

Prompt charmonia production and polarization at LHC in the NRQCD with k_T -factorization.

Part II: χ_c mesons

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Abstract

In the framework of k_T -factorization approach, the production of prompt χ_c mesons in pp collisions at the LHC energies is studied. Our consideration is based on the off-shell amplitudes for hard partonic subprocesses $g^*g^* \rightarrow \chi_{cJ}$ and non-relativistic QCD formalism for bound states. The transverse momentum dependent (unintegrated) gluon densities in a proton were derived from Ciafaloni-Catani-Fiorani-Marchesini evolution equation or, alternatively, were chosen in accordance with Kimber-Martin-Ryskin prescription. Taking into account both color singlet and color octet contributions, we deduce the corresponding non-perturbative long-distance matrix elements from the fits to the latest ATLAS data on χ_{c1} and χ_{c2} transverse momentum distributions at $\sqrt{s} = 7$ TeV. We find that these distributions at small and moderate p_T are formed mainly by the color singlet components. We successfully described the data on the differential cross sections and relative production rates $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ presented by the ATLAS, CMS and LHCb Collaborations. We find that the fit points to unequal wave functions of χ_{c1} and χ_{c2} states.

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1 Introduction

Since it was first observed, charmonium production in hadronic collisions remains a subject of considerable theoretical and experimental interest. It provides a sensitive tool probing Quantum Chromodynamics (QCD) in both perturbative and non-perturbative regimes, as the production mechanism involves both short and long distance interactions. Two theoretical approaches for the non-perturbative part are known in the literature: the color-singlet (CS) model [1] and the color-octet (CO) model [2]. As we have explained in our previous paper [3], none of the existing theoretical approaches is able to describe all of the data in their integrity. Our present study is a continuation of the work [3], where the prompt $\psi(2S)$ production and polarization at the LHC has been considered. The motivation for the whole business has already been given there. Here we turn to the production of P -wave states. It is known that the feed-down contributions from χ_c and $\psi(2S)$ states due to their radiative decays $\chi_c \rightarrow J/\psi + \gamma$ and $\psi(2S) \rightarrow J/\psi + \gamma$ give a significant impact on the J/ψ polarization [4–8]. These mechanisms constitute about 30% of the visible J/ψ cross section at the LHC [6–8]. Therefore, a clear understanding of χ_c and $\psi(2S)$ production is a crucial component of any general description of J/ψ production. Another important issue concerns the relative production rate $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at high transverse momenta. This ratio is sensitive to the CS and CO mechanisms and can provide information complementary to the study of the S -wave states [9, 10].

Below we present a systematic analysis of the ATLAS [11], CMS [12] and LHCb [13] data collected at $\sqrt{s} = 7$ TeV for χ_{c1} and χ_{c2} the transverse momentum distributions and for the ratio of the production rates $\sigma(\chi_{c2})/\sigma(\chi_{c1})$.

2 Theoretical framework

Our consideration is based on the off-shell gluon-gluon fusion subprocess that represents the true leading order in QCD:

$$g^*(k_1) + g^*(k_2) \rightarrow c\bar{c} \rightarrow \chi_{cJ}(p), \quad (1)$$

where the 4-momenta of all particles are indicated in parentheses. In general, the charmed quark pair is produced in a state ${}^{2S+1}L_J^{(a)}$ with spin S , orbital angular momentum L , total angular momentum J and color a , which can be either identical to the final charmonium quantum numbers, as it is accepted in the CS model, or different from those. In the latter case, the $c\bar{c}$ pair transforms into physical charmonium state by means of soft (non-perturbative) gluon radiation, as it is considered in the formalism of non-relativistic QCD (NRQCD) [14, 15]. The probability to form a given bound state is determined by the respective non-perturbative long-distance matrix elements (NMEs), which are assumed to be universal (process-independent), not depending on the charmonium momentum and obeying certain hierarchy in powers of the relative charmed quarks velocity v .

The production of heavy $c\bar{c}$ pairs in hard partonic subprocess is regarded as a purely perturbative stage and is considered in the framework of k_T -factorization approach [16, 17], where studying the quarkonium production and polarization has a long history (see, for example, [18–28] and references therein). A detailed description and discussion of the different

aspects of k_T -factorization can be found in reviews [29]. Here we see certain advantages in the fact that, even with the leading-order (LO) matrix elements for hard partonic subprocess, we can include a large piece of higher order QCD corrections (all NLO + NNLO + ... terms containing $\log 1/x$ enhancement) taking them into account in the form of transverse momentum dependent (TMD) gluon densities. The latter are obtained as numerical solutions to Balitsky-Fadin-Kuraev-Lipatov (BFKL) [30] or Catani-Ciafaloni-Fiorani-Marchesini (CCFM) [31] evolution equations and will be described below in more detail.

Summing over the initial gluon polarizations in (1) is done using the spin density matrix $\overline{\epsilon^\mu \epsilon^\nu} = \mathbf{k}_T^\mu \mathbf{k}_T^\nu / |\mathbf{k}_T|^2$, where \mathbf{k}_T is the component of the gluon momentum perpendicular to the proton beam direction [16, 17]. In the collinear limit, when $|\mathbf{k}_T| \rightarrow 0$, this expression converges to the ordinary $\overline{\epsilon^\mu \epsilon^\nu} = -g^{\mu\nu}/2$, while for non-zero $|\mathbf{k}_T|$ gluon polarization vectors acquire an admixture of longitudinal component. The evaluation of partonic amplitudes is straightforward and follow standard QCD Feynman rules in all other respects. Our results for perturbative production amplitudes squared and summed over polarization states agree with the ones [32].

The formation of final state quarkonium from $c\bar{c}$ pair (with any quantum numbers) is an essentially non-perturbative step. At the LO in the relative quark velocity v , the P -wave mesons χ_{cJ} with $J = 0, 1$ or 2 can be formed by a $c\bar{c}$ pair originally produced as color singlet ${}^3P_J^{(1)}$, or can evolve from an intermediate color octet ${}^3S_1^{(8)}$ state. The corresponding amplitudes can be obtained from an unspecified $c\bar{c}$ case by applying the relevant projection operators [1]:

$$\Pi [{}^3S_1] = \hat{\epsilon}(S_z) (\hat{p}_c + m_c) / m^{1/2}, \quad (2)$$

$$\Pi [{}^3P_J] = (\hat{p}_{\bar{c}} - m_c) \hat{\epsilon}(S_z) (\hat{p}_c + m_c) / m^{3/2}, \quad (3)$$

where $m = 2m_c$ is the mass of the considered $c\bar{c}$ state, p_c and $p_{\bar{c}}$ are the four-momenta of the charmed quark and anti-quark, $p_c = p/2 + q$, $p_{\bar{c}} = p/2 - q$, and q is the the relative four-momentum of the quarks in the bound state. States with various projections of the spin momentum onto the z axis are represented by the polarization four-vector $\epsilon_\mu(S_z)$. The probability for the charmed quarks to form a meson depends on the real (for color singlets) or fictitious (for color octets) bound state wave functions $\Psi^{(a)}(q)$. The corresponding NMEs are related to the wave functions in the coordinate space $\mathcal{R}^{(a)}(x)$, which are the Fourier transforms of $\Psi^{(a)}(q)$, and their derivatives [2, 14, 15]:

$$\langle \mathcal{O} [{}^{2S+1}L_J^{(a)}] \rangle = 2N_c(2J+1) |\mathcal{R}^{(a)}(0)|^2 / 4\pi, \quad (4)$$

for S -waves and

$$\langle \mathcal{O} [{}^{2S+1}L_J^{(a)}] \rangle = 6N_c(2J+1) |\mathcal{R}'^{(a)}|^2 / 4\pi, \quad (5)$$

for P -waves. For more details the reader can address the original papers [1, 2, 14, 15] or our previous note [3]. The CS NMEs can be extracted from the measured $\chi_{c2} \rightarrow \gamma\gamma$ decay width or obtained from the potential models [33–36]. However, below we consider them as free parameters (as well as the CO NMEs) and determine from fits to the LHC data.

Finally, the χ_c meson production cross section is calculated as a convolution of the off-

shell partonic cross sections and the TMD gluon densities in a proton:

$$\begin{aligned} \sigma(pp \rightarrow \chi_{cJ} + X) = & \int \frac{2\pi}{x_1 x_2 s F} f_g(x_1, \mathbf{k}_{1T}^2, \mu^2) f_g(x_2, \mathbf{k}_{2T}^2, \mu^2) \\ & \times |\bar{\mathcal{A}}(g^* + g^* \rightarrow \chi_{cJ})|^2 d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 dy \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi}, \end{aligned} \quad (6)$$

where $f_g(x, \mathbf{k}_T^2, \mu^2)$ is the TMD gluon density, y the rapidity of the produced χ_c meson and \sqrt{s} the pp center-of-mass energy. The initial off-shell gluons carry longitudinal momentum fractions x_1 and x_2 (with respect to the parent protons) and non-zero transverse momenta \mathbf{k}_{1T} and \mathbf{k}_{2T} oriented at the azimuthal angles ϕ_1 and ϕ_2 . The off-shell flux factor F is taken¹ in accordance with the general definition [37] as $F = 2\lambda^{1/2}(\hat{s}, k_1^2, k_2^2)$, where $\hat{s} = (k_1 + k_2)^2$.

In our numerical analysis we tried several sets of TMD gluon densities. Two of them (A0 [38] and JH [39]) have been obtained from CCFM equation where all input parameters have been fitted to the proton structure function $F_2(x, Q^2)$. Besides that, we used a parametrization obtained with Kimber-Martin-Ryskin (KMR) prescription [40] which provides a method to construct TMD quark and gluon densities out of conventional (collinear) distributions. In that case, we used for the input the leading-order Martin-Stirling-Thorn-Watt (MSTW'2008) set [41].

The renormalization and factorization scales μ_R and μ_F were set to $\mu_R^2 = m^2 + \mathbf{p}_T^2$ and $\mu_F^2 = \hat{s} + \mathbf{Q}_T^2$, where \mathbf{Q}_T is the transverse momentum of the initial off-shell gluon pair. The choice of μ_R is rather standard for charmonium production, whereas the special choice of μ_F is connected with the CCFM evolution [38, 39]. Following [42], we set the meson masses to $m_{\chi_{c1}} = 3.51$ GeV and $m_{\chi_{c2}} = 3.56$ GeV. We use the LO formula for the running coupling constant $\alpha_s(\mu_R^2)$ with $n_f = 4$ quark flavours and $\Lambda_{\text{QCD}} = 200$ MeV, so that $\alpha_s(M_Z^2) = 0.1232$. The multidimensional integration has always been performed by the means of Monte Carlo technique using the routine VEGAS [43]. The full C++ code is available from the authors on request².

The production of χ_c mesons is followed by their radiative decays. Here we rely on the dominance of electric dipole transitions³. The hypothesis of $E1$ dominance is supported by the data taken by the E835 Collaboration at the Tevatron [44]. The corresponding decay amplitudes read [45]

$$\mathcal{A}(\chi_{c1} \rightarrow J/\psi + \gamma) \sim \epsilon^{\mu\nu\alpha\beta} k_\mu \epsilon_\nu^{(\chi_{c1})} \epsilon_\alpha^{(J/\psi)} \epsilon_\beta^{(\gamma)}, \quad (7)$$

$$\mathcal{A}(\chi_{c2} \rightarrow J/\psi + \gamma) \sim p^\mu \epsilon_{(\chi_{c2})}^{\alpha\beta} \epsilon_\alpha^{(J/\psi)} [k_\mu \epsilon_\beta^{(\gamma)} - k_\beta \epsilon_\mu^{(\gamma)}], \quad (8)$$

where $\epsilon^{\mu\nu\alpha\beta}$ is the fully antisymmetric Levi-Civita tensor, k is the final state photon 4-momentum, $\epsilon_\mu^{(\chi_{c1})}$, $\epsilon_\mu^{(J/\psi)}$ and $\epsilon_\mu^{(\gamma)}$ are the polarization vectors of the respective spin-one particles and $\epsilon_{\mu\nu}^{(\chi_{c2})}$ is the polarization tensor of spin-two χ_{c2} meson. The absolute decay rates were normalized to the known branchings $B(\chi_{c1} \rightarrow J/\psi + \gamma) = 0.344$ and $B(\chi_{c2} \rightarrow J/\psi + \gamma) = 0.195$.

¹Effect of the different forms of the flux factor on numerical predictions has been studied in [24].

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³The same hypothesis has been used to study the production and polarization of Υ mesons at the Tevatron [25].

	$ \mathcal{R}'_{\chi_{c1}}(0) ^2/\text{GeV}^5$	$ \mathcal{R}'_{\chi_{c2}}(0) ^2/\text{GeV}^5$	$\langle \mathcal{O}^{\chi_{c0}} [{}^3S_1^{(8)}] \rangle/\text{GeV}^3$
A0	3.85×10^{-1}	6.18×10^{-2}	8.28×10^{-5}
JH	5.23×10^{-1}	9.05×10^{-2}	4.78×10^{-5}
KMR	3.07×10^{-1}	6.16×10^{-2}	1.40×10^{-4}
[9]	7.50×10^{-2}	7.50×10^{-2}	2.01×10^{-3}
[10]	3.50×10^{-1}	3.50×10^{-1}	4.40×10^{-4}

Table 1: The NMEs for χ_c mesons and color singlet wave functions $|\mathcal{R}'_{\chi_{c1}}(0)|^2$ and $|\mathcal{R}'_{\chi_{c2}}(0)|^2$ extracted from the fit of the ATLAS data [11]. The results obtained from the NLO NRQCD fits [9, 10] are shown for comparison.

3 Numerical results

The whole set of NMEs was determined from fitting the transverse momentum distributions of χ_{c1} and χ_{c2} mesons measured by the ATLAS Collaboration at $\sqrt{s} = 7$ TeV [11]. The measurements were done at moderate and high transverse momenta $12 < p_T < 30$ GeV within the decay J/ψ rapidity region $|y^{J/\psi}| < 0.75$, where the NRQCD formalism is believed to be reliable. The combined fit of χ_{c1} and χ_{c2} data was performed under the requirement that all NMEs be strictly positive. Following the suggestion [27], the χ_{c1} and χ_{c2} CS wave functions were treated as independent (not necessarily identical) parameters⁴. The results of our fit are displayed in Table 1 for three different gluon distributions together with two sets of NMEs taken from the literature. The calculated differential cross sections are presented in Figs. 1 and 2 as a functions of the χ_{cJ} and J/ψ transverse momenta, respectively. The ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is shown in Fig. 3 in comparison with the recent LHC data [11–13]. Using the fitted values of NMEs from Table 1, we achieve good simultaneous description of the measured χ_{c1} and χ_{c2} spectra and the ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ with each of the considered TMD gluon densities. We find that the χ_c production is dominated by the CS contributions, that agrees with earlier conclusions [20, 21]. However, a small CO admixture improves agreement with the LHC data at high transverse momenta (see Fig. 1).

The value of the CS wave function determined previously [10] from a combined fit to the Tevatron and LHC data is $|\mathcal{R}'(0)|^2 = 3.5 \times 10^{-1} \text{ GeV}^5$. It differs significantly from $|\mathcal{R}'(0)|^2 = 7.5 \times 10^{-2} \text{ GeV}^5$ obtained from the potential models [33–36]. The latter value is similar to the one extracted from the $\chi_{c2} \rightarrow \gamma\gamma$ decay width [42]. Note that the authors

⁴The reasoning refers to the fact that treating quarks as spinless particles in the potential models [33–36] might be an oversimplification, and that radiative corrections may be large.

of [9, 10] assume equal values of the wave functions for χ_{c1} and χ_{c2} mesons. On the other hand, our fitting procedure leads to unequal values of the χ_{c1} and χ_{c2} CS wave functions. This qualitatively agrees with the suggestions [27] that the ratio of the wave functions has to be modified as $|\mathcal{R}'_{\chi_{c1}}(0)|^2/|\mathcal{R}'_{\chi_{c2}}(0)|^2 \sim 5:3$. However, we find that the LHC data tend to support even larger ratio, namely $|\mathcal{R}'_{\chi_{c1}}(0)|^2/|\mathcal{R}'_{\chi_{c2}}(0)|^2 \sim 5:1$. Our fitted value of $|\mathcal{R}'_{\chi_{c2}}(0)|^2$ (but not $|\mathcal{R}'_{\chi_{c1}}(0)|^2$) is close to the estimations based on the potential models [33–36] and two-photon decay width [42].

4 Conclusions

We have considered prompt χ_c production in pp collisions at the energy $\sqrt{s} = 7$ TeV in the framework of the k_T -factorization approach incorporated with non-relativistic QCD formalism. Using the TMD gluon densities in a proton either derived from CCFM equation or constructed with Kimber-Martin-Ryskin method, we extracted the corresponding non-perturbative color-singlet and color-octet matrix elements from a combined fit to transverse momentum distributions of χ_{c1} and χ_{c2} mesons provided by the latest ATLAS measurements. Using the fitted NMEs, we successfully described the data on the relative production rates $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ presented by the ATLAS, CMS and LHCb Collaborations. We find that the χ_c production is dominated by the CS contributions. However, an admixture of CO contributions improves the description of the data at high transverse momenta. Our interpretation of the LHC data supports the idea of unequal values of the χ_{c1} and χ_{c2} CS wave functions.

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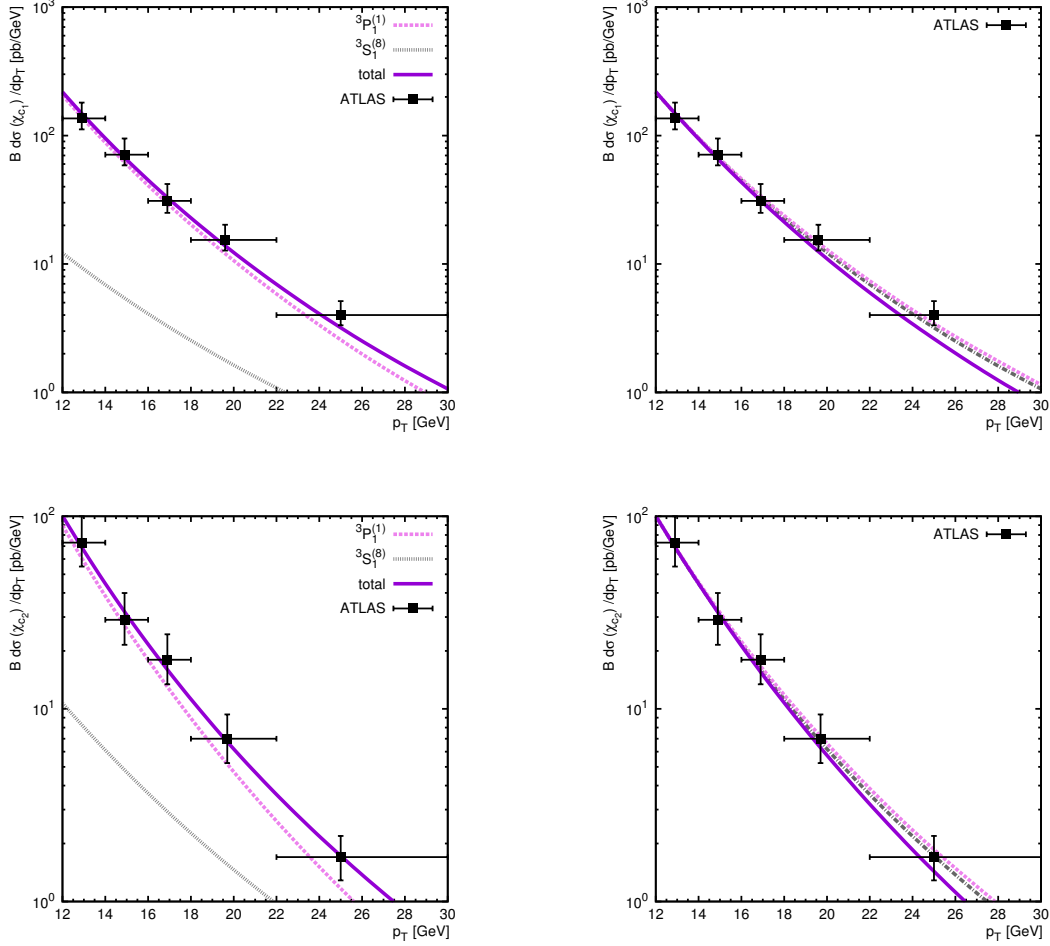


Figure 1: The prompt χ_c production at the LHC calculated as a function of χ_c mesons transverse momenta at $\sqrt{s} = 7$ TeV. Left panel: the dashed and dotted curves correspond to the color-singlet ${}^3P_J^{(1)}$ and color-octet ${}^3S_1^{(8)}$ contributions calculated with the KMR gluon density. The solid curve represent the sum of CS and CO terms. Right panel: the solid, dashed and dash-dotted curves correspond to the predictions obtained with the A0, JH and KMR gluon densities, respectively. The experimental data are from ATLAS [11].

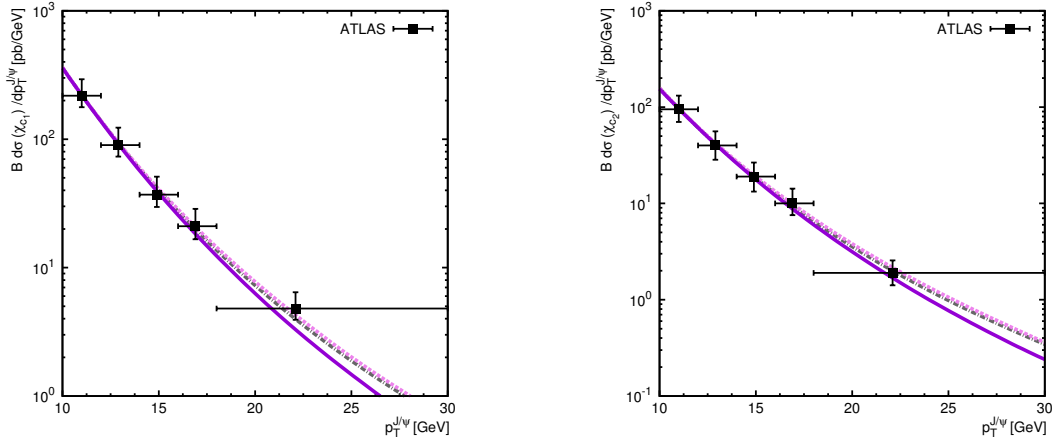


Figure 2: The prompt χ_c production at the LHC calculated as a function of decay J/ψ transverse momenta at $\sqrt{s} = 7$ TeV. The solid, dashed and dash-dotted curves correspond to the predictions obtained with the A0, JH and KMR gluon densities, respectively. The experimental data are from ATLAS [11].

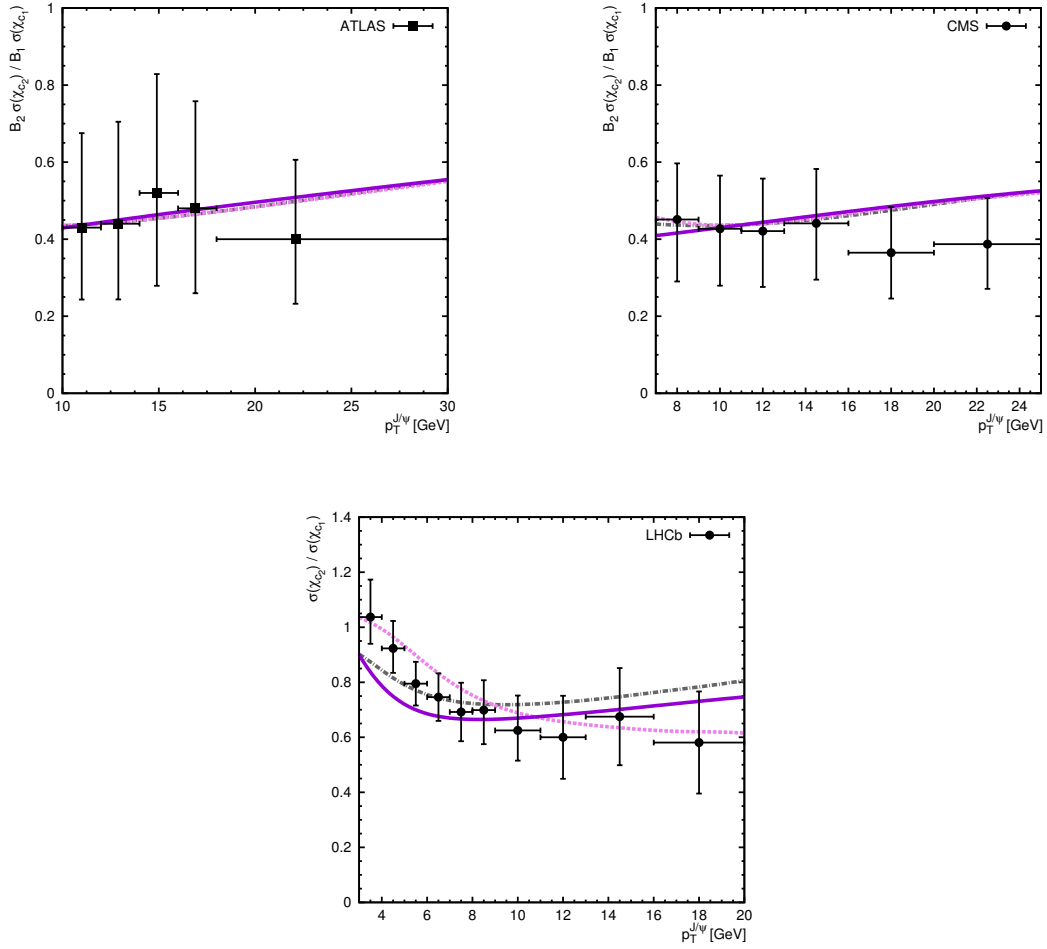


Figure 3: The relative production rate $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ calculated as a function of J/ψ meson transverse momenta at $\sqrt{s} = 7$ TeV. Notation of all curves is the same as in Fig. 2. The experimental data are from ATLAS [11], CMS [12] and LHCb [13].