Direct $J/\Psi$ hadroproduction in $k_{\perp}$-factorization and the color octet mechanism

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The hadroproduction of direct $J/\Psi$ in the framework of the $k_{\perp}$-factorization approach is studied. The color-singlet contribution is essentially larger than in the collinear approach but is still an order of magnitude below the data. The deficit may be well described by the color octet contribution with the value of the matrix element $\langle 0|Q_s^{1/2}(\gamma S_1)|0 \rangle$ substantially decreased in comparison with fits in the collinear factorization. This should lead to a reduction of the large transverse polarization, predicted in the collinear approach.

Recently we have considered the $\chi_c$ hadroproduction within the $k_{\perp}$ factorization scheme $[1]$. The crucial element in the description of this process was the effective vertex for the production of $q\bar{q}$ pairs with finite invariant mass, which appeared in calculations of the next-to-leading order (NLO) corrections to the Balitsky-Fadin-Kuraev-Lipatov (BFKL) kernel $[2]$. The effective $q\bar{q}$-production vertex contains - apart from the standard term - also additional terms describing the $q\bar{q}$ production by means of the Reggeon-Reggeon-gluon vertex $[3]$. This additional part does not contribute, if the $q\bar{q}$ pair is produced in the color-singlet (CS) state. For color-octet $q\bar{q}$ states these additional terms contribute and lead to a $p_{\perp}$ dependence which is very different from the experimentally observed one. Thus we concluded that for $\chi_c$ hadroproduction our result suggest that the color octet mechanism (COM) is negligible. Specifically, a dominant color-singlet term and $k_{\perp}$-factorization provide a fair description of the data.

It is interesting to extend this approach to the direct production of $J/\Psi$, which is known to be a long-standing puzzle (for review see e.g. $[4]$).

Because of the negative charge parity of the $J/\Psi$ the effective $q\bar{q}$ vertex can only give a contribution via the COM. In the case of $J/\Psi$ production in the CS model, one needs to know the $q\bar{q}$ production vertex with an additional produced gluon (fig. 1c). Such a $q\bar{q}g$ system with a finite invariant mass is called a cluster $[5]$. In the context of the BFKL approach this vertex corresponds to NNLLA corrections and is not yet known. However, the unknown terms in this vertex (e.g. see figs. 1c, 1d and 1e) should not contribute to the production of a CS state, in complete analogy with the $\chi_c$ case mentioned above $[6]$. The unknown part of the NNLLA vertex can include only diagrams where the additional gluon is emitted by the $t$-channel or the $s$-channel gluons. To produce a $J/\Psi$ in the CS model to LO in $\alpha_s$ three gluons have to be involved and one of them has to be emitted. Only those graphs contribute, in which the emitted gluon couples to a quark line (see figs. 1a and b).

The emission vertex of this gluon is described by the usual vertex since the interaction of partons forming cluster with finite invariant mass is governed by the usual QCD lagrangian $[7]$. Note that the colliding $t$-channel gluons are off-shell and longitudinally polarized.

In contrast to this the color-octet contribution requires the full effective NLLA vertex, as mentioned above. It is instructive to compare this situation with the standard collinear factorization case $[8]$. In that case, the emission of an additional hard gluon is required to balance the large transverse momentum of $J/\Psi$. The role of the color-octet states is to allow the fragmentation of high-$p_T$ gluons to $J/\Psi$.

In our case, the transverse momentum of the colliding gluons allows for the production of a high-$p_T$ color-octet state without emission of an additional hard gluon. The role of the gluon fragmentation (the production of $J/\Psi$ by a single gluon) is now played by the discussed additional term within the effective gluon vertex.

One should note the different role of singlet and octet contribution in comparison with $\chi_c$ production. While for $\chi_c$ the singlet and octet contributions are generated by the same hard scattering subprocess, the situation is different for $J/\Psi$. In this case the CS subprocess re-

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FIG. 1.
quires an extra gluon emission with respect to the CO one. Since the COM from the point of view of factorization corresponds to the emission of a soft gluon coupled through non-perturbative matrix elements, CO and CS contributions are in the perturbative expansion formally of the same order in $\alpha_s$. Therefore, one may expect a larger CO contribution for direct $J/\Psi$ production than for $\chi_c$ production. This point of view is confirmed by our results.

The cross section for heavy quarkonium hadroproduction with an additional produced gluon in the $k_{\perp}$ - factorization approach is [12,13]

$$
\sigma_{P_1P_2 \rightarrow J/\Psi g X} = \frac{1}{16(2\pi)^3} \int \frac{d^3P \, d^3k}{P^+} \frac{1}{k^+} \delta^2(q_{1\perp} - q_{2\perp} - P_{\perp} - k_{\perp}) \mathcal{F}(x_1, q_{1\perp}) \mathcal{F}(x_2, q_{2\perp}).$$

The momenta of the $J/\Psi$ and the produced gluon are denoted by $P$ and $k$. $\mathcal{F}(x, q_{\perp})$ is the unintegrated gluon distribution. The production amplitude $\psi_{J/\Psi g}(x_1, x_2, q_{1\perp}, q_{2\perp}, P, k)$ is factorized in a hard part which describes the production of the $q\bar{q}$ pair and the gluon and an amplitude describing the binding of this pair into a physical charmonium state. The explicit form of the hard part of the amplitude is given by the formulas from [12] supplemented with an usual additional gluon production vertex (figs. 1a, 1b). The formalisms used to describe the binding of the $q\bar{q}$ pair into a bound state as well as the unintegrated gluon distribution are the same as in [12].

The results allow for a good description in the framework of the COM. We performed new fits of CO matrix elements. As a result, the value of $\langle 0 \mid O_8^{J/\Psi}(3S_1) \mid 0 \rangle$ is reduced by a factor of $\approx 30$ in comparison with the analysis in the framework of collinear factorization. However, if this matrix element is put exactly to zero, the quality of the fit is much worse.

Let us note that from the strong reduction of the $\langle 0 \mid O_8^{J/\Psi}(3S_1) \mid 0 \rangle$ matrix element in comparison to the collinear approximation it doesn’t follow that the same happens in the case of $\langle 0 \mid O_8^{J/\Psi}(1S_0) \mid 0 \rangle$ and

$$
\begin{array}{|c|c|c|}
\hline
\text{only } S_0^8 \text{ contr.} & \text{only } S_{1,2}^8 \text{ contr.} \\
\langle O_8^{J/\Psi} (3P_J) \rangle = 0 & \langle O_8^{J/\Psi} (1S_0) \rangle = 0 \\
\langle O_8^{J/\Psi} (3S_1) \rangle = 0 & 5(\pm 1.2) \cdot 10^{-4} \\
M_8 (R = 5) & 1.4(\pm 0.1) \cdot 10^{-2} \\
\text{total } \chi^2/\text{NDOF} & 0.42 & 0.53 \\
\hline
\end{array}
$$

The errors are only statistical.

On the basis of these results we conclude that it is impossible to describe the data for direct $J/\Psi$ production entirely by the CS contribution. In our case the discrepancy between the CS contribution and the data is substantially smaller than for the NLO collinear factorization.

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Let us note that from the strong reduction of the $\langle 0 \mid O_8^{J/\Psi}(3S_1) \mid 0 \rangle$ matrix element in comparison to the collinear approximation it doesn’t follow that the same happens in the case of $\langle 0 \mid O_8^{J/\Psi}(1S_0) \mid 0 \rangle$ and
\langle 0|O_{8}^{J/\Psi}(3S_{1})|0 \rangle$. Indeed we find that the linear combination $M_{8}$, which we can extract from a fit to the data, is of same order of magnitude as the analogous combination in the collinear case. Taking this together we see that our larger cross sections primarily give a reduction of the $^{3}S_{1}^{0}$ contribution and do not lead to a uniform decrease of all color octet matrix elements. Now since $^{1}S_{0}^{0}$ and $^{3}P_{0}^{0}$ contributions to $J/\Psi$ in a different combination into the photoproduction cross section (while the contribution of $^{3}S_{1}^{0}$ is negligible), we cannot make definite predictions about the impact of our $k_{t}$-factorization calculation on $J/\Psi$ photoproduction. Besides this there is of course the need for considering higher order subprocesses in order to determine the color octet matrix elements more accurately.

In the context of photoproduction we would like to comment on the article [13] in which the photoproduction of charmonia in collinear factorization is studied. There the color octet contributions are taken into account, using for the CO matrix elements the values obtained in the collinear approach by Cho and Leibovich [8] for the hadroproduction of quarkonia. The results of [13] for $p_{\perp,J/\Psi} \geq 1 GeV$ (see fig. 4 in [13]) suggest that our values for the octet matrix elements support the good description of the data shown there. The only discrepancy occurs in the region of small $p_{\perp,J/\Psi}$ (see [13], fig.3). But as it was shown in the recent work by Braaten et al [14] the naive use of the color octet mechanism doesn’t allow to describe the data in the small $p_{\perp}$ region. The reason for this could be a stronger interplay of the soft-gluon emission from the hard $q\bar{q}$ subprocess with the soft gluon radiation described by the color octet mechanism.

The smallness of the color octet matrix element $\langle 0|O_{8}^{J/\Psi}(3S_{1})|0 \rangle$ is, however, quite promising from the point of view of $J/\Psi$ polarization. Please recall, that in the collinear factorization approach this matrix element provides the dominant contribution to the cross-section through the gluon fragmentation subprocess. As soon as the gluon is almost on-shell, it has a strong transverse polarization which should result in a strong transverse polarization of $J/\Psi$, in disagreement with the experimental data [13,16]. In contrast, in our approach this fragmentation mechanism is suppressed as it leads to a wrong $P_{\perp}$-dependence. Consequently the qualitative origin of the transverse polarization in the collinear approach is absent in the $k_{t}$-factorization approach. In contrast the longitudinal polarization of the colliding gluons in the $k_{t}$-factorization approach leads to a vanishing projection of the angular momentum of the produced $q\bar{q}$-pair on the collision axis resulting in particular in a longitudinal polarization of produced $\chi_{c}$’s.

Finally let us comment on the recent articles by F. Yuan and K.-T. Chao [17,18] who studied polarized and unpolarized charmonium production based on our approach [1]. In [17] they performed independently analogous calculations as in the present paper and found very similar numerical results. They have shown [18] that the $J/\Psi$’s are in fact nearly unpolarized, which confirms our expectation on the absence of strong transverse polarization in charmonium hadroproduction. Furthermore they demonstrated that $\chi_{c}$ states are predominantly longitudinally polarized [14].

We acknowledge the discussion with A. Tkabladze. This work was supported by DFG and BMBF. O. T. was also supported in part by RFFI grant 00-02-16696.

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