PROCEEDINGS OF SCIENCE

Double charmed meson production at the LHC: single versus double-scattering mechanism

Antoni Szczurek[*] [†]
Institute of Nuclear Physics PAN, PL-31-342 Cracow, Poland
University of Rzeszów, PL-35-959 Rzeszów, Poland, and
E-mail: `Antoni.Szczurek@ifj.edu.pl`

Rafał Maciuła, A. van Hameren

Institute of Nuclear Physics PAN, PL-31-342 Cracow, Poland

Kinematical correlations in azimuthal angle $\varphi_{D^0\overline{D}^0}$, invariant mass $M_{D^0\overline{D}^0}$ and rapidity difference $Y_{D^0\overline{D}^0}$ distributions are calculated. We also discuss production of two pairs of $c\bar{c}$ within the formalism of double-parton scattering (DPS). We compare results of calculations of single-parton scattering (SPS) and double-parton scattering (DPS) for production of $c\bar{c}c\bar{c}$ and for $D^0 - D^0$ meson-meson correlations. We compare our predictions for double charm production with recent results of the LHCb collaboration for azimuthal angle $\varphi_{D^0D^0}$ distribution, dimeson invariant mass $M_{D^0D^0}$ and rapidity distance between mesons $Y_{D^0D^0}$. The obtained results clearly demonstrate the dominance of DPS in the production of events with double charm.

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects
28 April - 2 May 2014
Warsaw, Poland

[*]Speaker.

[†]This work was partially supported by the Polish NCN grant: DEC-2011/01/B/ST2/04535.

PoS(DIS2014)169

1. Introduction

It was recently argued that the cross section for $c\bar{c}c\bar{c}$ production at LHC energies may be very large due to mechanism of double-parton scattering (DPS), which is a completely new situation [3, 4]. The double scattering effects were studied in several other processes such as four jet production, production of W^+W^- pairs or production of four charged leptons, however, in all the cases the DPS contributions have been found to be much smaller than the conventional single-parton scattering (SPS) mechanisms.

In the meanwhile the LHCb collaboration measured the cross section for the production of DD meson-meson pairs at $\sqrt{s}$ = 7 TeV which is surprisingly large, including interesting correlation distributions [2]. So far the double open charm production have been studied differentially only within the $k_{\perp}$-factorization approach using unintegrated gluon distributions [5], where several observables useful to identify the DPS effects in the case of double open charm production have been carefully discussed.

Separately the production of double hidden charm was studied e.g. in Ref. [6] for the $pp \to J/\psi J/\psi X$ process. There the SPS single-J/ψ and DPS double-J/ψ contributions are comparable. Furthermore, the DPS contribution exceeds the SPS contribution for large rapidity distance between the two J/ψ's. This is similar to the case of $c\bar{c}c\bar{c}$ production [5].

In order to draw definite conclusions about the DPS effects in double-D meson production it is necessary to carefully estimate contribution to $c\bar{c}c\bar{c}$ final state from the standard mechanism of single-parton scattering. The latter mechanism constitutes higher-order correction to conventional SPS single $c\bar{c}$ production and one may expect suppression in comparison to the DPS contribution, however, it should be accurately calculated in order to reduce uncertainty of the DPS theoretcal model. So far the SPS contribution was calculated only in high-energy approximation [7], which is relevant for large rapidity separation between produced mesons. Since, in the LHCb experiment the condition of large rapidity distances is not always fulfilled, it seems to be essential to perform exact calculations.

1.1 Charm-anticharm correlations at the LHCb

In order to calculate correlation observables for $D\overline{D}$ pair production, measured recently in the LHCb experiment [2], we follow here, similar as in the single meson production, the fragmentation function technique for hadronization process:

$$\frac{d\sigma(pp \to D\overline{D}X)}{dy_1 dy_2 d^2p_{1t}^D d^2p_{2t}^{\overline{D}}} \approx \int \frac{D_{c\to D}(z_1)}{z_1} \cdot \frac{D_{\bar{c}\to\overline{D}}(z_2)}{z_2} \cdot \frac{d\sigma(pp \to c\bar{c}X)}{dy_1 dy_2 d^2p_{1t}^c d^2p_{2t}^{\bar{c}}} dz_1 dz_2 \,, \tag{1.1}$$

where: $p_{1t}^c = \frac{p_{1,t}^D}{z_1}$, $p_{2,t}^{\bar{c}} = \frac{p_{2t}^{\bar{D}}}{z_2}$ and meson longitudinal fractions $z_1, z_2 \in (0,1)$. The multidimensional distribution for c quark and $\bar{c}$ antiquark is convoluted with respective fragmentation functions simultaneously. As the result of the hadronization one obtains corresponding two-meson multidimensional distribution. In the last step experimental kinematical cuts on the distributions can be imposed. Then the resulting distributions can be compared with experimental ones.

The LHCb collaboration presented distribution in the $D^0\overline{D}^0$ invariant mass $M_{D^0\overline{D}^0}$. In the left panel of Fig. 1 we show the corresponding theoretical result for different UGDFs. Both, the KMR

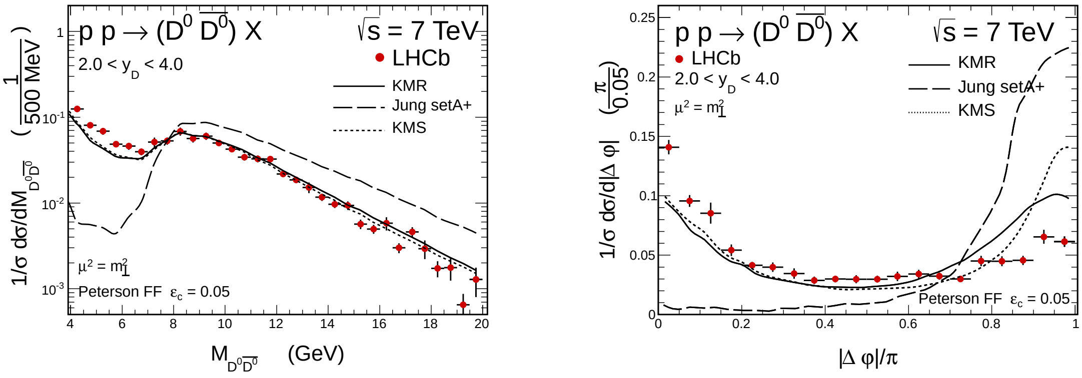

Figure 1: Invariant mass distribution of the $D^0\overline{D}^0$ system (left) and distribution in relative azimuthal angle between D^0 and $\overline{D}^0$ (right) for different UGDFs.

and KMS UGDFs provide the right shape of the distribution. The dip at small invariant masses is due to specific LHCb cuts on kinematical variables.

The LHCb detector has almost full coverage in azimuthal angle. In the right panel of Fig. 1 we show distribution in azimuthal angle between the D^0 and $\overline{D}^0$ mesons $\varphi_{D^0\overline{D}^0}$. Both, the KMR and KMS UGDFs give the enhancement of the cross section at $\phi_{D\bar{D}} \sim 0$. This is due to the fact that these approaches include effectively gluon splitting contribution, not included in the case of the Jung UGDFs. However, still one can observe some small missing strength at small angles. It may suggest that within the KMR and KMS models the gluon splitting contribution is not fully included.

2. Double charm production and meson-meson correlations

Production of $c\bar{c}c\bar{c}$ four-parton final state is particularly interesting especially in the context of experiments being carried out at the LHC and has been recently carefully discussed [3, 5]. The double-parton scattering formalism in the simplest form assumes two independent standard single-parton scatterings. Then in a simple probabilistic picture, in the so-called factorized Ansatz, the differential cross section for the DPS production of $c\bar{c}c\bar{c}$ system within the $k_\perp$-factorization approach can be written as:

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

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 partonic subprocesses are not correlated one with each other. The parameter σ_{eff} in the denominator of above formulae from a phenomenological point of view is a non-perturbative quantity related to the transverse size of the hadrons and has the dimension of a cross section. The dependence of σ_{eff} on the total energy at fixed scales is rather small and it is believed, that the value should be equal to the total non-diffractive cross section, if the hard-scatterings are really uncorrelated. More details of the theoretical framework for DPS mechanism applied here can be found in Ref. [5].

In turn, the elementary cross section for the SPS mechanism of double $c\bar{c}$ production has the following generic form:

$$d\hat{\sigma} = \frac{1}{2\hat{s}}\, \overline{|\mathcal{M}_{gg\to c\bar{c}c\bar{c}}|^2}\; d^4PS. \tag{2.3}$$

where

$$d^4PS = \frac{d^3p_1}{E_1(2\pi)^3}\frac{d^3p_2}{E_2(2\pi)^3}\frac{d^3p_3}{E_3(2\pi)^3}\frac{d^3p_4}{E_4(2\pi)^3}\delta^4\left(p_1+p_2+p_3+p_4\right) \tag{2.4}$$

is the 4-particle Lorentz invariant phase space and p_1, p_2, p_3, p_4 are four-momenta of final charm quarks and antiquarks.

Neglecting small electroweak corrections and taking into account also $q\bar{q}$ annihilation terms, the hadronic cross section takes the following form:

$$\begin{aligned} d\sigma \;=\; & \int dx_1 dx_2 [g(x_1,\mu_F^2) g(x_2,\mu_F^2)\; d\sigma_{gg\to c\bar{c}c\bar{c}} \\ & + \Sigma_f\; q_f(x_1,\mu_F^2)\bar{q}_f(x_2,\mu_F^2)\; d\sigma_{q\bar{q}\to c\bar{c}c\bar{c}}]\,. \end{aligned} \tag{2.5}$$

The matrix elements for single-parton scattering were calculated using color-connected helicity amplitudes. They allow for an explicit exact sum over colors, while the sum over helicities can be done by using Monte Carlo methods. The color-connected amplitudes were calculated following a recursive numerical Dyson-Schwinger approach. More details about the SPS calculation and useful references can be found in Ref. [18].

In Fig. 2 we show azimuthal angle correlation (left panel) and distributions in relative rapidity distance between two D^0 mesons (right panel) with kinematical cuts (rapidities and transverse momenta) corresponding to the LHCb experiment. The shapes of the distributions are rather well reproduced.

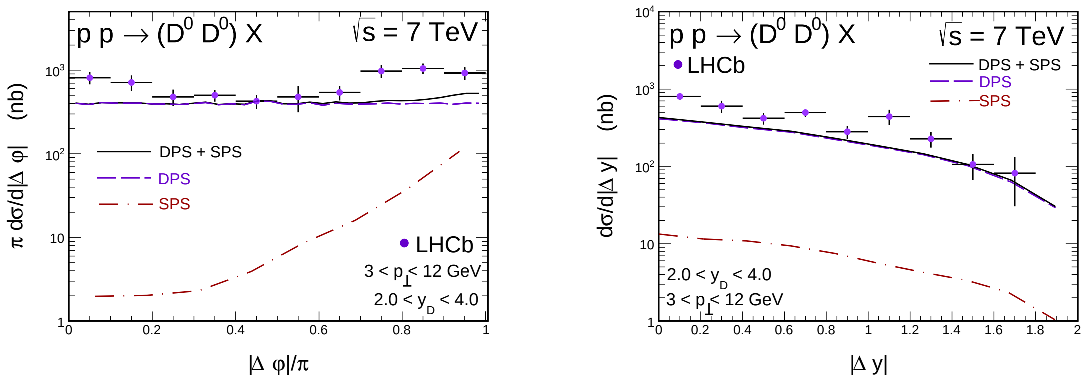

Figure 2: Azimuthal angle correlation between D^0D^0 (left) and distribution in rapidity difference between two D^0 mesons (right) for DPS and SPS contributions.

Other distributions in meson transverse momentum and two-meson invariant mass are shown in Fig. 3. The shape in the transverse momentum is almost correct but some cross section is still lacking. Two-meson invariant mass distribution is shown in the right panel. One can see some lacking strength particularly at large invariant masses.

In the figures shown here the SPS component (dash-dotted line) is compared to the DPS component (dashed line). The dominance of the DPS mechanism in description of the LHCb double charm data is clearly confirmed. The DPS mechanism provides almost fully qualitative explanation of the measured distribution, however some strength is still missing. This can be due to $3 \rightarrow 4$ parton splitting processes discussed recently e.g. in Ref. [19]. This will be a subject of separate studies.

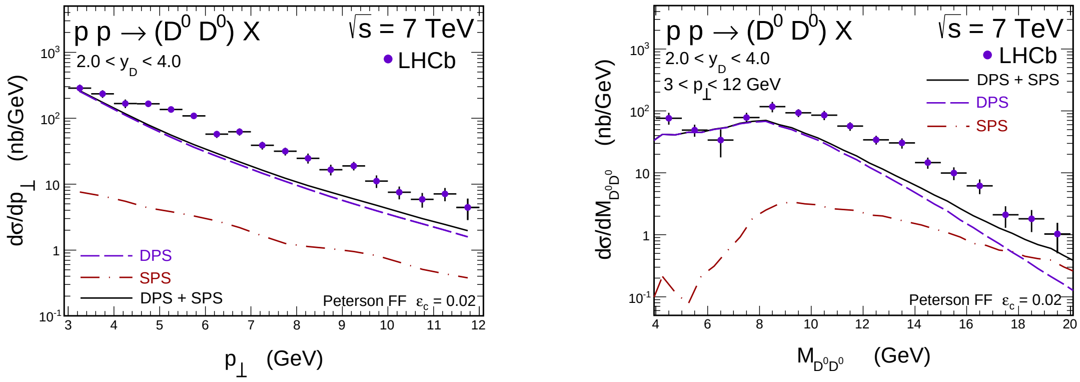

Figure 3: Distributions in meson transverse momentum when both mesons are measured within the LHCb acceptance (left) and corresponding distribution in meson invariant mass (right) for DPS and SPS contributions.

References

[1] R. Maciuła, and A. Szczurek, Phys. Rev. **D87**, 094022 (2013).

[2] R. Aaij et al. (The LHCb collaboration), J. High Energy Phys. **06** (2012) 141.

[3] M. Łuszczak, R. Maciuła, and A. Szczurek, Phys. Rev. **D85**, 094034 (2012).

[4] E. R. Cazaroto, V. P. Goncalves, and F. S. Navarra, Phys. Rev. **D88**, 034005 (2013).

[5] R. Maciuła, and A. Szczurek, Phys. Rev. **D87**, 074039 (2013).

[6] S. P. Baranov, A. M. Snigirev, N. P. Zotov, A. Szczurek, and W. Schäfer, Phys. Rev. **D87**, 034035 (2013).

[7] W. Schäfer, and A. Szczurek, Phys. Rev. **D85**, 094029 (2012).

[8] M.A. Kimber, A.D. Martin and M.G. Ryskin, Phys. Rev. **D63** (2001) 114027.

[9] J. Kwieciński, A.D. Martin and A.M. Staśto, Phys. Rev. **D56** (1997) 3991.

[10] K. Kutak and A.M. Stasto, Eur. Phys. J **C41** (2005) 343.

[11] H. Jung, G.P. Salam, Eur. Phys. J. **C19** (2001) 351.

[12] S. Catani, M. Ciafaloni and F. Hautmann, Nucl. Phys. **366** (1991) 135.

[13] C. Peterson, D. Schlatter, I. Schmitt, P.M. Zerwas, Phys. Rev. **D27** (1983) 105.

[14] E. Braaten et al., Phys. Rev. **D51** (1995) 4819.

[15] M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. **95** (2005) 122001.

[16] E. Lohrmann, arXiv:1112.3757 [hep-ex].

[17] A. van Hameren, arXiv:1003.4953 [hep-ph].

[18] A. van Hameren, R. Maciuła and A. Szczurek, arXiv:1402.6972 [hep-ph].

[19] J. R. Gaunt, J. High Energy Phys. **01**, 042 (2013).