Double open charm meson production at the LHC: New single- and double-parton scattering mechanisms

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Outline

Based on:

Maciuła, Saleev, Shipilova, Szczurek, Phys. Lett. B758, 458 (2016)

Hameren, Maciuła, Szczurek, Phys. Lett. B748, 167 (2015)

Hameren, Maciuła, Szczurek, Phys. Rev. D89, 094019 (2014)

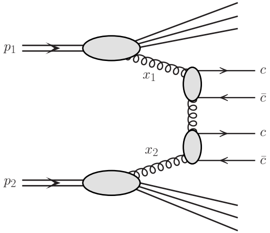
Maciuła, Szczurek, Phys. Rev. D87, 074039 (2013)

Łuszczak, Maciuła, Szczurek, Phys. Rev. D79, 094034 (2012)

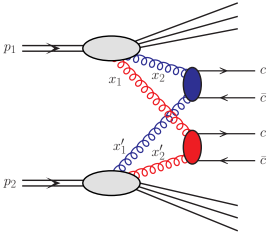
Why double charm?

Double charm ⇒ final state with two pairs of $c\bar{c}$

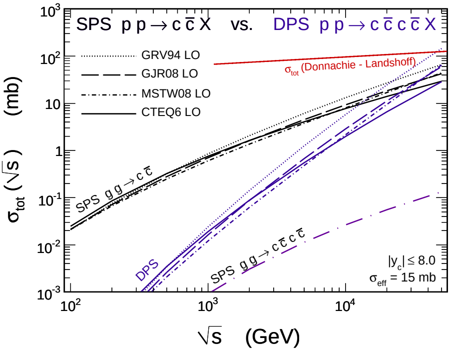
Single-parton scattering (SPS)



Double-parton scattering (DPS)



SINGLE vs. DOUBLE CHARM



- SPS $c\bar{c} \gg$ SPS $c\bar{c}c\bar{c}$: the SPS double charm is negligible higher-order correction only
- SPS $c\bar{c}$ vs. DPS $c\bar{c}c\bar{c}$: **comparable total cross sections at LHC energies!**

Best known place to study DPS effects at the LHC

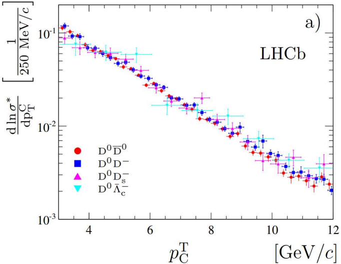
How the DPS effects in charm sector can be investigated experimentally?

Study of **CHARM MESON-MESON pair** production:

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

- impossible to produce within standard SPS single $c\bar{c}$ mechanism
- SPS double charm expected to be very small
- measurements of charm meson-meson pairs highly recommended at the LHC
- same-sign nonphotonic lepton pairs, e.g. $\mu^+\mu^+$ at ALICE

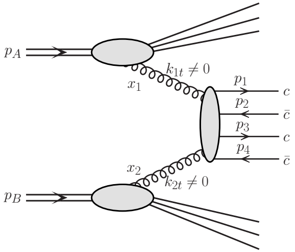
First measurement by LHCb: *Observation of double charm production involving open charm in pp collisions at* $\sqrt{s} = 7$ *TeV*, J. High Energy Phys. 06, 141 (2012)



Mode	σ [nb]
D^0D^0	$690 \pm 40 \pm 70$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$

- very large cross section: $\frac{\sigma(DD)}{\sigma(D\bar{D})} \approx 10\%$
- various *DD* modes
- several differential distributons

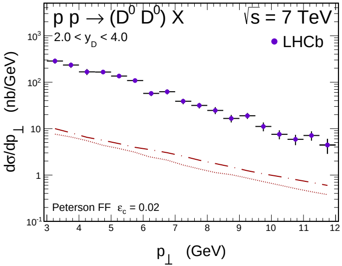
SPS double charm definitely negligible

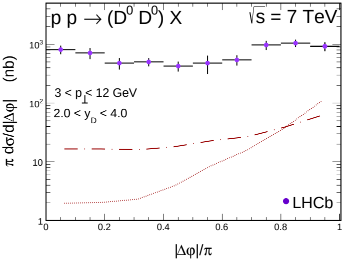


SPS double charm calculated in two different ways:

- LO collinear approach
- NEW: k_T-factorization approach
  (part of higher-order corrections included)
- first time: off-shell initial state partons ($2 \to 4$)

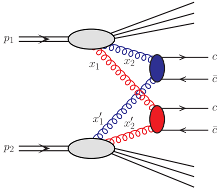
Monte Carlo: **AVHLIB** (A. van Hameren):
https://bitbucket.org/hameren/avhlib

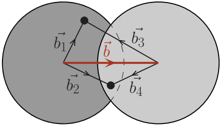




Can the LHCb data be explained by the DPS?

Double charm within double-parton scattering (DPS)





DPS in general form:

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

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

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

- longitudinal and transverse correlations between two partons
- spin, flavour and color correlations
- well established theory: *e.g.* Diehl, Ostermeier, Schafer, JHEP 03, 089 (2012)
  but not yet available for phenomenological studies

Factorized ansatz (pocket-formula)

In a simple probabilistic picture process initiated by:

two simultaneous hard gluon-gluon scatterings in one proton-proton interaction

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

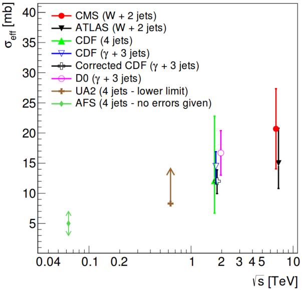
two subprocesses are not correlated and do not interfere

- $\sigma_{eff} \Rightarrow$ model parameter $\Rightarrow$ normalization of σ^{DPS}

Double charm within double-parton scattering (DPS)

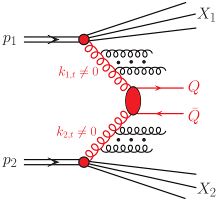
Factorized ansatz (pocket-formula)

- a good approximation for small-x partons $\Rightarrow$ charm at high energies
- color/flavour correlations suppressed in evolution (Kasemets et al., Phys. Rev. D91, 014015 (2015))
- DPDFs in multiplicative form: $\Gamma_{gg}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_g(x_1, \mu_1^2) F_g(x_2, \mu_2^2) F(b)$
- only transverse correlations taken into account
- $\sigma_{eff} = \left[\int d^2b \, (F(b))^2 \right]^{-1}$, $F(b)$ - overlap of the matter distribution in transverse plane where b is a distance between both gluons
- nonperturbative quantity with dimension of cross section, connected to transverse size of proton



- extracted from several experimental analyses
- in principle may not be universal
- detailed studies: Seymour, Siódmok, JHEP 10, 113 (2013)
- world average: $\sigma_{eff} \approx 15$ mb (large uncertainties)
- LHCb double charm data: $\sigma_{eff} \approx 15 - 30$ mb
- e.g. D^0D^0: $\sigma_{eff} \approx 21^{+7}_{-6}$ mb (arXiv:1308.6749 (hep-ph))
- For charm: spin (polarization) correlations very small (Echevarria et al. JHEP 04, 034 (2015))

Each step of DPS: two single-parton scatterings



k_t-factorization $\longrightarrow \kappa_{1,t},\ \kappa_{2,t} \neq 0$ e.g. Collins-Ellis, Nucl. Phys. B360 (1991) 3

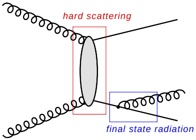
$\Rightarrow$ very efficient approach for $Q\bar{Q}$ correlations

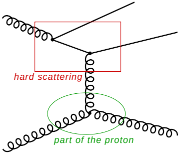
- multi-differential cross section

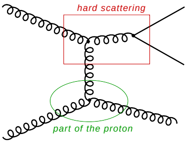
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{i^* j^* \to Q\bar{Q}}|^2}$$
$$\times\ \delta^2 \left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right)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

- **LO off-shell** $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$: e.g. Catani-Ciafaloni-Hautmann, Nucl. Phys. B366 (1991) 135
- $\mathcal{F}_i(x_1, \kappa_{1,t}^2),\ \mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated (k_t-dependent) gluon distributions
- some part of very important higher-order corrections effectively included

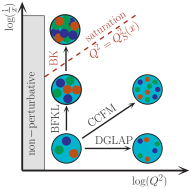
pair creation with gluon emission | *flavour excitation* | *gluon splitting*







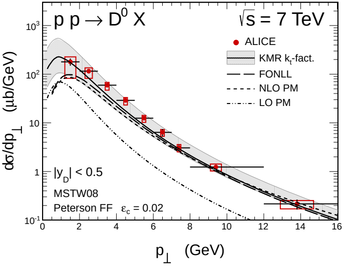
Unintegrated gluon distribution functions (UGDFs)

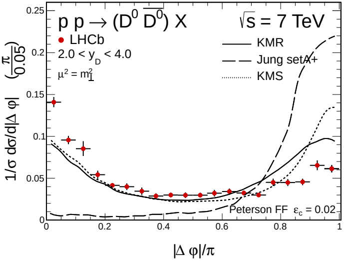


most popular models:

- Kwieciński, Jung (CCFM, wide range of x)
- Kimber-Martin-Ryskin (DGLAP-BFKL, wide range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, small x-values)
- Kutak-Staśto (BK, saturation, only small x-values)

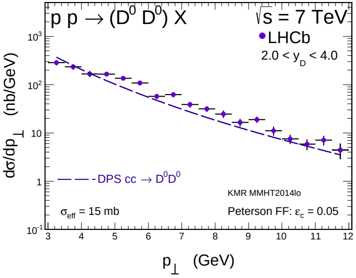
Lesson from inclusive single D meson and $D\bar{D}$ pair production at the LHC:

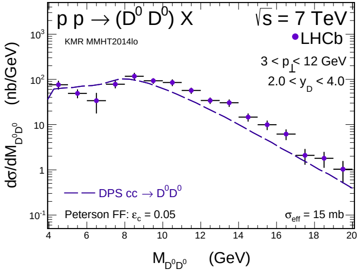


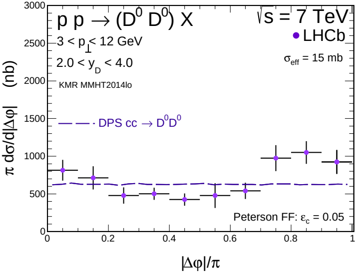


- KMR UGDF works very well (single particle spectra and correlation observables)

First DPS results vs. LHCb double charm data







- DPS mechanism describes the LHCb data
- clear evidence of DPS effects
- factorized ansatz: flat $\Delta\varphi$ distribution
- LHCb data: some $\Delta\varphi$ correlations suggested

Different fragmentation schemes

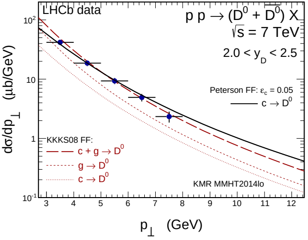
Standard approach (firs results):

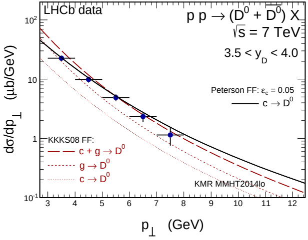
- Peterson et al.: scale-independent FFs
- only one component: $c \to D$
- k_t-factorization: Maciula, Szczurek, Phys.Rev.D87, 094022 (2013)

New scenario:

- KKKS08 (Kniehl et al.): several FFs of a parton (gluon, u, d, s, c, $\bar{u}$, $\bar{d}$, $\bar{s}$, $\bar{c}$) $\to D$ mesons
- scale-dependent FFs undergo DGLAP evolution
- $c \to D$ reduced with increasing p_t (scale)
- very important contribution from $g \to D$
- k_t-factorization: Karpishkov et al. Phys.Rev.D91, 054009 (2015)

Both prescriptions describe the LHCb data for single D meson production

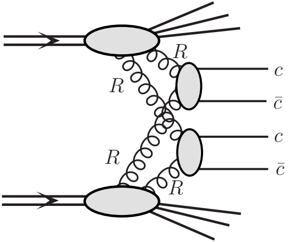




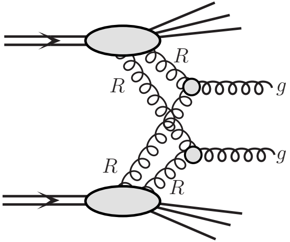
What are consequences of the new scenario for DPS double charm?

New scenario for double charm production

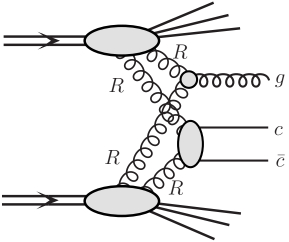
DPS: $cc \to DD$



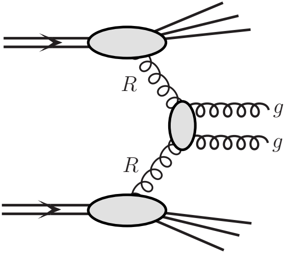
DPS: $gg \to DD$



DPS: $cg \to DD$

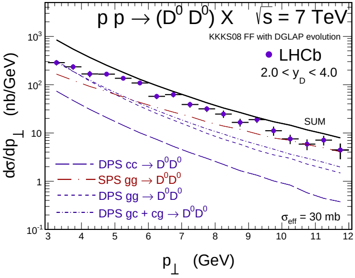


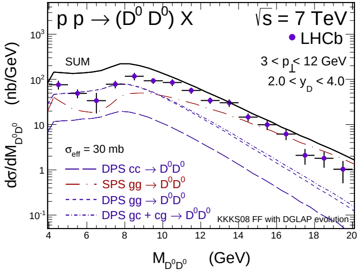
SPS: $gg \to DD$ (NEW!)

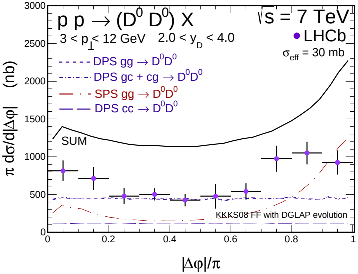


all diagrams calculated in the k_t-factorization approach

New scenario results vs. LHCb double charm data







- LHCb data overestimated
- SPS $gg \to DD$ contribution very important
- $\Delta\varphi$ correlation as in the LHCb data

Possible problems:

- massless DGLAP evolution?
- larger σ_{eff}?
- small-x (nonlinear) or large-x effects?

Conclusions

Production of double charm - *DD* meson-meson pairs - at the LHC

is dominated by the double-parton scattering (DPS) mechanism

Standard approach:

- very good description of the LHCb data with the DPS factorized ansatz and k_t-factorization
- some small $\Delta\varphi$ correlations visible in the LHCb data difficult to obtain within the factorized DPS model, even when including spin correlations between two partons in DPDFs

New scenario:

- $g \to D$ component which appears in the DGLAP evolution of FFs change the overal picture
- new mechanisms appear: DPS $gg \to DD$, DPS $cg \to DD$ and SPS $gg \to DD$
- the LHCb data overestimated
  BUT: $\Delta\varphi$ correlations arise due to the presence of the new SPS $gg \to DD$ component
- large contribution from the SPS $gg \to DD$ makes the extraction of σ_{eff} from the LHCb data more complex (revision of the existing extraction needed)

Thank You for attention!