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Associated production of D-mesons with jets at the LHC

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We present several differential distributions for the associated production of charm and dijets. Both single-parton scattering (SPS) and double-parton scattering (DPS) contributions are calculated in the k_T-factorization approach. We have found regions of the phase space where the SPS contribution is negligible compared to the DPS one. The distribution in transverse momentum of charmed mesons as well as azimuthal correlations (D^0-*jet*, $D^0\overline{D^0}$) can be used for experimental identification of the DPS effects.

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1 Introduction

Charm particles, quarks and/or mesons, are produced abundantly in double- [1, 2, 3, 4, 5] or multiple- [6, 3] parton scattering. The cross section for double charm production was shown to grow considerably with the collision energy [1]. In our previous papers we have explained that the LHCb double charm data [7] cannot be explained without inclusion of double-parton scattering. Many processes in association with charm quarks or mesons are possible and can be studied at the LHC. Recently we discussed inclusive production of single jet associated with $c\overline{c}$ or charmed mesons [8]. Quite large cross sections were found there. This reaction was discussed in the presented talk, however will be not considered in the following due to the limited form of the proceedings contribution.

Here we discuss inclusive production of dijets in association with $c\overline{c}$ production. We wish to include both single parton scattering (SPS) and double parton scattering (DPS) mechanisms and check whether the process can be used to extract the so-called σ_{eff} parameter which governs the strength of double parton scattering. Therefore we need to focus on how to disantangle single and double parton scattering contributions for a simultaneous production of $c\overline{c}$ (or charmed mesons) and dijets.

2 Formalism

2.1 Single-parton scattering

Within the k_T-factorization approach [9] the SPS cross section for $pp \to c\overline{c} + 2\mathrm{jets}\, X$ reaction can be written as

$$d\sigma_{pp\to c\overline{c}+2\mathrm{jets}} = \sum_{ij} \int dx_1 \frac{d^2k_{1t}}{\pi} dx_2 \frac{d^2k_{2t}}{\pi} \mathcal{F}_i(x_1, k_{1t}^2, \mu^2) \mathcal{F}_j(x_2, k_{2t}^2, \mu^2) d\hat{\sigma}_{ij\to c\overline{c}+2\mathrm{part.}} \,. \quad (1)$$

In the formula above $\mathcal{F}_i(x, k_t^2, \mu^2)$ is a unintegrated parton distribution function (uPDF) for a given type of parton $i = g, u, d, s, \overline{u}, \overline{d}, \overline{s}$. The uPDFs depend on longitudinal momentum fraction x, transverse momentum squared k_t^2 of the partons entering the hard process, and in general also on a (factorization) scale of the hard process μ^2. The elementary cross section in Eq. (1) can be written somewhat formally as:

$$d\hat{\sigma}_{ij\to c\overline{c}+2\mathrm{part.}} = \prod_{l=1}^{4} \frac{d^3p_l}{(2\pi)^3 2E_l} (2\pi)^4 \delta^4(\sum_{l=1}^{4} p_l - k_1 - k_2) \times \frac{1}{\mathrm{flux}} \overline{|\mathcal{M}_{i^*j^*\to c\overline{c}+2\mathrm{part.}}(k_1, k_2)|^2} \,, \quad (2)$$

where E_l and p_l are energies and momenta of final state particles. Above only dependence of the matrix element on four-vectors of incident partons 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 partons entering the hard process are off-shell with virtualities $k_1^2 = -k_{1t}^2$ and $k_2^2 = -k_{2t}^2$. We take into account all 9 channels of the $2 \to 4$ type contributing to the cross section at the parton-level:

$$\begin{array}{lll} \#1 = g\, g \to g\, g\, c\, \overline{c} & \#2 = g\, g \to q\, \overline{q}\, c\, \overline{c} & \#3 = g\, q \to g\, q\, c\, \overline{c} \\ \#4 = q\, g \to q\, g\, c\, \overline{c} & \#5 = q\, \overline{q} \to q'\, \overline{q}'\, c\, \overline{c} & \#6 = q\, \overline{q} \to g\, g\, c\, \overline{c} \\ \#7 = q\, q \to q\, q\, c\, \overline{c} & \#8 = q\, q' \to q\, q'\, c\, \overline{c} & \#9 = q\, \overline{q} \to q\, \overline{q}\, c\, \overline{c}. \end{array}$$

The calculation has been performed with the help of KaTie [10], which is a complete Monte Carlo parton-level event generator for hadron scattering processes. It can can be applied to any arbitrary processes within the Standard Model, for many final-state particles, and for any initial-state partons on-shell or off-shell.

2.2 Double-parton scattering

According to the general form of the multiple-parton scattering theory (see *e.g.* Refs. [11, 12]) the DPS cross sections can be expressed in terms of the double parton distribution functions (dPDFs). These objects should fulfill sum rules and take into account all the correlations between the two partons. The theory of dPDFs is well established but still not fully applicable for phenomenological studies. Instead of the general form, one usually follows the assumption of the factorization of the DPS cross section. Within this framework, the differential DPS cross section for $pp \to c\bar{c} + 2\text{jets}\; X$ reaction can be expressed as follows:

$$\frac{d\sigma^{DPS}(c\bar{c} + 2\text{jets})}{d\xi_1 d\xi_2} = \sum_{i,j} \frac{1}{\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(gg \to c\bar{c})}{d\xi_1} \cdot \frac{\sigma^{SPS}(ij \to 2\text{jets})}{d\xi_2}, \tag{3}$$

where ξ_1 and ξ_2 stand for generic phase space kinematical variables for the first and second scattering, respectively. When integrating over kinematical variables one recovers the commonly used pocket-formula:

$$\sigma^{DPS}(c\bar{c} + 2\text{jets}) = \sum_{i,j} \frac{\sigma^{SPS}(gg \to c\bar{c}) \cdot \sigma^{SPS}(ij \to 2\text{jets})}{\sigma_{eff}} \,. \tag{4}$$

The effective cross section σ_{eff} provides a proper normalization of the DPS cross section and can be roughly interpreted as a measure of the transverse correlation of the two partons inside the hadrons. The longitudinal parton-parton correlations should become far less important as the energy of the collision is increased, due to the increase in the parton multiplicity. It is belived that for small-x partons and for low and intermediate scales the possible longitudinal correlations can be safely neglected (see *e.g.* Ref. [13]). In this paper we use world-average value of $\sigma_{eff} = 15$ mb provided by several experiments (see e.g. Refs. [14, 15]).

The cross sections for each step of the DPS mechanism are calculated in the k_T-factorization approach, that is:

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

$$\begin{aligned}\frac{d\sigma^{SPS}(pp \to 2\text{jets}\; X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} &= \frac{1}{16\pi^2 \hat{s}^2} \sum_{ij} \int \frac{d^2k_{3t}}{\pi} \frac{d^2k_{4t}}{\pi} \overline{|\mathcal{M}_{i^*j^* \to 2\text{part.}}|^2} \\ &\times\; \delta^2\left(\vec{k}_{3t} + \vec{k}_{4t} - \vec{p}_{3t} - \vec{p}_{4t}\right) \mathcal{F}_i(x_3, k_{3t}^2, \mu^2) \mathcal{F}_j(x_4, k_{4t}^2, \mu^2).\end{aligned} \tag{5}$$

The numerical calculations for both SPS mechanisms are also done within the KaTie code.

3 Numerical results

3.1 $D^0 + 2$jets

We start with the predictions for single D^0 meson production in association with exactly two jets. In this analysis, the D^0 meson is required to have $|y^{D^0}| < 2.5$ and $p_T^{D^0} > 3.5$ GeV and the rapidities of both associated jets are $|y^{jet}| < 4.9$, which corresponds to the ATLAS detector acceptance. In Table 1 we collect the corresponding integrated cross sections for inclusive $D^0 + 2$jets production in pp-scattering at $\sqrt{s} = 13$ TeV for different cuts on transverse momenta of the associated jets, specified in the left column. We found large cross sections, of the order of a few, and up to even tens of microbarns, depending on the cuts on transverse momenta of the associated jets. The cross sections are dominated by the DPS mechanism with the relative DPS contribution at the level of $70 - 80\%$.

In Fig. 1 we show the differential cross section as a function of transverse momenta of the D^0 meson (left panel) and as a function of the azimuthal angle $\varphi_{D^0\text{-}jet}$ between the D^0 meson ($\overline{D^0}$ antimeson) and the leading jet (right panel). The DPS (dashed line) and the SPS (dotted line) components are shown separately together with their sum (solid line). We observe that in the region of D^0 meson transverse momenta $p_T < 10$ GeV the DPS mechanism significantly dominates over the SPS one. We also see that the presence and the dominant role of the DPS component leads to a significant enhancement of the cross section and to a visible decorrelation of the azimuthal distribution in contrast to the pure SPS-based predictions. In the left panel we plot in addition the typical uncertainty bands of the pQCD calculations for both,

Table 1: The calculated cross sections in microbarns for inclusive D^0+2jets production in pp-scattering at $\sqrt{s} = 13$ TeV for different cuts on transverse momenta of the associated jets. Here, the D^0 meson is required to have $|y^{D^0}| < 2.5$ and $p_T^{D^0} > 3.5$ GeV and the rapidities of the both associated jets are $|y^{jet}| < 4.9$, which corresponds to the ATLAS detector acceptance.

experimental jet-p_T mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
both jets $p_T > 20$ GeV	3.74	18.49	83 %
$p_T^{lead} > 35$ GeV, $p_T^{sub} > 20$ GeV	1.76	4.52	72 %
$p_T^{lead} > 50$ GeV, $p_T^{sub} > 35$ GeV	0.43	1.25	74 %

the SPS and the DPS components. The shaded bands represent the uncertainties related to the choice of renormalization/factorization scales and charm quark mass, summed in quadrature. We vary the charm quark mass $m_c = 1.5 \pm 0.25$ GeV and the scales μ^2 by a factor 2, which is a rather standard procedure. The calculated uncertainties are about $\pm 45\%$ for the SPS and $\pm 65\%$ for the DPS mechanism. These levels of uncertainty also apply for the integrated cross sections.

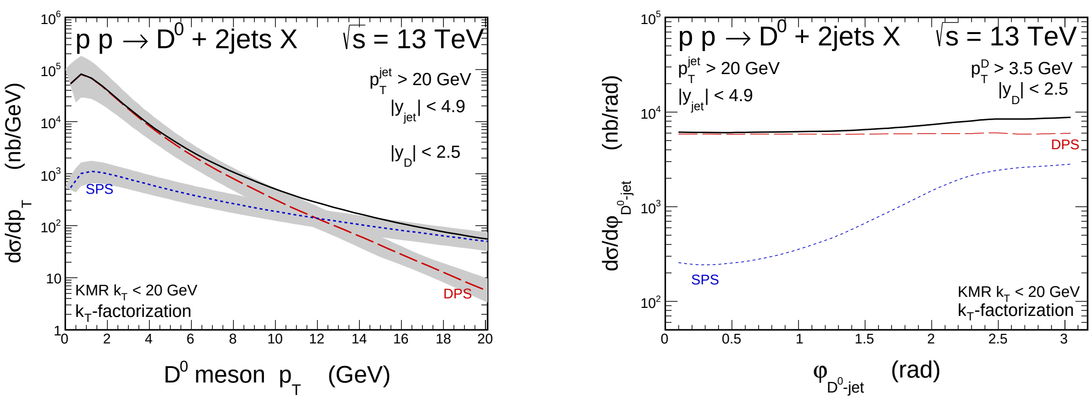

Figure 1: The transverse momentum (left) and azimuthal angle $\varphi_{D^0\text{-}jet}$ (right) distribution of the D^0 meson for SPS (dotted) and DPS (dashed) mechanisms for the ATLAS detector acceptance. The solid line represents a sum of the two components. Details are specified in the figure. For example in the left panel we show explicitly theoretical uncertainties, see discussion in the text.

3.2 $D^0\overline{D^0}$ + 2jets

Now we also consider the case of production of the $D^0\overline{D^0}$-pair in association with two jets. Both, D^0-meson and $\overline{D^0}$-antimeson are required to enter the ATLAS detector

Table 2: The same as in Table 1 but for inclusive $D^0\overline{D^0}$+2jets production. Here both, D^0 meson and $\overline{D^0}$ antimeson are required to enter the ATLAS detector acceptance.

experimental jet-p_T mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
both jets $p_T > 20$ GeV	1.10	2.35	68 %
$p_T^{lead} > 35$ GeV, $p_T^{sub} > 20$ GeV	0.55	0.58	51 %
$p_T^{lead} > 50$ GeV, $p_T^{sub} > 35$ GeV	0.15	0.14	52 %

acceptance. The corresponding theoretical cross sections are collected in Table 2. Here, the predicted cross sections for $D^0\overline{D^0}$ + 2jets are slightly smaller than in the case of D^0 + 2jets production (see Table 1) but still large (in the best scenario, of the order of a few microbarns). Also the relative DPS contribution is somewhat reduced and varies at the level of $50 - 70\%$.

In the case of the $D^0\overline{D^0}$+2jets final state we also find a very interesting correlation observable that may be useful to distinguish between the DPS and SPS mechanisms. Figure 2 presents the distributions in azimuthal angle $\varphi_{D^0\overline{D^0}}$ between the D^0 meson and $\overline{D^0}$ antimeson in the case of $D^0\overline{D^0}$+2jets production. One can observe an evident enhancement of the cross section in the region of $\varphi_{D^0\overline{D^0}} > \frac{\pi}{2}$ caused by the presence of the DPS mechanism.

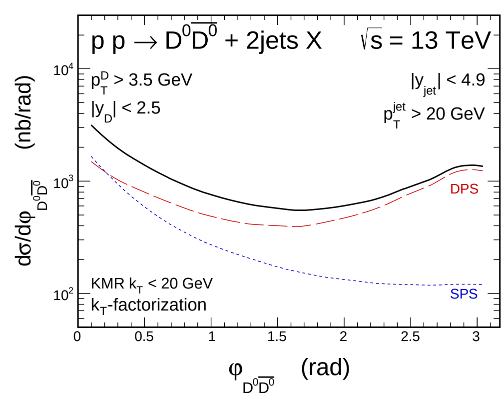

Figure 2: The azimuthal angle $\varphi_{D^0\overline{D^0}}$ distribution for SPS (dotted) and DPS (dashed) mechanisms for the ATLAS detector acceptance. The solid line represents a sum of the two components. Details are specified in the figure.

More details can be found in our original paper [16].

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