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NCN

4-jet production: DPS and SPS contributions

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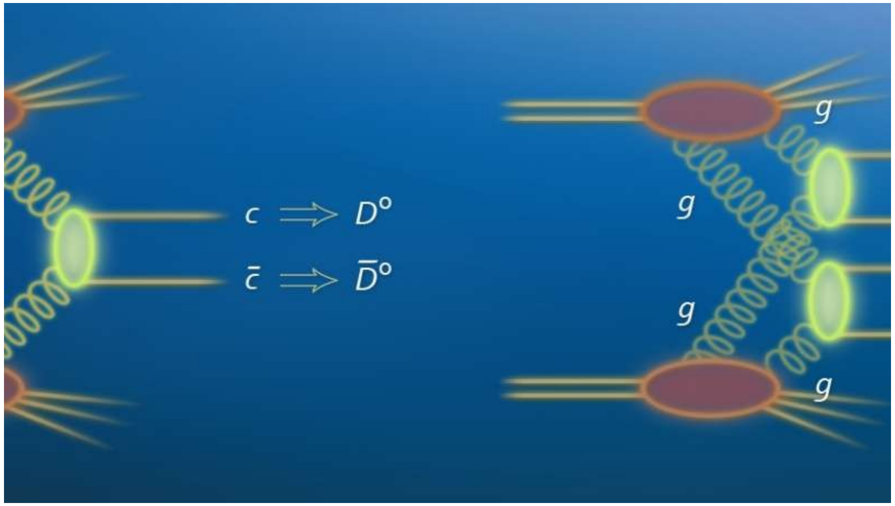
Based on:
K. Kutak, R. Maciuła, M. Serino, A.Szczurek, A. van Hameren
JHEP 1604 (2016) 175

K. Kutak, R. Maciuła, M. Serino, A.Szczurek, A. van Hameren
Phys. Rev. D 94, 014019 (2016)

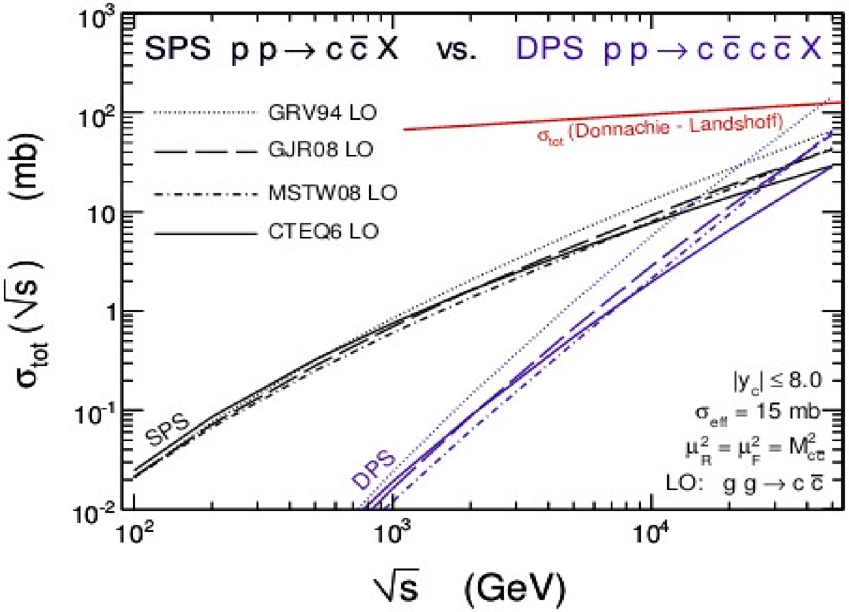
Motivation

Double parton scattering is a dominant mechanism of production of charm quarks and antiquarks

Cross section as a function of energy



http://phys.org/news/2016-06-lhc-charmed-twins-common-singles.html



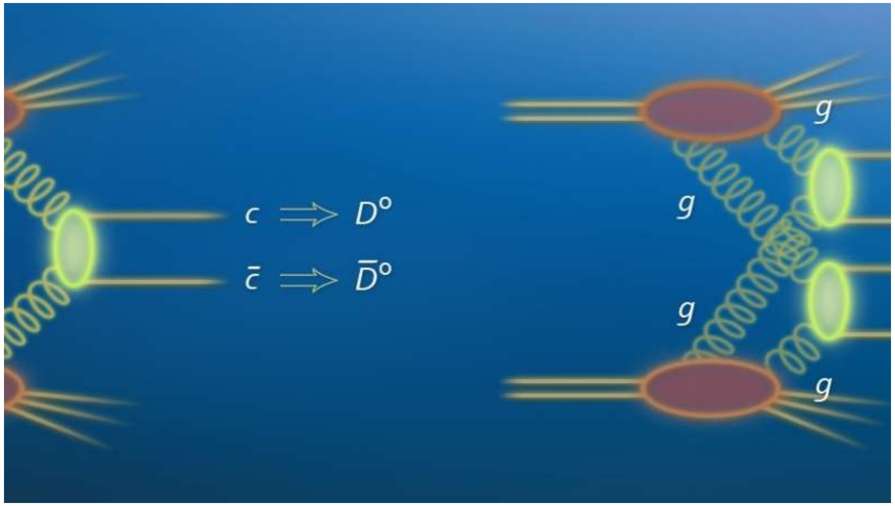
Maciula, Luszczak, Szczurek '11

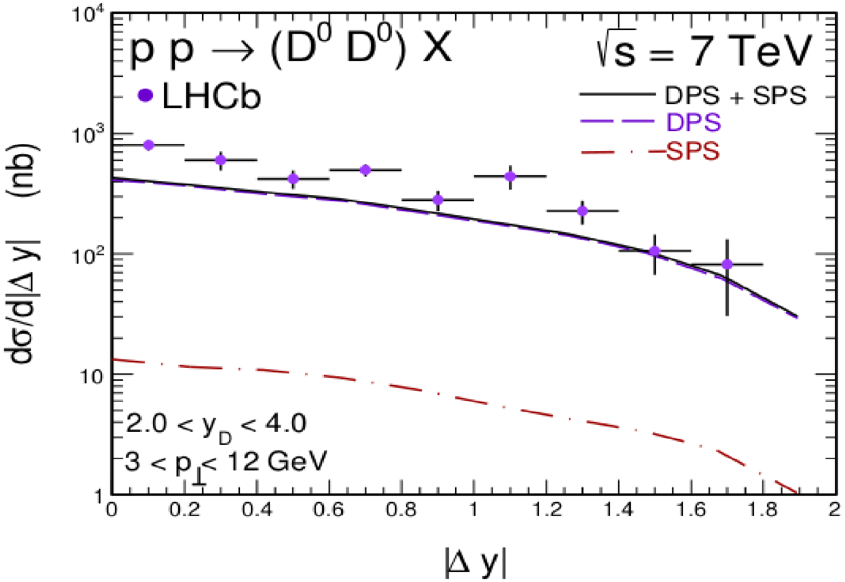
How universal is this mechanism? What about 4 jets?

Motivation

Double parton scattering is a dominant mechanism of production of charm quarks and antiquarks

Cross section as a function of rapidity distance between D0s



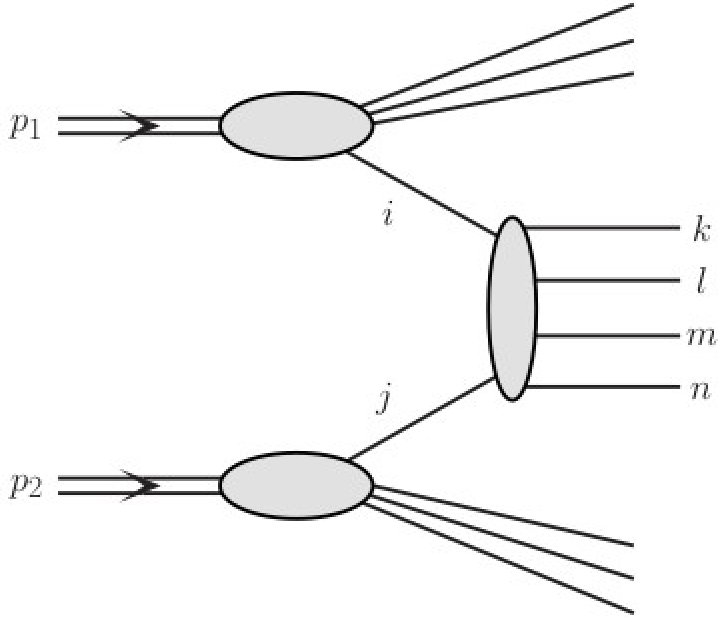


http://phys.org/news/2016-06-lhc-charmed-twins-common-singles.html

Maciula, van Hameren, Szczurek '14

How universal is this mechanism? What about 4 jets?

4 jets production: production mechanisms

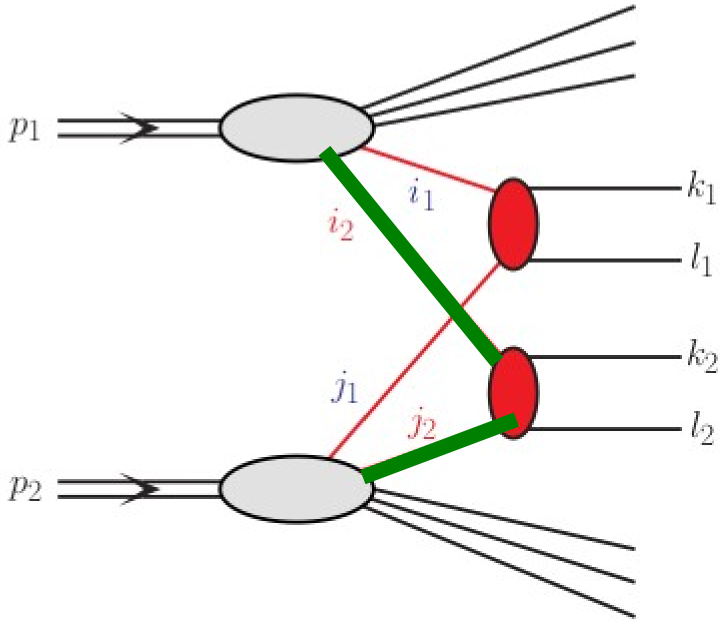


Single-parton scattering (SPS 2→ 4)

Kutak, Maciuła, Serino, Szczurek, Hameren, '16

High-Energy-Fact. (HEF) or k_T -factorization

first time: high multiplicity of final states with off-shell initial state partons



Double-parton scattering

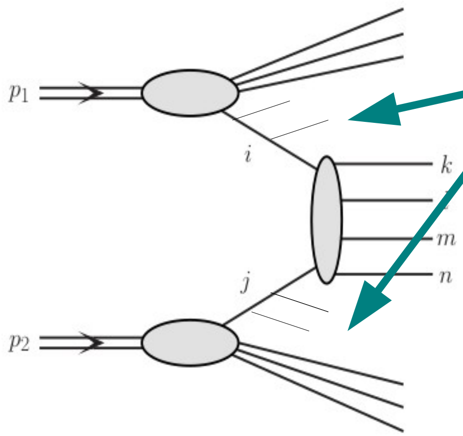
So called factorized ansatz

k_T -factorization approach (2 → 2 ⊗ 2 → 2)

offers more precise studies of kinematical characteristics and correlation observables

Single-parton scattering production of four jets

The collinear factorization approach



soft emissions or parton shower

Collinear pdfs of parton of i-th parton carrying x_1,x_2 momentum fraction probed at scale u_F

$$\sigma^B_{4-jets} = \sum_{i,j} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \, x_1 f_i(x_1,\mu_F)\, x_2 f_j(x_2,\mu_F)$$

$$\times \frac{1}{2\hat{s}} \prod_{l=i}^{4} \frac{d^3 k_l}{(2\pi)^3 2E_l} \Theta_{4-jet} \, (2\pi)^4 \, \delta\left(x_1 P_1 + x_2 P_2 - \sum_{l=1}^{4} k_i \right) \overline{|\mathcal{M}(i,j \to 4\,\mathrm{part.})|^2}$$

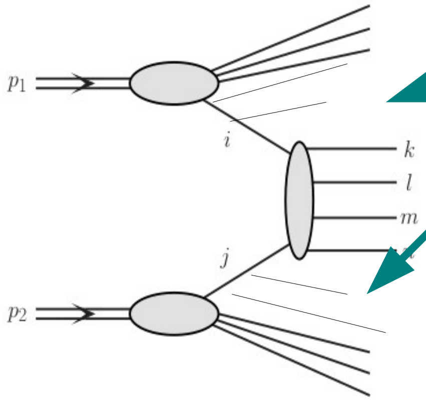
Partonic center of mass energy squared

Takes into account kinematical cuts applied

Hard matrix element characterizing parton-parton collision with production of 4 partons

Single-parton scattering production of four jets

The High Energy Factorization factorization approach



Formally emissions well separated from hard ME in rapidity

TMD pdf of parton of i-th parton carrying x_1,x_2 momentum fraction and transversal momentum k_{T1},k_{T2} probed at scale μ_F

$$\sigma_{4-jets} = \sum_{i,j} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} d^2 k_{T1} d^2 k_{T2} \, \mathcal{F}_i(x_1, k_{T1}, \mu_F) \, \mathcal{F}_j(x_2, k_{T2}, \mu_F)$$

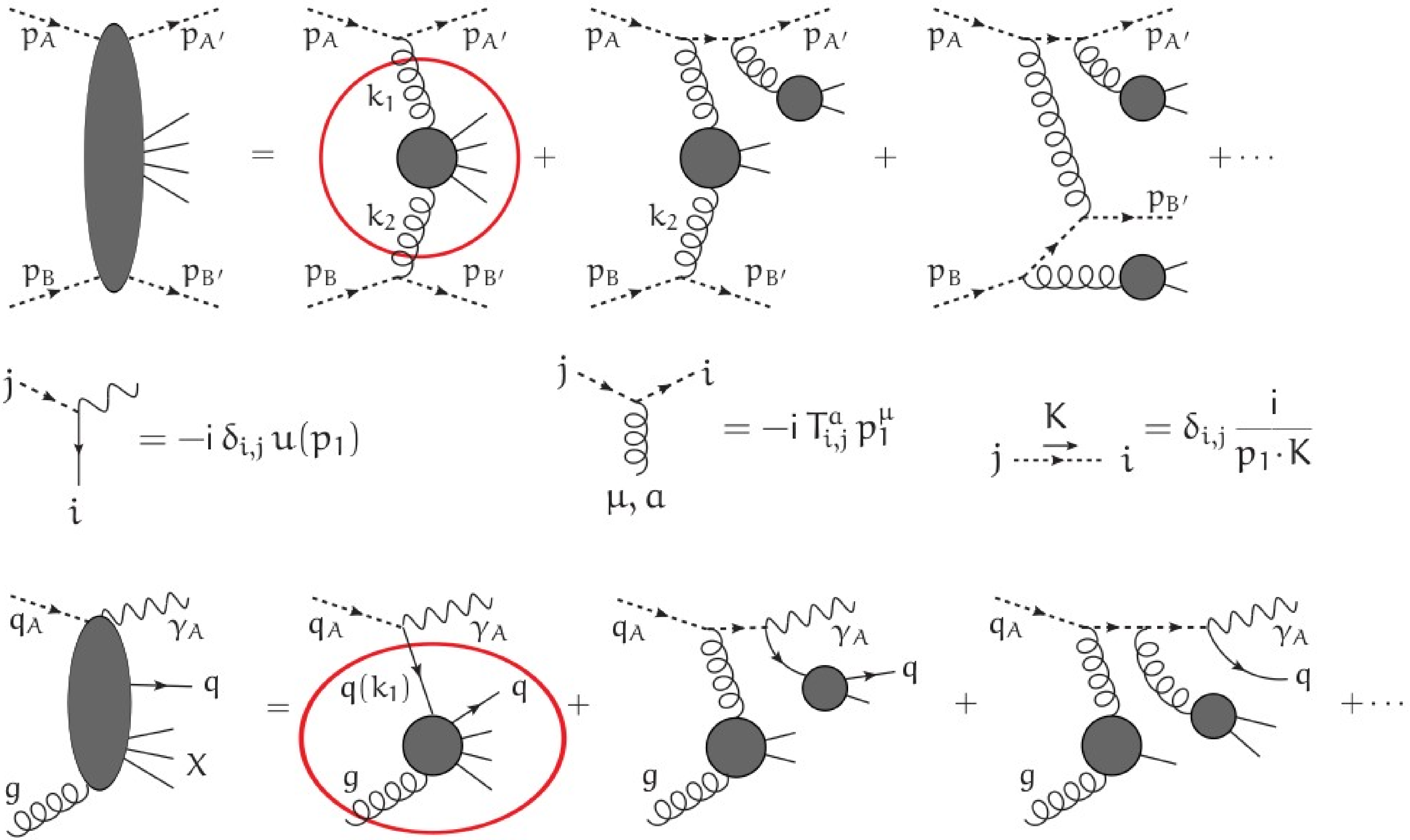
$$\times \frac{1}{2\hat{s}} \prod_{l=i}^{4} \frac{d^3 k_l}{(2\pi)^3 2E_l} \Theta_{4-jet} \, (2\pi)^4 \, \delta\left(P - \sum_{l=1}^{4} k_l\right) \overline{|\mathcal{M}(i^*, j^* \to 4\,\text{part.})|^2}$$

offshell initial state partons

Off-shell matrix elements

One considers embedding off-shell amplitude
in onshell and introduces eikonal lines or Wilson lines

Kotko, Kutak, van Hameren 2013,
Kutak, Salwa, van Hameren 2013



Off-shell matrix elements

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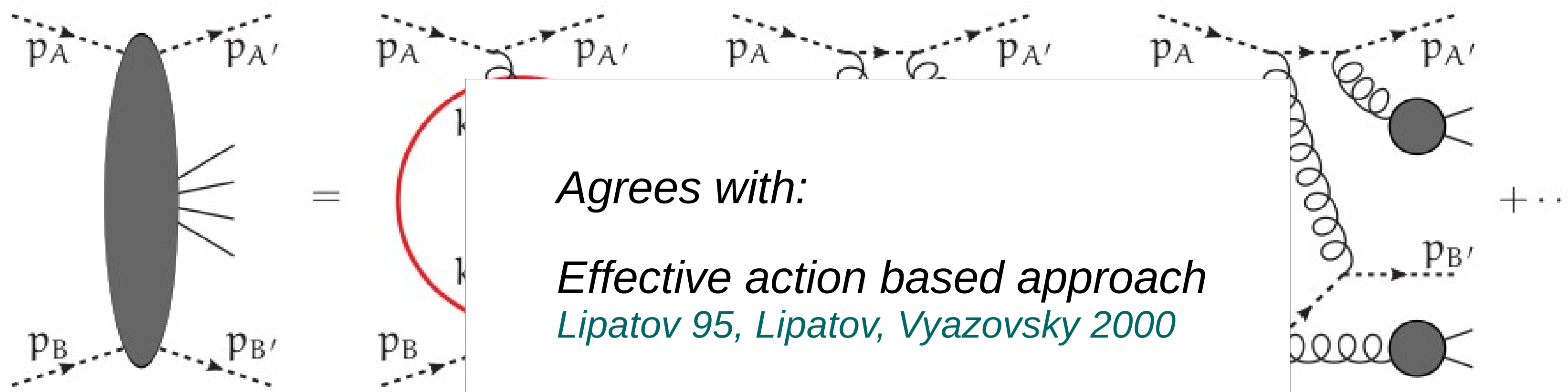
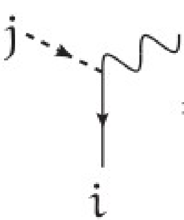


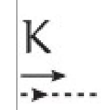


$$= -i\,\delta_{i,j}\,u(p_1)$$

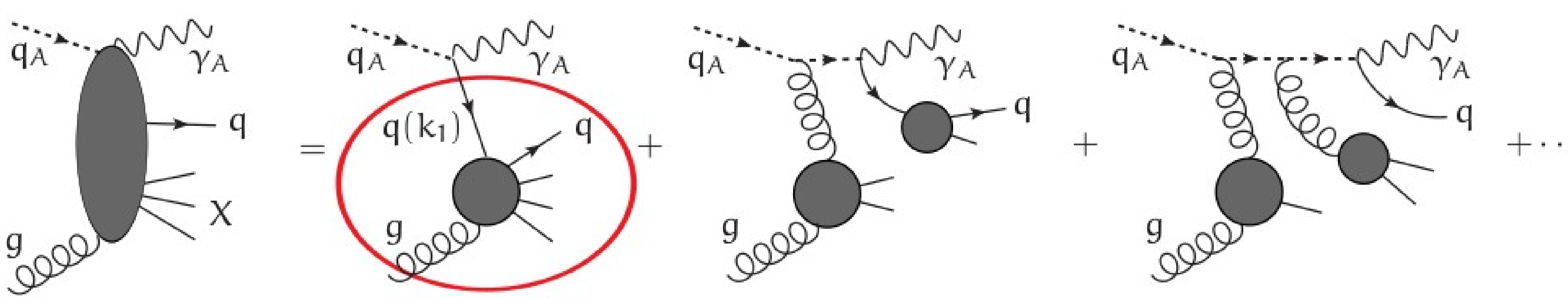
Agrees with:

Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

Gauge link based derivation
Kotko'14



$$= \delta_{i,j}\,\frac{i}{p_1\cdot K}$$



Numerical tool for HEF

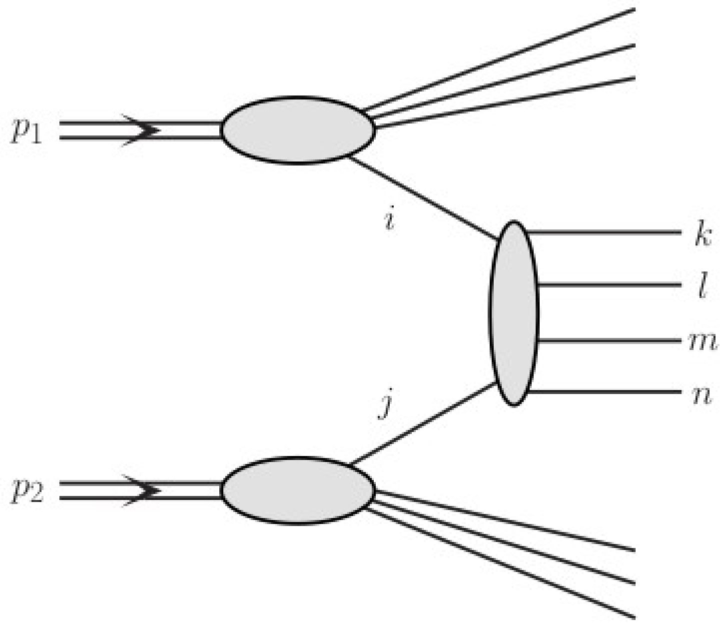
AVHLIB (A. van Hameren)

https://bitbucket.org/hameren/avhlib

- *complete Monte Carlo program for k_T factorized calculations*
- *any process within the Standard Model*
- *any initial-state partons on-shell or off-shell*
- *employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes*
- *automatic phase space optimization*

Contributing partons in single parton scattering process

There are 19 channels contributing to the cross section at the parton level



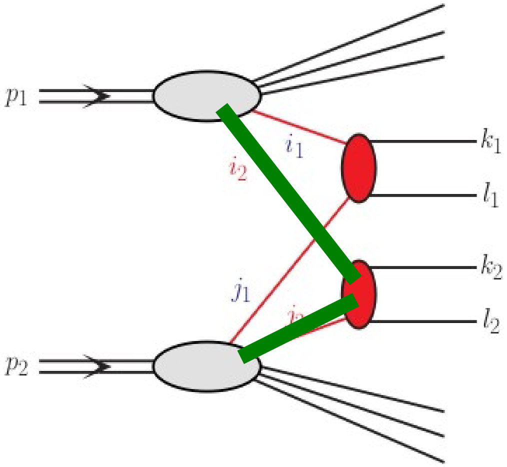
Combinations of partons in single parton scattering process

There are 19 channels contributing to the cross section at the parton level

$$
\begin{aligned}
&gg \to 4g\,,\, gg \to q\bar{q}\,2g\,,\, qg \to q\,3g\,,\, q\bar{q} \to q\bar{q}\,2g\,,\, qq \to qq\,2g\,,\, qq' \to qq'\,2g\,,\\
&gg \to q\bar{q}q\bar{q}\,,\, gg \to q\bar{q}q'\bar{q}'\,,\, qg \to qgq\bar{q}\,,\, qg \to qgq'\bar{q}'\,,\\
&q\bar{q} \to 4g\,,\, q\bar{q} \to q'\bar{q}'\,2g\,,\, q\bar{q} \to q\bar{q}q\bar{q}\,,\, q\bar{q} \to q\bar{q}q'\bar{q}'\,,\, q\bar{q} \to q'\bar{q}'q'\bar{q}'\,,\, q\bar{q} \to q'\bar{q}'q''\bar{q}''\,,\\
&qq \to qqq\bar{q}\,,\, qq \to qqq'\bar{q}'\,,\, qq' \to qq'q\bar{q}\,,
\end{aligned}
$$

The processes in the first line are the dominant channels, contributing together to ~ 93 % of the total cross section. This stays true in the k_T framework as well.

Factorized ansatz and Double Parton Distributions



$$\sigma^D_{(A,B)} = \frac{1}{1+\delta_{AB}} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2)\, \hat{\sigma}^A_{ik}(x_1, x_1')\, \hat{\sigma}^B_{jl}(x_2, x_2')$$
$$\times \Gamma_{kl}(x_1', x_2', b; Q_1^2, Q_2^2)\, dx_1 dx_2 dx_1' dx_2' d^2 b$$

more general parton densities

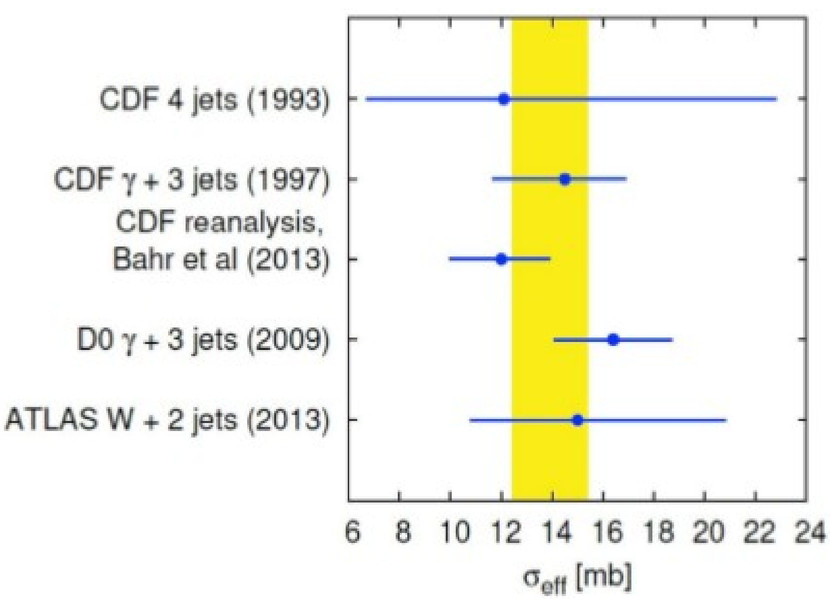
Flensburg, Gustafson Lonnblad' 11

$$\Gamma_{ij}(b, x_1, x_2; \mu_1^2, \mu_2^2) = f_i(x_1, \mu_1^2) f_j(x_2, \mu_2^2) F(b; x_1, x_2, \mu_1^2, \mu_2^2)$$

assumption: no x and scale dependence in F

$$F_{ij}(b; x_1, x_2, \mu_1^2, \mu_2^2) = f_i(x_1, \mu_1^2) f_j(x_2, \mu_2^2) F(b)$$

Used also in PYTHIA



$$\sigma^D_{(A,B)} = \frac{1}{(1+\delta_{AB})} \frac{\sigma^S_A \sigma^S_B}{\sigma_{\text{eff}}}$$

Factorization also supported by:
Golec-Biernat, Lewandowska
Serino, Stasto, Snyder' 15

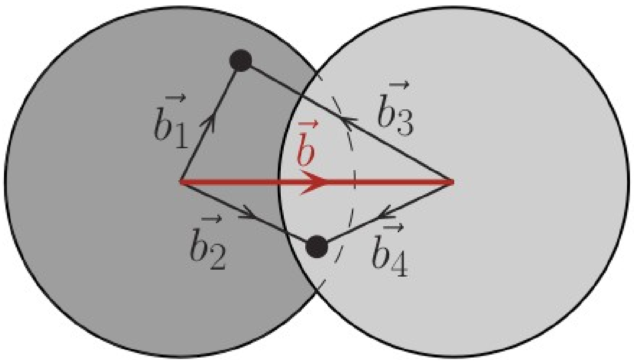
$$\sigma_{eff} = \left[\int d^2 (F(b))^2 \right]^{-1}$$

$$\sigma_{eff} = 15 mb$$

nonperturbative quantity

measure of correlation

Factorized ansatz and Double Parton Distributions



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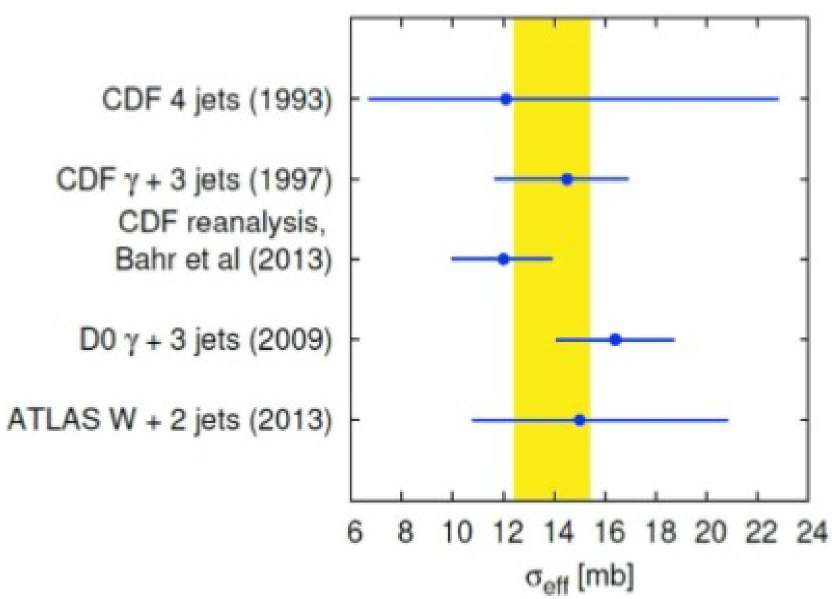

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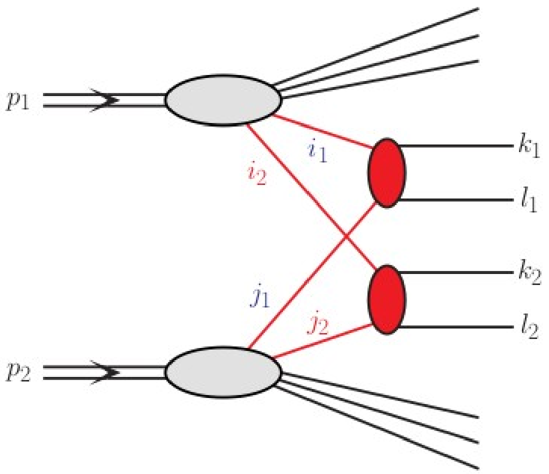
Double-parton scattering production of four jets



So finally we have:

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

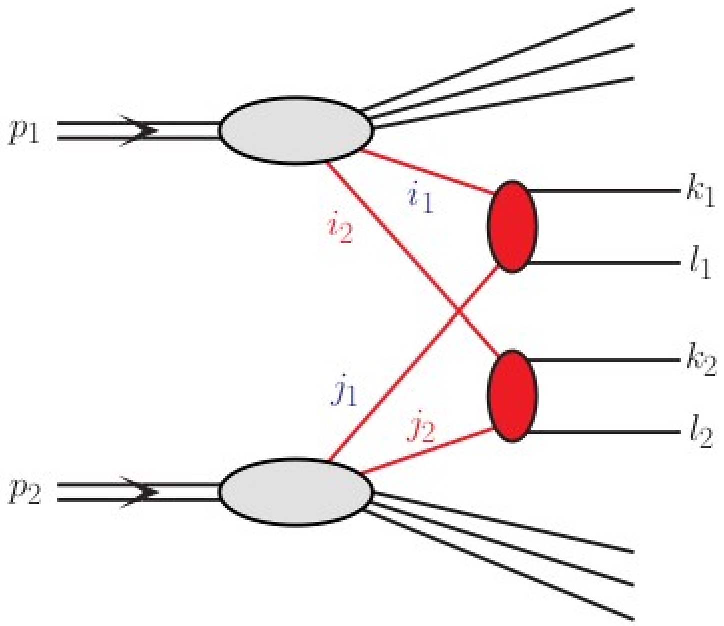
two subprocesses are not correlated and do not interfere

$$i, j, k, l = g, u, d, s, c, \bar{u}, \bar{d}, \bar{s}, \bar{c}.$$

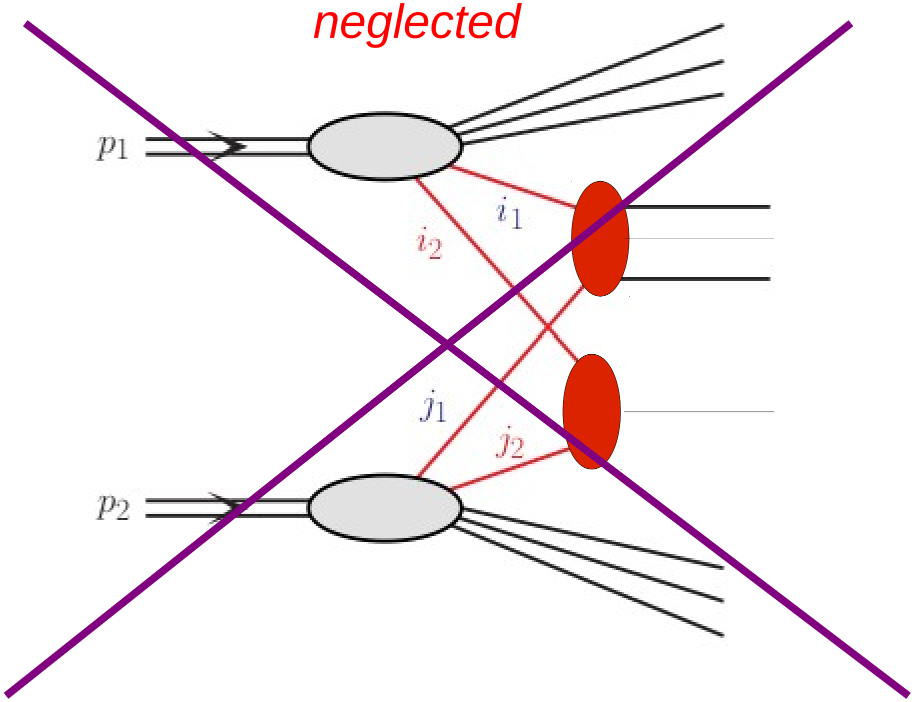
C combinatorial factor

Combinations of partons in DPS scattering process

We have to include all the possible 45 channels which can be obtained by coupling in all possible distinct ways the 8 channels for the 2 → 2 SPS process, i.e.



neglected



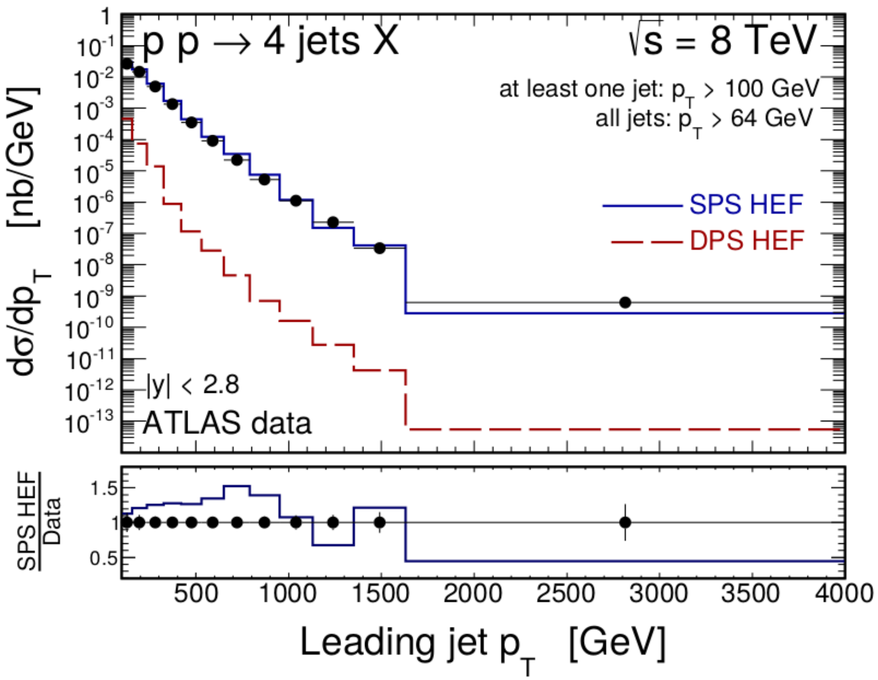
Combinations of partons in DPS scattering process

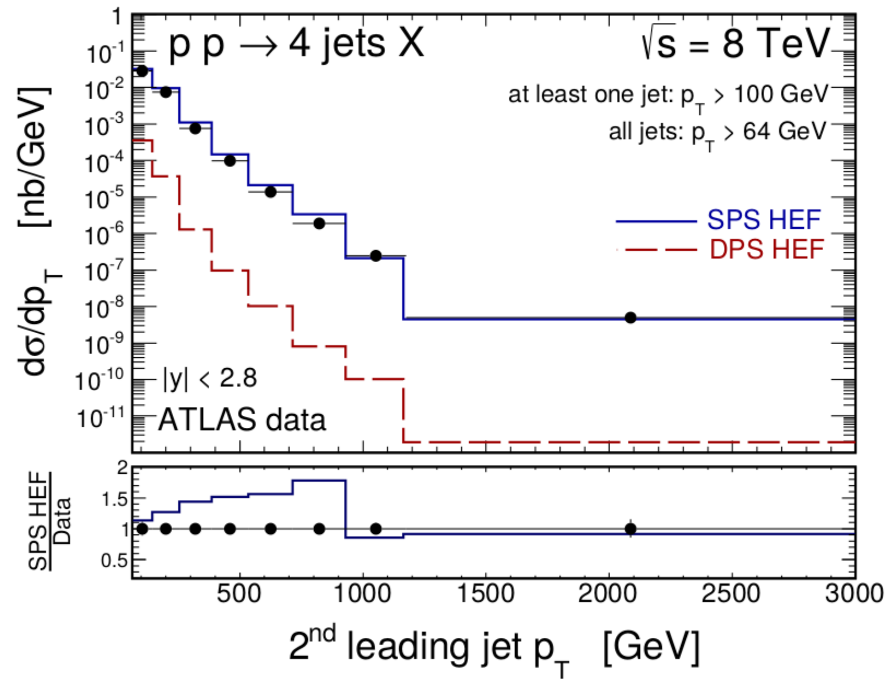
We have to include all the possible 45 channels which can be obtained by coupling in all possible distinct ways the 8 channels for the 2 → 2 SPS process, i.e.

$$
\begin{aligned}
\#1 &= gg \to gg\,, & \#5 = q\bar{q} \to q'\bar{q}' \,,\\
\#2 &= gg \to q\bar{q}\,, & \#6 = q\bar{q} \to gg \,,\\
\#3 &= qg \to qg\,, & \#7 = qq \to qq \,,\\
\#4 &= q\bar{q} \to q\bar{q}\,, & \#8 = qq' \to qq' \,.
\end{aligned}
$$

We find that the pairs (1, 1) , (1, 2) , (1, 3) , (1, 7) , (1, 8) , (3, 3) (3, 7) , (3, 8) account for more than 95 % of the total cross section for all the sets of cuts considered in this paper.

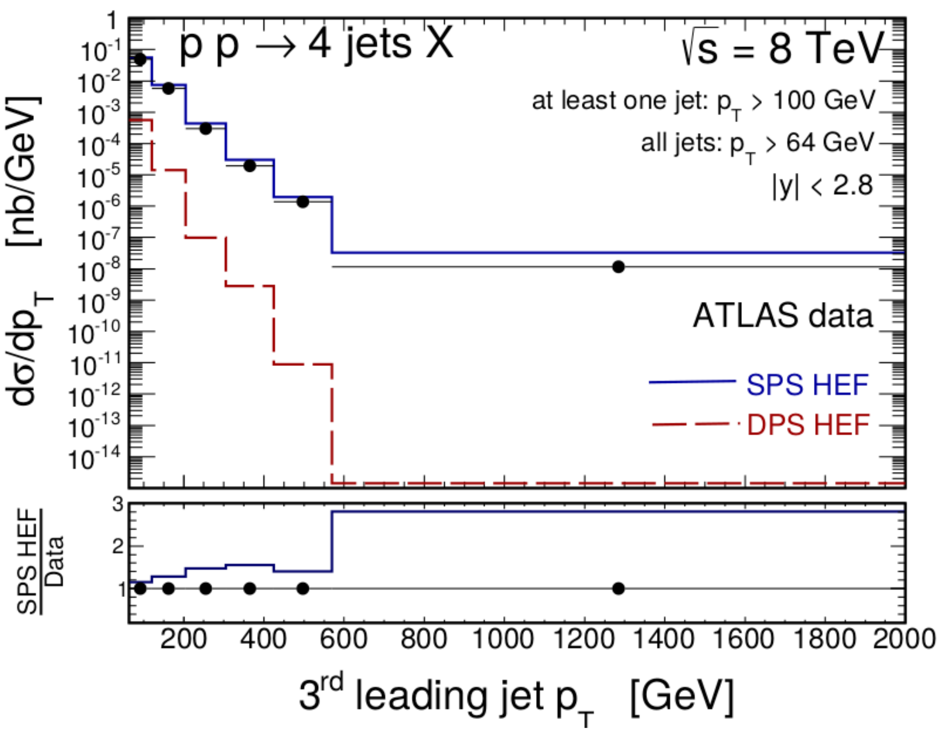
p_t spectra of jets

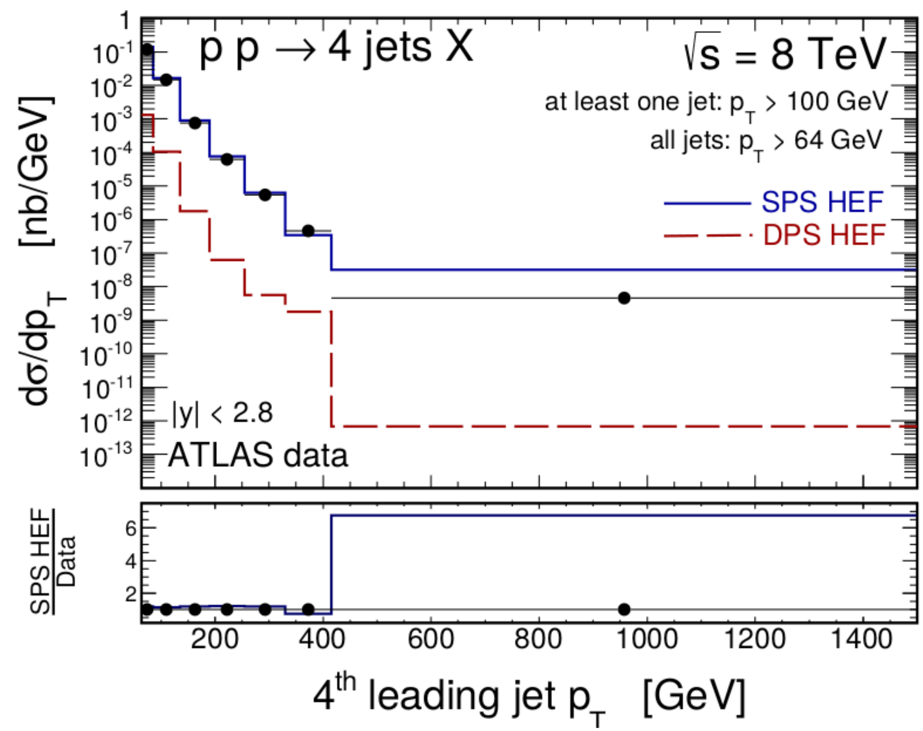




HEF prediction of the differential cross sections for the transverse momenta of the first two leading jets compared to the ATLAS data. In addition we show the ratio of the SPS HEF result to the ATLAS data.

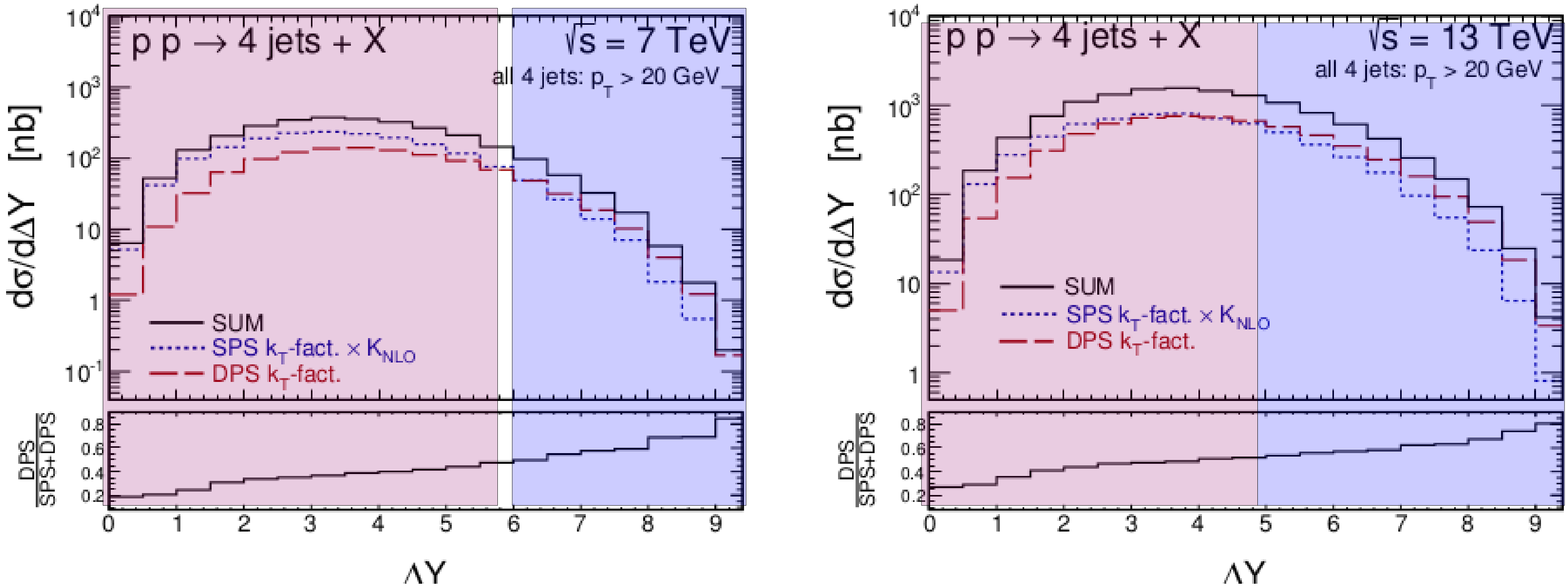
p_t spectra of jets





HEF prediction of the differential cross sections for the transverse momenta of the first two leading jets compared to the ATLAS data. In addition we show the ratio of the SPS HEF result to the ATLAS data.

CMS four-jets: SPS + DPS in the k T -factorization

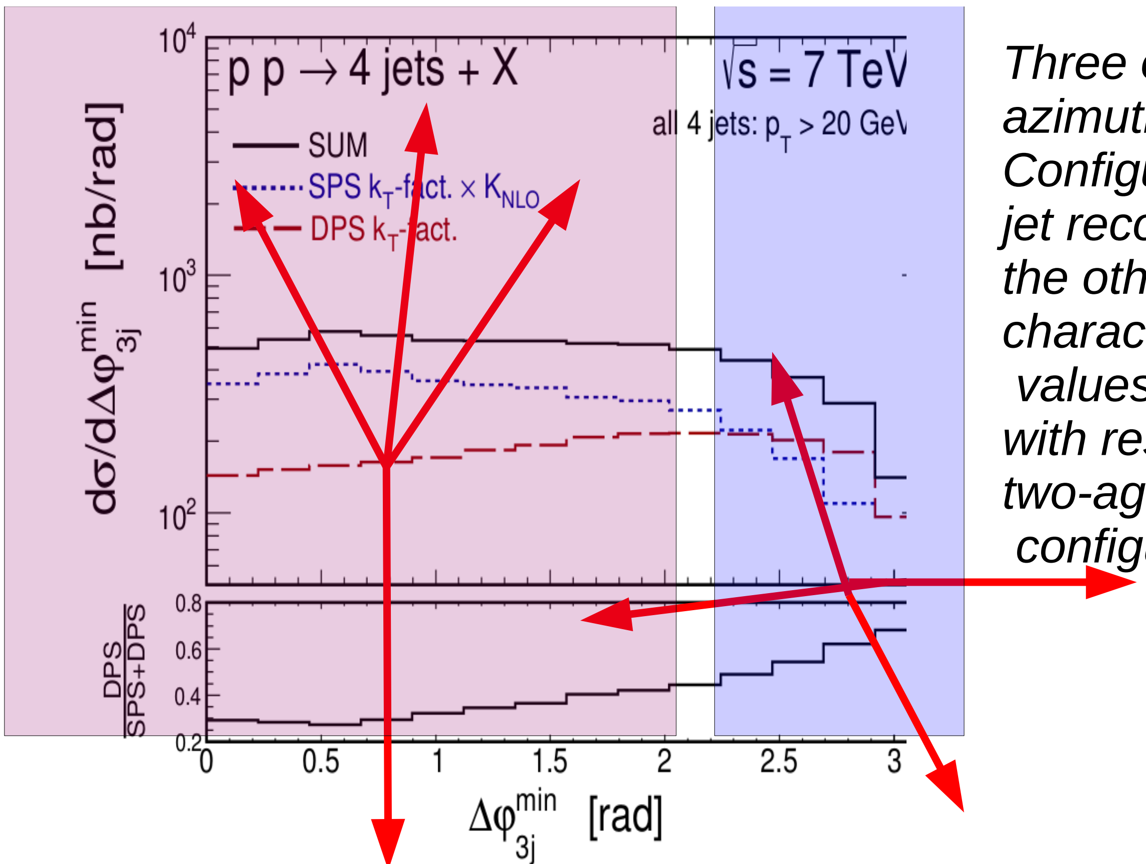


At 13 TeV and Δ Y > 6 four-jet sample dominated by DPS

DPS effects in four-jet sample: special angular correlation

$$\Delta\varphi_{3j}^{min} \equiv min_{\substack{i,j,k\in\{1,2,3,4\} \\ i\neq j\neq k}} \left(|\varphi_i - \varphi_j| + |\varphi_j - \varphi_k|\right)$$

variable proposed by ATLAS analysis: JHEP 12, 105 (2015)

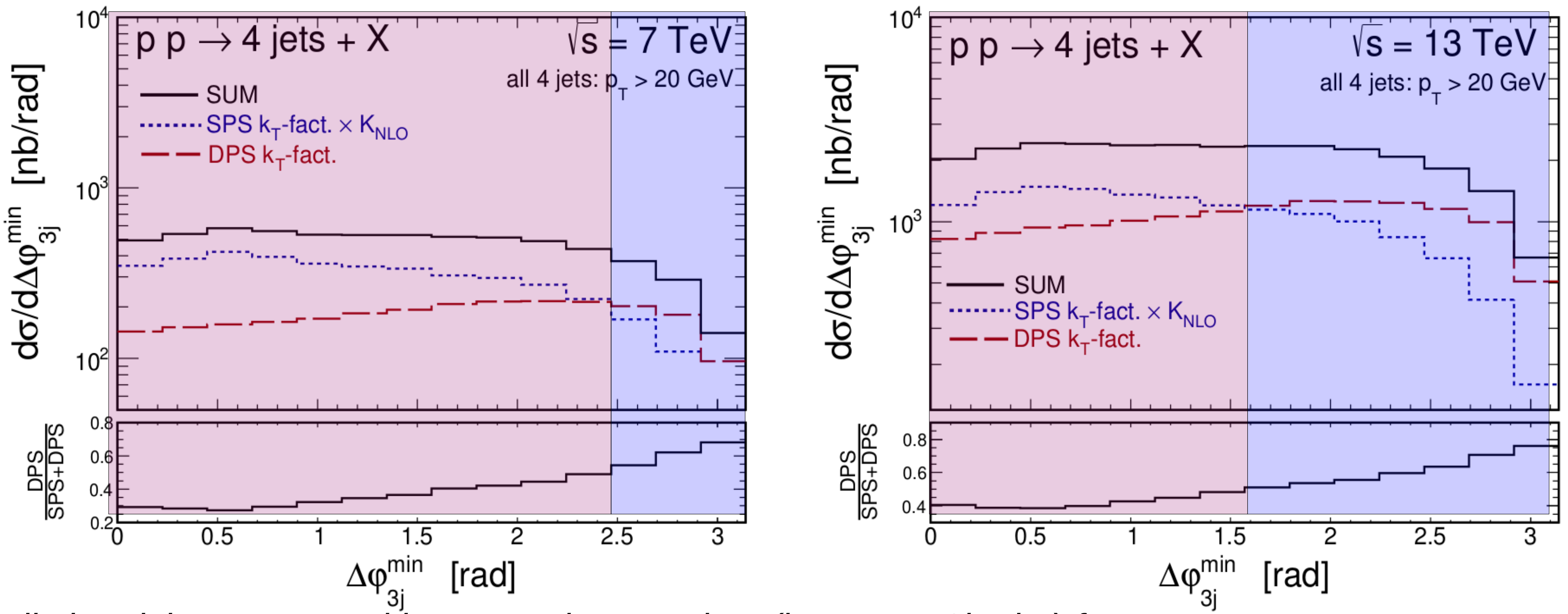


Three out of four azimuthal angles enter. Configurations with one jet recoiling against the other three are characterized by lower values of the variable with respect to the two-against-two configurations.

Monte Carlo Generators used in ATLAS paper describe data well when the cuts are high enough

A minimum, is obtained in the first case for the three i, j, k jets in the same half hemisphere, whereas it is not possible for the second configuration. The first one is allowed only by SPS in a collinear framework, whereas the second is enhanced by DPS. In k t -factorization approach this situation is smeared out by the presence of transverse momenta of the initial state partons.

DPS effects in four-jet sample: special angular correlation

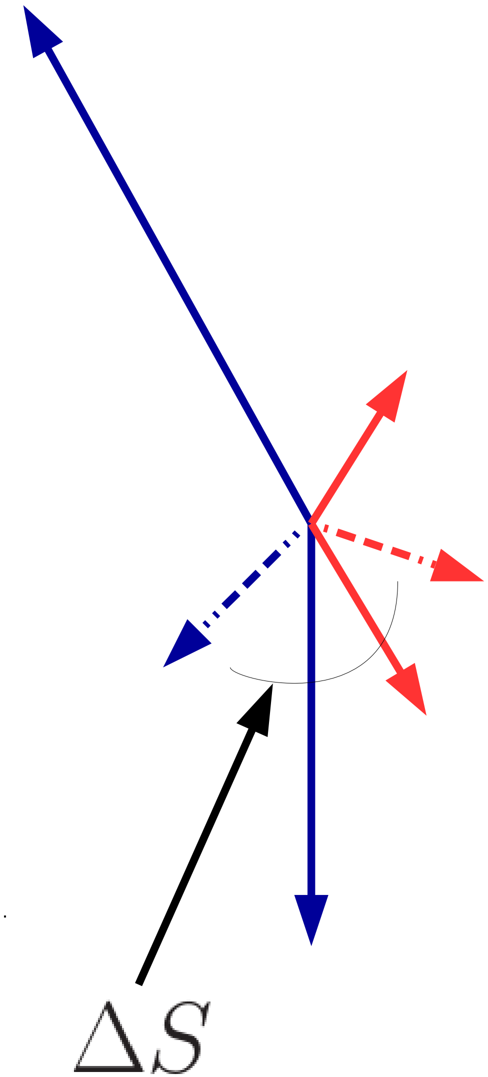


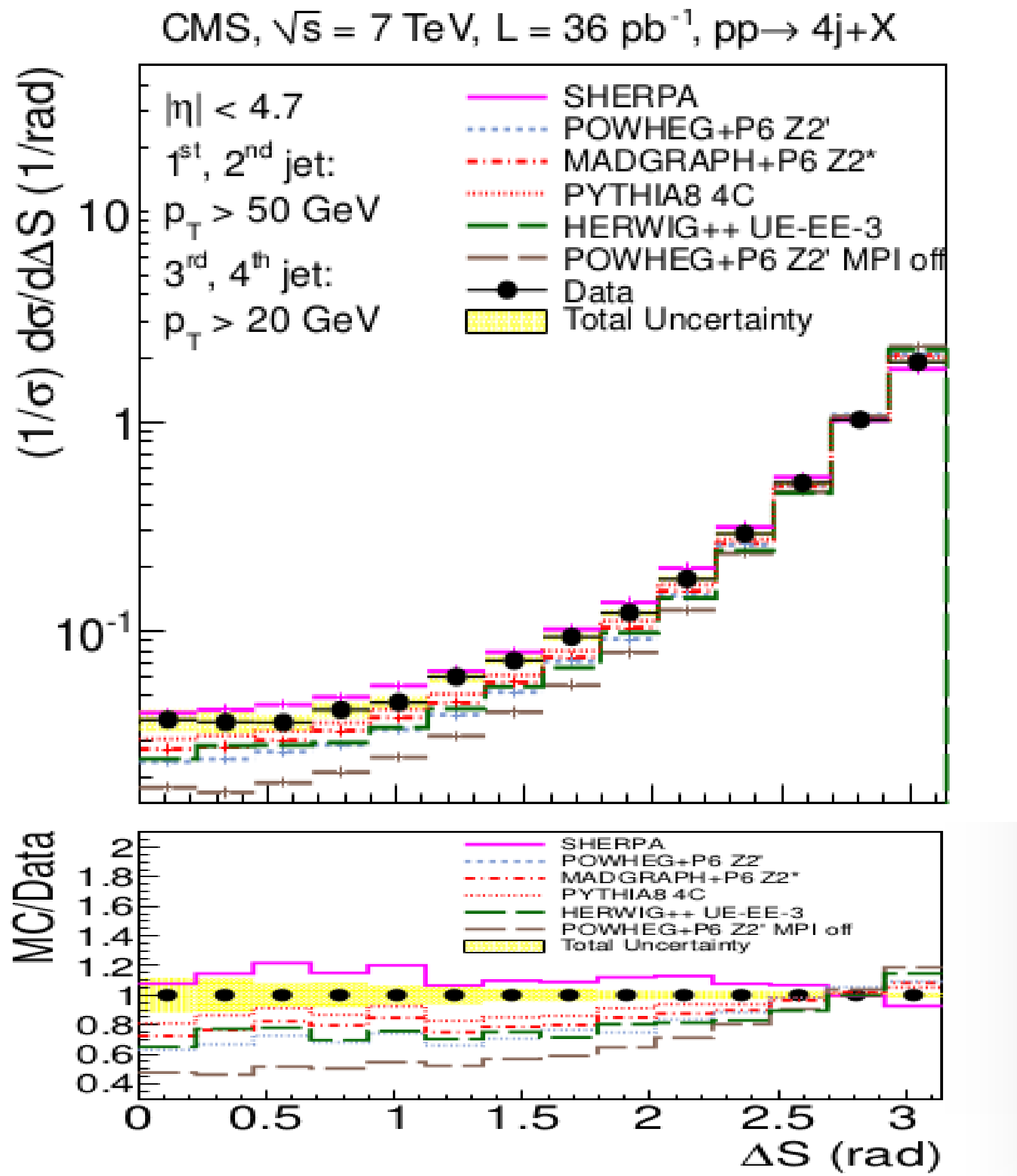
distinguishes events with two-against-two jets (large Δ φ 3j min) from the recoil of three jets against one jet (small Δ φ 3j min)

At 13 TeV cross section dominated by DPS

$$\Delta\varphi_{3j}^{min} > \frac{\pi}{2}$$

DPS smoking gun





DPS smoking gun

MADGRAPH ME 2 → 4

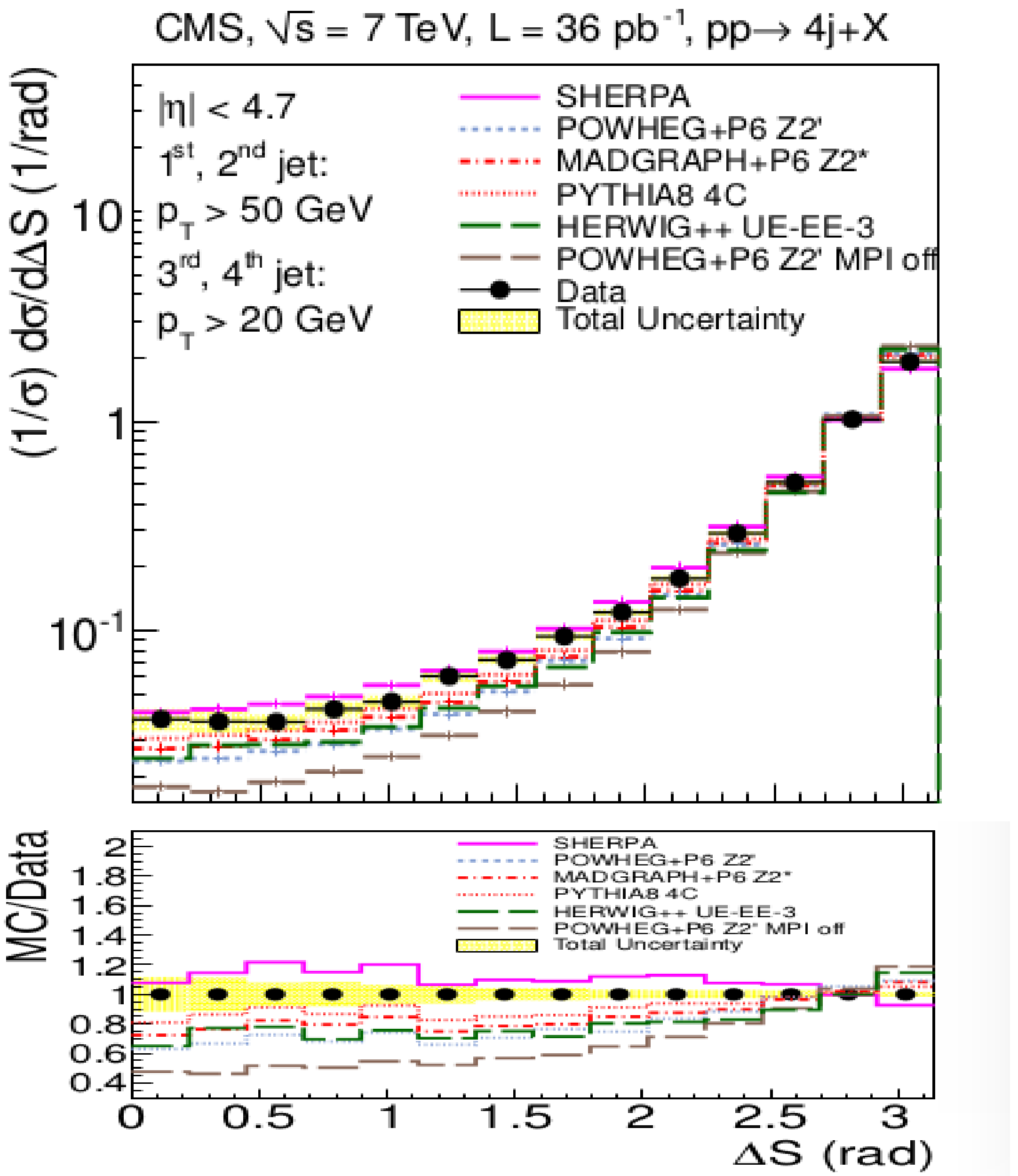
In all other at least one jet from Parton Shower

PYTHIA, HERWIG ME 2 → 2

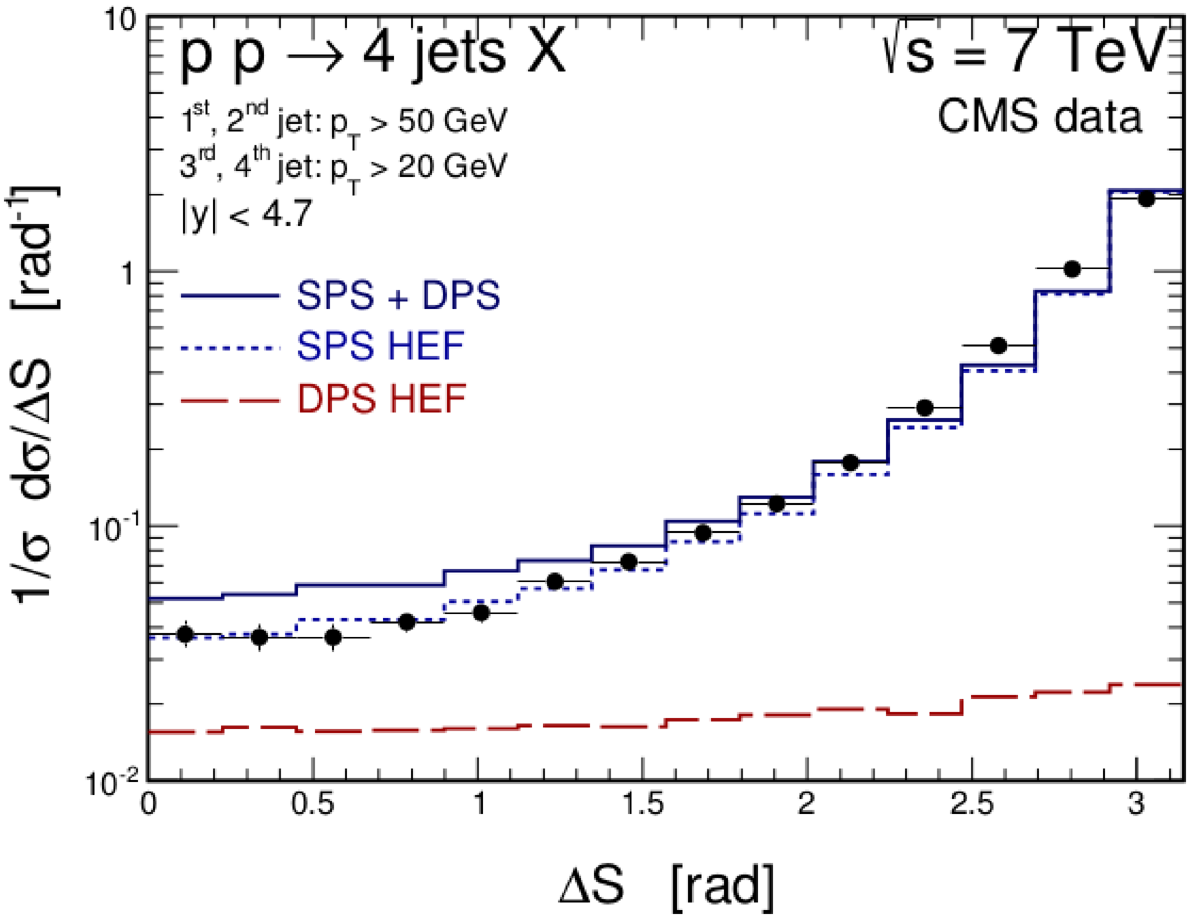
SHERPA ME 2 → 3

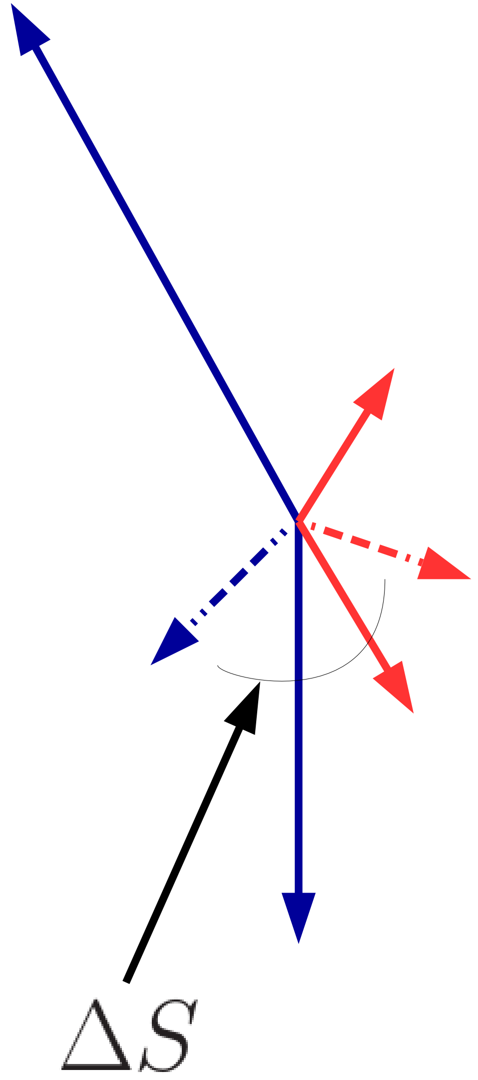
POWHEG ME 2 → 3, ME 2 → 2

Indication for the need of DPS in collinear factorization approach In order to describe this observable



DPS smoking gun?





- *Azimuthal angle between the sum of the two hardest jets and sum of the two softest jets.*

- *This variable has no distribution at LO in collinear factorization: pairs would have to be back-to-back*

Conclusions and outlook

Smaller DPS effects than in D0 production

It is possible to enhance DPS e.g. larger energy larger rapidity separation or study of suitable defined variables

4 jets in p + A → probably more room for DPS

Try A+A → one needs to combine HEF with some framework for modeling medium

NLO, FSR

Update the pdfs