Searching for optimal conditions for exploration of double-parton scattering in four-jet production at the LHC

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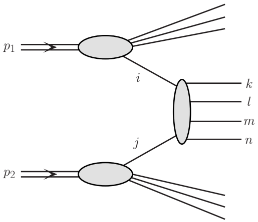
Outline

Based on:
Maciuła, Szczurek, Phys. Lett. B 749 (2015) 57-62 (collinear approximation)
Kutak, Maciuła, Serino, Szczurek, Hameren, paper in preparation
(complementary studies in k_T-factorization)

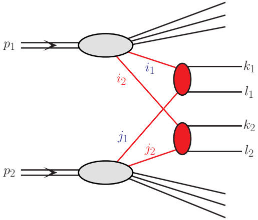
Four-jet production: Mechanisms under consideration



Single-Parton Scattering (SPS $2 \to 4$)

- Kutak, Maciuła, Serino, Szczurek, Hameren, arXiv:1602.06814 (hep-ph) (accepted in JHEP)

  AVHLIB (A. van Hameren): https://bitbucket.org/hameren/avhlib
- High-Energy-Fact. (HEF): LO k_T-factorization ($2 \to 4$)
- first time: off-shell initial state partons
- more details: talk by Mirko Serino



Double-Parton Scattering (DPS $4 \to 4$)

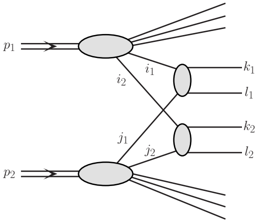
- Factorized Ansatz with experimental setup of σ_{eff}
- LO k_T-factorization approach ($2 \to 2 \otimes 2 \to 2$)
- more precise studies of kinematical characteristics and correlation observables

extension of our previous studies based on LO collinear approach (ALPGEN): Maciuła, Szczurek, Phys. Lett. B 749 (2015) 57-62

Four-jet production in double-parton scattering (DPS)

Factorized ansatz (pocket-formula)

In a simple probabilistic picture:



process initiated by two simultaneous hard parton-parton scatterings in one proton-proton interaction ⇒

$$\sigma^{DPS}(pp \to 4\mathrm{jets}X) = \frac{C}{\sigma_{eff}} \cdot \sigma^{SPS}(pp \to \mathrm{dijet}X_1) \cdot \sigma^{SPS}(pp \to \mathrm{dijet}X_2)$$

two subprocesses are not correlated and do not interfere

analogy: frequently considered mechanisms of double charm, double gauge boson production and double Drell-Yan anihillation

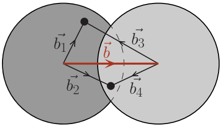
valid also differentially:

$$\frac{d\sigma^{DPS}(pp \to 4\mathrm{jets}\ X)}{d\xi_1 d\xi_2} = \sum_{\substack{i_1,j_1,k_1,l_1 \\ i_2,j_2,k_2,l_2}} \frac{C}{\sigma_{eff}} \frac{d\sigma(i_1 j_1 \to k_1 l_1)}{d\xi_1} \frac{d\sigma(i_2 j_2 \to k_2 l_2)}{d\xi_2},$$

where $C = \begin{Bmatrix} \frac{1}{2} & \text{if } i_1 j_1 = i_2 j_2 \wedge k_1 l_1 = k_2 l_2 \\ 1 & \text{if } i_1 j_1 \neq i_2 j_2 \vee k_1 l_1 \neq k_2 l_2 \end{Bmatrix}$ and $i, j, k, l = g, u, d, s, c, \bar{u}, \bar{d}, \bar{s}, \bar{c}$.

- combinatorial factors C include identity of the two subprocesses

Factorized ansatz and double-parton distributions (DPDFs)



DPDF - emission of parton i with assumption that second parton j is also emitted:

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

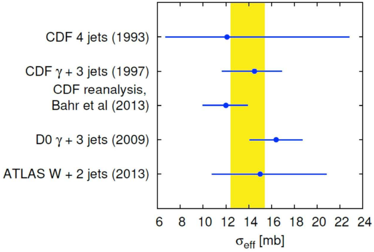
- correlations between two partons
  C. Flensburg et al., JHEP 06, 066 (2011)

in general:

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

Factorized ansatz:

- DPDF in multiplicative form: $F_{ij}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2) F_j(x_2, \mu_2^2) F(b)$
- $\sigma_{eff} = \left[\int d^2b\; (F(b))^2 \right]^{-1}$, $F(b)$ - energy and process independent



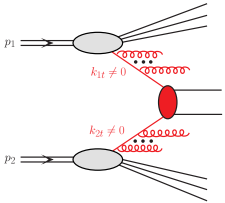
phenomenology: $\sigma_{eff} \Rightarrow$ nonperturbative quantity with a dimension of cross section, connected with transverse size of proton

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

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

- additional limitations: $x_1 + x_2 < 1$ oraz $x_1' + x_2' < 1$

SPS dijet production: k_t-factorization (semihard) approach



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

Collins-Ellis, Nucl. Phys. B360 (1991) 3; Catani-Ciafaloni-Hautmann, Nucl. Phys. B366 (1991) 135; Ball-Ellis, JHEP 05 (2001) 053

$\Rightarrow$ efficient approach for jet-jet or $Q\bar{Q}$ correlations

- multi-differential cross section

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

- $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$, $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated (k_t-dependent) PDFs
- **LO off-shell** $\overline{|\mathcal{M}_{i^* j^* \to kl}|^2} \Rightarrow$ calculated numerically in AVHLIB

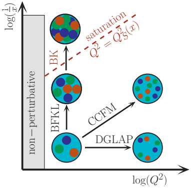
  analytical form: Nefedov, Saleev, Shipilova, Phys. Rev. D87, 094030 (2013)

  Quasi Multi Regge Kinematics (QMRK) with effective BFKL NLL vertices

  $$\sqrt{s} \gg p_T, M \gg \Lambda_{QCD} \text{ and } x \ll 1$$

  Parton-Reggeization Approach (k_T-factorization with Reggeized initial partons): an effective way to take into account amount part of radiative corrections at high energy Regge kinematics
- some part of higher-order corrections may be effectively included depending on UPDF model $\Rightarrow$ possible emission of extra (hard) gluons

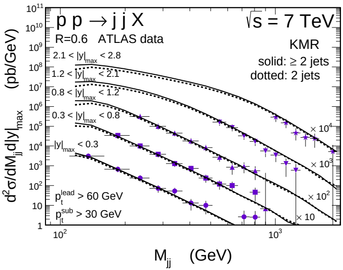
Unintegrated parton distribution functions (UPDFs)

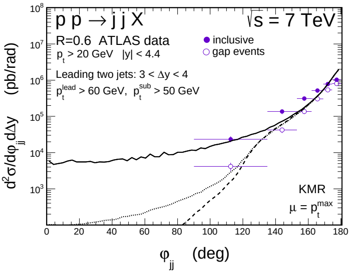


Different evolution equations (or their combinations):

- 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)

Lessons from inclusive dijet production at the LHC:





- KMR UPDFs work well for jet-jet correlation observables in dijet production

DPS in the framework of k_T-factorization

DPS production of four-jet system within k_T-factorization approach, assuming factorization of the DPS model:

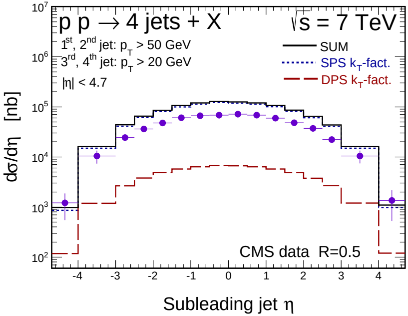
$$\frac{d\sigma^{DPS}(pp \to 4\text{jets}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{\mathcal{C}}{\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to j\,j\,X_1)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \cdot \frac{d\sigma^{SPS}(pp \to j\,j\,X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}}$$

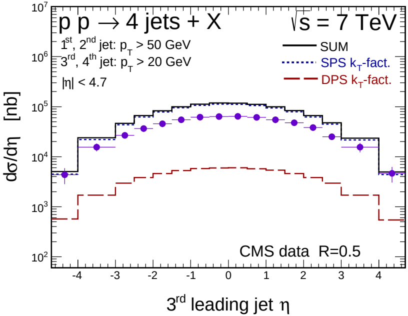
Each step of DPS (each individual scattering):

$$\frac{d\sigma^{SPS}(pp \to j\,j\,X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi} \overline{|\mathcal{M}_{i^* k^* \to j\,j}|^2} \times \delta^2\left(\vec{k}_{1t} + \vec{k}_{2t} - \vec{p}_{1t} - \vec{p}_{2t}\right) \mathcal{F}(x_1, k_{1t}^2, \mu^2) \mathcal{F}(x_2, k_{2t}^2, \mu^2)$$

- 9 channels from the $2 \to 2$ SPS $\Rightarrow$ 45 channels for the $4 \to 4$ DPS but only 14 contribute to $\geq 95\%$ of the cross section (see Mirko's talk)
- KMR UPDFs from CT10 NLO collinear PDFs
- $n_F = 4$ flavour scheme, running α_s@NLO from MSTW08 package
- scales: $\mu = \mu_R = \mu_F = \frac{1}{2} \sum_i p_T^i$ (sum over final state particles)
- all details the same for $2 \to 4$ SPS and $4 \to 4$ DPS calculations

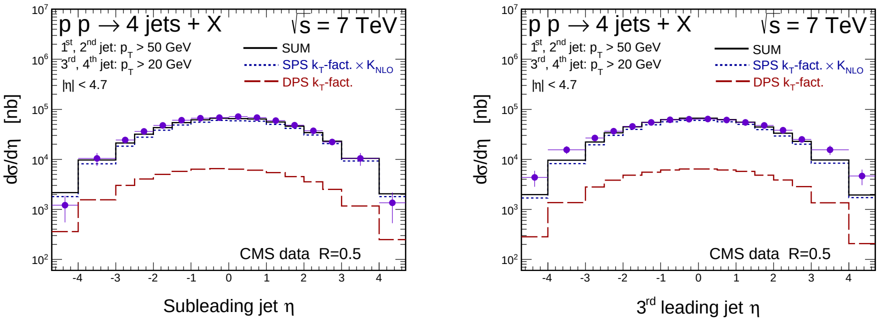
CMS four-jets: SPS + DPS in the k_T-factorization





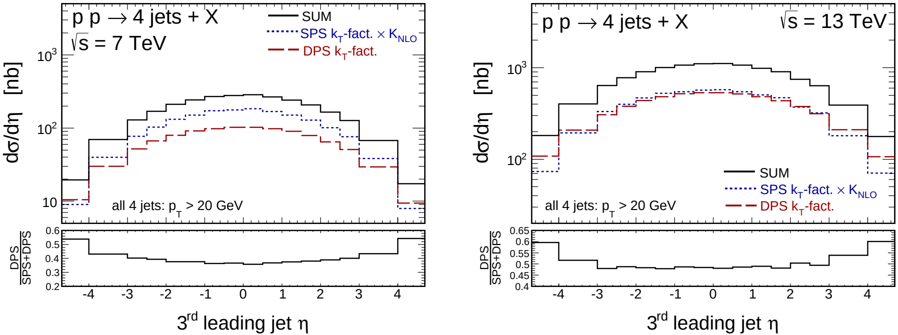
- the SPS component above the data $\Rightarrow$ the same problem with the ALPGEN code (LO collinear approach) $\Rightarrow$ exact SPS NLO calculations needed?
- first full SPS NLO (collinear) four-jets: Z. Bern et al., Phys. Rev. Lett. 109, 042001 (2012)
  NLO corrections $\Rightarrow$ damping of the cross section $\Rightarrow$ $K_{NLO} \approx 0.5$
- SPS $2 \to 2$: $K_{NLO} \approx 1.1 - 1.2$ $\Rightarrow$ much less important for DPS
- much better description of exp. data for harder p_T cuts (see Mirko's talk)

CMS four-jets: SPS + DPS in the k_T-factorization



- Now: quite good description of the CMS data
- 3rd leading jet (softer): forward/backward region slightly underestimated
- very small DPS contribution ⇒ unsupportive CMS cuts: $1^{st}, 2^{nd}$ jet $p_T > 50$ GeV
- **DPS favoured**: small p_T region (see Mirko's talk)

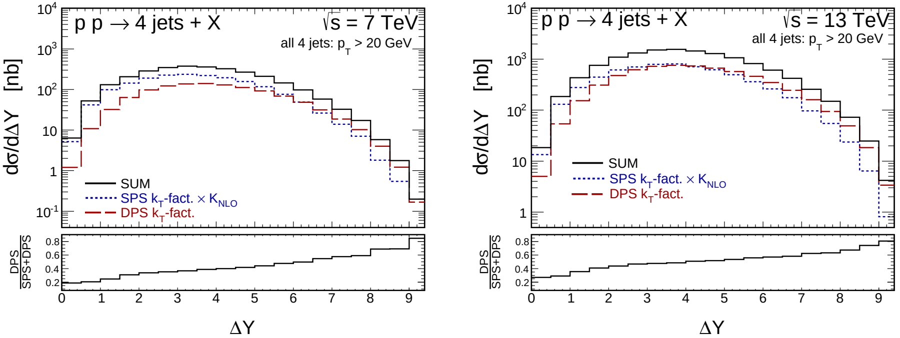
DPS effects in four-jet sample: lowering p_T cuts



- all 4 jets: $20 < p_T < 100 GeV$
- 13 TeV: DPS contribution $\geq 50\%$
- **DPS favoured**: forward/backward rapidity region

DPS effects in four-jet sample: large rapidity distance

Rapidity difference between jets most remote in rapidity

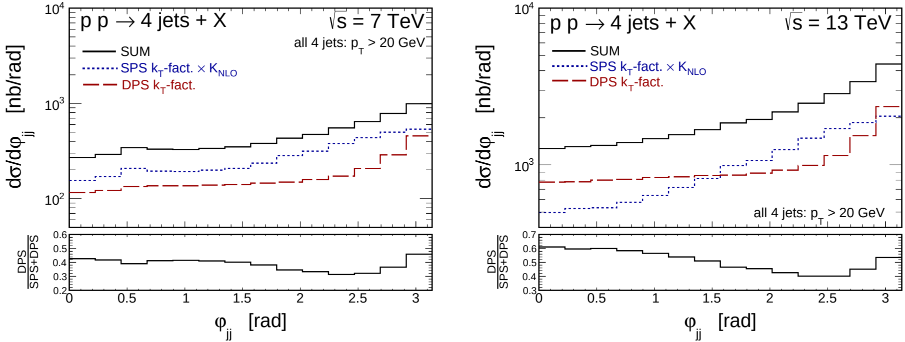


- 13 TeV:

  $\Delta Y > 6 \Rightarrow$ four-jet sample dominated by DPS

DPS effects in four-jet sample: large rapidity distance

Azimuthal angle between jets most remote in rapidity

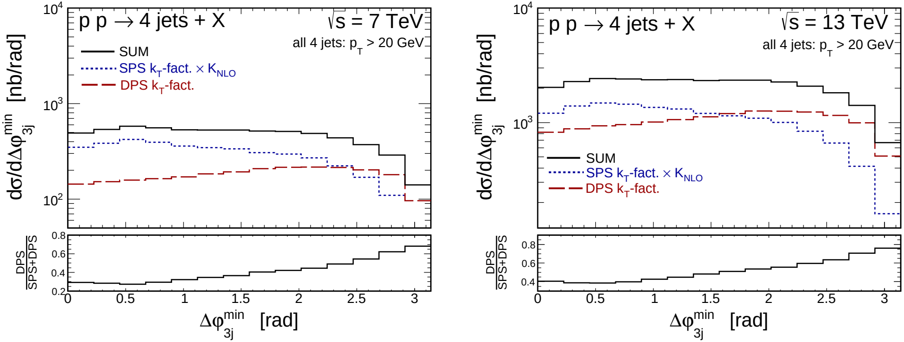


- 13 TeV:

  $\varphi_{jj} < \frac{\pi}{2} \Rightarrow$ four-jet sample dominated by DPS

DPS effects in four-jet sample: special angular correlation

Minimum azimuthal separation between any three jets



- variable proposed by ATLAS analysis: JHEP 12, 105 (2015) (see talk by Melissa Ridel)
- distinguishes events with pairs of nearby jets (which have large φ_{3j}^{min}) from the recoil of three jets against one (leading to small φ_{3j}^{min} values)
- 13 TeV:

  $$\Delta\varphi_{3j}^{min} > \frac{\pi}{2} \Rightarrow \text{four-jet sample dominated by DPS}$$

Conclusions

A recipe for DPS dominated four-jet sample at $\sqrt{s} = 13$ TeV:

1. crucial: lower transverse momentum cuts for all 4 jets: $p_T > 20$ GeV
   - asymmetric configuration also acceptable:
     leading jet $p_T > 35$ GeV; $2^{nd}, 3^{rd}, 4^{th}$ jet $p_T > 20$ GeV
     however any further increasing of the p_T cuts leads to significant damping of the DPS contribution
2. concentrate on large jet-jet rapidity separations: $\Delta Y > 6$
3. useful angular jet-jet correlations: $\varphi_{jj} < \frac{\pi}{2}$, $\Delta\varphi_{3j}^{min} > \frac{\pi}{2}$

Thank you for your attention!