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PRODUCTION OF $c\bar{c}$ AND $c\bar{c}c\bar{c}$ IN PROTON–PROTON COLLISIONS*

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We report on charm production at the LHC. The production of single $c\bar{c}$ pairs is calculated in the $k_{\rm t}$-factorization approach with different unintegrated gluon distributions. Examples of transverse momentum distributions for charmed mesons are presented and compared to recent experimental results from the LHC. Some missing strength is observed for most of UGDFs. Furthermore, we discuss production of two $c\bar{c}$ pairs within double-parton scattering (DPS) and single-parton scattering (SPS) mechanisms. Surprisingly, large cross sections comparable to single $c\bar{c}$ pair production are predicted. We discuss first experimental results from LHCb Collaboration on production of pairs of D mesons of the same flavour.

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1. Introduction

The cross section for open charm production at the LHC is very large. Different mesons have been measured recently [1, 2]. Some other experiments are preparing their experimental cross sections. Different theoretical approaches for heavy quark production were used in the literature. In the present communication, we present briefly some results for charmed meson production within $k_{\rm t}$-factorization approach. A more detailed analysis is presented elsewhere [3]. Previously, we used the $k_{\rm t}$-factorization approach for charm production at the Tevatron [5] and for nonphotonic electron production at the RHIC [6, 7]. The $k_{\rm t}$-factorization approach was also successfully used for beauty [8] and top [9] quark (antiquark) inclusive production.

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Recently, we have made first estimates for the production of two $c\bar{c}$ pairs [10, 11]. We have considered both double-parton scattering (DPS) mechanism [10] as well as single-parton scattering (SPS) mechanism [11] (see Fig. 1). Comparison of contributions of both mechanisms leads to the conclusion that the production of two $c\bar{c}$ pairs is a favourite place to study and identify double-parton scattering effects. Recently, the LHCb Collaboration has measured pairs of several D mesons [12]. We argue that their measurement confirms large double-parton scattering effects.

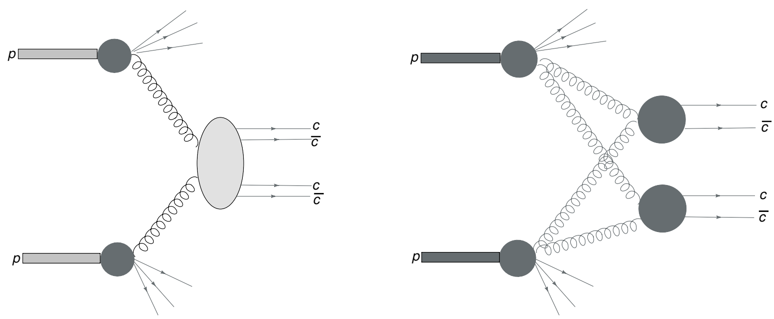

Fig. 1. SPS (left) and DPS (right) mechanisms of $(c\bar{c})(c\bar{c})$ production.

2. Sketch of formalism

In the leading-order (LO) approximation within the $k_{\rm t}$-factorization approach the quadruply differential cross section in the rapidity of Q (y_1) and $\bar{Q}$ (y_2), and in the transverse momentum of Q ($p_{1,{\rm t}}$) and $\bar{Q}$ ($p_{2,{\rm t}}$) is given as

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,{\rm t}} d^2p_{2,{\rm t}}} = \sum_{i,j} \int \frac{d^2\kappa_{1,{\rm t}}}{\pi} \frac{d^2\kappa_{2,{\rm t}}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{ij\to Q\bar{Q}}|^2}$$
$$\times \delta^2\left(\vec{\kappa}_{1,{\rm t}} + \vec{\kappa}_{2,{\rm t}} - \vec{p}_{1,{\rm t}} - \vec{p}_{2,{\rm t}}\right) \mathcal{F}_i\left(x_1, \kappa^2_{1,{\rm t}}\right) \mathcal{F}_j\left(x_2, \kappa^2_{2,{\rm t}}\right) ,$$

where $\mathcal{F}_i(x_1, \kappa^2_{1,{\rm t}})$ and $\mathcal{F}_j(x_2, \kappa^2_{2,{\rm t}})$ are so-called unintegrated gluon (parton) distributions. The unintegrated parton distributions are evaluated at

$$\begin{aligned} x_1 &= \frac{m_{1,{\rm t}}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,{\rm t}}}{\sqrt{s}} \exp(y_2) , \\ x_2 &= \frac{m_{1,{\rm t}}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,{\rm t}}}{\sqrt{s}} \exp(-y_2) , \end{aligned} \tag{1}$$

where $m_{i,{\rm t}} = \sqrt{p^2_{i,{\rm t}} + m^2_Q}$.

In Fig. 2, we show dependence of the unintegrated gluon distributions functions on gluon transverse momentum squared for longitudinal momentum fraction $x = 10^{-4}$ relevant for the production of charm quarks and antiquarks at the LHC. The dependences on transverse momentum of the initial gluon differ considerably. This have direct consequences for charm production.

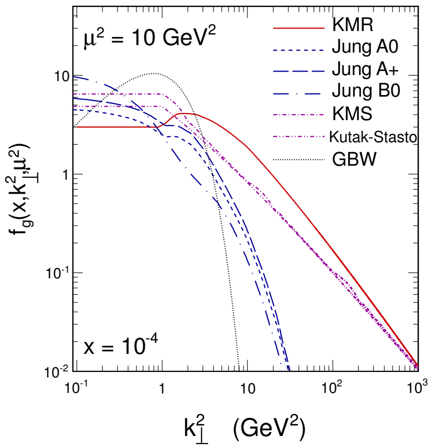

Fig. 2. Different UGDFs from the literature as a function of gluon transverse momentum for given values of longitudinal momentum fraction and factorization scale.

The hadronization is done in the way explained in Ref. [6].

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

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

which by construction reproduces the formula for integrated cross section [10]. This cross section is formally differential in 8 dimensions but can be 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 for double parton distributions [10].

Recently, we have generalized this approach to the $k_{\rm t}$-factorization approach [13], where transverse momenta of particles 1 and 2 as well as transverse momenta of particles 3 and 4 are not balanced. This approach generate effectively higher-order corrections.

3. Results

In Fig. 3, we show two examples of transverse momentum distribution of D mesons. Our results are compared with recent experimental data [1, 2]. Some strength seems to be missing. A possible explanation is discussed below. More distributions are shown in our recent publication [3].

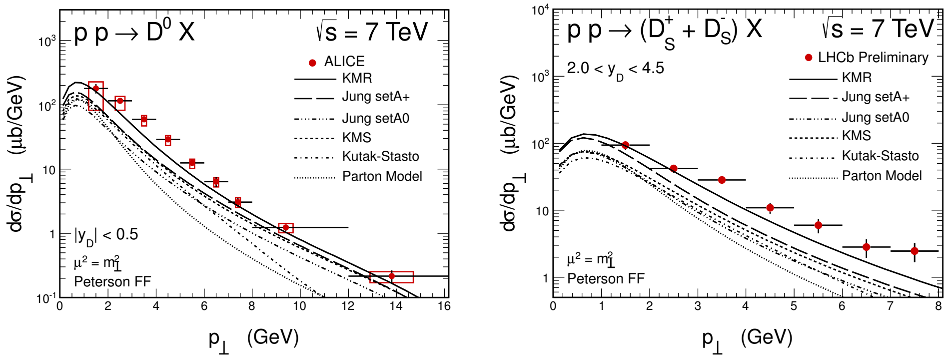

Fig. 3. Two examples of transverse momentum distribution of charmed mesons compared to ALICE (left panel) and LHCb (right panel) experimental data. The calculations are done for different UGDFs.

In Fig. 4, 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 single $c\bar{c}$ production. For reference, we show the proton–proton total cross section as a function of 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 proton–proton cross section.

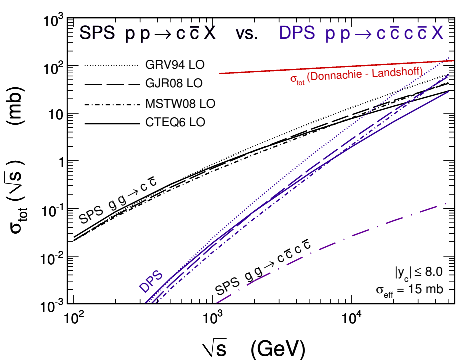

Fig. 4. Total LO cross section for single $c\bar{c}$ pair and SPS and DPS $c\bar{c}c\bar{c}$ production as a function of center-of-mass energy.

In Fig. 5, we show distributions in rapidity difference between quark and antiquark from the same scattering or between quarks from different scatterings (left panel). The distribution for y_{cc} from different scatterings is much broader than that for $c\bar{c}$ from the same scattering. In the right panel, we compare the SPS contribution with the DPS one.

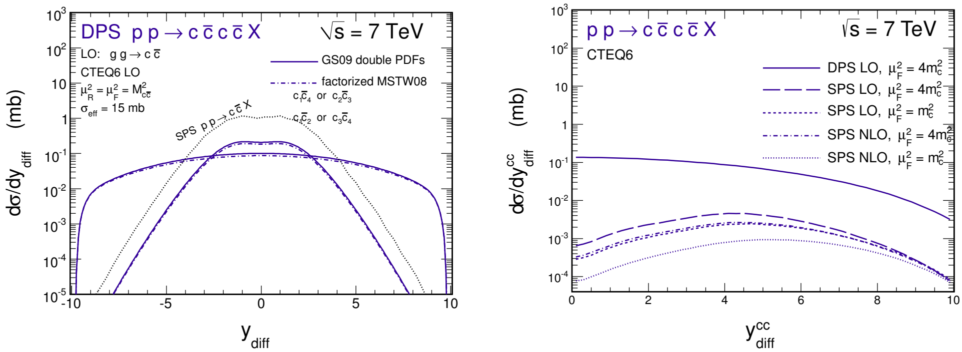

Fig. 5. Comparison of SPS and DPS contributions. Left panel shows results without and with QCD evolution of double parton distributions. Right panel compares results for DPS and SPS production of $c\bar{c}c\bar{c}$.

In Table I, we show our first estimate of the cross sections for the production of two D mesons, both containing cc quarks, for different UGDFs from the literature. More details, including differential distributions, are shown in [13]. Our DPS estimate gives good order of magnitude compared to the LHCb data.

TABLE I

Total cross sections for a production of pairs of mesons within the LHCb acceptance region.

Mode	$\sigma_{\mathrm{tot}}^{\mathrm{EXP}}$ [nb]	KMR	Jung setA0+	KMS
D^0D^0	$690 \pm 40 \pm 70$	256	101	100
D^0D^+	$520 \pm 80 \pm 70$	204	81	80
$D^0D_S^+$	$270 \pm 50 \pm 40$	72	29	28
D^+D^+	$80 \pm 10 \pm 10$	41	16	16
$D^+D_S^+$	$70 \pm 15 \pm 10$	29	12	11
$D_S^+D_S^+$	—	10	4	4

4. Conclusions

We have presented our selected new results for charmed meson production at LHC. Results of our calculation have been compared with recent ALICE and LHCb experimental data for transverse momentum distribution of D mesons. There seems to be a missing strength, especially for the LHCb kinematics.

One of possible explanations is a presence of DPS contributions. We have compared energy dependence of the DPS contribution to the $c\bar{c}c\bar{c}$ production with that for the $c\bar{c}$ production. The cross section for two pair production grows much faster than that for single pair production. At high energies, the two cross sections become comparable. We have also discussed some correlation observables that could be used to identify double-parton scattering contribution. The rapidity difference between cc (or $\bar{c}\bar{c}$) is one of the best examples.

We have also estimated corresponding single-parton scattering contributions in a high energy approach. The latter turned out to be much smaller than the double-parton scattering contributions.

In Ref. [10], we suggested that a good possibility to identify DPS effects would be to measure D mesons of the same flavour. Recently, the LHCb Collaboration has presented results of such first studies [12]. Our calculation predicts cross section of right order of magnitude.

In summary, we have found that the production of two $c\bar{c}$ pairs is one of the best places to study and identify double-parton scattering effects.

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