Measurement of the relative cross-section $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ of prompt $\chi_c$ mesons at LHCb

The LHCb Collaboration

Abstract

The production of heavy quarkonia remains a challenging problem for understanding Quantum Chromodynamics (QCD). This note reports on the production cross-section ratio of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ with the $\chi_c$ state decaying into $\chi_c \rightarrow J/\psi\gamma$. The $J/\psi$ is identified via the decay $J/\psi \rightarrow \mu^+\mu^-$ while the photon is reconstructed from conversions in the detector material.

The analysis is based on a data sample of 370 pb$^{-1}$ recorded by the LHCb experiment at the Large Hadron Collider in 2011. The results are compared to a study in which the photons are detected in the LHCb calorimeter using 37 pb$^{-1}$ of data recorded in 2010, as well as theoretical predictions.

1Conference report prepared for the Krakow Epiphany Conference on Present and Future of B-Physics, 9-11 January 2012, Krakow, Poland. Contact author: V. Gibson, U. Kerzel
1 Introduction

The production of heavy quarkonia remains a challenging problem for the understanding of Quantum Chromodynamics (QCD). At the Large Hadron Collider (LHC), $c\bar{c}$ pairs are expected to be produced mainly in Leading Order (LO) gluon-gluon interactions, which are computed using perturbative QCD. The formation of bound states is described by non-perturbative models. Recent approaches make use of the non-relativistic QCD factorisation approach (NRQCD) assuming a combination of colour-singlet (CS) and colour-octet (CO) states, as it evolves towards the final bound state via the exchange of soft gluons [1]. Next-to-Leading Order (NLO) QCD corrections in charmonium production are also essential for the description of the experimental data [2, 3]. The study of P-wave charmonia $\chi_{cJ}$ ($J=0,1,2$) production is important as it gives substantial feed-down contributions to the prompt $J/\psi$ production through their radiative decay $\chi_c \to J/\psi \gamma$ and can have significant consequences for the measurement of the $J/\psi$ polarisation. The measurement of the production rate ratio of $\chi_{c2}$ to $\chi_{c1}$ is sensitive to colour-singlet and colour-octet production mechanisms.

Measurements of $\chi_c$ production, followed by the decay $\chi_c \to J/\psi \gamma$, and the relative amounts of the $\chi_{c1}$ and $\chi_{c2}$ spin states, have been made previously in a variety of beam types and energies [4, 5].

This work complements the previous measurement by the LHCb Collaboration of the relative $\chi_c$ production ratio [6] which uses photons reconstructed in the calorimeter system. This analysis uses photons which have converted in the detector material into an electron-positron pair ($\gamma \to e^+e^-$). This approach allows to resolve the individual $\chi_{cJ}$ states due to the better resolution of the tracking system. On the other hand, the method suffers from large experimental inefficiencies due to the very light material budget ($\approx 0.23$ radiation lengths) of the vertex detector and hence from a limited effective dataset to perform the analysis with. The small branching fraction to the $\chi_{c0}$ state does not allow to consider this decay mode in the analysis.

2 Dataset and event selection

The study reported here uses a $pp$ collision data sample recorded by the LHCb experiment at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. The data correspond to an integrated luminosity of $370 \text{ pb}^{-1}$ recorded between January and June 2011.

The LHCb detector [7] is a single arm forward spectrometer ($2 < \eta < 5$) optimised for the study of the decay of mesons containing charm and beauty quarks. The detector includes a high precision tracking system which consists of a silicon vertex detector (VELO) and several dedicated tracking planes with silicon microstrip detectors (Inner Tracker) covering the region with high charged particle multiplicity and a straw tube detector (Outer Tracker) for the region with lower occupancy. The VELO is a silicon strip device that surrounds the $pp$ interaction region and is positioned with its sensitive area 8 mm from the beam during collisions. It provides precise measurements of the
positions of the primary $pp$ interaction vertices and decay vertices of long-lived hadrons. The Inner and Outer trackers are placed downstream of the dipole magnet providing a 4 Tm magnetic field to allow the measurement of the charged particles’ momenta as they traverse the detector. Excellent particle identification capabilities are provided by two Ring Imaging Cherenkov (RICH) detectors which allow charged pions, kaons and protons to be distinguished from each other in the momentum range of 2-100 GeV/c. Further downstream is a Preshower/Scintillating Pad Detector, an electromagnetic calorimeter, and a hadronic calorimeter. The muon detection system consists of five muon stations equipped with multi-wire proportional chambers, with the exception of the centre of the first station, which uses triple-GEM detectors.

The LHCb trigger system consists of two levels. The first level (L0), implemented in hardware, is designed to reduce the LHC bunch crossing frequency of 40 MHz to a maximum of 1 MHz, at which the complete detector is read out. The second level is a software trigger and performs a full event reconstruction to enrich signal events.

The simulated events are obtained using the Pythia event generator [8]. The detector response is simulated using the Geant toolkit [9]. The $\chi_c$ states are identified through their radiative decay $\chi_c \rightarrow J/\psi \gamma$ with $J/\psi \rightarrow \mu^+ \mu^-$ and $\gamma \rightarrow e^+ e^-$. The $J/\psi$, photon and $\chi_c$ candidates are selected using the NeuroBayes neural network package [10]. Following this multi-variate approach allows to exploit the correlation between the various input variables representing a wide range of measurements by the LHCb spectrometer such as kinematic properties of the particles, response from the particle identification (RICH), calorimeter and muon systems. In a first step, high-purity $J/\psi$ candidates are identified using a dedicated neural network. This network was trained on data recorded by the LHCb experiment early 2010. The $J/\psi$ component present in the data is identified by sWeights [11] which are used in a dedicated training method of the NeuroBayes package. Next, photons which have converted early in the detector material into an electron-positron pair are identified with a dedicated network which was trained using simulated events where the conversion photons have been identified by generator information. Finally, $\chi_c$ candidates are identified using a further neural network which includes kinematic information about the particles involved in the decay chain, as well as the network output of the $J/\psi$ and conversion identification network. Only prompt $\chi_c$ candidates are considered in this analysis.

3 Experimental method

3.1 Determination of the relative cross-section

The relative production cross-section ratio of the $\chi_{c1}$ and $\chi_{c2}$ states is measured by

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}} \cdot \epsilon_{J/\psi} \cdot \epsilon_{c1} \cdot \epsilon_{c1} \cdot B(\chi_{c1} \rightarrow J/\psi \gamma)}{N_{\chi_{c1}} \cdot \epsilon_{J/\psi} \cdot \epsilon_{\gamma} \cdot \epsilon_{c2} \cdot \epsilon_{c2} \cdot B(\chi_{c2} \rightarrow J/\psi \gamma)}, \quad (1)$$
where $N_{\chi_cJ}$ are the yields of the $\chi_cJ$ states extracted from an unbinned maximum likelihood fit to the data in bins of the transverse momentum $p_t$ of the $J/\psi$ candidate. The efficiency correction factors $\epsilon_{\chi_cJ}$, $\epsilon_{\gamma}$ and $\epsilon_{\text{sel}}$ account for the various efficiency losses due to event reconstruction and candidate selection and have been evaluated using simulated events. The branching fractions $B(\chi_cJ \to J/\psi\gamma)$ of the $\chi_c$ meson into the final state are taken from the current world average [13].

Owing to the limited dataset available, the relative yields can only be extracted in four bins of transverse momentum of the $J/\psi$ candidate, where the bin borders have been chosen such that they contain sufficient entries for the fit to the invariant mass-spectrum of the $\chi_c$ candidates to converge.

The bin ranges are: $2 < p_t(J/\psi) \leq 4$ GeV/c, $4 < p_t(J/\psi) \leq 6$ GeV/c, $6 < p_t(J/\psi) \leq 8$ GeV/c, $8 < p_t(J/\psi) \leq 15$ GeV/c.

### 3.2 Estimation of the combinatorial background

A significant amount of combinatorial background remains after applying the final event selection. In a data-driven approach, this background is studied using “wrong-sign” conversion photons, i.e. $\gamma \to e^-e^-$ or $\gamma \to e^+e^-$. This is mainly due to the fact that only a small magnetic field is present in the vertex detector and the electrons / positrons originating from a converted photon have very low energy. Fig. 1 shows the invariant mass difference spectrum $\Delta m = m(\chi_c) - m(J/\psi) = m(e^+e^-\mu^+\mu^-) - m(\mu^+\mu^-)$ for the “right-sign” combination ($\gamma \to e^+e^-$, black data points) and the “wrong-sign” combination (red histogram) in each of the four bins of transverse momentum of the $J/\psi$ candidate. The “wrong-sign” combination is normalised to match the “right-sign” combination in the region $0.5 \leq \Delta m < 0.7$ GeV/$c^2$, i.e. in the upper sideband.

The combinatorial background can be parametrised by an empirical function originally developed to model the $D^* - D^0$ mass difference:[2]

$$f_{bg} = \left[ 1 - \exp \left( -\frac{\Delta m}{m_0} \right) \right] \cdot \left[ \frac{\Delta m}{m_0} \right]^a + b \cdot \left[ \frac{\Delta m}{m_0} - 1 \right],$$

where the $a$, $b$, $c$ and $m_0$ are treated as free parameters in the fit.

### 3.3 Determination of the $\chi_c$ yield

In a first step, the central values of the mass difference of the $\chi_c$ states are determined from a fit to the invariant mass spectrum integrated over all transverse momenta of the $J/\psi$ candidate. The resulting invariant mass spectrum is shown in Fig. 2. The measured central values are close to the expected values from the current world averages [13]. They are kept fixed in the subsequent analysis of the four bins in the transverse momentum of the $J/\psi$ candidate.

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The efficiency terms used in Eq. 1 are determined from simulated events. The relative efficiency concerning the reconstruction of the $J/\psi$ candidate is given by

$$\frac{\epsilon_{J/\psi}^{X_c}}{\epsilon_{J/\psi}} = \frac{N_{J/\psi, rec}^{X_c}}{N_{J/\psi, rec}} \cdot \frac{N_{J/\psi, gen}^{X_c}}{N_{J/\psi, gen}}$$

## 4 Efficiency corrections

The efficiency terms used in Eq. 1 are determined from simulated events. The relative efficiency concerning the reconstruction of the $J/\psi$ candidate is given by

$$\frac{\epsilon_{J/\psi}^{X_c}}{\epsilon_{J/\psi}} = \frac{N_{J/\psi, rec}^{X_c}}{N_{J/\psi, rec}} \cdot \frac{N_{J/\psi, gen}^{X_c}}{N_{J/\psi, gen}}$$

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**Figure 1:** Invariant mass difference spectra in four transverse momentum bins of the $J/\psi$. “Right-sign” combinations are shown as black data points, “wrong-sign” combinations as the red histogram. Top left: $2 < p_t(J/\psi) \leq 4$ GeV/$c$, top right: $4 < p_t(J/\psi) \leq 6$ GeV/$c$, bottom left: $6 \leq < (J/\psi) \leq 8$ GeV/$c$, bottom right: $8 < p_t(J/\psi) \leq 15$ GeV/$c$. The yield ratio of the $\chi_{cJ}$ candidates is determined in each bin in the following way: first, the background parameters are determined by a fit to the invariant mass spectrum of the “wrong-sign” combination. These are then fixed in the subsequent fit to the “right-sign” invariant mass spectrum, where the $\chi_c$ signal is described by Crystal-Ball functions. The shape parameters of the Crystal-Ball functions ($a$, $s$ and $n$) are common to all $\chi_c$ states and are treated as free parameters in the fit.

The results of the four fits, uncorrected for efficiency effects, are shown in Fig. 3.
where $\epsilon_{\chi_c}^{J/\psi}$ is the efficiency to reconstruct a $J/\psi$ from a $\chi_c$ decay, $N_{J/\psi,\text{rec}}^{\chi_c}$ is the number of reconstructed $J/\psi$ candidates which originate from a $\chi_c$ decay and correspondingly $N_{J/\psi,\text{gen}}^{\chi_c}$ is the number of generated $J/\psi$ candidates which originate from a $\chi_c$ decay. These extracted efficiencies are compatible with unity.

The product of the efficiency for reconstructing and selecting a photon from a $\chi_c$ state, $\epsilon_{\gamma}^{\chi_c}$, and the efficiency for selecting the $\chi_c$ meson, $\epsilon_{\text{sel}}^{\chi_c}$, is given by the ratio of the number of reconstructed $\chi_c$ mesons and the number of reconstructed $J/\psi$ mesons which originate from the decay of a $\chi_c$ state:

$$
\epsilon_{\gamma}^{\chi_c} \epsilon_{\text{sel}}^{\chi_c} = \frac{N_{\chi_c,\text{rec}}^{\chi_c}}{N_{J/\psi,\text{rec}}^{J/\psi}}.
$$

Here, $N_{\chi_c,\text{rec}}^{\chi_c}$ is the number of $\chi_c$ candidates reconstructed in the sample, which also pass the selection criteria and are fully associated to generator information. The quantity $N_{J/\psi,\text{rec}}^{J/\psi}$ is the number of $J/\psi$ candidates which originate from the decay of a $\chi_c$ meson.

Fig. 4 shows the photon and $\chi_c$ meson reconstruction efficiency. The left part of the figure shows the photon reconstruction and selection efficiency multiplied by the $\chi_c$ selection efficiency separately for the $\chi_c$ and $\chi_c$ state. The right part of the figure shows the ratio of the two distributions. The extracted efficiencies are very similar and mostly compatible.
with unity. The deviation from unity in the range of $2 < p_t(J/\psi) \leq 4$ GeV/c is due to a bias introduced by the event selection on the transverse momentum of the $\chi_c$ candidate. A correction for this bias is applied to the final result and treated as a systematic uncertainty.

## 5 Polarisation effects

Since the polarisation of the $\chi_c$ states is not known, all states are assumed to be unpolarised in the event simulation and hence in the extraction of the efficiency correction. The presence of polarised $\chi_c$ states would modify these corrections and the potential effect is investigated by reweighting the simulation assuming fully polarised $\chi_c$ states. The polarisation weights $w_{\chi_c}^{\text{Pol}}$ which are used to reweight the simulated events are shown in Fig. 5.
Figure 4: Left: The photon reconstruction and selection efficiency multiplied by the \( \chi_c \) selection efficiency for the \( \chi_{c1} \) (black) and \( \chi_{c2} \) (red) states in bins of the transverse momentum of the \( J/\psi \) meson. Right: Ratio of the efficiencies for the \( \chi_{c1} \) and \( \chi_{c2} \) states. The parameter “M” denotes the polarisation state of the \( \chi_{cJ} \) meson.

Figure 5: Polarisation weights \( W_{pol}^{\chi_c} \) for \( \chi_{c1} \) (left) and \( \chi_{c2} \) (right) using simulated prompt \( \chi_c \) candidates which are fully matched to the generator information. The parameter “M” denotes the polarisation state of the \( \chi_{cJ} \) meson.

6 Evaluation of systematic uncertainties

Since this study evaluates the relative \( \chi_{c2} \) to \( \chi_{c1} \) cross-section ratio, most systematic effects cancel. The following contributions are found to contribute significantly to the sources of systematic uncertainties.

- **Event Selection**: Although the simulated events used in the training of the neural networks agree very well with the data recorded by the LHCb experiment, some residual discrepancies remain. Furthermore, the combinatorial background in data is higher than anticipated from the event simulation. In order to quantify this
effect, the cut on the neural network output used for the final event selection is varied in a wide window and the variation observed with respect to the nominal choice is taken as a conservative estimate of the systematic uncertainty. Due to the limited amount of data and simulated events available for the analysis this contribution contains a considerable effect from statistical fluctuations.

- **Branching Fractions:** The experimentally measured ratio of yields is expressed as a cross-section ratio using the known values of the branching fractions of the respective states. The numerical values have been taken from the current world average [13]. The errors are propagated and assigned as a systematic uncertainty.

- **Efficiency Correction:** The efficiency corrections obtained from simulated events are varied individually in each bin of $p_t(J/\psi)$ within their statistical uncertainty and the difference with respect to the nominal result is assigned as a systematic uncertainty. In addition, the difference of the efficiency correction obtained without the event selection with respect to the nominal case is assigned as a systematic uncertainty to account for the bias introduced by the event selection.

- **Combinatorial Background:** The effect of the treatment of the combinatorial background in the extraction of the yield is estimated performing the fit to the invariant mass spectrum keeping the shape parameters of the Crystal-Ball function fixed while treating the shape parameters of the combinatorial background as free parameters in the fit. The difference between the two results is assigned as an estimate of the systematic uncertainty.

The systematic uncertainties are added in quadrature. The largest contribution to the systematic uncertainties is related to the efficiency correction.

### 7 Results and conclusion

The relative cross-section $\sigma(\chi_c^2)/\sigma(\chi_c^1)$ for prompt $\chi_c$ mesons in the decay channel $\chi_c \rightarrow J/\psi\gamma$ has been measured with 370 pb$^{-1}$ of data recorded in 2011. The photons are required to have converted into an electron-positron pair. Fig. 6 shows the result obtained from the fit to the invariant mass spectrum in bins of transverse momentum of the $J/\psi$ meson. The inner error bars indicate the statistical error, the outer error bars correspond to the contribution from the sources of systematic uncertainties. The maximum effect of the unknown $\chi_c$ polarisation is indicated by the shaded area around the extracted data-points. The numerical result is summarised in Tab. 1.

The result obtained in the analysis of the data recorded in 2010 using photons detected in the calorimeter is shown together with the result of this analysis in Fig. 6. Both analyses agree well and the $p$-value between the results is $\approx 0.73$.

Two predictions from theoretical calculations are superimposed on the data. One prediction has been obtained using the ChiCGen generator [14], the other prediction has been obtained using NLO NRQCD calculations [2]. The latter is given as a range of
Figure 6: Relative cross-section $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in bins of transverse momentum of the $J/\psi$ candidate. The inner error bars correspond to the statistical errors originating from the outer of the $\chi_{c1}$ and $\chi_{c2}$ yield. The external error bars contain the contribution from the sources of systematic uncertainties. The shaded area around the data-points (in black) shows the maximum effect of the unknown $\chi_c$ polarisation. The result of the analysis performed on data recorded in 2010 using photons detected in the calorimeter system [6] is shown in green. The result of the CDF collaboration [5] is shown in magenta. The experimental results are shown together with theoretical predictions obtained from the ChiCGen generator [14] (in blue) and NLO NRQCD calculations [2] (in red).

allowed values rather than a central value with associated theoretical errors. The results obtained in this study agree with the predicted behaviour. However, given the size of the uncertainties much more data are needed to make a more precise statement.

Acknowledgments

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at CERN and at the LHCb institutes, and acknowledge support from the National Agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); CERN; NSFC (China); CNRS/IN2P3 (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (Netherlands); SCSR (Poland); ANCS (Romania); MinES of Russia and
Table 1: Preliminary results of the prompt production cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in bins of transverse momentum of the $J/\psi$ candidate. The first error is the statistical error, the second the contribution from the sources of systematic uncertainties added in quadrature. The maximum effect to the cross-section ratio of the unknown $\chi_e$ polarisation is listed in the third column.

<table>
<thead>
<tr>
<th>$p_t^{J/\psi}$ [GeV/c]</th>
<th>$\sigma(\chi_{c2})/\sigma(\chi_{c1})$</th>
<th>Polarisation</th>
</tr>
</thead>
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<tr>
<td>2 - 4</td>
<td>$1.01 \pm 0.11$^{+0.13}_{-0.13}$</td>
<td>$\pm 0.16$</td>
</tr>
<tr>
<td>4 - 6</td>
<td>$1.06 \pm 0.13$^{+0.15}_{-0.16}$</td>
<td>$\pm 0.16$</td>
</tr>
<tr>
<td>6 - 8</td>
<td>$1.16 \pm 0.24$^{+0.28}_{-0.21}$</td>
<td>$\pm 0.35$</td>
</tr>
<tr>
<td>8 - 15</td>
<td>$0.93 \pm 0.23$^{+0.21}_{-0.24}$</td>
<td>$\pm 0.37$</td>
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</table>

Rosatom (Russia); MICINN, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); NSF (USA). We also acknowledge the support received from the ERC under FP7 and the Region Auvergne.
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