

Single and double $c\bar{c}$ pair production at LHC

Antoni Szczurek

Institute of Nuclear Physics (PAN), Cracow, Poland

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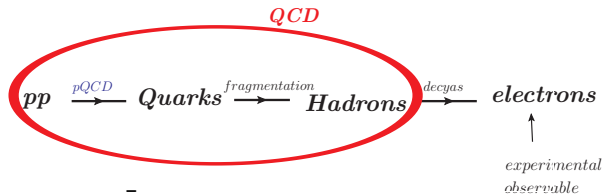
Contents

- General framework of $c\bar{c}$ production
- D meson production at LHC
- Double parton production of $c\bar{c}c\bar{c}$
- Single parton production of $c\bar{c}c\bar{c}$
- Conclusions

Low-x physics because c quark mass rather small

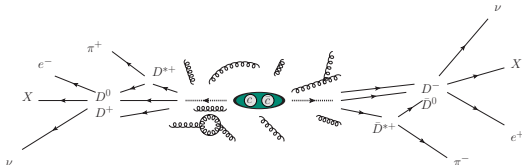


3-step process



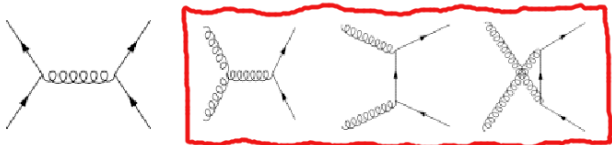
- 1 Heavy quarks $Q\bar{Q}$ pairs production
 - $m_c = 1.5 \text{ GeV}, m_b = 4.75 \text{ GeV} \rightarrow$ perturbative QCD
- 2 Heavy quarks hadronization (fragmentation)
- 3 Semileptonic decays of D and B mesons

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

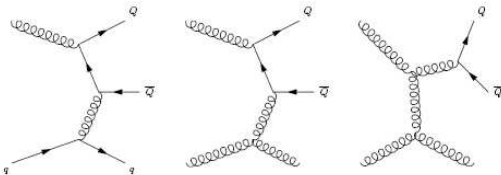


Dominant mechanisms of $Q\bar{Q}$ production

- 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



pQCD standard approach

collinear approximation → transverse momenta of the incident partons are assumed to be zero

- quadruply differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 p_i(x_1, \mu^2) x_2 p_j(x_2, \mu^2) \overline{|\mathcal{M}_{ij}|^2}$$

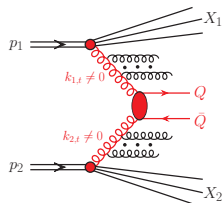
- $p_i(x_1, \mu^2), p_j(x_2, \mu^2)$ - standard parton distributions in hadron (e.g. CTEQ, GRV, GJR, MRST, MSTW)
- LO and NLO on-shell matrix elements well-known

several packages:

- FONLL** (Cacciari *et al.*) - one particle distributions and total cross sections
- more exclusive tools - PYTHIA, HERWIG, MC@NLO



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

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

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

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

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



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

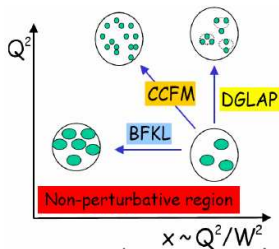
$$xp_k(x, \mu_F^2) = \int_0^\infty d\kappa_t^2 \mathcal{F}(x, \kappa_t^2, \mu_F^2)$$

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

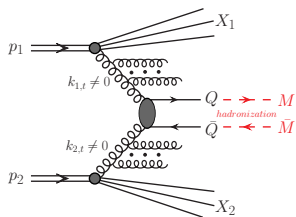
gg-fusion dominance \Rightarrow **great test of existing unintegrated gluon densities!**
especially at LHC (small- x)

several models:

- 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:

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

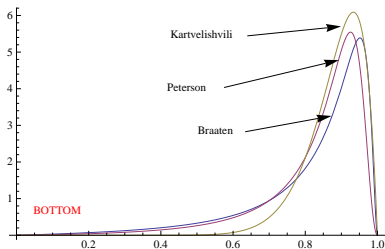
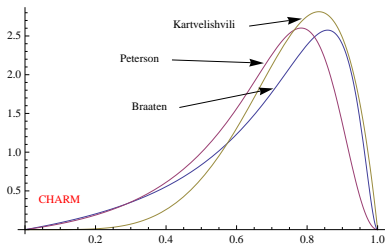
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

- **approximation:**

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



Different models of FFs



- **Peterson et al.**

$$D_{Q \rightarrow M}(z) = \frac{N}{z[1-(1/z)-\varepsilon_Q/(1-z)]}$$

$$\varepsilon_c = 0.06, \varepsilon_b = 0.006 \text{ from PDG}$$

- Braaten et al.

$$D_{Q \rightarrow M}(z) = N \frac{rz(1-z)^2}{(1-(1-r)z)^6} (F_1 + F_2)$$

$$F_1 = 6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2$$

$$F_2 = 3(1-r)^2(1-2r^2)z^4 - 2(1-r)(6-19r+18r^2)z^3$$

$$r_c = 0.2, r_b = 0.07$$

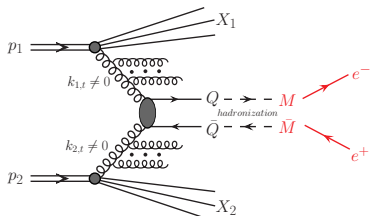
- Kartvelishvili et al.

$$D_{Q \rightarrow M}(z) = N(1-z)z^a$$

$$a_c = 5.0, a_b = 14.0$$

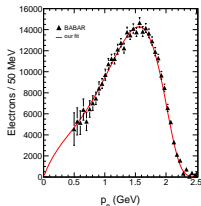
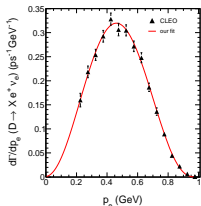


Experimental decay functions and Monte Carlo approach



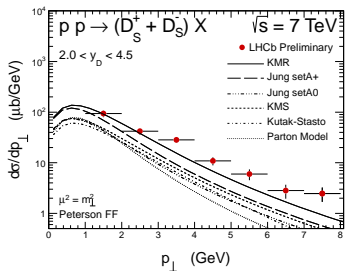
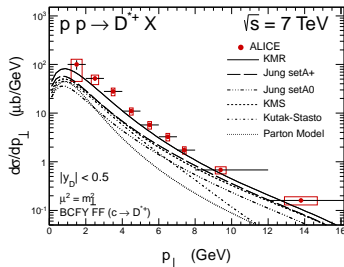
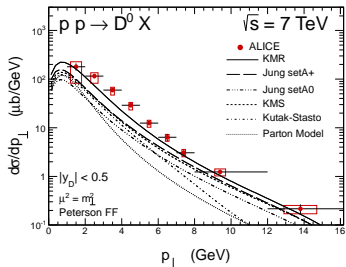
- CLEO** $e^+e^- \rightarrow \Psi(3770) \rightarrow D\bar{D} \rightarrow Xe\nu$
 $\text{BR}(D^+ \rightarrow e^+ \nu_e X) = 16.13 \pm 0.20(\text{stat.}) \pm 0.33(\text{syst.})\%$
 $\text{BR}(D^0 \rightarrow e^+ \nu_e X) = 6.46 \pm 0.17(\text{stat.}) \pm 0.13(\text{syst.})\%$
- BABAR** $e^+e^- \rightarrow \Upsilon(10600) \rightarrow B\bar{B} \rightarrow Xe\nu$
 $\text{BR}(B \rightarrow e\nu_e X) = 10.36 \pm 0.06(\text{stat.}) \pm 0.23(\text{syst.})\%$

- Monte Carlo** \implies directions and lengths of outgoing leptons momenta
- Our input** \implies experimental decay functions: $f_{\text{CLEO}}(p)$, $f_{\text{BABAR}}(p)$



- approximation:**
 D mesons ($D^\pm, D^0, \bar{D}^0, D_S^\pm, D^{*\pm}, D^{*0}, D_S^{*\pm}$)
 B mesons ($B^\pm, B^0, \bar{D}^0, B_S^0, \bar{B}_S^0, B^*, B_S^*$)
 $\text{BR}(D \text{ and } B \rightarrow X e \nu \approx 10\%)$

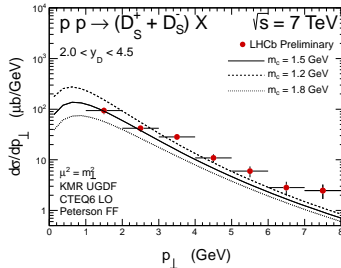
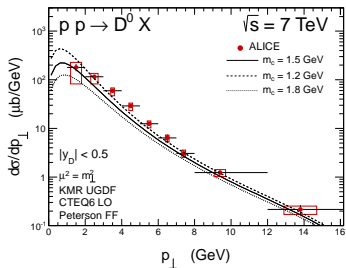
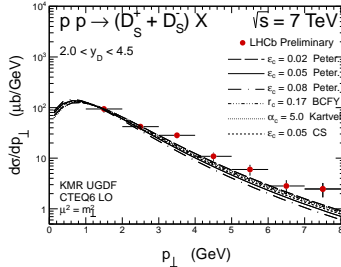
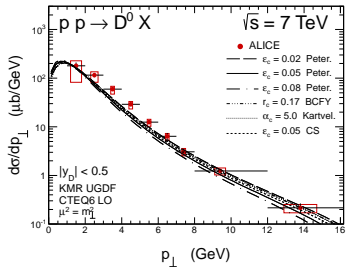


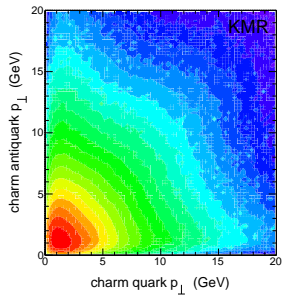
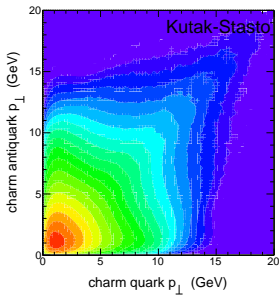
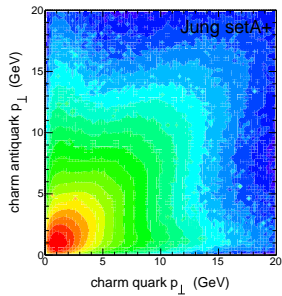
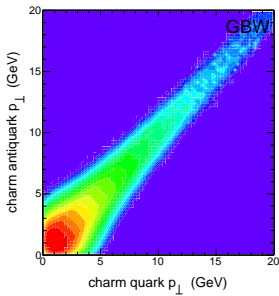


- various UGDFs models \rightarrow crucial test of their applicability at high energies and small x -values
- only **KMR model** gives good description of the ALICE and LHCb data
- significant difference between LO parton model and LO k_T -factorization



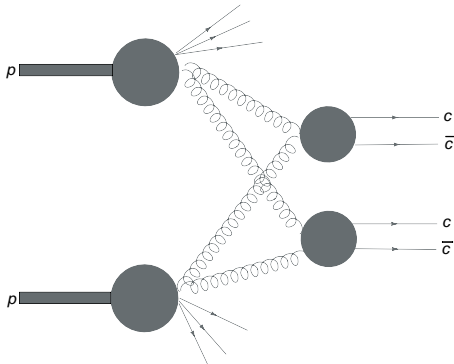
Effects of hadronization and quark mass uncertainty





Production of two $c\bar{c}$ pairs in double-parton scattering

Consider two hard (parton) scatterings



Not considered so far in the literature

Luszczak, Maciula, Szczurek, arXiv:1111.3255,

Phys.Rev. **D85** (2012) 094034.



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 (12-15 mb).



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**

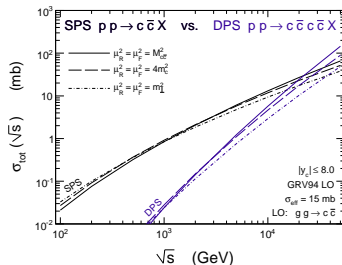
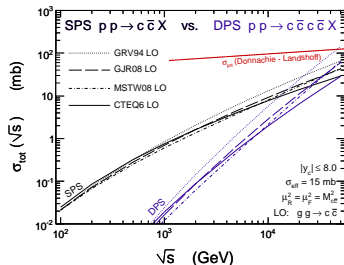
dPDF are subjected to special **evolution equations**

single scale evolution: **Snigireev**

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



DPS results

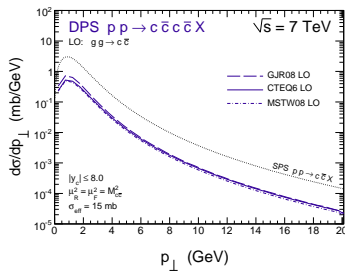
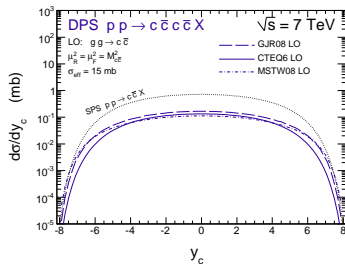


Inclusive cross section **more difficult** to calculate

$$\sigma_{SS}, 2\sigma_{DS} < \sigma_C^{\text{inclusive}} < \sigma_{SS} + 2\sigma_{DS}$$



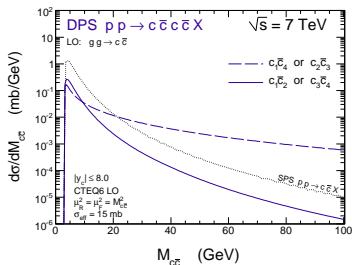
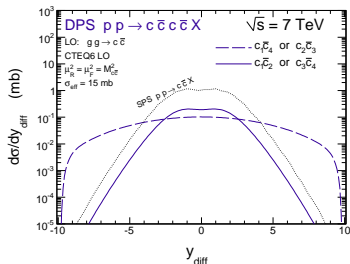
DPS results



In the **factorized model** inclusive double-scattering distributions in y and p_t are **identical** as for single- $c\bar{c}$ production.



DPS results

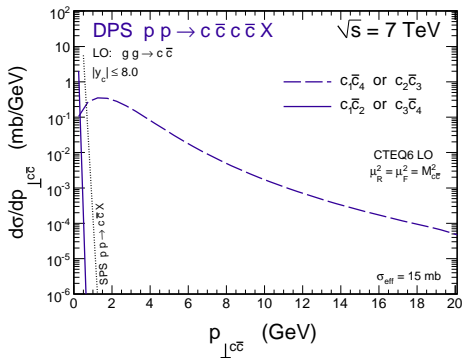


DPS: large rapidity differences, large invariant masses

- Not possible for quarks (antiquarks)
- mesons ?
- nonphotonic electrons (muons) ?



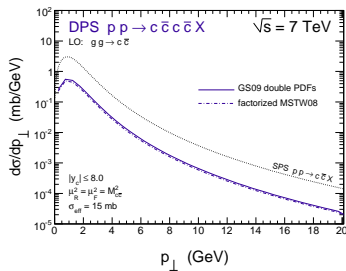
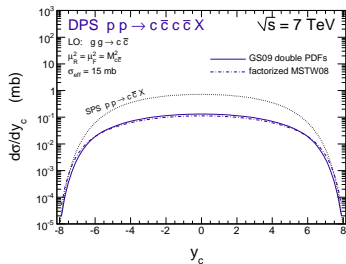
DPS results



Large transverse masses of the cc or $\bar{c}\bar{c}$ pairs



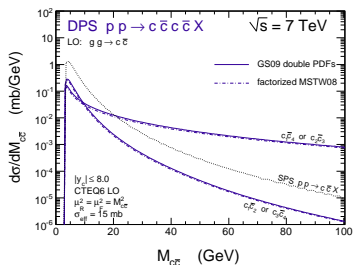
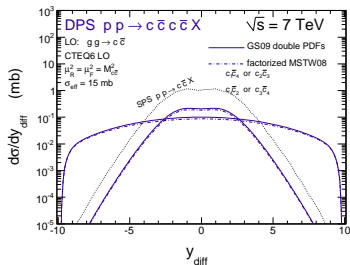
Evolution of dPDFs



Gaunt-Stirling dPDFs with evolution
 very small effect of the evolution



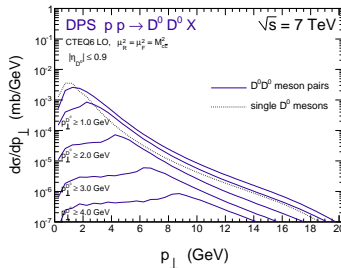
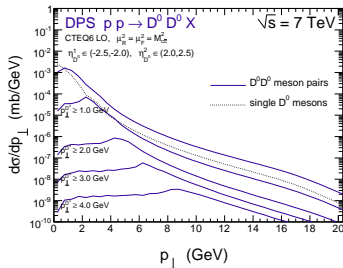
Evolution of dPDFs



Gaunt-Stirling dPDFs with evolution
 very small effect of the evolution



From quarks/antiquarks to D mesons



ATLAS: $-2.5 < \eta_1 < -2.0$ and $2.0 < \eta_2 < 2.5$

ALICE: $-0.9 < \eta_1, \eta_2 < 0.9$



$D^0\bar{D}^0$ and \bar{D}^0D^0 correlations

Table: The DPS cross section $(\sigma_{D^0\bar{D}^0} + \sigma_{\bar{D}^0D^0})/2$ in mb for the production of one meson in $\eta_1 \in (-2.5, 2.0)$ and the second meson in $\eta_2 \in (2.0, 2.5)$ (ATLAS, CMS) - second column, and for $\eta_1, \eta_2 \in (-0.9, 0.9)$ (ALICE) - third column, for different lower cuts on both mesons transverse momenta.

$p_{t,min}$ (GeV)	ATLAS or CMS	ALICE	ALICE $p_{t,D^0\bar{D}^0} > 4$ GeV
0.0	$2.59 \cdot 10^{-3}$	$0.66 \cdot 10^{-2}$	$0.58 \cdot 10^{-3}$
1.0	$1.47 \cdot 10^{-4}$	$2.48 \cdot 10^{-3}$	$0.41 \cdot 10^{-3}$
2.0	$0.32 \cdot 10^{-5}$	$2.93 \cdot 10^{-4}$	$1.54 \cdot 10^{-4}$
3.0	$2.55 \cdot 10^{-7}$	$0.35 \cdot 10^{-4}$	$2.46 \cdot 10^{-5}$
4.0	$2.33 \cdot 10^{-8}$	$0.62 \cdot 10^{-5}$	$0.49 \cdot 10^{-5}$

LHCb: $2.0 < y_D < 4.0, 3 \text{ GeV} < p_{t,D} < 12 \text{ GeV},$

$\sigma_{D^0\bar{D}^0} + \sigma_{\bar{D}^0D^0} = 51.8 \text{ nb}$

missing emissions of $c\bar{c}$ from c or \bar{c} ?



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

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

12 dimensions (!)



DPS in k_t -factorization

Each individual scattering in the k_t -factorization approach

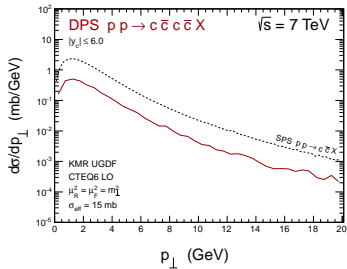
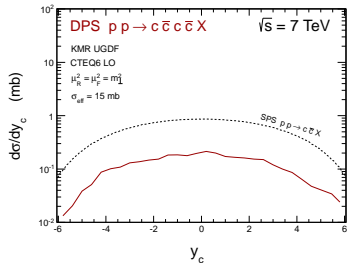
$$\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int |\overline{\mathcal{M}}_{\text{off}}|^2 \delta(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2) \frac{d^2 k_{1t}}{\pi} \frac{d^2 k_{2t}}{\pi}$$

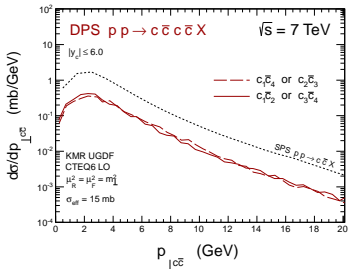
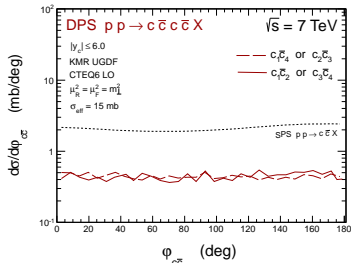
$$\frac{d\sigma}{dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int |\overline{\mathcal{M}}_{\text{off}}|^2 \delta(\vec{k}_{3t} + \vec{k}_{4t} - \vec{p}_{3t} - \vec{p}_{4t}) \mathcal{F}(x_3, k_{3t}^2, \mu^2) \mathcal{F}(x_4, k_{4t}^2, \mu^2) \frac{d^2 k_{3t}}{\pi} \frac{d^2 k_{4t}}{\pi}$$

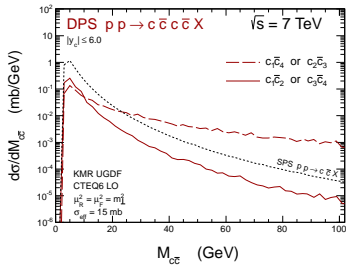
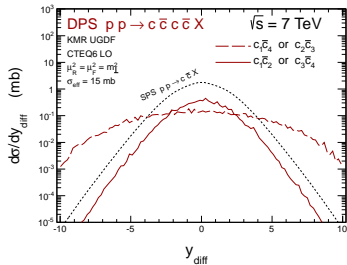
Effectively **16 dimensions**, Monte Carlo method

First results will be shown now



DPS in k_T -factorization, results

DPS in k_T -factorization, results

DPS in k_T -factorization, results

DPS in k_T -factorization, LHCb two-meson production

First results from LHCb Collaboration: [arXiv: 1205.0975 \(hep-ex\)](https://arxiv.org/abs/1205.0975)

$3 \text{ GeV} < p_T < 12 \text{ GeV}, 2 < y < 4$

$$BR(c \rightarrow D^0) = 0.565$$

$$BR(c \rightarrow D^+) = 0.22$$

$$BR(c \rightarrow D_s^+) = 0.116$$

Table: k_T -factorization predictions (preliminary) and LHCb data

$M_1 M_2$	theory	LHCb result
$D^0 D^0$	445.53 nb	$690 \pm 40 \pm 70$ nb
$D^0 D^+$	173.48 nb	$520 \pm 80 \pm 40$ nb
$D^0 D_s^+$	91.47 nb	$270 \pm 50 \pm 40$ nb
$D^+ D^+$	67.55 nb	$80 \pm 10 \pm 10$ nb
$D^+ D_s^+$	35.62 nb	$70 \pm 15 \pm 10$ nb

k_T -factorization DPS almost consistent with LHCb results

In the whole phase space $\sigma_{tot} = 1.45 \text{ mb}$ (huge!)



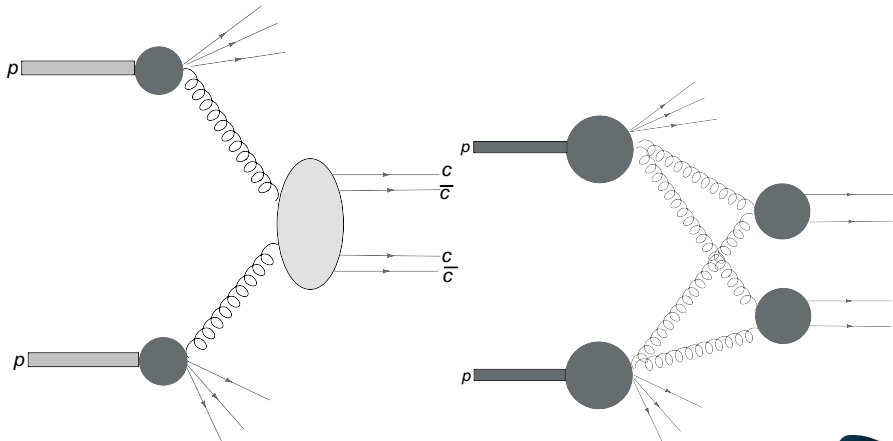
SPS production of $c\bar{c}c\bar{c}$ 

Figure: SPS (left) and DPS (right) mechanisms of $(c\bar{c})(c\bar{c})$ production.



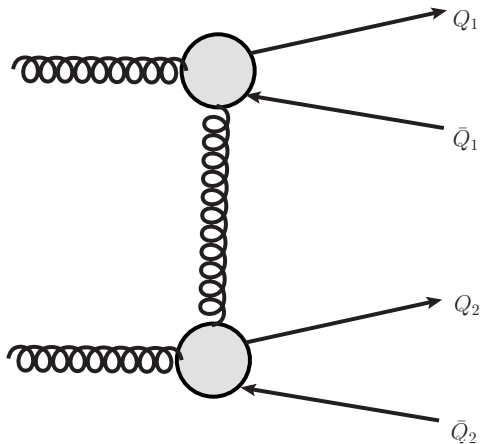
SPS production of $c\bar{c}c\bar{c}$ 

Figure: Subprocess: $gg \rightarrow (c\bar{c})(c\bar{c})$ production.



Impact factors

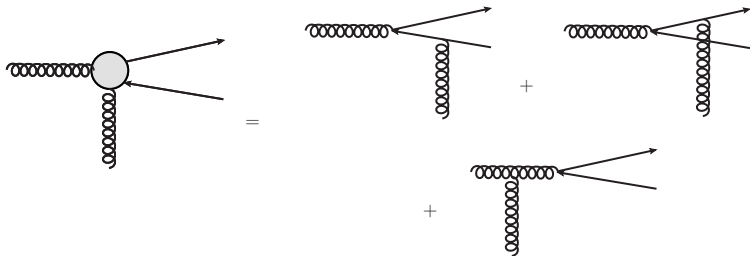


Figure: Coupling of (t-channel) gluon to g, Q, \bar{Q}

9 diagrams for the $gg \rightarrow c\bar{c}c\bar{c}$ cross section.



gg \rightarrow $c\bar{c}c\bar{c}$ collisions at high energy

1) In the **lightcone Fock-state expansion** of the incoming, physical, colliding gluons.

For the first gluon:

$$|g^a(\mathbf{b})\rangle = \sqrt{1 - n_{Q\bar{Q}}} |g_{\text{bare}}^a\rangle + \int d^2\mathbf{r} dz \Psi(\mathbf{z}, \mathbf{r}) |[Q\bar{Q}]_8^a; \mathbf{z}, \mathbf{r}\rangle. \quad (2)$$

Here, quark and antiquark in the gluon carry fractions z , $1 - z$ of the gluon's large light-cone plus-momentum and are separated by a distance \mathbf{r} in the impact parameter plane.

For the second gluon:

$$|g^c(\mathbf{b})\rangle = \sqrt{1 - n_{Q\bar{Q}}} |g_{\text{bare}}^c\rangle + \int d^2\mathbf{s} du \Psi(\mathbf{u}, \mathbf{s}) |[Q\bar{Q}]_8^c; \mathbf{u}, \mathbf{s}\rangle. \quad (3)$$

2) The normalized color-states of the quark-antiquark system in the **color-octet** and **color-singlet** states are:

$$|[Q\bar{Q}]_8^a\rangle = \sqrt{2} (t^a)_j^i |Q_i \bar{Q}'^j\rangle, \quad |[Q\bar{Q}]_1\rangle = \frac{1}{\sqrt{N_c}} \delta_j^i |Q_i \bar{Q}'^j\rangle.$$



gg \rightarrow $c\bar{c}c\bar{c}$ collisions at high energy

3) Interaction (gluon exchange) like helicity-conserving potential

Gunion-Soper:

$$V(\mathbf{b} + \mathbf{b}_i - \mathbf{s}_j) = (-i) \frac{a_S}{\pi} \int \frac{d^2 \mathbf{q}}{[\mathbf{q}^2 + \mu_G^2]} \exp[i(\mathbf{b} + \mathbf{b}_i - \mathbf{s}_j) \mathbf{q}] T_i^b \otimes T_j^b. \quad (5)$$

4) **Construct amplitude** (technically more complicated).

5) The total cross section, after **integrating** the squared amplitude **over** the **impact parameter** and **averaging over initial gluon colors**

$$\sigma_{tot} = \frac{1}{(N_c^2 - 1)^2} \sum_{a,c} \int d^2 \mathbf{b} |A(g^a g^c \rightarrow Q\bar{Q}Q\bar{Q}; \mathbf{b})|^2. \quad (6)$$



gg collisions, mixed representation

$$\sigma_{tot} = \int dz d^2 r du d^2 \mathbf{s} |\Psi(z, \mathbf{r})|^2 |\Psi(u, \mathbf{s})|^2 \Sigma(z, \mathbf{r}; u, \mathbf{s}). \quad (7)$$

where

$$\begin{aligned} \Sigma(z, \mathbf{r}; u, \mathbf{s}) &= \left(\frac{N_C^2}{N_C^2 - 1} \right)^2 \\ &\cdot \left\{ \sigma_{DD}((1-z)\mathbf{r}, (1-u)\mathbf{s}) + \sigma_{DD}((1-z)\mathbf{r}, u\mathbf{s}) - \frac{1}{N_C^2} \sigma_{DD}((1-z)\mathbf{r}, \mathbf{s}) \right. \\ &+ \sigma_{DD}(z\mathbf{r}, (1-u)\mathbf{s}) + \sigma_{DD}(z\mathbf{r}, u\mathbf{s}) - \frac{1}{N_C^2} \sigma_{DD}(z\mathbf{r}, \mathbf{s}) \\ &\left. - \frac{1}{N_C^2} \left(\sigma_{DD}(\mathbf{r}, (1-u)\mathbf{s}) + \sigma_{DD}(\mathbf{r}, u\mathbf{s}) - \frac{1}{N_C^2} \sigma_{DD}(\mathbf{r}, \mathbf{s}) \right) \right\}. \end{aligned} \quad (8)$$



gg collisions, mixed representation

The Born level dipole-dipole cross section reads

$$\sigma_{DD}(\mathbf{r}, \mathbf{s}) = \frac{N_c^2 - 1}{N_c^2} \frac{4\pi\alpha_s^2}{\mu_G^2} \left[1 - \mu_G r K_1(\mu_G r) - \mu_G s K_1(\mu_G s) + \mu_G |\mathbf{r} - \mathbf{s}| K_1(\mu_G |\mathbf{r} - \mathbf{s}|) \right] \quad (9)$$

The light-cone wave function for the $g \rightarrow Q\bar{Q}$ transition can be obtained from the well-known case for the photon as

Nikolaev-Zakharov:

$$|\Psi(z, \mathbf{r})|^2 = \frac{a_s(r)}{\delta a_{em}} |\Psi_\gamma(z, \mathbf{r})|^2 = \frac{a_s(r)}{(2\pi)^2} \left[\left(z^2 + (1-z)^2 \right) m_Q^2 K_1^2(m_Q r) + m_Q^2 K_0^2(m_Q r) \right] \quad (10)$$

where $K_{0,1}$ are generalized Bessel functions,
and in the spirit of collinear factorization, we took the gluon to be on-shell.



gg collisions, momentum representation

The compact cross section formula:

$$d\sigma = \frac{N_c^2 - 1}{N_c^2} \frac{4\pi^2 a_s^2}{[\mathbf{q}^2 + \mu_G^2]^2} l(z, \mathbf{k}, \mathbf{q}) l(u, l, -\mathbf{q}) dz \frac{d^2 \mathbf{k}}{(2\pi)^2} du \frac{d^2 l}{(2\pi)^2} \frac{d^2 \mathbf{q}}{(2\pi)^2}. \quad (11)$$

- 1) 8-dim integration
- 2) Impact factor are quite complicated.
- 3) First pair:

$$\mathbf{p}_Q = \mathbf{k} + z\mathbf{q}, \quad \mathbf{p}_{\bar{Q}} = -\mathbf{k} + (1-z)\mathbf{q}, \quad (12)$$

- 4) Second pair:

$$\mathbf{p}_Q = l - u\mathbf{q}, \quad \mathbf{p}_{\bar{Q}} = -l - (1-u)\mathbf{q}. \quad (13)$$



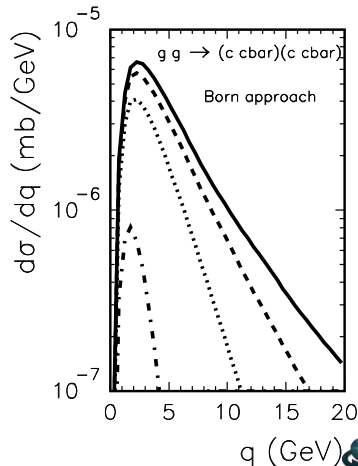
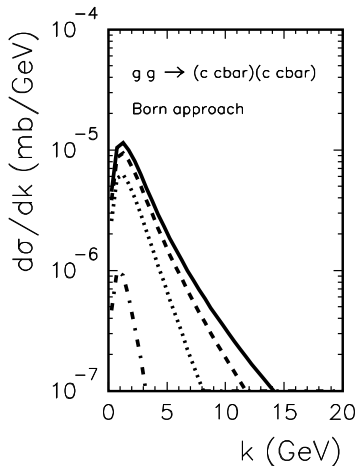
$pp \rightarrow (Q\bar{Q})(Q\bar{Q})$ inclusive cross section

$$\sigma_{pp \rightarrow (Q\bar{Q})(Q\bar{Q})}(W) = \int dx_1 dx_2 g(x_1, \mu_F^2) g(x_2, \mu_F^2) \sigma_{gg \rightarrow (Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2}), \quad (14)$$

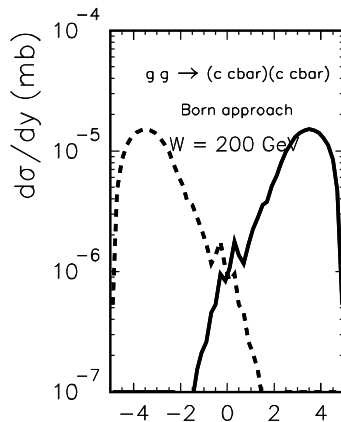
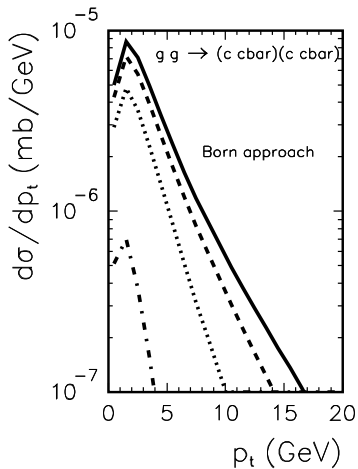
- $\sigma_{gg \rightarrow (Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2})$ - elementary cross section for $gg \rightarrow c\bar{c}c\bar{c}$.
Calculated and stored.
- $g(x_1, \mu_F^2), g(x_2, \mu_F^2)$ - collinear gluon distributions from the literature.
- The integral over $\xi_1 = \log_{10}(x_1)$ and $\xi_2 = \log_{10}(x_2)$ is performed next instead of x_1 and x_2 .
- $\hat{s} = x_1 x_2 W^2$.
- $\mu_F^2 = 4m_Q^2$ (or m_Q^2).



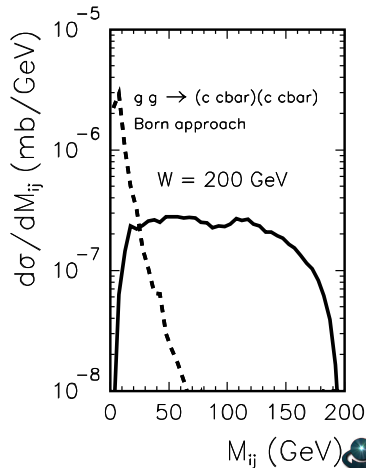
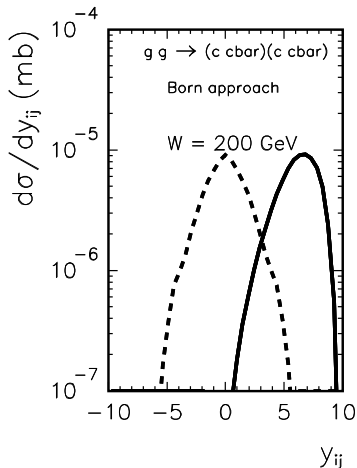
gg collisions, auxiliary distributions



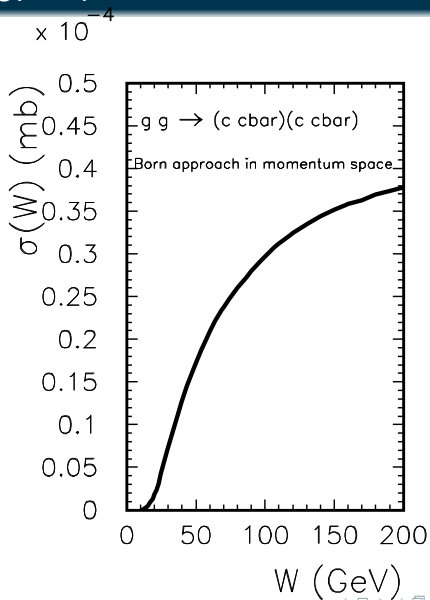
gg collisions, single particle distributions

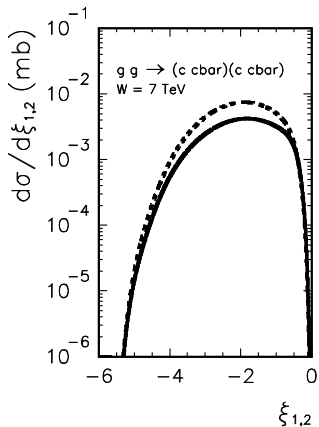


gg collisions, correlation observables



gg collisions, energy dependence



pp collisions, sensitivity to x_1 and x_2 

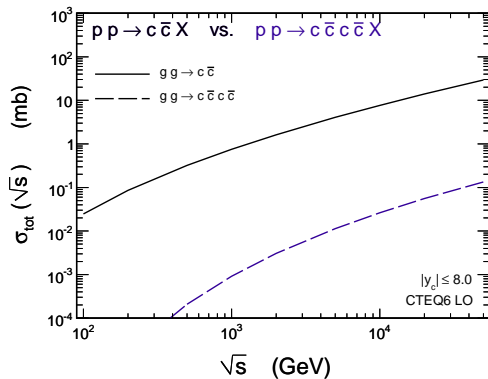
Rather intermediate x -range:

(a) gluons relatively well known

(b) collinear approach works

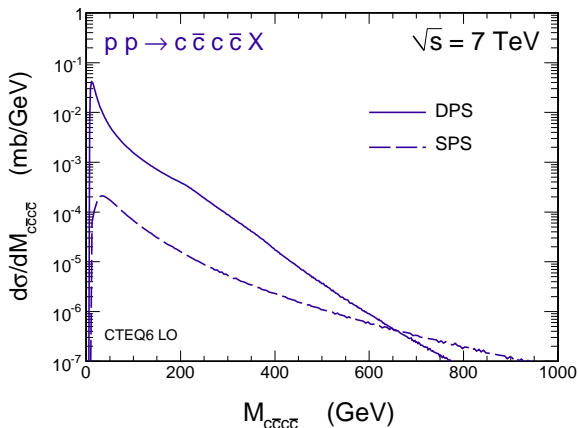


pp collisions, $c\bar{c}$ versus $c\bar{c}c\bar{c}$



Only about 1 % at high energies



pp collisions, $c\bar{c}c\bar{c}$ invariant mass distr.

At intermediate invariant masses $SPS \ll DPS$.

At very large invariant masses $SPS \gg DPS$.



SPS versus DPS

- Further investigation needed
- Compare **single particle distributions**
- Compare **correlation observables** (!)
- Compare SPS and DPS for DD and $\bar{D}\bar{D}$
- Large rapidity gaps for SPS enhanced by **BFKL ladders** ?



Conclusions

- k_t -factorization gives slightly **too small cross section** compared to recent data on D meson production.

Something missing ?

- Many small subleading contributions (**single and double diffraction, exclusive $c\bar{c}$, photon induced processes**).
- **Huge contribution** of double-parton scattering for $pp \rightarrow (c\bar{c})(c\bar{c})X$.
- Especially large cross section for cc or $\bar{c}\bar{c}$ with **large rapidity gap** between them.
- Especially large cross section for **large $p_{t,cc}$** .
- Idea: look at D^0D^0 (or $\bar{D}^0\bar{D}^0$) correlations.
ATLAS and CMS: at the edges of main detectors,
ALICE: large $p_{t,DD}$
- **Smaller contribution** of single-parton scattering for $pp \rightarrow (c\bar{c})(c\bar{c})X$.



Conclusions

- $SPS \ll DPS$ at intermediate invariant masses of $c\bar{c}c\bar{c}$.
- $SPS \gg DPS$ at large invariant mass of $c\bar{c}c\bar{c}$.
- Enhancement of large rapidity gap region of SPS by **BFKL ladders**.
- Result in k_T factorization for the same flavour charmed mesons **consistent with recent LHCb data**
- A detailed comparison of DPS and SPS for **mesons** or **nonphotonic electrons** is needed.

Thank You for attention!

