energies [4-6]. In this Letter, we report a measurement from the LHCb experiment of the ratio of the prompt cross-sections for the two $\chi_c$ spin states, $\sigma(\chi_{c2})/\sigma(\chi_{c1})$, as a function of the $J/\psi$ transverse momentum in the range $2 < p_T^{J/\psi} < 15$ GeV/c and in the rapidity range $2 < y^{J/\psi} < 4.5$. The $\chi_c$ candidates are reconstructed through their radiative decay $\chi_c \rightarrow J/\psi \gamma$, with $J/\psi \rightarrow \mu^+ \mu^-$, using a data sample with an integrated luminosity of 36 pb$^{-1}$ collected during 2010. This Letter, prompt production of $\chi_c$ refers to $\chi_c$ mesons that are produced at the interaction point and do not arise from the decay of a $b$-hadron. The sample therefore includes $\chi_c$ from the decay of short-lived resonances, such as $\psi(2S)$, which are also produced at the interaction point. All three $\chi_{cJ}$ states are considered in the analysis. Since the $\chi_{c0} \rightarrow J/\psi \gamma$ branching fraction is $\sim 30$ (17) times smaller than that of the $\chi_{c1}$ ($\chi_{c2}$), the yield of $\chi_{c0}$ is not significant. The measurements extend the $p_T^{J/\psi}$ coverage with respect to previous experiments.

2. LHCb detector and selection requirements

The LHCb detector [7] is a single-arm forward spectrometer with an angular coverage from approximately 10 mrad to 300 mrad (250 mrad) in the bending (non-bending) plane. The detector consists of a vertex detector (VELO), a dipole magnet, a tracking system, two ring-imaging Cherenkov (RICH) detectors, a calorimeter system and a muon system.

Of particular importance in this measurement are the calorimeter and muon systems. The calorimeter consists of a scintillating pad detector (SPD) and a pre-shower, followed by electromagnetic (ECAL) and hadronic calorimeters. The SPD and pre-shower are designed to distinguish between signals from photons and electrons. The ECAL is constructed from scintillating tiles interleaved with lead tiles. Muons are identified using hits in detectors interleaved with iron filters.

The signal simulation sample used for this analysis was generated using the PYTHIA 6.4 generator [8] configured with the parameters detailed in Ref. [9]. The EvtGen [10], PHOTOS [11]
and Geant4 [12] packages were used to decay unstable particles, generate QED radiative corrections and simulate interactions in the detector, respectively. The sample consists of events in which at least one \(J/\psi \rightarrow \mu^+\mu^-\) decay takes place with no constraint on the production mechanism.

The trigger consists of a hardware stage followed by a software stage which applies a full event reconstruction. For this analysis the trigger selects a pair of oppositely charged muon candidates, where either one of the muons has a transverse momentum \(p_T > 1.8\) GeV/c or one of the pair has \(p_T > 0.56\) GeV/c and the other has \(p_T > 0.48\) GeV/c. The invariant mass of the candidates is required to be greater than \(2.9\) GeV/c\(^2\). The photons are not involved in the trigger decision for this analysis.

Photons are identified and reconstructed using the calorimeter and tracking systems. The identification algorithm provides an estimator for the hypothesis that a calorimeter cluster originates from a photon. This is a likelihood-based estimator constructed from variables that rely on calorimeter and tracking information. For example, in order to reduce the electron background, candidate photon clusters are required not to be matched to a track extrapolated into the calorimeter. For each photon candidate a likelihood (CL\(_{\gamma}\)) is calculated based on simulated signal and background samples. The photons identified by the calorimeter and used in this analysis can be classified as two types: those that have not. Converted photons are identified as clusters in the ECAL converted in the material after the dipole magnet and those that do.

The mass and \(J/\psi\) identification criteria are identical to those used in Ref. [13]; each track must be identified as a muon with \(p_T > 700\) MeV/c and a quality of the track fit \(\chi^2/\text{ndf} < 4\), where ndf is the number of degrees of freedom. The two muons must originate from a common vertex with a probability of the vertex fit \(> 0.5\%.\) In addition, in this analysis the \(\mu^+\mu^-\) invariant mass is required to be in the range \(3062–3120\) MeV/c\(^2\). The \(J/\psi\) pseudodecay time, \(\tau\), is used to reduce the contribution from non-prompt decays, by requiring \(\tau = (2p_{TJ}/z_{\rho\psi})M_{J/\psi}/p_z < 0.1\) ps, where \(M_{J/\psi}\) is the reconstructed dimuon invariant mass, \(z_{J/\psi} - z_{\rho\psi}\) is the \(z\) separation of the reconstructed production (primary) and decay vertices of the dimuon, and \(p_z\) is the \(z\)-component of the dimuon momentum with the \(z\)-axis parallel to the beam line. Simulation studies show that, with this requirement applied, the remaining fraction of \(\chi\) from \(b\)-hadron decays is about 0.1%. This introduces an uncertainty much smaller than any of the other systematic or statistical uncertainties evaluated in this analysis and is not considered further.

In the data, the average \(\chi\) candidate multiplicity per selected event is \(1.3\) and the percentage of events with more than one genuine \(\chi\) candidate (composed of a unique \(J/\psi\) and photon) is estimated to be 0.23% from the simulation. All \(\chi\) candidates are considered for further analysis. The mass difference, \(\Delta M = M(\mu^+\mu^-) - M(\mu^+\mu^-)\), of the selected candidates is shown in Fig. 1 for the converted and non-converted samples; the overlaid fits are described in Section 3.

3. Experimental method

The production cross-section ratio of the \(\chi_{c2}\) and \(\chi_{c1}\) states is measured as

\[
\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \frac{\epsilon_{\chi_{c1}}}{\epsilon_{\chi_{c2}}} \frac{B(\chi_{c1} \rightarrow J/\psi\gamma)}{B(\chi_{c2} \rightarrow J/\psi\gamma)},
\]

where \(B(\chi_{c1} \rightarrow J/\psi\gamma)\) and \(B(\chi_{c2} \rightarrow J/\psi\gamma)\) are the \(\chi_{c1}\) and \(\chi_{c2}\) branching fractions to the final state \(J/\psi\gamma\), and

\[
\frac{\epsilon_{\chi_{c1}}}{\epsilon_{\chi_{c2}}} \frac{\epsilon_{\chi_{c1}}}{\epsilon_{\chi_{c2}}} = \frac{\epsilon_{J/\psi}}{\epsilon_{J/\psi}} \frac{\epsilon_{\chi_{c1}}}{\epsilon_{\chi_{c1}}} \frac{\epsilon_{\chi_{c1}}}{\epsilon_{\chi_{c1}}},
\]

where \(\epsilon_{J/\psi}\) is the efficiency to trigger, reconstruct and select a \(J/\psi\) from a \(\chi_{c1}\) decay, \(\epsilon_{\chi_{c1}}\) is the efficiency to reconstruct and select a photon from a \(\chi_{c1}\) decay and \(\epsilon_{\chi_{c1}}\) is the efficiency to subsequently select the \(\chi_{c1}\) candidate.

Since the mass difference between the \(\chi_{c1}\) and \(\chi_{c2}\) states is \(45.54 \pm 0.11\) MeV/c\(^2\), the signal peaks cannot be separately isolated using the calorimeter information. An unbinned maximum likelihood fit to the \(\Delta M\) mass difference distribution is performed to obtain the three \(N_{\chi_{c1}}\) yields simultaneously. The determination of the efficiency terms in Eq. (2) is described in Section 3.1.

The signal mass distribution is parametrised using three Gaussian functions \((\mathcal{F}_j)_{sig}\) for \(j = 0, 1, 2\). The combinatorial background is described by
decays is due to $\psi(l$ solutions fixed, a fit is performed to the data in the range $3 < T < 15$ GeV by $F$ respectively. The corresponding values in the simulation are $pJ$ for each fit in each bin in $T$. The fit is then performed in $T$ bins $2–3$ GeV and is not well described by $F_{\text{bgd}}$ when combined with the rest of the sample. Simulation studies show that the signal parameters for the $X_{c1}$ states in the $pT^{1/0}$ bin $2–3$ GeV/c are consistent with the parameters in the rest of the sample. The distributions of $\Delta M$ for the fits to the converted and non-converted candidates are shown in Fig. 1. The mass resolution, $\sigma^{\text{res}}_{X_{c1}}$, is measured to be $21.8 \pm 0.8$ MeV/c$^2$ and $18.3 \pm 0.4$ MeV/c$^2$ for converted and non-converted candidates respectively. The corresponding values in the simulation are $19.0 \pm 0.2$ MeV/c$^2$ and $17.5 \pm 0.1$ MeV/c$^2$ and show a weak dependence of $\sigma^{\text{res}}_{X_{c1}}$ on $pT^{1/0}$ which is accounted for in the systematic uncertainties.

In order to measure the $X_{c1}$ yields, the fit is then performed in bins of $pT^{1/0}$ in the range $2 < pT^{1/0} < 15$ GeV/c. For each $pT^{1/0}$ bin, the mass differences, the ratio of the mass resolutions and $\sigma^{\text{res}}_{X_{c1}}$ are fixed as described above. In total, there are eight free parameters for each fit in each bin in $pT^{1/0}$ and the results are summarised in Table 1: the fit $\chi^2$/ndf for the converted and non-converted samples is good in all bins. The total observed yields of $X_{c0}$, $X_{c1}$ and $X_{c2}$ are $820 \pm 650$, $38630 \pm 550$ and $26110 \pm 620$, respectively, calculated from the signal fractions $f_{X_{c1}}$ and the number of candidates in the sample. The raw $X_{c1}$ yields for converted and non-converted candidates are combined, corrected for efficiency (as described in Section 3.1) and the cross-section ratio is determined using Eq. (1).

### 3.1. Efficiencies

The efficiency ratios to reconstruct and select $X_{c1}$ candidates are obtained from simulation. Since the photon interaction with material is not part of the event generation procedure, the individual efficiencies for converted and non-converted candidates are not separated. Therefore, the combined efficiencies are calculated. The ratios of the overall efficiency for the detection of $J/\psi$ mesons originating from the decay of a $X_{c1}$ compared to a $X_{c2}$, $\epsilon^{X_{c1}}_{\text{sel}}/\epsilon^{X_{c2}}_{\text{sel}}$, are consistent with unity for all $pT^{1/0}$ bins, as shown in Fig. 2. The ratio of the efficiencies for reconstructing and selecting photons from $X_{c1}$ decays and then selecting the $X_{c1}$, $\epsilon^{X_{c1}}_{\text{res}}/\epsilon^{X_{c2}}_{\text{res}}$, are also shown in Fig. 2. In general these efficiency ratios are consistent with unity, except in the $pT^{1/0}$ bins $2–3$ GeV/c and $3–4$ GeV/c where the reconstruction and detection efficiencies for $X_{c1}$ are smaller than for $X_{c2}$. The increase in the efficiency ratio in these bins arises because the photon $pT$ spectra are different for $X_{c1}$ and $X_{c2}$. The photon $pT^{1/0}$ $> 650$ MeV/c requirement cuts harder in the case of the $X_{c1}$ and therefore lowers this efficiency. The increase in the efficiency ratio is a kinematic effect,
The production of polarised $\chi_c$ states would modify the efficiencies calculated from the simulation, which assumes unpolarised $\chi_c$. A measurement of the $\chi_c$ polarisation would require an angular analysis, which is not feasible with the present amount of data. Various polarisation scenarios are considered in Table 2. Assuming no azimuthal dependence in the production process, the $\chi_c \to J/\psi \gamma$ system is described by three angles: $\theta_{J/\psi}$, $\theta_{\chi_c}$, and $\phi$, where $\theta_{J/\psi}$ is the angle between the directions of the positive muon in the $J/\psi$ rest frame and the $J/\psi$ in the $\chi_c$ rest frame, $\theta_{\chi_c}$ is the angle between the directions of the $J/\psi$ in the $\chi_c$ rest frame and the $\chi_c$ in the laboratory frame, and $\phi$ is the angle between the plane formed from the $\chi_c$ and $J/\psi$ momentum vectors in the laboratory frame and the $J/\psi$ decay plane in the $J/\psi$ rest frame. The angular distributions are independent of the choice of polarisation axis (the direction of the $\chi_c$ in the laboratory frame) and are detailed in Ref. [5]. For each simulated event in the unpolarised sample, a weight is calculated from the distribution of these angles in the various polarisation hypotheses compared to the unpolarised distribution. The weights in Table 2 are then the average of these per-event weights in the simulated sample. For a given $(|m_{J1}|, |m_{J2}|)$ polarisation combination, the central value of the determined cross-section ratio in each $pT^{J/\psi}$ bin should be multiplied by the number in the table. The maximum effect from the possible polarisation of the $\chi_{c1}$ and $\chi_{c2}$ mesons is given separately from the systematic uncertainties in Table 4 and Fig. 3.

### 4. Systematic uncertainties

The branching fractions used in the analysis are $B(\chi_{c1} \to J/\psi \gamma) = 0.344 \pm 0.015$ and $B(\chi_{c2} \to J/\psi \gamma) = 0.195 \pm 0.008$, taken from Ref. [14]. The relative systematic uncertainty on the cross-section ratio resulting from the $\chi_c \to J/\psi \gamma$ branching fractions is 6%; the absolute uncertainty is given for each bin of $pT^{J/\psi}$ in Table 3.

The simulation sample used to calculate the efficiencies has approximately the same number of $\chi_c$ candidates as are observed in the data. The statistical errors from the finite number of simulated events are included as a systematic uncertainty in the final results. The uncertainty associated to this is determined by sampling the efficiencies used in Eq. (1) according to their errors. The relative systematic uncertainty due to the limited size of the simulation rather than a reconstruction effect, and is well modelled by the simulation.

### 3.2. Polarisation

The production of polarised $\chi_c$ states would modify the efficiencies calculated from the simulation, which assumes unpolarised $\chi_c$. A measurement of the $\chi_c$ polarisation would require an angular analysis, which is not feasible with the present amount of data. Various polarisation scenarios are considered in Table 2. Assuming no azimuthal dependence in the production process, the $\chi_c \to J/\psi \gamma$ system is described by three angles: $\theta_{J/\psi}$, $\theta_{\chi_c}$, and $\phi$, where $\theta_{J/\psi}$ is the angle between the directions of the positive muon in the $J/\psi$ rest frame and the $J/\psi$ in the $\chi_c$ rest frame, $\theta_{\chi_c}$ is the angle between the directions of the $J/\psi$ in the $\chi_c$ rest frame and the $\chi_c$ in the laboratory frame, and $\phi$ is the angle between the plane formed from the $\chi_c$ and $J/\psi$ momentum vectors in the laboratory frame and the $J/\psi$ decay plane in the $J/\psi$ rest frame. The angular distributions are independent of the choice of polarisation axis (the direction of the $\chi_c$ in the laboratory frame) and are detailed in Ref. [5]. For each simulated event in the unpolarised sample, a weight is calculated from the distribution of these angles in the various polarisation hypotheses compared to the unpolarised distribution. The weights in Table 2 are then the average of these per-event weights in the simulated sample. For a given $(|m_{J1}|, |m_{J2}|)$ polarisation combination, the central value of the determined cross-section ratio in each $pT^{J/\psi}$ bin should be multiplied by the number in the table. The maximum effect from the possible polarisation of the $\chi_{c1}$ and $\chi_{c2}$ mesons is given separately from the systematic uncertainties in Table 4 and Fig. 3.

### Table 2

Polarisation weights in $pT^{J/\psi}$ bins for different combinations of $\chi_{c1}$ and $\chi_{c2}$ polarisation states $|J, m_{J2}|$ with $|m_{J1}| = 0, \ldots, J$. The polarisation axis is defined as the direction of the $\chi_c$ in the laboratory frame. Unpol. means the $\chi_c$ is unpolarised.

| $(|m_{J1}|, |m_{J2}|)$ | $pT^{J/\psi}$ (GeV/c) |
|------------------------|-----------------------|
| (Unpol, 0)             | 0.99 0.97 0.94 0.91 0.88 0.87 0.86 0.85 0.85 0.85 0.85 0.85 0.88 |
| (Unpol, 1)             | 0.97 0.98 0.97 0.95 0.94 0.94 0.93 0.93 0.93 0.93 0.93 0.93 0.93 |
| (Unpol, 2)             | 1.03 1.04 1.07 1.11 1.14 1.17 1.18 1.18 1.19 1.18 1.19 1.19 1.16 |
| (0, Unpol)             | 1.01 0.99 0.97 0.93 0.90 0.89 0.87 0.86 0.85 0.87 0.86 0.86 0.84 |
| (1, Unpol)             | 0.99 1.00 1.02 1.04 1.05 1.06 1.06 1.07 1.08 1.07 1.07 1.08 1.08 |
| (0, 0)                 | 1.00 0.97 0.91 0.84 0.80 0.77 0.75 0.74 0.72 0.74 0.74 0.74 0.74 |
| (0, 1)                 | 0.98 0.97 0.93 0.88 0.85 0.83 0.81 0.79 0.78 0.78 0.78 0.78 0.78 |
| (0, 2)                 | 1.04 1.03 1.03 1.03 1.03 1.03 1.03 1.03 1.03 1.03 1.03 1.03 0.98 |
| (1, 0)                 | 0.99 0.97 0.96 0.94 0.93 0.92 0.92 0.92 0.91 0.91 0.91 0.91 0.91 |
| (1, 1)                 | 0.97 0.98 0.98 0.99 0.99 0.99 0.99 1.00 1.00 1.00 1.00 1.00 1.01 |
| (1, 2)                 | 1.03 1.04 1.09 1.15 1.20 1.23 1.26 1.26 1.28 1.26 1.26 1.27 1.25 |

### Fig. 3

Ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in bins of $2 < pT^{J/\psi} < 15$ GeV/c. The LHCb results, in the rapidity range $2.0 < y^{J/\psi} < 4.5$ and assuming the production of unpolarised $\chi_c$ mesons, are shown with solid black circles and the internal error bars correspond to the statistical error; the external error bars include the contribution from the systematic uncertainties (apart from the polarisation). The lines surrounding the data points show the maximum effect of the unknown $\chi_c$ polarisations on the result. The upper and lower limits correspond to the spin states as described in the text. The CDF data points, at $\sqrt{s} = 1.96$ TeV in $p\bar{p}$ collisions and in the $J/\psi$ pseudorapidity range $|\eta^{J/\psi}| < 1.0$, are shown in (a) with open blue circles [6]. The two hatched bands in (b) correspond to the ChiGen Monte Carlo generator [15] and NLO NRQCD [3] predictions.
Table 3
Summary of the systematic uncertainties (absolute values) on $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in each $p_T^{1/0}$ bin.

<table>
<thead>
<tr>
<th>$p_T^{1/0}$ (GeV/c)</th>
<th>2–3</th>
<th>3–4</th>
<th>4–5</th>
<th>5–6</th>
<th>6–7</th>
<th>7–8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching fractions</td>
<td>+0.08</td>
<td>+0.08</td>
<td>+0.06</td>
<td>+0.07</td>
<td>+0.07</td>
<td>+0.06</td>
</tr>
<tr>
<td>Size of simulation sample</td>
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<td>+0.01</td>
<td>+0.01</td>
<td>+0.01</td>
<td>+0.01</td>
<td>+0.01</td>
</tr>
<tr>
<td>Fit model</td>
<td>+0.04</td>
<td>+0.05</td>
<td>+0.03</td>
<td>+0.03</td>
<td>+0.03</td>
<td>+0.03</td>
</tr>
<tr>
<td>Simulation calibration</td>
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<td>+0.00</td>
<td>+0.00</td>
<td>+0.00</td>
<td>+0.00</td>
<td>+0.00</td>
</tr>
</tbody>
</table>

The systematic uncertainty associated with the shape of the fitted background function is incorporated by including or excluding the $\chi_{c0}$ signal shape, which peaks in the region where the background shape is most sensitive.

The background shape is also sensitive to the rise in the $\Delta M$ distribution. The systematic uncertainty from this is included by varying the lower edge of the fit range in the interval $\pm 10$ MeV/$c^2$ around its nominal value for each bin in $p_T$.

The overall systematic uncertainty from the fit is then determined from the distribution of the $\chi_{c2}/\chi_{c1}$ cross-section ratios by repeating the sampling procedure described above many times. The relative uncertainty is found to be in the range $(2.2–14.6)\%$ and is given for each bin of $p_T^{1/0}$ in Table 3.

A systematic uncertainty related to the calibration of the simulation is evaluated by performing the analysis on simulated events and comparing the efficiency-corrected ratio of yields, $(N(\chi_{c2})/N(\chi_{c1})) \cdot (\epsilon(\chi_{c2})/\epsilon(\chi_{c1}))$, to the true ratio generated in the sample. A deviation of $-9.6\%$ is observed, caused by non-Gaussian signal shapes in the simulation from the calorimeter calibration. These are not seen in the data, which is well described by Gaussian signal shapes. The deviation is included as a systematic error, by sampling from the negative half of a Gaussian with zero mean and a width of $9.6\%$. The relative uncertainty on the cross-section ratio is found to be less than $6.0\%$ and is given for each bin of $p_T^{1/0}$ in Table 3.

A second check of the procedure was performed using simulated events generated according to the distributions observed in the data, i.e. three overlapping Gaussians and a background shape similar to that in Fig. 1. In this case no evidence for a deviation was observed. Other systematic uncertainties due to the modelling of the detector in the simulation are negligible.

In summary, the overall systematic uncertainty, excluding that due to the branching fractions, is evaluated by simultaneously sampling the deviation of the cross-section ratio from the central value, using the distributions of the cross-section ratios described above. The separate systematic uncertainties are shown in bins of $p_T^{1/0}$ in Table 3 and the combined uncertainties are shown in Table 4.

5. Results and conclusions

The cross-section ratio, $\sigma(\chi_{c2})/\sigma(\chi_{c1})$, measured in bins of $p_T^{1/0}$ is given in Table 4 and shown in Fig. 3. Previous measurements from WA11 in $\pi^-e^+$ collisions at 185 GeV/c gave $\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 1.4 \pm 0.6$ [4], and from HERA-B in $p\bar{p}$ collisions at $\sqrt{s} = 41.6$ GeV with $p_T^{1/0}$ below roughly 5 GeV/c gave $\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 1.75 \pm 0.7$ [5]. The data points from CDF [6] at $\sqrt{s} = 1.96$ TeV in $p\bar{p}$ collisions are also shown in Fig. 3(a).
Theoretical predictions, calculated in the LHCb rapidity range $2.0 < y^{J/ψ} < 4.5$, from the ChiGen Monte Carlo generator [15], which is an implementation of the leading-order colour-singlet model described in Ref. [16], and from the NLO NRQCD calculations [3] are shown in Fig. 3(b). The hatched bands represent the uncertainties in the theoretical predictions.

Fig. 3 also shows the maximum effect of the unknown $x_c$ polarisations on the result, shown as the lines surrounding the data points. In the first $p_T^{J/ψ}$ bin, the upper limit corresponds to the spin state combination $(|m_{x_c}|, |m_{x_c}^2|) = (0, 2)$ and the lower limit corresponds to the spin state combination $(1, 1)$. In all subsequent $p_T^{J/ψ}$ bins, the upper limit corresponds to spin state combination $(1, 2)$ and the lower limit corresponds to $(0, 0)$.

In summary, the ratio of the $\sigma(x_c^2)/\sigma(x_c^1)$ prompt production cross-sections has been measured as a function of $p_T^{J/ψ}$ using 36 pb$^{-1}$ of data collected by LHCb during 2010 at a centre-of-mass energy $\sqrt{s} = 7$ TeV. The ChiGen generator describes the shape of the distribution reasonably well, although the data lie consistently above the model prediction. This could be explained by important higher order perturbative corrections and/or sizeable colour-octet terms not included in the calculation. The results are in agreement with the NLO NRQCD model for $p_T^{J/ψ} > 8$ GeV/c.

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References


LHCb Collaboration

R. Aaij$^{23}$, C. Abellan Beteta$^{35,n}$, B. Adeva$^{36}$, M. Adinolfi$^{42}$, C. Adrover$^{6}$, A. Affolder$^{48}$, Z. Ajaltouni$^{5}$, J. Albrecht$^{37}$, F. Alessio$^{37}$, M. Alexander$^{47}$, G. Alkhazov$^{29}$, P. Alvarez Cartelle$^{36}$, A.A. Alves Jr.$^{22}$, S. Amato$^{2}$, Y. Amhis$^{38}$, J. Anderson$^{39}$, R.B. Appleby$^{50}$, O. Aquines Gutierrez$^{10}$, F. Archilli$^{18}$, M. Arrubito$^{53}$, A. Artamonov$^{34}$, M. Artuso$^{52,37}$, E. Aslanides$^{6}$, G. Auriemma$^{22,m}$, S. Bachmann$^{11}$, J.J. Back$^{44}$, D.S. Bailey$^{50}$, V. Balagura$^{30,37}$, W. Baldini$^{16}$, R.J. Barlow$^{50}$, C.Barschel$^{37}$, S. Barsuk$^{7}$, W. Barter$^{43}$, A. Bates$^{47}$, C. Bauer$^{10}$, Th. Bauer$^{23}$, A. Bay$^{38}$, I. Bediaga$^{1}$, S. Belogurov$^{30}$, K. Belous$^{34}$, I. Belyaev$^{30,37}$, E. Ben-Haim$^{8}$, M. Benayoun$^{8}$, G. Bencivenni$^{18}$, S. Benson$^{46}$, J. Benton$^{42}$, R. Bernet$^{39}$, M.-O. Bettler$^{17}$, M. van Beuzekom$^{23}$, A. Bien$^{11}$, S. Bifani$^{12}$, T. Bird$^{50}$, A. Bizzeti$^{17,h}$, P.M. Bjørnstad$^{50}$, T. Blake$^{37}$, F. Blanc$^{38}$, C. Blanks$^{49}$, J. Blouw$^{11}$, S. Blusk$^{52}$, A. Bobrov$^{33}$, V. Bocci$^{22}$, A. Bondar$^{33}$, N. Bondar$^{29}$, W. Bonivento$^{15}$, S. Borghi$^{47}$, A. Borgia$^{52}$, T.J.V. Bowcock$^{48}$, C. Bozzi$^{16}$, T. Brambach$^{9}$, J. van den Brand$^{24}$, J. Bressieux$^{38}$, D. Brett$^{50}$, M. Britsch$^{10}$, T. Britton$^{52}$, N.H. Brook$^{42}$, H. Brown$^{48}$, A. Bünker-German$^{39}$, I. Burducea$^{28}$, A. Bursche$^{39}$, J. Buytaert$^{37}$, S. Cadeddu$^{15}$, O. Callot$^{7}$, M. Calvi$^{20,j}$, M. Calvo Gomez$^{35,n}$, A. Camboni$^{35}$, P. Campana$^{18,37}$, A. Carbone$^{14}$, G. Carboni$^{21,k}$, R. Cardinale$^{19,37,i}$, A. Cardini$^{15}$, L. Carson$^{49}$, K. Carvalho Akiba$^{2}$, G. Casi$^{48}$, M. Cattaneo$^{37}$, Ch. Cauet$^{9}$, M. Charles$^{51}$, Ph. Charpentier$^{37}$, N. Chiapolini$^{39}$, K. Ciba$^{37}$, X. Cid Vidal$^{36}$, G. Ciezarek$^{49}$, P.E.L. Clarke$^{46,37}$, M. Clemencic$^{37}$, H.V. Cliff$^{33}$, J. Closier$^{37}$, C. Coco$^{28}$, V. Coco$^{23}$, J. Cogan$^{6}$, P. Collins$^{37}$, A. Comerma-Montells$^{35}$, F. Constantin$^{28}$, G. Conti$^{38}$, A. Contu$^{51}$, A. Cook$^{42}$, M. Coombes$^{42}$, G. Corti$^{37}$, G.A. Cowan$^{38}$, R. Currie$^{46}$, B. D’Almagone$^{7}$, C. D’Ambrosio$^{37}$, P. David$^{8}$, P.N.Y. David$^{23}$, I. De Bonis$^{4}$, S. De Capua$^{21,k}$, M. De Cian$^{39}$, F. De Lorenzo$^{7}$, J.M. De Miranda$^{1}$, L. De Paula$^{2}$, P. De Simone$^{18}$,