Central Exclusive χ_c Production

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The amplitudes of the central exclusive production of χ_c mesons are calculated using different unintegrated gluon distribution functions (UGDFs). The procedure of generalisation of UGDF for non-forward case by saturation of positivity constraints is suggested. We compare exclusive production of all charmonium states $\chi_c(0^+)$, $\chi_c(1^+)$ and $\chi_c(2^+)$ including branching fraction for radiative $J/\Psi + \gamma$ decay channel. Kinematical enhancement of the maximal helicity amplitudes is shown.

1 QCD Factorisation and Durham Model

It is well known that the exclusive diffractive Higgs production provides a very convenient tool for Higgs searches at hadron colliders due a very clean environment unlike the inclusive production [1].

The QCD mechanism for the diffractive production of heavy central system has been proposed recently by Kaidalov, Khoze, Martin and Ryskin (Durham group, KKMR) for Higgs production at the LHC (see Refs. [1, 2, 3]). The QCD factorisation implies the separation of the amplitude of the exclusive $pp \to pXp$ process to the hard subprocess amplitude describing the fusion of two off-shell gluons into a heavy system $g^*g^* \to X$, and the soft hadronic parts containing information about emission of the relatively soft gluons from the proton lines (see Fig. 1). In the framework of $k_\perp$-factorisation approach these soft parts are written in terms of so-called off-diagonal unintegrated gluon distributions (UGDFs) and cannot be calculated perturbatively. The QCD factorisation is rigorously justified in the limit of very large factorisation scale being the transverse mass of the central system $M_\perp$.

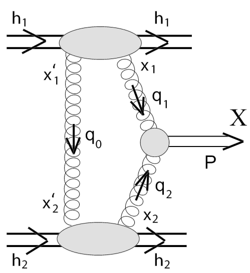

Figure 1: The QCD mechanism of diffractive production of the heavy central system X.

In order to check the underlying production mechanism it is worth to replace Higgs boson by a lighter (but still heavy enough to provide the QCD factorisation) meson which is easier to measure. In this respect the exclusive production of heavy quarkonia is under special interest from both experimental and theoretical points of view [4]. Testing the KKMR approach against various data on exclusive meson production at high energies is a good probe of nonperturbative dynamics of partons described by UGDFs.

Recently, the signal from the diffractive $\chi_c(0^+, 1^+, 2^+)$ charmonium production in the radiative $J/\Psi + \gamma$ decay channel has been measured by the CDF Collaboration [5]: $d\sigma/dy|_{y=0}(pp \to pp(J/\psi + \gamma)) \simeq (0.97 \pm 0.26)\,\mathrm{nb}$. In the very forward limit the contributions from $\chi_c(1^+, 2^+)$ vanish due to the $J_z = 0$ selection rule (see [6] and references therein); however, for general kinematics this might not be true. In particular, it was shown in Ref. [9] that the axial-vector $\chi_c(1^+)$ production, due a relatively large branching fraction of its radiative decay, may not be negligible and gives a noticeable contribution to the total signal measured by the CDF Collaboration. As shown below, the same holds also for the tensor $\chi_c(2^+)$ meson contribution.

The production of the axial-vector $\chi_c(1^+)$ meson has an additional suppression w.r.t. $\chi_c(0^+)$ and $\chi_c(2^+)$ in the limit of on-shell fusing gluons due to the Landau-Yang theorem [9]. Such an extra suppression may lead to the dominance of the $\chi_c(2^+)$ contribution in the radiative decay channel. Off-shell effects play a significant role also for the scalar $\chi_c(0^+)$ production reducing the total cross section by a factor of $2-5$ depending on UGDFs [10].

According to the KKMR approach the amplitude of the exclusive double diffractive colour singlet production $pp \to pp\chi_{cJ}$ is [11, 10]

$$\mathcal{M}_{J,\lambda} = const \cdot \delta_{c_1 c_2} \Im \int d^2 q_{0,t} V_{J,\lambda}^{c_1 c_2}(q_1, q_2, P) \frac{f^{\mathrm{off}}_{g,1}(x_1, x_1', q_{0,t}^2, q_{1,t}^2, t_1) f^{\mathrm{off}}_{g,2}(x_2, x_2', q_{0,t}^2, q_{2,t}^2, t_2)}{q_{0,t}^2\, q_{1,t}^2\, q_{2,t}^2}\,, \quad (1)$$

where $t_{1,2}$ are the momentum transfers along the proton lines, q_0 is the momentum of the screening gluon, $q_{1,2}$ are the momenta of fusing gluons, and $f^{\mathrm{off}}_{g,i}(x_i, x_i', q_{0,t}^2, q_{i,t}^2, t_i)$ are the off-diagonal UGDFs.

Traditional (asymmetric) form of the off-diagonal UGDFs is taken in the limit of very small $x' \ll x_{1,2}$ as proportional to conventional diagonal unintegrated density in analogy to collinear off-diagonal gluon distributions (with factorised t-dependence), i.e.

$$\begin{aligned} f^{\mathrm{off}}_{g,1} &= R_g\, f_g^{(1)}(x_1, Q_{1,t}^{\mathrm{eff}\,2}, \mu^2) \cdot F_N(t_1)\,, \\ f^{\mathrm{off}}_{g,2} &= R_g\, f_g^{(2)}(x_2, Q_{2,t}^{\mathrm{eff}\,2}, \mu^2) \cdot F_N(t_2), \quad \mu^2 = \frac{M_\perp^2}{2} \end{aligned} \quad (2)$$

with a nearly constant prefactor $R_g \simeq 1.4$, $Q_{1/2,t}^{\mathrm{eff}\,2} = \min(q_{0,t}^2, q_{1/2,t}^2)$ are the effective gluon transverse momenta, as adopted in Ref. [1, 11], $F_N(t)$ is the form factor of the proton vertex, which can be parameterised as $F_N(t) = \exp(b_0 t)$ with $b_0 = 2\,\mathrm{GeV}^{-2}$ [12], or by the isoscalar nucleon form factor $F_1(t)$ as we have done in Ref. [10].

Our results in Ref. [10] showed up the strong sensitivity of the KKMR numerical results on the definition of the effective gluon transverse momenta $Q_{1/2,t}^{\mathrm{eff}}$ and the factorisation scales $\mu_{1,2}$. This behaviour is explained by the fact that for heavy $q\bar{q}$ production the great part of the diffractive amplitude (1) comes from nonperturbatively small $q_{0,t} < 1\,\mathrm{GeV}$. It means that the total diffractive process is dominated by very soft screening gluon exchanges with no hard scale. So, the perturbatively motivated KMR UGDFs [1] based on the Sudakov suppression and conventional parton densities are not completely justified in the soft part of the gluon ladder [10], whereas for fusing gluons it can be still reliable due to a large scale μ there.

In principle, factor R_g in Eq. (2) should be a function of x' and x_1 or x_2. In this case the off-diagonal UGDFs do not depend on x' and $q_{0,t}^2$ (or $q_{1/2,t}^2$), and their evolution is reduced to diagonal UGDFs evolution corresponding to one "effective" gluon. In general, factor R_g can depend on UGDF and reflects complicated and still not well known dynamics at small x region.

2 Skewed UGPDs and Positivity Constraints

In order to test this small x dynamics and estimate the theoretical uncertainties related with introducing of one "effective" gluon instead of two gluons in Eq. (2), in Refs. [10, 13] we have suggested more general symmetrical prescription for the off-diagonal UGDFs. Actually, it is possible to calculate the off-diagonal UGDFs in terms of their diagonal counterparts as follows

$$\begin{aligned} f_{g,1}^{\text{off}} &= \sqrt{f_g^{(1)}(x_1', q_{0,t}^2, \mu_0^2) \cdot f_g^{(1)}(x_1, q_{1,t}^2, \mu^2)} \cdot F_N(t_1)\,, \\ f_{g,2}^{\text{off}} &= \sqrt{f_g^{(2)}(x_2', q_{0,t}^2, \mu_0^2) \cdot f_g^{(2)}(x_2, q_{2,t}^2, \mu^2)} \cdot F_N(t_2)\,, \end{aligned} \tag{3}$$

where

$$x_1' = x_2', \quad \mu_0^2 = q_{0,t}^2, \quad \mu^2 = \frac{M_\perp^2}{2}.$$

This form of skewed two-gluon UGDFs (3) is inspired by the positivity constraints for the collinear Generalised Parton Distributions [14], and may be considered as a saturation of the Cauchy-Schwarz inequality for the density matrix [15]. One may doubt what is the reason of such a saturation. Usually it happens when the dimension of the linear space where inequality is studied is small. Physically this corresponds to the small number of intermediate on-shell states in the imaginary part of the amplitudes, which is likely to happen at large rather than small x. However, the decreasing of the contribution of intermediate states with their invariant mass growing may effectively reduce the dimensionality of space relevant for saturation of positivity constraints.

It allows us to incorporate the actual dependence of the off-diagonal UGDFs on longitudinal momentum fraction of the soft screening gluon x' and its transverse momentum $q_{0,t}^2$ in explicitly symmetric way.

However, trying to incorporate the actual dependence of UGDFs on (small but nevertheless finite) x' we immediately encounter the problem. The kinematics of the double diffractive process $pp \to pXp$ does not give any precise expression for x' in terms of the phase space integration variables. From the QCD mechanism under consideration one can only expect the general inequality $x' \ll x_{1,2}$ and upper bound $x' \lesssim q_{0,t}/\sqrt{s}$ since the only scale appearing in the left part of the gluon ladder is the transverse momentum of the soft screening gluon $q_{0,t}$.

To explore the sensitivity of the final results on the values of x', staying in the framework of traditional KKMR approach, one can introduce naively $x' = \xi \cdot q_{0,t}/\sqrt{s}$ with an auxiliary parameter ξ [9]. In our earlier papers [10, 13] we considered the limited case of maximal x' (with $\xi = 1$). However, our recent results incorporating tensor $\chi_c(2^+)$ contribution [16] showed that the experimental CDF data demand smaller x' (softer gluon), i.e. $\xi < 1$. We will analyze this issue in greater details in the next section.

The hard vertex function $V_{J,\lambda}^{c_1c_2}(q_1, q_2, P)$ describes the coupling of two virtual gluons to χ_{cJ} mesons and appears also in the studies of their inclusive production [7, 8]. It can be found by using the next-to-leading-logarithmic-approximation (NLLA) BFKL $g^*g^*(q\bar{q})$-vertex in quasi-multi-Regge kinematics (QMRK) and projecting it out to the colour singlet bound state χ_{cJ} employing the pNRQCD technique (for scalar and axial-vector case, see Refs. [10, 9]). We do not take into account the NLO QCD corrections here, $K_{NLO} = 1$, until otherwise is mentioned.

3 Results

Results for the total cross section of diffractive $\chi_c(0^+, 1^+, 2^+)$ meson production at Tevatron energy $W = 1960\,\mathrm{GeV}$ are shown in Table 1. As have been pointed out in Ref. [6, 17] the absorptive corrections are quite sensitive to the meson spin-parity. This was studied before in the context of scalar and pseudoscalar Higgs production in Ref. [2]. In the last column we show the results for the expected observable signal in $J/\psi+\gamma$ channel summed over all χ_c spin states

$$\left.\frac{d\sigma_{obs}}{dy}\right|_{y=0} = K_{NLO}^2 \sum_{\chi} \langle S_{\mathrm{eff}}^2 \rangle \frac{d\sigma_{J/\psi\gamma}}{dy} \tag{4}$$

where we adopt the following effective gap survival factors (for $\langle p_t \rangle \simeq 0.5\,\mathrm{GeV}$), calculated for different spins in Ref. [6, 17]: $\langle S_{\mathrm{eff}}^2(\chi_c(0^+))\rangle \simeq 0.02$, $\langle S_{\mathrm{eff}}^2(\chi_c(1^+))\rangle \simeq 0.05$ and $\langle S_{\mathrm{eff}}^2(\chi_c(2^+))\rangle \simeq 0.05$. The NLO corrections factor in the $g^*g^* \to q\bar{q}$ vertex is assumed to be the same for all χ_c states $K_{NLO} = 1.5$.

We see from the Table that the calculated signal is below the CDF data for off-diagonal UGDFs calculated as in Eq. (3) with $\xi = 1$. This provides an argument that x' should be smaller than used, i.e. $\xi < 1$. Indeed, for Kutak-Stasto UGDF [19] and $\xi = 0.1$ we get the value for $d\sigma_{obs}/dy(y = 0) \simeq 0.8$, which is within the CDF error bars.

Table 1: Differential cross section $d\sigma_{\chi_c}/dy(y = 0)$ (in nb) of the exclusive diffractive production of $\chi_c(0^+, 1^+, 2^+)$ mesons and their partial and total signal in radiative $J/\psi + \gamma$ decay channel $d\sigma_{J/\psi\gamma}/dy(y = 0)$ at Tevatron for different UGDFs, t-dependent form factors $F_N(t)$ and values of auxiliary parameter ξ controlling the characteristic x' values.

UGDF	ξ	$\chi_c(0^+)$		$\chi_c(1^+)$		$\chi_c(2^+)$		ratio	signal
		$\frac{d\sigma_{\chi_c}}{dy}$	$\frac{d\sigma_{J/\psi\gamma}}{dy}$	$\frac{d\sigma_{\chi_c}}{dy}$	$\frac{d\sigma_{J/\psi\gamma}}{dy}$	$\frac{d\sigma_{\chi_c}}{dy}$	$\frac{d\sigma_{J/\psi\gamma}}{dy}$	$\frac{\chi_c(2^+)\to J/\psi}{\chi_c(0^+)\to J/\psi}$	$\frac{d\sigma_{obs}}{dy}$
GBW [18], (3)	1.0	48.4	0.55	0.8	0.27	15.6	3.03	5.5	0.40
	0.1	35.4	0.40	1.3	0.44	8.6	1.67	4.2	0.26
KS [19], (3),	1.0	72.5	0.83	0.5	0.17	7.9	1.53	1.8	0.23
$F_1(t)$	0.1	260	2.96	1.6	0.55	27	5.24	1.8	0.78
KS [19], (3), $\exp(b_0 t)$	0.1	238	2.71	1.2	0.41	20.3	3.94	1.45	0.61
KMR [1], (2) $R_g = 1.0$	–	216	2.5	1.4	0.5	13.5	2.6	1.04	0.46

The relative contributions of different charmonium states in $J/\psi + \gamma$ channel are found to be:

$$\sigma(0^+ \to J/\psi + \gamma) : \sigma(1^+ \to J/\psi + \gamma) : \sigma(2^+ \to J/\psi + \gamma) = \begin{cases} 1 : 0.71 : 4.64, & \text{KL} \\ 1 : 1.94 : 13.47, & \text{GBW} \\ 1 : 0.49 : 4.85, & \text{KS} \\ 1 : 0.55 : 2.81, & \text{KMR} \end{cases}$$

We see that the contribution of the tensor $\chi_c(2^+)$ meson dominates over $\chi_c(0^+, 1^+)$ for all UGDFs. As a normalization we took the contribution of $\chi_c(0^+)$ meson. Its production rate for KMR UGDF is calculated as $K^2_{NLO} \cdot \langle S^2_{\rm eff}(\chi_c(0^+))\rangle \cdot R^4_g \cdot \sigma(\chi_c(0^+))/dy(y=0) \simeq 37$ nb, which is very close to original KMR result 35 nb [17]. At the same time, the discrepancy with KMR results for higher spin mesons remains to be investigated.

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