

# Associated production of $D$ -mesons with one and two jets at the LHC

Rafał Maciuła

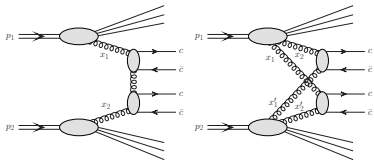
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SPS vs. DPS: Inclusive  $c\bar{c}c\bar{c}$ LHCb at  $\sqrt{s} = 7$  TeV

## CHARM MESON-MESON pair production:

DD pairs – both mesons containing c-quarks

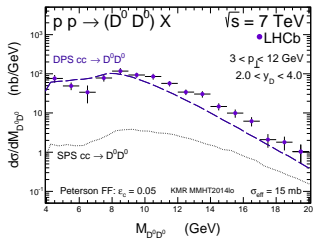
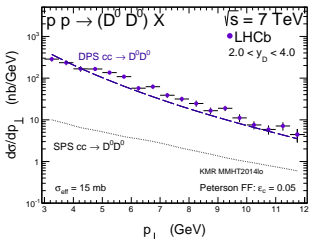
- impossible to be produced within standard SPS single  $c\bar{c}$  mechanism
- SPS double charm very small

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

Cross section much larger than the SPS predictions

⇒ clear evidence for DPS?

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



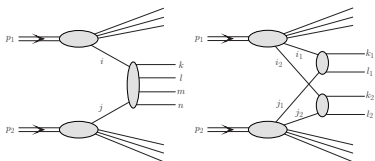
Łuszczak, Maciuta, Szczurek, Phys.Rev. D85 (2012) 094034

Maciuta, Szczurek, Phys.Rev. D87 (2013) no.7, 074039

Hameren, Maciuta, Szczurek, Phys.Rev. D89 (2014) no.9, 094019



## SPS vs. DPS: Inclusive 4jets

 $\sqrt{s} = 13 \text{ TeV}$ Optimal conditions for exploring DPS effects:

- keep jet- $p_T$ 's as low as possible:

symmetric: all 4 jets with  $p_T > 20 \text{ GeV}$

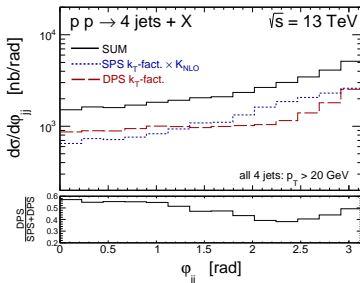
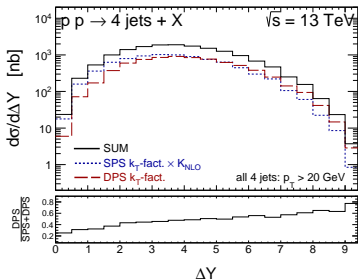
asymmetric: 1<sup>st</sup> jet:  $p_T > 35 \text{ GeV}$

2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup> jet:  $p_T > 20 \text{ GeV}$

- concentrate on jets most remote in rapidity

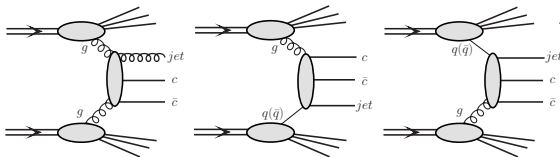
Maciuła, Szczurek, Phys.Lett. B749 (2015) 57-62

Kutak, Maciuła, Serino, Szczurek, Hameren, Phys.Rev. D94 (2016) no.1, 014019



- large rapidity distances between the most remote jets
- small azimuthal angles between the two jets most remote in rapidity



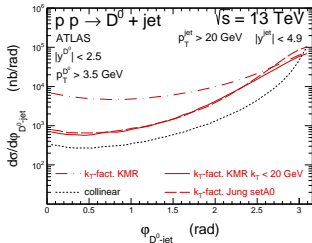
SPS: Inclusive  $c\bar{c} + \text{jet}$  $\sqrt{s} = 13 \text{ TeV}$ 

ATLAS detector acceptance:

- $D^0$  meson:  
 $|y| < 2.5, p_T > 3.5 \text{ GeV}$
- jet:  $|y| < 4.9$

The calculated "visible" cross sections in microbarns:

$p_{T,min}^{jet}$ cuts	collinear		$k_T$ -factorization approach	
	MMHT2014nlo	KMR	KMR $k_T < p_{T,min}^{jet}$	Jung setA0
$p_T^{jet} > 20 \text{ GeV}$	22.36	49.20	33.12	43.45
$p_T^{jet} > 35 \text{ GeV}$	3.70	9.60	6.76	6.79
$p_T^{jet} > 50 \text{ GeV}$	1.14	3.32	2.45	1.94

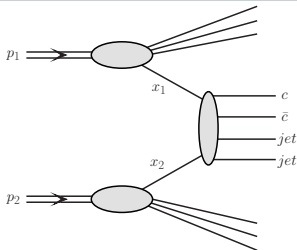


Maciuta, Szczurek, Phys.Rev. D94 (2016) no.11, 114037

- large cross sections (tens of  $\mu\text{b}$ )
- angular correlations between  $D^0$  and jet
- test of transverse momentum dependent PDFs beyond the standard  $2 \rightarrow 2$  pQCD partonic calculations

Nest step:  $c\bar{c} + 2\text{jets}$ 

# Single-Parton Scattering (SPS) mechanism



9 channels of 2  $\rightarrow$  4 pQCD subprocesses:

$g g \rightarrow g g c \bar{c}$	$q \bar{q} \rightarrow q' \bar{q}' c \bar{c}$
$g g \rightarrow q \bar{q} c \bar{c}$	$q \bar{q} \rightarrow g g c \bar{c}$
$g q \rightarrow g q c \bar{c}$	$q q \rightarrow q q c \bar{c}$
$q g \rightarrow q g c \bar{c}$	$q q' \rightarrow q q' c \bar{c}$
$q \bar{q} \rightarrow q \bar{q} c \bar{c}$	

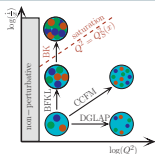
Calculations are done in two different ways:

- LO collinear parton-model approach
- **NEW:**  $k_T$ -factorization approach with fully gauge-invariant tree-level 2  $\rightarrow$  4 off-shell matrix elements
  - **first time:** off-shell initial state partons
  - exact kinematics from the very beginning and additional hard dynamics coming from transverse momenta of incident partons
  - part of higher-order corrections included (depending on the model of unintegrated, transverse momentum dependent PDFs)





# Unintegrated parton distribution functions (uPDFs)



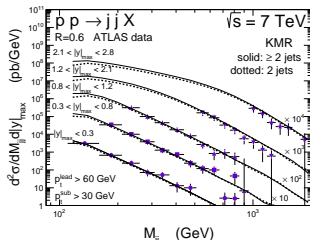
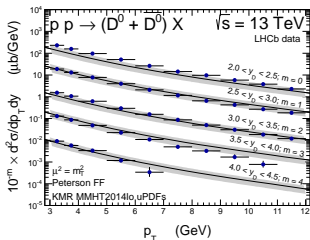
Most popular models:

- 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 mainly use: **Kimber-Martin-Ryskin (KMR) approach:**

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

works well, e.g. for inclusive charm and inclusive dijet at the LHC:



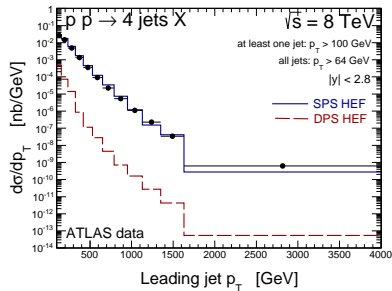
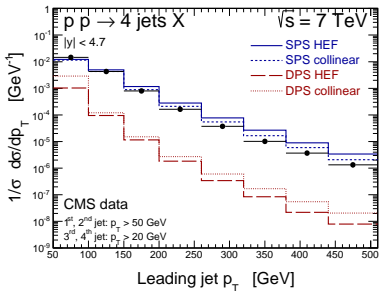
good starting point  
for DPS predictions for  
 $pp \rightarrow c\bar{c} + 2\text{jets } X$

- already also successfully used together with KaTie for multi-jet production



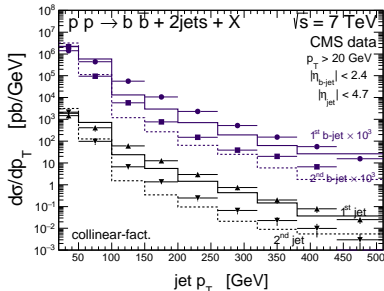
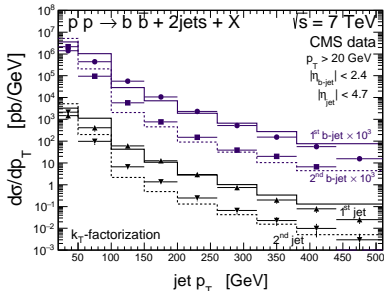


## Inclusive 4jets

CMS, ATLAS at  $\sqrt{s} = 7, 8 \text{ TeV}$ 

- CMS and ATLAS data described by the SPS mechanism
- DPS mechanism strongly suppressed by too hard jet- $p_T$  cuts
- KaTie + KMR uPDFs gives reasonable description of the data sets

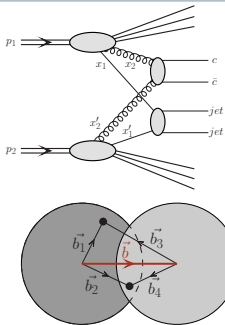


Inclusive  $2b + 2j$ CMS at  $\sqrt{s} = 7$  TeV

- CMS data described with the SPS mechanism
- DPS effects in  $b$ -flavour production are expected to be negligible
- KaTie + KMR uPDFs gives reasonable description of the data sets ( $p_T$ -slope better described than in the collinear case)



# Double-parton scattering (DPS) mechanism



**DPS in general form** for  $pp \rightarrow c \bar{c} k l X$ :

$$d\sigma^{DPS} = \frac{1}{2} \cdot \sum_{i,j,k,l} \Gamma_{i\bar{j}}(b, x_1, x_2; \mu_1^2, \mu_2^2) \Gamma_{j\bar{k}}(b, x'_1, x'_2; \mu_1^2, \mu_2^2) \\ \times d\sigma_{ij \rightarrow kl}(x'_1, x_1, \mu_1^2) \cdot d\sigma_{g\bar{g} \rightarrow c\bar{c}}(x_2, x'_2, \mu_2^2) dx_1 dx_2 dx'_1 dx'_2 d^2b$$

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

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

- longitudinal and transverse correlations between two partons
- spin, 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**

$$\sigma^{DPS} = \frac{1}{\sigma_{eff}} \cdot \sum_{i,j,k,l} \sigma^{SPS}(ij \rightarrow kl) \cdot \sigma^{SPS}(g\bar{g} \rightarrow c\bar{c})$$

**two subprocesses are not correlated and do not interfere**

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



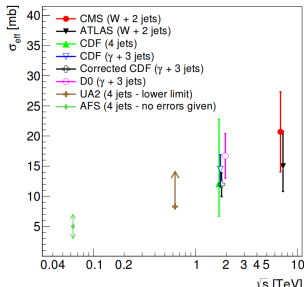
# Double-parton scattering (DPS) mechanism

## Factorized ansatz (pocket-formula)

- a good approximation for **small-x partons**
- **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

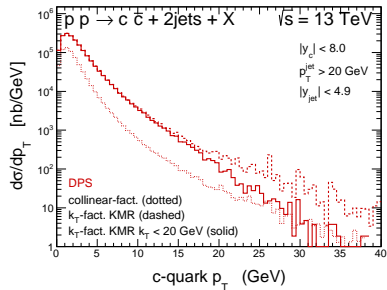
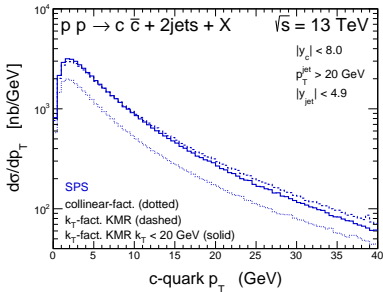


- extracted from several experimental analyses
- in principle may not be universal
- detailed studies: Seymour, Siódmok, JHEP 10, 113 (2013)
- **LHCb double charm data:**  $\sigma_{eff} = 21_{-6}^{+7}$  mb
- **ATLAS 4jets data:**  $\sigma_{eff} = 14.9$  mb
- **world average:**  $\sigma_{eff} \approx 15$  mb (large uncertainties)



Inclusive  $c\bar{c} + 2\text{jets}$ 

$$\sqrt{s} = 13 \text{ TeV}$$

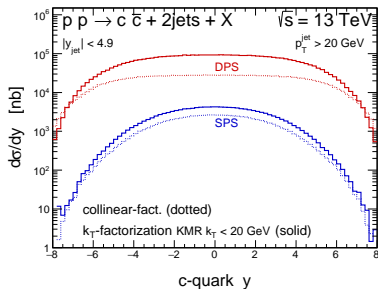
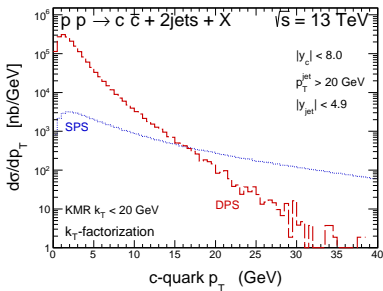


- $k_T$ -factorization predictions significantly larger than the collinear one
- Two sets of calculations for the KMR uPDFs:
  - number of jets = 2
  - number of jets  $\geq 2$



Inclusive  $c\bar{c} + 2\text{jets}$ 

$$\sqrt{s} = 13 \text{ TeV}$$



- DPS mechanism dominates over the SPS in the region of  $c$ -quark  $p_T \lesssim 15 \text{ GeV}$





Inclusive  $D^0 + 2\text{jets}$ 

$$\sqrt{s} = 13 \text{ TeV}$$

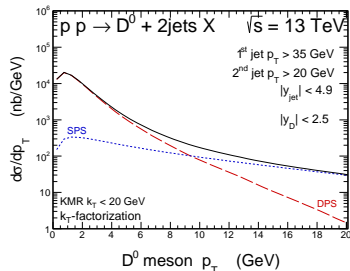
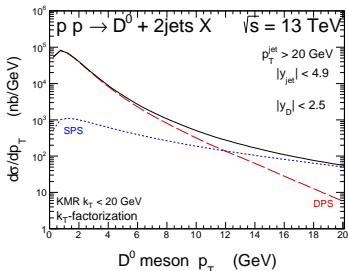
The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

$D^0$  meson (or  $\bar{D}^0$  antimeson):  $|y| < 2.5$ ,  $p_T > 3.5 \text{ GeV}$

both jets:  $|y| < 4.9$ ,  $R_{\text{cone}} = 0.5$

experimental jet- $p_T$ mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
both jets $p_T > 20 \text{ GeV}$	3.74	18.49	83 %
$p_T^{\text{lead}} > 35 \text{ GeV}$ , $p_T^{\text{sub}} > 20 \text{ GeV}$	1.76	4.52	72 %
$p_T^{\text{lead}} > 50 \text{ GeV}$ , $p_T^{\text{sub}} > 35 \text{ GeV}$	0.43	1.25	74 %

- large cross sections ( $\mu\text{b}$ )
- DPS dominated samples



Evident enhancement in the region of  $p_T \lesssim 10 \text{ GeV}$   
 because of the presence of the DPS mechanism





# Inclusive $D^0 + 2\text{jets}$

 $\sqrt{s} = 13 \text{ TeV}$ 

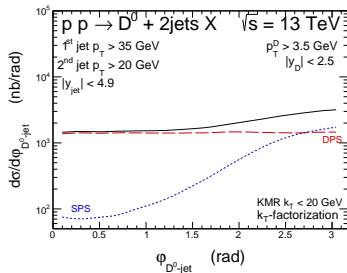
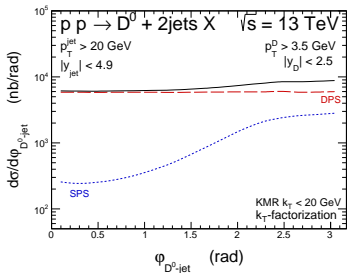
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- large cross sections ( $\mu\text{b}$ )
- DPS dominated



Almost decorrelated distribution in  $\varphi_{D^0\text{-jet}}$  azimuthal angle  
 because of the presence of the DPS mechanism



# Inclusive $D^0\bar{D}^0 + 2\text{jets}$

## $\sqrt{s} = 13 \text{ TeV}$

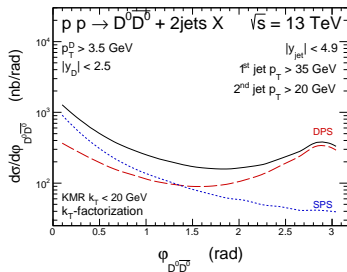
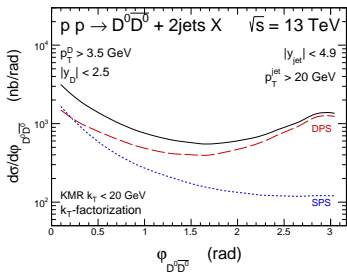
The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

both,  $D^0$  meson and  $\bar{D}^0$  antimeson:  $|y| < 2.5$ ,  $p_T > 3.5 \text{ GeV}$

both jets:  $|y| < 4.9$ ,  $R_{\text{cone}} = 0.5$

experimental jet- $p_T$ mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
both jets $p_T > 20 \text{ GeV}$	1.10	2.35	68 %
$p_T^{\text{lead}} > 35 \text{ GeV}$ , $p_T^{\text{sub}} > 20 \text{ GeV}$	0.55	0.58	51 %
$p_T^{\text{lead}} > 50 \text{ GeV}$ , $p_T^{\text{sub}} > 35 \text{ GeV}$	0.15	0.14	52 %

- smaller than in the single- $D$  case but still large
- the relative DPS contribution slightly reduced



Evident enhancement in the region of  $\varphi_{D^0\bar{D}^0} \gtrsim \frac{\pi}{2}$   
because of the presence of the DPS mechanism



# Conclusions

- We have predicted large cross sections for associated production of charm and two jets at the LHC
- both SPS and DPS mechanisms were carefully examined
- regions of phase space where the DPS mechanism dominates over the SPS one are identified

How to search for the double-parton scattering effects in  $pp \rightarrow c\bar{c} + 2\text{jets } X$ :

$D^0 + 2\text{jets}$

- look at the transverse momentum distribution of  $D^0$  meson  $\Rightarrow$  unexpected enhancement in the region of  $p_T \lesssim 10$  GeV
- look at the  $\varphi_{D^0\text{-jet}}$  azimuthal angle distribution  $\Rightarrow$  unexpected decorrelation

$D^0\overline{D^0} + 2\text{jets}$

- look at the  $\varphi_{D^0\overline{D^0}}$  distribution  $\Rightarrow$  unexpected enhancement in the region  $\gtrsim \frac{\pi}{2}$

Thank You for attention!

