Different aspects of charm production

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Faces of QCD

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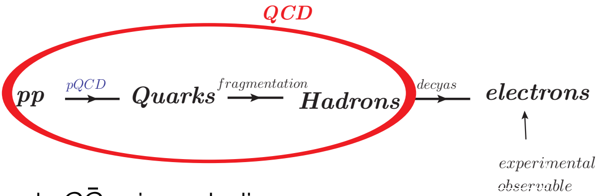
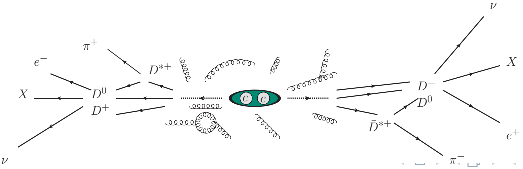
3-step process



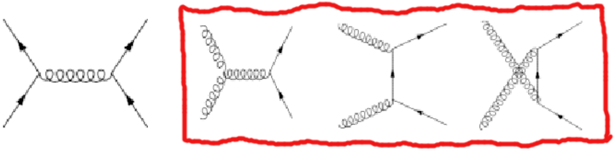
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

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

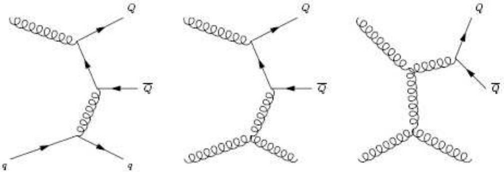


Dominant mechanisms of $Q\bar{Q}$ production

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

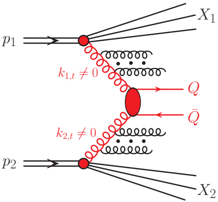


- **gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ anihilation important only near the threshold
- some of next-to-leading order diagrams:



NLO contributions $\longrightarrow$ K-factor

k_t-factorization (semihard) approach



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

LO k_t-factorization approach $\longrightarrow \kappa_{1,t}, \kappa_{2,t} \neq 0$
$\Rightarrow Q\bar{Q}$ correlations

- multi-differential cross section

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

- off-shell $\overline{|\mathcal{M}_{gg\to Q\bar{Q}}|^2} \longrightarrow$ Catani, Ciafaloni, Hautmann (rather long formula)
- major part of NLO corrections automatically included
- $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$, $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated parton distributions
- $x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$,

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

Unintegrated parton distribution functions

- k_t-factorization → replacement: $p_k(x, \mu_F^2) \longrightarrow \mathcal{F}_k(x, \kappa_t^2, \mu_F^2)$
- PDFs ⟶ UPDFs

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

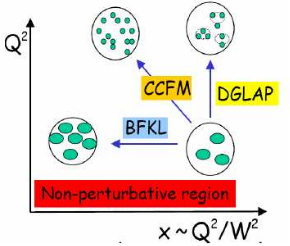
- UPDFs - needed in less inclusive measurements which are sensitive to the transverse momentum of the parton

gg-fusion dominance ⇒ great test of existing unintegrated gluon densities!

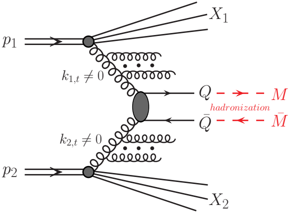
especially at LHC (small-x)

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.
- rescalling transverse momentum

  at a constant rapidity (angle)

- from heavy quarks to heavy mesons:

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

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

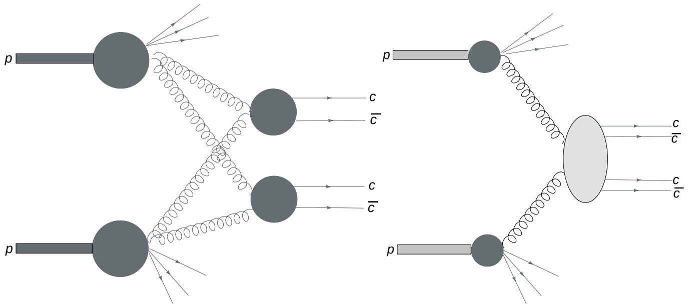
- **approximation:**

  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: $pp \to c\bar{c}c\bar{c}X$

Modeling double-parton scattering

Factorized form:

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

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

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

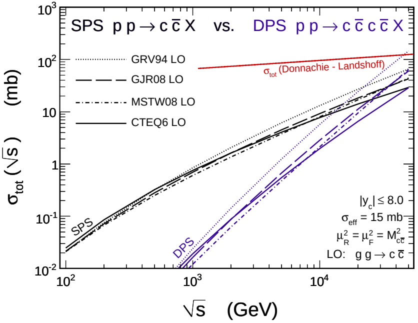
$F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2)$, $F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2)$
are called double parton distributions

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



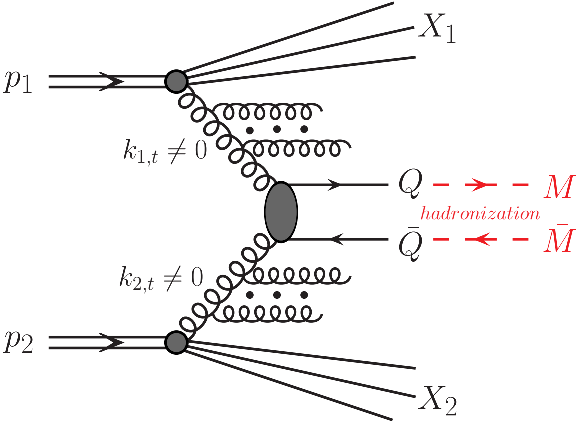
Luszczak, Maciula, Szczurek, Phys. Rev. **C86** (2012) 014905

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

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

DPS in k_t-factorization

Each individual scattering in the k_t-factorization approach

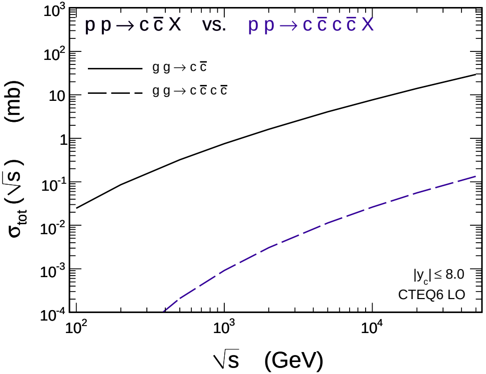
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \overline{|\mathcal{M}_{off}|^2} \delta\left(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}\right) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2) \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi}$$

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

Effectively 16 dimensions, Monte Carlo method

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

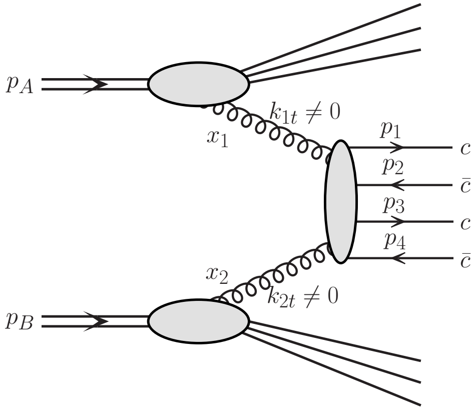
Single parton scattering $2 \to 4$ process?



Only about 1 % at high energies

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

SPS in k_t-factorization approach



W. Schäfer, A. Szczurek, Phys. Rev. **D85** (2012) 094029. (not all diagrams)

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 $pp \to c\bar{c}c\bar{c}X$ reaction can be written as

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

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

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

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 highlited explicitly we have

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

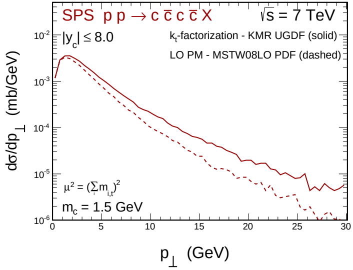
Matrix element squared with off-shell initial gluons calculated with an automated code of A. van Hameren

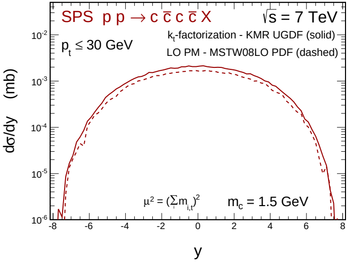
(Dyson-Schwinger recursion method, JHEP. 01 (2013) 078.)

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

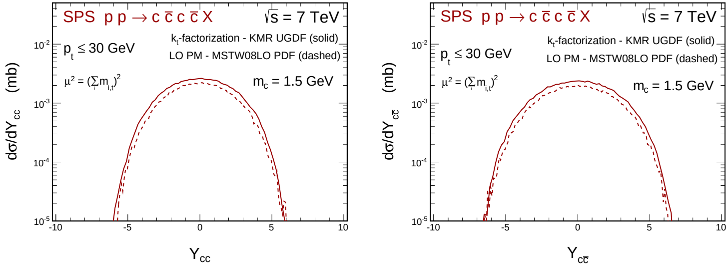


Figure: $Y_{cc} = (y_c + y_c)/2$ (left panel) and $Y_{c\bar{c}} = (y_c + y_{\bar{c}})/2$ (right panel).

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

k_t-factorization and collinear results similar

Results for k_t-factorization approach

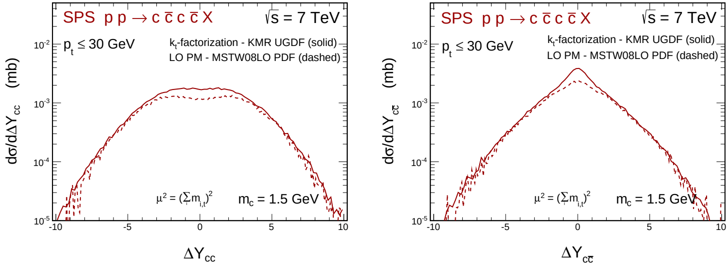


Figure: $\Delta Y_{cc} = y_c - y_c$ (left panel) and $\Delta Y_{c\bar{c}} = y_c - y_{\bar{c}}$ (right panel).

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

Results for k_t-factorization approach

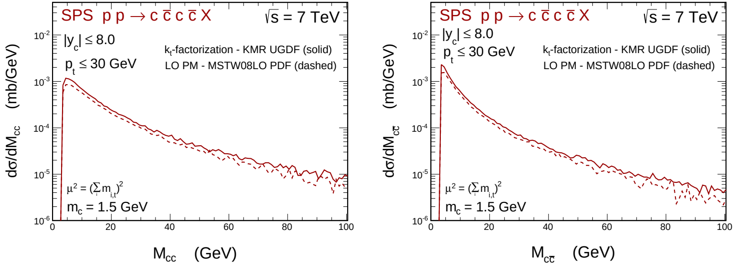


Figure: M_{cc} (left panel) and $M_{c\bar{c}}$ (right panel).

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

Results for k_t-factorization approach

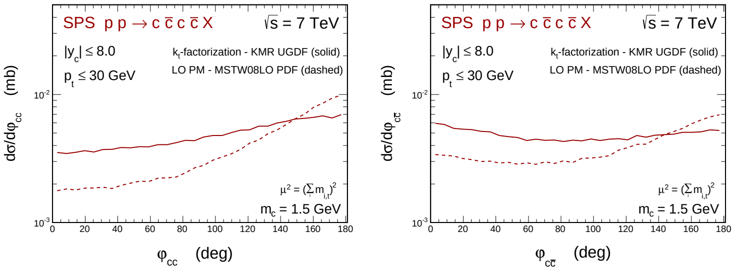
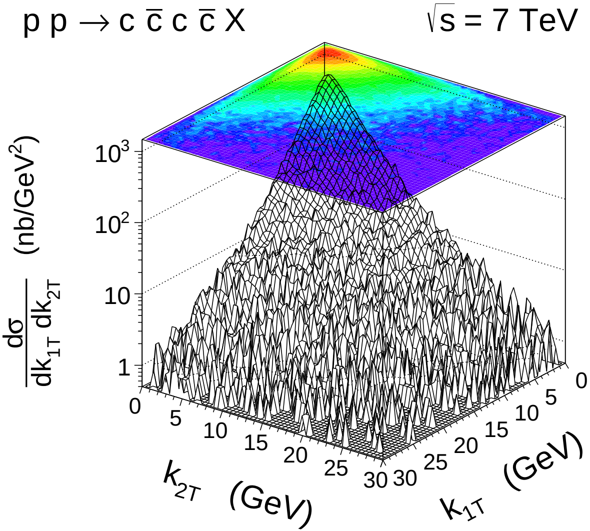


Figure: Azimuthal angle correlations between two c quarks (left panel) and between c and $\bar{c}$ (right panel).

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

k_t-factorization gives more decorrelation than collinar-factorization

Results for k_t-factorization approach



Results for k_t-factorization approach

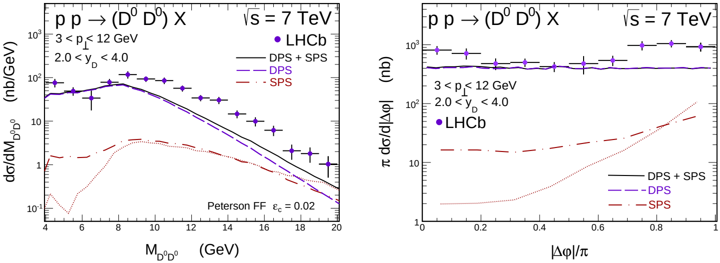
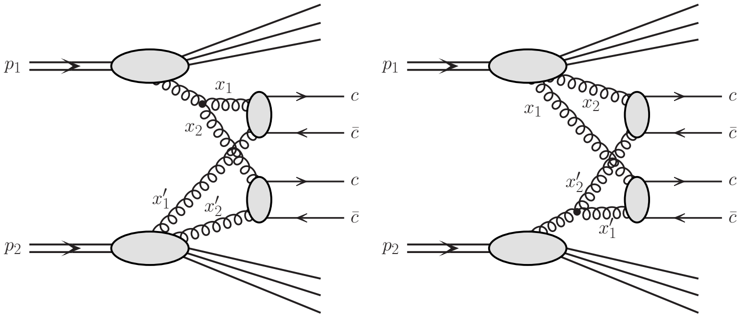


Figure: Distributions in D^0D^0 invariant mass (left) and in azimuthal angle between both D^0's (right) within the LHCb acceptance. The DPS contribution (dashed line) and the SPS contribution within the k_t-factorization approach (dashed-dotted line). The collinear SPS result from our previous studies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

$$\sigma(2v2) = \frac{1}{2}\frac{1}{\sigma_{eff,2v2}} \int dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t} \frac{1}{16\pi \hat{s}^2} \overline{|\mathcal{M}(gg \to c\bar{c})|^2}\, x_1 x_1' x_2 x_2' \times D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2)\, D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2) \quad (5)$$

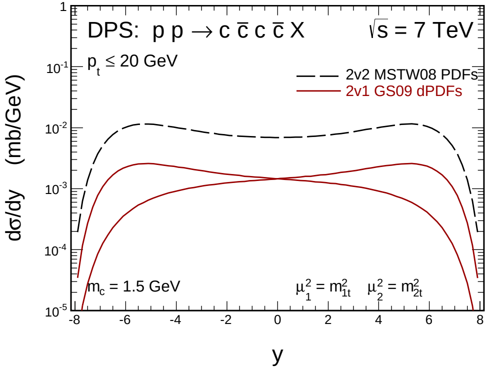
Parton splitting DPS

$$\sigma(2v1) = \frac{1}{2}\frac{1}{\sigma_{eff,2v1}} \int dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t} \frac{1}{16\pi \hat{s}^2} \overline{|\mathcal{M}(gg \to c\bar{c})|^2}\, x_1 x_1' x_2 x_2' \times \Big(\hat{D}^{gg}(x_1', x_2', \mu_1^2, \mu_2^2) D^{gg}(x_1, x_2, \mu_1^2, \mu_2^2) + D^{gg}(x_1', x_2', \mu_1^2, \mu_2^2) \hat{D}^{gg}(x_1, x_2, \mu_1^2 \ldots$$

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

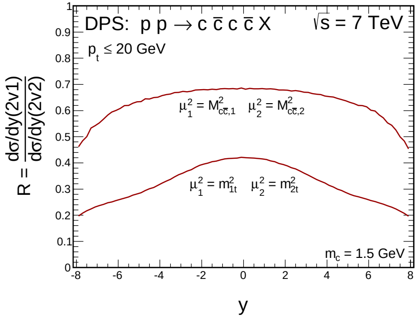
Presence of the two components leads to a dependence of effective parameter on different kinematical variables.

Parton splitting vs conventional DPS



Asymmetric $1v2$ and $2v1$ contributions

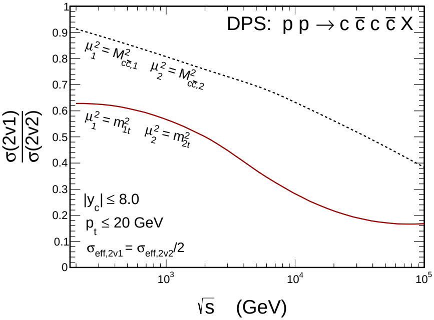
Parton splitting vs conventional DPS



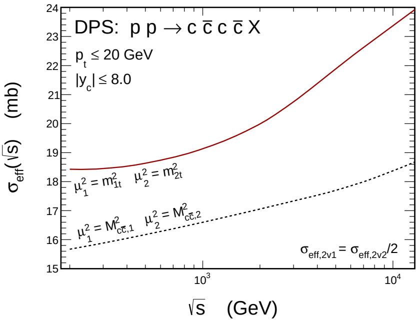
Rapidity and factorization scale dependence

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

- Kniehl 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 $g \to D$ (Kniehl, 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?
  (Maciula, Saleev, Shipilova, Szczurek - Phys. Lett. **B758** (2016) 458.)

DGLAP evolution of fragmentation functions

Fragmentation functions fulfill the DGLAP equation:

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

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: $\mu^2 = m_t^2$

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 $gg \to c\bar{c} \to D$ mechanism at intermediate and large p_t and appearence of new terms.

Single D meson production

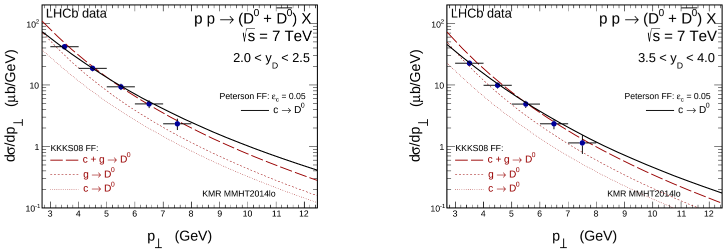


Figure: Left and right panels correspond to two different rapidity intervals. The Peterson $c \longrightarrow D$ FF (solid lines) are compared to the second scenario calculations with the KKKS08 FF (long-dashed lines) with $c \longrightarrow D$ (dotted) and $g \longrightarrow D$ (short-dashed) components that undergo DGLAP evolution equation.

Both methods describe inclusive D meson data

New mechanisms

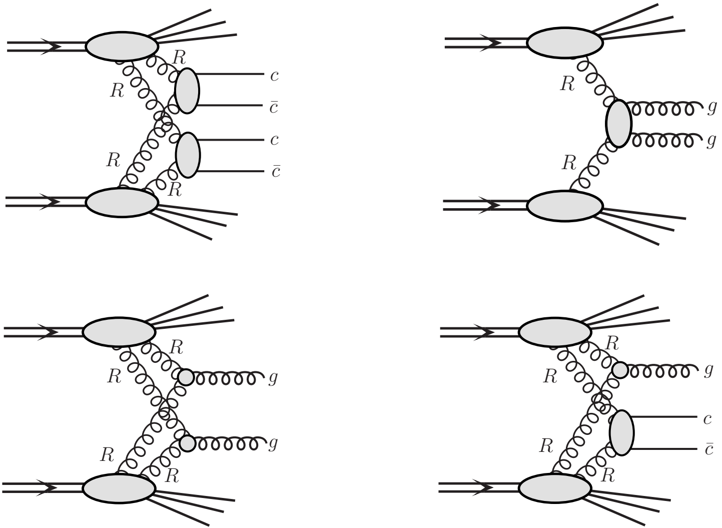


Figure: A diagrammatic illustration of the considered mechanisms.

List of mechanisms for double D meson production

- our old mechanism:
  $(gg \to c\bar{c}) \otimes (gg \to c\bar{c})$
  and double fragmentation $c \to D$ or $\bar{c} \to \bar{D}$
  with fragmentation functions with DGLAP evolution.
- a new SPS mechanism:
  $gg \to g(\to D)g(\to D)$
  possible correlations in azimuth or $p_{t,pair}$.
  Makes the previous extractions of σ_{eff} from the LHCb data invalid!
- a new mixed DPS mechanisms:
  $(gg \to g) \otimes (gg \to c\bar{c})$ or
  $(gg \to c\bar{c}) \otimes (gg \to c)$
  followed by $g \to D/\bar{D}$ and $c \to D$ or $\bar{c} \to \bar{D}$ fragmentation functions with DGLAP evolution.
- a new DPS mechanism: $(gg \to g) \otimes (gg \to g)$
  followed by $g \to D, \bar{D}$ fragmentation with fragmentation function with DGLAP evolution.

DPS parton production mechanisms

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

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

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

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

SPS parton production mechanisms

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

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

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

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

Fragmentation

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

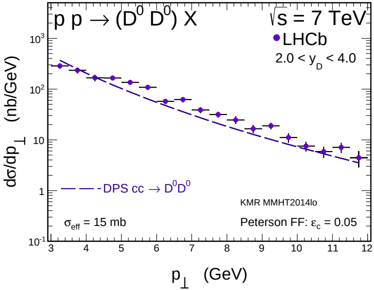
$$\frac{d\sigma^{DPS}_{cc}(pp \to DDX)}{dy_1 dy_2 d^2p^D_{1t} d^2p^D_{2t}} = \int \frac{D_{c\to D}(z_1)}{z_1} \cdot \frac{D_{c\to D}(z_2)}{z_2} \cdot \frac{d\sigma^{DPS}(pp \to ccX)}{dy_1 dy_2 d^2p^c_{1t} d^2p^c_{2t}} dz_1 dz_2$$
$$+ \int \frac{D_{g\to D}(z_1)}{z_1} \cdot \frac{D_{g\to D}(z_2)}{z_2} \cdot \frac{d\sigma^{DPS}(pp \to ggX)}{dy_1 dy_2 d^2p^g_{1t} d^2p^g_{2t}} dz_1 dz_2$$
$$+ \int \frac{D_{g\to D}(z_1)}{z_1} \cdot \frac{D_{c\to D}(z_2)}{z_2} \cdot \frac{d\sigma^{DPS}(pp \to gcX)}{dy_1 dy_2 d^2p^g_{1t} d^2p^c_{2t}} dz_1 dz_2$$

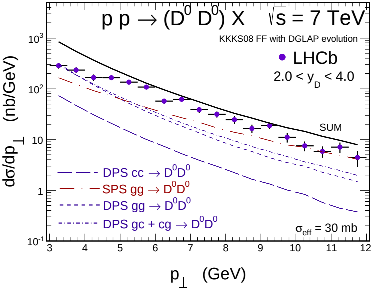
where: $p^{g,c}_{1t} = \frac{p^D_{1,t}}{z_1}$, $p^{g,c}_{2,t} = \frac{p^D_{2t}}{z_2}$ and meson longitudinal fractions $z_1, z_2 \in (0, 1)$.
For SPS DD-production via digluon fragmentation:

$$\frac{d\sigma^{SPS}_{gg}(pp \to DDX)}{dy_1 dy_2 d^2p^D_{1t} d^2p^D_{2t}} \approx \int \frac{D_{g\to D}(z_1)}{z_1} \cdot \frac{D_{g\to D}(z_2)}{z_2} \cdot \frac{d\sigma^{SPS}(pp \to ggX)}{dy_1 dy_2 d^2p^g_{1t} d^2p^g_{2t}} dz_1 dz_2 ,$$

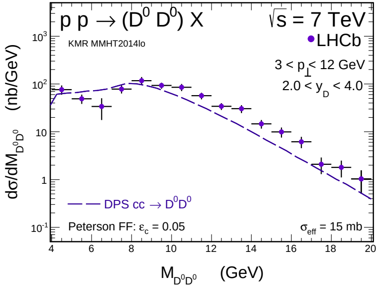
where: $p^g_{1t} = \frac{p^D_{1,t}}{z_1}$, $p^g_{2,t} = \frac{p^D_{2t}}{z_2}$ and meson longitudinal fractions $z_1, z_2 \in (0, 1)$.

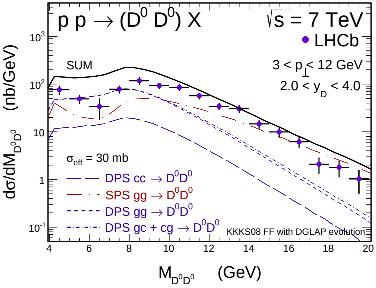
First results in the new approach



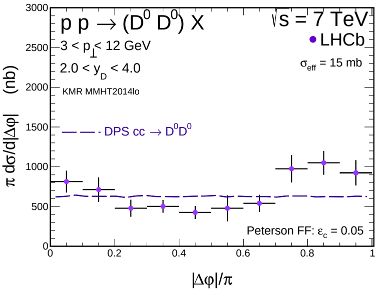


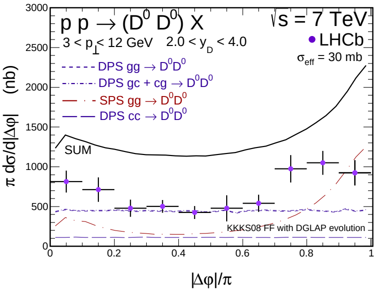
First results in the new approach





First results in the new approach





Potential problems

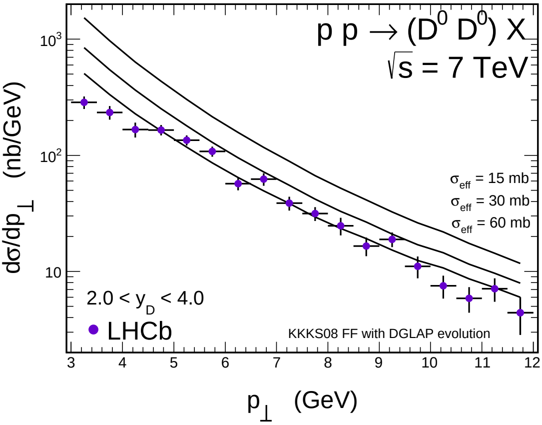
We get much too much.

What can be a reason:

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

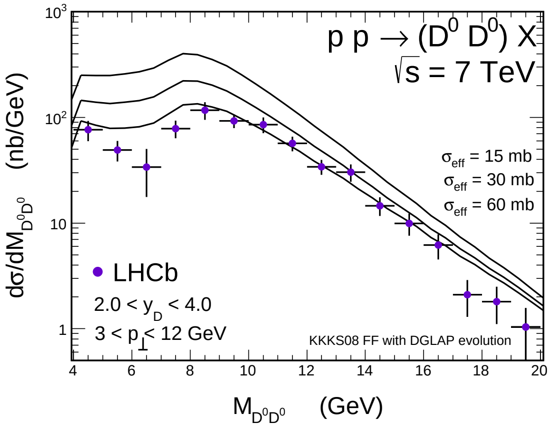
Below we will address some of them

Larger σ_{eff}



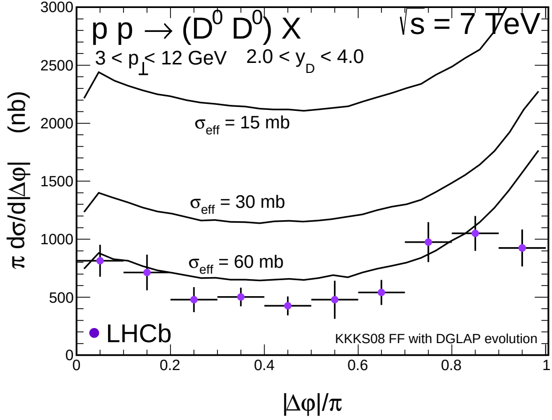
σ_{eff} = 60 mb describes the data

Larger σ_{eff}



σ_{eff} = 60 mb describes the data

Larger σ_{eff}



σ_{eff} = 60 mb describes the data

Charm associated with jet

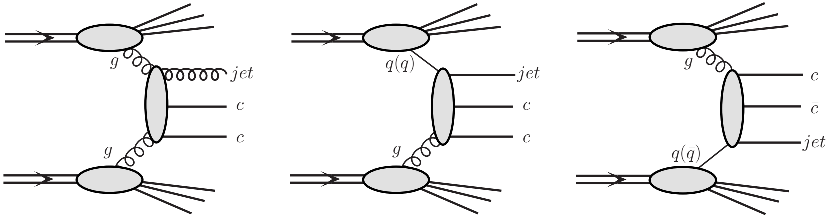


Figure: A diagrammatic representation of the considered mechanism for $pp \to c\bar{c} + jet$ reaction.

R. Maciula and A. Szczurek, arXiv:1610.01810

Charm associated with jet, collinear approach

The hadronic cross section for inclusive $pp \to c\bar{c} + jet$ reaction in the leading-order (LO) collinear approach can be written as:

$$\begin{aligned} d\sigma(pp \to c\bar{c} + jet) = \int dx_1 dx_2 \Big[& g(x_1,\mu_F^2) g(x_2,\mu_F^2)\; d\hat{\sigma}_{gg\to c\bar{c}g} \\ & + \sum_f q_f(x_1,\mu_F^2) g(x_2,\mu_F^2)\; d\hat{\sigma}_{qg\to c\bar{c}q} + g(x_1,\mu_F^2) \sum_f q_f(x_2,\mu_F^2)\; d\hat{\sigma} \\ & + \sum_f \bar{q}_f(x_1,\mu_F^2) g(x_2,\mu_F^2)\; d\hat{\sigma}_{\bar{q}g\to c\bar{c}\bar{q}} + g(x_1,\mu_F^2) \sum_f \bar{q}_f(x_2,\mu_F^2)\; d\hat{\sigma} \end{aligned} \tag{7}$$

where $g(x_{1,2},\mu_F^2)$, $q_f(x_{1,2},\mu_F^2)$ and $\bar{q}_f(x_{1,2},\mu_F^2)$ are the standard collinear parton distribution functions (PDFs) for gluons, quarks and antiquarks, respectively, carrying $x_{1,2}$ momentum fractions of the proton and evaluated at the factorization scale μ_F. Here, $d\hat{\sigma}$ are the elementary partonic cross sections for a given $2 \to 3$ subprocess.

Charm associated with jet

$$d\hat{\sigma} = \frac{1}{2\hat{s}} \overline{|\mathcal{M}_{gg\to c\bar{c}g}|^2} \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} (2\pi)^4 \delta^3 \left(p_1 + p_2 + p_3 - k_1 - \right. \tag{8}$$

where $\mathcal{M}_{gg\to c\bar{c}g}$ is the partonic on-shell matrix element, $\hat{s}$ is the partonic center-of-mass energy squared,

Charm associated with jet, k_t-factorization approach

For k_T-factorization approach:

$$d\sigma(pp \to c\bar{c} + jet) = \int dx_1 \frac{d^2k_{1t}}{\pi} dx_2 \frac{d^2k_{2t}}{\pi} \Big[\mathcal{F}_g(x_1, k_{1t}^2, \mu_F^2)\mathcal{F}_g(x_2, k_{2t}^2, \mu_F^2)\, d\hat{\sigma}_{g^*g^*\to c\bar{c}g}$$
$$+ \mathcal{F}_q(x_1, k_{1t}^2, \mu_F^2)\mathcal{F}_g(x_2, k_{2t}^2, \mu_F^2)\, d\hat{\sigma}_{q^*g^*\to c\bar{c}q} + \mathcal{F}_g(x_1, k_{1t}^2, \mu_F^2)\mathcal{F}_q(x_2, k_{2t}^2, \mu_F^2)\, d\hat{\sigma}_{g^*q^*\to c}$$
$$+ \mathcal{F}_{\bar{q}}(x_1, k_{1t}^2, \mu_F^2)\mathcal{F}_g(x_2, k_{2t}^2, \mu_F^2)\, d\hat{\sigma}_{\bar{q}^*g^*\to c\bar{c}\bar{q}} + \mathcal{F}_g(x_1, k_{1t}^2, \mu_F^2)\mathcal{F}_{\bar{q}}(x_2, k_{2t}^2, \mu_F^2)\, d\hat{\sigma}_{g^*\bar{q}^*\to c} \quad (9)$$

Here, $k_{1,2t}$ are transverse momenta of incident partons (new degrees of freedom) and $\mathcal{F}(x, k_t^2, \mu_F^2)$'s are transverse momentum dependent, unintegrated parton distribution functions (uPDFs). The elementary partonic cross sections are defined in terms of off-shell matrix elements, that takes into account that both partons entering the hard process are off-shell with virtualities $k_1^2 = -k_{1t}^2$ and $k_2^2 = -k_{2t}^2$.

Charm associated with jet, collinear-factorization

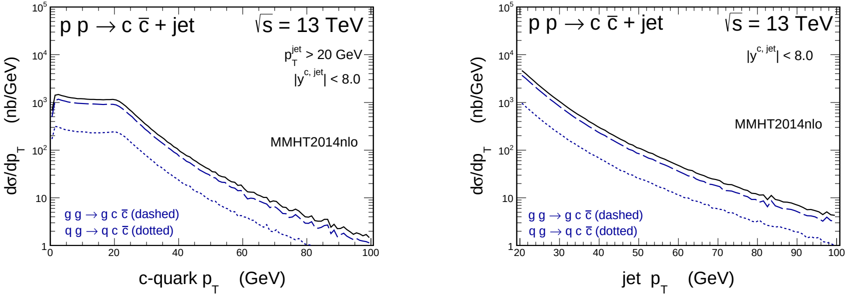


Figure:

qg and *gq* contributions much smaller than *gg* contribution

plateau at small $p_{t,c}$

Charm associated with jet, collinear-factorization

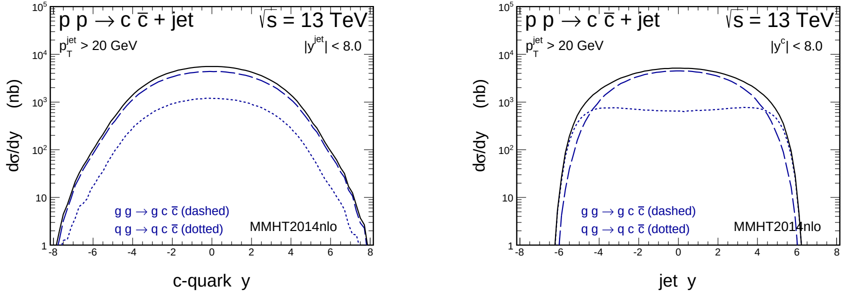


Figure:

Situation changes at large rapidities (*qg* may be important for atmospheric neutrinos).

Charm associated with jet, k_t-factorization

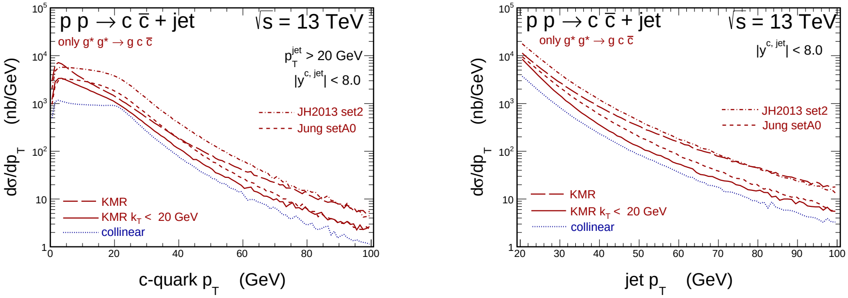


Figure:

strong dependence on UGDFs

Charm associated with jet, k_t-factorization

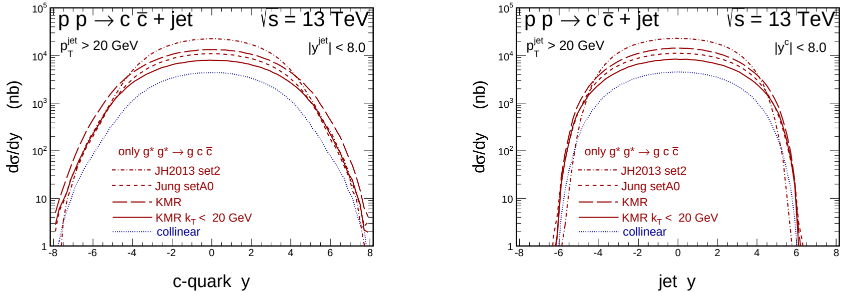


Figure:

strong dependence on UGDFs

2to2 versus 2to3

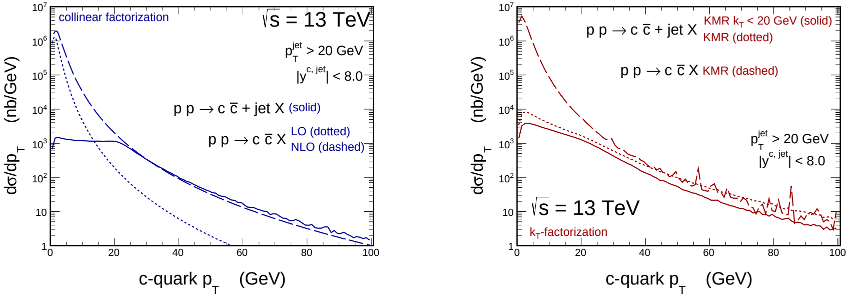


Figure:

$\frac{d\sigma_{c\bar{c}}}{dp_{t,c}} \approx \frac{d\sigma_{c\bar{c}j}}{dp_{t,c}}$ at large transverse momenta

D^0 + jet production

Table: The calculated cross sections in microbarns for inclusive $D^0 + \mathrm{jet}$ (plus $\bar{D}^0 + \mathrm{jet}$) production in pp-scattering at $\sqrt{s} = 13$ TeV for different cuts on transverse momentum of the associated jet. Here, the D^0 meson is required to have $|y^{D^0}| < 2.5$ and $p_T^{D^0} > 3.5$ GeV and the rapidity of the associated jet is $|y^{jet}| < 4.9$, that corresponds to the ATLAS detector acceptance.

$p_{T,min}^{jet}$ cuts	collinear	k_T-factorization approach		
	MMHT2014nlo	KMR	KMR $k_T < p_{T,min}^{jet}$	Jung setA0
$p_T^{jet} > 20$ GeV	22.36	49.20	33.12	43.45
$p_T^{jet} > 35$ GeV	3.70	9.60	6.76	6.79
$p_T^{jet} > 50$ GeV	1.14	3.32	2.45	1.94

Relatively large cross sections -- could be measured.

D^0 + jet production

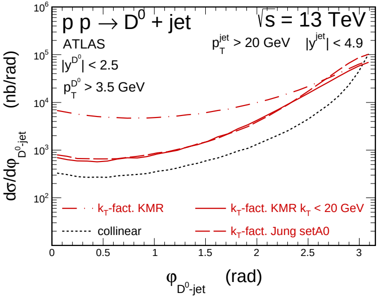


Figure: Azimuthal angle correlation between D^0 or $\bar{D}^0$ meson and jet for the collinear and k_T-factorization approaches.

New possibility to test UGDFs

Single-diffractive production of charm in k_t-factorization

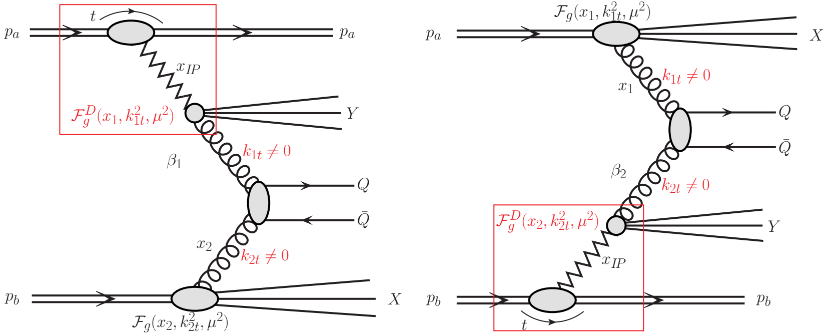


Figure: A diagrammatic representation of the mechanisms of single-diffractive production of heavy quark pairs within the k_t-factorization approach.

M. Luszczak, R. Maciula, A. Szczurek, M. Trzebinski, arXiv:1606.09512

Single-diffractive production of charm in k_t-factorization

$$d\sigma^{SD(a)}(p_a p_b \to p_a c\bar{c}\, XY) = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi}\, d\hat{\sigma}(g^* g^* \to c\bar{c}) \times \mathcal{F}_g^D(x_1, k_{1t}^2, \mu^2) \cdot \mathcal{F}_g(x_2, k_{2t}^2, \mu^2), \quad (10)$$

$$d\sigma^{SD(b)}(p_a p_b \to c\bar{c} p_b\, XY) = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi}\, d\hat{\sigma}(g^* g^* \to c\bar{c}) \times \mathcal{F}_g(x_1, k_{1t}^2, \mu^2) \cdot \mathcal{F}_g^D(x_2, k_{2t}^2, \mu^2), \quad (11)$$

Single-diffractive production of charm in k_t-factorization

$$g^D(x,\mu^2) = \int dx_P d\beta\, \delta(x - x_P\beta) g_P(\beta,\mu^2)\, f_P(x_P) = \int_x^{x^{max}} \frac{dx_P}{x_P} f_P(x_P) g_P(\frac{x}{x_P},\mu^2), \quad (12)$$

where $\beta = \frac{x}{x_P}$ is the longitudinal momentum fraction of pomeron carried by gluon and the flux of pomerons may be taken as:

$$f_P(x_P) = \int_{t_{min}}^{t_{max}} dt\, f(x_P,t). \quad (13)$$

Diffractive unintegrated gluon distribution (standard KMR approach)

$$f_g^D(x,k_t^2,\mu^2) \equiv \frac{\partial}{\partial \log k_t^2}\left[g^D(x,k_t^2)\, T_g(k_t^2,\mu^2) \right] = T_g(k_t^2,\mu^2)\, \frac{\alpha_S(k_t^2)}{2\pi} \times \quad (14)$$

$$\int_x^1 dz \left[\sum_q P_{gq}(z) \frac{x}{z}\, q^D\left(\frac{x}{z},k_t^2\right) + P_{gg}(z) \frac{x}{z}\, g^D\left(\frac{x}{z},k_t^2\right) \Theta\left(\Delta - z\right) \right],$$

The calculation for first time in k_t-factorization.

Single-diffractive production of charm in k_t-factorization

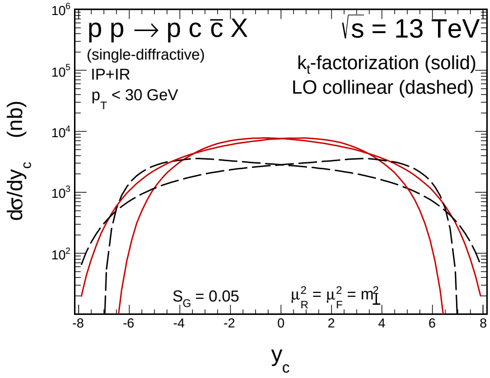


Figure:

Large cross section (feasibility studies)

Differences at larger rapidities

Single-diffractive production of charm in k_t-factorization

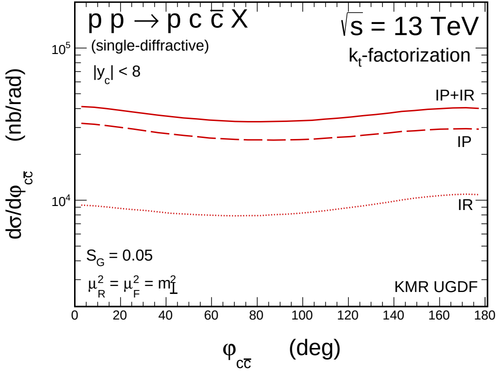


Figure:

Large decorrelation as for the inclusive case

Single-diffractive production of charm in k_t-factorization

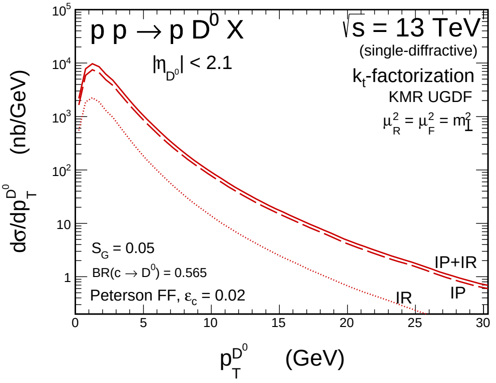


Figure:

reggeon contribution much smaller than pomeron contribution

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 $D^0 D^0$.
- 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
  $\longrightarrow$ important for recombination/coalescence
  $\longrightarrow$ 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)
- $d\sigma/d\phi_{DD} \neq$ const
  Difficult to get it from DPS mechanisms (Echevarria, Kasemets, Mulders, Pisano) as spin correlations.
- Too big $D^0 D^0$ cross section with canonical value σ_{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?

Conclusion, continued

- Associated production of $c\bar{c}jet$ for a first time in the k_t-factorization approach
- Many new correlation observables have been calculated
- Relation between $2 \to 2$ and $2 \to 3$ processes both in collinear and k_T-factorization approach
- First predictions for D^0-jet production for ATLAS acceptance
- First calculation for single-diffractive production of charm in k_t-factorization approach.
- Large cross section but no consistent treatment of gap survival factor.