

Prompt inclusive production of J/ψ , ψ' , and χ_c mesons at $\sqrt{s} = 68.5$ GeV energy within the NRQCD k_t -factorization approach

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We discuss prompt production of J/ψ mesons in proton-proton collisions at the $\sqrt{s} = 68.5$ GeV energy within the nonrelativistic quantum chromodynamics k_t -factorization approach using different unintegrated gluon distribution functions (UGDFs). We include both direct color-singlet production ($gg \rightarrow J/\psi g$) as well as a feed-down from $\chi_c \rightarrow J/\psi \gamma$ and $\psi' \rightarrow J/\psi X$ decays. The production of the decaying mesons χ_c or ψ' is also calculated within the nonrelativistic quantum chromodynamics k_t -factorization approach. Differential distributions in the rapidity and transverse momentum of J/ψ are calculated and compared with experimental data of LHCb collaboration. The LHCb fixed target data allow us to test UGDFs in a new range of x .

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I. INTRODUCTION

The production of J/ψ in proton-proton collisions is known as a rather challenging task. The color-singlet leading-order collinear approach gives a much smaller cross section than that measured at Fermilab or the LHC. Often, color octet contributions must be introduced to describe experimental data. Different authors use different long-distance matrix elements to get a satisfactory description of the data. Here, we shall concentrate on prompt J/ψ production, i.e., the decays of b and $\bar{b}$ (or rather B and $\bar{B}$) will be neglected. The direct production is not sufficient, and one also has to include production and decays of other quarkonia, which give sizeable contributions.

Some time ago, we showed that the k_t -factorization approach with nonrelativistic approximation and unintegrated gluon distributions provides a quite good description of the world data [1]. This is because the k_t -factorization approach includes effectively higher-order QCD corrections.

In the present study, we wish to test how good is such an approach at lower energies. A few years ago, LHCb

collaboration presented a first result for so-called fixed target experiments using the so-called system for measuring overlap with gas device. In this analysis, a neon target was used and the data were divided by $A = 20$ and present for one nucleon. An updated result was published in [2] (see also [3]). So far, the unintegrated gluon distribution functions (UGDFs) have been tested in different processes rather than at energies in which one is sensitive to the region of not-too-high longitudinal momentum fractions carried by the gluon in the proton (nucleon). The region of UGDFs at larger values of x has not been well tested so far. Therefore, the relatively new fixed target data provide a chance for such tests. A first test will be done here.

II. FORMALISM

In our calculation, we completely neglect all nuclear effects that should be rather small for $A = 20$. The nuclear effects for J/ψ production in $p + {}^{20}\text{Pb}$ collisions are typically less than 20% [4].

A. Direct production

The main color-singlet mechanism of J/ψ meson production is illustrated in Fig. 1. In this case, J/ψ is produced directly in association with an extra “hard” gluon due to C-parity conservation.

We calculate the dominant color-singlet $gg \rightarrow J/\psi g$ contribution, taking into account transverse momenta of initial gluons. In the k_t -factorization approach, the differential cross section can be written as

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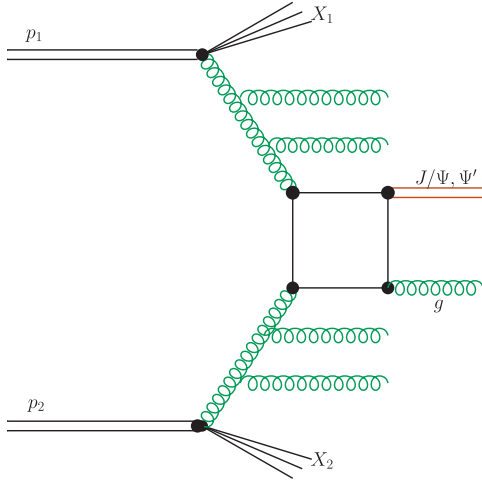


FIG. 1. The diagram for direct J/ψ (ψ') meson production in the k_t -factorization approach.

$$\begin{aligned} \frac{d\sigma(pp \rightarrow J/\psi g X)}{dy_{J/\psi} dy_g d^2 p_{J/\psi, t} d^2 p_{g, t}} &= \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2 q_{1t}}{\pi} \frac{d^2 q_{2t}}{\pi} \\ &\times |\overline{\mathcal{M}}_{g^* g^* \rightarrow J/\psi g}^{\text{off-shell}}|^2 \\ &\times \delta^2(\vec{q}_{1t} + \vec{q}_{2t} - \vec{p}_{H, t} - \vec{p}_{g, t}) \\ &\times \mathcal{F}_g(x_1, q_{1t}^2, \mu^2) \mathcal{F}_g(x_2, q_{2t}^2, \mu^2), \end{aligned} \quad (2.1)$$

where $\mathcal{F}_g$ are unintegrated gluon distribution functions.

The corresponding matrix element squared for the $gg \rightarrow J/\psi g$ is

$$|\mathcal{M}_{gg \rightarrow J/\psi g}|^2 \propto \alpha_s^3 |R(0)|^2. \quad (2.2)$$

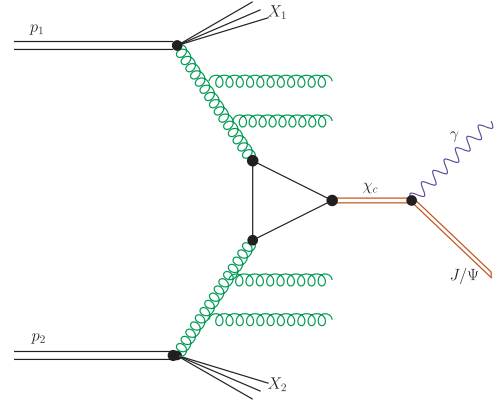


FIG. 2. The leading-order diagram for χ_c meson production and decay in the k_t -factorization approach.

Running coupling constants are used in the present calculation. Different combinations of renormalization scales are tried. We decide to use

$$\alpha_s^3 \rightarrow \alpha_s(\mu_1^2) \alpha_s(\mu_2^2) \alpha_s(\mu_3^2), \quad (2.3)$$

where $\mu_1^2 = \max(q_{1t}^2, m_t^2)$, $\mu_2^2 = \max(q_{2t}^2, m_t^2)$, and $\mu_3^2 = m_t^2$. Here, m_t is the J/ψ transverse mass. The factorization scale in the calculation is taken as $\mu_F^2 = (m_t^2 + p_{t, g}^2)/2$.

B. J/ψ from decays

Similarly, we perform a calculation for P-wave χ_c meson production. Here, the lowest-order subprocess $gg \rightarrow \chi_c$ is allowed by positive C -parity of χ_c mesons. In the k_t -factorization approach, the leading-order cross section for the χ_c meson production can be written somewhat formally as

$$\sigma_{pp \rightarrow \chi_c} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \frac{d^2 q_{1t}}{\pi} \frac{d^2 q_{2t}}{\pi} \delta((q_1 + q_2)^2 - M_{\chi_c}^2) \sigma_{gg \rightarrow \chi_c}(x_1, x_2, q_1, q_2) \mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2), \quad (2.4)$$

where $\mathcal{F}_g$ are unintegrated (or transverse-momentum-dependent) gluon distributions and $\sigma_{gg \rightarrow \chi_c}$ is the $gg \rightarrow \chi_c$ (off-shell) cross section. The situation is illustrated diagrammatically in Fig. 2.

The matrix element squared for the $gg \rightarrow \chi_c$ subprocess is

$$|\mathcal{M}_{gg \rightarrow \chi_c}|^2 \propto \alpha_s^2 |R'(0)|^2. \quad (2.5)$$

After some manipulation,

$$\sigma_{pp \rightarrow \chi_c} = \int dy d^2 p_t d^2 q_t \frac{1}{sx_1 x_2 m_{t, \chi_c}^2} \overline{|\mathcal{M}_{g^* g^* \rightarrow \chi_c}|^2} \mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2) / 4, \quad (2.6)$$

which can also be used to calculate the rapidity and transverse momentum distribution of the χ_c mesons.

In the last equation, $\vec{p}_t = \vec{q}_{1t} + \vec{q}_{2t}$ is the transverse momentum of the χ_c meson, and $\vec{q}_t = \vec{q}_{1t} - \vec{q}_{2t}$ is an auxiliary variable, which is used for the integration of the cross section. Furthermore, m_{t, χ_c} is the so-called χ_c transverse mass, and $x_1 = \frac{m_{t, \chi_c}}{\sqrt{s}} \exp(y)$, while $x_2 = \frac{m_{t, \chi_c}}{\sqrt{s}} \exp(-y)$. The factor $\frac{1}{4}$ is the Jacobian of transformation from $(\vec{q}_{1t}, \vec{q}_{2t})$ to $(\vec{p}_t, \vec{q}_t)$ variables.

As for the J/ψ production, running coupling constants are used. Different combination of scales are tried. The best choices are

$$\alpha_s^2 \rightarrow \alpha_s(\mu_1^2)\alpha_s(\mu_2^2), \quad (2.7)$$

where $\mu_1^2 = \max(q_{1t}^2, m_t^2)$ and $\mu_2^2 = \max(q_{2t}^2, m_t^2)$. Above, m_t is the transverse mass of the χ_c meson. The factorization scale(s) for the χ_c meson production are fixed traditionally as $\mu_F^2 = m_t^2$.

The J/ψ mesons are produced then by the $\chi_c \rightarrow J/\psi\gamma$ decays, which are dominated by the E1 transitions.

III. RESULTS

In this presentation, we will perform calculations with the following unintegrated gluon distribution functions used previously in the literature:

- (a) Kimber-Martin-Ryskin (KMR) (see [5,6]),
- (b) Jung-Hautmann (JH2013) (see [7]),

- (c) Gaussian, with $\sigma = 0.5$ GeV and CTEQ-Tea parton distribution functions (see [8]),
- (d) Kharzeev-Levin (KL) (see [9]),
- (e) Kutak-Stasto (KS) (see [10]),
- (f) Moriggi-Peccini-Machado (MPM) (see [11]).

The MPM distribution was corrected by a factor $(1-x)^7$, which strongly modifies gluon distributions at large gluon longitudinal momentum fractions.

Some of those UGDFs give good descriptions of different data for larger energies, i.e., smaller values of longitudinal momentum fractions. The KMR distribution gives a good description of different data in a broad range of energies. The JH2013 UGDF was tested for inclusive production of D mesons for p + A fixed target collisions (see [12–14]). The KL UGDF was used to describe particle, mostly pion, production.

Let us start from analyzing x_1 and x_2 values relevant for production of $\chi_c(1^+)$ and $\chi_c(2^+)$ and J/ψ production.

In Fig. 3, we show distributions in x_1 or x_2 for production of $\chi_c(1^+)$ (top) and $\chi_c(2^+)$ (bottom) mesons for the fixed

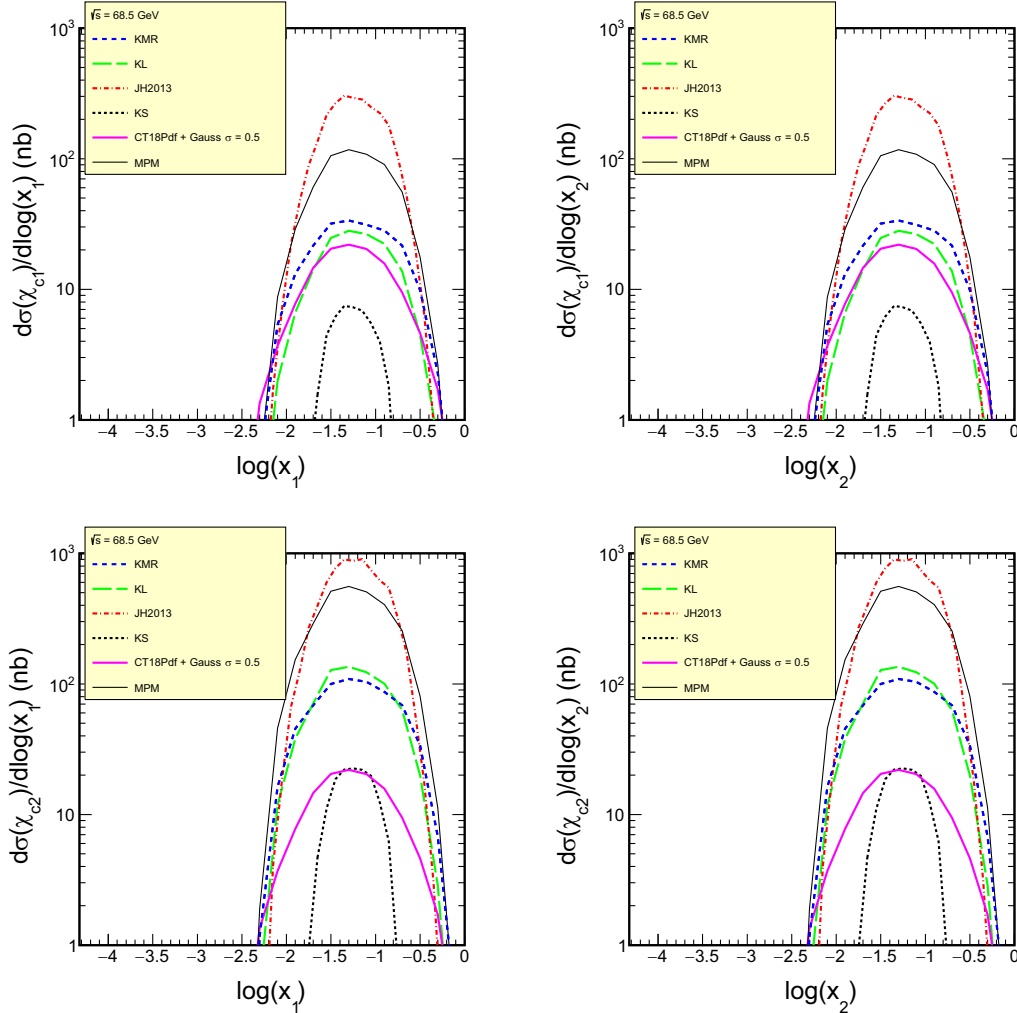


FIG. 3. x_1 (left) and x_2 (right) distributions for production of $\chi_c(1^+)$ (top) and $\chi_c(2^+)$ (bottom) for different UGDFs. In this calculation, $\sqrt{s} = 68.5$ GeV.

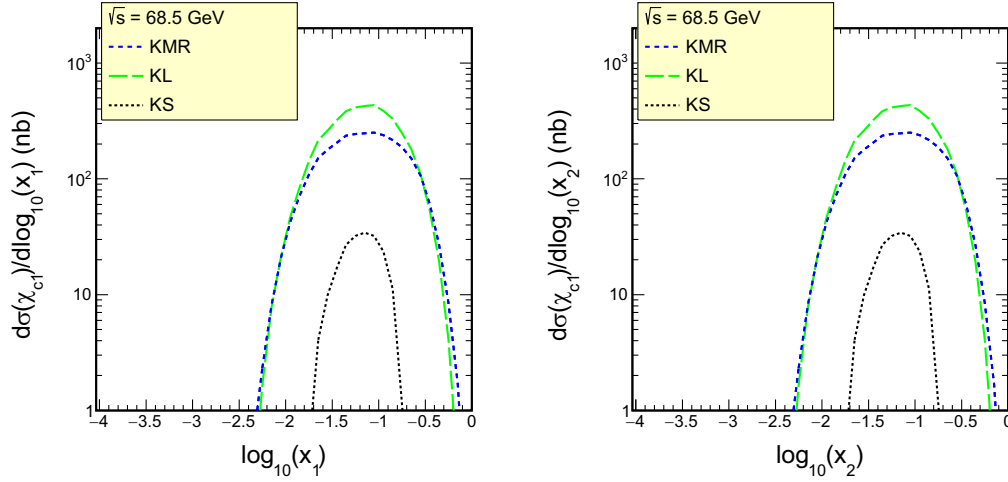


FIG. 4. x_1 (left) and x_2 (right) distributions for direct production of J/ψ for different UGDFs. Here, $\sqrt{s} = 68.5$ GeV.

target experiment at $\sqrt{s} = 68.5$ GeV. At $\sqrt{s} = 68.5$ GeV, one tests UGDFs at $x_1, x_2 \sim 10^{-2}$ – 10^{-1} . We show distributions for different UGDFs. Some of them are relevant for small x , usually $x < 10^{-2}$, while some are relevant in a broader range of x . Already, here, one sees the huge span of the cross section when using the different UGDFs. Therefore, the fixed target measurements at the LHC are very useful for testing UGDFs.

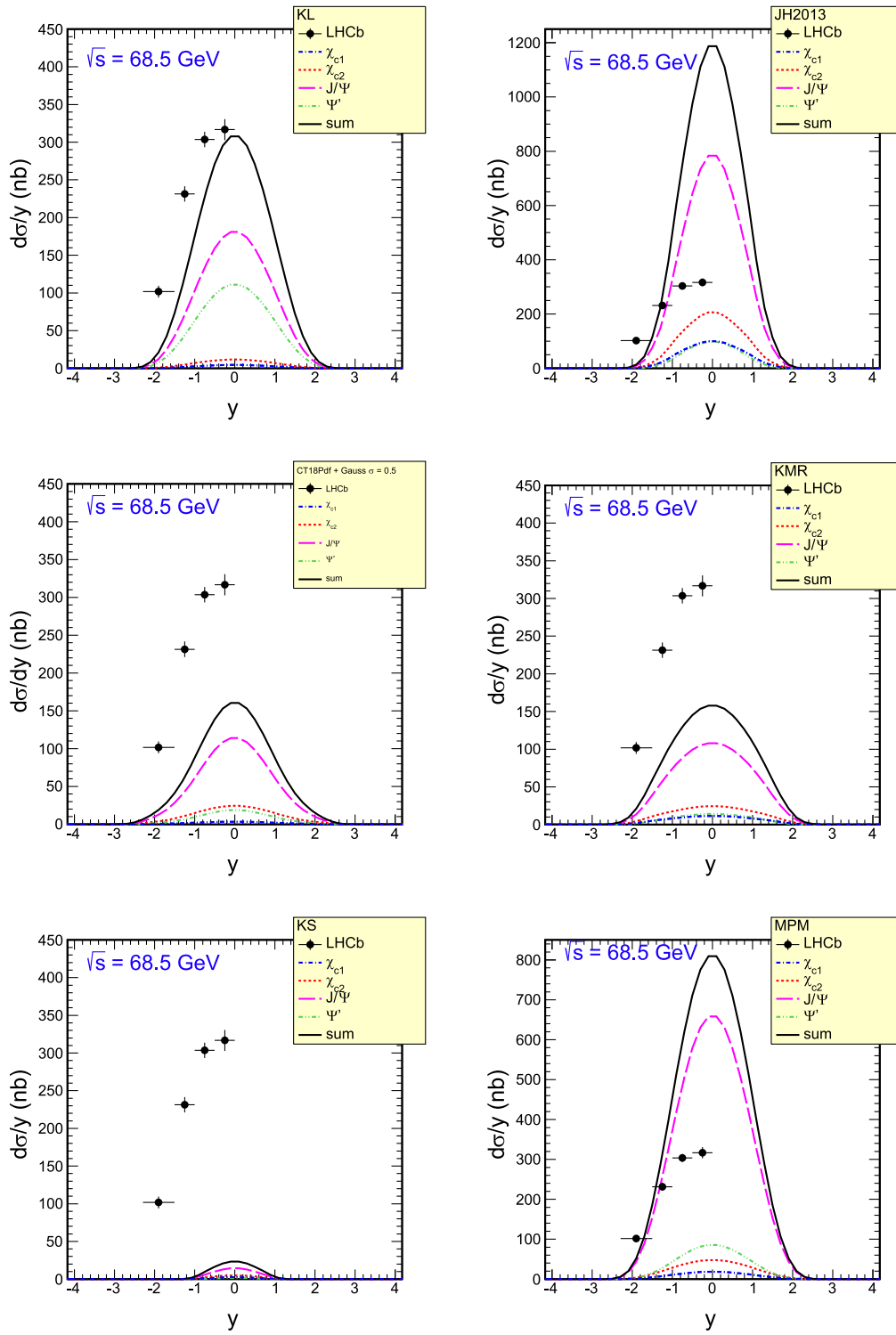
In Fig. 4, we show similar distributions for direct production of J/ψ (Fig. 1). The range is, of course, similar to that for the χ_c production (compare Figs. 4 and 3). We observe a similar span of the results.

Now, we shall present distributions in measurable quantities. In Fig. 5, we present the distribution in the rapidity of J/ψ transformed to the $p + \text{Ne}$ center of mass, again for different UGDFs. Then, our distributions are symmetric with respect to $y = 0$ (only the $g + g$ subprocess, no nuclear effects). Although the MPM unintegrated

gluon distribution is corrected at large x , the resulting distribution is above the experimental data.

In Fig. 6, we present our results for transverse momentum distributions of J/ψ mesons. In Figs. 5 and 6, we show separately both direct contributions and contributions from decays of $\chi_c(1)$, $\chi_c(2)$, and ψ' mesons. The solid lines represent the sum of these four components. The numerical results are compared with experimental data of LHCb collaboration. For some UGDFs, the cross section is too small, for others it is much too large, but for some of them the results are close to the experimental data.

When inspecting Figs. 5 and 6, we conclude that the best description of the LHCb data is obtained with the KL UGDF distribution. The KMR UGDF gives a slightly too small cross section, and MPM, corrected for the large x region, a slightly too large cross section. The KS UGDF seems to be excluded by the fixed target data.

FIG. 5. Rapidity distribution of J/ψ mesons for all considered mechanisms for different unintegrated gluon distribution functions.

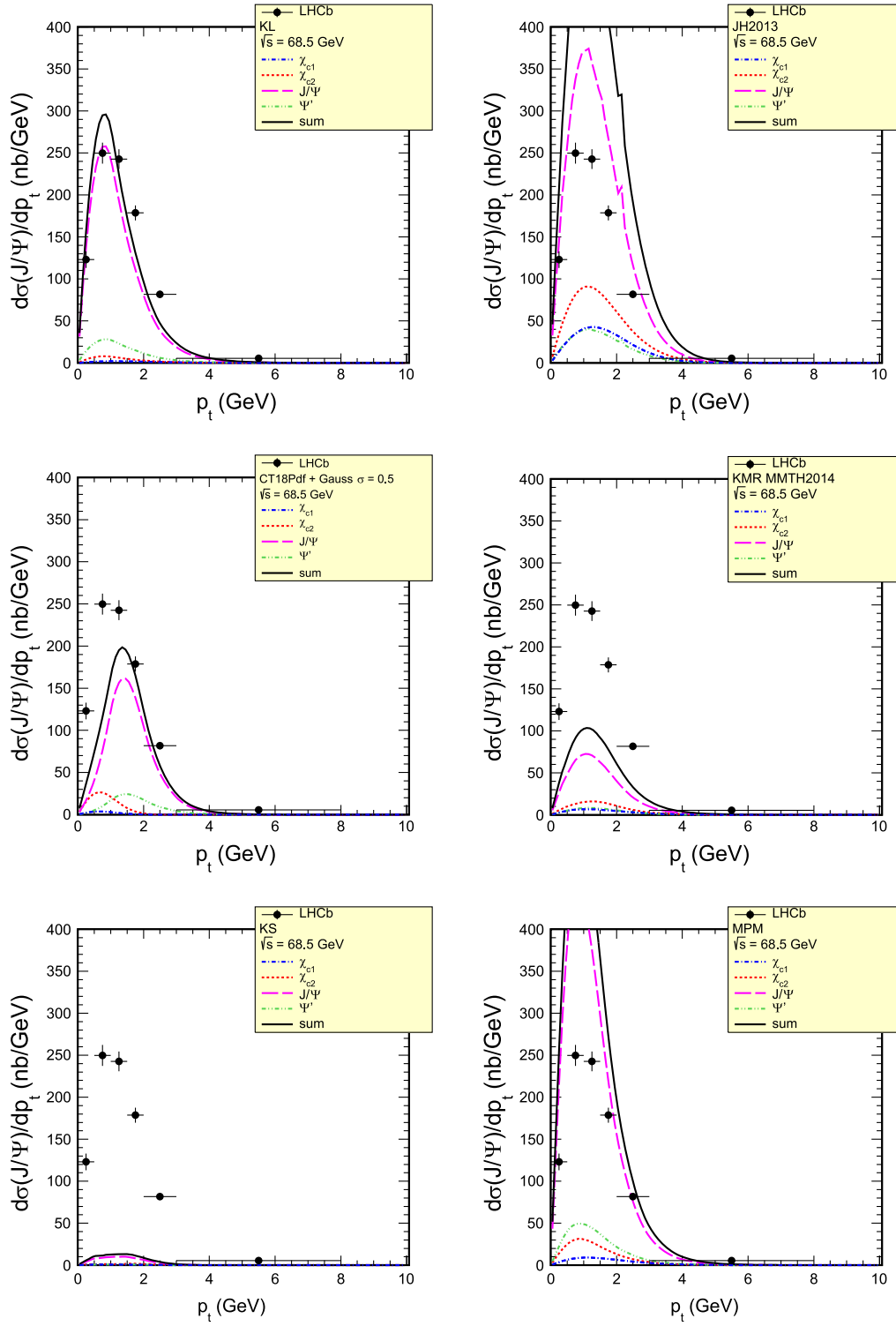


FIG. 6. Transverse momentum distribution of J/ψ mesons for all considered mechanisms for different unintegrated gluon distribution functions.

IV. CONCLUSIONS

In the present paper, we have analyzed prompt production of J/ψ quarkonia for energies corresponding to fixed target LHCb $p + \text{Ne}$ data. In the experiment, a relatively light nucleus was used, and the nuclear data were transformed to $p + N$ collisions, neglecting nuclear effects. The LHCb experiment corresponded to $\sqrt{s} = 68.5$ GeV.

Neglecting quark-induced processes that were still, for this low energy, much smaller than the purely gluonic effects, we have assumed the same mechanisms for $p + p$ and $p + n$ binary collisions. In this approximation, one has, therefore, $\sigma_{pA}^{J/\psi} \approx A\sigma_{pp}^{J/\psi}$, also for differential distributions.

In this exploratory study, we have, therefore, performed calculations within the k_t -factorization, as we did previously in high-energy collisions [1]. The formalism used here is, therefore, the same as that used previously. At high energies ($\sqrt{s} \sim 10$ TeV), one is sensitive to the region of very small x of the order of 10^{-4} . Here, one is sensitive to much larger values of x_1 or x_2 , typically larger than 10^{-2} . It is, therefore, interesting how the different UGDFs from the literature perform at the relatively low energies.

We have calculated distributions in the rapidity and transverse momentum of J/ψ . The obtained results have been compared to the LHCb data. As one could expect, there was a relatively large spread of results for this intermediate- x region. The best description was obtained when using the extremely simple KL UGDF, used previously for light particle production. The KMR and MPM unintegrated gluon distributions also yielded a reasonable description of the data. The KS distribution was excluded by the LHCb data.

There is a rich future program for studying production of quarkonia, especially J/ψ , at fixed target experiments [15,16]. This will include polarized proton as a target (see, e.g., [17]). For example, LHCb collaboration has a project of polarized targets [18].

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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