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

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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. The conditions how to identify the DPS contribution are presented. The discussed mechanism leads to the production of pairs of mesons: each containing c quarks or each containing $\bar{c}$ antiquarks. We discuss corresponding production rates and some differential distributions for $(D^0 D^0 + \bar{D}^0 \bar{D}^0)$ production. Within large theoretical uncertainties the predicted DPS cross section is fairly similar to the cross section measured recently by the LHCb collaboration. The best description is obtained with the Kimber-Martin-Ryskin (KMR) unintegrated gluon distribution. The contribution of SPS, calculated in the high-energy approximation, turned out to be rather small. Finally, we emphasize significant contribution of DPS mechanism to inclusive charmed meson spectra measured recently by ALICE, ATLAS and LHCb.

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1. Introduction

There is recently growing interest in studying double-parton scattering (DPS) effects (see e.g. [1] and references therein). Recently we have shown that the production of $c\bar{c}c\bar{c}$ is an ideal place to study DPS effects [2]. Here, the quark mass is small enough to assure that the cross section for DPS is very large, and large enough to treat the problem within pQCD. The calculation performed in Ref. [2] was done in the leading-order (LO) collinear approximation. Recently [3] we have shown that this is not sufficient when comparing the results of the calculation with real experimental data. In the meantime the LHCb collaboration presented new experimental data for simultaneous production of two charmed mesons [4]. In spite of limited acceptance they have observed large percentage of events with two mesons, both containing c quark.

In our recent analysis [3] we have argued that the LHCb data provide a footprint of double parton scattering. In addition, we have also estimated $c\bar{c}c\bar{c}$ production via single-parton scattering (SPS) within a high-energy approximation [5]. This approach seems to be an efficient tool especially when the distance in rapidity between cc or/and $\bar{c}\bar{c}$ is large.

Another piece of evidence for the DPS effects is that their absence leads to a missing contribution to inclusive charmed meson production, as noted in Ref. [6]. The measured inclusive cross sections include events where two D (or two $\bar{D}$) mesons are produced, therefore corresponding theoretical predictions should also be corrected for the DPS effects.

In Ref. [7] the authors estimated DPS contribution based on the experimental inclusive D meson spectra measured at LHC. In their approach fragmentation was included only in terms of the branching fractions for the transition $c \rightarrow D$. In our approach we include full kinematics of hadronization process.

2. Sketch of the formalism

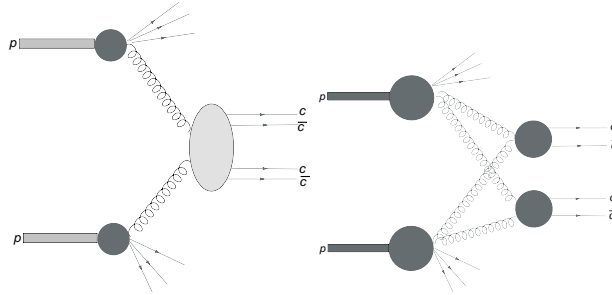Two possible mechanisms of the production of two $c\bar{c}$ pairs are shown in Fig.1.

Figure 1: SPS (left) and DPS (right) mechanisms of $(c\bar{c})(c\bar{c})$ production.

The cross section for differential distribution in a simple double-parton scattering in leading-order collinear approximation can be written as

$$\frac{d\sigma}{dy_1 dy_2 d^2 p_{1t} dy_3 dy_4 d^2 p_{2t}} = \frac{1}{2\sigma_{eff}} \frac{d\sigma}{dy_1 dy_2 d^2 p_{1t}} \cdot \frac{d\sigma}{dy_3 dy_4 d^2 p_{2t}} \tag{2.1}$$

which by construction reproduces the formula for integrated cross section [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). This can be easily generalized by including QCD evolution effects [2].

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:

$$\frac{d\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t} dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}} =$$
$$\frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_1)}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} \cdot \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_2)}{dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}}. \quad (2.2)$$

These formulae assume that the two parton subprocesses are not correlated one with each other. The parameter σ_{eff} in the denominator of above formulae can be understood in the impact parameter space as:

$$\sigma_{eff} = \left[\int d^2 b \ (T(\vec{b}))^2 \right]^{-1}, \quad (2.3)$$

where the overlap function

$$T(\vec{b}) = \int f(\vec{b_1}) f(\vec{b_1} - \vec{b}) \ d^2 b_1, \quad (2.4)$$

In the presented here analysis cross section for each step is calculated in the k_t-factorization approach:

$$\frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_1)}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2 k_{1t}}{\pi} \frac{d^2 k_{2t}}{\pi} \overline{|\mathcal{M}_{g^*g^* \rightarrow c\bar{c}}|^2}$$
$$\times \ \delta^2 \left(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t} \right) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2),$$

$$\frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_2)}{dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2 k_{3t}}{\pi} \frac{d^2 k_{4t}}{\pi} \overline{|\mathcal{M}_{g^*g^* \rightarrow c\bar{c}}|^2}$$
$$\times \ \delta^2 \left(\vec{k}_{3t} + \vec{k}_{4t} - \vec{p}_{3t} - \vec{p}_{4t} \right) \mathcal{F}(x_3, k_{3t}^2, \mu^2) \mathcal{F}(x_4, k_{4t}^2, \mu^2). \quad (2.5)$$

The matrix elements for $g^* g^* \rightarrow c\bar{c}$ (off-shell gluons) are calculated including transverse momenta of initial gluons [10, 11, 12]. The unintegrated (k_t-dependent) gluon distributions (UGDFs) in the proton are taken from the literature [13, 14, 15].

How the single scattering contribution is calculated is explained in Ref.[6]. In this approach a high-energy approximation is used, and the calculation should be reliable for larger rapidity distance between two cc or two $\bar{c}\bar{c}$ quarks. A full calculation of the single scattering contribution is in progress [8].

3. Results

In Fig. 2 we compare cross sections for the single $c\bar{c}$ pair production as well as for single-parton and double-parton scattering $c\bar{c}c\bar{c}$ production as a function of proton-proton center-of-mass

energy. At low energies the conventional single $c\bar{c}$ pair production cross section is much larger. The cross section for SPS production of $c\bar{c}c\bar{c}$ system is more than two orders of magnitude smaller than that for $c\bar{c}$ production. For reference we also show the parametrization of proton-proton total cross section as a function of center-of-mass energy. At higher energies the DPS contribution of $c\bar{c}c\bar{c}$ quickly approaches that for single $c\bar{c}$ production as well as the total cross section.
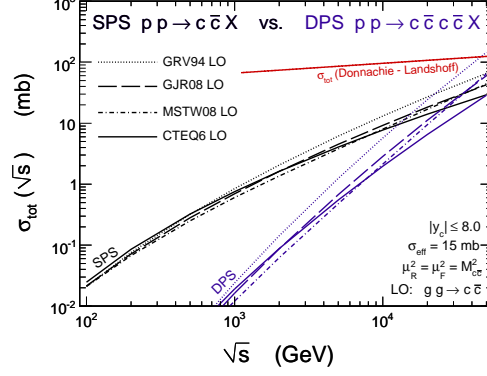

Figure 2: Total LO cross section for single $c\bar{c}$ pair and SPS and DPS $c\bar{c}c\bar{c}$ production as a function of center-of-mass energy.

In Ref. [2] we have proposed several correlation distributions to be studied in order to identify the DPS effects. Here in Fig. 3 we show only distributions in rapidity difference of quarks/antiquarks $Y_{diff} = y_c - y_{\bar{c}}$ from the same scattering ($c_1\bar{c}_2$ or $c_3\bar{c}_4$) and from different scatterings ($c_1\bar{c}_4$ or $c_3\bar{c}_2$ or c_1c_3 or $\bar{c}_2\bar{c}_4$) for various UGDFs. The shapes of distributions in the figure are almost identical as that obtained in LO collinear approach in Ref. [2]. One can clearly see that the double-scattering effects dominate in the region of large rapidity distances. This is a potential place to identify them. As discussed in Ref.[3] this is not very easy option with the existing detectors. Further studies are needed.
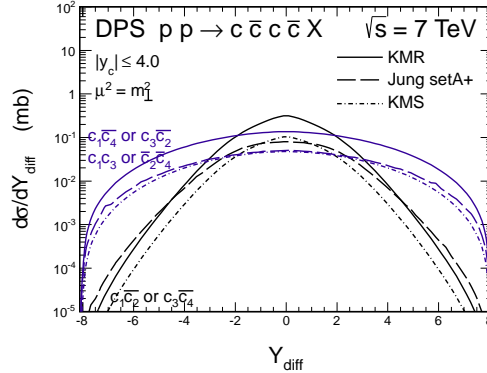

Figure 3: Distribution in rapidity distance between quarks/antiquarks Y_{diff} from the same ($c_1\bar{c}_2$ or $c_3\bar{c}_4$) and from different scatterings ($c_1\bar{c}_4$ or $c_3\bar{c}_2$ or c_1c_3 or $\bar{c}_2\bar{c}_4$), calculated with different UGDFs.

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In Fig. 4 we present distribution in transverse momentum of one of the D^0 mesons, provided that both are measured within the LHCb experiment coverage. Our theoretical distributions have shapes in rough agreement with the experimental data. The shapes of the distributions are almost identical for different UGDFs used in the calculations (left panel) and are almost independent of the choice of scales in the case of the KMR model (right panel).
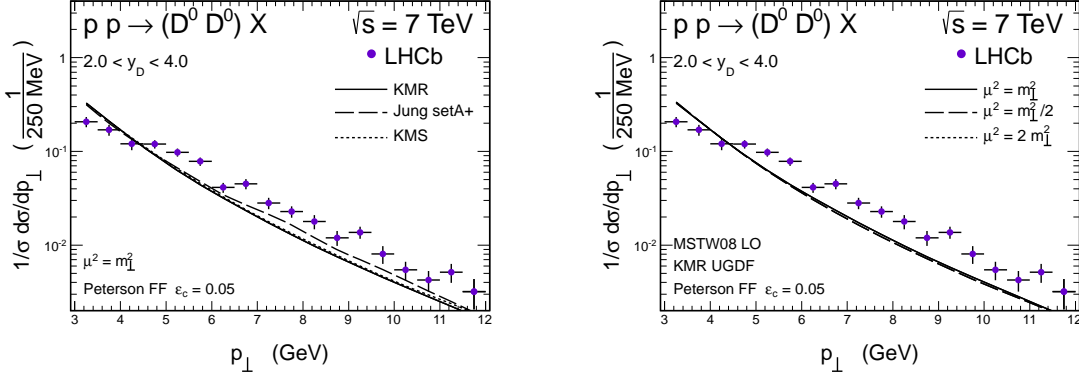

Figure 4: Transverse momentum distribution of D^0 mesons from the $D^0 D^0$ pair contained in the LHCb kinematical region. The left panel shows dependence on UGDFs, while the right panel illustrates dependence of the result for the KMR UGDF on the factorization/renormalization scales. The MSTW08 collinear distribution was used to generate KMR UGDF.

In Fig. 5 we show distribution in the $D^0 D^0$ invariant mass $M_{D^0 D^0}$ for both D^0's measured in the kinematical region covered by the LHCb experiment. Here the shapes of the distributions have the same behavior for various UGDFs and are insensitive to changes of scales as in the previous figure. The characteristic minimum at small invariant masses is a consequnce of experimental cuts (see Ref. [6]) and is rather well reproduced. Our approach fails at large dimeson invariant masses. The large $M_{D^0 D^0}$ invariant masses are probably correlated to large scales $\mu^2_{1/2}$ and/or $\mu^2_{3/4}$. If these can be related to the effects of factorization violation discussed in [9] requires dedicated studies.
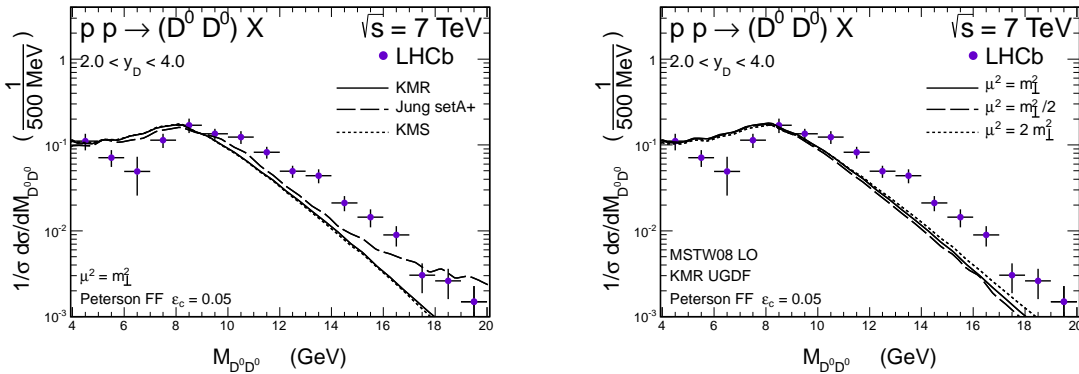

Figure 5: $M_{D^0 D^0}$ invariant mass distribution for $D^0 D^0$ contained in the LHCb kinematical region. The left panel shows dependence on UGDFs, while the right panel illustrates dependence of the result on the factorization/renormalization scales for KMR UGDF.

Finally in Fig. 6 we show distribution in azimuthal angle $\varphi_{D^0 D^0}$ between both D^0's. While the theoretical DPS contribution is independent of the relative azimuthal angle, there is a small dependence on azimuthal angle in experimental distribution. This may show that there is some missing mechanism which gives contributions both at small and large $\Delta\varphi$. However, this discrepancy may be also an inherent property of the DPS factorized model which does not allow for azimuthal correlations between particles produced in different hard scatterings. We wish to emphasize in this context that the angular azimuthal correlation pattern for $D^0 \bar{D}^0$, discussed in Ref. [6], and for $D^0 D^0$ ($\bar{D}^0 \bar{D}^0$), discussed here, are quite different. The distribution for $D^0 D^0$ ($\bar{D}^0 \bar{D}^0$) is much more flat compared to the $D^0 \bar{D}^0$ one which shows a pronounced maximum at $\varphi_{D^0 \bar{D}^0} = 180°$ and $\varphi_{D^0 \bar{D}^0} = 0°$. This qualitative difference is in our opinion a model independent proof of the dominance of DPS effects in the production of $D^0 D^0$ ($\bar{D}^0 \bar{D}^0$).
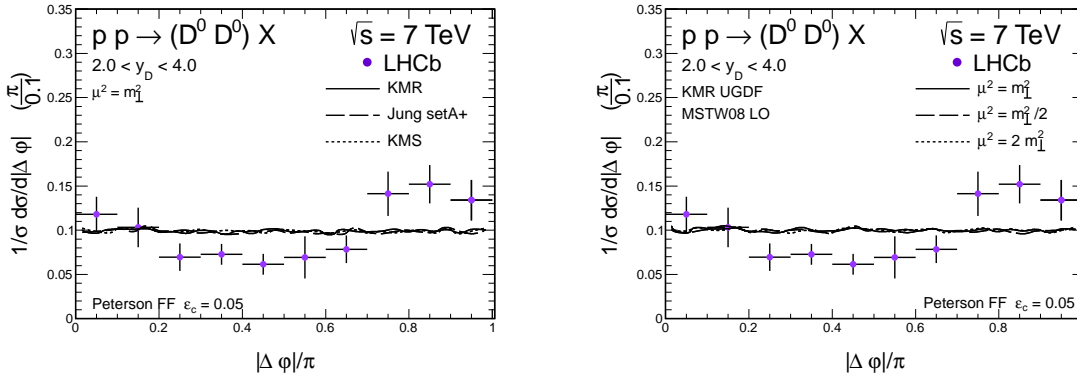

Figure 6: Distribution in azimuthal angle $\varphi_{D^0 D^0}$ between both D^0's. The left panel shows dependence on UGDFs, while the right panel illustrates dependence of the result for the KMR UGDF on the factorization/renormalization scales.

4. Conclusions

In this presentation we have discussed production of $c\bar{c}c\bar{c}$ in the double-parton scattering (DPS) and single-parton scattering (SPS) in the $gg \to c\bar{c}c\bar{c}$ subprocess. The double-parton scattering is calculated in the factorized Ansatz with each step calculated in the k_t-factorization approach, i.e. including effectively higher-order QCD corrections.

The distribution in rapidity difference between quarks/antiquarks from the same and different scatterings turned out to have similar shape as in the LO collinear approach. The same is true for invariant masses of pairs of quark-quark, antiquark-antiquark and quark-antiquark, etc. The distribution in transverse momentum of the pair from the same scattering turned out to be similar to that for the pairs originating from different scatterings.

The total rates of the meson pair production depend on the unintegrated gluon distributions. The best agreement with the LHCb result has been obtained for the Kimber-Martin-Ryskin UGDF. This approach, as discussed already in the literature, effectively includes higher-order QCD corrections.

As an example we have also calculated several differential distributions for $D^0 D^0$ pair production. We have reproduced the main trends of the LHCb data for transverse momentum distribution

of D^0 ($\bar{D}^0$) mesons and $D^0 D^0$ invariant mass distribution. The distribution in azimuthal angle between both D^0's suggests that some mechanisms may be still missing. The single parton scattering contribution, calculated in the high energy approximation, turned out to be rather small. This is being checked in exact $2 \rightarrow 4$ parton model calculations.

The DPS mechanism of $c\bar{c}c\bar{c}$ production gives a new significant contribution to inclusive charmed meson spectra [3]. For instance the description of the inclusive ATLAS, ALICE and LHCb data is very difficult in terms of the conventional SPS ($c\bar{c}$) contribution [**?**].

Summarizing, the present study of $c\bar{c}c\bar{c}$ reaction in the k_t-factorization approach has shown that this reaction is one of the best places for testing double-parton scattering effects.

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