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# Production of $c\bar{c}c\bar{c}$ in single- and double-parton scattering in collinear and $k_t$-factorization approaches

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We discuss production of two pairs of $c\bar{c}$ in proton-proton collisions at the LHC. Both double-parton scattering (DPS) and single-parton scattering (SPS) contributions are included in the analysis. Each step of DPS is calculated within $k_t$-factorization approach which effectively includes some next-to-leading order corrections. The discussed mechanisms unavoidably lead to the production of pairs of mesons: $D_iD_j$ (each containing $c$ quarks) or $\bar{D}_i\bar{D}_j$ (each containing $\bar{c}$ antiquarks). We calculate corresponding differential distribution for $(D^0D^0 + \bar{D}^0\bar{D}^0)$ production. Within large theoretical uncertainties the predicted DPS cross section is fairly similar to the cross section measured recently by the LHCb collaboration. We also present first results for the $2 \to 4$ single-parton scattering $gg \to c\bar{c}c\bar{c}$ subprocess for the first time fully within the $k_t$-factorization approach. In this calculation we have used an off-shell matrix element squared calculated using recently developed techniques. The results are compared with our earlier result obtained within the collinear approach. Only slightly larger cross sections are obtained than in the case of the collinear approach but still the SPS mechanism contribution is much smaller than the DPS one. Inclusion of transverse momenta of gluons entering the hard process leads to a much stronger azimuthal decorrelation between $cc$ and $\bar{c}\bar{c}$ than in the collinear-factorization approach. A comparison to predictions of double parton scattering (DPS) results and the LHCb data strongly suggests that the assumption of two fully independent DPS ($gg \to c\bar{c} \otimes gg \to c\bar{c}$) may be too approximate.

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## 1. Introduction

The $pp \to c\bar{c}c\bar{c}X$ reaction has been recognized recently to be a golden reaction to study double-parton scattering (DPS) processes [1, 2]. The LHCb collaboration confirmed the theoretical predictions and obtained a large cross section for production of two mesons, both containing $c$ quarks or both containing $\bar{c}$ antiquarks [3]. The single-parton scattering (SPS) contribution was discussed in Refs. [4] and [5]. In the first case [4] a high-energy approximation was used neglecting some unimportant at high energies Feynman diagrams. Last year we have calculated the lowest-order SPS cross section(s) including a complete set of Feynman diagrams [5] in the collinear-factorization approach. The final result was only slightly different than that obtained in the high-energy approximation.

Now we go one step further and calculate the SPS cross sections for the $pp \to c\bar{c}c\bar{c}X$ reaction consistently in the $k_t$-factorization approach [6]. In this theoretical framework a sizeable part of higher-order corrections can be included and studies of kinematical correlations are available. From the technical point of view this is a first calculation within the $k_t$-factorization approach based on a $2 \to 4$ subprocesses with two off-shell initial-state partons (gluons). The result is important in the context of studying DPS as the considered SPS mechanism constitutes an irreducible background, and its estimation is therefore crucial if deeper conclusions concerning DPS can be drawn from measurements at the LHC.

A convenient formalism for the automation of the calculation of tree-level scattering amplitudes with off-shell gluons for arbitrary processes was introduced recently in Ref. [7]. Off-shell gluons are replaced by eikonal quark-antiquark pairs, and the amplitude can be calculated with the help of standard local Feynman rules, including the eikonal gluon-quark-antiquark vertex and the eikonal quark-antiquark propagator. The well-known successful recursive methods to calculate tree-level amplitudes can directly be applied, including the "on-shell" recursion, or Britto-Cachazo-Feng-Witten recursion, as shown in Ref. [8]. The heuristic introduction of the formalism in Ref. [7] has be given solid ground in Ref. [9].

## 2. Formalism

In leading-order (LO) collinear approximation the differential distributions for $c\bar{c}$ production depend e.g. on the rapidity of the quark, the rapidity of the antiquark and the transverse momentum of one of them (they are identical). In the next-to-leading order (NLO) collinear approach or in the $k_t$-factorization approach the situation is more complicated as there are more kinematical variables necessary to describe the kinematical situation. In the $k_t$-factorization approach the differential cross section for DPS production of $c\bar{c}c\bar{c}$ system, assuming factorization of the DPS model, can be written as:

$$\frac{d\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}X_1)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}}. \quad (2.1)$$

When integrating over kinematical variables one obtains

$$\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}} \sigma^{SPS}(pp \to c\bar{c}X_1) \cdot \sigma^{SPS}(pp \to c\bar{c}X_2). \tag{2.2}$$

These formulae assume that the two parton subprocesses are not correlated.

Experimental data obtained at Tevatron [10, 11] and LHC [12, 3, 13] provide an estimate of $\sigma_{eff}$ in the denominator of formula (2.2). Phenomenological studies of $\sigma_{eff}$ are summarized e.g. in Ref. [14] with the average value $\sigma_{eff} \approx 15$ mb.

Within the $k_t$-factorization approach the SPS cross section for $pp \to c\bar{c}c\bar{c}X$ reaction can be written as

$$d\sigma_{pp \to c\bar{c}c\bar{c}} = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi} \mathscr{F}(x_1, k_{1t}^2, \mu^2) \mathscr{F}(x_2, k_{2t}^2, \mu^2) d\hat{\sigma}_{gg \to c\bar{c}c\bar{c}} \,. \tag{2.3}$$

In the formula above $\mathscr{F}(x, k_t^2, \mu^2)$ are unintegrated gluon distributions that depend on longitudinal momentum fraction $x$, transverse momentum squared $k_t^2$ of the gluons entering the hard process, and in general also on a (factorization) scale of the hard process $\mu^2$. The elementary cross section in Eq. (2.3) can be written somewhat formally as:

$$\begin{aligned} d\hat{\sigma} \; = \; & \frac{d^3 p_1}{2E_1(2\pi)^3} \frac{d^3 p_2}{2E_2(2\pi)^3} \frac{d^3 p_3}{2E_3(2\pi)^3} \frac{d^3 p_4}{2E_4(2\pi)^3} (2\pi)^4 \delta^4(p_1 + p_2 + p_3 + p_4 - k_1 - k_2) \\ & \times \frac{1}{\text{flux}} \overline{|\mathscr{M}_{g^* g^* \to c\bar{c}c\bar{c}}(k_1, k_2)|^2} \,, \end{aligned} \tag{2.4}$$

where only dependence of the matrix element on four-vectors of gluons $k_1$ and $k_2$ is made explicit. In general all four-momenta associated with partonic legs enter. The matrix element takes into account that both gluons entering the hard process are off-shell with virtualities $k_1^2 = -k_{1t}^2$ and $k_2^2 = -k_{2t}^2$. The matrix element squared is rather complicated and explicit formula will be not given here.

## 3. Results

In this section we compare the new results of the $k_t$-factorization approach for SPS mechanism to those obtained by us in Ref. [5] in the collinear-factorization approach.

In Fig. 1 we show standard single particle distributions in charm quark/antiquark transverse momentum (left panel) and its rapidity (right panel). We predict an enhancement of the cross section at large transverse momenta of $c$ or $\bar{c}$ compared to the collinear-factorization approach. The rapidity distributions in both approaches are rather similar (see the left panel of the figure).

From the DPS studies point of view, the azimuthal angle correlations between $c$ and $c$ or $c$ and $\bar{c}$ are very interesting. The corresponding distributions are shown in Fig. 2. We note much bigger decorrelation of two $c$ quarks or $c$ and $\bar{c}$ in the $k_t$-factorization approach compared to the collinear approach. This is due to explict account of gluon virtualities (transverse momenta). We will return to this point when discussing azimuthal correlations between mesons at the end of this section.

So far we have considered production of $c\bar{c}c\bar{c}$ quarks/antiquarks. In the following we have included also $c \to D$ hadronization effects, which are important for the LHCb acceptance in meson

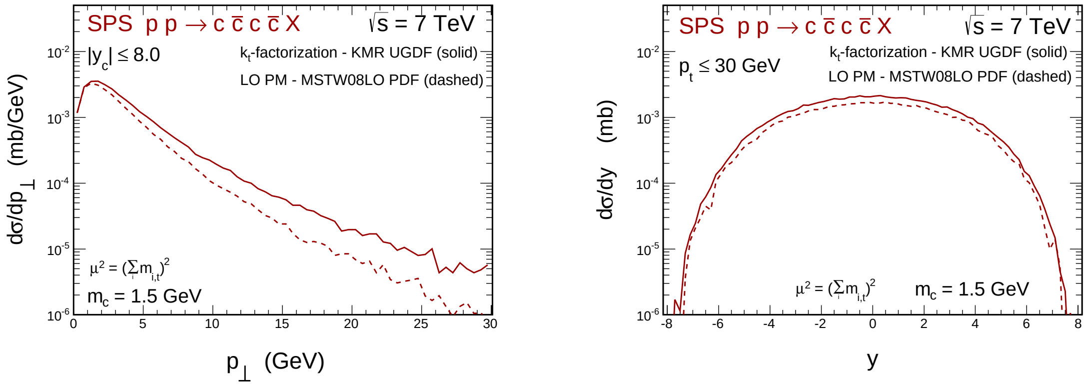


**Figure 1:** Distributions in $c$ quark ($\bar{c}$ antiquark) transverse momentum (left panel) and rapidity (right panel). The $k_t$-factorization result (solid line) is compared with the collinear-factorization result (dashed line).

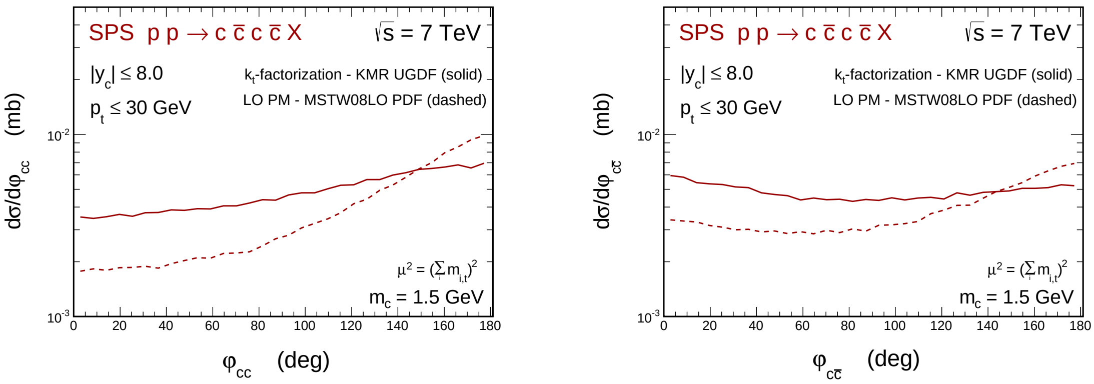


**Figure 2:** Azimuthal angle correlations between two $c$ quarks (left panel) and between $c$ and $\bar{c}$ (right panel).

transverse momentum. Details how the hadronization of heavy quarks is done within the fragmentation function technique were explained e.g. in Ref. [15]. Here we have used the Peterson fragmentation function with $\varepsilon_c = 0.02$. As explained in Ref. [5] the DPS gives cross sections very similar to those measured by the LHCb collaboration [3]. How important is the SPS contribution discussed in this paper, calculated here in the $k_t$-factorization, is shown in Fig. 3. For comparison we show also SPS results calculated in collinear-factorization approach [5]. The two approaches give somewhat different shapes of correlation observables, inspite that the integrated cross sections are rather similar as discussed already at the parton level. Our results, so far the most advanced in the literature as far as the SPS contribution is considered, are not able to explain discrepancy between DPS contribution and the LHCb experimental data. Whether the discrepancies are due to simplifications in the treatment of DPS requires further studies including for example spin and flavour correlations. Some works in this direction already started [16].

## 4. Conclusions

We have presented results of a first calculation of the SPS cross section for $pp \to c\bar{c}c\bar{c}X$ in the $k_t$-factorization approach, This is a first $2 \to 4$ process for which $k_t$-factorization is applied. In

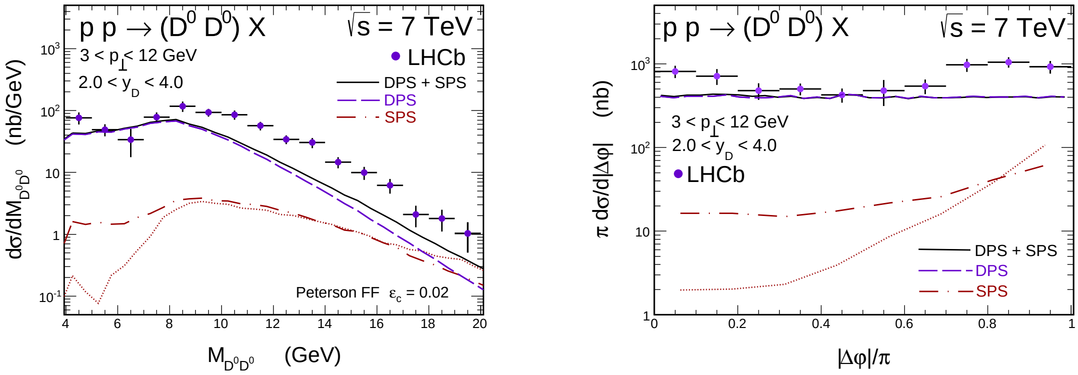


**Figure 3:** Distributions in $D^0D^0$ invariant mass (left) and in azimuthal angle between both $D^0$'s (right) within the LHCb acceptance. The DPS contribution (dashed line) is compared with the SPS one calculated within the $k_t$-factorization approach (dashed-dotted line). The SPS result from our previous studies [5], calculated in the LO collinear-factorization approach, is also shown here (dotted line).

this calculation we have used the Kimber-Martin-Ryskin unintegrated gluon distribution(s) which effectively includes the dominant higher-order corrections. The off-shell matrix element was calculated using a new technique developed recently in Kraków.

The results of the $k_t$-factorization approach were compared with the results of the collinear-factorization approach. In general, the $k_t$-factorization results are only slightly bigger than those for collinear approach. An exception is the transverse momentum distribution for transverse momenta above 10 GeV where a sizeable enhancement has been observed. Inclusion of gluon virtualities leads to a decorrelation in azimuthal angle between $c$ and $c$ or $c$ and $\bar{c}$.

Since the cross section is in general very similar as for the collinear-factorization approach we conclude that the $c\bar{c}c\bar{c}$ final state at the LHC energies is dominantly produced by the double parton scattering as discussed in our recent papers, and the SPS contribution, although interesting by itself, is rather small. A comparison to predictions of double-parton scattering results and recent LHCb data for azimuthal angle correlations between $D^0$ and $D^0$ or $\bar{D}^0$ and $\bar{D}^0$ mesons strongly suggests that the assumption of two fully independent DPS ($gg \to c\bar{c} \otimes gg \to c\bar{c}$) may be too approximate or some other mechanisms contribute.

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