Supported by Narodowe Centrum Nauki (NCN)
with Sonata BIS grant

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4-jet production: DPS and SPS contributions

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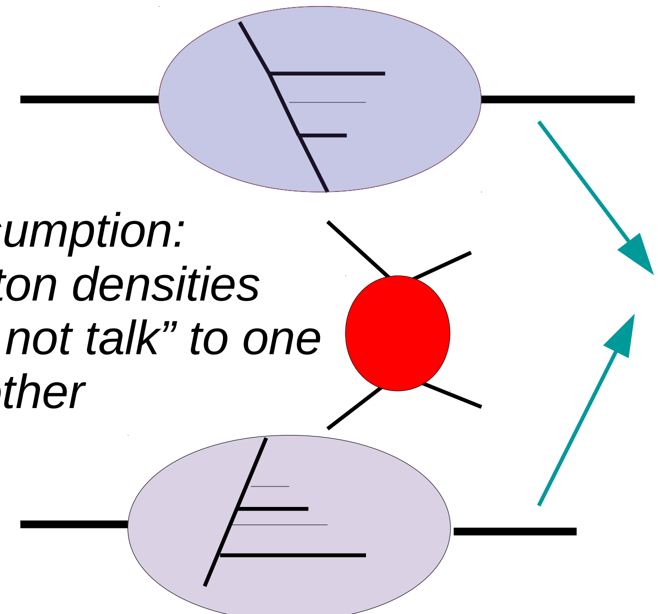
Based on:
K. Kutak, R. Maciuła, M. Serino, A.Szczurek, A. van Hameren
JHEP 1604 (2016) 175

High Energy Factorization

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{c,d} \int \frac{d^2k_{1t}}{\pi} \frac{d^2k_{2t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{g^*g^*\to cd}|}^2 \mathcal{F}_A(x_1, k_{1t}^2)\, \mathcal{F}_B(x_2, k_{2t}^2) \frac{1}{1+\delta_{cd}}$$



Decreasing longitudianal momentum fractions of off-shell partons BFKL like

Originally written for total coss section

Assumption: parton densities “do not talk” to one another

Gluons dominate in the t channel
Obtained for heavy quarks in final state.

Decreasing longitudianal momentum fractions of off-shell partons BFKL like

Advantage of HEF/CGC:
saturation physics can be addressed i.e. one can estimate/calculate the deparure from linear evolution.
Not he case in collinear physics.

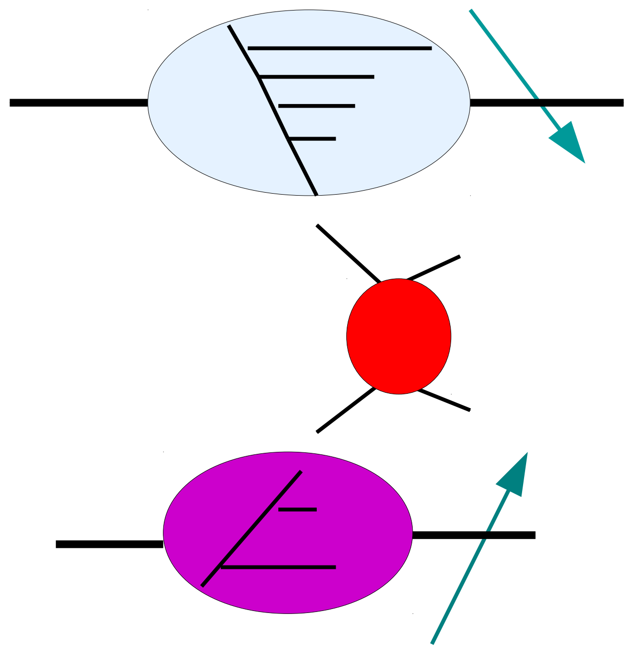
Gribov, Levin, Ryskin '81
Ciafaloni, Catani, Hautman '93

Does not take into account MPI as formulated in DGLAP i.e. emissions from independent chains

Helicity based method for any tree level process
KK, Kotko, van Hameren '13

hybrid High Energy Factorization

There is certain class of processes (forward processes) where one can assume that partons in one of hadrons are just collinear with hadron and in other are not



Strongly decreasing transversal momentum of DGLAP like partons

Strongly decreasing longitudinal momentum fractions of off-shell BK like partons

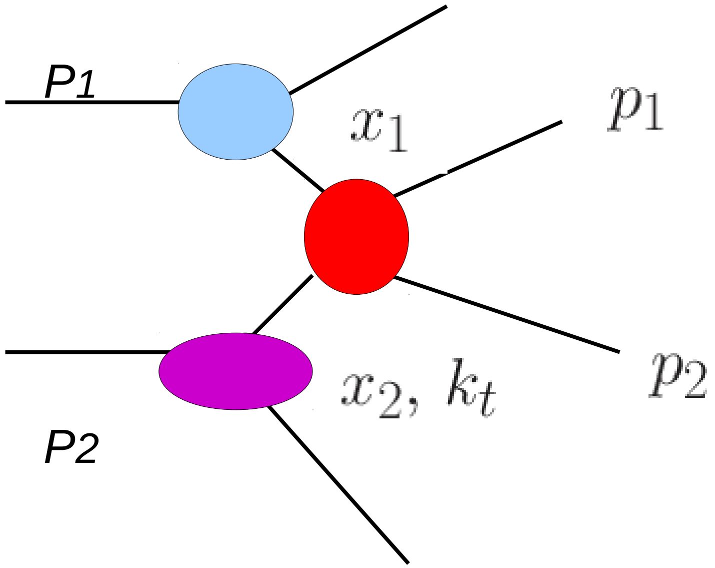
Hybrid factorization and dijets

$$\frac{d\sigma_{\rm SPS}^{P_1P_2\to {\rm dijets}+X}}{dy_1dy_2dp_{1t}dp_{2t}d\Delta\phi} = \frac{p_{1t}p_{2t}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/P_1}(x_1,\mu^2)\,|\overline{\mathcal{M}_{ag^*\to cd}}|^2\;\; \mathcal{F}_{g/P_2}(x_2,k_t^2)\frac{1}{1+\delta_{cd}}$$

Deak, Jung, KK, Hautmann '09

Generalised to account CGC effects (neglects kt in ME)
Dominguez, Juan, Marquet, Xiao '11

Generalised to account CGC and kt in ME
Kotko, KK, Marquet, Petreska, Sapeta, van Hameren '15



resummation of logs of x

logs of hard scale

knowing well parton densities at large x one can get information about low x physics

PDFS we use at present

KS nonlinear → gluon density from extension of momentum space version of BK equation to include:

- *kinematical constraint,*
- *complete splitting function,*
- *running coupling*
- *quarks*

KK, Kwiecinski '03 fitted to '10 HERA data KK, Sapeta '12,nonlinear extension of unified BFKL DGLAP Kwiecinski, Martin, Staśto framework '97.

KS linear → linearized version of the above

KS hardscale → KS+ Sudakov effects

Double Logs Coherence 2016 → unintegrated partons (quarks and gluons) obtained by resumation of soft gluons following Kimber, Martin, Ryskin prescription

Numerical tools for HEF

AVHLIB

http://bitbucket.org/hameren/avhlib (A. van Hameren)

·*complete Monte Carlo program for tree-level 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*

AMP4HEF

http://bitbucket.org/hameren/amp4hef (A.van Hameren, M.Bury, K.Bilko, H.Milczarek)

·only provides tree-level matrix elements (or color-ordered helicity amplitudes)
·employs BCFW recursion to calculate color-ordered helicity amplitudes
·available processes (plus those with fewer on-shell gluons):

$$\emptyset \to g\,g + 4g \qquad \emptyset \to \bar{q}\,q + 3g \qquad \emptyset \to \bar{q}^*\,q + 3g$$
$$\emptyset \to g^*\,g + 4g \qquad \emptyset \to g^* + \bar{q}\,q + 2g \qquad \emptyset \to \bar{q}\,q^* + 3g$$
$$\emptyset \to g^*\,g^* + 4g$$

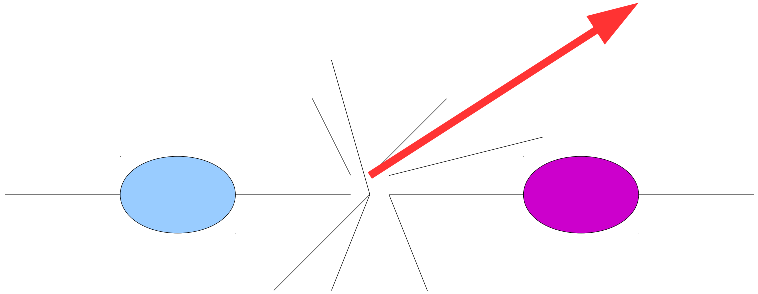
Easy to use in Fortran and C++

LxJet

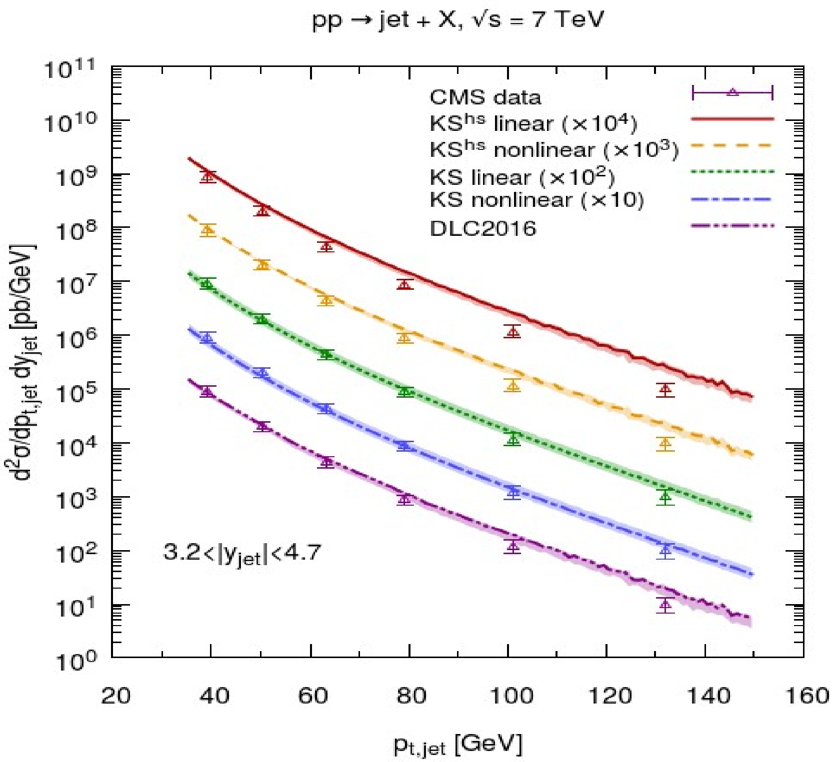
http://annapurna.ifj.edu.pl/~pkotko/LxJet.html (P. Kotko)

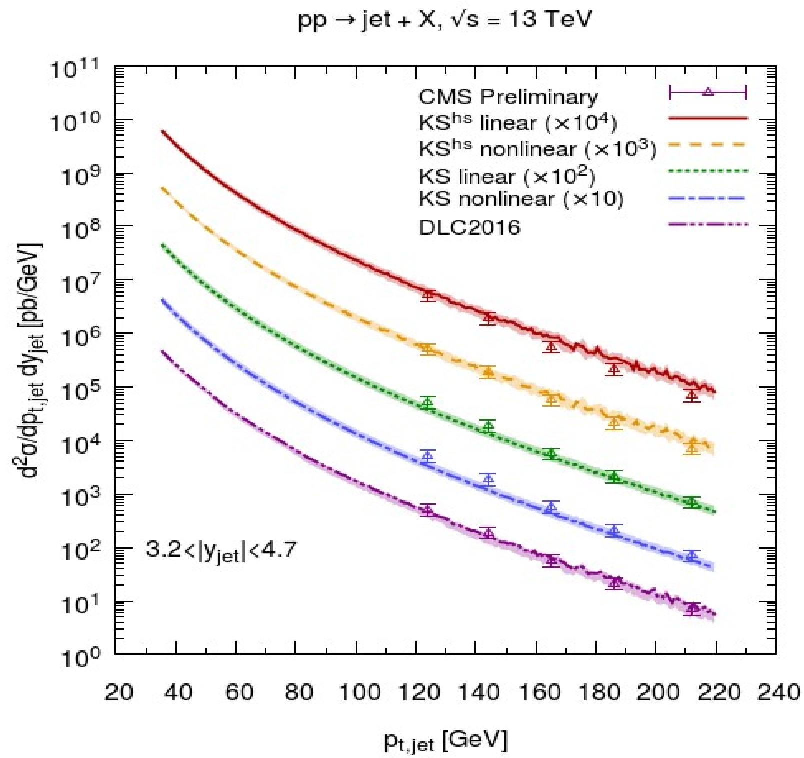
•*hybrid high energy factorization suitable for forward jets,*
•*implemented helicity tree-level amplitudes for all channels for dijets and three jets*
•*recursive relation for color ordered tree-level amplitudes with single off-shell leg for arbitrary number of gluons*
•*currently the native phase space generator is up to three final state partons*

Inclusive-forward jet



Test of pdfs: forward single inclusive jet spectra





$|3.2| < y <|4.7|$

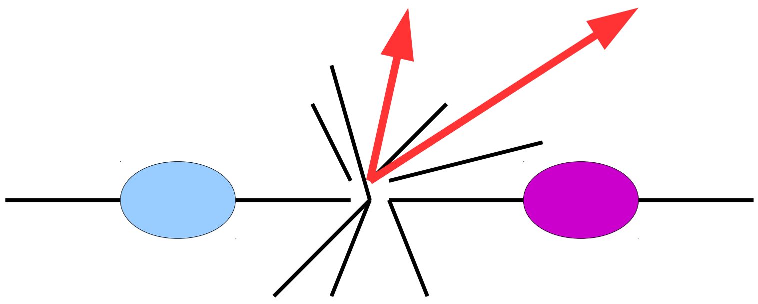
Shape comparison 7 TeV
Ducloue, Wallon, Szymanowski '15

Bury, Deak , K.K, Sapeta '16

$$\frac{d\sigma}{dy\, dp_t} = \frac{\pi\, p_t}{2(x_1 x_2 s)^2} \sum_{a,b,c} \overline{|\mathcal{M}_{ab^*\to c}|}^2 x_1 f_{a/A}(x_1,\mu^2)\mathcal{F}_{b/B}(x_2,p_t^2,\mu^2)$$

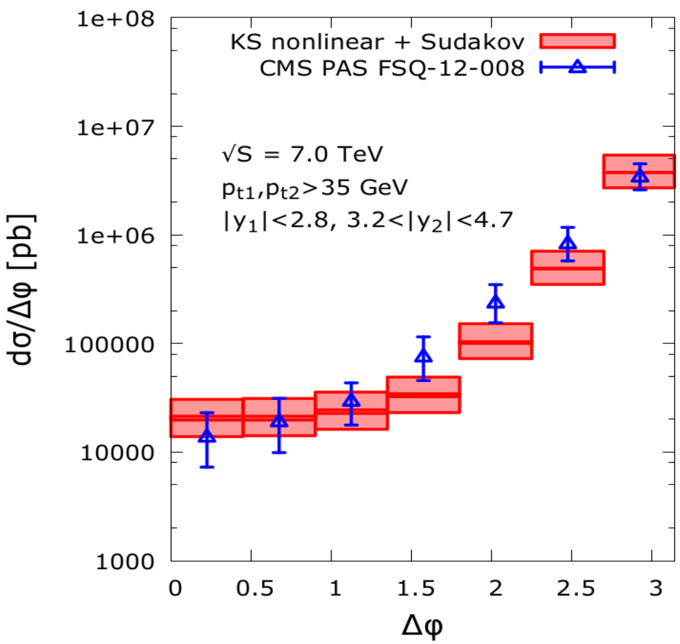
LO formula by Dumitru, Jalilian-Marian, Hayashigaki '05

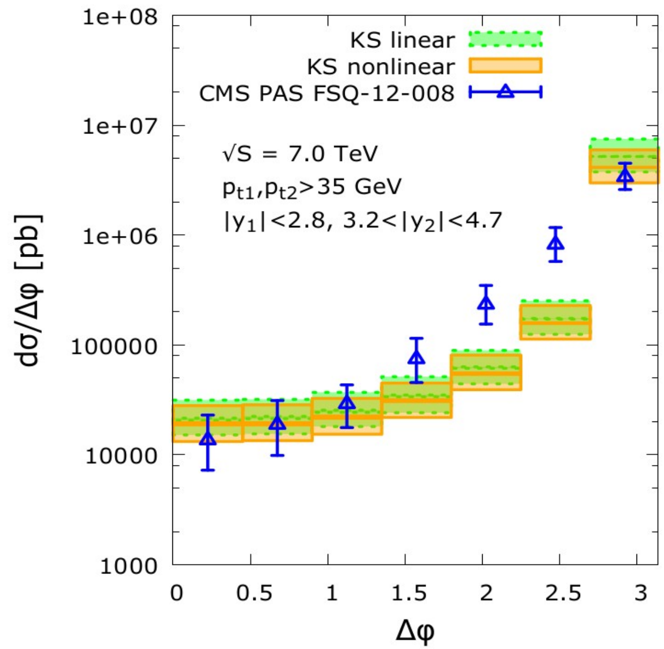
Central-forward di-jets



Decorelations inclusive scenario forward-central

Kotko, K.K, Sapeta, van Hameren '14



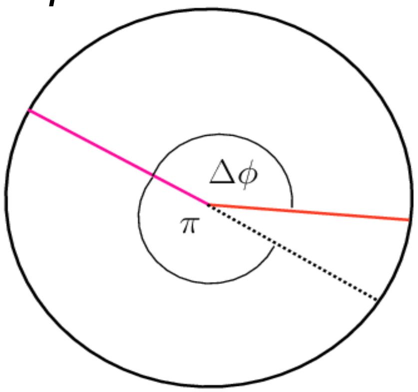


$$p_{t1},\, p_{t2} > 35\, GeV$$

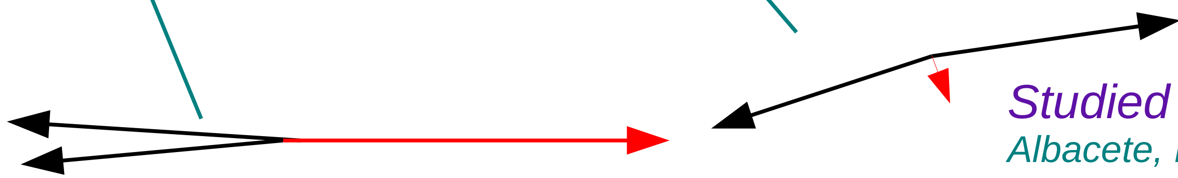
$$3.2 < |y_2| < 4.7$$

$$|y_1| < 2.8$$

Leading jets, no further requirement



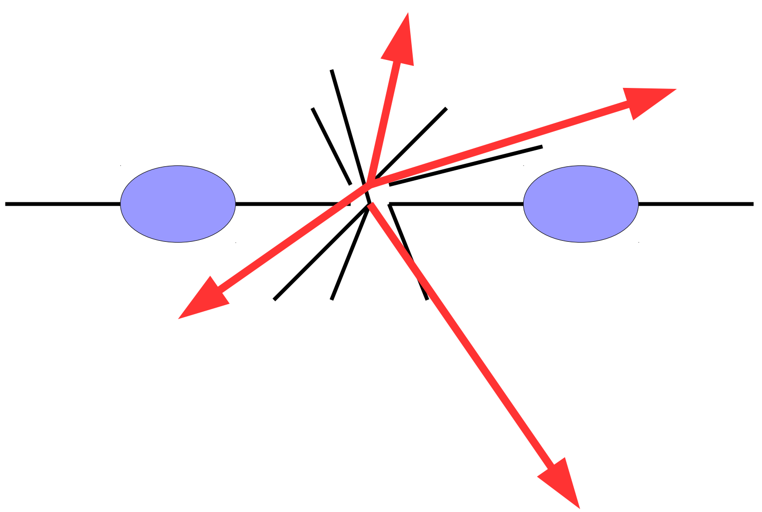
In DGLAP approach i.e 2 →2 + pdf one would get delta function



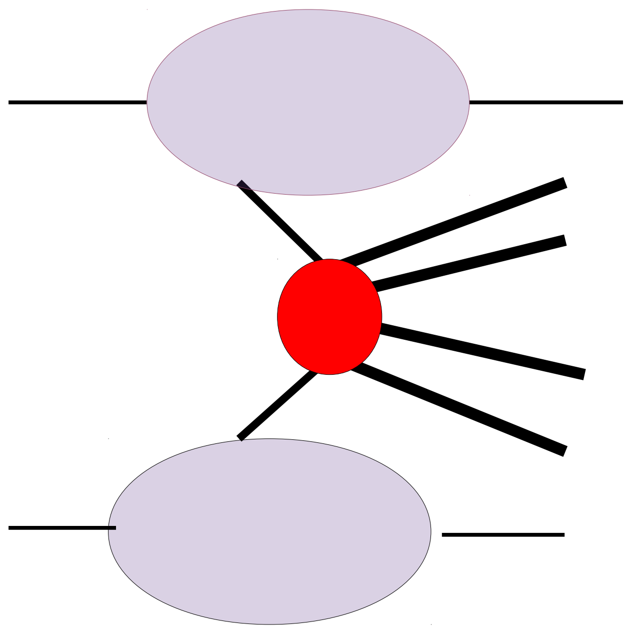
Observable suggested to study BFKL effects
Sabio-Vera, Schwensen '06

Studied also context of RHIC
Albacete, Marquet '10

Central-central 4 jets



SPS contribution to 4 jets in HEF



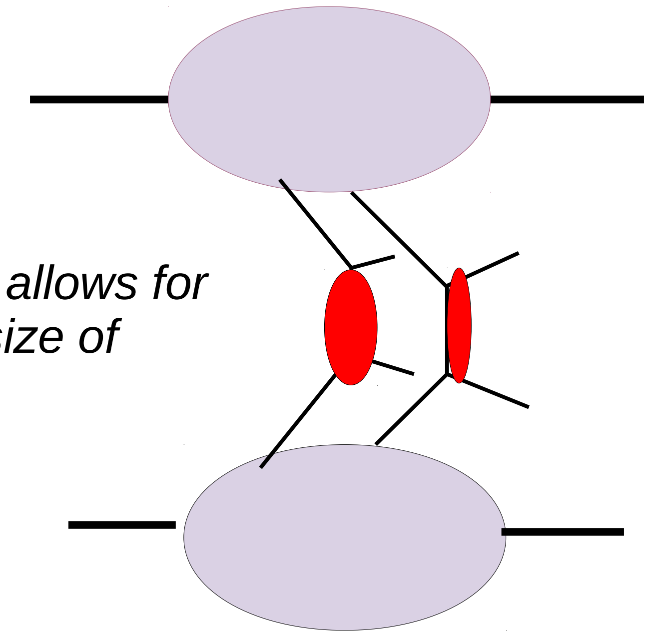
- *20 channels*
- *No K factors*

Conjecture formula

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

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

DPS contribution to 4 jets in HEF



In principle allows for studies of size of hadrons

- *45 channels*
- *No K factors*

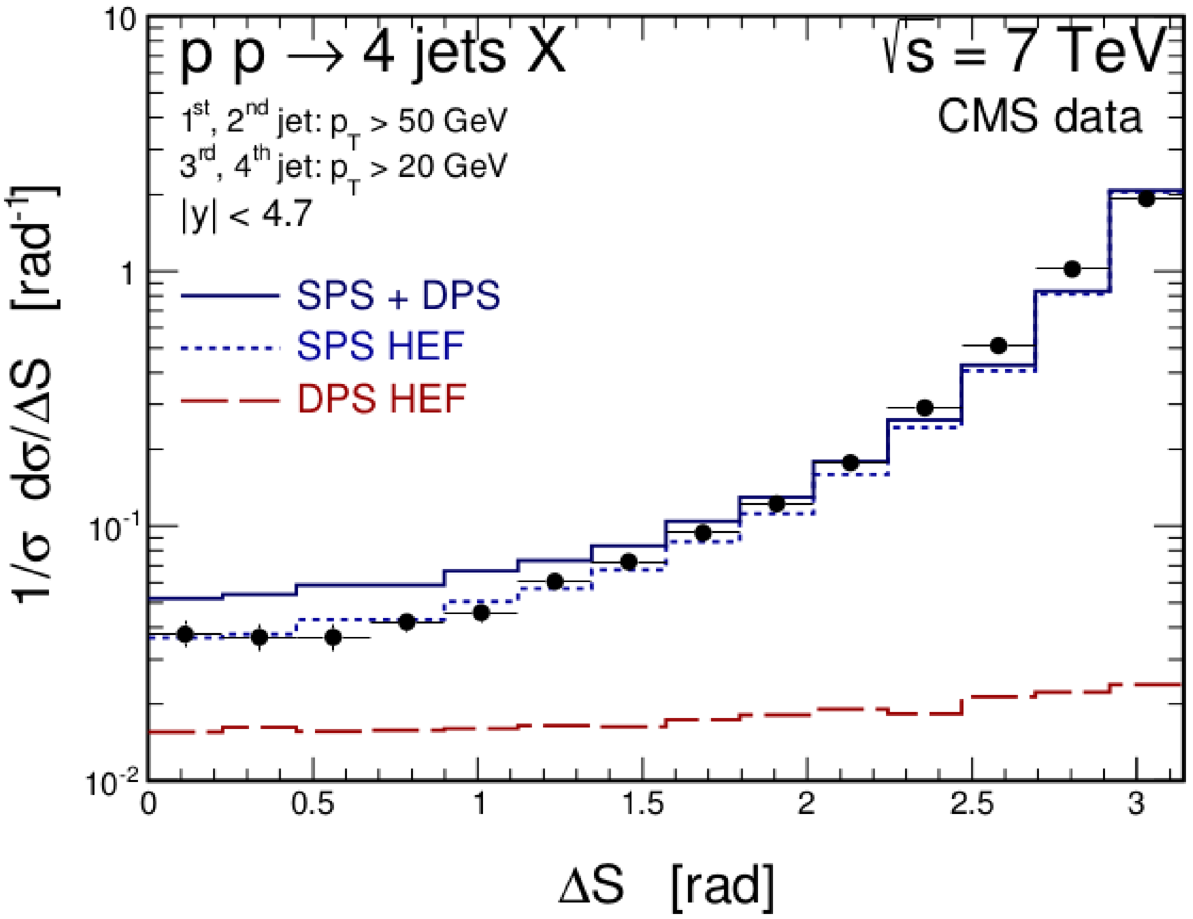
Factorization justified if the p_t are not too low

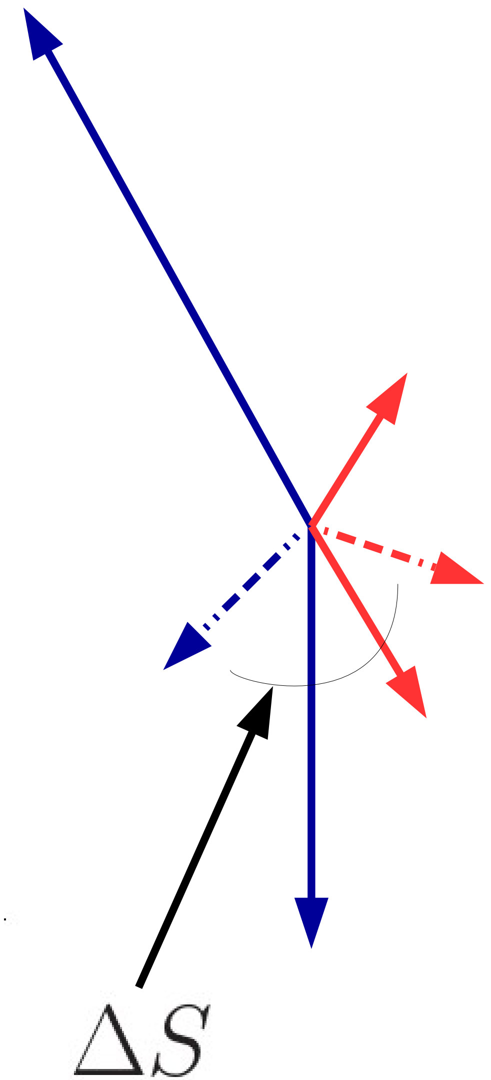
Golec-Biernat, Lewandowska, Stasto, Serino, Snyder '15

$$\sigma = \sum_{i,j,a,b;k,l,c,d} \frac{\mathcal{S}}{\sigma_{eff}} \sigma(i,j \to a,b)\,\sigma(k,l \to c,d)$$

$$\mathcal{S} = \begin{cases} 1/2 & \text{if} \quad i\,j = k\,l \quad \text{and} \quad a\,b = c\,d \\ 1 & \text{if} \quad i\,j \neq k\,l \quad \text{or} \quad a\,b \neq c\,d \end{cases} \qquad \sigma_{eff} = 15\,mb$$

DPS contribution to 4 jets in HEF

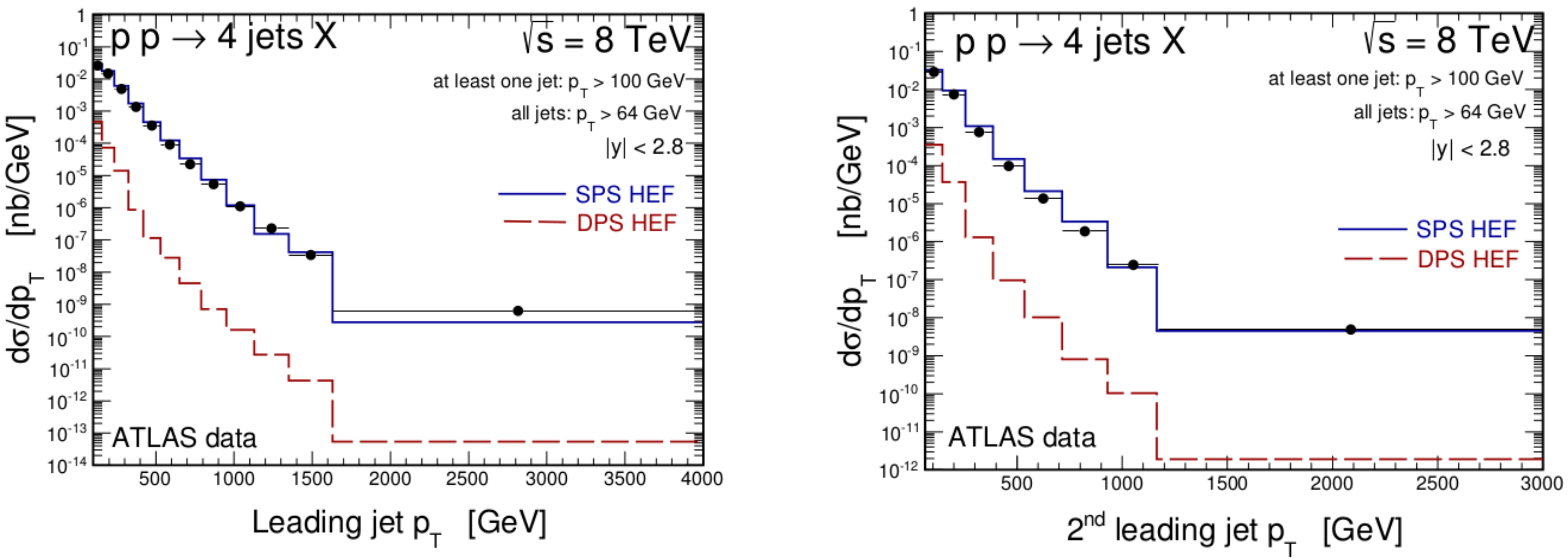




- *Azimuthal angle between the sum of the two hardest jets and sum of the two softest jets.*

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

p_t spectra of jets



- *Good agreement with data*
- *To enhance DPS one needs to go for lower cuts ...*

DPS in collinear and HEF: symmetric cuts

Inspired by Maciula and Szczurek '15
DPS should be relevant for CMS cuts Phys. Rev D89 (2014)

$$p_T(1,2) \geq 50GeV,\ \ p_T(3,4) \geq 20GeV,\ \ |\eta| < 4.7$$

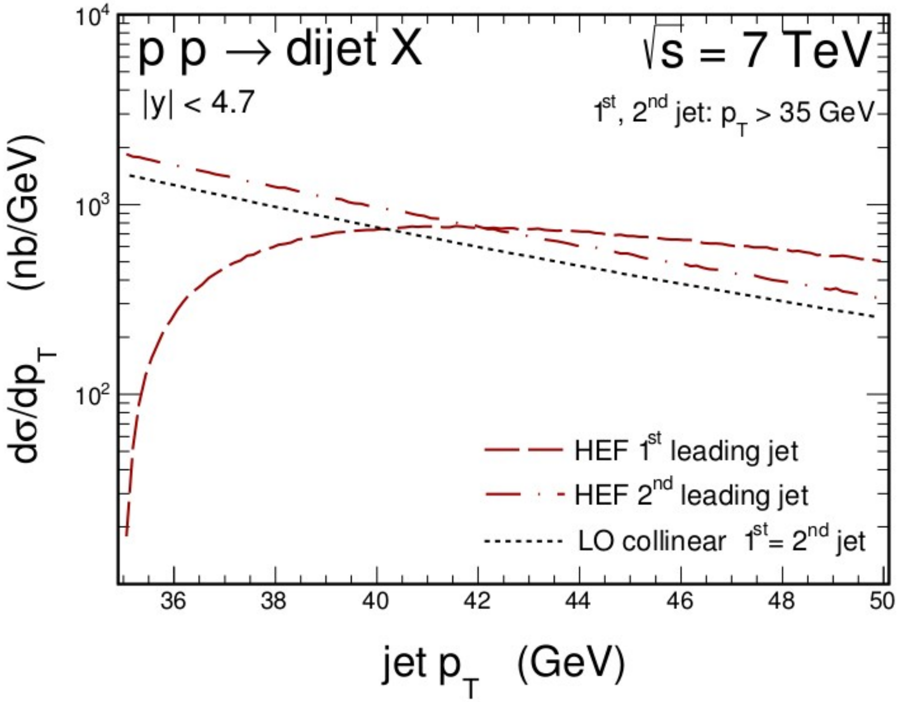
CMS $\quad \sigma_{tot} = 330 \pm 5(stat.) \pm 45(syst)nb$

collinear $\quad \sigma_{SPS} = 697nb,\ \ \sigma_{DPS} = 125nb$

HEF $\quad \sigma_{SPS} = 548nb,\ \ \sigma_{DPS} = 33nb$

In HEF DPS gets suppressed

Instability of NLO correction to 2 – jet production



The transverse momentum distribution of the leading (long dashed line) and subleading (long dashed-dotted line) jet for the dijet production in HEF

NLO corrections to 2 -jet production suffer from instability problem when using symmetric cuts: Frixione, Ridolfi, '97

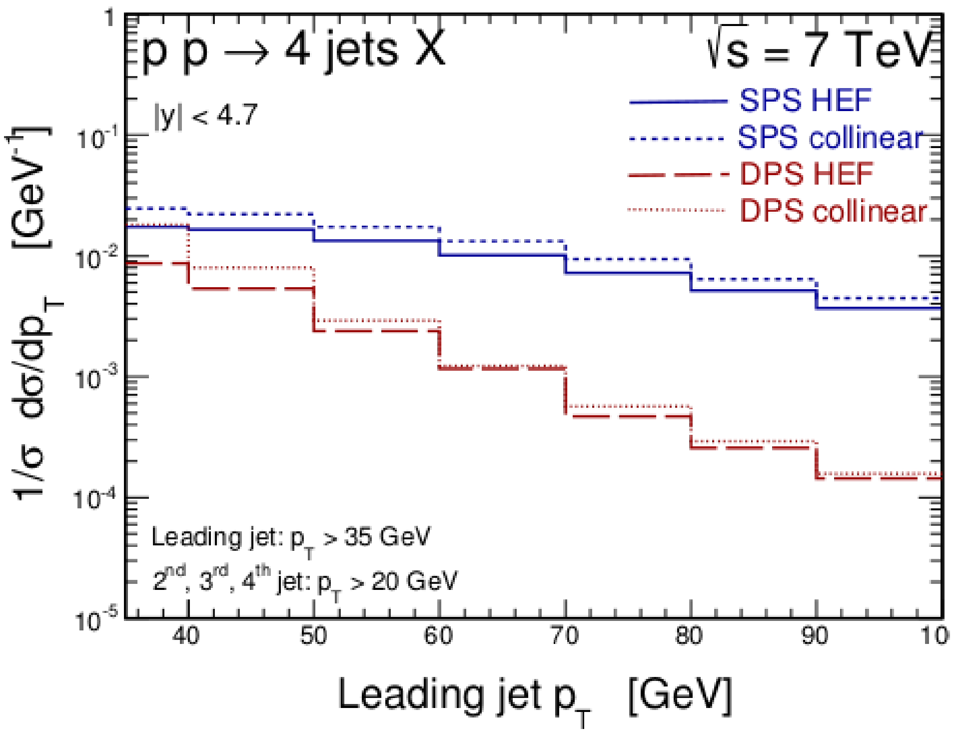
Symmetric cuts rule out from integration final states in which the momentum imbalance due to the initial state transversal momentum gives to one of the jets a lower transverse momentum than the treshold

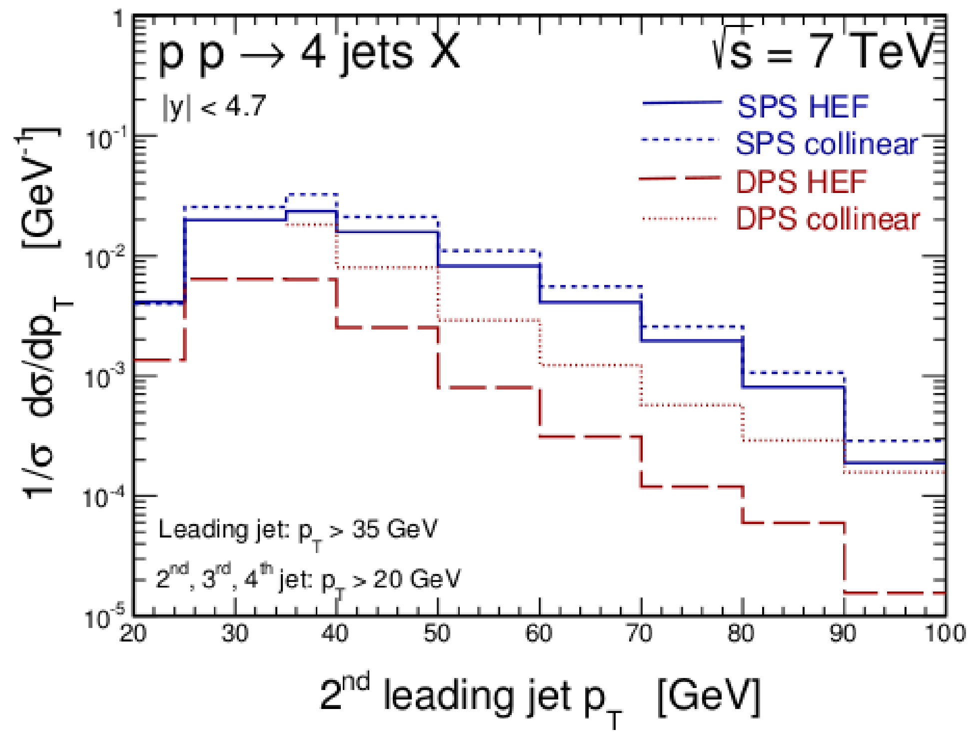
DPS in collinear and HEF: asymmetric cuts

$$p_T(1) \geq 35GeV,\ p_T(2,3,4) \geq 20GeV,\ \ |\eta| < 4.7$$

Collinear $\sigma_{SPS} = 1969\, nb\,, \quad \sigma_{DPS} = 514\, nb\,, \quad \sigma_{tot} = 2309\, nb$

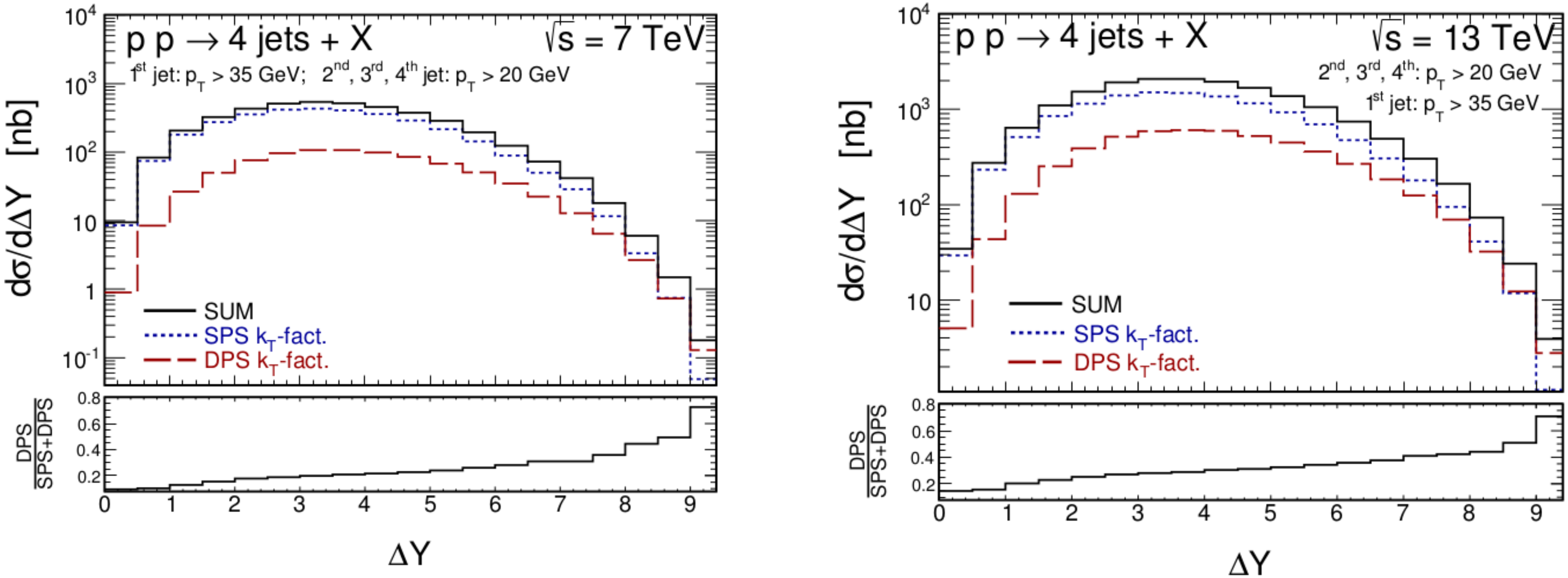
HEF $\sigma_{SPS} = 1506\, nb\,, \quad \sigma_{DPS} = 297\, nb\,, \quad \sigma_{tot} = 1803\, nb$





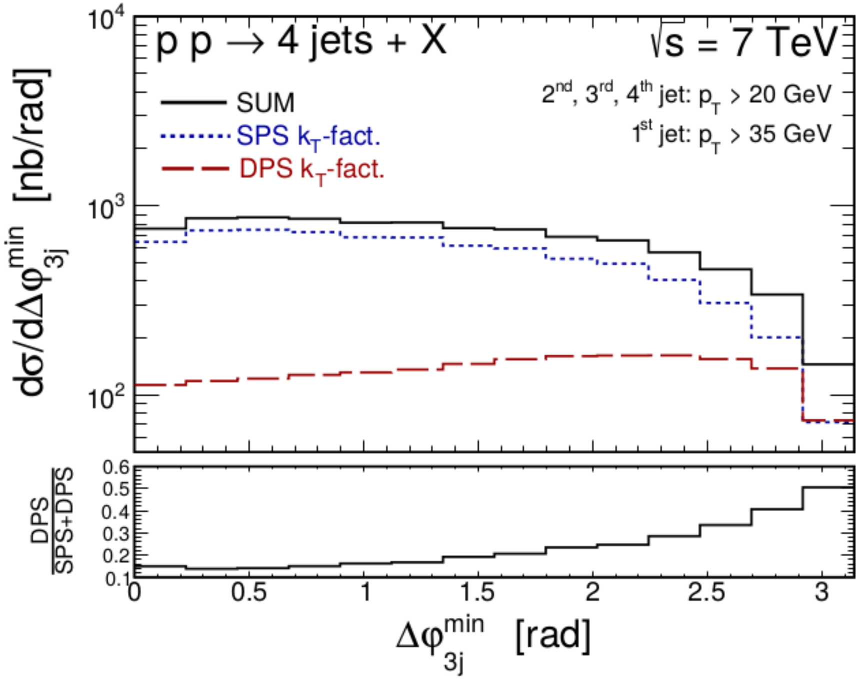
DPS restored in HEF

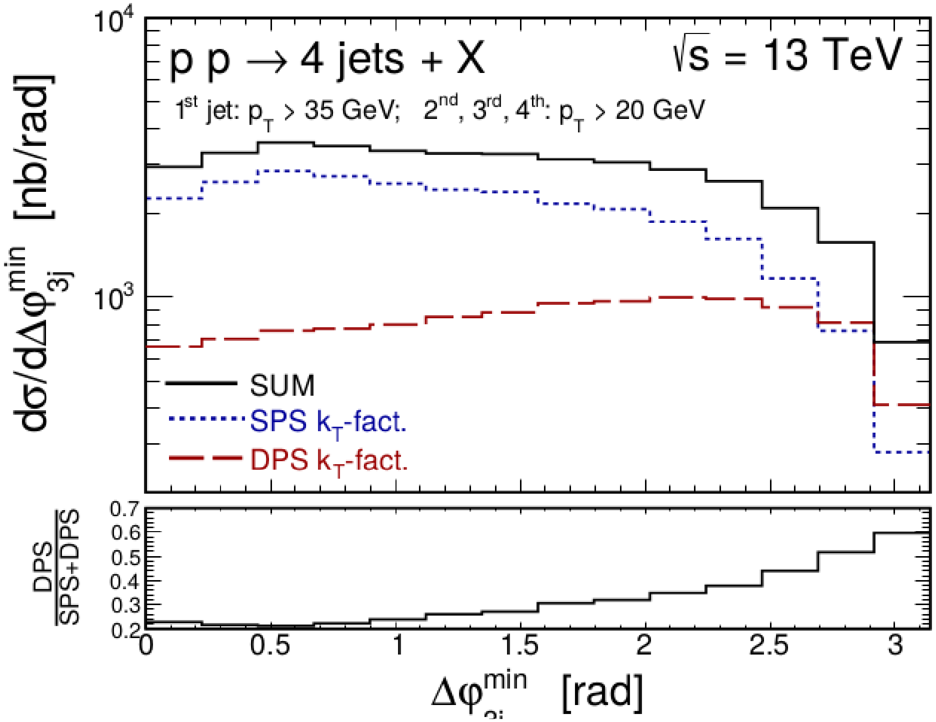
Pinning down DPS: large rapidity separation



- *Define variables which make DPS apparent*
- *The large rapidity separation in the four jet sample is an example such variable, especially at 13 TeV*

Pinning down DPS: "min 3" azimuthal separation





$$\Delta\phi_3^{min} = min_{i,j,k[1,4]}(|\phi_i - \phi_j| + |\phi_j - \phi_k|) \qquad i \neq j \neq k$$

- *Proposed by ATLAS JHEP 12 105 (2015)*
- *High value for back-to-back configurations*

Total cross section dominated for $\Delta\phi_3^{min} \geq \pi/2$

Outlook

4 jets in p + A

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

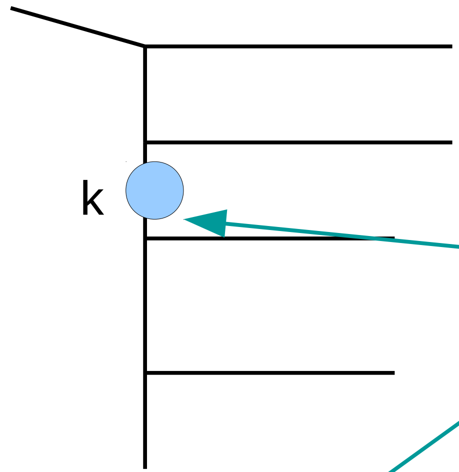
NLO, FSR

Update the pdfs

Back up

Introducing hard scale dependence

The relevance in low x physics
at linear level rcognized by:
Catani, Ciafaloni, Fiorani,Marchesini;
Kimber,Martin,Ryskin;
Collins, Jung



hard scale

Survival probability
of the gap without
emissions

Survival probability of the gap
without emissions

DLC 2016set (KMR like procedure)

$$T_s(\mu^2, k^2) = \exp\left(-\int_{k^2}^{\mu^2} \frac{dk'^2}{k'^2} \frac{\alpha_s(k'^2)}{2\pi} \sum_{a'} \int_0^{1-\Delta} dz' P_{a'a}(z')\right)$$

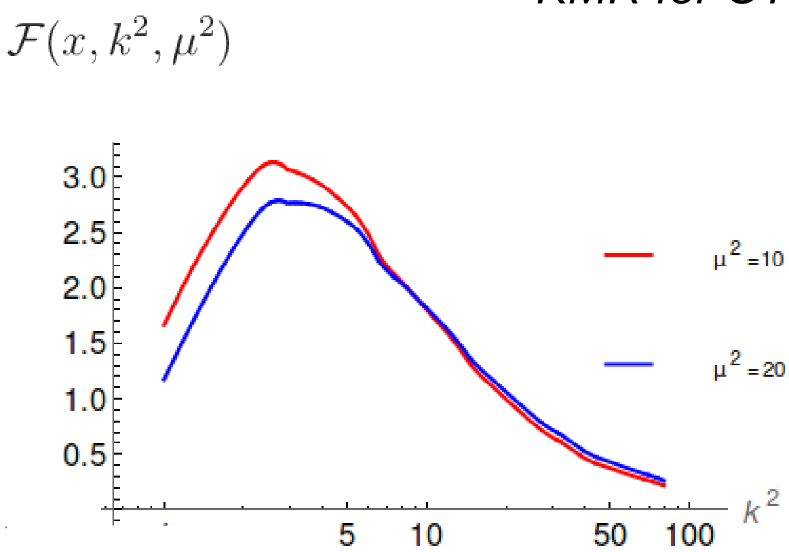
$$\Delta = \frac{\mu}{\mu+k}$$

$$\mathcal{F}(x, k^2, \mu^2) \sim \partial_{\lambda^2}(T(\lambda^2, \mu^2) x g(x, \lambda^2))|_{\lambda^2 = k^2}$$

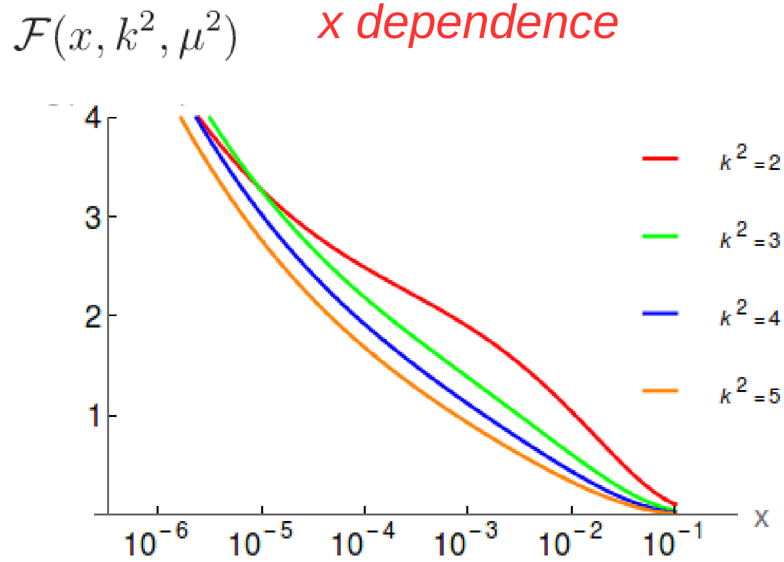
KS^{hs} *(KK2015PRD) → introduce Sudakov effects to BK or BFKL*

Introducing hard scale dependence

KMR for CTEQ 10 NLO



Fundamental difference.
x dependence



KShardscale