Open charm meson production at LHC

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12th International Workshop on Meson Production, Properties and Interaction,

KRAKÓW, POLAND, 31 May - 5 June 2012

Outline

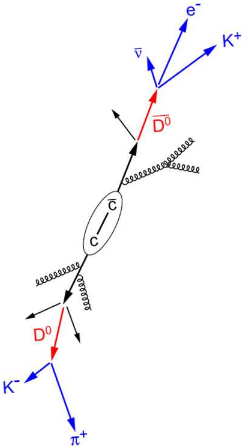
Based on:

Łuszczak, Maciuła, Szczurek, Phys. Rev. D 79 (2009) 034009

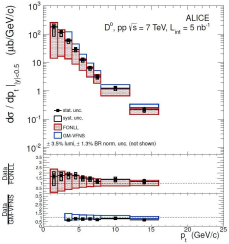
Maciuła, Szczurek, Ślipek, Phys. Rev. D 83 (2011) 054014

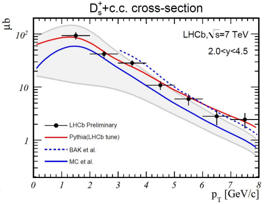
Łuszczak, Maciuła, Szczurek, Phys. Rev. D 85, 094034 (2012)

Heavy quarks measurements at LHC



- direct: open charm/bottom mesons → reconstruction of all decay products ($K^-\pi^+$, $K^+K^-\pi^+$, $K^-\pi^+\pi^+$)
- indirect: nonphotonic electrons/muons → leptons from semileptonic decays of heavy flavoured mesons

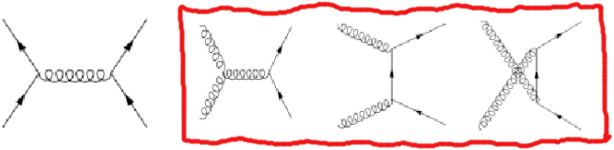




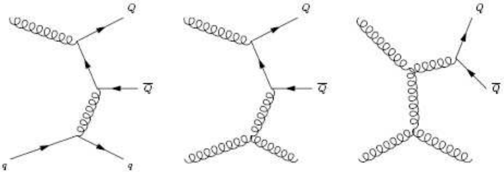
- ALICE, $|y_D| < 0.5$, JHEP, 01 (2012) 128,
- LHCb, $2.0 < y_D < 4.5$, small x region! LHCb-CONF-2010-013
- ATLAS, widest rapidity interval, $|\eta| < 2.5$

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:



very important NLO contributions $\rightarrow$ factor 2

pQCD standard approach

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

- quadrupuly differential cross section:

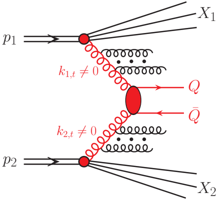
$$\frac{d\sigma}{dy_1\, dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 p_i(x_1\,, \mu^2)\; x_2 p_j(x_2\,, \mu^2)\; \overline{|\mathcal{M}_{ij}|^2}$$

- $p_i(x_1\,, \mu^2),\, p_j(x_2\,, \mu^2)$ - standard parton distributions in hadron (e.g. CTEQ, GRV, GJR, MRST, MSTW)
- 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 (very 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 $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$.

Different models of 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

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

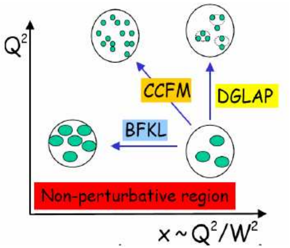
- UPDFs - needed in less inclusive measurements which are sensitive to the transverse momentum of the parton

gg-fusion dominance ⇒ great test of existing unintegrated gluon densities!

especially at LHC (small-x)

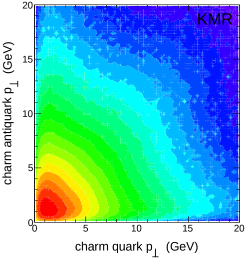
several models:

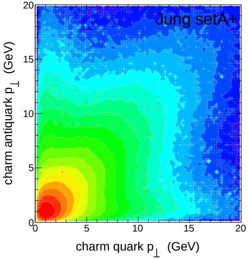
- Kwiecinski, Jung (CCFM, wide x-range)
- Kimber-Martin-Ryskin (larger x-values)
- Kutak-Stasto, GBW (small-x, saturation effects)
- Ivanov-Nikolaev, KMS, etc.

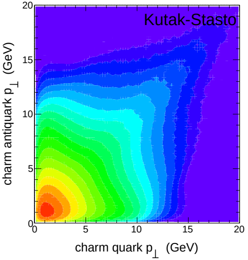


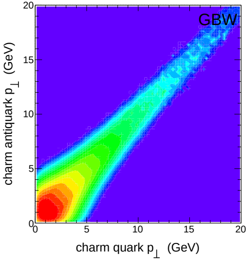
Differential cross section for charm quarks

$$\frac{d\sigma}{dp_{1t}dp_{2t}}$$

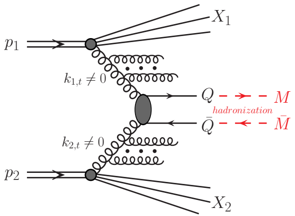








Fragmentation functions technique



- phenomenology $\rightarrow$ fragmentation functions extracted from e^+e^- data
- often used: Peterson et al., Braaten et al., Kartvelishvili et al.
- numerically performed by rescalling transverse momentum at a constant rapidity (angle)

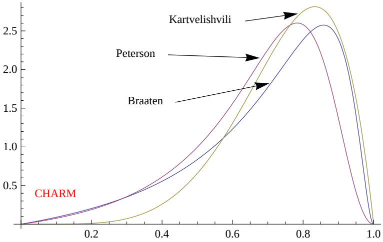
- from heavy quarks to heavy mesons:

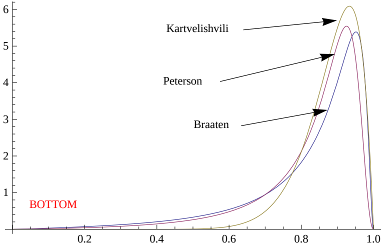
$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q\rightarrow M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

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

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

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.

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

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

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

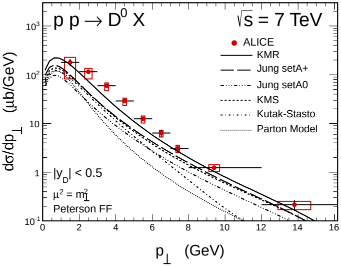
  $r_c = 0.2$, $r_b = 0.07$

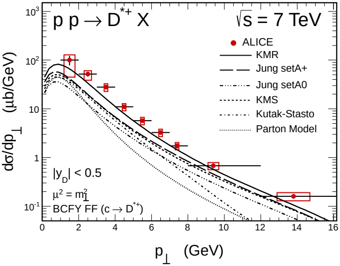
- Kartvelishvili et al.

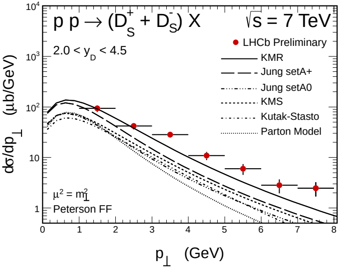
  $$D_{Q\to M}(z) = N(1-z)z^a$$

  $a_c = 5.0$, $a_b = 14.0$

p_t spectra in different rapidity regions @ ALICE and LHCb

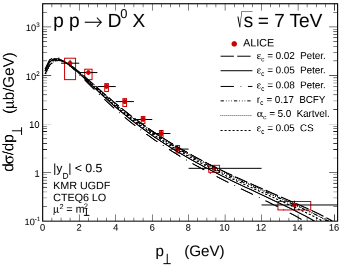


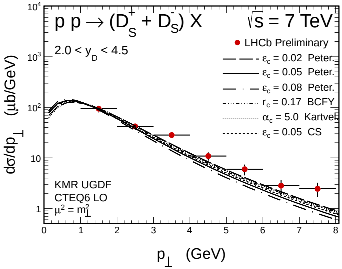


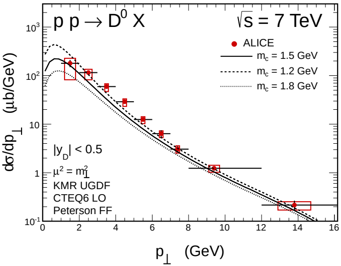


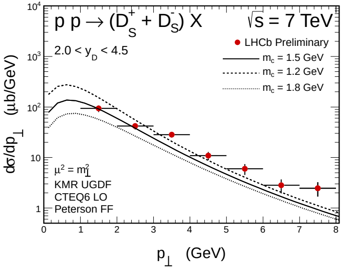
- various UGDFs models → crucial test of their applicability at high energies and small x-values
- only KMR model gives well description of the ALICE and LHCb data
- significant difference between LO parton model and LO k_t-factorization

effects of hadronization and quark mass uncertainty



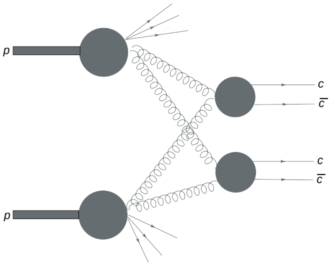






Production of two $c\bar{c}$ pairs in Double Parton Scattering

Consider $pp \to (c\bar{c})(c\bar{c})$ process, initiated by two hard (parton) scatterings in one proton-proton interaction



Łuszczak, Maciuła, Szczurek, Phys. Rev. D 85, 094034 (2012)

in the analogy to frequently considered mechanisms of

double gauge boson production or double Drell-Yan anihillation.

Formalism of theoretical DPS modelling

The double-parton scattering formalism assumes two single-parton scatterings so in a simple probabilistic picture the cross section for DPS can be written as:

$$\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}} \sigma^{SPS}(pp \to c\bar{c}X_1) \cdot \sigma^{SPS}(pp \to c\bar{c}X_2)$$

The simple formula above can be generalized to include differential distributions:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 dy_2 d^2p_{1t}} \cdot \frac{d\sigma}{dy_3 dy_4 d^2p_{2t}}$$

- two subprocesses are not correlated and do not interfere
- $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb $\Rightarrow$ Tevatron, CDF, F.Abe et al., PRD 56 3811 (1997)
- extra limitations for longitudinal momentum fractions of gluons: $x_1 + x_2 < 1$ and $x_1' + x_2' < 1$ cause the "second" emission must take into account that some momentum was used up in the "first" parton collision

double Parton Distribution Functions

A more general formula for the cross section in terms of so-called double-parton distributions (dPDFs):

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

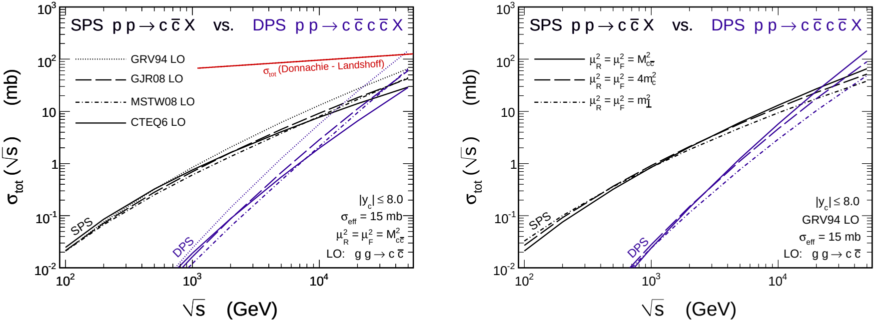
factorized form with standard PDFs

- $F_{gg}(x_1, x_2, b) = g(x_1)g(x_2)F(b)$, where $F(b)$ is an overlap of the matter distribution in the transverse plane
- $1/\sigma_{eff} = \int d^2b F^2(b) \Rightarrow$ universal factor (energy and process independent)

dPDFs from special evolution equations

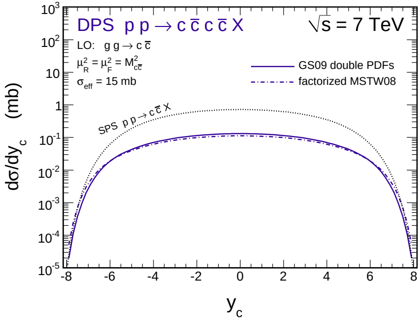
- equal scales: $\mu_1 = \mu_2 = \mu$ (Snigireev)
- unequal scales: $\mu_1 \neq \mu_2$ (Ceccioperi, Gaunt-Stirling)

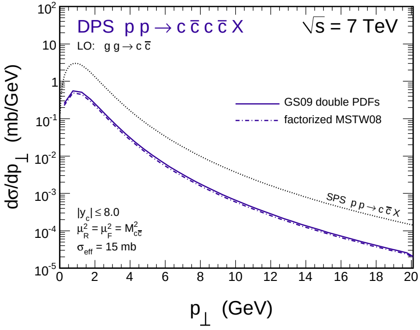
LO collinear predictions for DPS charm production



- DPS mechanism gives a large contributions to inclusive charm production
- dangerous approaching of the Donnachie-Landschoff parametrization of the total cross section ⇒ inclusion of unitarity effect and/or saturation of parton distributions may be necessary

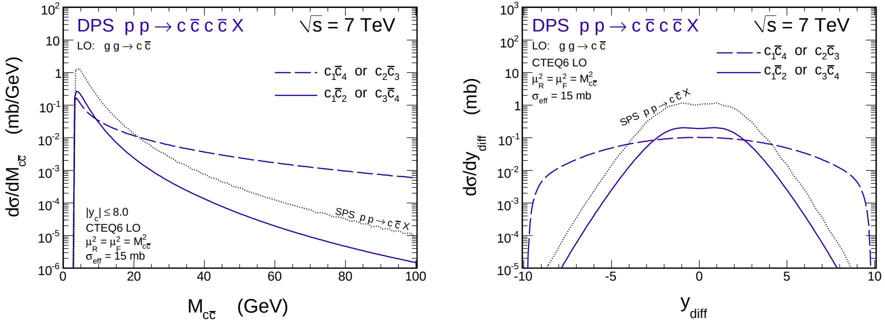
double evolution dPDFs vs. factorized form with PDFs





- inclusive double-scattering distributions in y and $p_\perp$ are identical as for single-scattering
- no difference between both prescriptions in the case of charm production

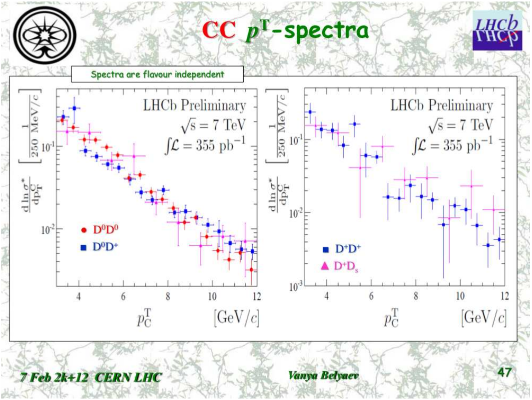
Invariant mass and rapidity difference spectra



- DPS dominates at large rapidity difference and/or large invariant masses
- unique feature of DPS: possible production of *cc* pairs ⇒ experimental signature D^0D^0, D^0D^+, D^+D^+, D^+D_s

Preliminary data from LHCb

Very recent news from CERN! LHCb-PAPER-2012-003 (V. Belayev)



- $\frac{\sigma_{D^0D^0}}{\sigma_{D^0\bar{D}^0}} \sim 11\%$, $\frac{\sigma_{D^0D^+}}{\sigma_{D^0D^-}} \sim 13\%$, $\frac{\sigma_{D^0D_s^+}}{\sigma_{D^0D_s^-}} \sim 16\%$, $\frac{\sigma_{D^+D_s^+}}{\sigma_{D^+D_s^-}} \sim 12\%$, $\frac{\sigma_{D^+D^+}}{\sigma_{D^+D^-}} \sim 10\%$
- SPS mechanism of $c\bar{c}c\bar{c}$ production can also contributes!

see Schafer, Szczurek, Phys. Rev. D 85, 094029 (2012)

D mesons from DPS mechanism (LO parton model)

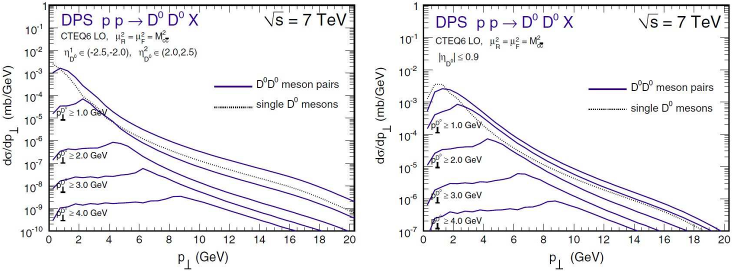


TABLE I. The DPS cross section $(\sigma_{D^0 D^0} + \sigma_{\bar{D}^0 \bar{D}^0})/2$ in mb for the production of one meson in $\eta_1 \in (-2.5, 2.0)$ and the second meson in $\eta_2 \in (2.0, 2.5)$ (ATLAS, CMS), second column, and for η_1, $\eta_2 \in (-0.9, 0.9)$ (ALICE), third column, for different 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}

Summary

- good description of the transverse momentum distributions of open charm mesons measured by ALICE and LHCb
- huge contribution to charm production cross section from Double-Parton-Scattering → application of the k_t-factorization approach in our next step
- waiting for ATLAS data from large rapidity interval $|\eta_D| < 2.5$ (5 units, large rapidity difference)

Thank You for attention!