Production of one and two $c\bar{c}$ pairs at LHC

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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 $c\bar{c}c\bar{c}$
- Same flavour DD production (first results)
- $pp \to J/\psi J/\psi X$
- Conclusions

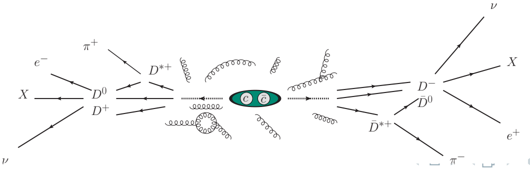
Low-x physics because c quark mass rather small

3-step process

$$\underbrace{pp \xrightarrow{pQCD} Quarks \xrightarrow{fragmentation} Hadrons}_{QCD} \xrightarrow{decyas} \underset{\uparrow \atop \text{experimental observable}}{electrons}$$

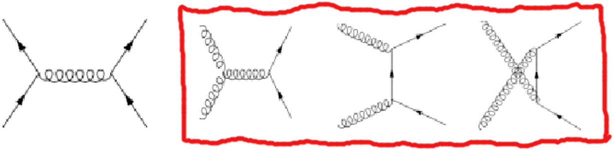
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

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

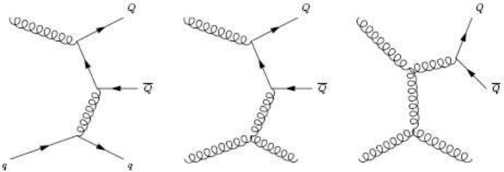


Dominant mechanisms of $Q\bar{Q}$ production

- 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 $\rightarrow$ transverse momenta of the incident partons are assumed to be zero

- quadrupuly differential cross section:

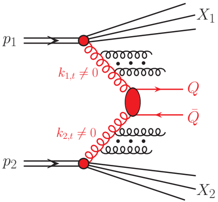
$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} \sum_{i,j} x_1 p_i(x_1,\mu^2)\; x_2 p_j(x_2,\mu^2)\; \overline{|\mathcal{M}_{ij}|^2}$$

- $p_i(x_1,\mu^2)$, $p_j(x_2,\mu^2)$ - 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

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

- 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

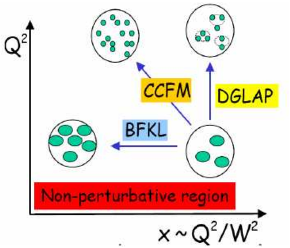
$$xp_k(x,\mu_F^2) = \int_0^\infty d\kappa_t^2 \mathcal{F}(x,\kappa_t^2,\mu_F^2)$$

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

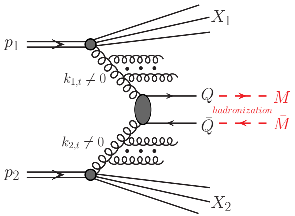
gg-fusion dominance ⇒ great test of existing unintegrated gluon densities!
especially at LHC (small-x)

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)

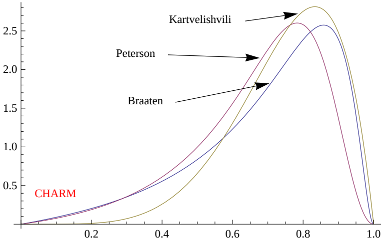
- from heavy quarks to heavy mesons:

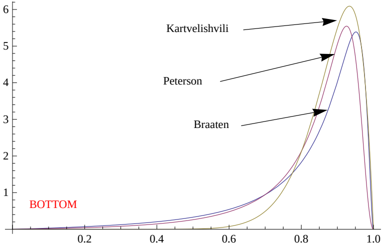
$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

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

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

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.

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

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

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

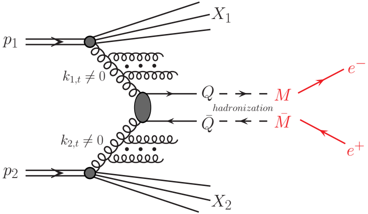
  $r_c = 0.2$, $r_b = 0.07$

- Kartvelishvili et al.

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

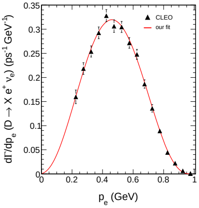
  $a_c = 5.0$, $a_b = 14.0$

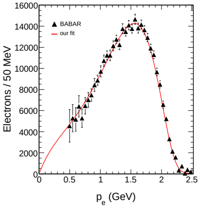
Experimental decay functions and Monte Carlo approach



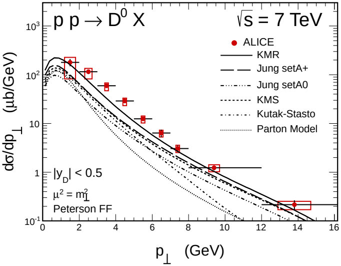
- **CLEO** $e^+e^- \to \Psi(3770) \to D\bar{D} \to Xe\nu$
  BR($D^+ \to e^+\nu_e X$)=16.13±0.20(stat.)±0.33(syst.)%
  BR($D^0 \to e^+\nu_e X$)=6.46±0.17(stat.)±0.13(syst.)%
- **BABAR** $e^+e^- \to \Upsilon(10600) \to B\bar{B} \to Xe\nu$
  BR($B \to e\nu_e X$)=10.36±0.06(stat.)±0.23(syst.)%

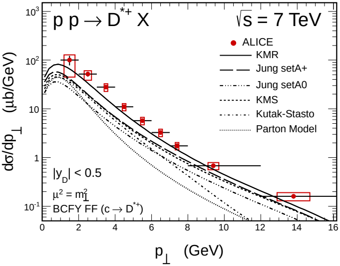
- Monte Carlo $\Longrightarrow$ directions and lengths of outgoing leptons momenta
- Our input $\Longrightarrow$ experimental decay functions: $f_{CLEO}(p)$, $f_{BABAR}(p)$

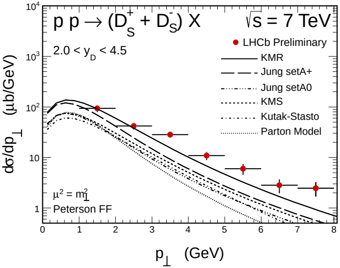




- approximation:
  D mesons $(D^\pm, D^0, \bar{D}^0, D_S^\pm, D^{*0}, D^{*\pm}, D_S^{*\pm})$
  B mesons $(B^\pm, B^0, \bar{D}^0, B_S^0, \bar{B}_S^0, B^*, B_S^*)$
  BR(D and $B \longrightarrow X\ e\ \nu \approx 10\%$)

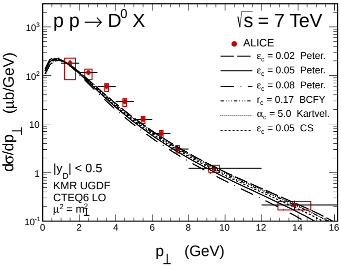


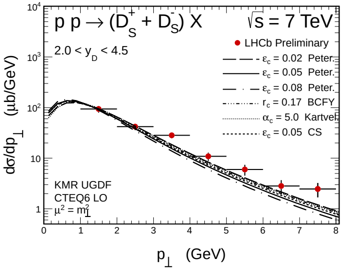


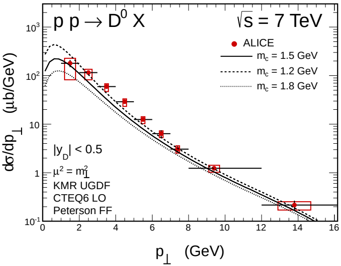


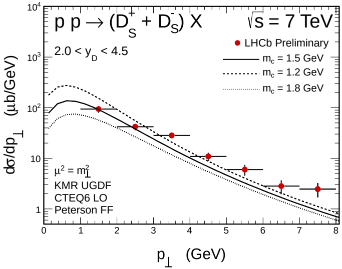
- various UGDFs models → crucial test of their applicability at high energies and small x-values
- only KMR model gives good description of the ALICE and LHCb data
- significant difference between LO parton model and LO k_t-factorization

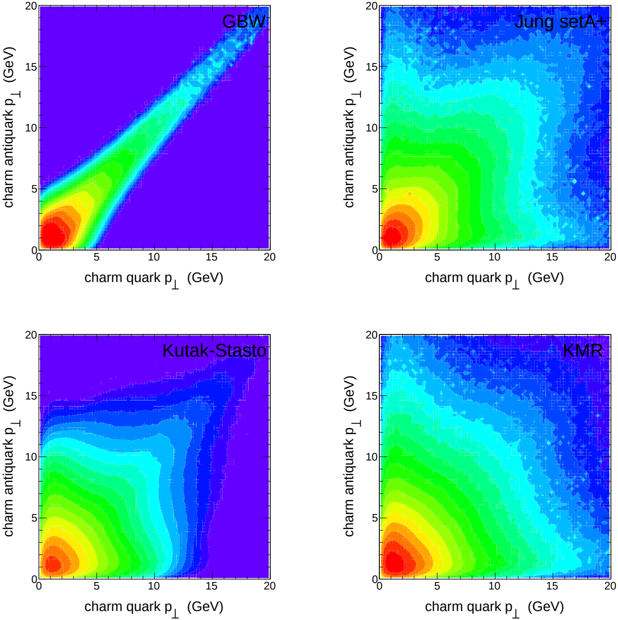
Effects of hadronization and quark mass uncertainty





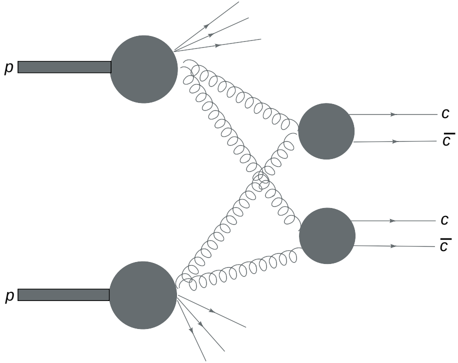





GBW
Jung setA+
Kutak-Stasto
KMR
charm antiquark $p_\perp$ (GeV)
charm quark $p_\perp$ (GeV)

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: $pp \to c\bar{c}c\bar{c}X$

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: 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:

$$\Gamma_{i,j}(x_1, x_2; \mathbf{b_1}, \mathbf{b_2}; \mu_1^2, \mu_2^2) = F_{i,j}(x_1, x_2; \mu_1^2, \mu_2^2) f(\mathbf{b_1}) f(\mathbf{b_2}) \quad .$$

Simple approximation:
$f(\mathbf{b_i})$ universal functions for all kind of partons with:

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

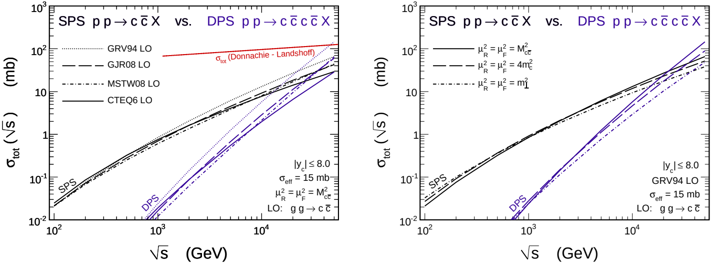
where

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

is the overlap function.
Then:

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

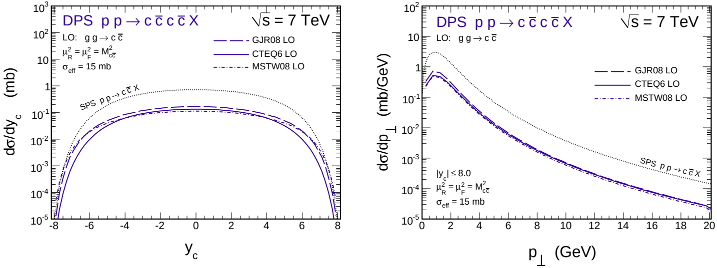
DPS results



Inclusive cross section more difficult to calculate

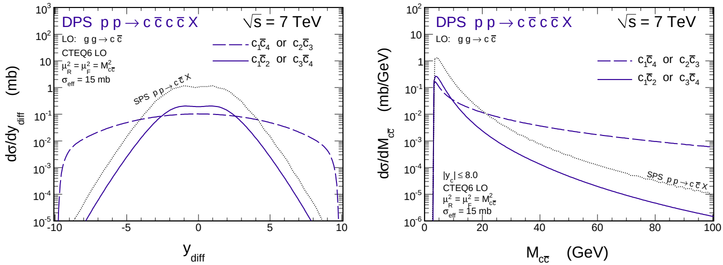
$\sigma_{SS}, 2\sigma_{DS} < \sigma_c^{inclusive} < \sigma_{SS} + 2\sigma_{DS}$

DPS results



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

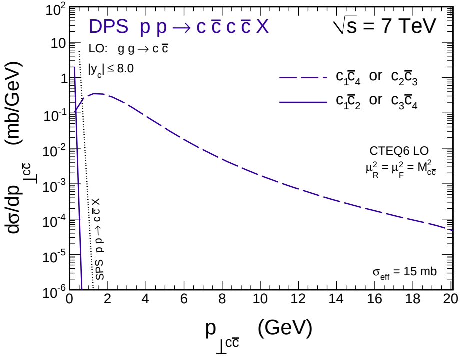
DPS results



DPS: large rapidity differences, large invariant masses

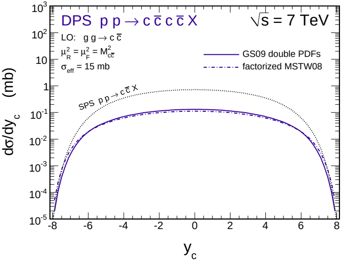
- Not possible for quarks (antiquarks)
- mesons ?
- nonphotonic electrons (muons) ?

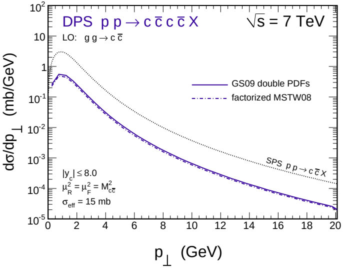
DPS results



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

Evolution of dPDFs

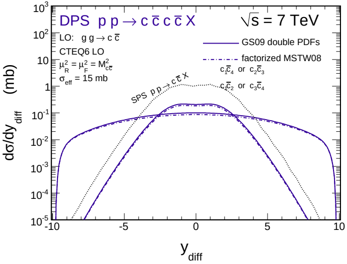


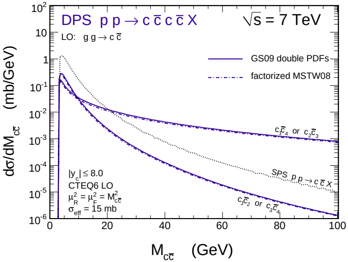


Gaunt-Stirling dPDFs with evolution

very small effect of the evolution

Evolution of dPDFs

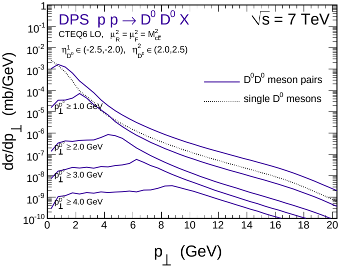


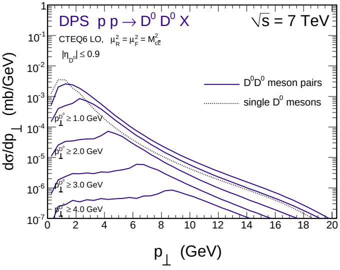


Gaunt-Stirling dPDFs with evolution

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^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

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2}$$

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

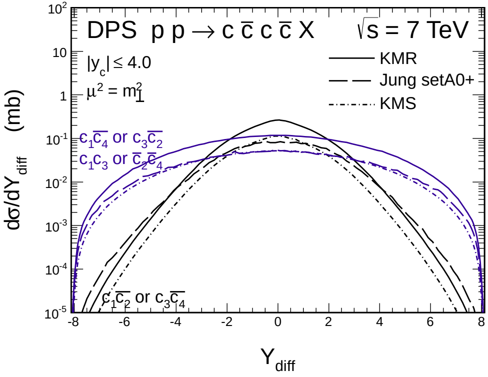
$$\frac{d\sigma}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{16\pi^2 \hat{s}^2}$$

$$\int \overline{|\mathcal{M}_{off}|^2} \delta\left(\vec{k}_{3t} + \vec{k}_{4t} - \vec{p}_{3t} - \vec{p}_{4t}\right) \mathcal{F}(x_3, k_{3t}^2, \mu^2) \mathcal{F}(x_4, k_{4t}^2, \mu^2) \frac{d^2k_{3t}}{\pi} \frac{d^2k_{4t}}{\pi}$$

Effectively 16 dimensions, Monte Carlo method

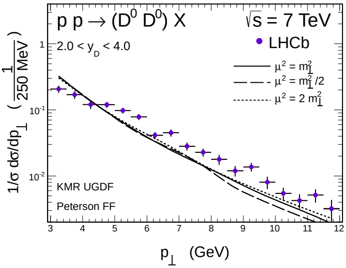
Maciula-Szczurek in preparation

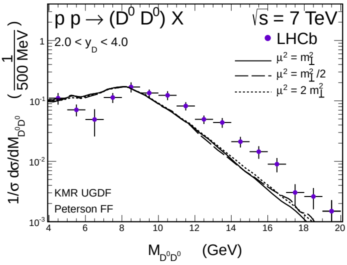
DPS k_t-factorization calculation



The same situation as in collinear approach

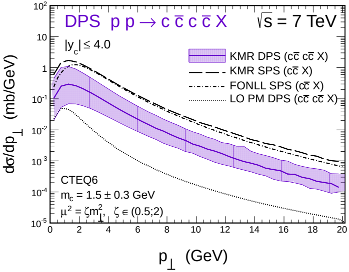
DPS k_t-factorization calculation vs LHCb

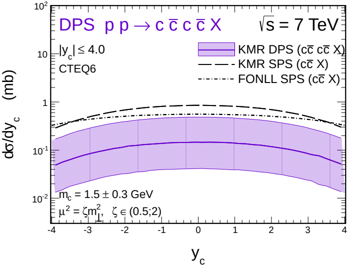




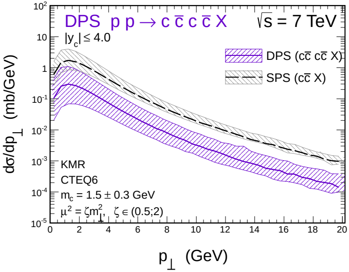
missing SPS contributions ?

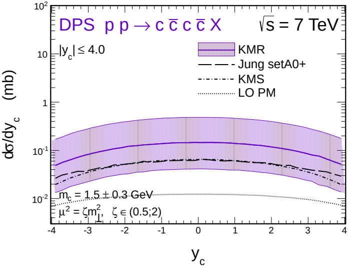
Charm inclusive cross section



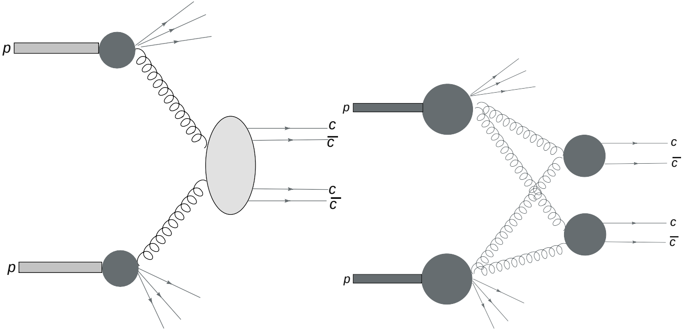


One and two pair production, uncertainties





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



SPS were also not discussed in the literature !

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

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

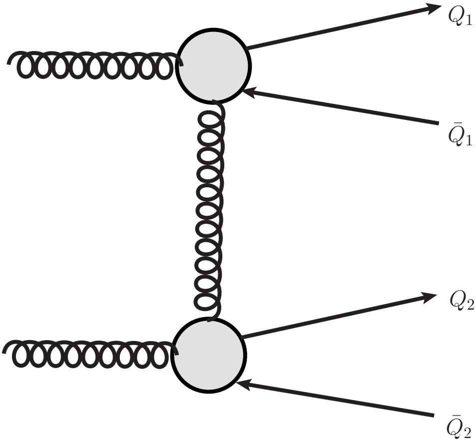


Figure: Subprocess: $gg \to (c\bar{c})(c\bar{c})$ production.

Impact factors

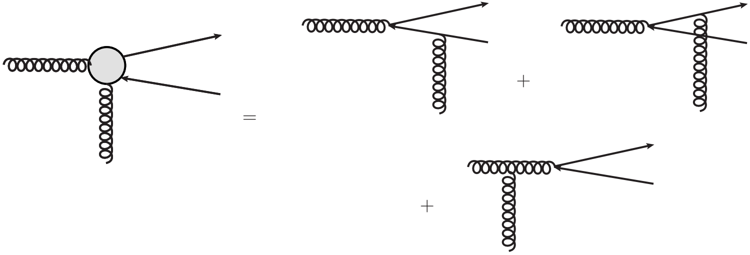


Figure: Coupling of (t-channel) gluon to $g, Q, \bar{Q}$

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

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

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

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

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 $\boldsymbol{r}$ in the impact parameter plane.
For the second gluon:

$$|g^c(\boldsymbol{b})\rangle = \sqrt{1 - n_{Q\bar{Q}}}\,|g^c_{\mathrm{bare}}\rangle + \int d^2\boldsymbol{s} du\, \Psi(u, \boldsymbol{s}) |[Q\bar{Q}]^c_8; u, \boldsymbol{s}\rangle\,. \qquad (3)$$

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

$$|[Q\bar{Q}]^a_8\rangle = \sqrt{2}\,(t^a)^i_j\,|Q_i\bar{Q}^j\rangle\,,\ |[Q\bar{Q}]_1\rangle = \frac{1}{\sqrt{N_c}}\,\delta^i_j\,|Q_i\bar{Q}^j\rangle\,. \qquad (4)$$

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

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

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

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

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

gg collisions, mixed representation

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

where

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

gg collisions, mixed representation

The Born level dipole-dipole cross section reads

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

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:

$$|\Psi(z,\boldsymbol{r})|^2 = \frac{\alpha_S(r)}{6\alpha_{em}}|\Psi_\gamma(z,\boldsymbol{r})|^2 = \frac{\alpha_S(r)}{(2\pi)^2}\left[\left(z^2+(1-z)^2\right)m_Q^2K_1^2(m_Q r)+m_Q^2K_0^2(m_Q r)\right] \quad (10)$$

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:

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

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

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

4) Second pair:

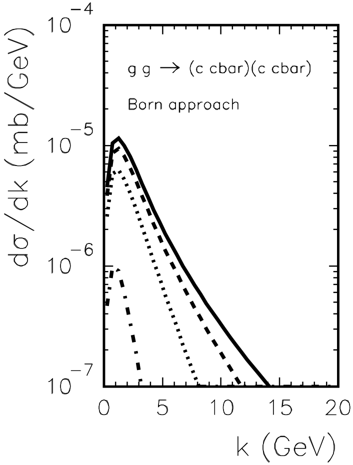
$$\boldsymbol{p}_Q = \boldsymbol{l} - u\boldsymbol{q},\quad \boldsymbol{p}_{\bar{Q}} = -\boldsymbol{l} - (1-u)\boldsymbol{q}\,. \tag{13}$$

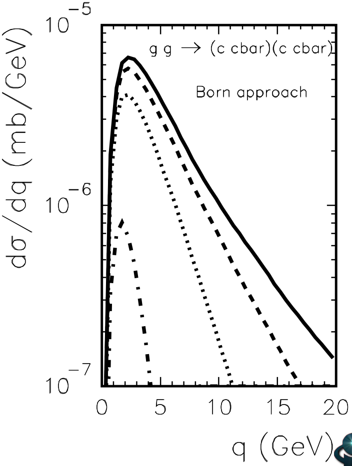
$pp \to (Q\bar{Q})(Q\bar{Q})$ inclusive cross section

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

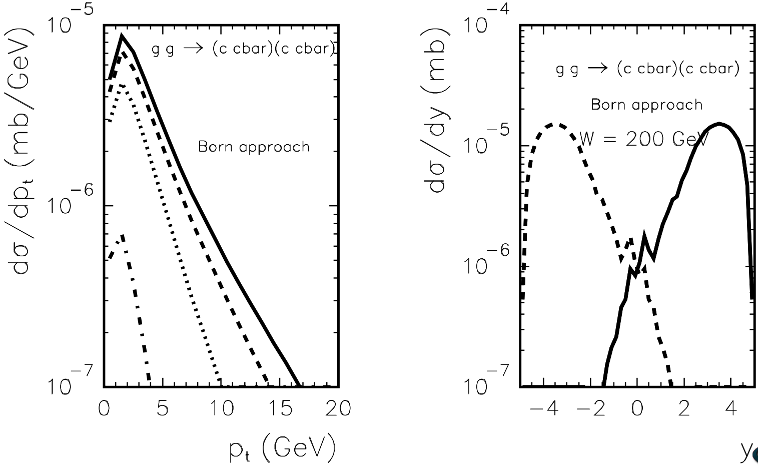
- $\sigma_{gg\to(Q\bar{Q})(Q\bar{Q})}(\hat{s}^{1/2})$ - elementary cross section for $gg \to c\bar{c}c\bar{c}$. Calculated and stored.
- $g(x_1, \mu_F^2), g(x_2, \mu_F^2)$ - collinear gluon distributions from the literature.
- The integral over $\xi_1 = log_{10}(x_1)$ and $\xi_2 = log_{10}(x_2)$ is performed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

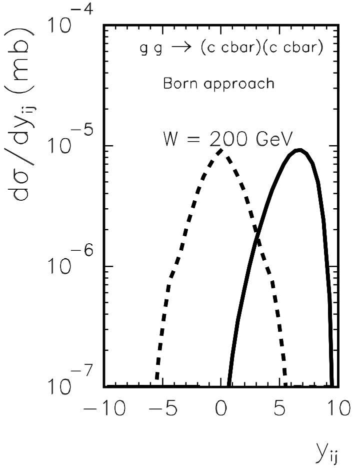


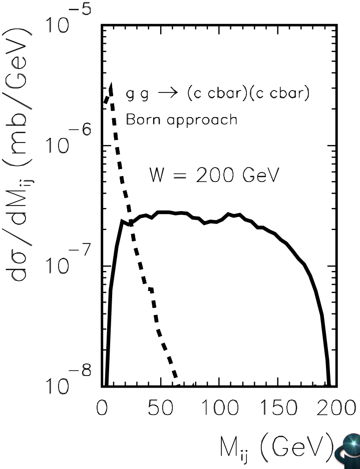


gg collisions, single particle distributions

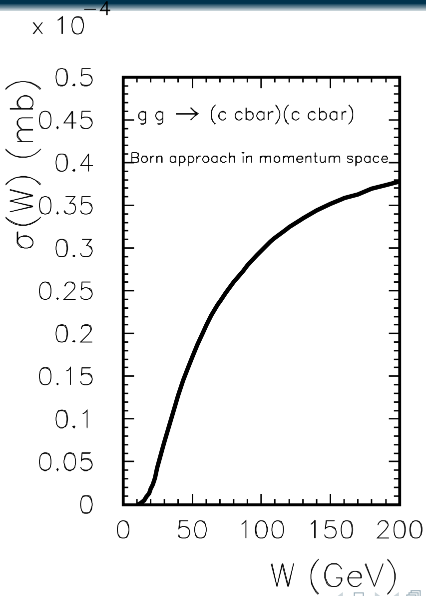


gg collisions, correlation observables

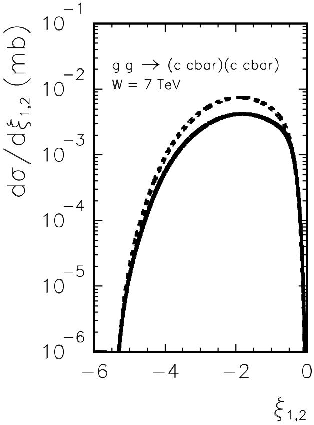




gg collisions, energy dependence



pp collisons, sensitivity to x_1 and x_2

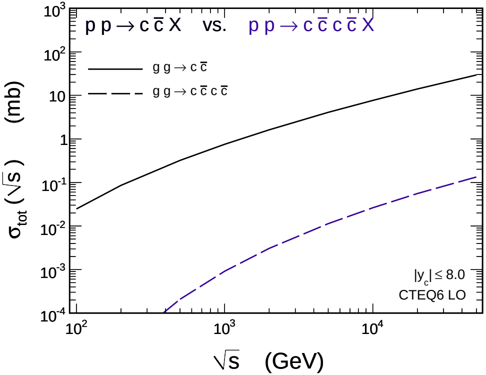


Rather intermediate x-range:

(a) gluons relatively well known

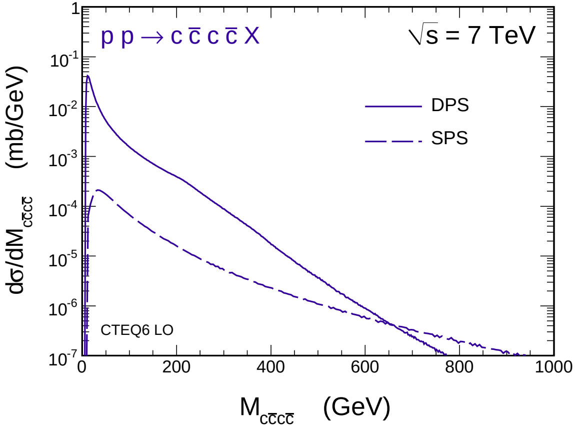
(b) collinear approach works

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 $\bar{D}\bar{D}$
- Missing terms at small rapidity differences ?
- Large rapidity gaps for SPS enhanced by BFKL ladders ?

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

theory: Berezhnoy-Likhoded-Luchinsky-Novoselov
Kom-Kulesza-Stirling
Baranov-Snigirev-Zotov
experiment: LHCb
mechanisms included so far:

- $gg \to boxes \to J/\psi J/\psi$ (SPS)
- $(gg \to J/\psi X) \times (gg \to J/\psi X)$ (DPS)

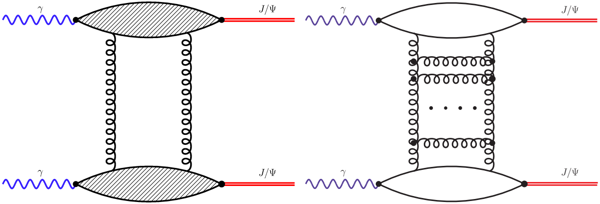
problems:

- $\sigma_{SPS}^{box} \sim \sigma_{DPS}$
- some mechanisms missing (in preparation !!!)

solution:

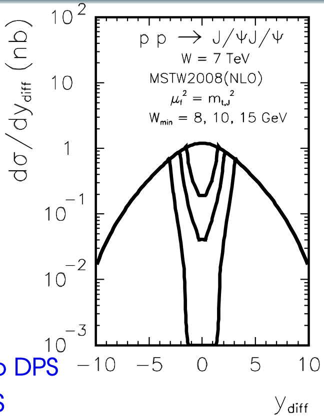
- clever cuts (Baranov-Snigirev-Schäfer-Szczurek-Zotov)

A missing mechanism



higher-order, formally three-loops

The missing mechanism



similar characteristics to DPS

seems smaller than DPS

$y_{diff} = y_1 - y_2$

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 $pp \to (c\bar{c})(c\bar{c})X$.
- 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.
- 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!