Charm production in association with one and two jets at the LHC

Rafał Maciuła

Institute of Nuclear Physics PAN, Kraków, Poland

in collaboration with Antoni Szczurek

5th Workshop on Resummation, Evolution, Factorization - REF 2018

19-23 November 2018, IFJ PAN, Kraków, Poland

Multi-particle final states at the LHC

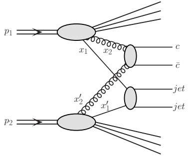
The high luminosity already achieved at the LHC potentially allows to study more complicated final states and opens new possibilities in testing dynamics of pQCD processes

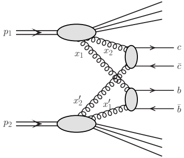
Our interest: phenomena of Multiple-Parton Interactions (MPI)

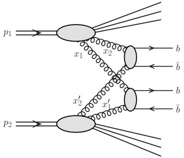
During last years: Double-Parton Scattering (DPS) effects in pp–collisions

- $pp \to c\bar{c}c\bar{c}\,X$ (supported by the LHCb double charm data)
- $pp \to 4\text{jets}\,X$ (needs dedicated experimental analyses)

Very recently: $pp \to c\bar{c} + 2\text{jets}\,X$, $pp \to c\bar{c}b\bar{b}\,X$, $pp \to b\bar{b}b\bar{b}\,X$

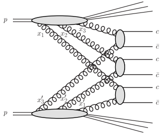






Can we observe some evidence of DPS effects in these cases?

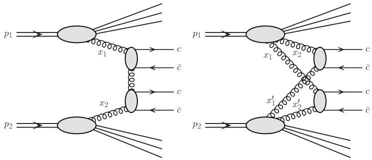
A step beyond the DPS: Triple-parton scattering (TPS) in $pp \to c\bar{c}c\bar{c}c\bar{c}\,X$



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

In this talk: DPS effects in $pp \to D^0 + 2\text{jets}\,X$ and $pp \to D^0\overline{D^0} + 2\text{jets}\,X$

SPS vs. DPS: Double charm — LHCb at $\sqrt{s} = 7$ TeV



CHARM MESON-MESON pair production:

DD pairs – both mesons containing *c*-quarks

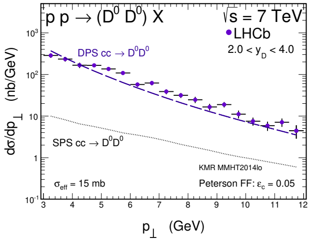
- impossible to be produced within standard SPS single $c\bar{c}$ mechanism
- SPS double charm very small

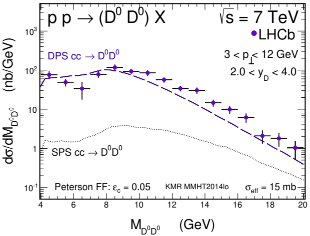
First measurement by LHCb: J. High Energy Phys. 06, 141 (2012)

Cross section much larger than the SPS predictions

$\Rightarrow$ clear evidence for DPS?

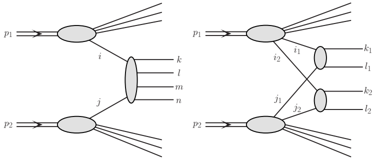
Mode	σ [nb]
D^0D^0	$690 \pm 40 \pm 70$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$





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

SPS vs. DPS: 4jet-sample $\sqrt{s} = 13$ TeV

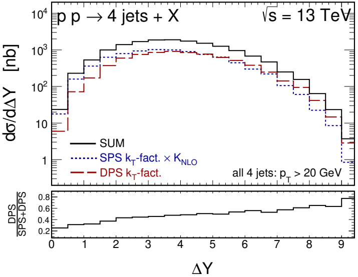


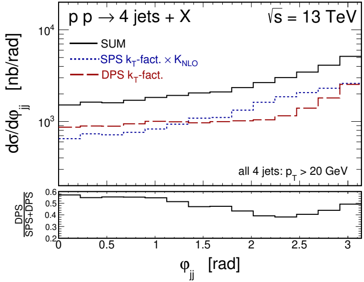
Optimal conditions for exploring DPS effects:

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

  symmetric: all 4 jets with $p_T > 20$ GeV
  asymmetric: 1^{st} jet: $p_T > 35$ GeV
  $2^{nd}, 3^{rd}, 4^{th}$ jet: $p_T > 20$ GeV
- concentrate on jets most remote in rapidity

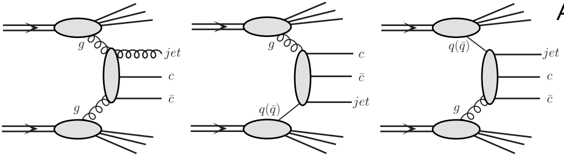
Maciuła, Szczurek, Phys.Lett. B749 (2015) 57-62
Kutak, Maciuła, Serino, Szczurek, Hameren, Phys.Rev. D94 (2016) no.1, 014019





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

SPS: D^0 + single jet $\sqrt{s} = 13$ TeV

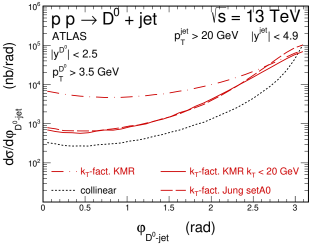


ATLAS detector acceptance:

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

The calculated "visible" cross sections in microbarns:

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



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

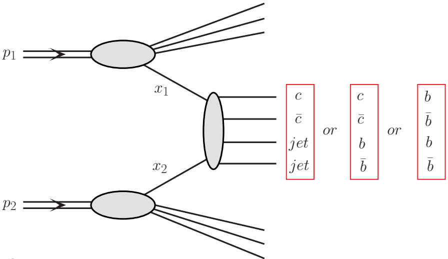
- large cross sections (tens of μb)
- angular correlations between D^0 and jet

Test of transverse momentum dependent PDFs beyond the standard $2 \to 2$ pQCD partonic calculations!

(TMDs discussed on Monday morning session)

Our next step: $c\bar{c}$ + 2jets

Single-Parton Scattering (SPS) mechanism



$2 \to 4$ pQCD subprocesses:

9 channels for $c\bar{c} + 2\mathrm{jets}$

$g\,g \to g\,g\,c\,\bar{c}$	$q\,\bar{q} \to q'\,\bar{q}'\,c\,\bar{c}$
$g\,g \to q\,\bar{q}\,c\,\bar{c}$	$q\,\bar{q} \to g\,g\,c\,\bar{c}$
$g\,q \to g\,q\,c\,\bar{c}$	$q\,q \to q\,q\,c\,\bar{c}$
$q\,g \to q\,g\,c\,\bar{c}$	$q\,q' \to q\,q'\,c\,\bar{c}$
$q\,\bar{q} \to q\,\bar{q}\,c\,\bar{c}$	

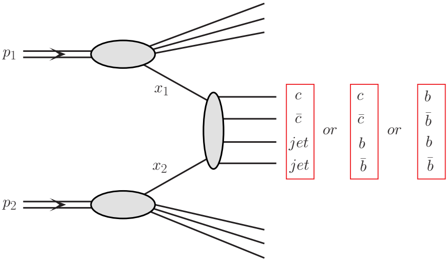
2 channels for $c\bar{c}b\bar{b}$ and $b\bar{b}b\bar{b}$

$g\,g \to c\,\bar{c}\,b\,\bar{b}$	$q\,\bar{q} \to c\,\bar{c}\,b\,\bar{b}$
$g\,g \to b\,\bar{b}\,b\,\bar{b}$	$q\,\bar{q} \to b\,\bar{b}\,b\,\bar{b}$

Calculations are done in two different ways:

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

Single-Parton Scattering (SPS) mechanism



$2 \rightarrow 4$ pQCD subprocesses:

9 channels for $c\bar{c} + 2\text{jets}$

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

2 channels for $c\bar{c}b\bar{b}$ and $b\bar{b}b\bar{b}$

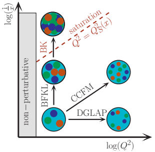
$g\, g \rightarrow c\, \bar{c}\, b\, \bar{b}$ $q\, \bar{q} \rightarrow c\, \bar{c}\, b\, \bar{b}$
$g\, g \rightarrow b\, \bar{b}\, b\, \bar{b}$ $q\, \bar{q} \rightarrow b\, \bar{b}\, b\, \bar{b}$

KaTie (Andreas van Hameren): https://bitbucket.org/hameren/KaTie
Comput. Phys. Commun. 224 (2018) 371 (see talk by A. Kusina on Z+jet)

basics of the theory behind: *e.g.* Kutak, Kotko, Hameren, J. High Energy Phys. 01 (2013) 078

- complete Monte Carlo program for tree-level calculations of any process within the Standard Model
- any initial-state partons on-shell or off-shell
- scattering amplitudes are calculated numerically via Dyson-Schwinger recursion generalized also to tree-level off-shell amplitudes
- double-parton scattering available too!

Unintegrated parton distribution functions (uPDFs)

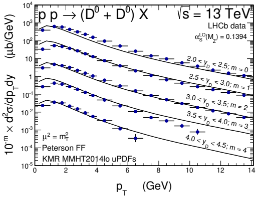


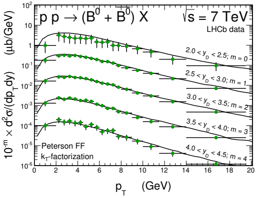
Most popular models:

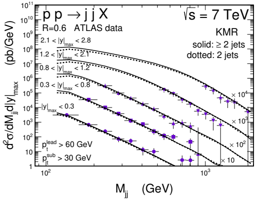
- Kwieciński, Jung (CCFM, wide range of x)
- Kimber-Martin-Ryskin (DGLAP-BFKL, wide range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, small x-values)
- Kutak-Staśto (BK, saturation, only small x-values)

We 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)



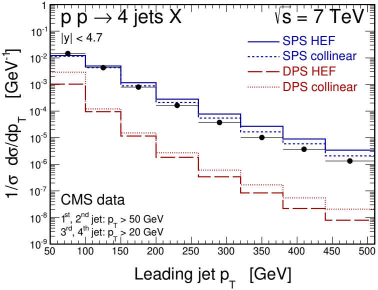


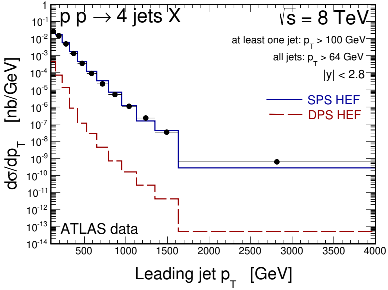


- works well for inclusive charm, bottom and inclusive dijet at the LHC
- good starting point for DPS predictions for $c\bar{c}$ + 2jets, $c\bar{c}b\bar{b}$ and $b\bar{b}b\bar{b}$

4jets CMS, ATLAS at $\sqrt{s} = 7, 8$ TeV

Testing SPS 2 → 4 calculations: KaTie + KMR uPDFs in multi-jet production

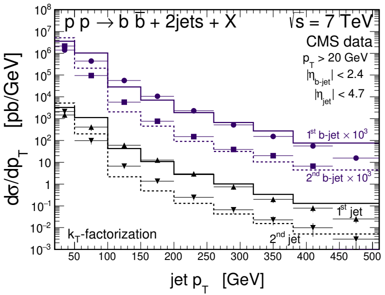


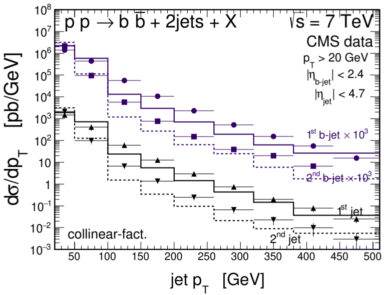


- CMS and ATLAS data described by the SPS mechanism
- DPS mechanism strongly suppressed by too hard jet-p_T cuts
- KaTie + KMR uPDFs gives reasonable description of the data sets

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

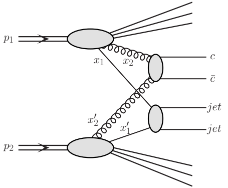
Testing SPS 2 → 4 calculations: KaTie + KMR uPDFs in multi-jet production

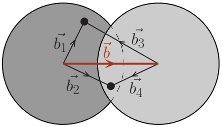




- CMS data described with the SPS mechanism
- DPS effects in hard-p_T b-flavour production are expected to be negligible
- KaTie + KMR uPDFs gives reasonable description of the data sets (p_T-slope better described than in the collinear case)

Double-parton scattering (DPS) mechanism





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

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

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

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

- 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

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

two subprocesses are not correlated and do not interfere

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

Double-parton scattering (DPS) mechanism

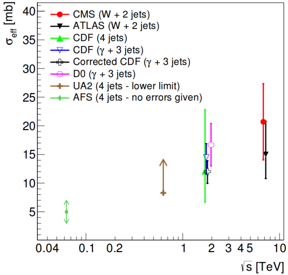
Factorized ansatz (pocket-formula)

(see talk by A. Staśto)

- 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))

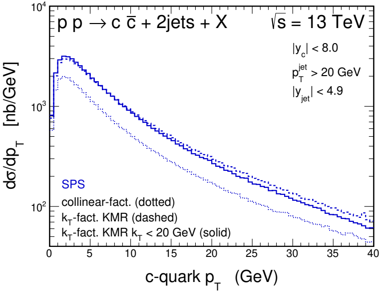
Separation of longitudinal and transverse degrees of freedom

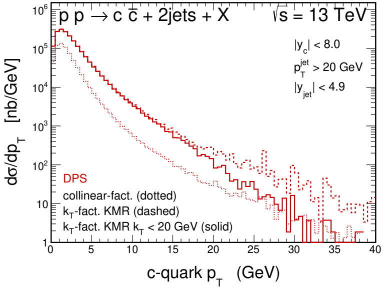
- DPDFs in multiplicative form: $\Gamma_{ij}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2) F_j(x_2, \mu_2^2) F(b)$
- only transverse correlations taken into account
- $\sigma_{eff} = \left[\int d^2b \, (F(b))^2 \right]^{-1}$, $F(b)$ - overlap of the matter distribution in transverse plane where 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: $\sigma_{eff} = 21^{+7}_{-6}$ mb
- ATLAS 4jets data: $\sigma_{eff} = 14.9$ mb
- world average: $\sigma_{eff} \approx 15$ mb (large uncertainties)

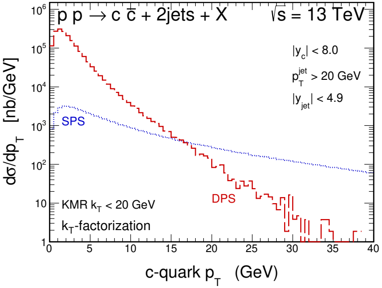
$c\bar{c} + 2\text{jets}$ $\sqrt{s} = 13$ TeV

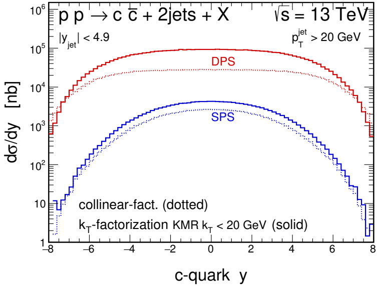




- k_T-factorization predictions significantly larger than the collinear one
- Two sets of calculations for the KMR uPDFs:
  - number of jets $= 2$ (exactly two jets)
  - number of jets ≥ 2 (up to 4, hard emissions from uPDFs)
- here and in the following: hard process calculations + uPDFs (without parton-shower effects, see talk by H. Jung)

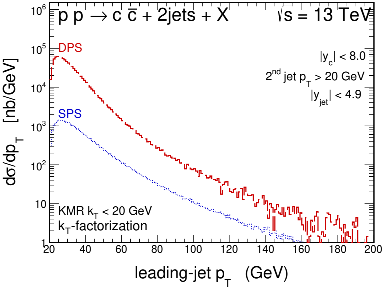
$c\bar{c} + 2$jets $\sqrt{s} = 13$ TeV

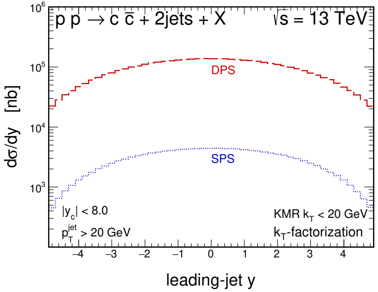




- DPS mechanism dominates over the SPS in the region of c-quark $p_T \lesssim 15$ GeV

$c\bar{c}$ + 2jets $\sqrt{s}$ = 13 TeV





- DPS mechanism dominates over the SPS in the whole range of leading-jet p_T
- changing jet-p_T cuts to harder values leads to smaller cross sections but should not dramatically change the $\frac{DPS}{SPS+DPS}$ ratio

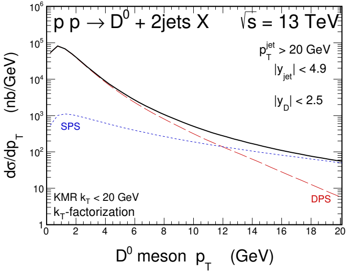
$D^0 + 2\text{jets}$ $\sqrt{s} = 13$ TeV

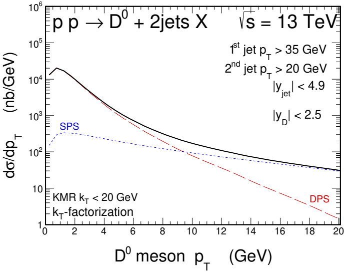
The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

D^0 meson (or $\overline{D^0}$ antimeson): $|y| < 2.5$, $p_T > 3.5$ GeV both jets: $|y| < 4.9$, $R_{cone} = 0.5$

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

- large cross sections (μb)
- DPS dominated samples





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

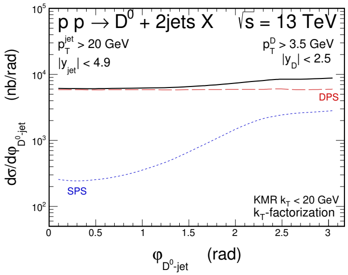
$D^0 + 2\text{jets}$ $\sqrt{s} = 13$ TeV

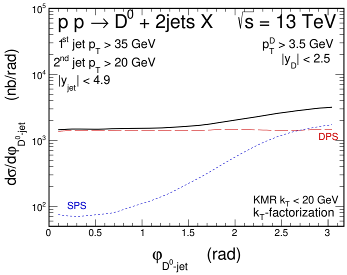
The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

D^0 meson (or $\overline{D^0}$ antimeson): $|y| < 2.5$, $p_T > 3.5$ GeV both jets: $|y| < 4.9$, $R_{cone} = 0.5$

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

- large cross sections (μb)
- DPS dominated





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

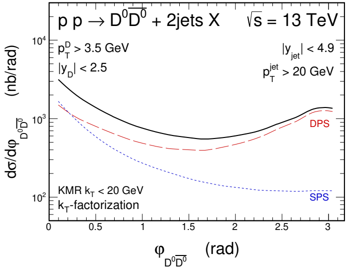
$D^0\overline{D^0}$ + 2jets $\sqrt{s} = 13$ TeV

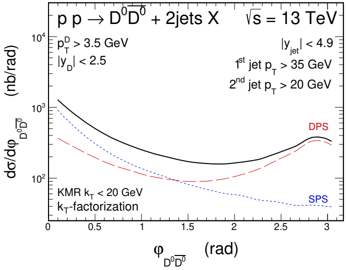
The calculated "visible" cross sections in microbarns for the ATLAS detector acceptance:

both, D^0 meson and $\overline{D^0}$ antimeson: $|y| < 2.5$, $p_T > 3.5$ GeV both jets: $|y| < 4.9$, $R_{cone} = 0.5$

experimental jet-p_T mode	SPS	DPS	$\frac{DPS}{SPS+DPS}$
both jets $p_T > 20$ GeV	1.10	2.35	68 %
$p_T^{lead} > 35$ GeV, $p_T^{sub} > 20$ GeV	0.55	0.58	51 %
$p_T^{lead} > 50$ GeV, $p_T^{sub} > 35$ 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 $\varphi_{D^0\overline{D^0}} \gtrsim \frac{\pi}{2}$ because of the presence of the DPS mechanism

Conclusions

- **We have predicted large cross sections for associated production of charm plus one and two jets at the LHC**
- **charm plus one jet**: meson-jet correlations, test of the unintegrated PDFs
- **charm plus two jets**: both SPS and DPS mechanisms were carefully examined, regions of phase space where the DPS mechanism dominates over the SPS one are identified
- **Still to be done**: important effects of parton-shower (see talk by H. Jung)

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

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

- 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!