

Double $c\bar{c}$ production

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Workshop on Multi-Parton Interactions at the LHC
CERN, Switzerland, December 3 - 7, 2012



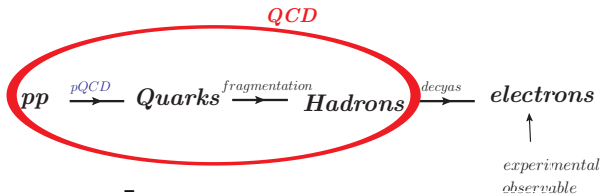
Contents

- 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 $c\bar{c}c\bar{c}$
- Same flavour DD production (first results)
(relevance to the recent LHCb results, Vanya Belayev's talk)
- $pp \rightarrow J/\psi J/\psi X$
covered in the Sergey Baranov's talk
- Conclusions

Low-x physics because c quark mass rather small

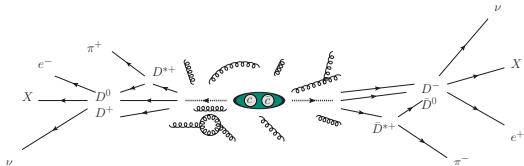


3-step process



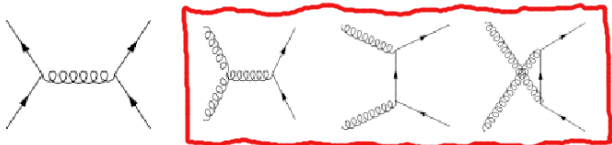
- ❶ Heavy quarks $Q\bar{Q}$ pairs production
 - $m_c = 1.5 \text{ GeV}, m_b = 4.75 \text{ GeV} \rightarrow$ perturbative QCD
- ❷ Heavy quarks hadronization (fragmentation)
- ❸ Semileptonic decays of D and B mesons

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

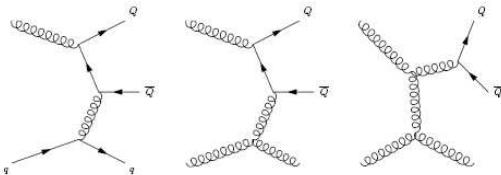


Dominant mechanisms of $Q\bar{Q}$ production

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

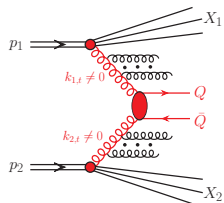


- gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ annihilation important only near the threshold
- some of next-to-leading order diagrams:



NLO contributions \rightarrow K-factor

k_t -factorization (semihard) approach



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

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

- multi-differential cross section

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

- 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

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

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



Unintegrated parton distribution functions

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

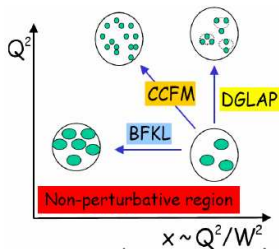
$$xp_k(x, \mu_F^2) = \int_0^\infty d\kappa_t^2 \mathcal{F}(x, \kappa_t^2, \mu_F^2)$$

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

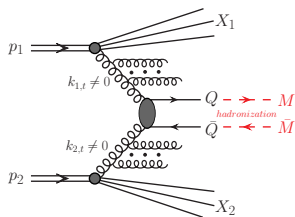
gg-fusion dominance \Rightarrow **great test of existing unintegrated gluon densities!**
especially at LHC (small- x)

several models:

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



Fragmentation functions technique



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

- from heavy quarks to heavy mesons:

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

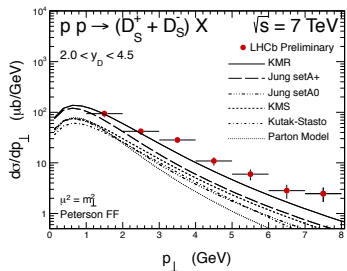
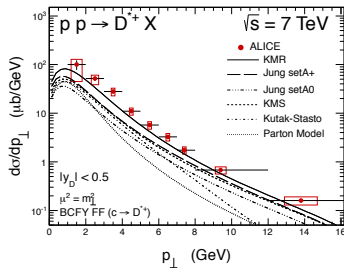
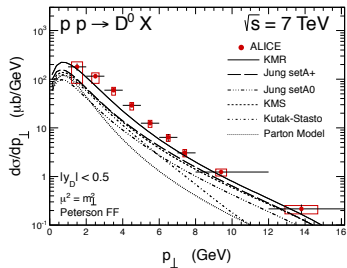
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

- **approximation:**

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



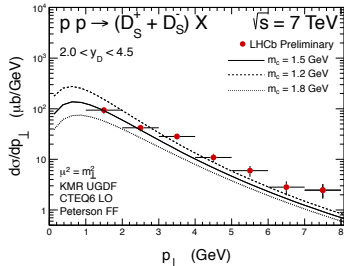
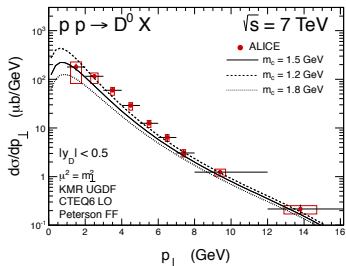
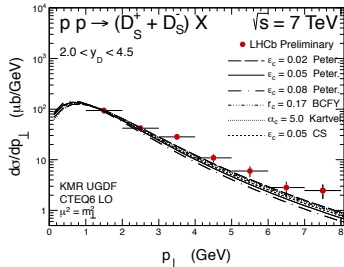
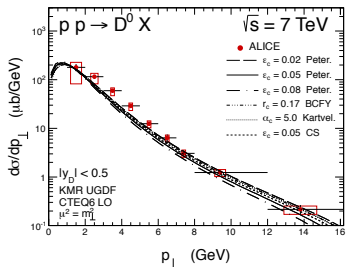
D mesons, different UGDFs



- 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

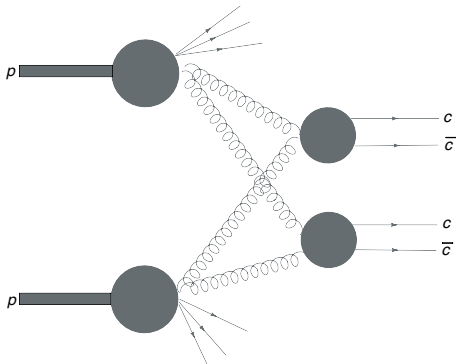


Effects of hadronization and quark mass uncertainty for KMR UGDF



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

Consider two hard (parton) scatterings



Luszczak, Maciula, Szczurek, arXiv:1111.3255,
Phys.Rev. **D85** (2012) 094034,
Maciula, Szczurek, in preparation



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: **Snigirev**

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



What the σ_{eff} is?

It is much easier to understand the DPS in the impact parameter space.

Then one considers even **more generalized objects**:

$$\Gamma_{i,j}(x_1, x_2; \mathbf{b}_1, \mathbf{b}_2; \mu_1^2, \mu_2^2) = F_{i,j}(x_1, x_2; \mu_1^2, \mu_2^2) f(\mathbf{b}_1) f(\mathbf{b}_2) \quad .$$

$f(\mathbf{b}_i)$ **universal functions for all kinds of partons** with:

$$\int f(\mathbf{b}_1) f(\mathbf{b}_1 - \mathbf{b}) d^2 b_1 d^2 b = \int T(\mathbf{b}) d^2 b = 1 \quad ,$$

where

$$T(\mathbf{b}) = \int f(\mathbf{b}_1) f(\mathbf{b}_1 - \mathbf{b}) d^2 b_1$$

is the overlap function.

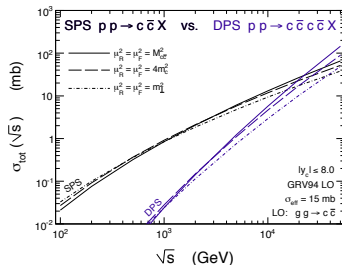
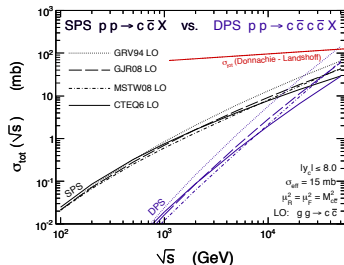
Then:

$$\sigma_{eff} = \left(\int d^2 b (T(b))^2 \right)^{-1} \quad .$$

Universal function



DPS results, collinear approximation

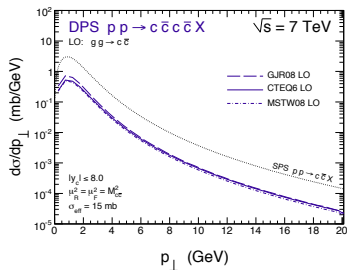
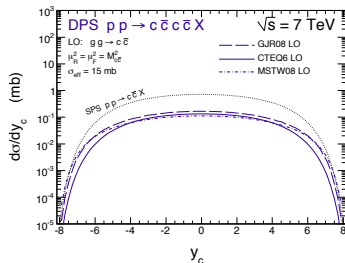


Inclusive cross section **more difficult** to calculate

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



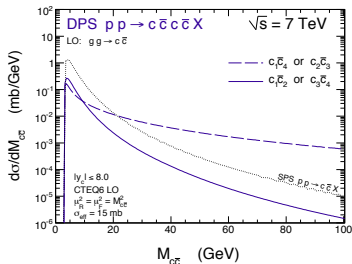
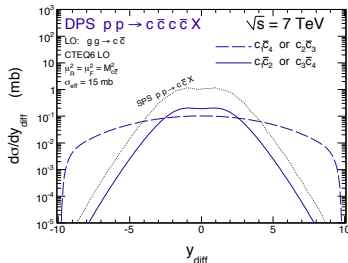
DPS results, collinear approximation



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



DPS results, collinear approximation

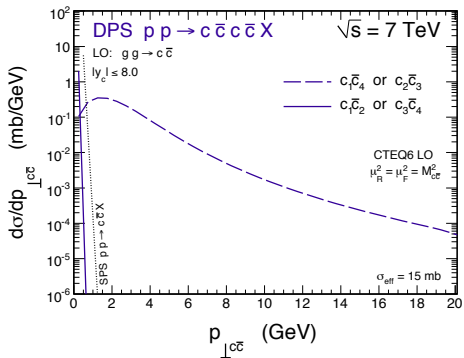


DPS: large rapidity differences, large invariant masses

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



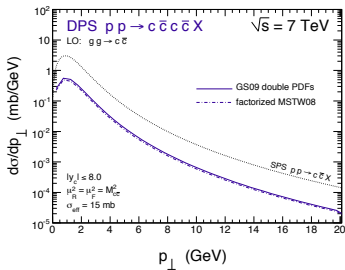
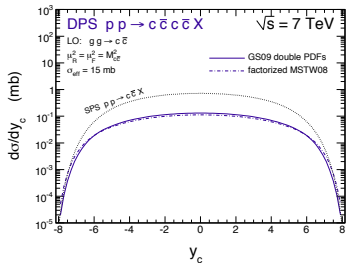
DPS results, collinear approximation



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



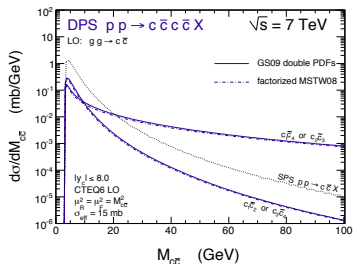
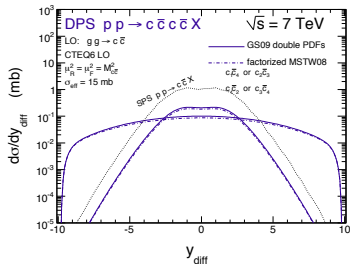
Evolution of dPDFs



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



Evolution of dPDFs

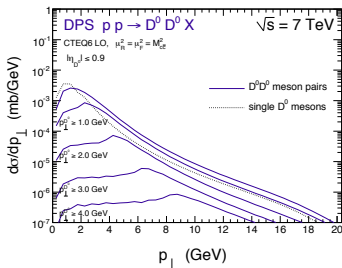
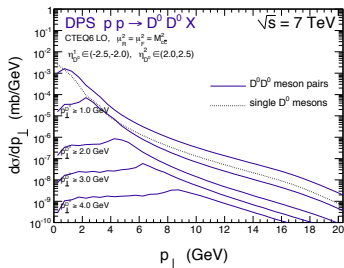


Gaunt-Stirling dPDFs with evolution
very small effect of the evolution



From quarks/antiquarks to D mesons

large transverse momentum of cc or $\bar{c}\bar{c}$
 transverse $D^0\bar{D}^0$ momentum distribution



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

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

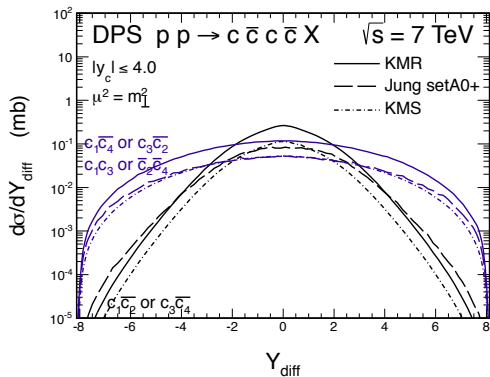
$$\frac{d\sigma}{dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int |\overline{\mathcal{M}}_{\text{off}}|^2 \delta(\vec{k}_{3t} + \vec{k}_{4t} - \vec{p}_{3t} - \vec{p}_{4t}) \mathcal{F}(x_3, k_{3t}^2, \mu^2) \mathcal{F}(x_4, k_{4t}^2, \mu^2) \frac{d^2 k_{3t}}{\pi} \frac{d^2 k_{4t}}{\pi}$$

Effectively 16 dimensions, Monte Carlo method

Maciula-Szczurek in preparation



DPS k_T -factorization calculation



The same situation as in collinear approach



DPS k_T -factorization calculation vs LHCb

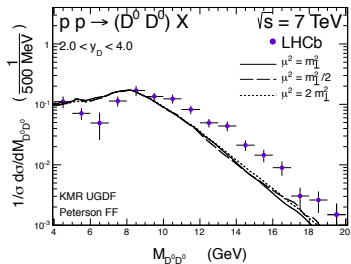
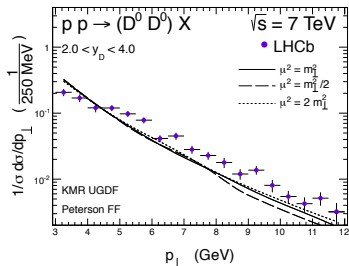
Table: Total cross sections

Mode	σ_{tot}^{EXP}	KMR	Jung setA0+	KMS
$D^0 D^0$	$690 \pm 40 \pm 70$	256	101	100
$D^0 D^+$	$520 \pm 80 \pm 70$	204	81	80
$D^0 D_S^+$	$270 \pm 50 \pm 40$	72	29	28
$D^+ D^+$	$80 \pm 10 \pm 10$	41	16	16
$D^+ D_S^+$	$70 \pm 15 \pm 10$	29	12	11
$D_S^+ D_S^+$	—	10	4	4

LHCb acceptance:

$$2 < y < 4, \quad 3 \text{ GeV} < p_{\perp} < 12 \text{ GeV}$$

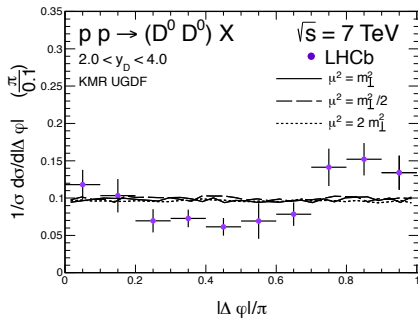


DPS k_T -factorization calculation vs LHCb

missing SPS contributions (extra gluon splitting) ?



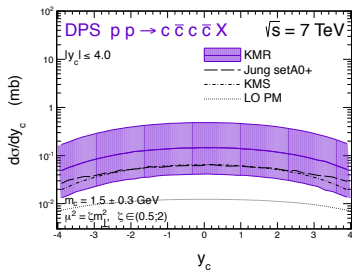
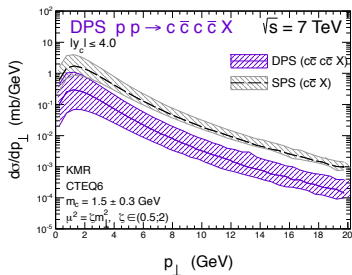
DPS k_T -factorization calculation vs LHCb

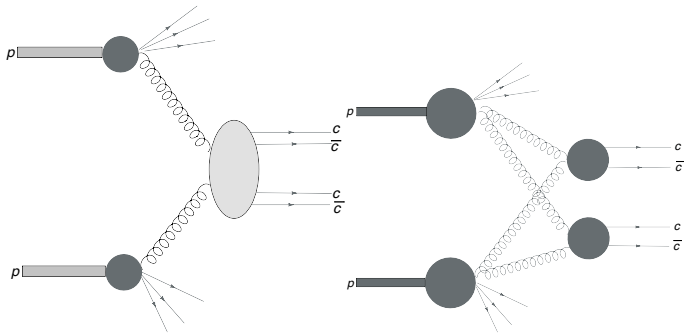


missing SPS contributions ?



One and two pair production, uncertainties



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

W. Schäfer, A. Szczurek, arXiv:1203.4129(hep-ph), Phys. Rev. **D85** (2012) 094029.



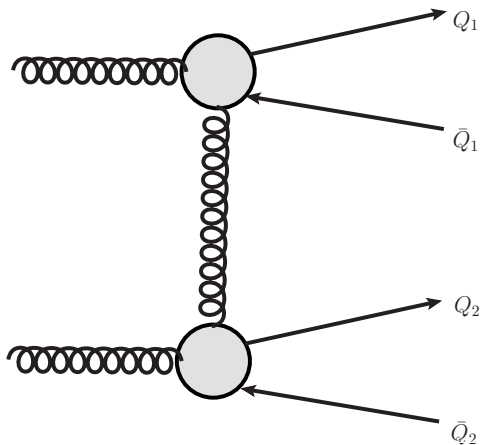
SPS production of $c\bar{c}c\bar{c}$ 

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



Impact factors

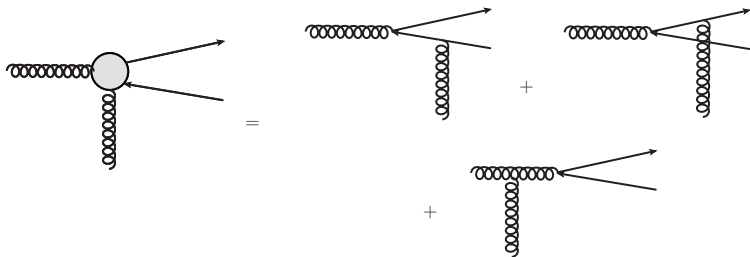


Figure: Coupling of (t-channel) gluon to g, Q, \bar{Q}

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



gg collisions, momentum representation

The compact cross section formula:

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

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

$$\mathbf{p}_Q = \mathbf{k} + z\mathbf{q}, \quad \mathbf{p}_{\bar{Q}} = -\mathbf{k} + (1-z)\mathbf{q}, \quad (3)$$

- 4) **Second pair:**

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



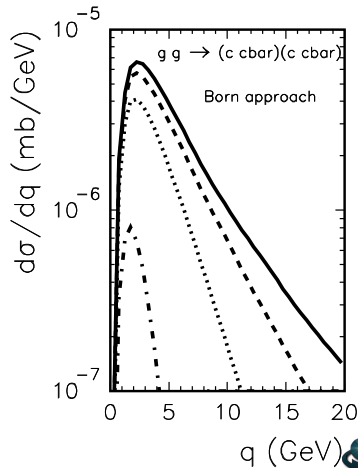
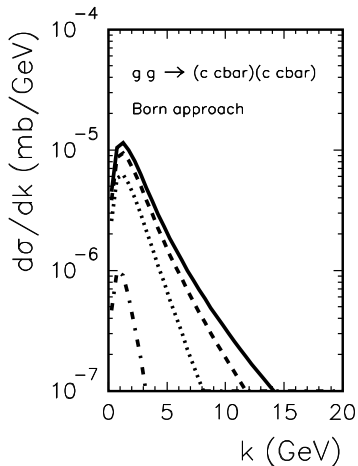
$pp \rightarrow (Q\bar{Q})(Q\bar{Q})$ inclusive cross section

$$\sigma_{pp \rightarrow (Q\bar{Q})(Q\bar{Q})}(W) = \int dx_1 dx_2 g(x_1, \mu_F^2) g(x_2, \mu_F^2) \sigma_{gg \rightarrow (Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2}), \quad (5)$$

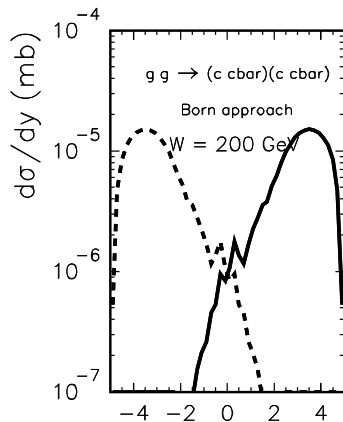
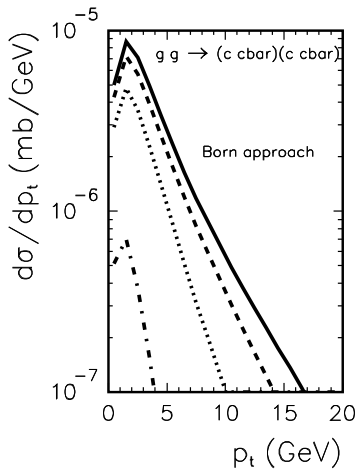
- $\sigma_{gg \rightarrow (Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2})$ - elementary cross section for $gg \rightarrow c\bar{c}c\bar{c}$.
Calculated and stored.
- $g(x_1, \mu_F^2), g(x_2, \mu_F^2)$ - collinear gluon distributions from the literature.
- The integral over $\xi_1 = \log_{10}(x_1)$ and $\xi_2 =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



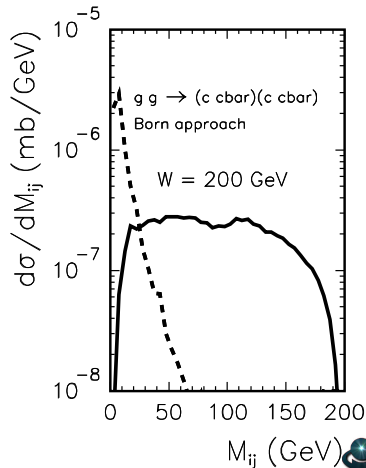
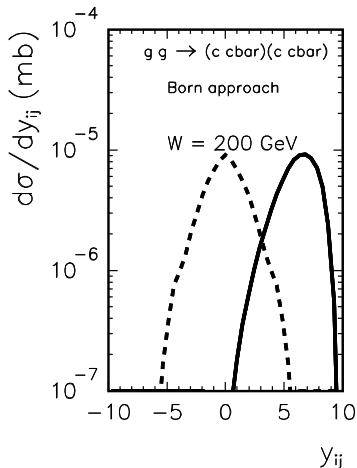
gg collisions, auxiliary distributions



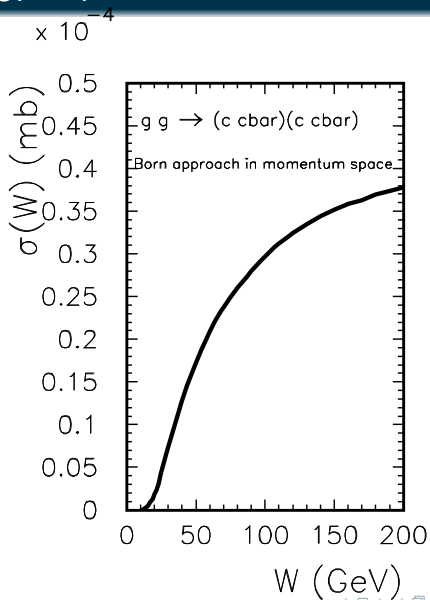
gg collisions, single particle distributions

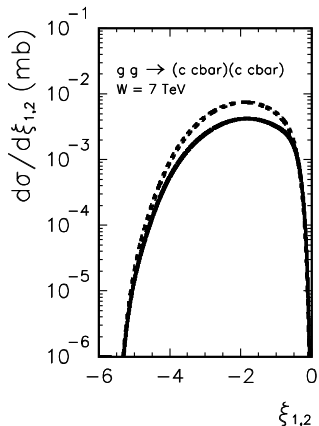


gg collisions, correlation observables



gg collisions, energy dependence



pp collisions, sensitivity to x_1 and x_2 

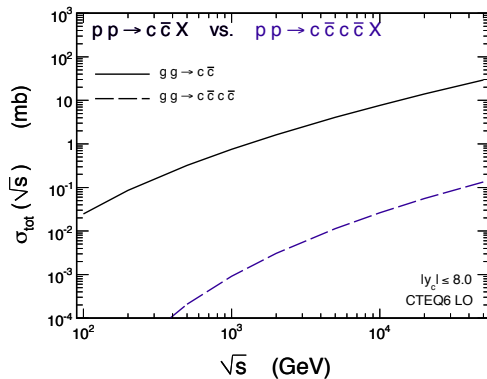
Rather intermediate x -range:

(a) gluons relatively well known

(b) collinear approach works

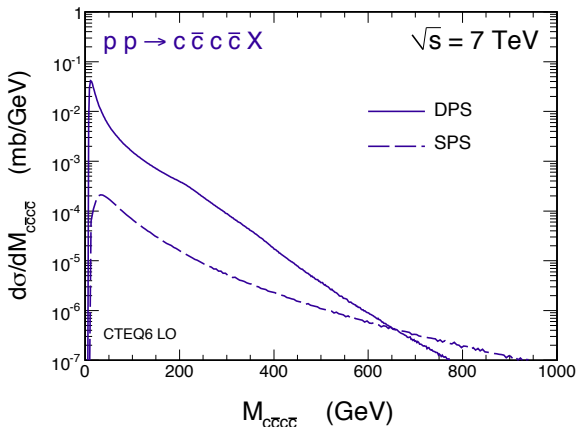


pp collisions, $c\bar{c}$ versus $c\bar{c}c\bar{c}$



Only about 1 % at high energies



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

At intermediate invariant masses $\text{SPS} \ll \text{DPS}$.

At very large invariant masses $\text{SPS} \gg \text{DPS}$.



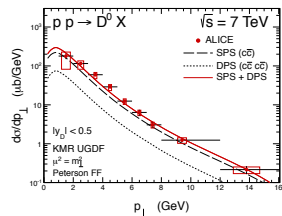
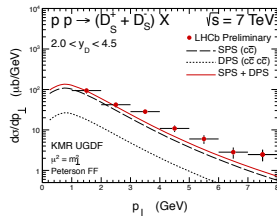
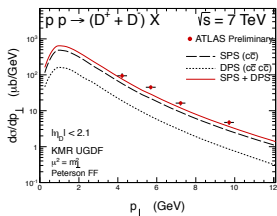
DPS contribution to inclusive D meson distributions

Let us consider for example transverse momentum distribution

$$\begin{aligned}
 \frac{d\sigma_{inc}^{D_i, DPS}}{dp_t} = & P_{D_i}(1 - P_{D_i}) \frac{d\sigma^D}{dp_{1,t}} \Big|_{p_{1,t}=p_t} (-2.1 < \eta_1 < 2.1, -\infty < \eta_2 < \infty) \\
 & + P_{D_i}(1 - P_{D_i}) \frac{d\sigma^D}{dp_{2,t}} \Big|_{p_{2,t}=p_t} (-\infty < \eta_1 < \infty, -2.1 < \eta_2 < 2.1) \\
 & + P_{D_i}P_{D_i} \frac{d\sigma^D}{dp_{1,t}} \Big|_{p_{1,t}=p_t} (-2.1 < \eta_1 < 2.1, -\infty < \eta_2 < \infty) \\
 & + P_{D_i}P_{D_i} \frac{d\sigma^D}{dp_{2,t}} \Big|_{p_{2,t}=p_t} (-\infty < \eta_1 < \infty, -2.1 < \eta_2 < 2.1). \quad (6)
 \end{aligned}$$



DPS contribution to inclusive D meson distributions



even slightly larger(!)



SPS versus DPS

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



DPS in $pp \rightarrow J/\psi J/\psi X$

theory:

Berezhnoy-Likhoded-Luchinsky-Novoselov

Kom-Kulesza-Stirling

Baranov-Snigirev-Zotov

experiment: LHCb

mechanisms included so far:

- $gg \rightarrow \text{boxes} \rightarrow J/\psi J/\psi$ (SPS)
- $(gg \rightarrow J/\psi X) \times (gg \rightarrow J/\psi X)$ (DPS)

problems:

- $\sigma_{SPS}^{box} \sim \sigma_{DPS}$

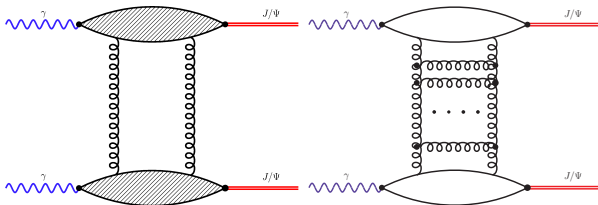
solution:

- clever cuts (Baranov-Snigirev-Schäfer-Szczurek-Zotov, arXiv:1210.1806(hep-ph),)

DPS – large rapidity distance between two J/ψ 's



A new missing SPS mechanism



higher-order, formally three-loops

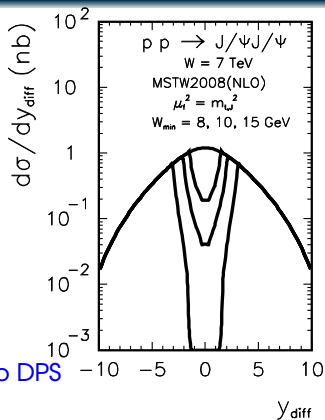
in addition to box (SPS) and DPS

$$(pp \rightarrow J/\psi gX) \otimes (pp \rightarrow J/\psi gX)$$

$$(pp \rightarrow \chi_c(\rightarrow J/\psi \gamma)X) \otimes (pp \rightarrow \chi_c(\rightarrow J/\psi \gamma)X)$$



The missing mechanism



similar characteristics to DPS

smaller than DPS

$$y_{\text{diff}} = y_1 - y_2$$



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 $D^0\bar{D}^0$ (or \bar{D}^0D^0) correlations (LHCb)
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!

