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Exclusive double-diffractive production of open charm in proton–proton and proton–antiproton collisions

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ABSTRACT

We calculate differential cross sections for exclusive double diffractive (EDD) production of open charm in proton–proton and proton–antiproton collisions. Sizeable cross sections are found. The EDD contribution constitutes about 1% of the total inclusive cross section for open charm production. A few differential distributions are shown and discussed. The EDD contribution falls faster both with transverse momentum of the c quark/antiquark and the $c\bar{c}$ invariant mass than in the inclusive case.

1. Introduction

The open charm production is often considered as a flag reaction to test the gluon distributions in the nucleon. For the $c\bar{c}$ and $b\bar{b}$ production at high-energies the gluon–gluon fusion is assumed to be the dominant mechanism. This process was calculated in the NLO collinear [1] as well as in the k_t-factorization [2–5] approaches by several authors. These analyses seem to report on missing strength.[1] This suggests that other processes ignored so far should be carefully evaluated.

The number of potential contributions is not small. In the present Letter we concentrate on exclusive double diffractive (EDD) mechanism, which was not considered so far for the $c\bar{c}$ production. The mechanism of the exclusive double-diffractive production of open charm is shown in Fig. 1.

Similar mechanism of gluon–gluon fusion was successfully applied in Refs. [7–10] for prediction of exclusive diffractive production of charmonia in pp collisions. As was shown in Refs. [7, 9] the off-shellness of fusing gluons plays a significant role in the $\chi_c(0^+, 2^+)$ mesons production reducing the total cross section by a factor of 2–5 depending on UGDFs, whereas for axial-vector $J = 1^+$ production it provides the leading contribution [7]. The major part of the diffractive amplitude comes from rather small

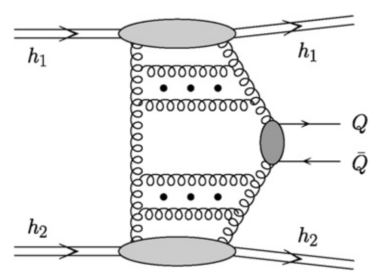

Fig. 1. The mechanism of exclusive double-diffractive production of open charm.

gluon transverse momenta $Q_t < 1$ GeV, so the precise prediction of the observable signal requires a detailed knowledge of the non-perturbative gluon dynamics described by UGDFs. This means that one has to be very careful in interpreting the gluon distributions in this region.

In this Letter we consider the production of $c\bar{c}$ as a pair of jets without its projection onto a particular bound state. The dependence of the matrix element squared on the proton transverse momenta $p_{1/2,t}$ is explicitly included into kinematics of the process, and exact numerical integration over the 4-particle phase space is performed. Note, that we keep exact kinematics with off-shell gluons and quarks with arbitrary helicities. In this case all spin states of $q\bar{q}$ pair are included, and the amplitude does not disappear in the forward limit providing the leading contribution to diffractive $c\bar{c}$ dijet production.

The EDD $b\bar{b}$ reaction constitutes a irreducible background to the exclusive Higgs boson production [6] measured in the $b\bar{b}$ channel. Up to now only approximate estimates of the $b\bar{b}$ production were presented in the literature. In the present Letter we consider the $pp \to pp c\bar{c}$ reaction as a genuine 4-body process with exact

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[1] The situation is often somewhat clouded by studying the uncertainty bands due to variation of renormalization and factorization scales. These analyses lead to rather broad uncertainty bands which prevent definite conclusions.

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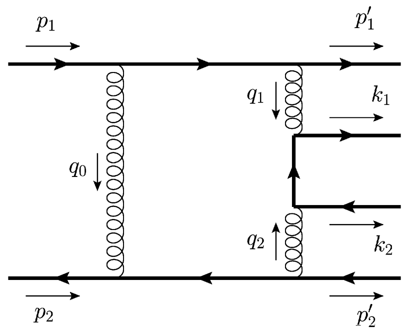

Fig. 2. Kinematical variables of exclusive diffractive production of $q\bar{q}$ pair.

kinematics which can be easily used with kinematical cuts. The amplitude of the genuine four-body reaction is written in analogy to the Kaidalov–Khoze–Martin–Ryskin (KKMR) approach used previously for the exclusive Higgs boson production [11–13].

2. Matrix element and the cross section for exclusive double diffractive $q\bar{q}$ pair production

Inclusive heavy quark/antiquark pair production was considered in detail, e.g. in Refs. [4,5]. It looks quite natural to apply similar ideas to exclusive diffractive $q\bar{q}$ (unbound) pair production.

2.1. Kinematics

The kinematical variables for the process $pp \to p + \text{“gap”} + (q\bar{q}) + \text{“gap”} + p$ are shown in Fig. 2.

We adopt here the following standard definition of the light cone coordinates

$$k^+ \equiv n^+_\alpha k^\alpha = k^0 + k^3, \qquad k^- \equiv n^-_\alpha k^\alpha = k^0 - k^3,$$
$$k_t = \left(0, k^1, k^2, 0\right) = (0, \mathbf{k}, 0),$$

where $n^\pm$ are the light-cone basis vectors. In the c.m.s. frame

$$n^+ = \frac{p_2}{E_{cms}}, \qquad n^- = \frac{p_1}{E_{cms}}, \tag{2.1}$$

and the momenta of the scattering hadrons are given by

$$p_1^+ = p_2^- = \sqrt{s}, \qquad p_1^- = p_2^+ = p_{1,t} = p_{2,t} = 0,$$

with the Mandelstam variable $s = 4E^2_{cms}$.

Within the standard k_t-factorization approach, the decomposition of gluon momenta into longitudinal and transverse parts in the high-energy limit is

$$q_1 = x_1 p_1 + q_{1,t}, \qquad q_2 = x_2 p_2 + q_{2,t}, \quad 0 < x_{1,2} < 1,$$
$$q_0 = x_1' p_1 + x_2' p_2 + q_{0,t}, \quad x_1' \sim x_2' \ll x_{1,2}, \qquad q^2_{0,1,2} \simeq q^2_{0/1/2,t}. \tag{2.2}$$

Making use of energy–momentum conservation laws

$$q_1 = p_1 - p_1' - q_0, \qquad q_2 = p_2 - p_2' + q_0,$$
$$q_1 + q_2 = k_1 + k_2 \tag{2.3}$$

we write

$$s x_1 x_2 = M^2_{q\bar{q}} + |\mathbf{P}_t|^2 \equiv M^2_{q\bar{q},\perp}, \quad M^2_{q\bar{q}} = (k_1 + k_2)^2, \tag{2.4}$$

where $M_{q\bar{q}}$ is the invariant mass of the $q\bar{q}$ pair, and $\mathbf{P}_t$ is its transverse 3-momentum.

2.2. The amplitude for $pp \to pp Q\bar{Q}$

Let us concentrate on the simplest case of production of $q\bar{q}$ pair in the color singlet state. Color octet state would demand an emission of an extra gluon [14] which considerably complicates the calculations, and we postpone such an analysis for future studies.

In analogy to the Kaidalov–Khoze–Martin–Ryskin approach (KKMR) [11–13] for Higgs boson production, we write the amplitude of the exclusive diffractive $q\bar{q}$ pair production $pp \to p(q\bar{q})p$ in the color singlet state as

$$\mathcal{M}^{pp\to ppq\bar{q}}_{\lambda_q\lambda_{\bar{q}}}(p_1', p_2', k_1, k_2)$$
$$= s \cdot \pi^2 \frac{1}{2} \frac{\delta_{c_1c_2}}{N_c^2 - 1} \Im \int d^2 q_{0,t}\, V^{c_1c_2}_{\lambda_q\lambda_{\bar{q}}}(q_1, q_2, k_1, k_2)$$
$$\times \frac{f^{\text{off}}_{g,1}(x_1, x_1', q^2_{0,t}, q^2_{1,t}, t_1) f^{\text{off}}_{g,2}(x_2, x_2', q^2_{0,t}, q^2_{2,t}, t_2)}{q^2_{0,t} q^2_{1,t} q^2_{2,t}}, \tag{2.5}$$

where λ_q, $\lambda_{\bar{q}}$ are helicities of heavy q and $\bar{q}$, respectively. Above f_1^{off} and f_2^{off} are the off-diagonal unintegrated gluon distributions in nucleon 1 and 2, respectively. They will be discussed in a separate subsection below.

The longitudinal momentum fractions of active gluons are calculated based on kinematical variables of outgoing quark and antiquark

$$x_1 = \frac{m_{3,t}}{\sqrt{s}} \exp(+y_3) + \frac{m_{4,t}}{\sqrt{s}} \exp(+y_4),$$
$$x_2 = \frac{m_{3,t}}{\sqrt{s}} \exp(-y_3) + \frac{m_{4,t}}{\sqrt{s}} \exp(-y_4), \tag{2.6}$$

where $m_{3,t}$ and $m_{4,t}$ are transverse masses of the quark and antiquark, respectively, and y_3 and y_4 are corresponding rapidities.

The bare amplitude above is subjected to absorption corrections which, in general, depend on collision energy and on the spin-parity of the produced central system [10]. We shall discuss this issue shortly when presenting our results.

2.3. $gg \to Q\bar{Q}$ vertex

Let us consider the subprocess amplitude for the $q\bar{q}$ pair production via off-shell gluon–gluon fusion. The vertex factor $V^{c_1c_2}_{\lambda_q\lambda_{\bar{q}}} = V^{c_1c_2}_{\lambda_q\lambda_{\bar{q}}}(q_1, q_2, k_1, k_2)$ in expression (2.5) is the production amplitude of a pair of massive quark q and antiquark $\bar{q}$ with helicities λ_q, $\lambda_{\bar{q}}$ and momenta k_1, k_2, respectively. Within the QMRK approach [15], the color singlet $q\bar{q}$ pair production amplitude can be written as

$$V^{c_1c_2}_{\lambda_q\lambda_{\bar{q}}}(q_1, q_2, k_1, k_2) \equiv n^+_\mu n^-_\nu V^{c_1c_2,\mu\nu}_{\lambda_q\lambda_{\bar{q}}}(q_1, q_2, k_1, k_2),$$
$$V^{c_1c_2,\mu\nu}_{\lambda_q\lambda_{\bar{q}}}(q_1, q_2, k_1, k_2)$$
$$= -g^2 \sum_{i,k} \langle 3i, \bar{3}k | 1 \rangle \bar{u}_{\lambda_q}(k_1) \big(t^{c_1}_{ij} t^{c_2}_{jk} b^{\mu\nu}(q_1, q_2, k_1, k_2)$$
$$- t^{c_2}_{kj} t^{c_1}_{ji} \bar{b}^{\mu\nu}(q_1, q_2, k_1, k_2) \big) v_{\lambda_{\bar{q}}}(k_2), \tag{2.7}$$

where t^c are the color group generators in the fundamental representation, $u(k_1)$ and $v(k_2)$ are on-shell quark and antiquark spinors, respectively, $b, \bar{b}$ are vertices (2.8) arising from the Feynman rules:

$$b^{\mu\nu}(q_1, q_2, k_1, k_2) = \gamma^\nu \frac{\hat{q}_1 - \hat{k}_1 - m}{(q_1 - k_1)^2 - m^2} \gamma^\mu,$$

$$\bar{b}^{\mu\nu}(q_1, q_2, k_1, k_2) = \gamma^\mu \frac{\hat{q}_1 - \hat{k}_2 + m}{(q_1 - k_2)^2 - m^2} \gamma^\nu. \tag{2.8}$$