Double-parton scattering effects in double charm production within gluon fragmentation scenario

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August 9, 2017

Abstract

We discuss charm D^0D^0 meson-meson pair production in the forward rapidity region related to the LHCb experimental studies at $\sqrt{s} = 7$ TeV. We consider double-parton scattering mechanisms of double $c\bar{c}$ production and subsequent standard $cc \to D^0D^0$ scale-independent hadronization as well as new double g and mixed $gc\bar{c}$ production mechanisms with $gg \to D^0D^0$ and $gc \to D^0D^0$ scale-dependent hadronization. The new scenario with gluon fragmentation components results also in a new single-parton scattering mechanism of gg production which is also taken here into account. Results of the numerical calculations are compared with the LHCb data for several correlation observables. The new mechanisms lead to a larger cross sections and to slightly different shapes of the calculated correlation observables.

1 Introduction

Some time ago we have predicted that at large energies, relevant for the LHC, production of double charm should be dominated by the double-parton scattering (DPS) mechanism [1]. Afterwards, those leading-order (LO) collinear predictions were extended to the k_t-factorization approach that effectively includes higher-order QCD effects [2, 3]. The improved studies provide a relatively good description of the LHCb experimental data [4]. Besides, the single-parton scattering (SPS) $gg \to c\bar{c}c\bar{c}$

mechanism was found to be much smaller than the DPS one, and is not able to explain the LHCb double charm data [3, 5].

The theoretical analyses introduced above were based on the standard $c \to D$ hadronization scenario with scale-independent Peterson fragmentation function (FF) [6]. An alternative approach for hadronization effects is to apply scale-dependent FFs of a parton (gluon, $u, d, s, \bar{u}, \bar{d}, \bar{s}, c, \bar{c}$) to D mesons proposed by Kniehl et al. [7, 8], that undergo DGLAP evolution equations. Both prescriptions were found to provide a very good description of the LHC data on inclusive D meson production at not too small transverse momenta (see e.g. Refs. [9, 10]). In the latter approach, a dominant contribution comes from $g \to D$ fragmentation that appears in the evolution of the scale-dependent FFs and the $c \to D$ component is damped with respect to the scale-independent fragmentation scheme.

The presence of the gluonic components modify the overall picture for the double charm production. In the (new) scenario with scale-dependent hadronization the number of contributing DPS processes grows. In addition, a new single-parton scattering mechanism SPS $gg \to DD$ appears. Taking into account gluon fragmentation components there are more processes for single D meson production (two dominant components $g, c \to D$) and as a consequence many more processes for DPS DD production appear. Now there are three classes of DPS contributions. In addition to the coventional DPS $cc \to DD$, discussed very carefully in Refs. [2, 3, 5] there is a double $g \to D$ fragmentation mechanism, called here DPS $gg \to DD$ as well as the mixed DPS $gc \to DD$ contribution.

Here the gluon and digluon production is considered in the k_t-factorization approach with reggeized gluons in the t-channel [11] via subprocesses $RR \to g$ and $RR \to gg$, where R is the reggeized gluon. We use scale-dependent fragmentation functions of Kneesch-Kniehl-Kramer-Schienbein (KKKS08) [12] as implemented in the code available on the Web [13]. All details of the calculations presented here can be found in our original paper [14].

2 A sketch of the theoretical formalism

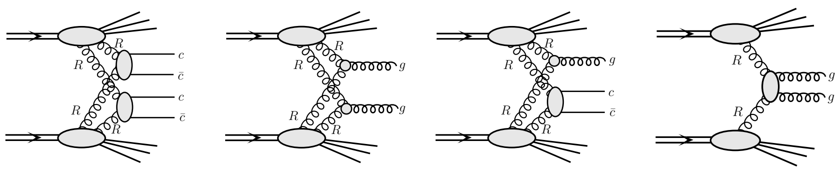

Figure 1: A diagrammatic illustration of the considered mechanisms.

We will compare numerical results for $D^0 D^0$ meson-meson production obtained with the two different fragmentation scenarios. According to the scheme with scale-dependent FFs more processes for single D meson production (c and $g \to D$ components) has to be taken into consideration. This also causes an extension of the standard DPS DD pair production by new mechanisms. In addition to the coventional DPS $cc \to DD$ (left diagram in Fig.1) considered in Refs. [2, 3, 5] there is a double $g \to D$ (or double $g \to \bar{D}$) fragmentation mechanism, called here DPS $gg \to DD$ (middle-left diagram in Fig.1) as well as the mixed DPS $gc \to DD$ contribution (middle-right diagram in Fig.1).

As a consequence of the new approach to fragmentation a new SPS $gg \to DD$ mechanism shows up (right diagram in Fig.1). In this case the two produced gluons are correlated in azimuth and the mechanism will naturally lead to an azimuthal correlation between two D mesons. Such a correlation was actually observed in the LHCb experimental data [4] and so far could not be explained theoretically.

DPS cross section for production of cc, gg or gc system, assuming factorization of the DPS model, can be written as:

$$\frac{d\sigma^{DPS}(pp \to ccX)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}X_1)}{dy_1 d^2p_{1,t}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}X_2)}{dy_2 d^2p_{2,t}}, \quad (1)$$

$$\frac{d\sigma^{DPS}(pp \to ggX)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to gX_1)}{dy_1 d^2p_{1,t}} \cdot \frac{d\sigma^{SPS}(pp \to gX_2)}{dy_2 d^2p_{2,t}}. \quad (2)$$

$$\frac{d\sigma^{DPS}(pp \to gcX)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to gX_1)}{dy_1 d^2p_{1,t}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}X_2)}{dy_2 d^2p_{2,t}}. \quad (3)$$

The often called pocket-formula is a priori a severe approximation. The flavour, spin and color correlations may lead, in principle, to interference effects that result in its violation as discussed e.g. in Ref. [15]. Even for unpolarized proton beams, the spin polarization of the two partons from one hadron can be mutually correlated, especially when the partons are relatively close in phase space (having comparable x's). Moreover, in contrast to the standard single PDFs, the two-parton distributions have a nontrivial color structure which also may lead to a non-negligible correlations effects. Such effects are usually not included in phenomenological analyses. They were exceptionally discussed in the context of double charm production [16]. However, the effect on e.g. azimuthal correlations between charmed quarks was found there to be very small, much smaller than effects of the SPS contribution associated with double gluon fragmentation discussed here. In addition, including perturbative parton splitting mechanism also leads to a breaking of the pocket-formula [17]. This formalism was so far formulated for the collinear leading-order approach which for charm (double charm) may be a bit academic as it leads to underestimation of the cross section. Imposing sum rules also leads to a breaking of the factorized Ansatz but the effect almost vanishes for small longitudinal momentum fractions [18]. Taken the above arguments we will use the pocket-formula in the following.

All the considered mechanisms (see Fig. 1) are calculated in the k_t-factorization approach with off-shell initial state partons and unintegrated (k_t-dependent) PDFs (unPDFs). Fully gauge invariant treatment of the initial-state off-shell gluons and quarks can be achieved in the k_t-factorization approach only when they are considered as Reggeized gluons or Reggeons. We use the LO Kimber-Martin-Ryskin (KMR) unPDFs, generated from the LO set of a up-to-date MMHT2014 collinear PDFs fitted also to the LHC data (for more details see Ref.[14]).

3 Comparison to the LHCb data

We start this section with a revision of inclusive single D^0 meson production measured some time ago by the LHCb collaboration [19]. We compare here corresponding theoretical predictions based on both, the first (only $c \to D$) [9] and the second

($c + g \to D$) scenario [10], keeping the same set of α_S, scales, unPDFs and other details. This comparison is crucial for drawing definite conclusions from double D meson production. As shown in Fig. 2, both prescriptions give a very good description of the LHCb experimental data. Some small differences between them can be observed for both very small and large meson transverse momenta. The latter effect can be relatd to the DGLAP evolution which makes the slope of the transverse momentum distribution in the second scenario a bit steeper. In the region of very small p_t's the second scenario gives larger cross sections and slightly overestimates the experimental data points. This may come from the $g \to D$ fragmentation component which approaches a problematic region when $p_t \sim 2m_c$. Then the treatment of charm quarks as massless in the DGLAP evolution of fragmentation function for very small evolution scale can be a bit questionable and may lead to a small overestimation of the integrated cross sections.

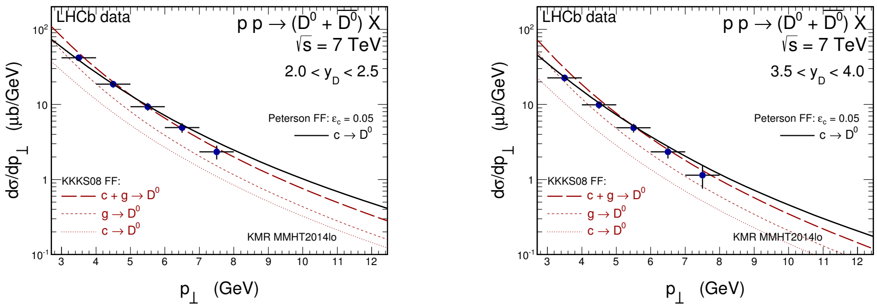

Figure 2: Charm meson transverse momentum distribution within the LHCb acceptance for inclusive single D^0 mesons (plus their conjugates) production. The left and right panels correspond to two different rapidity intervals. Theoretical predictions for the Peterson $c \to D$ fragmentation function (solid lines) are compared to the second scenario calculations with the KKKS08 fragmentation functions (long-dashed lines) with $c \to D$ (dotted) and $g \to D$ (short-dashed) components that undergo DGLAP evolution equation.

Now we go to double charm meson D^0D^0 production. In Fig. 3 we compare results of our calculation with experimental distribution in transverse momentum of one of the meson from the D^0D^0 (or $\bar{D}^0\bar{D}^0$) pair. We show results for the first scenario when standard Peterson FF is used for the $c \to D^0$ (or $\bar{c} \to \bar{D}^0$) fragmentation (left panel) as well as the result for the second scenario when the KKKS08 FFs with DGLAP evolution for $c \to D^0$ (or $\bar{c} \to \bar{D}^0$) and $g \to D^0$ (or $g \to \bar{D}^0$) are used. One can observe that the DPS $cc \to D^0D^0$ contribution in the new scenario is much smaller than in the old scenario. In addition, the slope of the distribution in transverse momentum changes. Both the effects are due to evolution of corresponding fragmentation functions. The different new mechanisms give contributions of similar size. We can obtain an agreement in the second case provided σ_{eff} parameter is increased from conventional 15 mb to 30 mb. Even then we overestimate the LHCb data for $3 < p_T < 5$ GeV. Possible effects that may result in larger value of σ_{eff} and in its transverse momentum dependence are discussed in our original paper [14].

In Fig. 4 we show dimeson invariant mass distribution $M_{D^0D^0}$ again for the two cases considered. In the first scenario we get a good agreement only for small

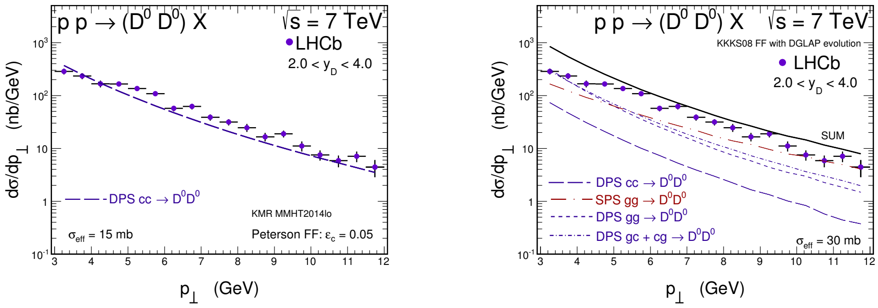

Figure 3: D^0 meson transverse momentum distribution within the LHCb acceptance region. The left panel is for the first scenario and for the Peterson $c \to D$ fragmentation function while the right panel is for the second scenario and for the fragmentation function that undergo DGLAP evolution equation.

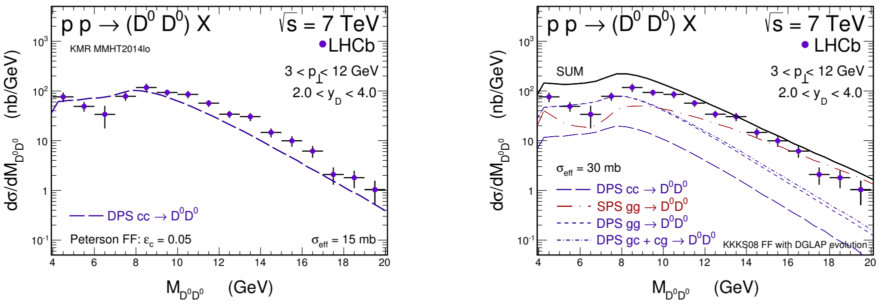

Figure 4: $M_{D^0D^0}$ dimeson invariant mass distribution within the LHCb acceptance region. The left panel is for the first scenario and for the Peterson $c \to D$ fragmentation function while the right panel is for the second scenario and for the fragmentation function that undergo DGLAP evolution equation.

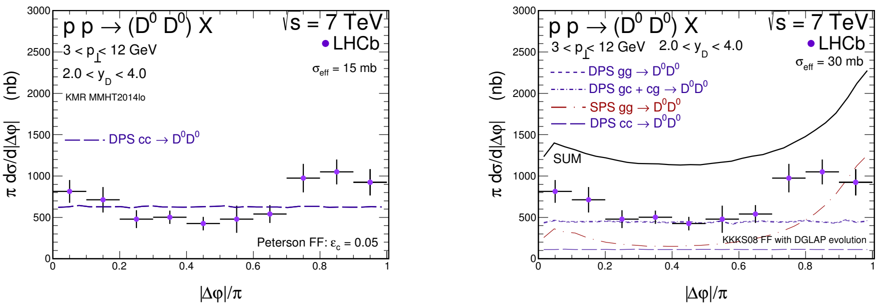

Figure 5: Distribution in azimuthal angle $\varphi_{D^0D^0}$ between the two D^0 mesons within the LHCb acceptance region. The left panel is for the first scenario and for the Peterson $c \to D$ fragmentation function while the right panel is for the second scenario and for the fragmentation function that undergo DGLAP evolution equation.

invariant masses while in the second scenario we get a good agreement only for large invariant masses. The large invariant masses are strongly correlated with large transverse momenta, so the situation here (for the invariant mass distribution) is quite similar as in Fig. 3 for the transverse momentum distribution.

In Fig. 5 we show azimuthal angle correlation $\varphi_{D^0 D^0}$ between D^0 and D^0 (or $\bar{D}^0$ and $\bar{D}^0$ mesons). While the correlation function in the first scenario is completely flat, the correlation function in the second scenario shows some tendency similar as in the experimental data.

To summarize the present situation for the second scenario, in Fig. 6 we show again the azimuthal angle distribution discussed above for different values of σ_{eff}. Good description can be obtained only for extremely large values of σ_{eff} which goes far beyond the geometrical picture [17] and that are much larger than for other reactions and in this sense is inconsistent with the factorized Ansatz. We think that the solution of the inconsistency is not only in the DPS sector as already discussed in this paper.

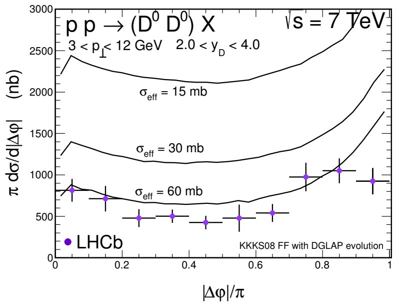

Figure 6: The dependence of the results of the second scenario on the parameter σ_{eff} used in the calculation of the DPS contributions. Here the three lines correspond to σ_{eff} equal to 15, 30, and 60 mb, from top to bottom, respectively.

4 Conclusions

The new scenario with scale-dependent FFs for double D meson production give similar result as the first scenario with one fragmentation subprocess ($cc \to DD$) and fixed (scale-independent) FFs. However, correlation observables, such as dimeson invariant mass or azimuthal correlations between D mesons, are slightly better described in the second scenario as long as we consider only their shapes. However, to get the proper normalization of the cross sections calculated within the second scenario a much larger value of σ_{eff} is needed.

The observed overestimation of the correlation observables in the second scenario comes from the region of small transverse momenta. It may be related to the fact that the fragmentation function used in the new scenario were obtained in the DGLAP formalism with massless c quarks and $\bar{c}$ antiquarks which may be a too severe approximation, especially for low factorization scales (i.e. low transverse momenta) for fragmentation functions. On the other hand, the situation can be also improved when a proper transverse momentum dependence of σ_{eff} and/or when perturbative-parton-splitting mechanisms will be included, but this needs further studies.

Acknowledgments

We thank V. A. Saleev and A. V. Shipilova for collaboration in obtaining results presented here. This study was partially supported by the Polish National Science Center grant DEC-2014/15/B/ST2/02528.

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