

Single and double charmed meson production at the LHC

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13th International Workshop on Meson Production, Properties and Interaction,
29th May - 3rd June 2014, KRAKÓW, POLAND



Outline

- 1 Open charm production at the LHC
 - Theoretical framework within the k_T -factorization approach
 - Inclusive single D meson spectra
 - Production of $D\bar{D}$ pairs and kinematical correlations
- 2 Mechanism of double-parton scattering (DPS)
 - Simple factorized theoretical model
 - Double charm (DD pairs) production vs. LHCb data
 - DPS effects and inclusive D meson spectra

Based on:

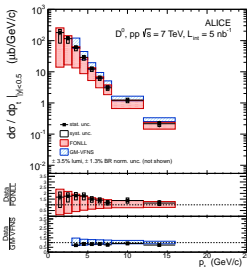
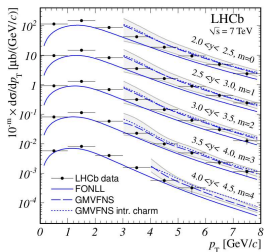
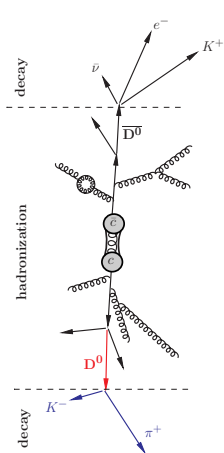
- vanHameren, Maciuła, Szczurek, Phys. Rev. D89, 094019 (2014)
Maciuła, Szczurek, Phys. Rev. D87, 094022 (2013)
Maciuła, Szczurek, Phys. Rev. D87, 074039 (2013)
Łuszczak, Maciuła, Szczurek, Phys. Rev. D79, 094034 (2012)



Theoretical framework within the k_T -factorization approach

Heavy quarks measurements in pp scattering at the 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; Phys. Lett. B718 (2012) 279
- LHCb, $2.0 < y_D < 4.5$, $p_\perp < 8 \text{ GeV}$, Nucl. Phys. B871 (2013) 1-20
very small x region! (down to 10^{-5})
- ATLAS, $|\eta_D| < 2.1$, $p_\perp > 3.5 \text{ GeV}$, ATLAS-CONF-2011-017
wide rapidity interval



Theoretical framework within the k_T -factorization approach

Standard approach of perturbative QCD

collinear approximation → transverse momenta of the incident partons are assumed to be zero (Wiesacker-Williams method in QED)

- quadruply 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 collinear PDFs in the proton (e.g. CTEQ, GRV, GJR, MRST, MSTW)
- NLO on-shell matrix elements well-known

Nason et al., Nucl. Phys. B303 (1988) 607; Nucl. Phys. B327 (1989) 49

Beenakker et al., Phys. Rev. D40 (1989) 54; Nucl. Phys. B351 (1991) 505

several approaches: improved schemes of NLO collinear calculations

- **FONLL** (Cacciari *et al.*) JHEP 05 (1998) 007; JHEP 03 (2001) 006
- **GM-VFNS** (Kniehl, Kramer *et al.*) Phys. Rev. D71 (2005) 014018; Phys. Rev. D79 (2009) 094009

state-of-art: σ_{tot} and inclusive single particle spectra

BUT cannot be applied in more exclusive studies of KINEMATICAL CORRELATIONS



Theoretical framework within the k_t -factorization approachBasic concepts of the k_t -factorization (semihard) approach **k_t -factorization $\rightarrow \kappa_{1,t}, \kappa_{2,t} \neq 0$**

Collins-Ellis, Nucl. Phys. B360 (1991) 3;

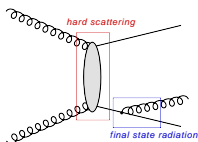
Catani-Ciafaloni-Hautmann, Nucl. Phys. B366 (1991) 135; Ball-Ellis, JHEP 05 (2001) 053

 \Rightarrow very efficient approach for $Q\bar{Q}$ correlations

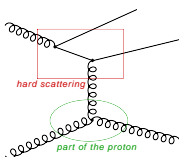
- multi-differential cross section

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

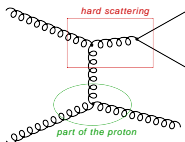
- LO off-shell** $|\overline{\mathcal{M}_{g^*g^* \rightarrow Q\bar{Q}}}|^2 \Rightarrow$ Catani-Ciafaloni-Hautmann (CCH) analytic formulae or QMRK approach with effective BFKL NLL vertices
- $\mathcal{F}_i(x_1, \kappa_{1,t}^2), \mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated (k_t -dependent) gluon distributions
- major part of **NLO corrections effectively included**

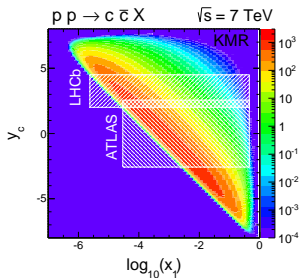
pair creation
with gluon emission

flavour excitation

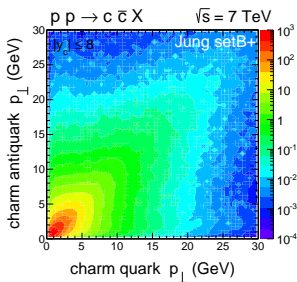
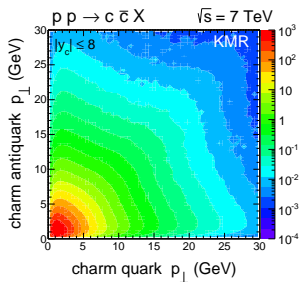
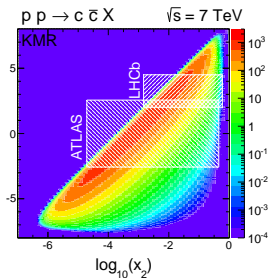


gluon splitting

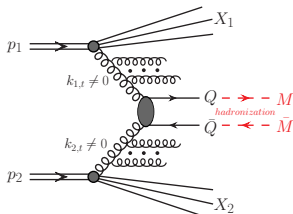


Theoretical framework within the k_T -factorization approach2Dim-differential cross sections for charm quarks $\sqrt{s} = 7 \text{ TeV}$ 

LHC:
 $x \gtrsim 10^{-4}$ (ATLAS)
 $x \gtrsim 10^{-5}$ (LHCb)



Fragmentation functions technique



- phenomenology:
fragmentation functions extracted from e^+e^- data
- often used (older parametrizations):
Peterson et al., Braaten et al., Kartvelishvili et al.
- more up-to-date: charm nonperturbative fragmentation functions determined from recent Belle, CLEO, ALEPH and OPAL data:
Kneesch-Kniehl-Kramer-Schienbein (KKKS08) + DGLAP evolution
- FONLL → Braaten et al. (charm) and Kartvelishvili et al. (bottom)
GM-VFNS → KKKS08 + evolution

- numerically performed by rescaling transverse momentum at a constant rapidity (angle)
- from heavy quarks to heavy mesons:

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

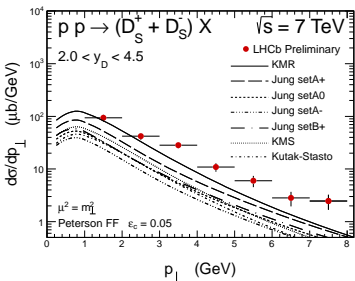
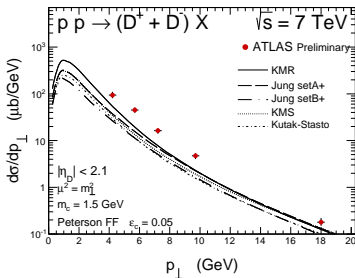
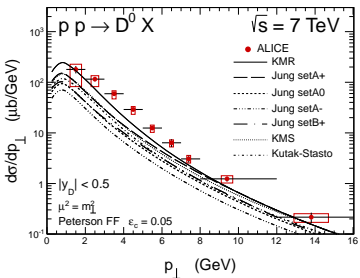
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

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



Inclusive D meson spectra

ALICE, ATLAS, LHCb



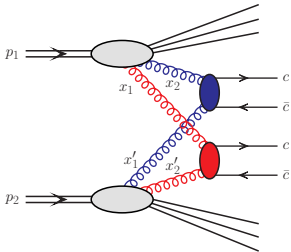
- all of the UGDFs models underestimate experimental data points
- only the **KMR UGDF** gives results which are close to the measured values



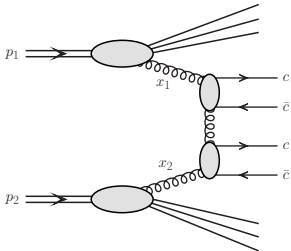
Simple factorized theoretical model

Double charm production (final state with two pairs of $c\bar{c}$)

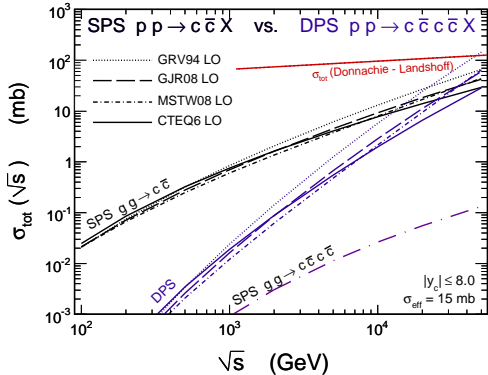
Double-parton scattering (DPS)



Single-parton scattering (SPS)



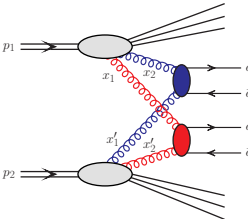
SINGLE CHARM vs. DOUBLE CHARM mechanism



- SPS $c\bar{c}$ vs. DPS $c\bar{c}c\bar{c}$: **comparable total cross sections at LHC energies!**
- SPS $c\bar{c}c\bar{c}$ negligible



Simple DPS picture and factorized Ansatz



process initiated by **two simultaneous hard gluon-gluon scatterings** in one proton-proton interaction \Rightarrow

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

two subprocesses are not correlated and do not interfere

analogy: frequently considered mechanisms of double gauge boson production and double Drell-Yan annihilation

$$\frac{d\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{2\sigma_{\text{eff}}} \cdot \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_1)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \cdot \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}}$$

in more general form:

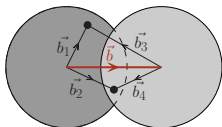
$$d\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X) = \frac{1}{2} \cdot \Gamma_{gg}(b, x_1, x_2; \mu_1^2, \mu_2^2) \Gamma_{gg}(b, x'_1, x'_2; \mu_1^2, \mu_2^2) \times d\sigma_{gg \rightarrow c\bar{c}}(x_1, x'_1, \mu_1^2) \cdot d\sigma_{gg \rightarrow c\bar{c}}(x_2, x'_2, \mu_2^2) dx_1 dx_2 dx'_1 dx'_2 d^2b$$

DPDF - emission of one parton with assumption that second parton is also emitted



Simple factorized theoretical model

Double-parton distributions (DPDFs) and factorized Ansatz



$$\Gamma_{ij}(b, x_1, x_2; \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2) F_j(x_2, \mu_2^2) F(b; x_1, x_2, \mu_1^2, \mu_2^2)$$

- correlations between two partons

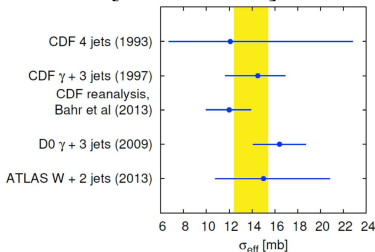
C. Flensburg et al., JHEP 06, 066 (2011)

in general:

$$\sigma_{\text{eff}}(x_1, x_2, x'_1, x'_2, \mu_1^2, \mu_2^2) = \left(\int d^2b F(b; x_1, x_2, \mu_1^2, \mu_2^2) F(b; x'_1, x'_2, \mu_1^2, \mu_2^2) \right)^{-1}$$

factorized Ansatz:

- additional limitations: $x_1 + x_2 < 1$ or $x'_1 + x'_2 < 1$
- DPDF in multiplicative form: $\Gamma_{gg}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_g(x_1, \mu_1^2) F_g(x_2, \mu_2^2) F(b)$
- $\sigma_{\text{eff}} = \left[\int d^2b (F(b))^2 \right]^{-1}$, $F(b)$ - energy and process independent



phenomenology: $\sigma_{\text{eff}} \Rightarrow$ nonperturbative quantity with a dimension of cross section, connected with transverse size of proton

$$\sigma_{\text{eff}} \approx 15 \text{ mb} \quad (p_{\perp}\text{-independent})$$

a detailed analysis of σ_{eff} :
 Seymour, Siódmok, JHEP 10, 113 (2013)

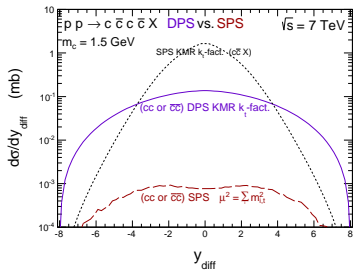


How the DPS mechanism can be investigated?

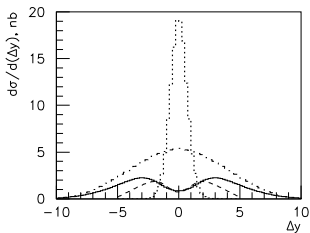
Study of **MESON-MESON pairs** production:

DD pairs - both containing c quarks or both containing \bar{c} antiquark

- impossible to produce within standard SPS single $c\bar{c}$ production mechanism
- measurements of charm meson-meson pairs highly recommended at the LHC
- larger rapidity differences between particles: DD pairs at ATLAS
- same-sign nonphotonic lepton pairs, e.g. $\mu^+\mu^+$ at ALICE



Double open charm ($c\bar{c}c\bar{c}$)



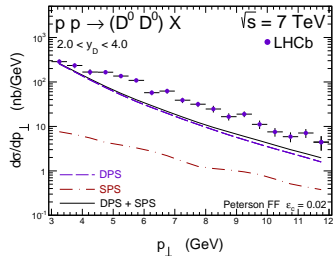
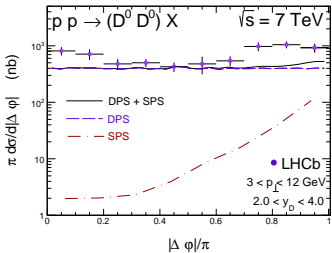
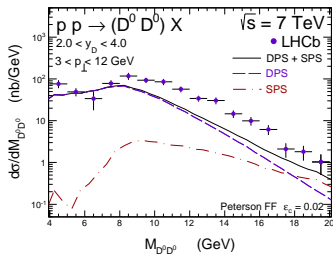
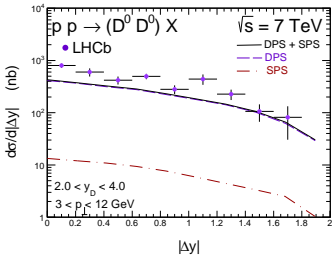
Double hidden charm ($J/\psi J/\psi$)

Baranov et al., Phys.Rev. D87, 034035 (2013)



Double charm (DD pairs) production vs. LHCb data

First clean signature of the DPS mechanism?

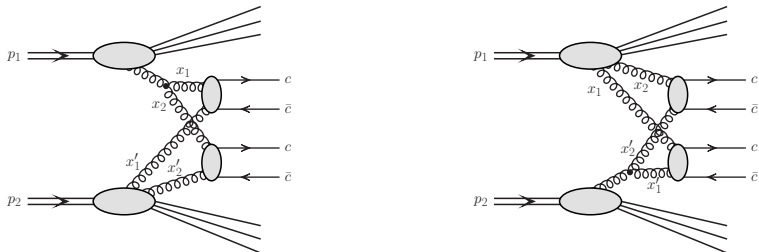


proper order of magnitude but still something is missing (about factor 2)



What can be still missing?

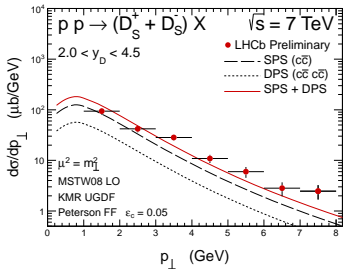
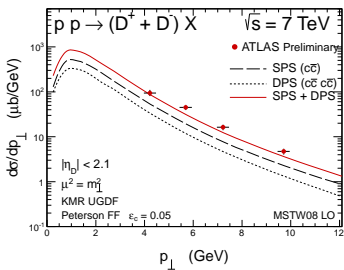
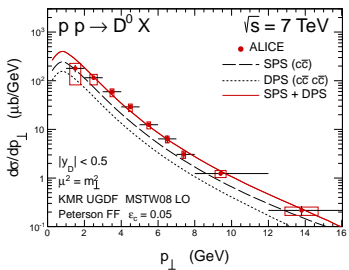
Different class of the DPS diagrams ($3 \rightarrow 4$) \Rightarrow **perturbative parton splitting**



- LO calculations available using **splitting DPDFs** J.Gaunt, JHEP, 01, 042 (2013)
- our first rough estimation: $\frac{DPS(3 \rightarrow 4)}{DPS(4 \rightarrow 4)} \approx 30-60\%$
- inclusion of the DPS($3 \rightarrow 4$) contributions in the LHCb data very difficult (unknown $\sigma_{eff}^{3 \rightarrow 4}$; the LO collinear formalism is not sufficient for charm)
- more precise calculations, beyond the factorized Ansatz, are NOT possible in the moment \Rightarrow more advanced framework have to be worked out



Does the DPS contribute to inclusive D mesons spectra?



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



Conclusions

SPS $c\bar{c}$:

- only KMR UGDF allows for results which are close to the LHC inclusive charm data (rest of tested UGDFs seem to underestimate significantly experimental data)
- only upper limits of our theoretical predictions give quite reasonable description of the ALICE, ATLAS and LHCb data (also true for FONLL)
- k_T -factorization approach together with KMR UGDF is very efficient for studying kinematical correlations in less inclusive measurements of $D\bar{D}$ pairs

DPS $c\bar{c}c\bar{c}$:

- SPS $c\bar{c}$ and DPS $c\bar{c}c\bar{c}$ cross sections become comparable at LHC energies
- Production of double charm (DD pairs) is an extremely good testing ground of double-parton scattering effects
- DPS mechanism can give a very important contribution to inclusive D meson distributions?

Thank You for attention!

