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

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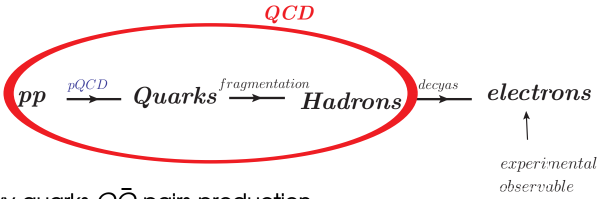
Contents

- General framework of $c\bar{c}$ production
- D meson production at LHC(R. Maciula's talk)
- 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
- Conclusions

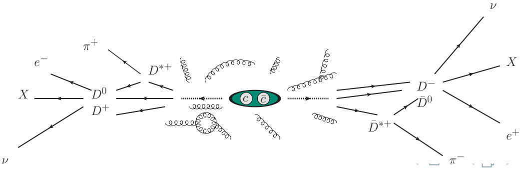
Low-x physics because c quark mass rather small

3-step process



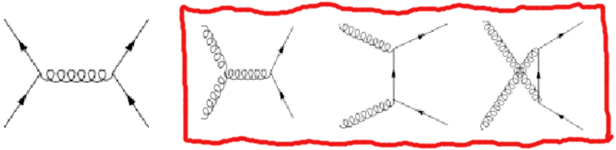
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

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

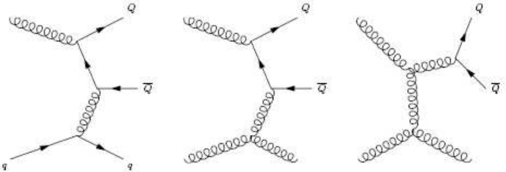


Dominant mechanisms of $Q\bar{Q}$ production

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

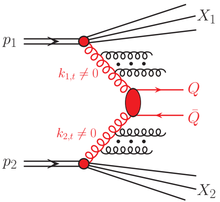


- **gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ anihilation important only near the threshold
- some of next-to-leading order diagrams:



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

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

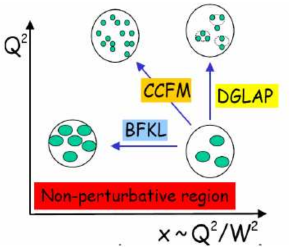
$$xp_k(x, \mu_F^2) = \int_0^\infty d\kappa_t^2 \mathcal{F}(x, \kappa_t^2, \mu_F^2)$$

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

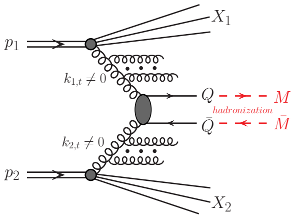
gg-fusion dominance ⇒ great test of existing unintegrated gluon densities!
especially at LHC (small-x)

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)

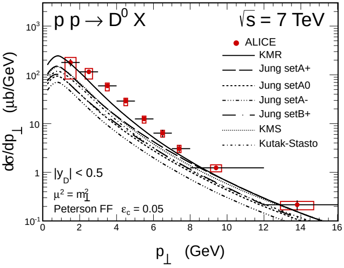
- from heavy quarks to heavy mesons:

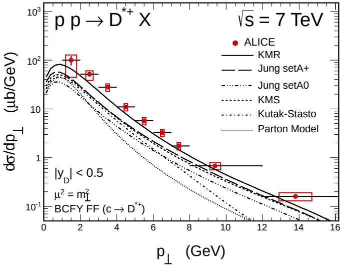
$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

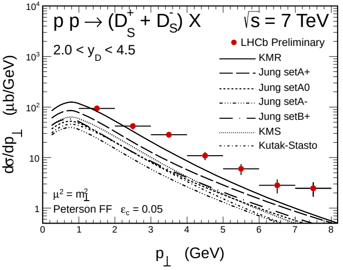
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

- **approximation:**
  rapidity unchanged in the fragmentation process $\rightarrow y_Q \approx y_M$

D mesons, different UGDFs

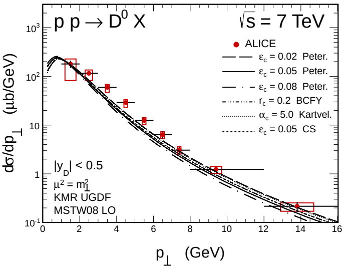


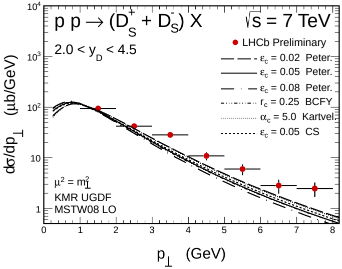


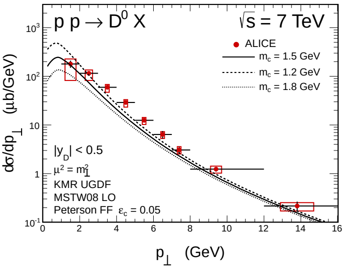


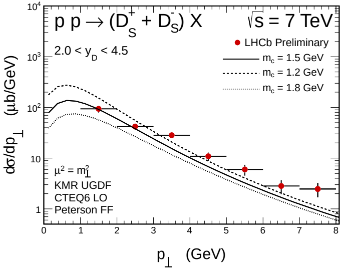
- various UGDFs models → crucial test of their applicability at high energies and small *x*-values
- only KMR model gives good description of the ALICE and LHCb data
- significant difference between LO parton model and LO k_t-factorization

Effects of hadronization and quark mass uncertainty for KMR UGDF



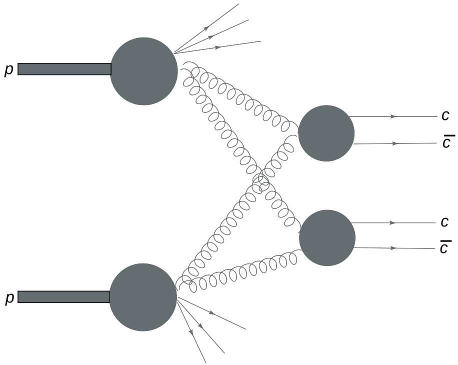






Production of two $c\bar{c}$ pairs in double-parton scattering

Consider two hard (parton) scatterings



Luszczak, Maciula, Szczurek, arXiv:1111.3255,
Phys.Rev. **D85** (2012) 094034,
Maciula, Szczurek, arXiv:1301.4469, in print in Phys. Rev. D

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 (12-15 mb).

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

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:

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

where

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

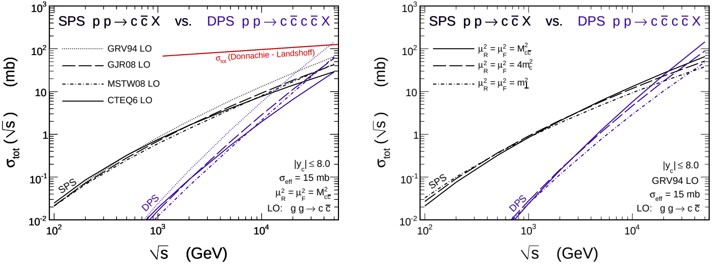
is the overlap function.

Then:

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

Universal function

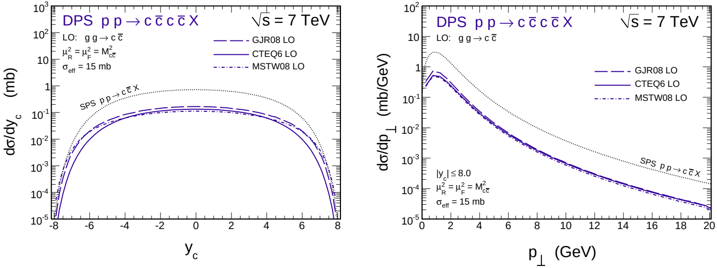
DPS results, collinear approximation



Inclusive cross section more difficult to calculate

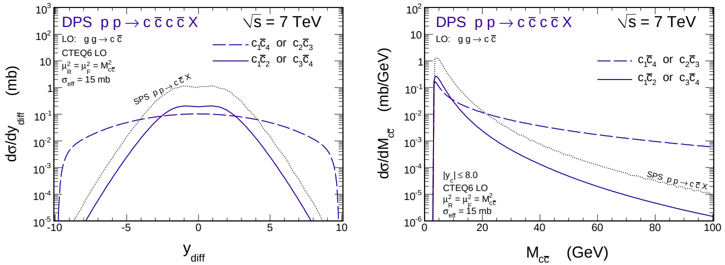
$$\sigma_{SS}, 2\sigma_{DS} < \sigma_c^{inclusive} < \sigma_{SS} + 2\sigma_{DS}$$

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.

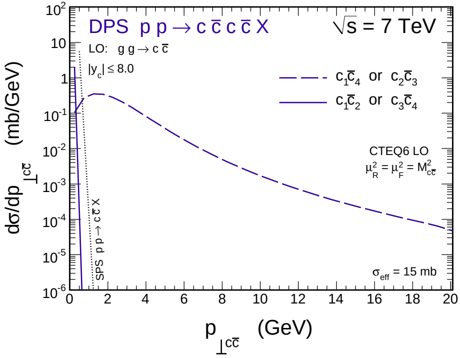
DPS results, collinear approximation



DPS: large rapidity differences, large invariant masses

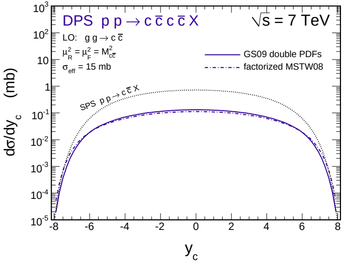
- Not possible for quarks (antiquarks)
- mesons ?
- nonphotonic electrons (muons) ?

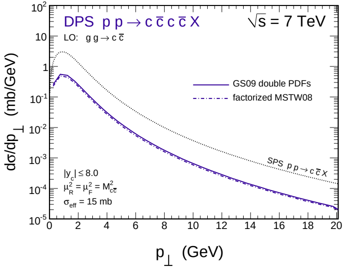
DPS results, collinear approximation



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

Evolution of dPDFs

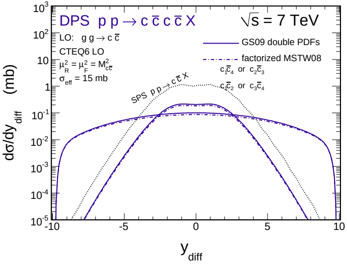


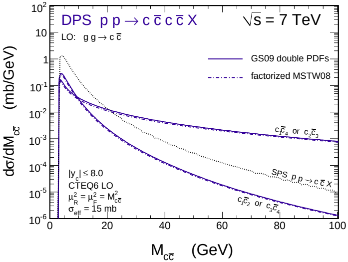


Gaunt-Stirling dPDFs with evolution

very small effect of the evolution

Evolution of dPDFs





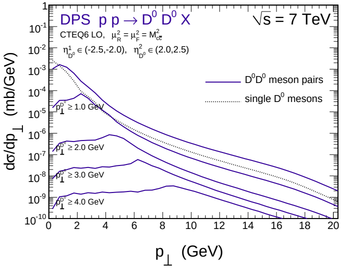
Gaunt-Stirling dPDFs with evolution

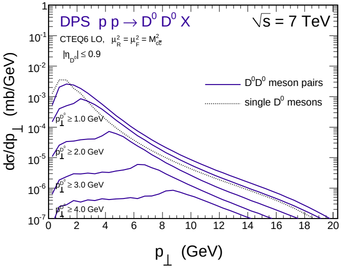
very small effect of the evolution

From quarks/antiquarks to D mesons

large transverse momentum of cc or $\bar{c}\bar{c}$

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

Table: The DPS cross section $(\sigma_{D^0D^0} + \sigma_{\bar{D}^0\bar{D}^0})/2$ 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 $p_{t,D^0D^0} > 4$ GeV
0.0	$2.59\ 10^{-3}$	$0.66\ 10^{-2}$	$0.58\ 10^{-3}$
1.0	$1.47\ 10^{-4}$	$2.48\ 10^{-3}$	$0.41\ 10^{-3}$
2.0	$0.32\ 10^{-5}$	$2.93\ 10^{-4}$	$1.54\ 10^{-4}$
3.0	$2.55\ 10^{-7}$	$0.35\ 10^{-4}$	$2.46\ 10^{-5}$
4.0	$2.33\ 10^{-8}$	$0.62\ 10^{-5}$	$0.49\ 10^{-5}$

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

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

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

12 dimensions (!)

DPS in k_t-factorization

Each individual scattering in the k_t-factorization approach

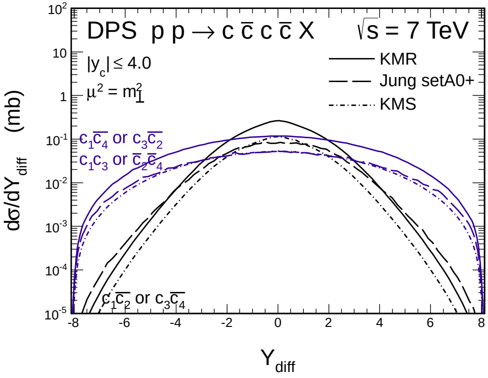
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \overline{|\mathcal{M}_{off}|^2} \delta\left(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}\right) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2) \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi}$$

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

Effectively 16 dimensions, Monte Carlo method

Maciula-Szczurek, hep-ph-1301.4469, in print in Phys. Rev.D

DPS k_t-factorization calculation



The same situation as in collinear approach

DPS k_t-factorization calculation vs LHCb

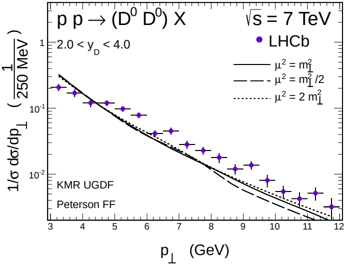
Table: Total cross sections

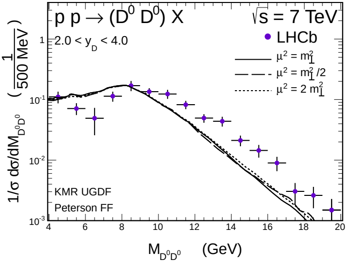
Mode	σ_{tot}^{EXP}	KMR	Jung setA0+	KMS
$D^0 D^0$	$690 \pm 40 \pm 70$	256	101	100
$D^0 D^+$	$520 \pm 80 \pm 70$	204	81	80
$D^0 D_S^+$	$270 \pm 50 \pm 40$	72	29	28
$D^+ D^+$	$80 \pm 10 \pm 10$	41	16	16
$D^+ D_S^+$	$70 \pm 15 \pm 10$	29	12	11
$D_S^+ D_S^+$	–	10	4	4

LHCb acceptance:

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

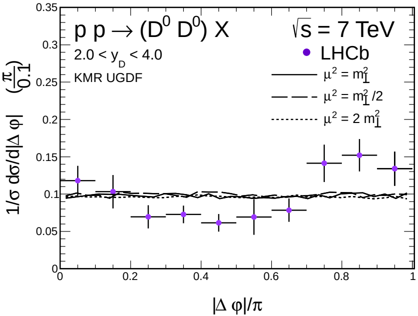
DPS k_t-factorization calculation vs LHCb





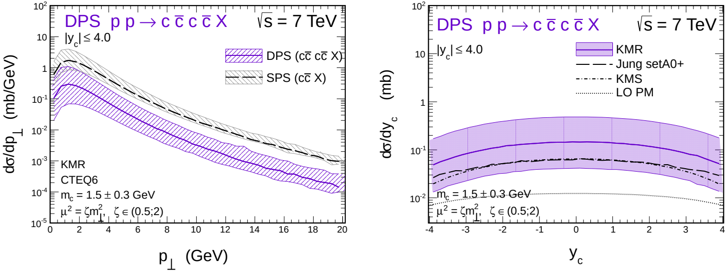
missing SPS contributions (extra gluon splitting) ?

DPS k_t-factorization calculation vs LHCb

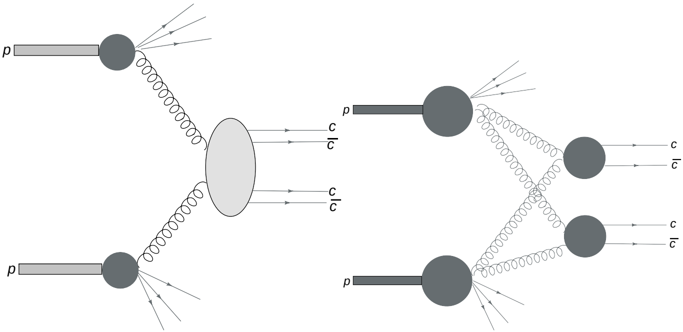


missing SPS contributions ?

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 $c\bar{c}c\bar{c}$

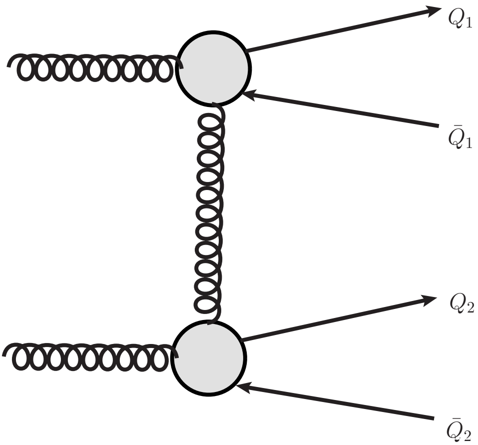


Figure: Subprocess: $gg \rightarrow (c\bar{c})(c\bar{c})$ production.

Impact factors

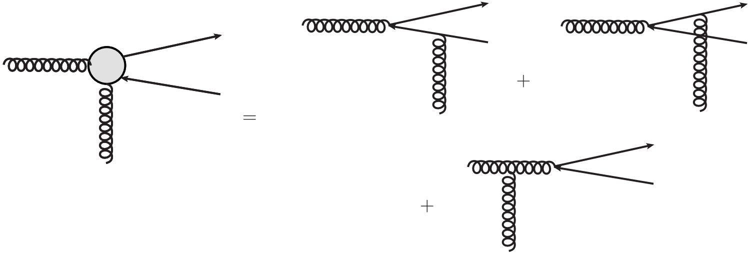


Figure: Coupling of (t-channel) gluon to g, Q, $\bar{Q}$

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

gg collisions, momentum representation

The compact cross section formula:

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

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

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

4) Second pair:

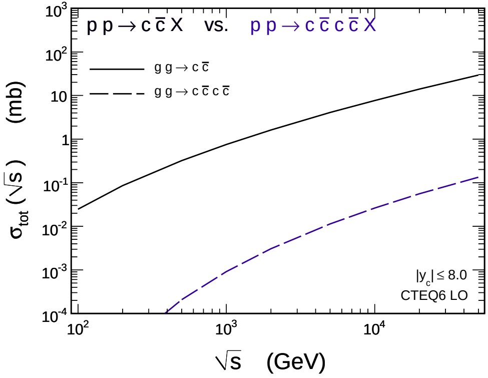
$$\boldsymbol{p}_Q = \boldsymbol{l} - u\boldsymbol{q}, \quad \boldsymbol{p}_{\bar{Q}} = -\boldsymbol{l} - (1-u)\boldsymbol{q} \,. \tag{4}$$

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

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

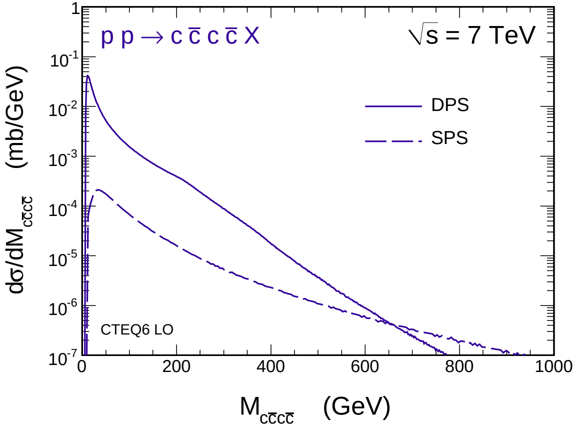
- $\sigma_{gg\to(Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2})$ - elementary cross section for $gg \to c\bar{c}c\bar{c}$. Calculated and stored.
- $g(x_1,\mu_F^2), g(x_2,\mu_F^2)$ - collinear gluon distributions from the literature.
- The integral over $\xi_1 = log_{10}(x_1)$ and $\xi_2 = log_{10}(x_2)$ is performed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

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.

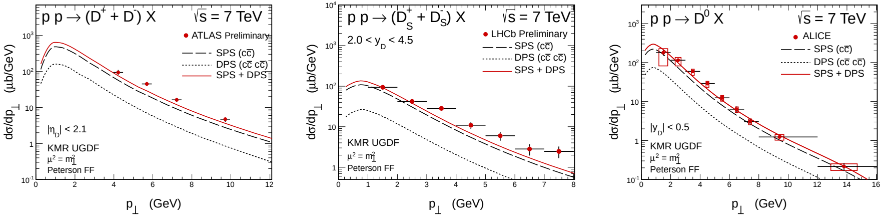
At very large invariant masses SPS $\gg$ DPS.

DPS contribution to inclusive D meson distributions

Let us consider for example transverse momentum distribution

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

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 SPS terms at small rapidity differences ?
- Large rapidity differences 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 $pp \to (c\bar{c})(c\bar{c})X$.
- Especially large cross section for cc or $\bar{c}\bar{c}$ with large rapidity distance between them.
- Especially large cross section for large $p_{t,cc}$.
- Idea: look at $D^0 D^0$ (or $\bar{D}^0 \bar{D}^0$) correlations (LHCb)
  ATLAS and CMS: at the edges of main detectors,
  ALICE: large $p_{t,DD}$
- Smaller contribution of single-parton scattering for $pp \to (c\bar{c})(c\bar{c})X$.

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 almost consistent with recent LHCb data
- A detailed comparison of DPS and SPS for mesons or nonphotonic electrons is needed.

Thank You for attention!