Production of two $c\bar{c}$ pairs in double-parton scattering

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(Dated: November 15, 2011)

Abstract

We discuss production of two pairs of $c\bar{c}$ within a simple formalism of double-parton scattering (DPS). Surprisingly very large cross sections, comparable to single-parton scattering (SPS) contribution, are predicted for LHC energies. Both total inclusive cross section as a function of energy and differential distributions for $\sqrt{s}$ are shown. We discuss a perspective how to identify the double scattering contribution.

PACS numbers: 13.85.-t, 14.65.Dw, 11.80.La
I. INTRODUCTION

It is commonly believed that gluon-gluon fusion is the dominant mechanism of $c\bar{c}$ or $\bar{c}c$ production at high energies. Then in leading-order (LO) approximation the differential cross section for the single-parton scattering (SPS) production of heavy quark and heavy antiquark pair reads:

$$\frac{d\sigma}{dy_1dy_2d^2p_t} = \frac{1}{16\pi^2s^2}x_1g(x_1,\mu^2)\ x_2g(x_2,\mu^2)\ |M_{gg\rightarrow Q\bar{Q}}|^2,\quad (1.1)$$

where longitudinal momentum fractions can be calculated from kinematical variables of final quark and antiquark as:

$$x_1 = \frac{m_t}{\sqrt{s}}(\exp(y_1) + \exp(y_2)),\quad x_2 = \frac{m_t}{\sqrt{s}}(\exp(-y_1) + \exp(-y_2))$$

with $y$'s being quark (antiquark) rapidities and $m_t$ being a quark (antiquark) transverse mass. We have limited here to gluon-gluon fusion only which is the dominant mechanism at high energies. The quark-antiquark annihilation plays some role only close to the kinematical threshold and/or large rapidities. In general, the higher-order corrections do not change most of observables leading to a rough renormalization of the cross section by the so-called $K$ factor.

In the present paper we wish to estimate the contribution of double-parton scatterings (DPS). The mechanism of double-parton scattering production of two pairs of heavy quark and heavy antiquark is shown in Fig. 1.

The double-parton scattering has been recognized and discussed already in seventies and eighties [1–9]. The activity stopped when it was realized that their contribution at those times available center-of-mass energies was negligible. Several estimates of the cross section for different processes have been presented in recent years [10–18]. The theory of the double-parton scattering is quickly developing (see e.g. [19–26]).

In the present analysis we wish to concentrate on the production of $((c\bar{c})((c\bar{c}))$ four-parton final state which has not been carefully discussed so far, but, as will be shown here, is particularly interesting especially in the context of experiments being carried out at LHC and/or high-energy atmospheric and cosmogenic neutrinos (antineutrinos).

The double-parton scattering formalism proposed so far assumes two single-parton scatterings. Then in a simple probabilistic picture the cross section for double-parton scattering can be written as:

$$\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}}\sigma^{SPS}(pp \rightarrow c\bar{c}X_1)\cdot \sigma^{SPS}(pp \rightarrow c\bar{c}X_2).\quad (1.2)$$

This formula assumes that the two subprocesses are not correlated and do not interfere. At low energies one has to include parton momentum conservation i.e. extra limitations: $x_1 + x_3 < 1$ and $x_2 + x_4 < 1$, where $x_1$ and $x_3$ are longitudinal momentum fractions of gluons emitted from one proton and $x_2$ and $x_4$ their counterparts for gluons emitted from the second proton. The "second" emission must take into account that some momentum was used up in the first parton collision. This effect is important at large quark or antiquark rapidities. Experimental data [27] provide an estimate of $\sigma_{eff}$ in the denominator of formula (1.2). In our analysis we take a rather conservative value $\sigma_{eff} = 15$ mb.

The simple formula (1.2) can be generalized to include differential distributions. Again in leading-order approximation differential distribution can be written as

$$\frac{d\sigma}{dy_1dy_2d^2p_{1t}dy_3dy_4d^2p_{2t}} = \frac{1}{2\sigma_{eff}}\frac{d\sigma}{dy_1dy_2d^2p_{1t}}\cdot \frac{d\sigma}{dy_3dy_4d^2p_{2t}}\quad (1.3)$$
which by construction reproduces formula for integrated cross section (1.2). This cross section is formally differential in 8 dimensions but can be easily reduced to 7 dimensions noting that physics of unpolarized scattering cannot depend on azimuthal angle of the pair or on azimuthal angle of one of the produced \( c \) (\( \bar{c} \)) quark (antiquark). The differential distributions for each single scattering step can be written in terms of collinear gluon distributions with longitudinal momentum fractions \( x_1, x_2, x_3 \) and \( x_4 \) expressed in terms of rapidities \( y_1, y_2, y_3, y_4 \) and transverse momenta of quark (or antiquark) for each step (in the LO approximation identical for quark and antiquark).

A more general formula for the cross section can be written formally in terms of double-parton distributions, e.g. \( F_{gg}, F_{qq} \), etc. In the case of heavy quark (antiquark) production at high energies:

\[
\frac{1}{2\sigma_{eff}} F_{gg}(x_1, x_2, \mu_1, \mu_2) F_{gg}(x'_1, x'_2, \mu'_1, \mu'_2) \]

\[
d\sigma_{gg\rightarrow cc}(x_1, x'_1, \mu_1^2) d\sigma_{gg\rightarrow cc}(x_2, x'_2, \mu_2^2) \ dx_1 dx_2 dx'_1 dx'_2.
\]  

(1.4)

It is physically motivated to write the double-parton distributions rather in the impact parameter space \( F_{gg}(x_1, x_2, b) = g(x_1)g(x_2)F(b) \), where \( g \) are usual conventional parton distributions and \( F(b) \) is an overlap of the matter distribution in the transverse plane where \( b \) is a distance between both gluons in the transverse plane [28]. The effective cross section in (1.2) is then \( 1/\sigma_{eff} = \int d^2 b F^2(b) \) and in this approximation is energy independent.

The double-parton distributions in Eq.(1.4) are generally unknown. Usually one assumes a factorized form and expresses them via standard distributions for SPS. Even if factorization is valid at some scale, QCD evolution may lead to a factorization breaking. Evolution is known only in the case when the scale of both scatterings is the same [19, 20, 22] i.e. for heavy object, like double gauge boson production. For double \( c\bar{c} \) production this is not the case and was not discussed so far in the literature. In the present preliminary study we shall therefore apply the commonly used in the literature factorized model. A refinement will be done elsewhere. In explicit calculations presented below we use leading order collinear gluon distributions (GRV94 [29], CTEQ6 [30], GJR08 [31], MSTW08 [32]).
In Fig. 2 we compare cross sections for the single and double-parton scattering as a function of proton-proton center-of-mass energy. At low energies the conventional single-parton scattering dominates. For reference we show the proton-proton total cross section as a function of energy as parametrizes in Ref. [33]. At low energy the \( c \bar{c} \) or \( c \bar{c} c \bar{c} \) cross sections are much smaller than the total cross section. At higher energies the contributions dangerously approach the expected total cross section\(^1\). This shows that inclusion of unitarity effect and/or saturation of parton distributions may be necessary. The effect of saturation in \( c \bar{c} \) production has been included e.g. in Ref. [34] but not checked versus experimental data. Presence of double-parton scattering changes the situation. The double-parton scattering is therefore potentially very important ingredient in the context of high energy neutrino production in the atmosphere [34–36] or of cosmogenic origin [37]. We leave this rather difficult issue for future studies where the LHC charm data must be included. At LHC energies the cross section for both terms become comparable\(^2\). This is a completely new situation when the double-parton scattering gives a huge contribution to inclusive charm production.

\(^1\) New experiments at LHC will provide new input for parametrizations of the total cross section.

\(^2\) If inclusive cross section for \( c \) or \( \bar{c} \) was shown the cross section should be multiplied by a factor of two – two \( c \) or two \( \bar{c} \) in each event.

FIG. 2: Total LO cross section for single-parton and double-parton scattering as a function of center-of-mass energy (left panel) and uncertainties due to the choice of (factorization, renormalization) scales (right panel). We show in addition a parametrization of the total cross section in the left panel. Cross section for DPS should be multiplied in addition by a factor 2 in the case when all \( c \) (\( \bar{c} \)) are counted.

In Figs. 3, 4 we present single \( c \) (\( \bar{c} \)) distributions. Within approximations made in this paper the distributions are identical in shape to single-parton scattering distributions. This means that double-scattering contribution produces naturally an extra center-of-mass energy dependent \( K \) factor to be contrasted with approximately energy-independent \( K \)-factor due to next-to-leading order corrections. One can see a strong dependence on the factorization and renormalization scales which produces almost order-of-magnitude uncertainties.
and precludes a more precise estimation. A better estimate could be done when LHC charm data are published and the theoretical distributions are somewhat adjusted to experimental data.

![Diagram](image1.png)

**FIG. 3:** Distribution in rapidity (left panel) and transverse momentum (right panel) of $c$ or $\bar{c}$ quarks at $\sqrt{s} = 7$ TeV. Cross section for DPS should be multiplied in addition by a factor 2 in the case when all $c$ ($\bar{c}$) are counted.

![Diagram](image2.png)

**FIG. 4:** Uncertainties related to renormalization and factorization scales choice for distributions in rapidity (left panel) and transverse momentum (right panel) of $c$ or $\bar{c}$ quarks at $\sqrt{s} = 7$ TeV. Cross section for DPS should be multiplied in addition by a factor 2 in the case when all $c$ ($\bar{c}$) are counted.

So far we have discussed only single particle spectra of $c$ or $\bar{c}$ (rapidity, transverse momentum distributions) which due to scale dependence do not provide a clear test of the existence of double-parton scattering contributions. A more stringent test could be performed by studying correlation observables. In particular, correlations between $c$ and $\bar{c}$ are very interesting even without double-parton scattering terms [38]. In Fig. 5 we show distribution in the difference of $c$ and $\bar{c}$ rapidities $y_{\text{diff}} = y_c - y_{\bar{c}}$ (left panel) as well as in the $c\bar{c}$ invariant mass $M_{c\bar{c}}$ (right panel). We show both terms: when $c\bar{c}$ are emitted in the same parton scattering ($c_1\bar{c}_2$ or $c_3\bar{c}_4$) and when they are emitted from different parton scatterings ($c_1\bar{c}_4$ or $c_2\bar{c}_3$). In the latter case we observe a long tail for large rapidity difference.
as well as at large invariant masses of $c\bar{c}$. Such distributions cannot be directly measured for $c\bar{c}$ but could be measured for mesons (rapidity difference up to 5 for the main ATLAS or CMS detector) or electron-positron or $\mu^+\mu^-$. The ALICE forward muon spectrometer [39] covers the pseudorapidity interval $2.5 < \eta < 4$ which when combined with the central detector means pseudorapidities differences up to 5. This is expected to be a region of phase space where double-parton scattering contribution would most probably dominate over single-parton scattering contribution. This will be a topic of a forthcoming analysis. Next-to-leading order corrections are not expected to give major contribution at large pseudorapidity differences or/and large invariant masses of $\mu^+\mu^-$ but this must be verified in the future. The CMS detector is devoted especially to measurements of muons. The lower transverse momentum threshold is however rather high, the smallest being about 1.5 GeV at $\eta = \pm (2 - 2.4)$ which may be interesting for double-parton scattering searches. This requires special dedicated Monte Carlo studies.

\[X_{c\bar{c}} \rightarrow SP, p + p = 7 \text{ TeVs}\]

\[X_{c\bar{c}} \rightarrow LO: g + g\]

\[R_{\mu} = 15 \text{ mb}\]

In contrast, double-parton scattering mechanism provide a broad distribution extending to large transverse momenta. Next-to-leading order corrections obviously destroy the $\delta$-like leading-order correlation. We believe that similar distributions for $D\bar{D}$ or/and $e^+e^-$ or $\mu^+\mu^-$ pairs would be a useful observables to identify the DPS contributions but this requires real Monte Carlo simulations including actual limitations of experimental apparatus. Correlations between outgoing nonphotonic electrons has been studied at much lower RHIC energy in Ref. [40].

Production of two $c\bar{c}$ pairs in the leading order approximation is only a first step in trying to identify DPS contribution. In the next step we plan next-to-leading order calculation of the same process. Inclusion of hadronization and/or semileptonic decays would be very useful in planning experimental searches.

Acknowledgments

We are indebted to Wolfgang Schäfer for interesting conversion and Jacek Okołowicz for careful reading of this manuscript. This work was partially supported by the polish grant.
FIG. 6: Distribution in transverse momentum of $c\bar{c}$ pairs from the same parton scattering and from different parton scatterings at $\sqrt{s} = 7$ TeV.

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