Inclusive production of $J/\psi$
in proton-proton collisions at RHIC

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Abstract. Inclusive cross sections for $J/\psi$ production in proton-proton collisions were calculated in the $k_t$-factorization approach for the RHIC energy. Several mechanisms were considered. Radiative $\chi_c$ decays and direct color-singlet contributions constitute the dominant mechanisms of $J/\psi$ production. The results are compared with recent RHIC data.

1. Introduction
The inclusive production of $J/\psi$ mesons was a theoretical puzzle for the last decade. First, the Tevatron data in 1990s revealed a more than one order-of-magnitude discrepancy with theoretical expectations. This led to the introduction of new production mechanisms, known as the color-octet model [1]. The situation became even more intriguing after the measurements of $J/\psi$ spin alignment [2]-[3]. These experiments have demonstrated clear disagreement with the newly accepted explanation.

At the same time, it has been shown that the incorporation of the usual color-singlet production scheme within $k_t$-factorization approach can provide a reasonable and consistent picture. Within the latter approach, a good description of data on the production of $J/\psi$, $\chi_c$, and $\Upsilon$ mesons at the Tevatron [4].

Recently, the PHENIX collaboration at the BNL Relativistic Heavy Ion Collider (RHIC) has measured inclusive $J/\psi$ production in pp collisions [6]. In our recent analysis [5] we have presented a detailed analysis of the RHIC data based on the $k_t$-factorization approach and a large variety of unintegrated gluon distribution functions (UGDFs). We have shown that the new precise data at small $J/\psi$ transverse momenta impose stringent constraints on UGDFs.

2. Mechanisms of inclusive $J/\psi$ production
In the analysis in Ref.[5] we have included the following mechanisms:

- Direct color-singlet $J/\psi$ production via gluon-gluon fusion $g + g \rightarrow J/\psi + g$;
- direct production of $\psi'$ meson ($g + g \rightarrow \psi' + g$) and its subsequent decay $\psi' \rightarrow J/\psi + X;$
• production of $P$-wave charmonium states $\chi_{cJ}$ ($J = 0, 1, 2$) ($g + g \rightarrow \chi_{cJ}$) followed by their radiative decays $\chi_{cJ} \rightarrow J/\psi + \gamma$;

• production of $b$ quarks and antiquarks ($g + g \rightarrow b + \bar{b}$) followed by their fragmentation into $B$ mesons and subsequent weak decays $B \rightarrow J/\psi + X$;

• production of $J/\psi$ mesons in association with unbound charmed quarks ($g + g \rightarrow J/\psi + c + \bar{c}$).

For the direct production mechanism the fully differential cross section reads

$$d\sigma(pp \rightarrow \psi X) = \frac{\pi \alpha_s^2 |R(0)|^2}{s^2} \frac{1}{4} \sum_{\text{spins}} \sum_{\text{colors}} |\mathcal{M}(gg \rightarrow \psi g)|^2$$

$$\times \mathcal{F}_g(x_1, k_{1T}^2, \mu^2) \mathcal{F}_g(x_2, k_{2T}^2, \mu^2) \, dk_{1T}^2 \, dk_{2T}^2 \, d\phi_3 \, dy_3 \, d\phi_\psi \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{d\phi_\psi}{2\pi},$$

(1)

where $\phi_1$, $\phi_2$ and $\phi_3$ are the azimuthal angles of the initial and final gluons, and $y_\psi$ and $\phi_\psi$ the rapidity and the azimuthal angle of $J/\psi$ particle. The explicit expressions for the parton level matrix elements $|\mathcal{M}(gg \rightarrow \psi g)|^2$ are presented in Ref.[4].

For the production of $\chi_c$ mesons via the subprocess we have

$$d\sigma(pp \rightarrow \chi_{cJ}) = \frac{12\pi^2 \alpha_s^2 |R'(0)|^2}{s^2} \frac{1}{4} \sum_{\text{spins}} \sum_{\text{colors}} |\mathcal{M}'(gg \rightarrow \chi_{cJ})|_{q=0}|^2$$

$$\times \mathcal{F}_g(x_1, k_{1T}^2, \mu^2) \mathcal{F}_g(x_2, k_{2T}^2, \mu^2) \, dk_{1T}^2 \, dk_{2T}^2 \, dy_3 \, d\phi_3 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi}.$$ 

(2)

The explicit expressions for the parton level matrix elements $|\mathcal{M}(gg \rightarrow \chi_{cJ})|^2$ are presented in Ref. [4]. The numerical value of the wave function is taken from the potential model [8]: $|R'_X(0)|^2 = 0.075$ GeV$^5$. The decay branchings to $J/\psi$ meson are known to be [7] $Br(\chi_{cJ} \rightarrow J/\psi \gamma) = 0.006$, 0.35, and 0.135 for $J = 0$, 1, and 2, respectively.

3. Results

In Fig.1 we show contribution of different mechanisms discussed above to the rapidity distributions of $J/\psi$ meson for the RHIC energy. In this calculation so-called derivative UGDFs, i.e. the ones obtained by differentiating the standard collinear distributions (see [5] for details).

In Fig.2 we show corresponding contributions to the transverse momentum distribution of the $J/\psi$ meson. In the $k_T$-factorization approach the contribution due to decays of $\chi_c$ mesons dominate over the direct (color-singlet) contribution at large transverse momenta of $J/\psi$. Also the B-meson decay mechanism gives a sizeable contribution at larger transverse moments.

At the RHIC energy the dominant production mechanisms are radiative decays of $\chi_c(2^+)$ and direct color-singlet mechanism. In the following we shall concentrate exclusively on the two dominant mechanisms.

In Fig.3 we present distributions in rapidity of $J/\psi$ produced by direct color-singlet mechanism for different UGDFs. The distribution obtained with Ivanov-Nikolaev glue exceeds the experimental PHENIX data [6], while the other theoretical distributions are smaller than experimental data. This is rather natural as contributions of other mechanisms are not included. The corresponding distributions in transverse momentum are shown in Fig.4 for two different intervals in rapidity. Very similar distributions are obtained for mid- and intermediate rapidity intervals. The result with Ivanov-Nikolaev UGDF exceeds the experimental data in the region of small transverse momenta.

Now we shall show results obtained with different UGDFs for radiative decays of $\chi_c(2^+)$. The rapidity distribution of corresponding $J/\psi$ is shown in Fig.5. Different UGDFs give a similar result. The distributions obtained with Ivanov-Nikolaev is slightly higher than those obtained.
Figure 1. Contributions of different mechanisms for the production of $J/\psi$ in $d\sigma/dy$ distributions. In this calculation we have used simple “derivative UGDF”.

Figure 2. Contributions of different mechanisms for the production of $J/\psi$ in $d\sigma/dp_t$ distributions. In this calculation we have used simple “derivative UGDF”. The cross section is integrated over the full range of rapidity.

with other distributions. In Fig.6 we show distributions of radiatively produced $J/\psi$. The differences in the results for different UGDFs are up to factor 2 or even larger. Again IN UGDF gives the highest cross section for small transverse momenta.

4. Conclusions
We have quantitatively discussed several mechanisms of inclusive $J/\psi$ production at RHIC energies within the formalisms of $k_t$-factorization. Different unintegrated distributions from the literature were used. We have found that radiative decays of $\chi_c$ mesons and direct color singlet contributions are the dominant mechanisms of inclusive $J/\psi$ production.

We have compared our results for dominant mechanisms (direct color-singlet and radiative $\chi_c(2^+)$ decays) with recent experimental data of the PHENIX collaboration. Both rapidity and
Figure 3. Direct color-singlet contribution to rapidity distribution of $J/\psi$ for different models of UGDFs. The solid (red on line) curve corresponds to the Kwiecinski UGDF, the dashed line to the Kharzeev-Levin UGDF, the dotted line to the BFKL UGDF, the dash-dotted line to the Ivanov-Nikolaev UGDF. The new PHENIX data are shown as full circles.

Figure 4. Direct color-singlet contribution to transverse momentum distribution of $J/\psi$ for different models of UGDFs for different intervals in rapidity: (a) $-0.35 < y < 0.35$ (left panel), (b) $1.2 < |y| < 2.2$ (right panel). The meaning of the curves is the same as in Fig. 3. The new PHENIX data are shown as full circles.

Transverse momentum distributions have been discussed. We have found that at RHIC energies the Kwiecinski distribution gives the best description of the recent PHENIX data on inclusive $J/\psi$ production.

We do not find much room for color-octet contribution which was advocated in the literature as a solution of the $J/\psi$ puzzle.

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Figure 5. $\chi_c$-decay contribution to rapidity distribution of $J/\psi$ for different models of UGDFs. The meaning of the curves is the same as in Fig. 3. The new PHENIX data are shown as full circles.

Figure 6. $\chi_c$-decay contribution to transverse momentum distribution of $J/\psi$ for different models of UGDFs for different intervals in rapidity: (a) $-0.35 < y < 0.35$ (left panel), (b) $1.2 < |y| < 2.2$ (right panel). The meaning of the curves is the same as in Fig. 3. The new PHENIX data are shown as full circles.

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