Production of $c\bar{c}$ pairs at LHC: k_t-factorization and double-parton scattering

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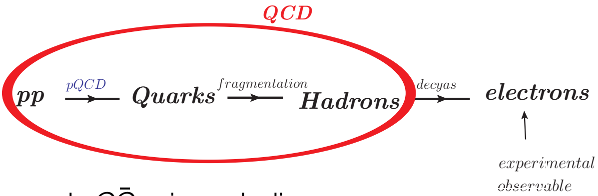
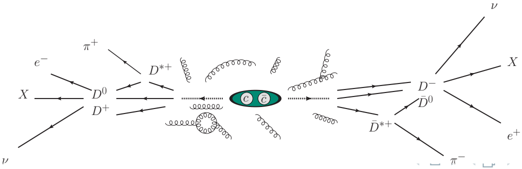
- General framework of $c\bar{c}$ production
- D meson production at LHC
- Double parton production of $c\bar{c}c\bar{c}$
- Single parton production of $c\bar{c}c\bar{c}$
- Conclusions

3-step process



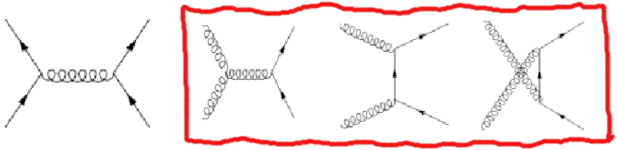
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

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

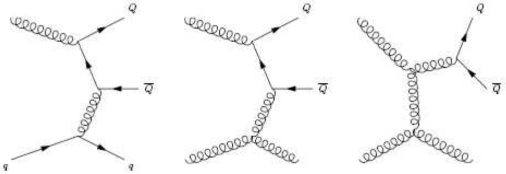


Dominant mechanisms of $Q\bar{Q}$ production

- 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

pQCD standard approach

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

- quadrupuly differential cross section:

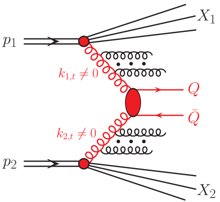
$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} \sum_{i,j} x_1 p_i(x_1,\mu^2)\; x_2 p_j(x_2,\mu^2)\; \overline{|\mathcal{M}_{ij}|^2}$$

- $p_i(x_1,\mu^2)$, $p_j(x_2,\mu^2)$ - 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 $\longrightarrow$ gluon-gluon fusion
- QCD collinear approach $\rightarrow$ only inclusive one particle distributions, total cross sections

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

$\Rightarrow Q\bar{Q}$ correlations

- multi-differential cross section

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

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

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

Unintegrated parton distribution functions

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

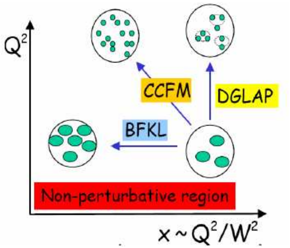
$$xp_k(x, \mu_F^2) = \int_0^\infty d\kappa_t^2 \mathcal{F}(x, \kappa_t^2, \mu_F^2)$$

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

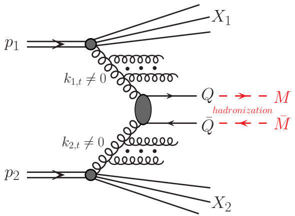
gg-fusion dominance ⇒ great test of existing unintegrated gluon densities!
especially at LHC (small-x)

several models:

- 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)

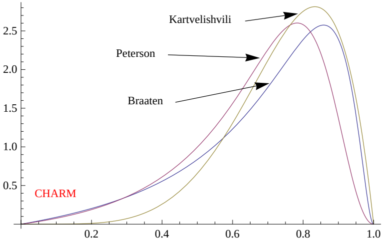
- from heavy quarks to heavy mesons:

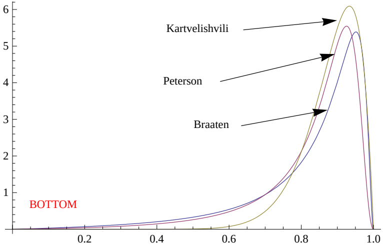
$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

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

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

Different models of FFs





- **Peterson et al.**

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

  $\varepsilon_c = 0.06$, $\varepsilon_b = 0.006$ from PDG

- Braaten et al.

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

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

  $$F_2 = 3(1-r)^2(1-2r_2r^2)z^4 - 2(1-r)(6-19r+18r^2)z^3$$

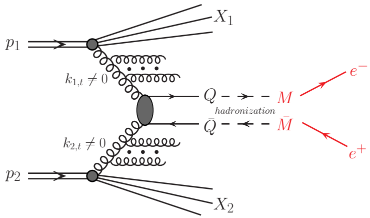
  $r_c = 0.2$, $r_b = 0.07$

- Kartvelishvili et al.

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

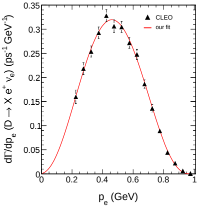
  $a_c = 5.0$, $a_b = 14.0$

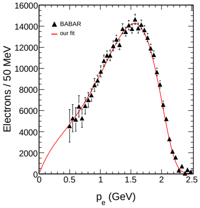
Experimental decay functions and Monte Carlo approach



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

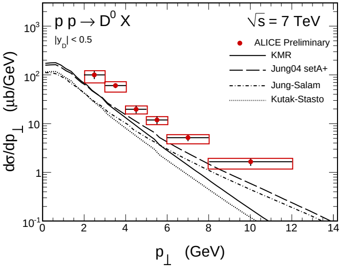
- Monte Carlo $\Longrightarrow$ directions and lengths of outgoing leptons momenta
- Our input $\Longrightarrow$ experimental decay functions: $f_{CLEO}(p)$, $f_{BABAR}(p)$

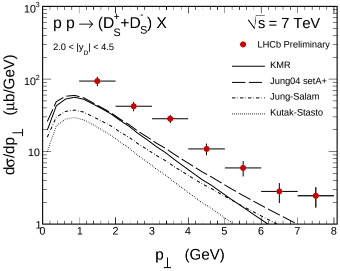




- approximation:
  D mesons $(D^{\pm}, D^0, \bar{D}^0, D_S^{\pm}, D^{*0}, D^{*\pm}, D_S^{*\pm})$
  B mesons $(B^{\pm}, B^0, \bar{D}^0, B_S^0, \bar{B}_S^0, B^*, B_S^*)$
  BR(D and $B \longrightarrow X\ e\ \nu \approx 10\%$)

LHC, charmed mesons

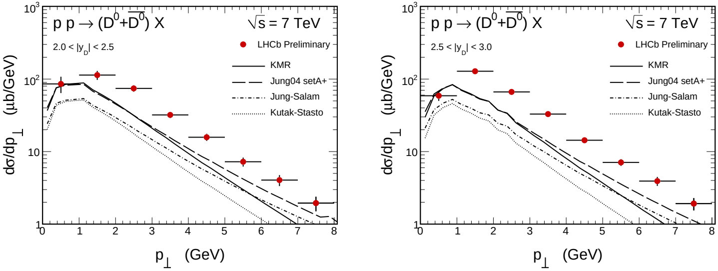




ALICE, LHCb (LHCb-CONF-2010-013)

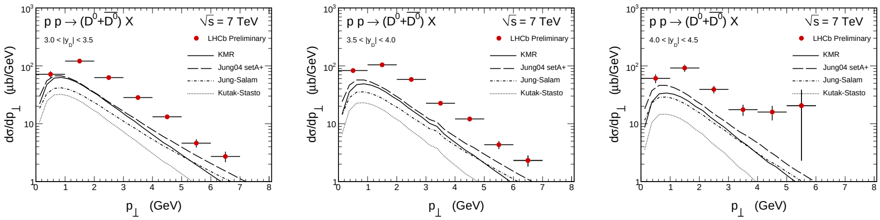
KMR UGDF: $\mu_F^2 = M_{c\bar{c}}^2$

LHC, charmed mesons



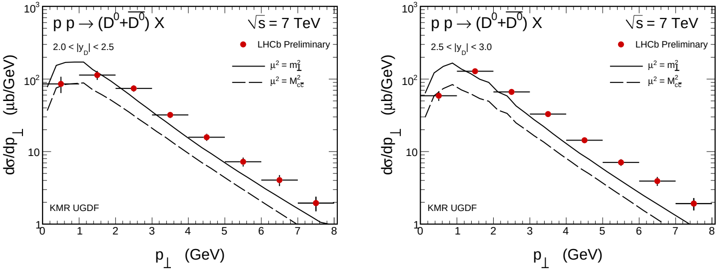
Kimber-Martin-Ryskin, Jung, Kutak-Stasto UGDF

LHC, charmed mesons



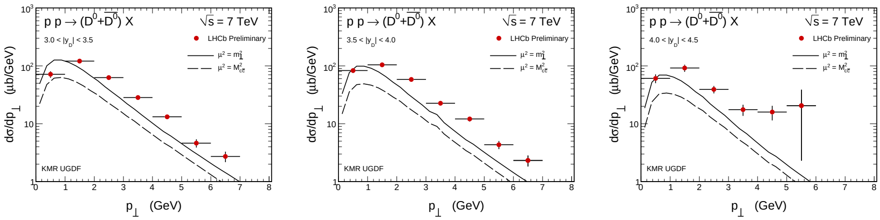
something missing?

KMR UGDF, scale dependence



$\mu^2 = M^2_{c\bar{c}}$ or m_t^2

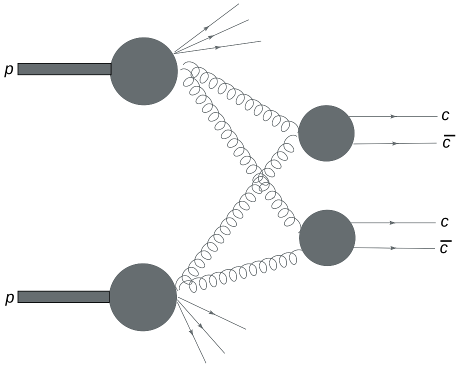
KMR UGDF, scale dependence



$\mu^2 = M_{c\bar{c}}^2$ or m_t^2

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

Consider two hard (parton) scatterings



Not consider so far in the literature

Luszczak, Maciula, Szczurek, arXiv:1111.3255

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

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

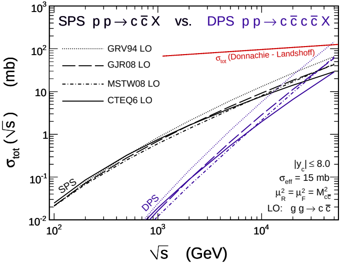
$F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2)$, $F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2)$
are called double parton distributions

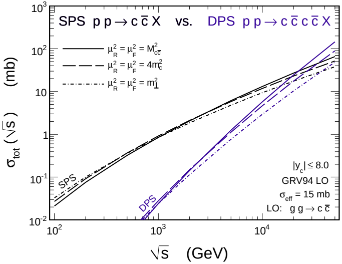
dPDF are subjected to special evoultion equations

single scale evolution: Snigireev

double scale evolution: Ceccopieri, Gaunt-Stirling

DPS results

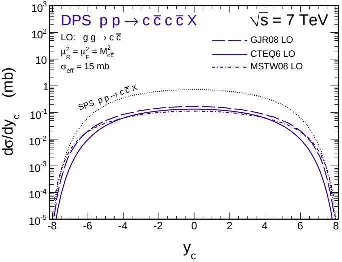


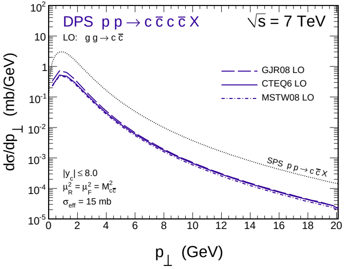


Inclusive cross section more difficult to calculate

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

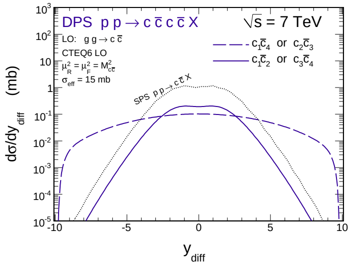
DPS results

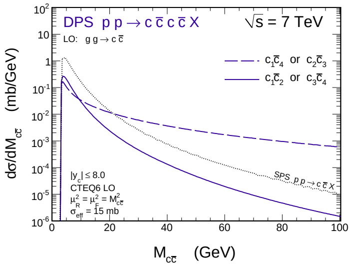




In the factorized model inclusive double-scattering distributions in y and p_t are identical as for single-$c\bar{c}$ production.

DPS results

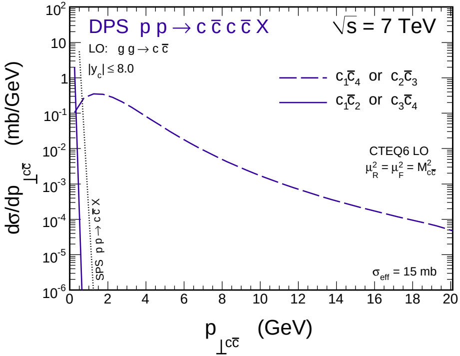




DPS: large rapidity differences, large invariant masses

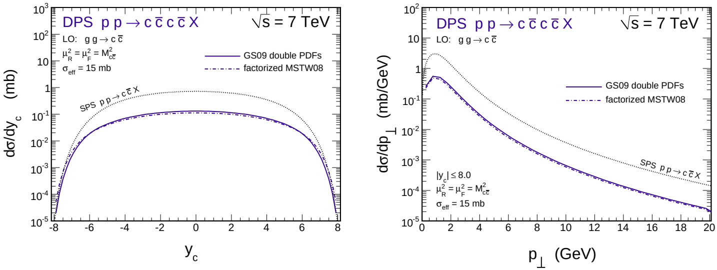
- Not possible for quarks (antiquarks)
- mesons ?
- nonphotonic electrons (muons) ?

DPS results



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

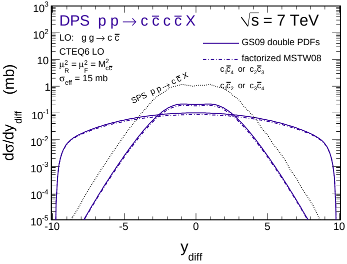
Evolution of dPDFs

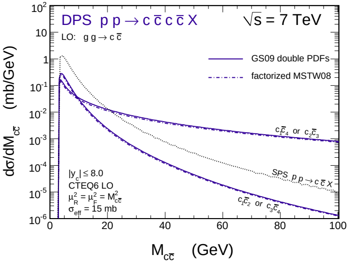


Gaunt-Stirling dPDFs with evolution

very small effect of the evolution

Evolution of dPDFs

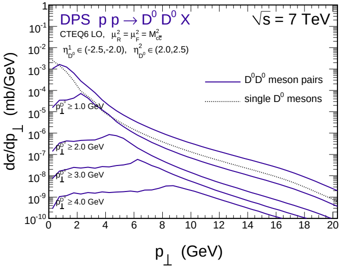


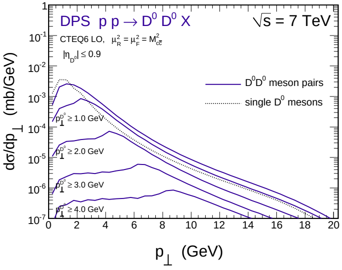


Gaunt-Stirling dPDFs with evolution

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

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

Table: The DPS cross section $(\sigma_{D^0 D^0} + \sigma_{\bar{D}^0 \bar{D}^0})/2$ 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,

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

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

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

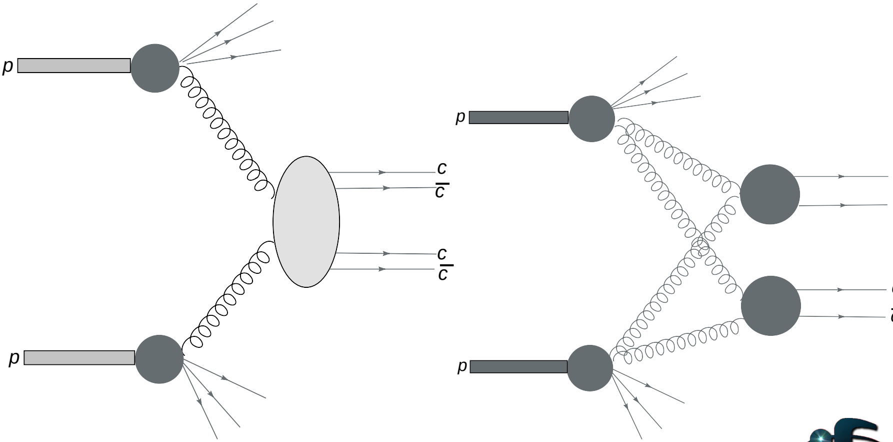


Figure: SPS (left) and DPS (right) mechanisms of $(c\bar{c})(c\bar{c})$ production.

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

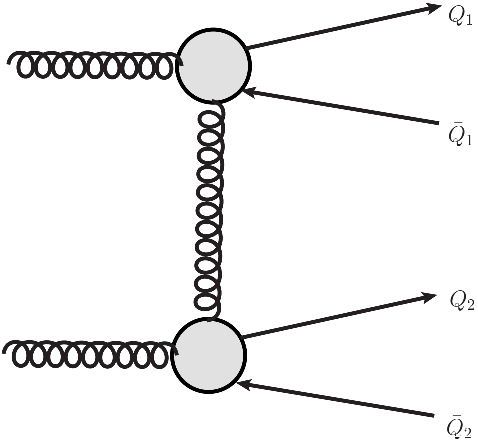


Figure: Subprocess: $gg \to (c\bar{c})(c\bar{c})$ production.

Impact factors

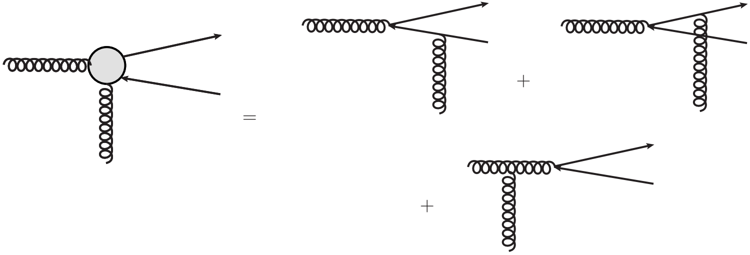


Figure: Coupling of (t-channel) gluon to $g, Q, \bar{Q}$

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

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

1) In the lightcone Fock-state expansion of the incoming, physical, colliding gluons.
For the first gluon:

$$|g^a(\mathbf{b})\rangle = \sqrt{1 - n_{Q\bar{Q}}}\,|g^a_{\rm bare}\rangle + \int d^2\mathbf{r}dz\,\Psi(z,\mathbf{r})|[Q\bar{Q}]^a_8; z, \mathbf{r}\rangle\,. \qquad (1)$$

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

$$|g^c(\mathbf{b})\rangle = \sqrt{1 - n_{Q\bar{Q}}}\,|g^c_{\rm bare}\rangle + \int d^2\mathbf{s}du\,\Psi(u,\mathbf{s})|[Q\bar{Q}]^c_8; u, \mathbf{s}\rangle\,. \qquad (2)$$

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

$$|[Q\bar{Q}]^a_8\rangle = \sqrt{2}\,(t^a)^i_j\,|Q_i\bar{Q}^j\rangle\,,\; |[Q\bar{Q}]_1\rangle = \frac{1}{\sqrt{N_c}}\,\delta^i_j\,|Q_i\bar{Q}^j\rangle\,. \qquad (3)$$

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

3) Interaction (gluon exchange) like helicity-conserving potential Gunion-Soper:

$$V(\boldsymbol{b} + \boldsymbol{b}_i - \boldsymbol{s}_j) = (-i)\frac{\alpha_S}{\pi} \int \frac{d^2\boldsymbol{q}}{[\boldsymbol{q}^2 + \mu_G^2]} \exp[i(\boldsymbol{b} + \boldsymbol{b}_i - \boldsymbol{s}_j)\boldsymbol{q}]\, T_i^b \otimes T_j^b \,. \quad (4)$$

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

$$\sigma_{tot} = \frac{1}{(N_c^2 - 1)^2} \sum_{a,c} \int d^2\boldsymbol{b} |A(g^a g^c \to Q\bar{Q}Q\bar{Q}; \boldsymbol{b})|^2 \,. \quad (5)$$

gg collisions, mixed representation

$$\sigma_{tot} = \int dz d^2\mathbf{r} du d^2\mathbf{s} |\Psi(z,\mathbf{r})|^2 |\Psi(u,\mathbf{s})|^2 \, \Sigma(z,\mathbf{r};u,\mathbf{s}) \,. \tag{6}$$

where

$$\begin{aligned} \Sigma(z,\mathbf{r};u,\mathbf{s}) \,. \quad &= \left(\frac{N_c^2}{N_c^2-1}\right)^2 \\ &\cdot \Big\{ \sigma_{DD}((1-z)\mathbf{r},(1-u)\mathbf{s}) + \sigma_{DD}((1-z)\mathbf{r},u\mathbf{s}) - \frac{1}{N_c^2}\sigma_{DD}((1-z)\mathbf{r},\mathbf{s}) \\ &+ \sigma_{DD}(z\mathbf{r},(1-u)\mathbf{s}) + \sigma_{DD}(z\mathbf{r},u\mathbf{s}) - \frac{1}{N_c^2}\sigma_{DD}(z\mathbf{r},\mathbf{s}) \\ &- \frac{1}{N_c^2}\Big(\sigma_{DD}(\mathbf{r},(1-u)\mathbf{s}) + \sigma_{DD}(\mathbf{r},u\mathbf{s}) - \frac{1}{N_c^2}\sigma_{DD}(\mathbf{r},\mathbf{s})\Big)\Big\} \,. \end{aligned} \tag{7}$$

gg collisions, mixed representation

The Born level dipole-dipole cross section reads

$$\sigma_{DD}(\boldsymbol{r},\boldsymbol{s}) = \frac{N_c^2-1}{N_c^2}\frac{4\pi\alpha_S^2}{\mu_G^2}\Big[1-\mu_G r K_1(\mu_G r)-\mu_G s K_1(\mu_G s)+\mu_G|\boldsymbol{r}-\boldsymbol{s}|K_1(\mu_G|\boldsymbol{r}-\boldsymbol{s}|)\Big] \quad (8)$$

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

$$|\Psi(z,\boldsymbol{r})|^2 = \frac{\alpha_S(r)}{6\alpha_{em}}|\Psi_\gamma(z,\boldsymbol{r})|^2 = \frac{\alpha_S(r)}{(2\pi)^2}\Big[\Big(z^2+(1-z)^2\Big)m_Q^2K_1^2(m_Q r)+m_Q^2K_0^2(m_Q r)\Big] \quad (9)$$

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:

$$d\sigma = \frac{N_c^2-1}{N_c^2}\frac{4\pi^2\alpha_S^2}{[\mathbf{q}^2+\mu_G^2]^2} I(z,\mathbf{k},\mathbf{q}) I(u,\mathbf{l},-\mathbf{q})\, dz \frac{d^2\mathbf{k}}{(2\pi)^2}\, du \frac{d^2\mathbf{l}}{(2\pi)^2}\frac{d^2\mathbf{q}}{(2\pi)^2}\,. \tag{10}$$

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

$$\mathbf{p}_Q = \mathbf{k} + z\mathbf{q}, \quad \mathbf{p}_{\bar{Q}} = -\mathbf{k} + (1-z)\mathbf{q}\,, \tag{11}$$

4) Second pair:

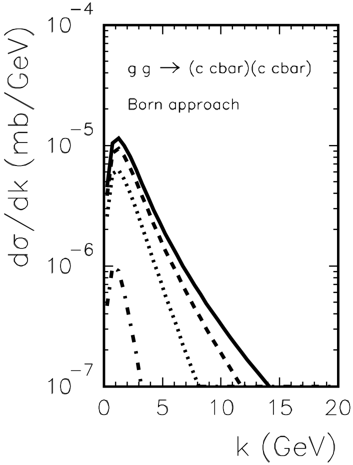
$$\mathbf{p}_Q = \mathbf{l} - u\mathbf{q}, \quad \mathbf{p}_{\bar{Q}} = -\mathbf{l} - (1-u)\mathbf{q}\,. \tag{12}$$

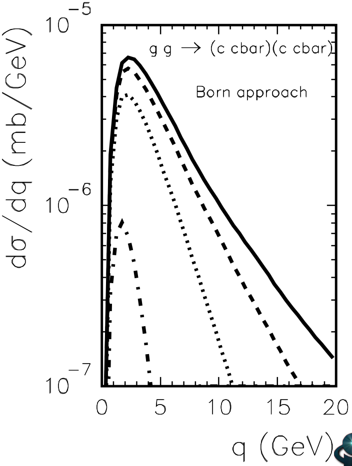
$pp \to (Q\bar{Q})(Q\bar{Q})$ inclusive cross section

$$\sigma_{pp\to(Q\bar{Q})(Q\bar{Q})}(W) = \int dx_1 dx_2 \; g(x_1,\mu_F^2)\; g(x_2,\mu_F^2)\; \sigma_{gg\to(Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2}) \,, \tag{13}$$

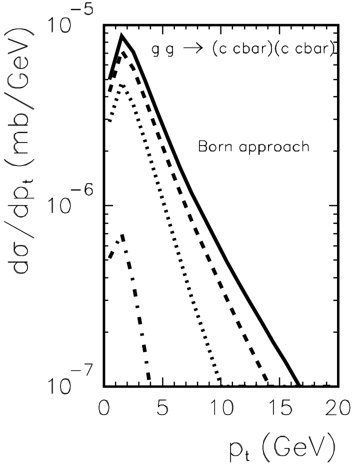
- $\sigma_{gg\to(Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2})$ - elementary cross section for $gg \to c\bar{c}c\bar{c}$. Calculated and stored.
- $g(x_1,\mu_F^2), g(x_2,\mu_F^2)$ - collinear gluon distributions from the literature.
- The integral over $\xi_1 = log_{10}(x_1)$ and $\xi_2 = log_{10}(x_2)$ is performed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

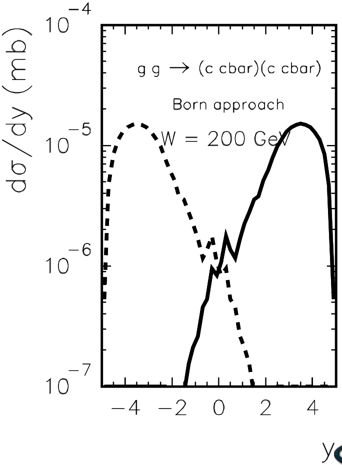
gg collisions, auxiliary distributions



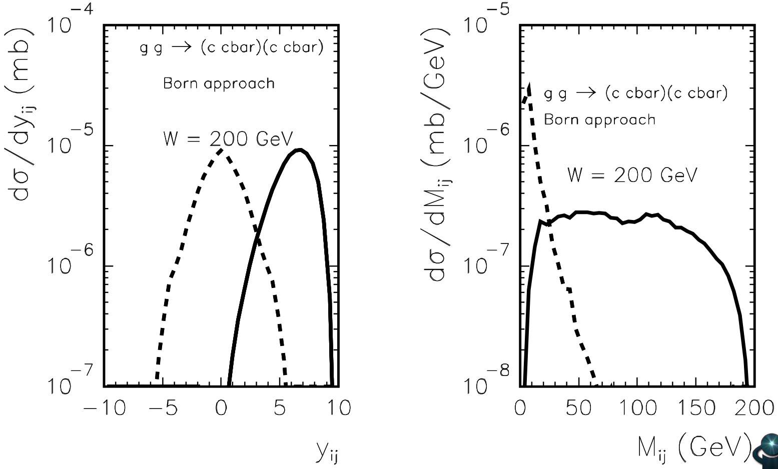


gg collisions, single particle distributions

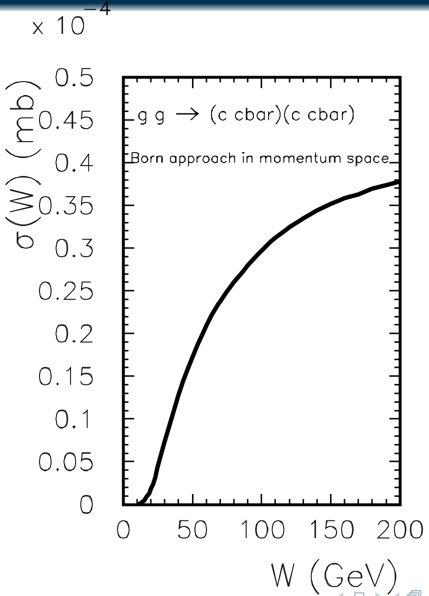




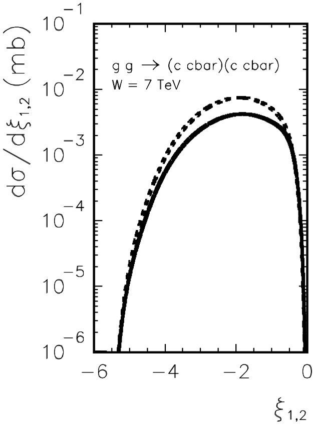
gg collisions, correlation observables



gg collisions, energy dependence



pp collisons, sensitivity to x_1 and x_2

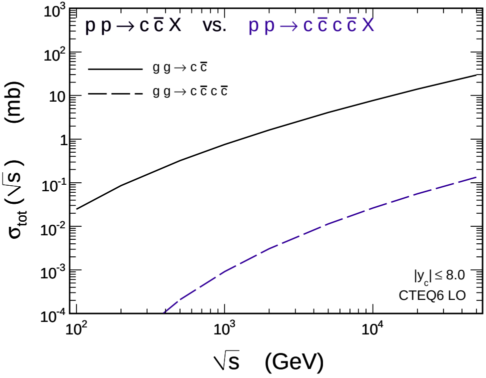


Rather intermediate x-range:

(a) gluons relatively well known

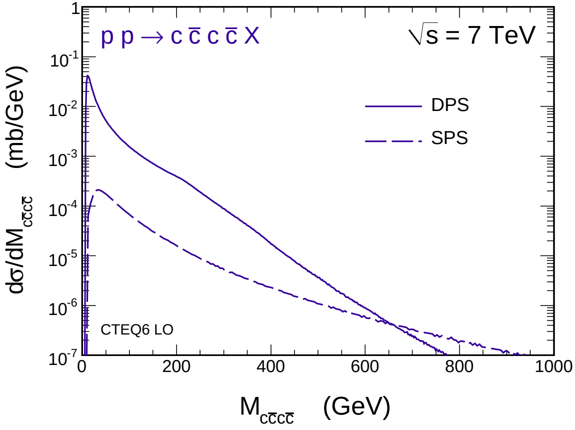
(b) collinear approach works

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 $pp \to (c\bar{c})(c\bar{c})X$.
- 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 $D^0 D^0$ (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 $pp \to (c\bar{c})(c\bar{c})X$.

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.
- A detailed comparison of DPS and SPS for mesons or nonphotonic electrons is needed.

Thank You for attention!