Effects of double-parton scattering in four-jet production at the LHC

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Outline

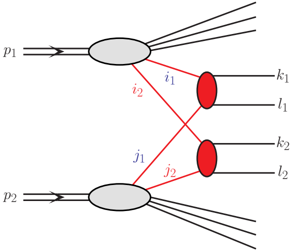
Based on:

Maciuła, Szczurek, Phys. Lett. B **749** (2015) 57-62 (collinear approximation)

Maciuła, Szczurek, paper in preparation (complementary studies in k_T-factorization)

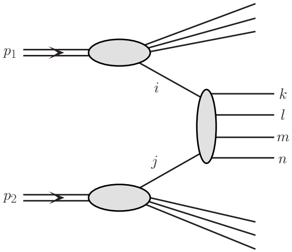
Four-jet production: Mechanisms under consideration

Analysis driven by the recent CMS four-jet data: Phys.Rev.D**89** (2014) 092010



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

- Factorized ansatz with experimental setup of σ_{eff}
- LO collinear approximation (2 $\longrightarrow$ 2 $\otimes$ 2 $\longrightarrow$ 2)
- extension to the k_T-factorization framework for more exclusive and precise studies of kinematical correlations

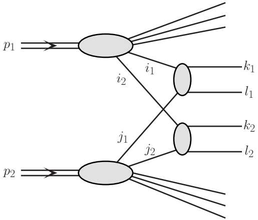


Single-Parton Scattering (SPS 2 $\longrightarrow$ 4)

- ALPGEN code: Mangano et al. JHEP 07 (2003) 001
- LO collinear approximation (2 $\longrightarrow$ 4)
- important NLO corrections in the form of K-factor estimated from the first 4-jet NLO computations: Bern et al., Phys. Rev. Lett. 109 (2012) 042001

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

In a simple probabilistic picture:



process initiated by two simultaneous hard parton-parton scatterings in one proton-proton interaction $\Rightarrow$

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

two subprocesses are not correlated and do not interfere

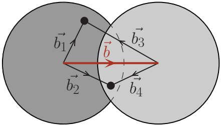
analogy: frequently considered mechanisms of double gauge boson production and double Drell-Yan anihillation

$$\frac{d\sigma^{DPS}(pp \to 4\mathrm{jets}\ X)}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \sum_{\substack{i_1,j_1,k_1,l_1 \\ i_2,j_2,k_2,l_2}} \frac{\mathcal{C}}{\sigma_{eff}} \frac{d\sigma(i_1 j_1 \to k_1 l_1)}{dy_1 dy_2 d^2p_{1t}} \frac{d\sigma(i_2 j_2 \to k_2 l_2)}{dy_3 dy_4 d^2p_{2t}},$$

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

- combinatorial factors $\mathcal{C}$ 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:

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

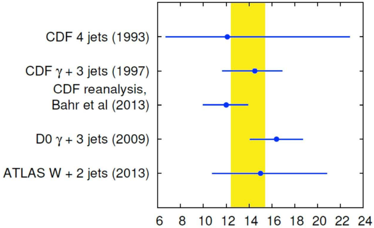
- correlations between two partons
  C. Flensburg et al., JHEP 06, 066 (2011)

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:

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

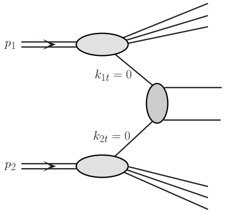


phenomenology: $\sigma_{eff} \Rightarrow$ nonperturbative quantity with a dimension of cross section, connected with transverse size of proton

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

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

Standard pQCD dijet production



collinear approximation → transverse momenta of the incident partons are assumed to be zero

quadrupuly differential cross section:

$$\frac{d\sigma(ij \to kl)}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 f_i(x_1, \mu^2)\; x_2 f_j(x_2, \mu^2)\; \overline{|\mathcal{M}_{ij\to kl}|^2}$$

$f_i(x_1, \mu^2)$, $f_j(x_2, \mu^2)$ - standard collinear PDFs

- at LO: 9 classes of 2 → 2 subprocesses (on-shell ME e.g. Ellis, Stirling, Webber textbook)
- **state of the art**: on-shell ME's at

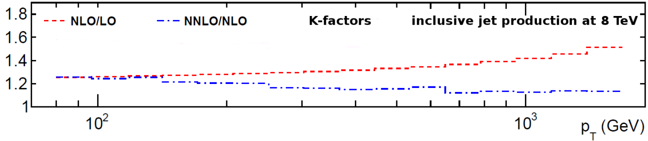
  NLO (e.g. Ellis et al., Phys. Rev. Lett. 69, 3615 (1992); Giele et al., Phys. Rev. Lett. 73, 2019 (1994))

  NNLO (J. Currie et al., JHEP, 01, 110 (2014))

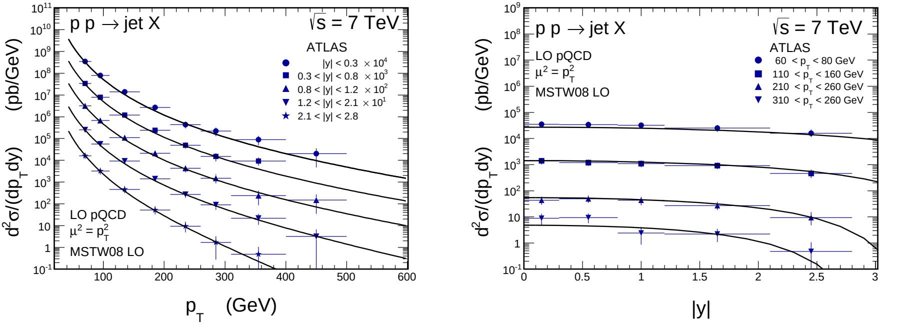
NLO corrections also accesible within the K-factor: $K_{NLO} \approx 1.2 - 1.3$

- energy, p_t and rapidity independent in the kinematical regime relevant for the DPS effects studies

(Campbell et al., Rept. Prog. Phys. 70, 89 (2007); Gehrmann-De Ridder et al., Eur. Phys. J. C71, 1512 (2011))

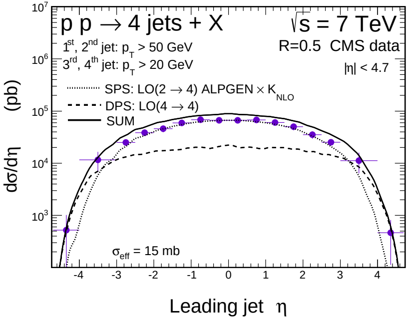


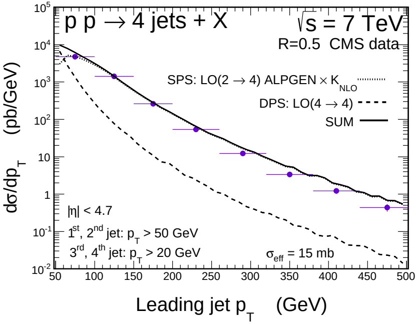
ATLAS inclusive jet data vs. LO pQCD



- fairly reasonable agreement with the recent inclusive jet ATLAS data even within LO pQCD collinear approach
- it allows us to use the same distributions for first rough evaluation of DPS effects in four-jet production

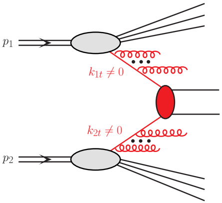
CMS four-jets: SPS ALPGEN + DPS LO collinear





- central region slightly overestimated ⇒ exact SPS NLO calculations needed?
- forward/backward region underestimated within SPS mechanism
- DPS seems to improve the forward/backward situation but it is hard to draw definite conclusions in the moment ⇒ large uncertainties (TH/EXP)
- DPS favoured small p_T and large rapidities regions

Basic concepts of the 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

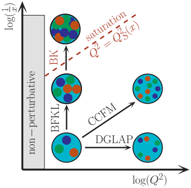
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{i^* j^* \to kl}|^2} \times \delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \mathcal{F}_i(x_1,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

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

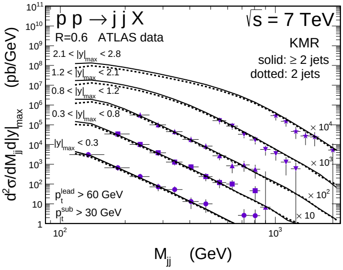
Unintegrated parton distribution functions (UPDFs)

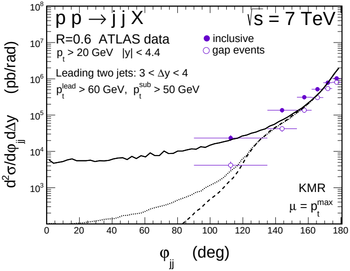


most popular models:

- 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)

Lessons from inclusive dijet production at the LHC:





- KMR UPDFs work well for jet-jet correlation observables

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:

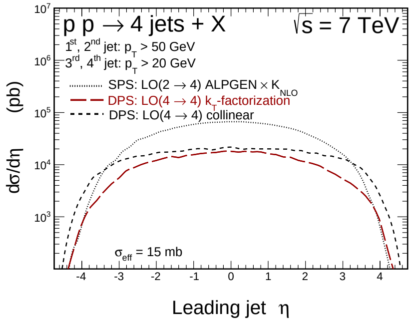
$$\frac{d\sigma^{DPS}(pp \to 4\mathrm{jets}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma^{SPS}(pp \to j\,j\,X_1)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \cdot \frac{d\sigma^{SPS}(pp \to j\,j\,X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}}$$

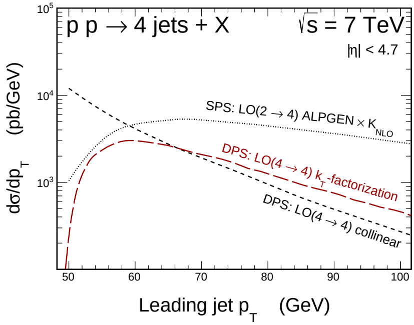
Each step of DPS (each individual scattering):

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

- in considered kinematical regime: $g^*g^* \to gg$, $g^*q^* \to gq$ and $q^*g^* \to qg$ partonic subprocesses are important and sufficient
- technically more complicated calculations: effectively 16 dimensions
- Monte Carlo method: VEGAS algorithm

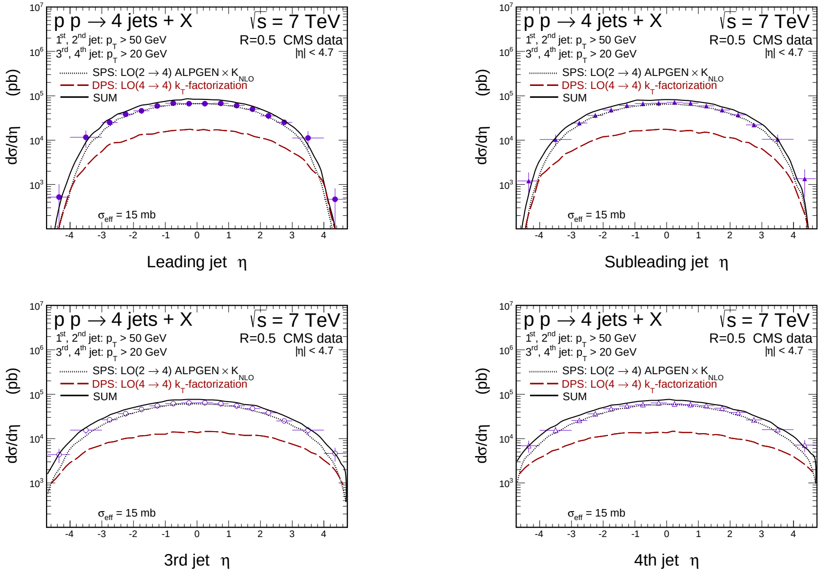
DPS four-jets: LO pQCD vs. k_T-factorization approach





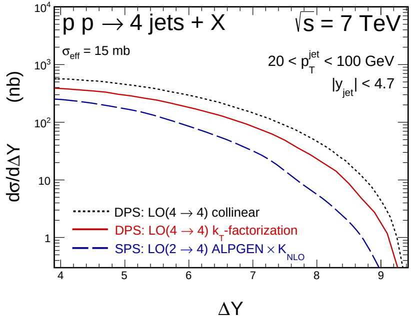
- significant differences between collinear approach and k_T-factorization
- DPS contribution in the forward/backward region slightly reduced

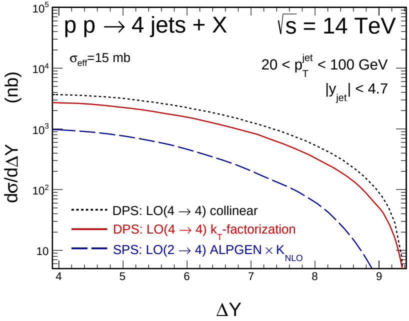
CMS four-jets: SPS ALPGEN + DPS k_T-factorization



DPS favoured: Jets most remote in rapidity

Rapidity difference

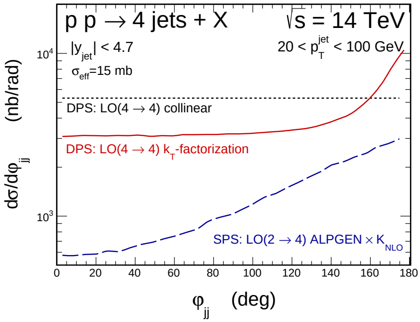




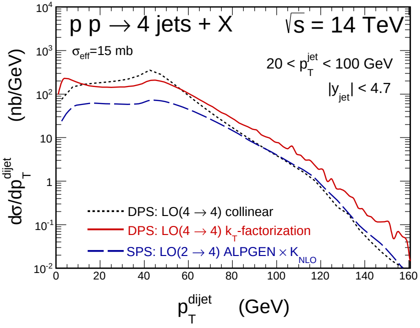
- DPS contribution dominates over SPS one
- the dominance increases with energy
- similar situation as in the case of 2-jet production with large rapidity separation where DPS has been proposed as an important mechanism in the context of BFKL Mueller-Navelet jet studies: Maciula, Szczurek, Phys. Rev. D **90** (2014) 014022

DPS favoured: Jets most remote in rapidity

Azimuthal angle



Dijet transverse momentum



- Distribution in azimuthal angle between jets most remote in rapidity shows how the DPS signal may be further enhanced $\Rightarrow \varphi_{jj} < \pi/2$

Four-jet production: Relative DPS contribution

Table: Integrated cross sections in nanobarns for $\sqrt{s} = 14$ TeV, for different cuts on jet transverse momenta as well as on rapidity distance and azimuthal angle between the most remote jets. Here, $\sigma_{eff} = 15$ mb has been used for calculating the DPS.

Kinematics: $\sqrt{s} = 14$ TeV, $\lvert y\rvert < 4.7$	ALPGEN σ^{SPS}	collinear σ^{DPS}	collinear $\frac{DPS}{SPS+DPS}$	k_T-factorization σ^{DPS}	k_T-factorization $\frac{DPS}{SPS+DPS}$
$35 < p_T < 100$ GeV	197.74	275.23	58%	181.62	48%
$20 < p_T < 100$ GeV	4 194.11	16 652.39	80%	8 996.72	69%
$20 < p_T < 100$ GeV, $\Delta Y > 7.0$	151.70	1 194.28	89%	726.77	82%
$20 < p_T < 100$ GeV, $0 < \varphi_{jj} < \frac{\pi}{2}$	1 157.15	8 326.19	88%	4 627.48	80%

Conclusions

- We have calculated DPS contribution to four-jet production at the LHC in both, collinear and k_T-factorization approaches
- We have found that the SPS mechanism seems not to be able to explain the CMS experimental distributions in the forward/backward rapidity region
- We have shown that the DPS mechanism may improve the agreement with the CMS experimental data in this corner of the phase space.
- We have indicated phase-space corners where the DPS content is enhanced relatively to the SPS one

Thank you for your attention!