

New single- and double-parton scattering mechanisms for double charmed meson production

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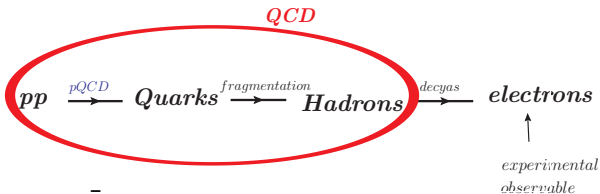
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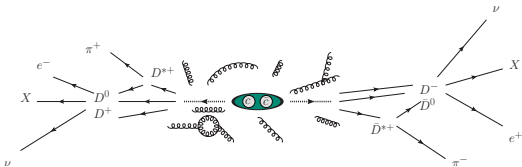


3-step process



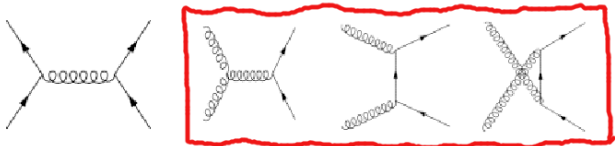
- 1 Heavy quarks $Q\bar{Q}$ pairs production
 - $m_c = 1.5 \text{ GeV}, m_b = 4.75 \text{ GeV} \rightarrow$ perturbative QCD
- 2 Heavy quarks hadronization (fragmentation)
- 3 Semileptonic decays of D and B mesons

$$\frac{d\sigma^e}{dyd^2p} = \frac{d\sigma^Q}{dyd^2p} \otimes D_{Q \rightarrow H} \otimes f_{H \rightarrow e}$$

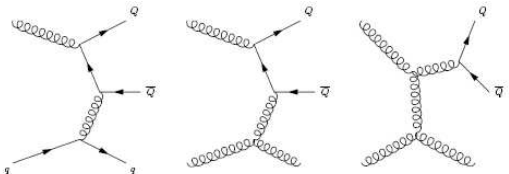


Dominant mechanisms of $Q\bar{Q}$ production

- Leading order processes contributing to $Q\bar{Q}$ production:

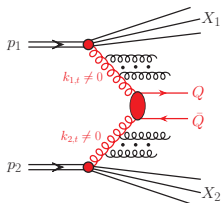


- gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ annihilation important only near the threshold
- some of next-to-leading order diagrams:



NLO contributions \rightarrow K-factor

k_T -factorization (semihard) approach



- charm and bottom quarks production at high energies
→ gluon-gluon fusion
- QCD collinear approach → only inclusive one particle distributions, total cross sections

LO k_T -factorization approach → $\kappa_{1,t}, \kappa_{2,t} \neq 0$
⇒ $Q\bar{Q}$ correlations

- multi-differential cross section

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{ij} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2(x_1 x_2 s)^2} \overline{|\mathcal{M}_{j \rightarrow Q\bar{Q}}|^2}$$

$$\times \delta^2(\bar{\kappa}_{1,t} + \bar{\kappa}_{2,t} - \bar{p}_{1,t} - \bar{p}_{2,t}) F_i(x_1, \kappa_{1,t}^2) F_j(x_2, \kappa_{2,t}^2)$$

- off-shell $\overline{|\mathcal{M}_{gg \rightarrow Q\bar{Q}}|^2}$ → Catani, Ciafaloni, Hautmann (rather long formula)
- major part of **NLO corrections automatically included**
- $F_i(x_1, \kappa_{1,t}^2), F_j(x_2, \kappa_{2,t}^2)$ - unintegrated parton distributions

- $x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2),$

$$x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2), \quad \text{where } m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}.$$



Unintegrated parton distribution functions

- k_T -factorization \rightarrow replacement: $p_k(x, \mu_F^2) \rightarrow \mathcal{F}_k(x, \kappa_T^2, \mu_F^2)$
- PDFs \rightarrow UPDFs

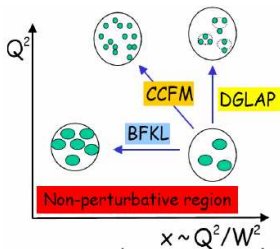
$$xp_k(x, \mu_F^2) = \int_0^\infty d\kappa_T^2 \mathcal{F}(x, \kappa_T^2, \mu_F^2)$$

- UPDFs - needed in less inclusive measurements which are sensitive to the transverse momentum of the parton

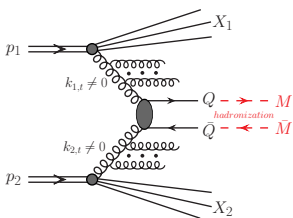
gg-fusion dominance \Rightarrow **great test of existing unintegrated gluon densities!**
 especially at LHC (small- x)

several models:

- Jung, Kwiecinski (CCFM, wide x -range)
- Kimber-Martin-Ryskin (higher x -values)
- Kutak-Stasto (small- x , saturation effects)
- Ivanov-Nikolaev, GBW, Karzeev-Levin, etc.



Fragmentation functions technique



- fragmentation functions extracted from e^+e^- data
- often used: Braaten et al., Kartvelishvili et al., Peterson et al.
- rescaling transverse momentum at a constant rapidity (angle)

- from heavy quarks to heavy mesons:

$$\frac{d\sigma(y, p_t^M)}{dyd^2p_t^M} \approx \int \frac{D_{Q \rightarrow M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dyd^2p_t^Q} dz$$

where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

- **approximation:**

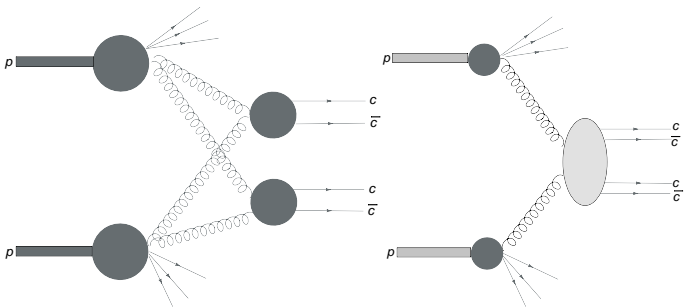
rapidity unchanged in the fragmentation process $\rightarrow y_Q \approx y_M$

Production of D mesons in this framework:

Maciula, Szczurek, Phys. Rev. **D87** (2013) 094022.



Production of $c\bar{c}c\bar{c}$



Łuszczak, Maciuła, Szczurek, Phys. Rev. **D85** (2012) 014905.



Formalism

Consider reaction: $pp \rightarrow c\bar{c}c\bar{c}X$

Modeling double-parton scattering

Factorized form:

$$\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}} \sigma^{SPS}(pp \rightarrow c\bar{c}X_1) \cdot \sigma^{SPS}(pp \rightarrow c\bar{c}X_2).$$

The simple formula can be generalized to include differential distributions

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

σ_{eff} is a model parameter (15 mb).

Found e.g. from experimental analysis of four jets (see also [Siódmok et al](#))

In principle does not need to be universal.



Formalism

$$d\sigma^{DPS} = \frac{1}{2\sigma_{\text{eff}}} F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2) F_{gg}(x'_1, x'_2, \mu_1^2, \mu_2^2) d\sigma_{gg \rightarrow c\bar{c}}(x_1, x'_1, \mu_1^2) d\sigma_{gg \rightarrow c\bar{c}}(x_2, x'_2, \mu_2^2) dx_1 dx_2 dx'_1 dx'_2.$$

$$F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2), F_{gg}(x'_1, x'_2, \mu_1^2, \mu_2^2)$$

are called **double parton distributions**

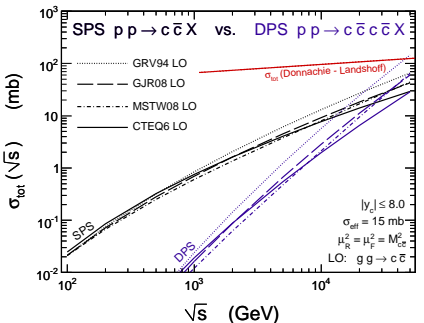
dPDF are subjected to special **evolution equations**

single scale evolution: **Snigirev**

double scale evolution: **Ceccopieri, Gaunt-Stirling**



Energy dependence of $c\bar{c}c\bar{c}$ production



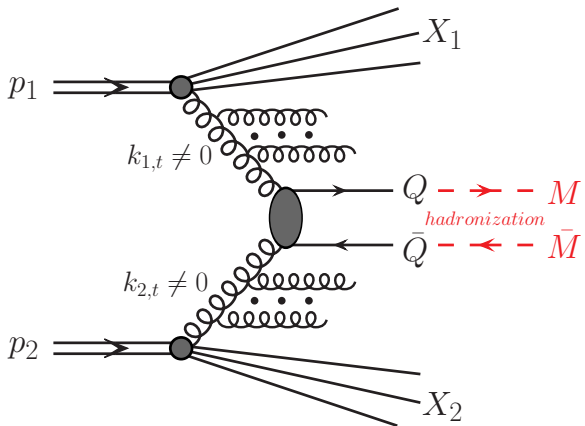
Luszczak, Maciula, Szczurek, Phys. Rev. **C86** (2012) 014905

spectacular result:

Already at the LHC production of two pairs as probable as production of one pair.

DPS in k_T -factorization

each step:



DPS in k_T -factorization

Generalize the **LO collinear** approach to
 k_T -factorization approach.

More complicated (**more kinematical variables**) as momenta of outgoing partons are less correlated

We need information about each quark and antiquark

$$\frac{1}{2\sigma_{\text{eff}}} \cdot \frac{\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}}}{d\sigma} \cdot \frac{\frac{d\sigma}{dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}}}{d\sigma} = \quad (1)$$



DPS in k_T -factorization

Each individual scattering in the k_T -factorization approach

$$\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int |\overline{\mathcal{M}}_{\text{off}}|^2 \delta(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2) \frac{d^2 k_{1t}}{\pi} \frac{d^2 k_{2t}}{\pi}$$

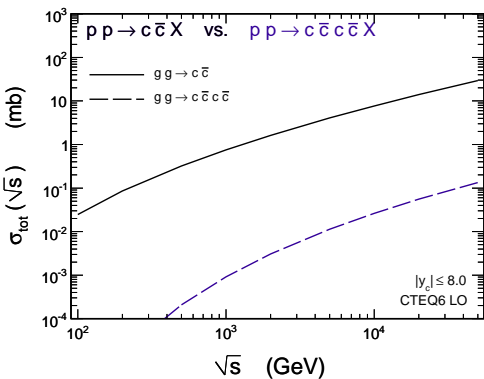
$$\frac{d\sigma}{dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int |\overline{\mathcal{M}}_{\text{off}}|^2 \delta(\vec{k}_{3t} + \vec{k}_{4t} - \vec{p}_{3t} - \vec{p}_{4t}) \mathcal{F}(x_3, k_{3t}^2, \mu^2) \mathcal{F}(x_4, k_{4t}^2, \mu^2) \frac{d^2 k_{3t}}{\pi} \frac{d^2 k_{4t}}{\pi}$$

Effectively 16 dimensions, Monte Carlo method

Maciula, Szczurek, hep-ph-1301.4469, Phys. Rev. **D87** (2013) 074039.



Single parton scattering $2 \rightarrow 4$ process?

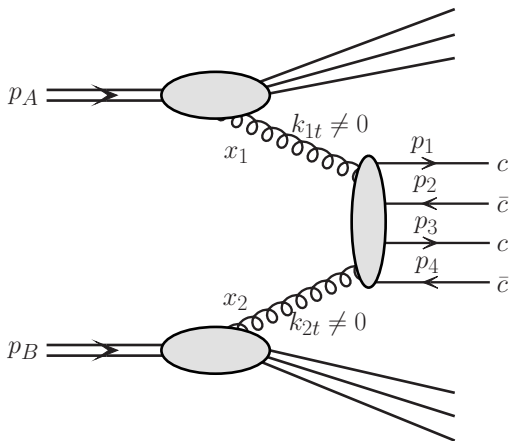


Only about 1 % at high energies

Much smaller than DPS production of $c\bar{c}c\bar{c}$



SPS in k_t -factorization approach



include gluon transverse momenta

A. van Hameren, R. Maciula and A. Szczurek,

arXiv:1504.06490, Phys. Lett. **B748** (2015) 737.



Basic formulae

Within the k_T -factorization approach the SPS cross section for $pp \rightarrow c\bar{c}c\bar{c}X$ reaction can be written as

$$d\sigma_{pp \rightarrow c\bar{c}c\bar{c}} = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi} \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2) d\hat{\sigma}_{gg \rightarrow c\bar{c}c\bar{c}} \quad (2)$$

The elementary cross section in Eq. (2) can be written somewhat formally as:

$$d\hat{\sigma} = \frac{d^3 p_1}{2E_1(2\pi)^3} \frac{d^3 p_2}{2E_2(2\pi)^3} \frac{d^3 p_3}{2E_3(2\pi)^3} \frac{d^3 p_4}{2E_4(2\pi)^3} (2\pi)^4 \delta^4(p_1 + p_2 + p_3 + p_4 - k_1 - k_2) \times \frac{1}{\text{flux}} |\overline{\mathcal{M}_{g^*g^* \rightarrow c\bar{c}c\bar{c}}(k_1, k_2)}|^2, \quad (3)$$

where only dependence of the matrix element on four-vectors of gluons k_1 and k_2 is made explicit.



Matrix element squared

Denoting by \mathcal{M}^a the amplitude with the color of one off-shell gluon highlighted explicitly we have

$$\sum_a |\mathcal{M}^a|^2 = \sum_a \left| \sqrt{2} \sum_{i,j} \mathcal{M}_{ij} T_{ij}^a \right|^2 = \sum_{i,j,k,l} \mathcal{M}_{ij} \mathcal{M}_{kl}^* \left(\delta_{ik} \delta_{lj} - \frac{1}{N_c} \delta_{ij} \delta_{kl} \right) = \sum_{i,j} |\mathcal{M}_{ij}|^2 \quad (4)$$

Matrix element squared with **off-shell initial gluons** calculated with an **automated code** of **A. van Hameren**

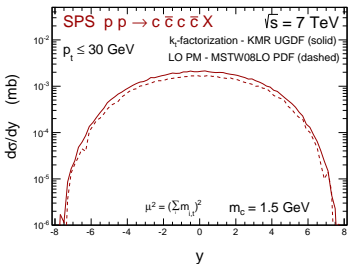
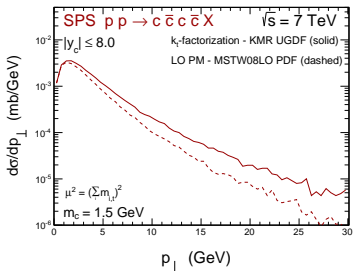
(Dyson-Schwinger recursion method, JHEP. 01 (2013) 078.)

Spinor helicity representation

Monte Carlo generation of events and constructing distributions from the kinematically complete weighted events



Results for k_T -factorization approach



$$\mu_f^2 = \left(\sum_i^4 m_{i,t} \right)^2$$

k_T -factorization and collinear results similar



Results for k_T -factorization approach

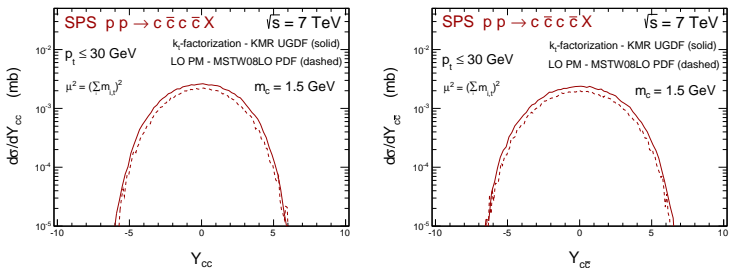


Figure: $Y_{cc} = (y_c + y_{\bar{c}})/2$ (left panel) and $Y_{c\bar{c}} = (y_c + y_{\bar{c}})/2$ (right panel).

$$\mu_f^2 = \left(\sum_i^4 m_{i,t} \right)^2$$

k_T -factorization and collinear results similar



Results for k_T -factorization approach

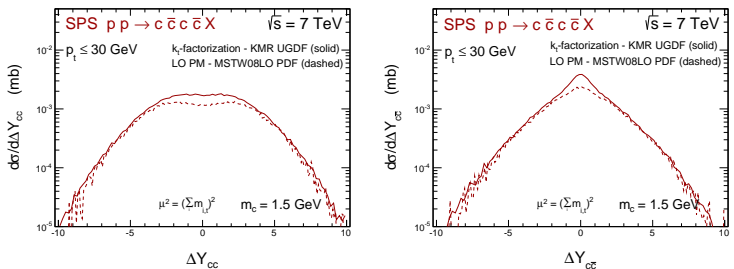


Figure: $\Delta Y_{cc} = y_c - y_{\bar{c}}$ (left panel) and $\Delta Y_{c\bar{c}} = y_c - y_{\bar{c}}$ (right panel).

$$\mu_f^2 = \left(\sum_i^4 m_{i,t} \right)^2$$



Results for k_T -factorization approach

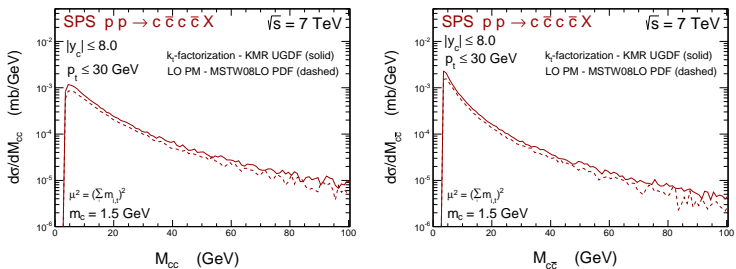


Figure: M_{cc} (left panel) and $M_{c\bar{c}}$ (right panel).

$$\mu_f^2 = \left(\sum_i^4 m_{i,t} \right)^2$$



Results for k_T -factorization approach

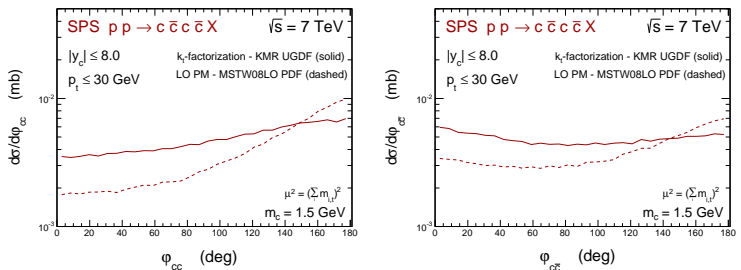


Figure: Azimuthal angle correlations between two c quarks (left panel) and between c and \bar{c} (right panel).

$$\mu_f^2 = \left(\sum_i^4 m_{i,t} \right)^2$$

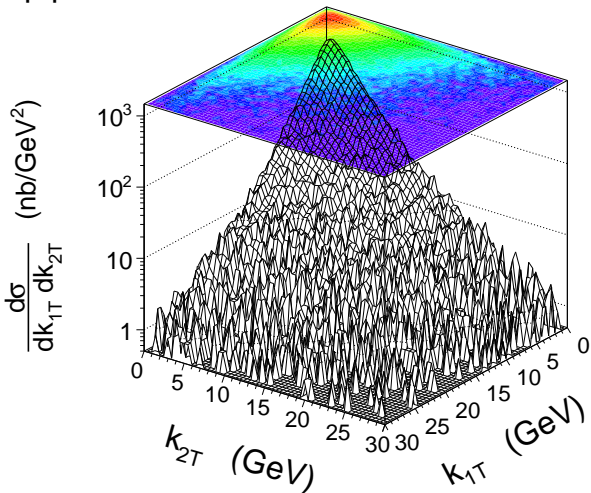
k_T -factorization gives more decorrelation than collinear-factorization



Results for k_T -factorization approach

$$p p \rightarrow c \bar{c} c \bar{c} X$$

$$\sqrt{s} = 7 \text{ TeV}$$



Results for k_T -factorization approach

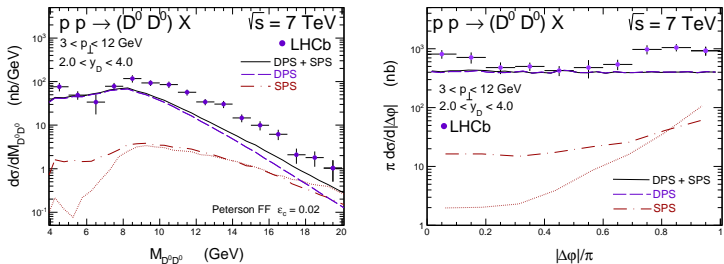
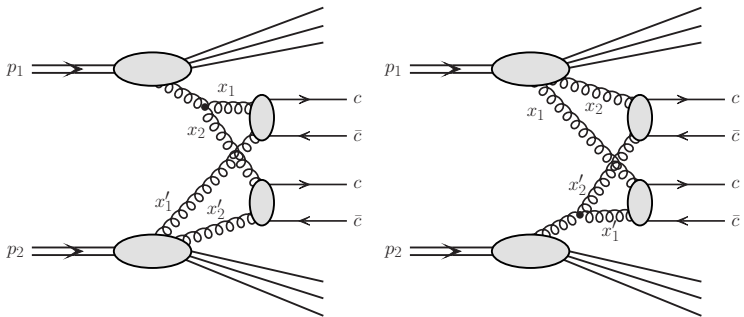


Figure: Distributions in $D^0 D^0$ invariant mass (left) and in azimuthal angle between both D^0 's (right) within the LHCb acceptance. The DPS contribution (dashed line) and the SPS contribution within the k_T -factorization approach (dashed-dotted line). The collinear SPS result from our previous studies (dotted line).



Parton splitting mechanism

There are perturbative mechanisms not included in **conventional DPS**.



Gaunt, Maciuła, Szczurek, Phys. Rev. **D90** (2014) 054017.



A bit of formalism for parton splitting

Conventional DPS:

$$\sigma(2v2) = \frac{1}{2} \frac{1}{\sigma_{\text{eff},2v2}} \int dy_1 dy_2 d^2 p_{1\perp} dy_3 dy_4 d^2 p_{2\perp} \frac{1}{16\pi\hat{s}^2} \overline{|\mathcal{M}(gg \rightarrow c\bar{c})|^2} x_1 x'_1 x_2 x'_2 \times D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2) D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2)$$

Parton splitting DPS

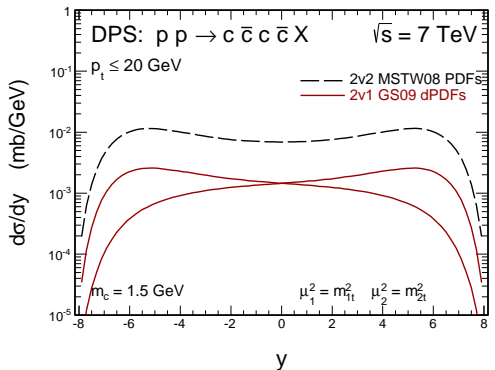
$$\sigma(2v1) = \frac{1}{2} \frac{1}{\sigma_{\text{eff},2v1}} \int dy_1 dy_2 d^2 p_{1\perp} dy_3 dy_4 d^2 p_{2\perp} \frac{1}{16\pi\hat{s}^2} \overline{|\mathcal{M}(gg \rightarrow c\bar{c})|^2} x_1 x'_1 x_2 x'_2 \times \left(\hat{D}^{gg}(x'_1, x'_2, \mu_1^2, \mu_2^2) D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2) + D^{gg}(x'_1, x'_2, \mu_1^2, \mu_2^2) \hat{D}^{gg}(x_1, x_2, \mu_1^2, \mu_2^2) \right)$$

There are two different normalization parameters. They are related in a geometrical picture.

Presence of the two components leads to a dependence of effective parameter on different kinematical variables.



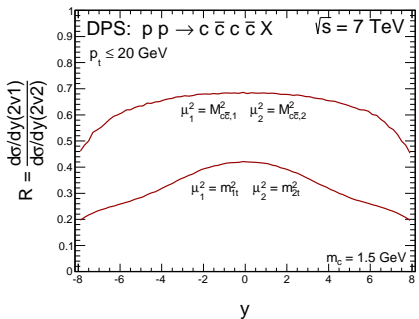
Parton splitting vs conventional DPS



Asymmetric 1v2 and 2v1 contributions



Parton splitting vs conventional DPS

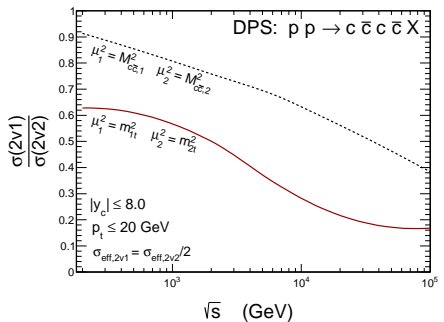


Rapidity and factorization scale dependence

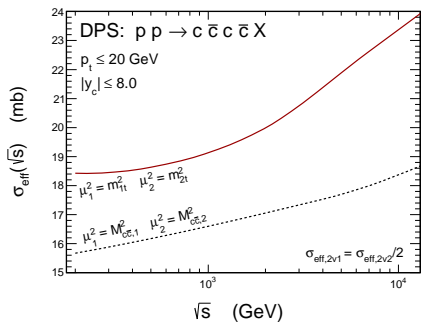
There could be also transverse momentum dependence.



Parton splitting vs conventional DPS



Parton splitting vs conventional DPS



σ_{eff} is no longer a constant



Gluon fragmentation to D mesons

- **Kniesl and Kramer** discussed several fragmentation of a parton (gluon, $u, d, s, \bar{u}, \bar{d}, \bar{s}, c, \bar{c}$) to D mesons
- Important contribution to inclusive production of D mesons in $p\bar{p}$ collisions comes from $g \rightarrow D$ (**Kniesl, Kramer, Schienbein, Spiesberger**)
- Similar calculation in k_T -factorization by **Karpishkov, Nefedov, Saleev, Shipilova, 2015**.
Good description of D meson transverse momentum distributions at the LHC (similar to **Maciula, Szczurek**).
- What are consequences of the "new" mechanism for **double D meson production**?
(with **Maciula, Saleev and Shipilova** - submitted to Phys. Lett. B).



DGLAP evolution of fragmentation functions

Fragmentation functions fulfill the DGLAP equation:

$$\frac{d}{d\ln\mu_f^2} D_a(x, \mu_f) = \frac{a_s(\mu)}{2\pi} \sum_b \int_x^1 \frac{dy}{y} P_{a \rightarrow b}^T(y, a_s(\mu)) D_b\left(\frac{x}{y}, \mu_f\right).$$

where $a = g, u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}$

Initial conditions:

$$D_c(z, \mu_0^2) = N_c \frac{z(1-z)^2}{((1-z) + \epsilon)^2}$$
$$D_g(z, \mu_0^2) = 0.$$

In our case we will take: $\mu^2 = m_f^2$

Fragmentation functions fitted (with **massless** DGLAP evolution) to e^+e^- data
(with **mass effects** in the cross section)

A consequence of the evolution is a **much smaller contribution of**
 $gg \rightarrow c\bar{c} \rightarrow D$ mechanism at intermediate and large p_T
and **appearance of new terms.**



Single D meson production

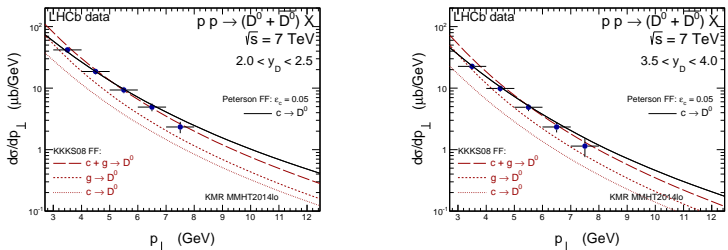


Figure: Left and right panels correspond to **two different rapidity intervals**. The Peterson $c \rightarrow D$ FF (solid lines) are compared to the second scenario calculations with the KKKs08 FF (long-dashed lines) with $c \rightarrow D$ (dotted) and $g \rightarrow D$ (short-dashed) components that undergo DGLAP evolution equation.

discussed in details in talk by Anton Karpishkkov at DIS2016

Both methods describe the existing data



New mechanisms

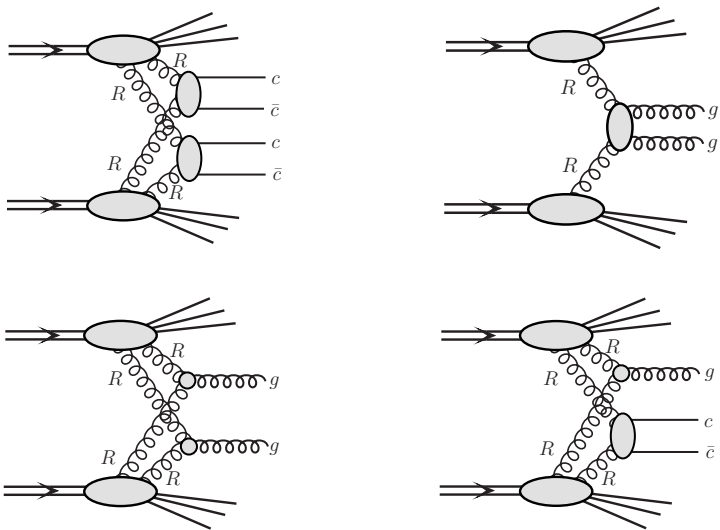


Figure: A diagrammatic illustration of the considered mechanisms. ▶

List of mechanisms for double D meson production

- our old mechanism:

$$(gg \rightarrow c\bar{c}) \otimes (gg \rightarrow c\bar{c})$$

and double fragmentation $c \rightarrow D$ or $\bar{c} \rightarrow \bar{D}$

with fragmentation functions with DGLAP evolution.

- a new SPS mechanism:

$$gg \rightarrow g(\rightarrow D)g(\rightarrow D)$$

possible correlations in azimuth or $p_{t, \text{pair}}$.

Makes the previous extractions of σ_{eff} from the LHCb data invalid!

- a new mixed DPS mechanisms:

$$(gg \rightarrow g) \otimes (gg \rightarrow c\bar{c}) \text{ or}$$

$$(gg \rightarrow c\bar{c}) \otimes (gg \rightarrow c)$$

followed by $g \rightarrow D/\bar{D}$ and $c \rightarrow D$ or $\bar{c} \rightarrow \bar{D}$ fragmentation functions with DGLAP evolution.

- a new DPS mechanism: $(gg \rightarrow g) \otimes (gg \rightarrow g)$

followed by $g \rightarrow D, \bar{D}$ fragmentation with fragmentation function with

DGLAP evolution.

DPS parton production mechanisms

DPS production of cc or gg system, assuming factorization of the DPS model:

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

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

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



SPS parton production mechanisms

In the k_T -factorization approach, the cross section for relevant SPS cross sections:

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

$$\frac{d\sigma^{SPS}(pp \rightarrow ggX)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{16\pi^2(x_1 x_2 S)^2} \int \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi} \overline{|\mathcal{M}_{RR \rightarrow gg}|^2} \\ \times \delta^2(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2),$$

$$\frac{d\sigma^{SPS}(pp \rightarrow gX)}{dy d^2p_t} = \frac{\pi}{(x_1 x_2 S)^2} \int \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi} \overline{|\mathcal{M}_{RR \rightarrow g}|^2} \\ \times \delta^2(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_t) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2).$$



Fragmentation

In order to calculate correlation observables for two mesons we follow the fragmentation function technique for hadronization process:

$$\begin{aligned} \frac{d\sigma_{cc}^{DPS}(pp \rightarrow DDX)}{dy_1 dy_2 d^2 p_{1t}^D d^2 p_{2t}^D} &= \int \frac{D_{c \rightarrow D}(z_1)}{z_1} \cdot \frac{D_{c \rightarrow D}(z_2)}{z_2} \cdot \frac{d\sigma^{DPS}(pp \rightarrow ccX)}{dy_1 dy_2 d^2 p_{1t}^c d^2 p_{2t}^c} dz_1 dz_2 \\ &+ \int \frac{D_{g \rightarrow D}(z_1)}{z_1} \cdot \frac{D_{g \rightarrow D}(z_2)}{z_2} \cdot \frac{d\sigma^{DPS}(pp \rightarrow ggX)}{dy_1 dy_2 d^2 p_{1t}^g d^2 p_{2t}^g} dz_1 dz_2 \\ &+ \int \frac{D_{g \rightarrow D}(z_1)}{z_1} \cdot \frac{D_{c \rightarrow D}(z_2)}{z_2} \cdot \frac{d\sigma^{DPS}(pp \rightarrow gcX)}{dy_1 dy_2 d^2 p_{1t}^g d^2 p_{2t}^c} dz_1 dz_2 \end{aligned}$$

where: $p_{1t}^{g,c} = \frac{p_{1t}^D}{z_1}$, $p_{2t}^{g,c} = \frac{p_{2t}^D}{z_2}$ and meson longitudinal fractions $z_1, z_2 \in (0, 1)$.

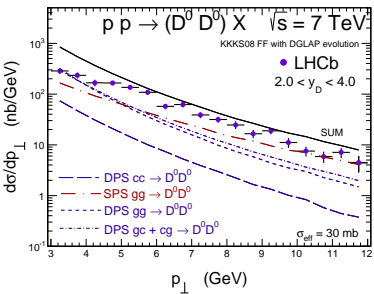
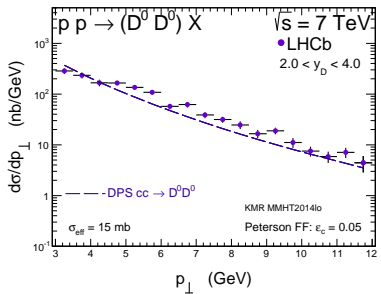
For SPS DD -production via digluon fragmentation:

$$\frac{d\sigma_{gg}^{SPS}(pp \rightarrow DDX)}{dy_1 dy_2 d^2 p_{1t}^D d^2 p_{2t}^D} \approx \int \frac{D_{g \rightarrow D}(z_1)}{z_1} \cdot \frac{D_{g \rightarrow D}(z_2)}{z_2} \cdot \frac{d\sigma^{SPS}(pp \rightarrow ggX)}{dy_1 dy_2 d^2 p_{1t}^g d^2 p_{2t}^g} dz_1 dz_2$$

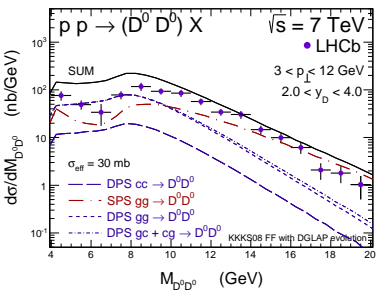
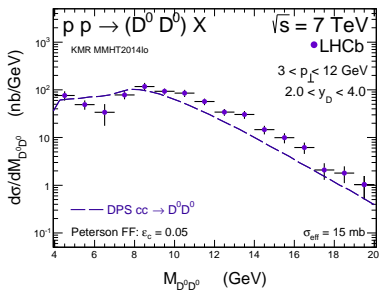
where: $p_{1t}^g = \frac{p_{1t}^D}{z_1}$, $p_{2t}^g = \frac{p_{2t}^D}{z_2}$ and meson longitudinal fractions $z_1, z_2 \in (0, 1)$.



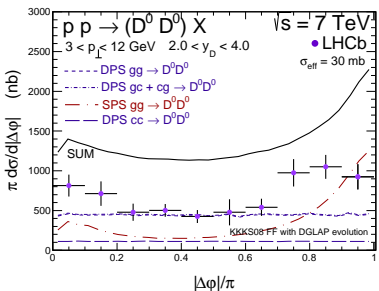
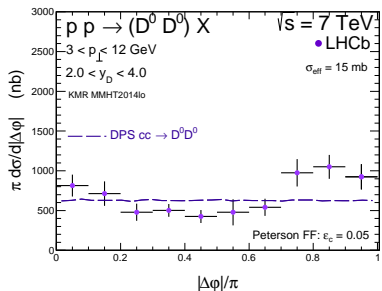
First results in the new approach



First results in the new approach



First results in the new approach



Potential problems

We get much too much.

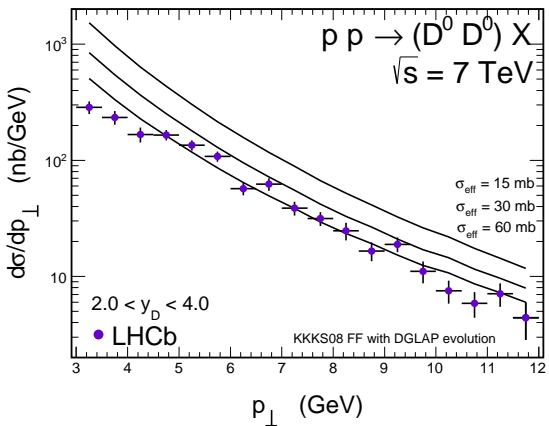
What can be a reason:

- Massless DGLAP evolution ?
- Different (bigger) σ_{eff} ?
- Low- x (nonlinear) effects ?
- High- x effects ?
- All of them ?

Below we will address some of them



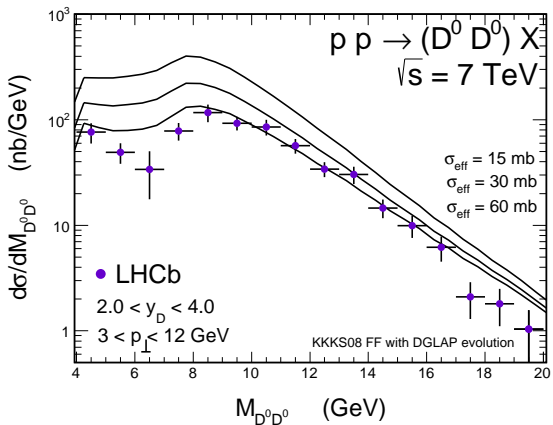
Larger σ_{eff}



$\sigma_{\text{eff}} = 60 \text{ mb}$ describes the data



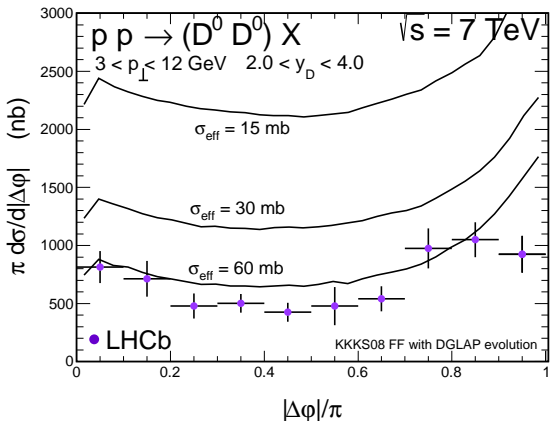
Larger σ_{eff}



$\sigma_{\text{eff}} = 60 \text{ mb}$ describes the data



Larger σ_{eff}



$\sigma_{\text{eff}} = 60 \text{ mb}$ describes the data



Conclusions

- k_T -factorization provides good description of charm production at RHIC and LHC.
- Surprisingly large cross sections for inclusive $c\bar{c}c\bar{c}$ due to DPS.
- Relatively small cross sections for SPS $c\bar{c}c\bar{c}$.
- **Multiple $c\bar{c}$ pairs** can be produced in p p collisions at the LHC and FCC.
- Look at correlations between **same flavour charmed mesons** such as D^0D^0 .
- Look at correlations between $e^+\mu^+$ or $e^-\mu^-$ from semileptonic decays (ALICE, CMS).
- **Enhancement of the number of $c\bar{c}$ pairs in AA collisions**
 - important for recombination/coalescence
 - further **enhancement of hidden-charm meson production** ($J/\psi, \psi'$) at higher energies.



Conclusion, continued

- Gluon fragmentation changes the picture.
- Several new contributions (both DPS and SPS)
- $d\sigma/d\phi_{DD} \neq \text{const}$
Difficult to get it from DPS mechanisms (Echevarria, Kasemets, Mulders, Pisano) as spin correlations.
- Too big $D^0\bar{D}^0$ cross section with canonical value $\sigma_{\text{eff}} = 15$ mb.
- Possible solutions:
 - larger σ_{eff} (good reasons) (larger rapidity)
 - wrong small-x UGDF, saturation? (strong effect)
 - wrong large-x UGDF ?
 - problems with massless evolution of FF ?
- We can describe the LHCb data with strongly reduced σ_{eff} and strongly modified low-x glue. Are the strong low-x modifications consistent with other processes?

