Production of dijets with large rapidity separation: Mueller-Navelet mechanism versus double-parton scattering

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DIS 2014 - XXII International Workshop on Deep-Inelastic Scattering and Related Subjects,
University of Warsaw, 28 April - 2 May 2014
Motivation

Four-jet production within double-parton scattering

DPS effects for large-rapidity-distance jets

Summary

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Based on:
Motivation - search for BFKL effects

Mueller-Navelet jets


- decorrelation in relative azimuthal angle of the large-rapidity-distance jets due to diffusion along the exchange BFKL ladder
- study of angular decorrelation ⇒ sensitivity to additional emissions
- DGLAP contribution suppressed in events with two jets of similar $p_t$ and large separation in rapidity
- an alternative is BFKL/CCFM evolution

- $\Delta Y$ forward-backward jets emitted at small angle with respect to the beam

- state of the art: Ducloue, Szymanowski, Wallon, JHEP, 05, 096 (2013)
- NLL BFKL corrections both to Green’s function and to the jet vertices
Motivation - experimental studies

Large-rapidity-distance jets ⇒ only at high energies where the rapidity span is large due to kinematics

- $\sqrt{s} = 1.8$ TeV, $E_T > 20$ GeV, $|\eta| < 3$
- $\Delta \eta$ limited only up to 5 units
- some decorrelation observed (broadening of the $\phi_{jj}$ distribution with growing $\Delta \eta$)
- theoretical interpretation is not clear

Current status: BFKL effects were not observed in Tevatron experimental data

LHC opens possibility to study those effect quantitatively
- CMS, $\sqrt{s} = 7$ TeV, $p_t > 35$ GeV, $|\eta| < 4.7$
- $\Delta \eta$ up to 9.4 units
- not absolutely normalized $\phi_{jj}$ angular distributions
- correlation coefficients $<\cos(n \phi_{jj})>$ and their ratios

Absolute M-N jets cross section expected soon
Motivation - a new important mechanism?

Double-parton scattering (DPS) - our previous experiences

- Double open charm production

- Double $J/\psi$ meson production

recent studies of multiparton interactions have shown that they may easily produce objects which are emitted far in rapidity (larger rapidity distances than in standard single-parton scattering mechanisms)

could the DPS effects be important for large-rapidity-distance jets?
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Four-jet final state via Double-Parton Scattering (DPS)

In a simple probabilistic picture:

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

\[ \sigma^{DPS}(pp \rightarrow 4\text{jets}X) = \frac{C}{\sigma_{eff}} \cdot \sigma^{SPS}(pp \rightarrow \text{dijet}X_1) \cdot \sigma^{SPS}(pp \rightarrow \text{dijet}X_2) \]

two subprocesses are not correlated and do not interfere

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

\[
\frac{d\sigma^{DPS}(pp \rightarrow 4\text{jets} X)}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \sum_{i_1 j_1 \rightarrow k_1 l_1} C \frac{d\sigma(i_1 j_1 \rightarrow k_1 l_1)}{dy_1 dy_2 d^2p_{1t}} \frac{d\sigma(i_2 j_2 \rightarrow k_2 l_2)}{dy_3 dy_4 d^2p_{2t}},
\]

where

\[
C = \begin{cases}
\frac{1}{2} & \text{if } i_1 j_1 = i_2 j_2 \land k_1 l_1 = k_2 l_2 \\
1 & \text{if } i_1 j_1 \neq i_2 j_2 \lor k_1 l_1 \neq k_2 l_2
\end{cases}
\]

and \( i, j, k, l = g, u, d, s, \bar{u}, \bar{d}, \bar{s} \).

- combinatorial factors \( C \) include identity of the two subprocesses

differential cross sections for the production of exactly four jets measured recently by the CMS collaboration, CMS-FSQ-12-013
Factorized Ansatz and double-parton distributions (DPDFs)

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

$$\Gamma_{i,j}(b, x_1, x_2; \mu^2_1, \mu^2_2) = F_i(x_1, \mu^2_1) F_j(x_2, \mu^2_2) F(b; x_1, x_2, \mu^2_1, \mu^2_2)$$

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

In general:

$$\sigma_{\text{eff}}(x_1, x_2, x'_1, x'_2, \mu^2_1, \mu^2_2) = \left(\int d^2 b \ F(b; x_1, x_2, \mu^2_1, \mu^2_2) F(b; x'_1, x'_2, \mu^2_1, \mu^2_2)\right)^{-1}$$

**Factorized Ansatz:**

- additional limitations: $x_1 + x_2 < 1$ oraz $x'_1 + x'_2 < 1$

- DPDF in multiplicative form: $F_{ij}(b; x_1, x_2, \mu^2_1, \mu^2_2) = F_i(x_1, \mu^2_1) F_j(x_2, \mu^2_2) F(b)$

- $\sigma_{\text{eff}} = \left[\int d^2 b \ (F(b))^2\right]^{-1}$, $F(b)$ - energy and process independent

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

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

A detailed analysis of $\sigma_{\text{eff}}$:

Seymour, Siódmok, JHEP 10, 113 (2013)
Standard pQCD dijet production

**LO collinear approximation** → transverse momenta of the incident partons are assumed to be zero (Wiezsacker-Williams method in QED)

- quadruply differential cross section:
  \[ \frac{d\sigma(ij \rightarrow kl)}{dy_1 dy_2 d^2 p_T} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 f_i(x_1, \mu^2) x_2 f_j(x_2, \mu^2) |M_{ij \rightarrow kl}|^2 , \]

- 9 classes of the $2 \rightarrow 2$ subprocesses (on-shell ME e.g. Ellis, Stirling and Webber textbook)

- $f_i(x_1, \mu^2), f_j(x_2, \mu^2)$ - standard parton distributions in proton (PDFs)

**state of the art:** NLO (e.g. Ellis et al., Phys. Rev. Lett. 69, 3615 (1992); Giele et al., Phys. Rev. Lett. 73, 2019 (1994)) and NNLO (J. Currie et al., JHEP, 01, 110 (2014)) on-shell ME’s

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

- with a good approximation: energy, $p_T$ and rapidity independent in the kinematical regime relevant for the Mueller-Navelet jet studies (e.g. Campbell et al., Rept. Prog. Phys. 70, 89 (2007); Gehrmann-De Ridder et al., Eur. Phys. J. C71, 1512 (2011))
fairly reasonable agreement with the recent inclusive jet ATLAS data even within LO pQCD approach

it allows us to use the same distributions for first evaluation of the DPS effects for large-rapidity-distance jets (as a first approximation)
CMS inclusive jet data vs. LO pQCD

- gluon-gluon and quark-gluon contributions clearly dominate over the rest.
for the CMS configuration our DPS contribution is smaller than the SPS dijet or LL BFKL M-N jets contribution even at high rapidity distances and only slightly smaller than that for the NLL BFKL M-N jets calculation

the four-jet (DPS) and dijet final state can be easily distinguished and, in principle, one can concentrate only on the DPS contribution which is interesting by itself
DPS 4-jet vs. SPS dijet production (lower jet-$p_T$)

- the DPS contribution is growing with decreasing jet transverse momenta
- this growth is enhanced with the energy increase
DPS 4-jet vs. SPS dijet production (semihard particles)

- the relative effect of DPS could be increased by further lowering of the $p_t$ of "mini-jets" but such measurements can be difficult if not impossible.

- alternatively, one could study correlations of semihard ($p_t \sim 10$ GeV) pions distant in rapidity

- correlations of two neutral pions could be done, at least in principle, with the help of zero-degree calorimeters present at each main detectors at the LHC
the DPS mechanism generates situations with large transverse momentum imbalance, this could be used in addition to enhance the content of DPS effects by taking a lower cut on the dijet imbalance.

the transverse momentum imbalance for jets remote in rapidity is bigger than that for jets close in rapidity.

the corresponding distribution for Mueller-Navelet jets has maximum at $p_{t,\text{sum}} \sim 0$ (see e.g. Del Duca, Schmidt, Phys. Rev. D51, 2150 (1995))
Conclusions

- we have discussed how the double-parton scattering effects may contribute to large-rapidity-distance dijet correlations
- present exploratory calculation has been performed in the LO pQCD approximation to understand and explore the general situation
- we have identified the dominant LO partonic pQCD subprocesses relevant for the production of jets with large rapidity distance ($gg \rightarrow gg$, $qg \rightarrow qg$)
- the results of the dijet SPS and LL/NLL BFKL M-N jets mechanisms have been compared to the DPS 4-jet production
- the contribution of the DPS mechanism increases with increasing distance in rapidity between jets
- for the CMS configuration our DPS contribution is smaller than the SPS LO pQCD dijet contribution as well as than LL BFKL M-N jets calculation even at high rapidity distances BUT only slightly smaller than that for the NLL BFKL calculation
- the relative effect of DPS could be increased by lowering the transverse momenta of jets (large-rapidity-distance semihard pions)
- more definite conclusions? ⇒ DPS contribution within $k_T$-factorization and cooperation with the M-N jets group: e.g. Ducloue-Szymanowski-Wallon are necessary

Thank You for attention!
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The double-differential distribution in \( (p_t(y_{\text{min}}) \times p_t(y_{\text{max}})) \)

- The distribution for the DPS is rather different than for dijet SPS and MN jets