Double parton effects for jets with large rapidity separation

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Outline

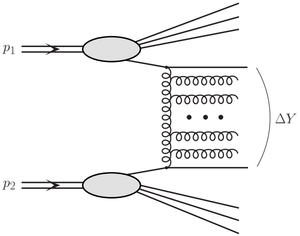
1. Motivation
2. Four-jet production within double-parton scattering
3. DPS effects for large-rapidity-distance jets
4. Present situation at the LHC
5. Summary

Based on:
Maciuła, Szczurek, arXiv:1403.2595 (hep-ph)
Phys. Rev. **D90** (2014) 014022.

Motivation - search for BFKL effects

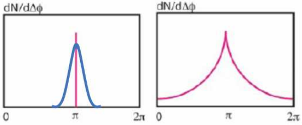
Mueller-Navelet jets

Nucl. Phys. B282, 727 (1987)



forward-backward jets emitted at small angle with respect to the beam

- **decorrelation in relative azimuthal angle** of the large-rapidity-distance jets due to diffusion along the exchanged BFKL ladder

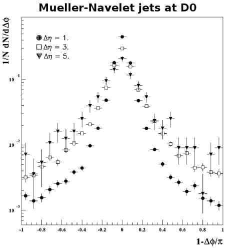


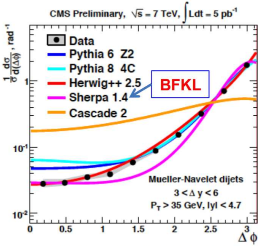
- study of angular decorrelation ⇒ sensitivity to additional emissions
- DGLAP contribution suppressed in events with two jets of similar p_t and large separation in rapidity
- an alternative is BFKL/CCFM evolution

- LL BFKL - e.g. Del Duca, Schmidt, Phys. Rev. D49, 4510 (1994); Kwieciński et al., Phys. Lett. B514, 355 (2001)
- higher-order BFKL - e.g. Bartels et al., Eur. Phys. J. C24, 83 (2002); Sabio Vera, Schwennsen, Nucl. Phys. B776, 170 (2007); Marquet, Royon, Phys. Rev. D79, 034028 (2009); Ivanov, Papa, JHEP 05, 086 (2012); F. Caporale et al. Nucl.Phys. B877, 73 (2013)
- **state of the art**: Ducloue, Szymanowski, Wallon, JHEP, 05, 096 (2013)
  NLL BFKL corrections both to Green's function and to the jet vertices
- NLO collinear approach - Aurenche et al., Eur. Phys J. C57, 681 (2008)

Motivation - experimental studies

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





Mueller-Navelet jets at CMS

D0 collaboration, Phys. Rev. Lett. 77, 595 (1996)

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

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

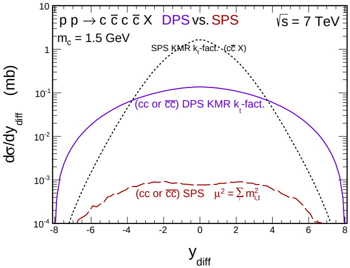
LHC opens possibility to study those effect quantitatively

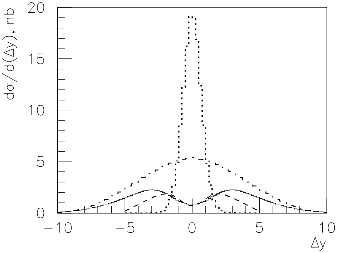
- **CMS**, $\sqrt{s} = 7$ TeV, $p_t > 35$ GeV, $|\eta| < 4.7$
- $\Delta\eta$ up to 9.4 units
- not absolutely normalized φ_{jj} angular distributions
- correlation coefficients $< cos(n\varphi_{jj}) >$ and their ratios

absolute M-N jets cross section expected soon

Motivation - a new important mechanism?

Double-parton scattering (DPS) - our previous experiences





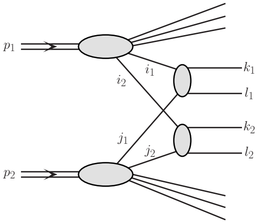
- Double open charm production
  Phys.Rev. D85, 094034 (2012); Phys.Rev. D87, 074039 (2013); arXiv:1402.6972 (hep-ph)
- Double J/ψ meson production
  Phys.Rev. D87, 034035 (2013)

- 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?

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 ⇒

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

two subprocesses are not correlated and do not interfere

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

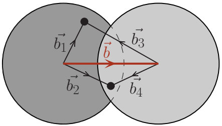
$$\frac{d\sigma^{DPS}(pp \to 4\text{jets}\ X)}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \sum_{\substack{i_1,j_1,k_1,l_1 \\ i_2,j_2,k_2,l_2}} \frac{C}{\sigma_{eff}} \; \frac{d\sigma(i_1 j_1 \to k_1 l_1)}{dy_1 dy_2 d^2p_{1t}} \; \frac{d\sigma(i_2 j_2 \to k_2 l_2)}{dy_3 dy_4 d^2p_{2t}} \,,$$

where $C = \left\{ \begin{array}{ll} \frac{1}{2} & \text{if } i_1 j_1 = i_2 j_2 \wedge k_1 l_1 = k_2 l_2 \\ 1 & \text{if } i_1 j_1 \neq i_2 j_2 \vee k_1 l_1 \neq k_2 l_2 \end{array} \right\}$ 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)



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

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

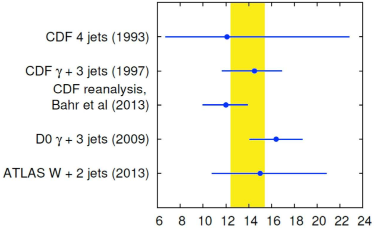
- correlations between two partons
  C. Flensburg et al., JHEP 06, 066 (2011)

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

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

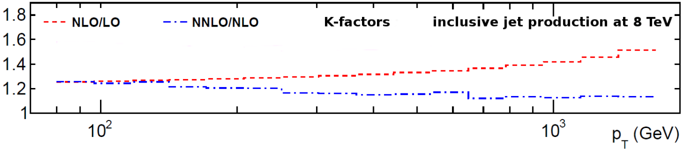
- quadrupuly differential cross section:

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

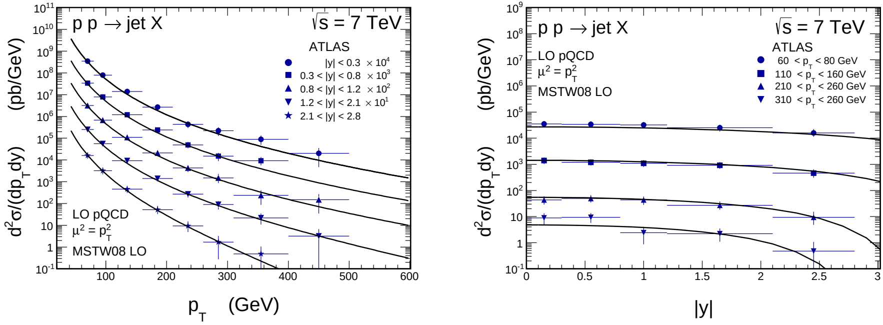
- 9 classes of the 2 → 2 subprocesses (on-shell ME e.g. Ellis, Stirling and Webber textbook)
- $f_i(x_1,\mu^2)$, $f_j(x_2,\mu^2)$ - standard parton distributions in proton (PDFs)
- **state of the art**: NLO (e.g. Ellis et al., Phys. Rev. Lett. 69, 3615 (1992); Giele et al., Phys. Rev. Lett. 73, 2019 (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))

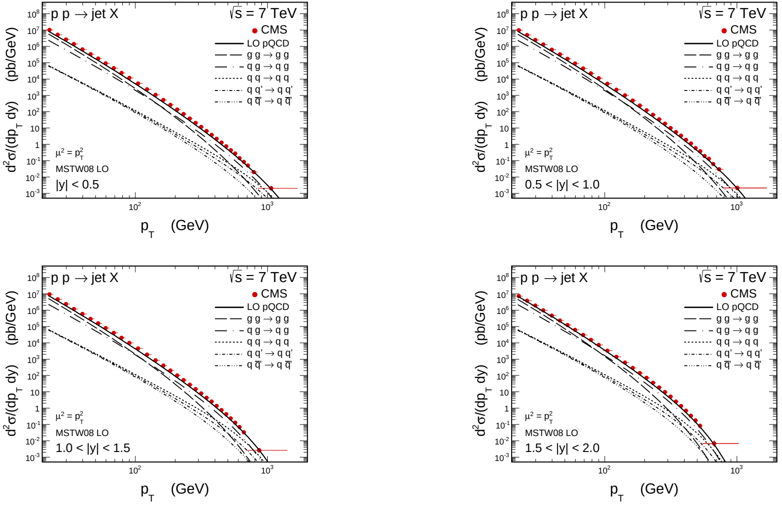


ATLAS inclusive jet data vs. LO pQCD



- fairly reasonable agreement with the recent inclusive jet ATLAS data even within LO pQCD approach
- it alows us to use the same distributions for first evalution of the DPS effects for large-rapidity-distance jets

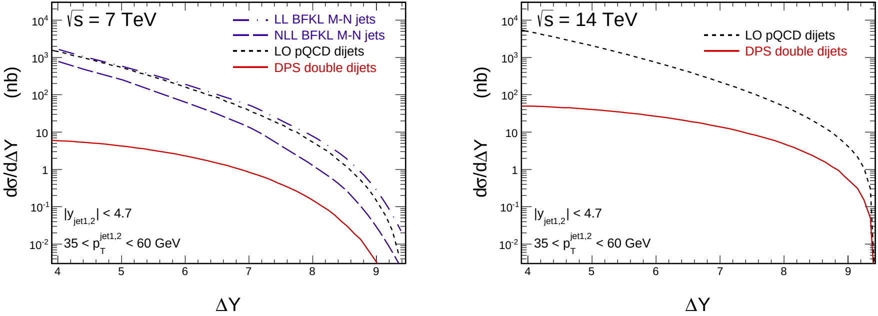
CMS inclusive jet data vs. LO pQCD



- gluon-gluon and quark-gluon contributions clearly dominate over the rest

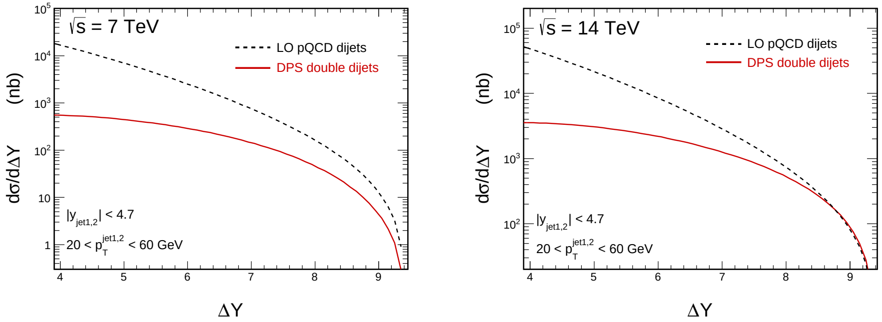
DPS 4-jet vs. SPS LO dijet and Mueller-Navelet jets

M-N jet results from:
Ducloue, Szymanowski, Wallon, JHEP, 05, 096 (2013)



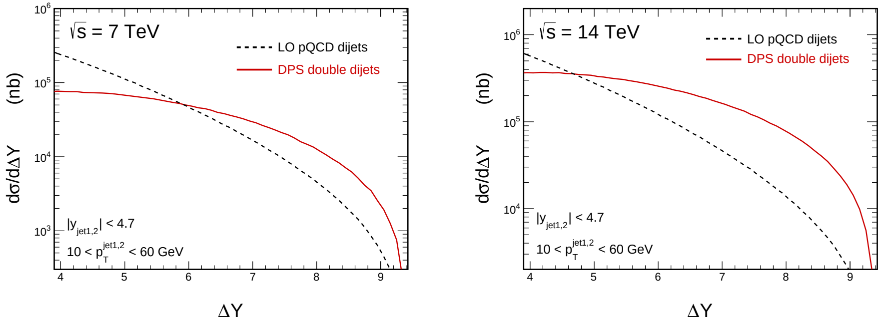
- for the CMS configuration our DPS contribution is smaller than the SPS dijet or LL BFKL M-N jets contribution even at high rapidity distances and only slightly smaller than that for the NLL BFKL M-N jets calculation
- the four-jet (DPS) and dijet final state can be easily distinguished and, in principle, one can concentrate only on the DPS contribution which is interesting by itself

DPS 4-jet vs. SPS dijet production (lower jet-p_t)



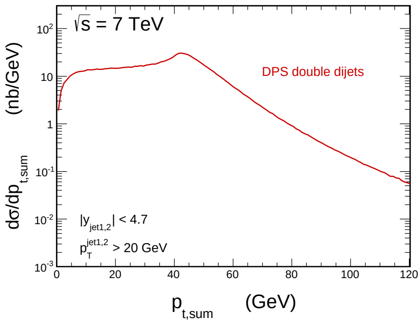
- the DPS contribution is growing with decreasing jet transverse momenta
- this growth is even enhanced with the energy increase

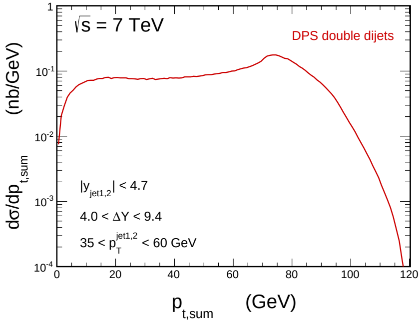
DPS 4-jet vs. SPS dijet production (semihard particles)



- the relative effect of DPS could be increased by further lowering 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

Transverse momentum imbalance





- 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 $p_{t,sum} \sim 0$ (see e.g. Del Duca, Schmidt, Phys. Rev. D51, 2150 (1995))

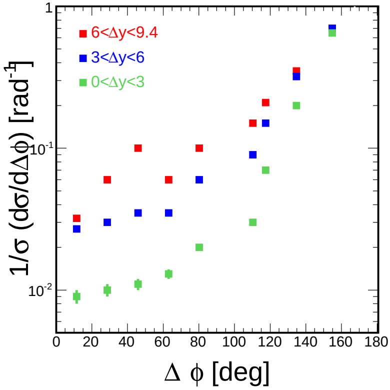
CMS analysis

CMS PAS FSQ-12-002 (see Grigory Safronov's talk)

Details of their selection:

- events with only one primary vertex (pileups)
- at least two jets with $p_t > 35$ GeV and $|y| < 4.7$
- pairs of jets with largest rapidity separation (MN)
- three different intervals of rapidity distances
  - $\Delta y < 3.0$
  - $3.0 < \Delta y < 6.0$
  - $6.0 < \Delta y < 9.4$
- extracted
  - $\frac{d\sigma/d\phi_{jj}}{\sigma}$
  - $< \cos(n(\pi - \Delta\phi_{jj})) >$

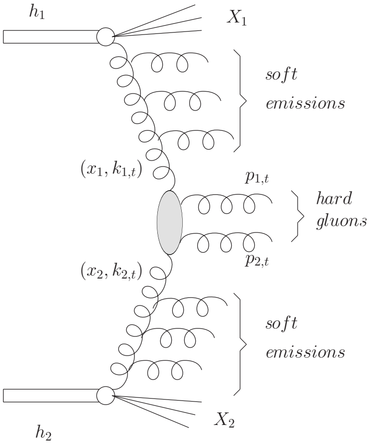
Experimental results



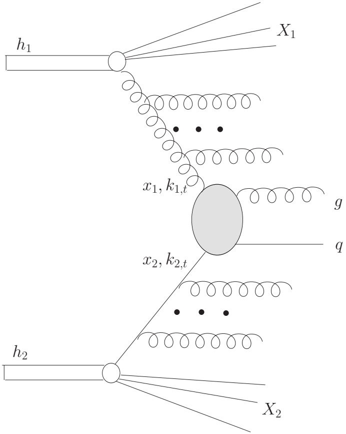
decorrelation slightly increases with growing rapidity distance.

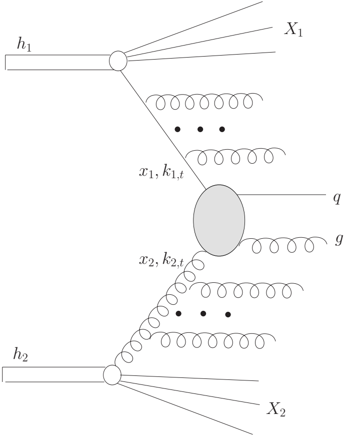
What does it mean ?

k_t-factorization



k_t-factorization





k_t-factorization calculation

with A. Cisek and R. Maciuła (work in progress)

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

i,j - reggeized partons

subprocess: reggeon+reggeon → particle+particle scattering

subprocesses included:

$gg \to gg, gg \to q\bar{q}$

$qg \to qg, \bar{q}g \to \bar{q}g$

$gq \to gq, g\bar{q} \to g\bar{q}$

off-shell matrix elements, Fadin-Lipatov effective vertices

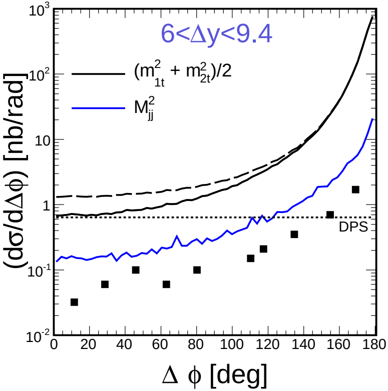
several works:

Leonidov-Ostrovsky, Nefedov-Saleev-Shipilova

Kotko-Kutak-van Hameren

k_t-factorization preliminary results

absolutely normalized cross section

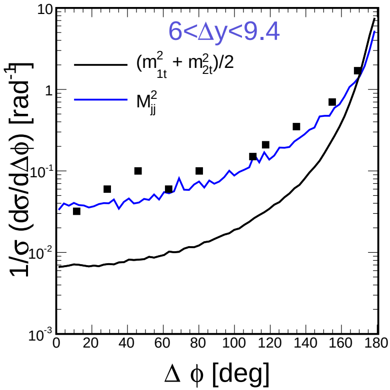


KMR UGDF

Cross section strongly depends on factorization/renormalization scale

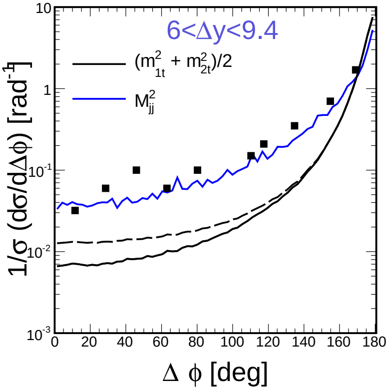
k_t-factorization preliminary results

shape only



$\mu^2 = M^2_{jj}$ better describes the CMS data than $\mu^2 = m^2_t$

k_t-factorization + DPS



DPS modifies the shape of the distribution

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 only 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 ($gg \to gg$, $qg \to qg$)
- 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 jet result. 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 NLO collinear or k_t-factorization approaches and a detailed comparison with differential distributions for MN jets.

Future work

- include parton splitting
  as in our recent paper (Gaunt, Maciula, Szczurek)
  arXiv:1407.5821, in print in Phys. Rev. D.
- DPS in k_t-factorization
  as in our paper (Maciula, Szczurek) on $c\bar{c}c\bar{c}$ production

Thank You for attention!

Backup

MPI@LHC 2014 in Krakow

MPI@LHC 2014 in Kraków

6th International Workshop on Multiple Partonic Interactions at the LHC

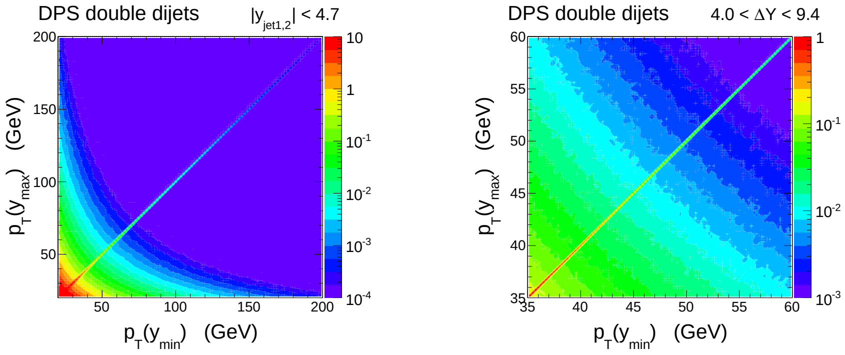
3-7 November

abstract submission:

30 September

http://indico.cern.ch/e/MPI2014

The double-differential distribution in $(p_t(y_{min}) \times p_t(y_{max}))$



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