Triple charm production at the LHC

Rafał Maciuła
Institute of Nuclear Physics PAN, Kraków, Poland

WE-Heraeus Physics School: QCD - Old Challenges and New Opportunities,
Physikzentrum Bad Honnef, Germany, Sept 24 - 30, 2017

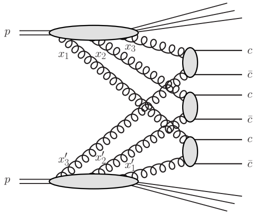
Multiple-Parton Interactions (MPI) at the LHC

Our previous studies:

Hard Double-Parton Scattering (DPS) effects in proton-proton collisions:

- $pp \to c\bar{c}c\bar{c}\ X$ (predictions confirmed by the LHCb double charm data)
  Phys.Rev. D87 (2013) no.7, 074039; Phys.Lett. B758 (2016) 458-464
- $pp \to 4\text{jets}\ X$ (needs dedicated experimental analyses: ATLAS, CMS)
  Phys.Lett. B749 (2015) 57-62; Phys.Rev. D94 (2016) no.1, 014019
- $pp \to c\bar{c} + 2\text{jets}\ X$ (experimentally available at ATLAS)
  arXiv:1707.08366 (hep-ph), accepted in PRD
- $pp \to c\bar{c}b\bar{b}\ X$ (experimentally available at LHCb) soon on arXiv
- $pp \to b\bar{b}b\bar{b}\ X$ (experimentally available at LHCb and CMS) soon on arXiv

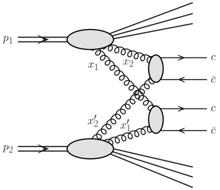
In this talk: Triple-parton scattering (TPS) in $pp \to c\bar{c}c\bar{c}c\bar{c}\ X$

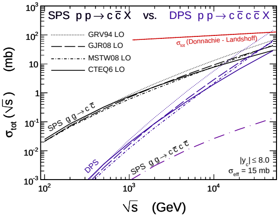


Can we observe some evidence of TPS effects at the LHC in the case of triple charm production?

Multiple charm quark production at the LHC

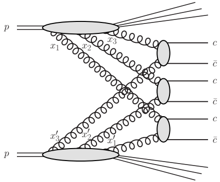
Double-parton scattering in double $c\bar{c}$ pair production
Luszczak, Maciula, Szczurek, Phys.Rev. D85 (2012) 094034)

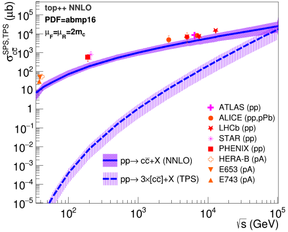




Total cross sections for
SPS single $c\bar{c}$ and DPS double $c\bar{c}$ become comparable at LHC energies

Triple-parton scattering in triple $c\bar{c}$ pair production
d'Enterria, Snigirev, Phys. Rev. Lett. 118, 122001 (2017)





Total cross section for
TPS triple $c\bar{c}$ at LHC energies become sizeable ($\sim$ 100 μb)

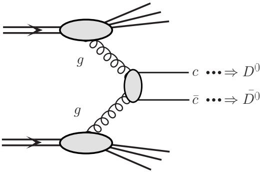
Can we observe the TPS effects experimentally?

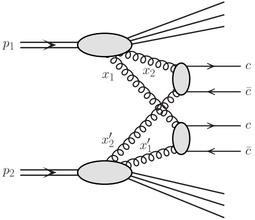
The idea behind

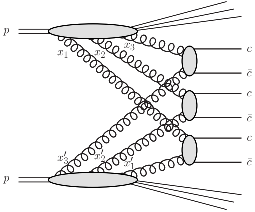
Our goal: Reliable predictions for $D^0 D^0 D^0$ production for the LHCb experiment

- we try to stay in contact with experimental data for single D^0 and double D^0 production to minimize the theoretical uncertainties.
- theoretical uncertainties in the SPS get amplified roughly by factors of 2 and 3 for the DPS and TPS

SPS single D^0 $\Rightarrow$ DPS double D^0 $\Rightarrow$ TPS triple D^0



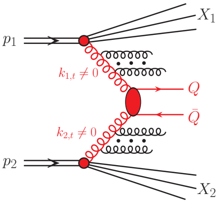




- use the model calculation that provides a good (of the same quality) "parametrizations" of both the single and the double charm LHCb data

The LHCb single and double charm data well described within the k_t-factorization approach with standard set of pQCD calculation parameters

Theoretical framework



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

e.g. Collins-Ellis, Nucl. Phys. B360 (1991) 3; Catani-Ciafaloni-Hautmann, Nucl. Phys. B366 (1991) 135;

- exact kinematics from the very beginning and additional hard dynamics coming form transverse momenta of incident partons
- very efficient approach for correlation studies

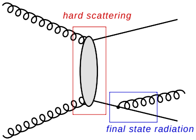
multi-differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$$

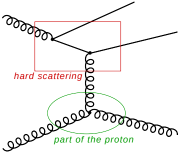
$$\times \; \delta^2 \left(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t} \right) \mathcal{F}_g(x_1, k_{1,t}^2) \, \mathcal{F}_g(x_2, k_{2,t}^2)$$

- leading-order **off-shell** matrix elements $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$
- $\mathcal{F}_g(x, k_t^2)$ - **transverse momentum dependent** gluon distributions
- part of higher-order real corrections effectively included

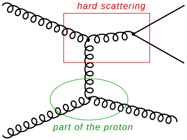
pair creation
with gluon emission



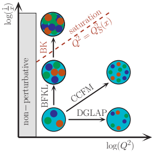
flavour excitation



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)

We use: Kimber-Martin-Ryskin (KMR) approach:

$$f_g(x, k_t^2, \mu^2) \equiv \frac{\partial}{\partial \log k_t^2}\left[g(x, k_t^2)\, T_g(k_t^2, \mu^2) \right] = T_g(k_t^2, \mu^2)\, \frac{\alpha_S(k_t^2)}{2\pi} \sum_b \int_x^1 dz\, P_{gb}(z)\, b\left(\frac{x}{z}, k_t^2\right)$$

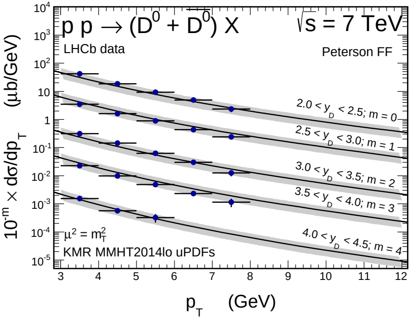
$$f_g(x, k_t^2, \mu^2) = T_g(k_t^2, \mu^2)\, \frac{\alpha_S(k_t^2)}{2\pi} \times \int_x^1 dz \left[\sum_q P_{gq}(z) \frac{x}{z} q\left(\frac{x}{z}, k_t^2\right) + P_{gg}(z) \frac{x}{z} g\left(\frac{x}{z}, k_t^2\right) \Theta\left(\frac{\mu}{\mu + k_t} - z\right) \right]$$

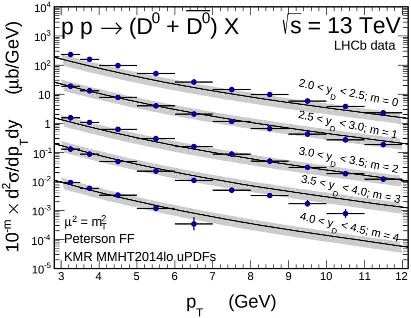
$$\mathcal{F}_g(x, k_t^2, \mu^2) \equiv \frac{1}{k_t^2}\, f_g(x, k_t^2, \mu^2)\ .$$

- calculated from collinear PDFs (most up-to-date PDF sets can be used)
  we take: MMHT2014lo gluon PDF
- unintegrated quarks available (important for reliable predictions *e.g.* for jets)
- unique feature: possible additional hard emission from the uPDF
  (part of higher-order real corrections)

Inclusive D^0 production $\sqrt{s} = 7, 13$ TeV

The LHCb fiducial volume under interest: $3 < p_T^D < 12$ GeV, $2 < y^D < 4$

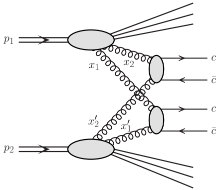


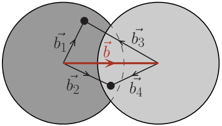


- a very good description of the LHCb inclusive charm data with the central value of the standard uncertainty bands at both energies
- the usual variation of these parameters is not necessary in order to stay in touch with the data
- The $\pm 40\%$ uncertainty is related with factorization/renormalization scales and charm quark mass and will be propagated to the double and triple meson case

Then such a "parametrization" of the data can be used for the predictions for **DPS double** and **TPS triple** D^0 production

Double-parton scattering (DPS) mechanism





see lecture by K. Golec-Biernat

DPS in general form for $pp \to c\,\bar{c}\,c\,\bar{c}\,X$:

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

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

$$\Gamma_{gg}(b, x_1, x_2; \mu_1^2, \mu_2^2) = F_g(x_1, \mu_1^2)\, F_g(x_2, \mu_2^2)\, F(b; x_1, x_2, \mu_1^2, \mu_2^2)$$

- longitudinal and transverse correlations between two partons
- spin, flavor 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 parton-parton scatterings in one proton-proton interaction

$$\sigma^{DPS} = \frac{1}{2\sigma_{eff}} \cdot \sigma^{SPS}(g\,g \to c\,\bar{c}) \cdot \sigma^{SPS}(g\,g \to c\,\bar{c})$$

two subprocesses are not correlated and do not interfere

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

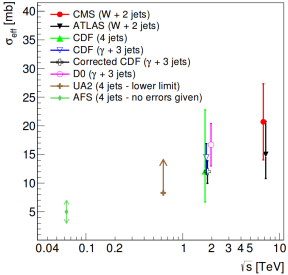
Double-parton scattering (DPS) mechanism

Factorized ansatz (pocket-formula)

- a good approximation for small-x partons (*e.g.* Golec-Biernat et al., Phys. Lett. B750 (2015) 559)
- color/flavor correlations suppressed in evolution (Kasemets et al., Phys. Rev. D91, 014015 (2015))
- spin (polarization) correlations very small (Echevarria et al. JHEP 04, 034 (2015))

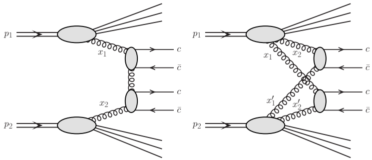
Separation of longitudinal and transverse degrees of freedom

- dPDFs in multiplicative form: $\Gamma_{ij}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2) F_j(x_2, \mu_2^2) F(b)$
- 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 partons
- 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)
- LHCb double charm data: $\sigma_{eff} = 21^{+7}_{-6}$ mb
- ATLAS 4jets data: $\sigma_{eff} = 14.9$ mb
- world average: $\sigma_{eff} \approx 15$ mb (large uncertainties)

Double charm production LHCb at $\sqrt{s} = 7$ TeV



CHARM MESON-MESON pair production:

DD pairs – both mesons containing *c*-quarks

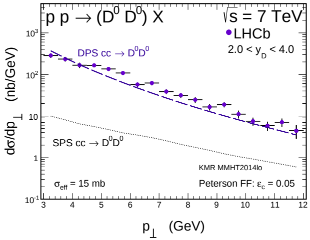
- impossible to be produced within standard SPS single $c\bar{c}$ mechanism
- SPS double $c\bar{c}$ very small

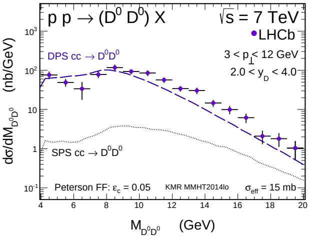
First measurement by LHCb: J. High Energy Phys. 06, 141 (2012)

Cross section much larger than the SPS predictions

⇒ clear evidence for DPS?

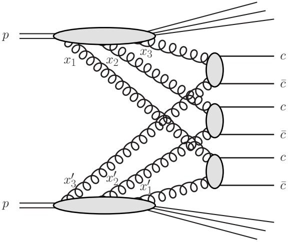
Mode	σ [nb]
D^0D^0	$690 \pm 40 \pm 70$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$





Łuszczak, Maciuła, Szczurek, Phys.Rev. D85 (2012) 094034
Maciuła, Szczurek, Phys.Rev. D87 (2013) no.7, 074039
Hameren, Maciuła, Szczurek, Phys.Rev. D89 (2014) no.9, 094019

Triple charm in triple-parton scattering (TPS)



First theoretical analysis for charm quarks:

d'Enterria, Snigirev, Phys.Rev.Lett. 118, no. 12, 122001 (2017)

- a generic expressions to compute TPS cross sections
- total charm quark cross sections in NNLO collinear approach

Our calculations:

Maciula, Szczurek, arXiv:1703.07163 (hep-ph)

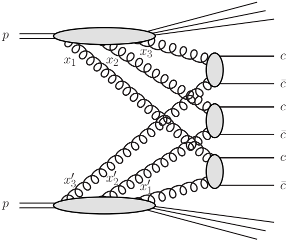
- analysis for triple D meson production
- k_t-factorization approach
- differential distributions

TPS cross section in a general form:

$$\sigma^{\rm TPS}_{pp\to c\bar{c}c\bar{c}c\bar{c}} = \left(\frac{1}{3!}\right)\int \Gamma^{ggg}_p(x_1,x_2,x_3;\vec{b}_1,\vec{b}_2,\vec{b}_3;\mu_1^2,\mu_2^2,\mu_3^2)$$
$$\times\ \hat{\sigma}^{gg}_{c\bar{c}}(x_1,x'_1,\mu_1^2)\ \hat{\sigma}^{gg}_{c\bar{c}}(x_2,x'_2,\mu_2^2)\ \hat{\sigma}^{gg}_{c\bar{c}}(x_3,x'_3,\mu_3^2)$$
$$\times\ \Gamma^{ggg}_p(x'_1,x'_2,x'_3;\vec{b}_1-\vec{b},\vec{b}_2-\vec{b},\vec{b}_3-\vec{b};\mu_1^2,\mu_2^2,\mu_3^2)$$
$$\times\ dx_1\ dx_2\ dx_3\ dx'_1\ dx'_2\ dx'_3\ d^2b_1\ d^2b_2\ d^2b_3\ d^2b$$

- triple-parton distribution functions (triple PDFs)
- adoption to real calculations much more limited than in the case of dPDFs

Triple charm in triple-parton scattering (TPS)



First theoretical analysis for charm quarks:

d'Enterria, Snigirev, Phys.Rev.Lett. 118, no. 12, 122001 (2017)

- a generic expressions to compute TPS cross sections
- total charm quark cross sections in NNLO collinear approach

Our calculations:

Maciula, Szczurek, arXiv:1703.07163 (hep-ph)

- analysis for triple D meson production
- k_t-factorization approach
- differential distributions

Factorized ansatz for TPS (pocket-formula)

In a simple probabilistic picture process initiated by:

three simultaneous hard parton-parton scatterings in one proton-proton interaction

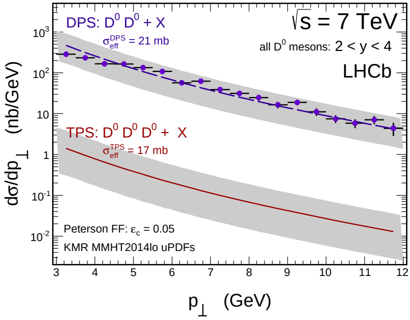
$$\sigma^{\mathrm{TPS}}_{pp \to c\bar{c}c\bar{c}c\bar{c}} = \left(\frac{1}{3!}\right) \frac{\sigma^{\mathrm{SPS}}_{pp\to c\bar{c}} \cdot \sigma^{\mathrm{SPS}}_{pp\to c\bar{c}} \cdot \sigma^{\mathrm{SPS}}_{pp\to c\bar{c}}}{\sigma^2_{\mathrm{eff,TPS}}}$$

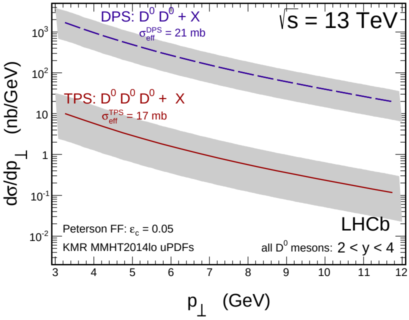
three subprocesses are not correlated and do not interfere

- $\sigma_{\mathrm{eff,TPS}} = k \times \sigma_{\mathrm{eff,DPS}}$, with $k = 0.82 \pm 0.11$
- $\sigma_{\mathrm{eff,DPS}} = 21$ mb (extracted from LHCb data) $\Rightarrow \sigma_{\mathrm{eff,TPS}} = 17$ mb

Inclusive $D^0D^0D^0$ $\sqrt{s} = 7, 13$ TeV

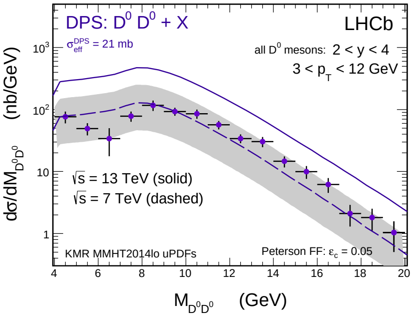
The transverse momentum distribution of one of the D^0 meson from the D^0D^0 pair or from the $D^0D^0D^0$ triplet

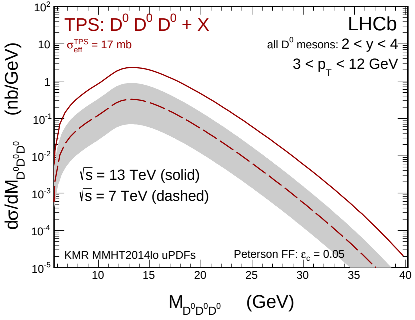




Inclusive $D^0 D^0 D^0$ $\sqrt{s} = 7, 13$ TeV

The invariant mass distribution of $D^0 D^0$ pair and of $D^0 D^0 D^0$ triplet





Inclusive $D^0 D^0 D^0$ $\sqrt{s} = 7, 13$ TeV

The integrated cross sections for double and triple D^0 meson production (in nb) within the LHCb acceptance: $2 < y_{D^0} < 4$ and $3 < p_T^{D^0} < 12$ GeV calculated in the k_T-factorization approach.

Final state	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
DPS: $\sigma(D^0 D^0 + X)$	784.74	2992.91
TPS: $\sigma(D^0 D^0 D^0 + X)$	2.38	17.71

Number of events for different values of the feasible integrated luminosity in the LHCb experiment for the calculated cross sections

$\sqrt{s}$	Integrated Luminosity	DPS ($D^0 D^0$)	TPS ($D^0 D^0 D^0$)
7 TeV	355 pb^{-1}	0.43×10^6	51
	1106 pb^{-1}	1.34×10^6	159
13 TeV	1665 pb^{-1}	7.70×10^6	1789
	5000 pb^{-1}	23.11×10^6	5374

- a few thousands of events of triple D^0 production at $\sqrt{s} = 13$ TeV

Conclusions

We have presented first estimation of the triple-parton scattering production of triple open charm meson at the LHC:
$pp \to D^0 D^0 D^0 \; X$

- expected cross section: tens of nanobarns (with precision of factor ≈ 3)
- a few thousands of events of triple D^0 production can be observed at $\sqrt{s} = 13$ TeV within the LHCb detector acceptance

Thank You for attention!