Some new aspects of double parton scattering effects in the reactions with at least single charm pair production

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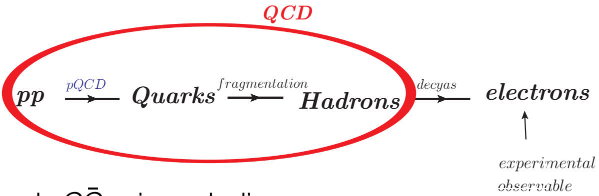
Outline

Introduction

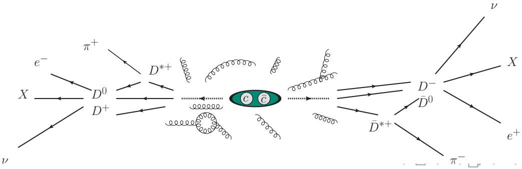
- Eearly extraction of σ_{eff} $\sim$ gave 15 mb
- Recently some confusion from recent analyses
  - $\sigma_{eff} = 4.8 \pm 0.5 \pm 2.5$ mb from $J/\psi J/\psi$ at D0
  - $\sigma_{eff} = 2.2 \pm 0.7 \pm 0.9$ mb from $J/\psi \Upsilon$ at D0
  - $\sigma_{eff} = 60$ mb from MSSS2016 analysis of $D^0 D^0$
- Naive geometry with smeared gluons: $\sigma_{eff} \approx 30$ mb
  Gaunt, Maciuła, Szczurek, Phys. Rev. **D90** (2014) 054017.
- Parton splitting effectively modifies σ_{eff} (down)
  $\sigma_{eff} = \sigma_{eff}(\Delta y)$
- Nonperturbative parton splitting (Blok, Strikman)
- More involved analyses regarding SPS and DPS contributions needed
- Here we consider two new processes:
  - $pp \to c\bar{c}j$ (SPS, collinear- and k_t-factorization)
    helpfull in understanding $c\bar{c}$ production
  - $pp \to c\bar{c}jj$ (DPS and SPS, collinear factorization)
    competition of DPS and SPS

3-step process



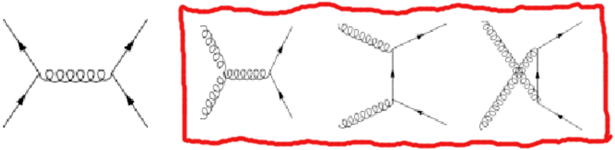
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

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

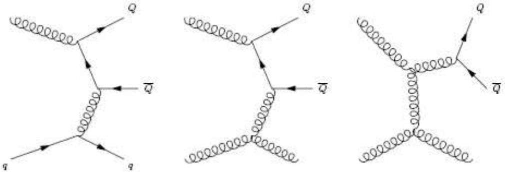


Dominant mechanisms of $Q\bar{Q}$ production

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

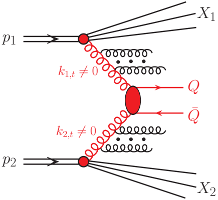


- **gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ anihilation important only near the threshold
- some of next-to-leading order diagrams:



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

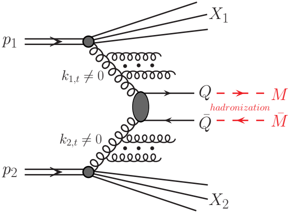
- multi-differential cross section

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

- 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 $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$.

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 $z \in (0, 1)$

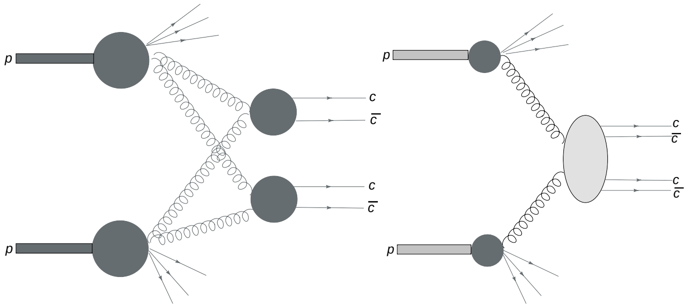
- **approximation:**

  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:

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

In general σ_{eff} can depend on kinematics The simple formula above can be generalized to include differential distributions

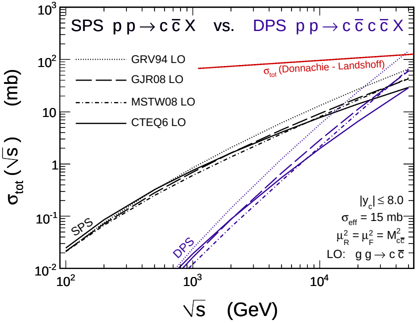
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 dy_2 d^2p_{1t}} \cdot \frac{d\sigma}{dy_3 dy_4 d^2p_{2t}} .$$

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.

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



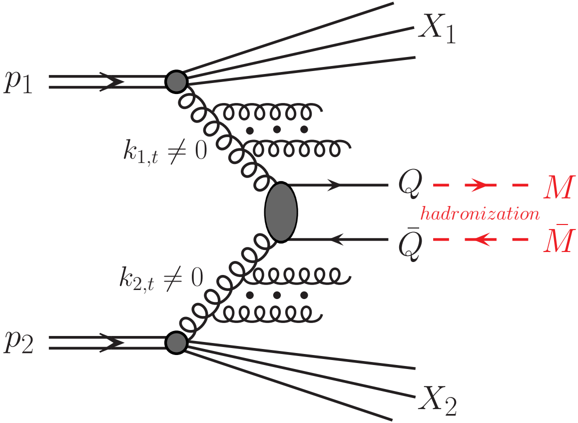
Luszczak,Maciula,Szczurek, Phys. Rev. **C86** (2012) 014905

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

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

DPS in k_t-factorization

Each individual scattering in the k_t-factorization approach

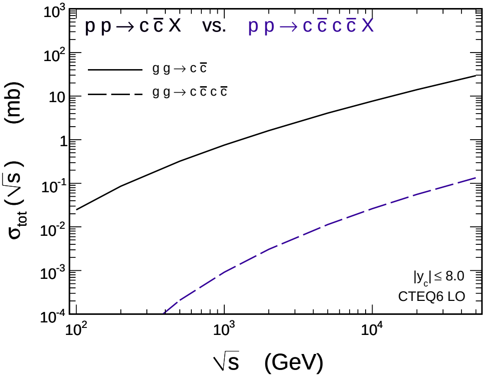
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2}$$
$$\int \overline{|\mathcal{M}_{off}|^2} \delta\left(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}\right) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2) \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi}$$

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

Effectively 16 dimensions, Monte Carlo method

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

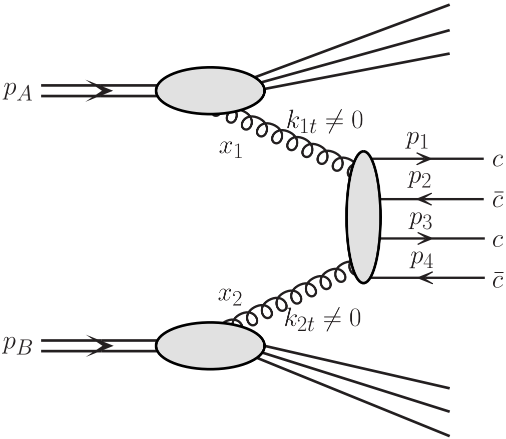
Single parton scattering $2 \to 4$ process?



Only about 1 % at high energies

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

SPS in k_t-factorization approach



include gluon transverse momenta

A. van Hameren, R. Maciula and A. Szczurek,
arXiv:1504.06490, Phys. Lett. **B748** (2015) 737.

Results for k_t-factorization approach

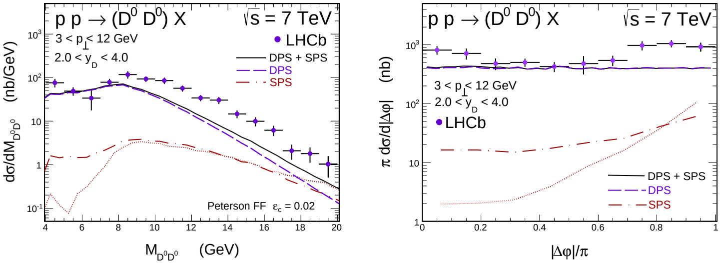
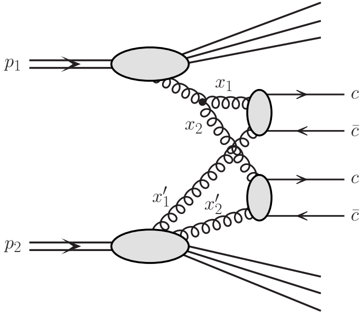


Figure: Distributions in D^0D^0 invariant mass (left) and in azimuthal angle between both D^0's (right) within the LHCb acceptance. The DPS contribution (dashed line) and the SPS contribution within the k_t-factorization approach (dashed-dotted line). The collinear SPS result from our previous studies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

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

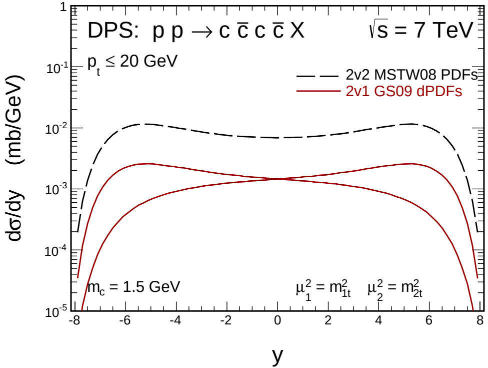
Parton splitting DPS

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

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

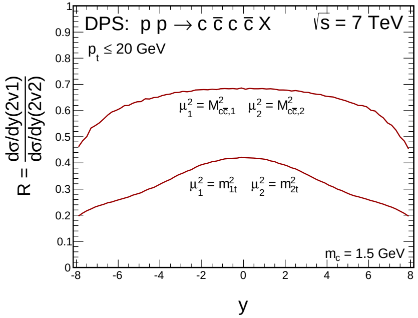
Presence of the two components leads to a dependence of effective parameter on different kinematical variables.

Parton splitting vs conventional DPS



Asymmetric 1v2 and 2v1 contributions

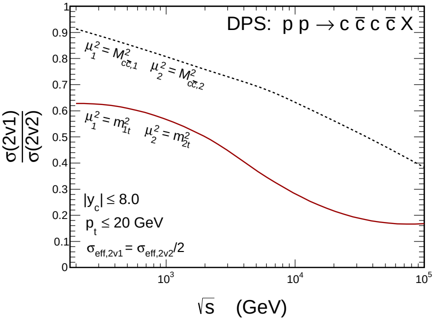
Parton splitting vs conventional DPS



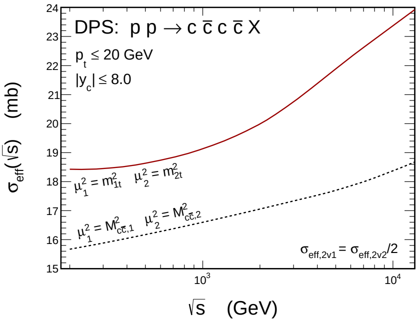
Rapidity and factorization scale dependence

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?
  (with Maciula, Saleev and Shipilova - work in preparation).

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

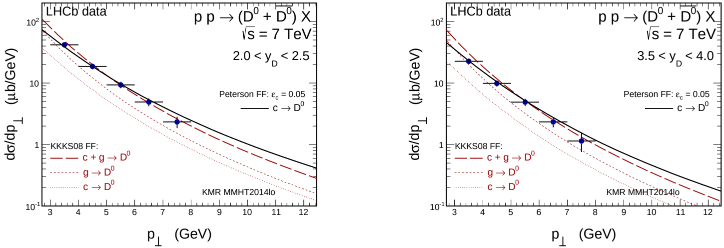


Figure: Left and right panels correspond to two different rapidity intervals. The Peterson $c \to D$ FF (solid lines) are compared to the second scenario calculations with the KKKS08 FF (long-dashed lines) with $c \to D$ (dotted) and $g \to D$ (short-dashed) components that undergo DGLAP evolution equation.

Both methods describe the existing data

New mechanisms

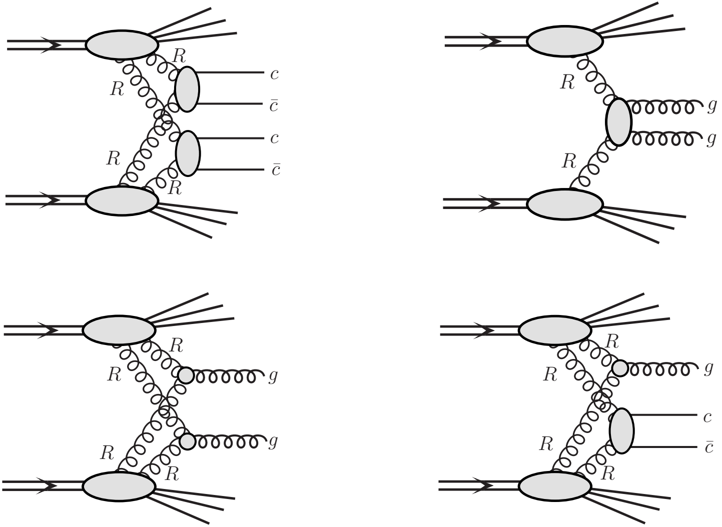


Figure: A diagrammatic illustration of the considered mechanisms.

DPS parton production mechanisms

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

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

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

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

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:

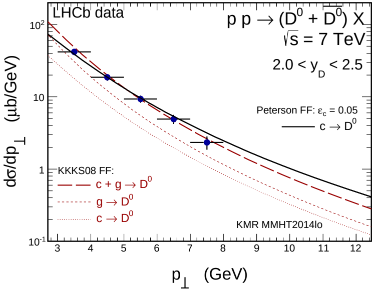
$$\frac{d\sigma^{DPS}_{cc}(pp \to DDX)}{dy_1 dy_2 d^2p^D_{1t} d^2p^D_{2t}} = \int \frac{D_{c\to D}(z_1)}{z_1} \cdot \frac{D_{c\to D}(z_2)}{z_2} \cdot \frac{d\sigma^{DPS}(pp \to ccX)}{dy_1 dy_2 d^2p^c_{1t} d^2p^c_{2t}} dz_1 dz_2$$
$$+ \int \frac{D_{g\to D}(z_1)}{z_1} \cdot \frac{D_{g\to D}(z_2)}{z_2}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

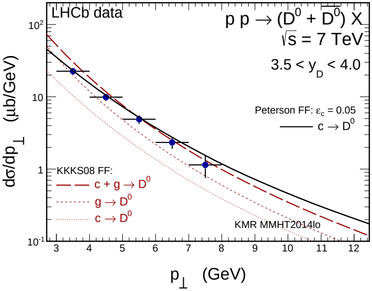
where: $p^{g,c}_{1t} = \frac{p^D_{1,t}}{z_1}$, $p^{g,c}_{2,t} = \frac{p^D_{2t}}{z_2}$ and meson longitudinal fractions $z_1, z_2 \in (0,1)$.
For SPS DD-production via digluon fragmentation:

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

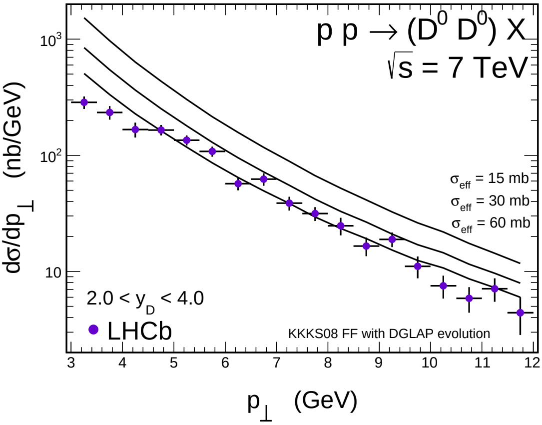
where: $p^g_{1t} = \frac{p^D_{1,t}}{z_1}$, $p^g_{2,t} = \frac{p^D_{2t}}{z_2}$ and meson longitudinal fractions $z_1, z_2 \in (0,1)$.

First results in the new approach



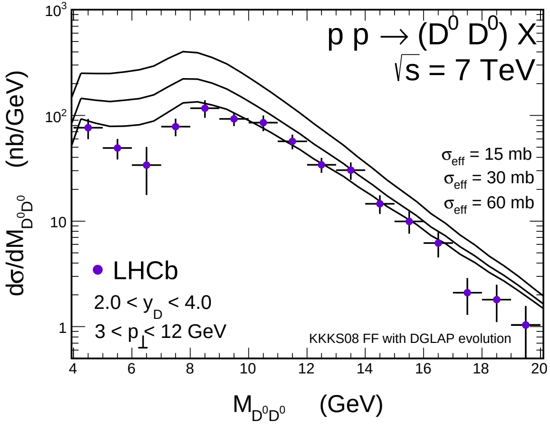


Larger σ_{eff}



σ_{eff} = 60 mb describes the data

Larger σ_{eff}



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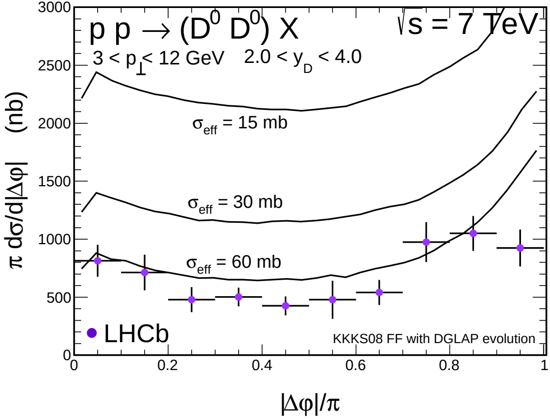
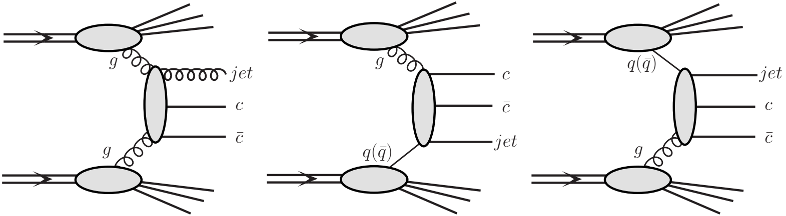


σ_{eff} = 60 mb describes the data

First exploration of $c\bar{c}j$



Only SPS mechanisms

full phase space

Production of $c\bar{c}j$ in collinear factorization

$$d\sigma(pp \to c\bar{c} + jet) = \int dx_1 dx_2 \, [g(x_1,\mu_F^2) g(x_2,\mu_F^2) \; d\hat{\sigma}_{gg \to c\bar{c}g}$$
$$+ \quad \Sigma_f \; q_f(x_1,\mu_F^2) g(x_2,\mu_F^2) \; d\hat{\sigma}_{qg \to c\bar{c}q} + g(x_1,\mu_F^2) \Sigma_f \; q_f(x_2,\mu_F^2) \; d\hat{\sigma}_{gq \to c\bar{c}q}$$
$$+ \quad \Sigma_f \; \bar{q}_f(x_1,\mu_F^2) g(x_2,\mu_F^2) \; d\hat{\sigma}_{\bar{q}g \to c\bar{c}\bar{q}} + g(x_1,\mu_F^2) \Sigma_f \; \bar{q}_f(x_2,\mu_F^2) \; d\hat{\sigma}_{g\bar{q} \to c\bar{c}\bar{q}}] \; , \tag{4}$$

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 $2 \to 3$ subproces

Production of $c\bar{c}j$ in k_t-factorization

$$d\sigma(pp \to c\bar{c} + jet) = \int dx_1 \frac{d^2k_{1t}}{\pi} dx_2 \frac{d^2k_{2t}}{\pi} \left[\mathcal{F}_g(x_1, k_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, k_{2t}^2, \mu_F^2) \; d\hat{\sigma} \right.$$

$$+ \quad \mathcal{F}_q(x_1, k_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, k_{2t}^2, \mu_F^2) \; d\hat{\sigma}_{q^* g^* \to c\bar{c}q} + \mathcal{F}_g(x_1, k_{1t}^2, \mu_F^2) \mathcal{F}_q(x_2, k_{2t}^2, \mu_F^2)$$

$$+ \quad \mathcal{F}_{\bar{q}}(x_1, k_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, k_{2t}^2, \mu_F^2) \; d\hat{\sigma}_{\bar{q}^* g^* \to c\bar{c}\bar{q}} + \mathcal{F}_g(x_1, k_{1t}^2, \mu_F^2) \mathcal{F}_{\bar{q}}(x_2, k_{2t}^2, \mu_F^2)$$

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, so-called, unintegrated parton distribution functions (uPDFs)

Results, collinear factorization

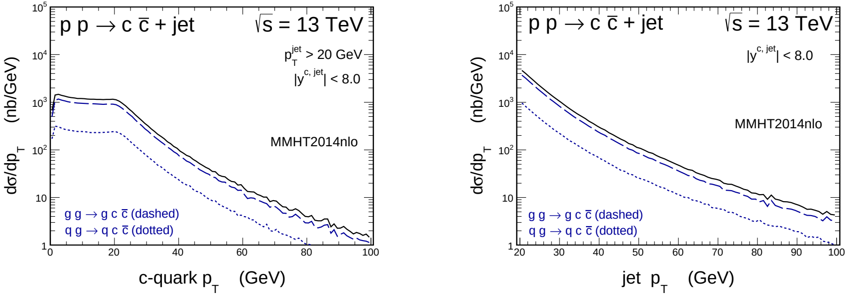


Figure: Transverse momentum distribution of c-quark (let panel) and associated jet (right panel) in the collinear approach.

Results, collinear factorization

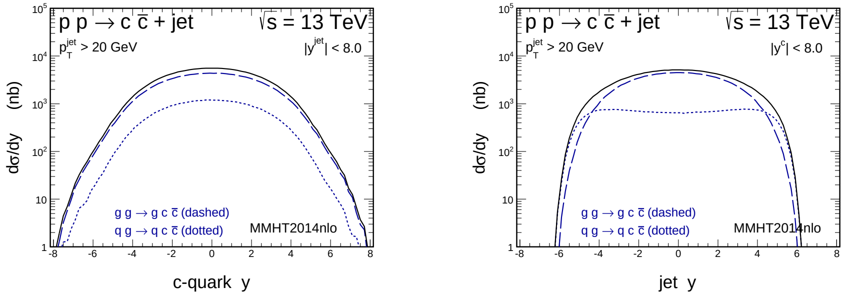


Figure: Rapidity distribution of c-quark (left panel) and associated jet (right panel) in the collinear appraoch.

Results, collinear factorization

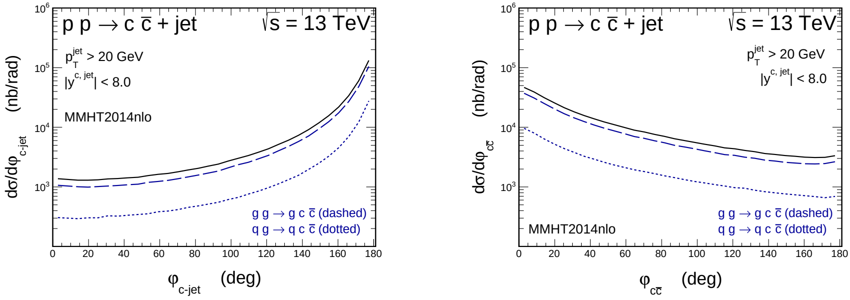


Figure: Distribution in azimuthal angle between c-quark and jet (left panel) and between c-quark and $\bar{c}$-antiquark (right panel) in the collinear approach.

Results, k_t-factorization

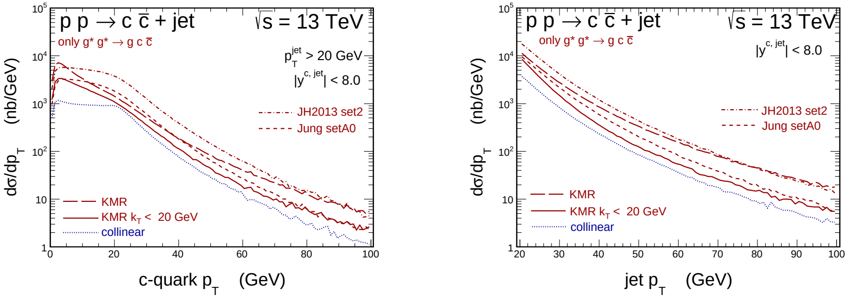


Figure: Transverse momentum distribution of c-quark (let panel) and associated jet (right panel) in the k_T-factorization approach with different uGDFs.

Results, k_t-factorization

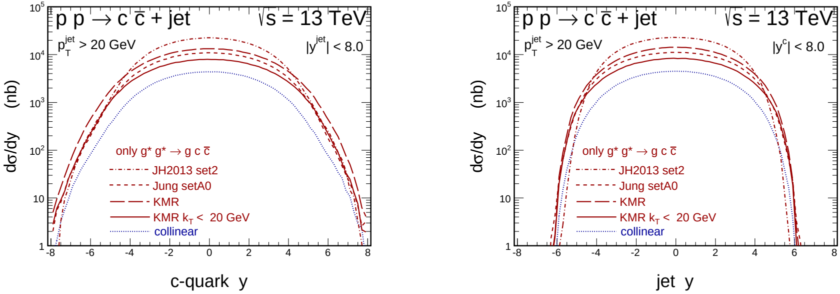


Figure: Rapidity distribution of c-quark (left panel) and associated jet (right panel) in the k_T-factorization appraoch with different uGDFs.

Results, k_t-factorization

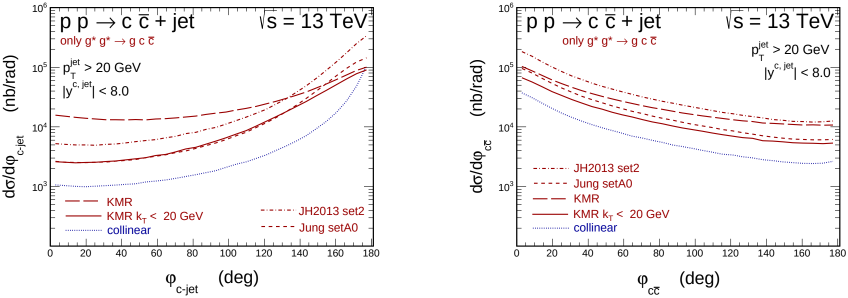


Figure: Distribution in azimuthal angle between c-quark and jet (left panel) and between *c*-quark and $\bar{c}$-antiquark (right panel) in the k_T-factorization approach with different uGDFs.

Results, comparison of both methods

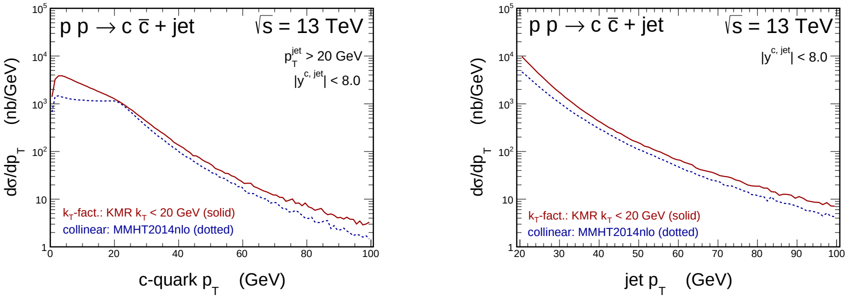


Figure: Comparison of transverse momentum distributions of c-quark (let panel) and associated jet (right panel) for collinear approach (dotted) and the k_T-factorization approach with the KMR uGDF and extra cut on initial gluon transverse momenta (solid).

Results, comparison of both methods

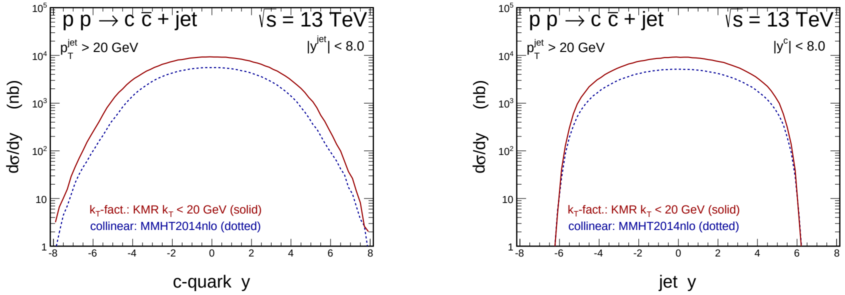


Figure: Comparison of rapidity distribution of c-quark (left panel) and associated jet (right panel) in the collinear approach (dotted) and the k_T-factorization appraoch with the KMR uGDF and extra cut on initial gluon transverse momenta (solid).

Results, comparison of both methods

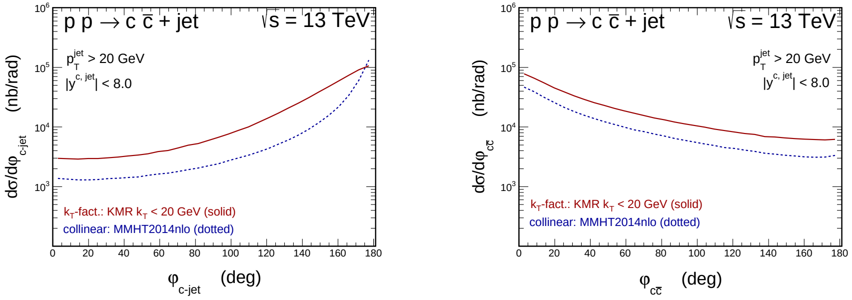


Figure: Comparison of distribution in azimuthal angle between c-quark and jet (left panel) and between c-quark and $\bar{c}$-antiquark (right panel) in the collinear approach (dotted) and in the k_T-factorization approach with the KMR uGDF and extra cut on initial gluon transverse momenta (solid).

Predictions for D^0 + *jet* production at the LHC

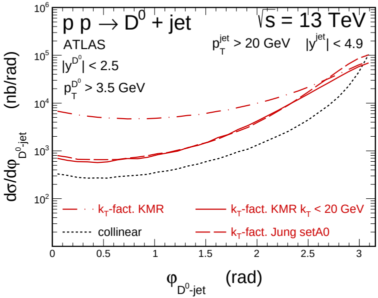


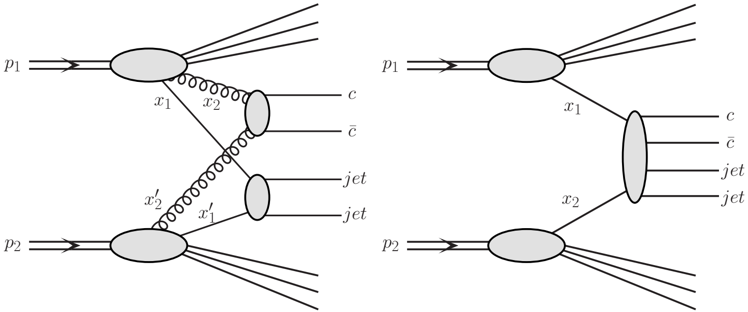
Figure: Azimuthal angle correlation between D^0 meson and jet for collinear and k_T-factorization approaches. The cuts are specified in the figure caption.

Predictions for $D^0 + jet$ production at the LHC

Table: The calculated cross sections in microbarns for inclusive $D^0 + \mathrm{jet}$ production in pp-scattering at $\sqrt{s} = 13$ TeV 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.

Cuts	collinear MMHT2014nlo	KMR	KMR $k_T < 20$
$p_T^{jet} > 20$ GeV	22.36	49.20	33.12
$p_T^{jet} > 35$ GeV	3.70	9.60	4.90
$p_T^{jet} > 50$ GeV	1.14	3.32	1.49

First exploration of $pp \to c\bar{c}jj$



Both DPS and SPS mechanisms

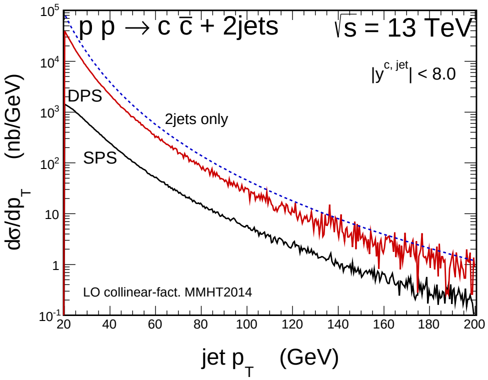
full phase space

Processes included in SPS

9 types:

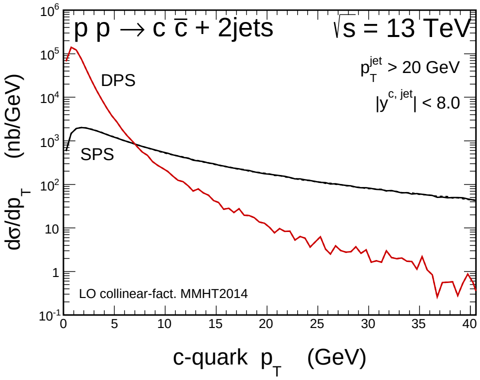
- $gg \to ggc\bar{c}$
- $gg \to q\bar{q}c\bar{c}$
- $gq/\bar{q} \to gq/\bar{q}c\bar{c}$
- $q/\bar{q}g \to gq/\bar{q}c\bar{c}$
- $q\bar{q} \to q'\bar{q}'c\bar{c}$
- $q\bar{q} \to ggc\bar{c}$
- $qq \to qqc\bar{c}$
- $qq' \to qq'c\bar{c}$

Jet transverse momentum distribution



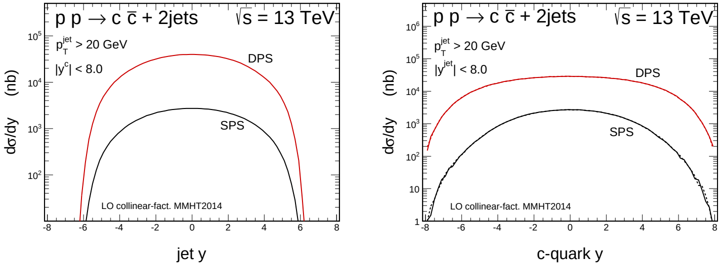
The cross section for dijets only slightly bigger than that for dijets associated with charm

Charm transverse momentum distribution



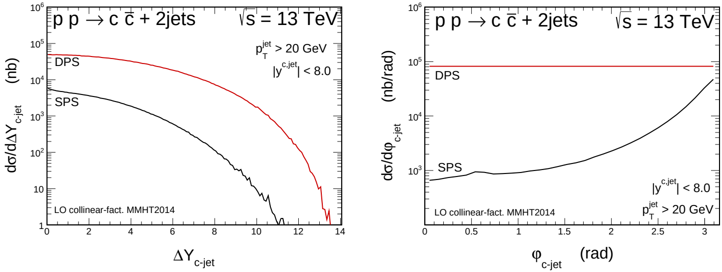
DPS dominates at low transverse momenta

Rapidity distributions



The charm DPS distribution broader than charm SPS distribution

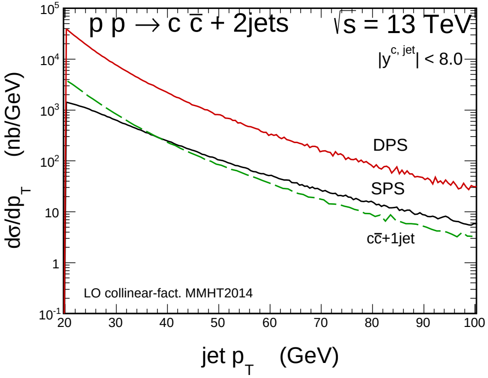
Other distributions



The DPS distribution in $\Delta\eta_{cj}$ is broader than its SPS counterpart

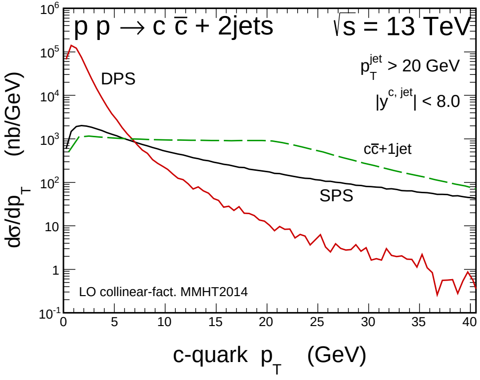
The distribution in ϕ_{cj} should be very flat.

Comparison of $c\bar{c}j$ and $c\bar{c}jj$



$c\bar{c}jj$ much bigger than $c\bar{c}j$

Comparison of $c\bar{c}j$ and $c\bar{c}jj$



Summary:

$c\bar{c} > c\bar{c}jj(DPS) \sim jj > c\bar{c}jj(SPS) \sim c\bar{c}j$

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

- First theoretical study related to associated production of charm and single jet production.
- We have limited to c ($\bar{c}$) quark level and full phase space.
- The results, one dimesional and two-dimensional distributions, with the KMR uGDF and a practical correction to exclude production of more than one jet are very similar as those obtained within the collinear approach.
- We have performed first feasibility studies for ATLAS (and/or CMS) cuts. We have obtained rather large cross section.
- We have presented first calculations for $c\bar{c}jj$ within collinear factorization approach
- DPS contribution much larger than SPS contribution
- SPS $c\bar{c}jj$ of the same order as SPS $c\bar{c}j$
- $\sigma(jj) \sim \sigma(jjc\bar{c})$ - search for associated production of charm outside of the jets to identify DPS.