Supported by Polish Academy of Science and
Research Foundation Flanders

Single Inclusive jet production at Very Forward Rapidities

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based on 1701.07370
In collaboration with H. Van Haevermaet P. Van Mechelen

Why jets?

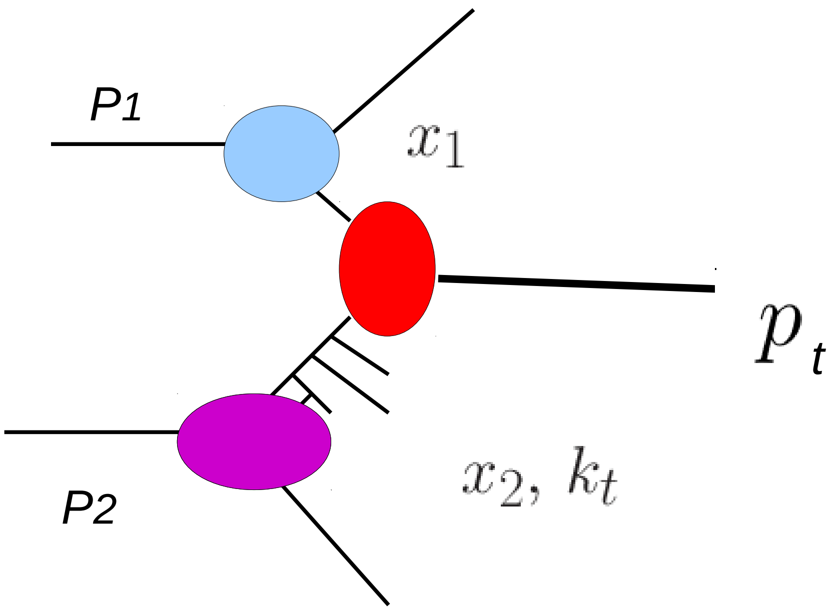
Jets are manifestations of partonic nature of hadrons which is not completely known

Jets can be used to uncover dynamics of QCD in semi perturbative and perturbative region

Forward jets can be used to study so called low x phenomena i.e. saturation of gluon density

Jets can be used to perform tomography of QGP

Inclusive-forward jet



The pt of the final state is given by the kt of initial state off-shell gluon

In collinear factorization the 2 → 1 matrix elements with 3 on-shell partons is zero

At LO
A. Dumitru, A. Hayashigaki and J. Jalilian-Marian, Nucl. Phys. A 765 (2006)

At NLO
Giovanni A. Chirilli, Bo-Wen Xiao, Feng Yuan Phys.Rev.Lett. 108 (2012) 122301

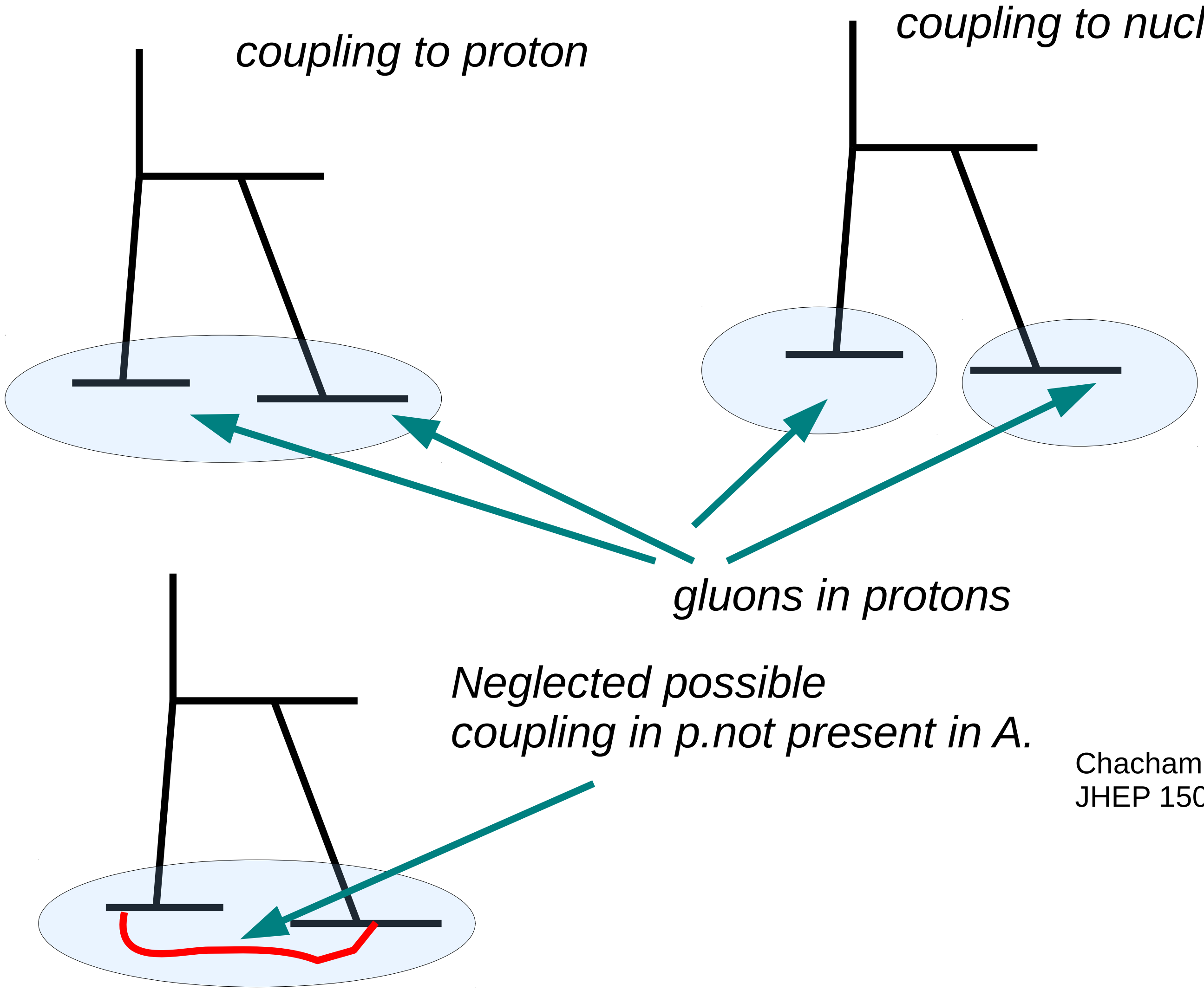
E. Iancu, A.H. Mueller, D.N. Triantafyllopoulos . A JHEP 1612 (2016) 041

$$x_1 = \frac{p_t\, e^{y}}{\sqrt{S}} \qquad x_2 = \frac{p_t\, e^{-y}}{\sqrt{S}}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\,\mathrm{d}p_\mathrm{T}} = \frac{1}{2}\frac{\pi\, p_\mathrm{T}}{(x_1x_2s)^2}\left[\sum_{\mathrm{q}(\bar{\mathrm{q}})}\overline{|\mathcal{M}_{\mathrm{g}^*\mathrm{q}(\bar{\mathrm{q}})\to\mathrm{q}(\bar{\mathrm{q}})}|}^2 x_1 f_{\mathrm{q}(\bar{\mathrm{q}})/\mathrm{A}}(x_1,\mu^2)\,\mathcal{F}^{\mathrm{F}}_{\mathrm{g}^*/\mathrm{B}}(x_2,p_\mathrm{T}^2,\mu^2) + \overline{|\mathcal{M}_{\mathrm{g}^*\mathrm{g}\to\mathrm{g}}|}^2 x_1 g_{\mathrm{g}/\mathrm{A}}(x_1,\mu^2)\,\mathcal{F}^{\mathrm{A}}_{\mathrm{g}^*/\mathrm{B}}(x_2,p_\mathrm{T}^2,\mu^2))\right]$$

Unintegrated gluon density

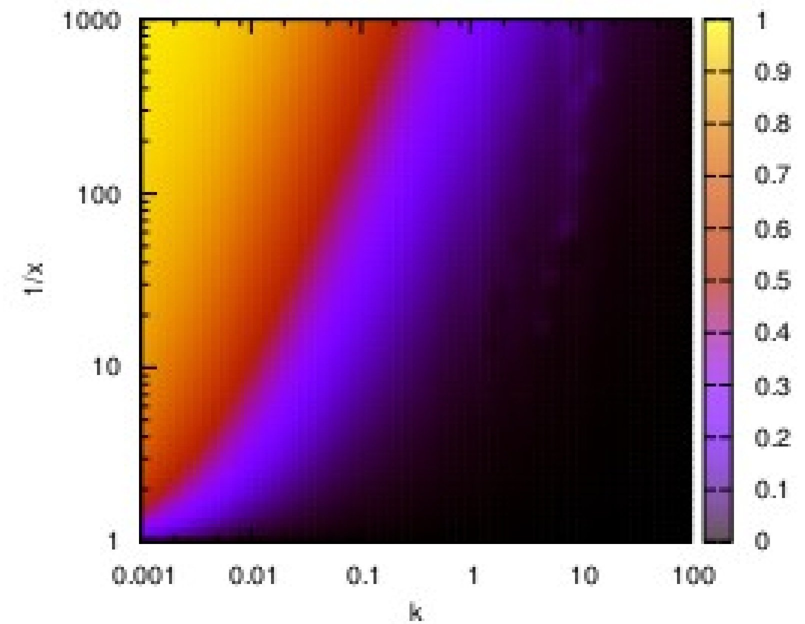
Formula originally derived for p A. Application to p-p neglects fluctuations and proton is vieved as nucleus with smaller saturation scale



Formalism used also at purely linear level e.g. for calculation of heavy quark production

Chachamis,Deák , Hentschinski, Germán Rodrigo, Sabio Vera
JHEP 1509 (2015) 123

High energy factorization and saturation



Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.

BK related nonlinearity appear in:
Single inclusive jet production,
Dumitru, Jalian-Marian, Hashiyagaki,

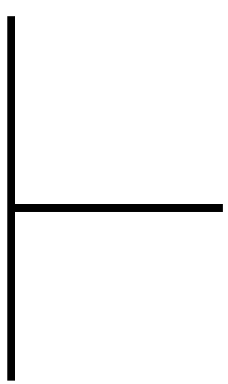
Double inclusive jet production
Xiao, Yuan, Dominguez, Marquet

Diffractive processes
Bartels; Levin, Kovchegov; Hentschinski, Weigert, Schaffer

On microscopic level it means that gluon apart splitting recombine

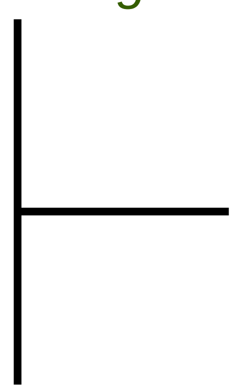
splitting

Linear evolution equation



Nonlinear evolution equations

splitting



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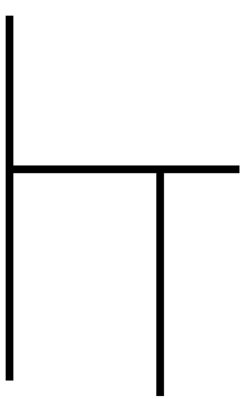
recombination



The saturation problem: supressing gluons at small k_t

Originally formulated in coordinate space

Balitsky '96, Kovchegov '99

Now at NLO accuracy

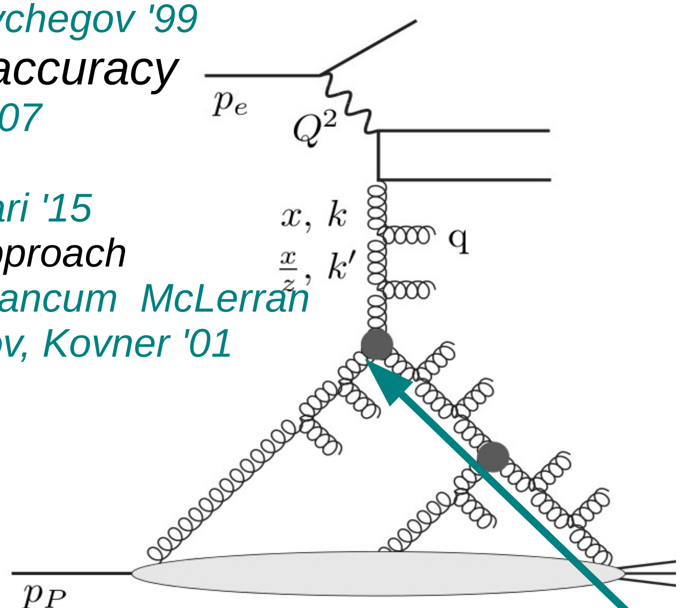
Balitsky, Chirilli '07

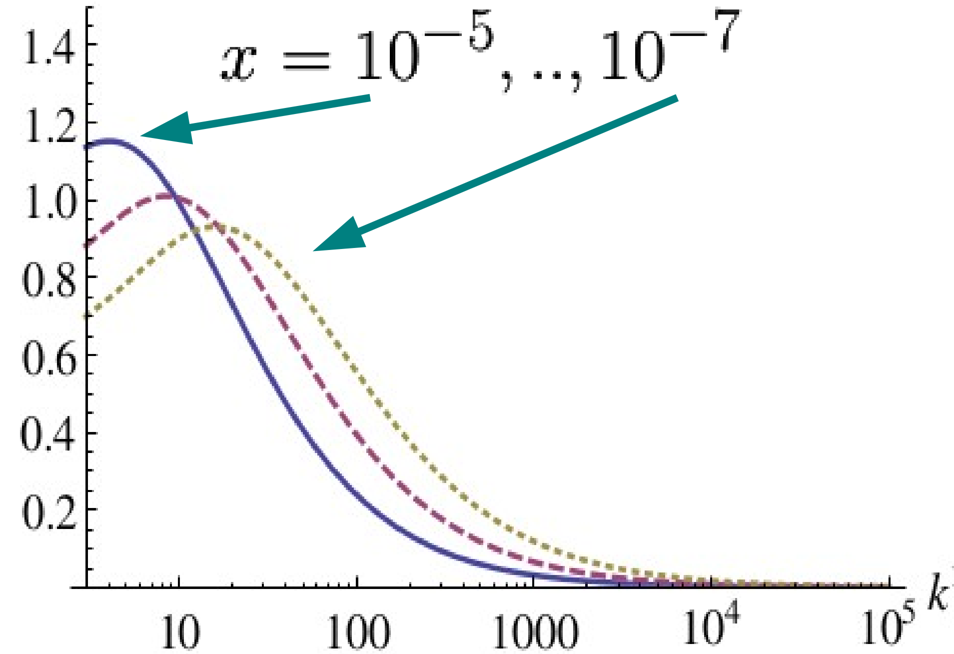
and solved

Lappi, Mantysaari '15

More general approach

Jalian-MarianI, Iancum McLerran Weigert Leonidov, Kovner '01





Solution of the equation

The BK equation for dipole gluon density

$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} - \frac{1}{R^2} V \otimes \mathcal{F}^2$$

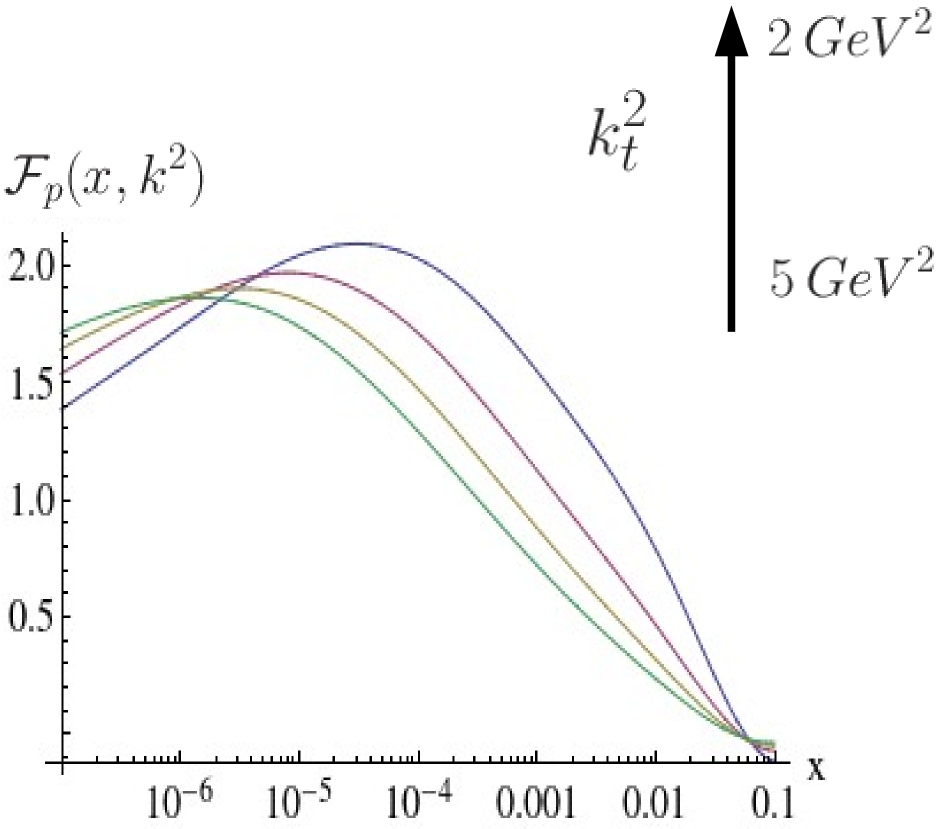
Momentum space

Kwiecinski, Kutak '02

Nikolaev, Schafer '06

hadron's radius

x dependence of nonlinear - glue in p



Innvoking uncerainity principle. The plots show that saturation makes it harder to get many gluons which are extended in the longitudinal direction

Maximum signalize emergence of saturation scale

PDF we use at present

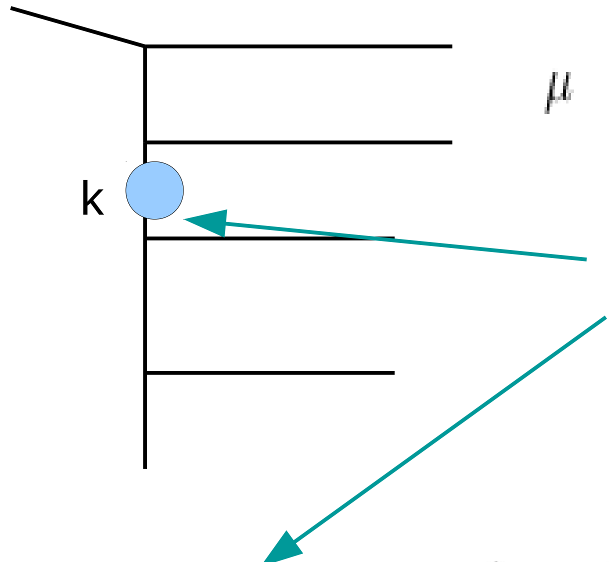
KS (Kutak-Sapeta) nonlinear → gluon density from extension of momentum space version of BK equation to include:

- *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.

Other relevant effects – Sudakov form factor in ISR

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



μ *hard scale*

Survival probability of the gap without emissions

Survival probability of the gap without emissions

Kimber, Martin, Ryskin procedure '01:

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

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

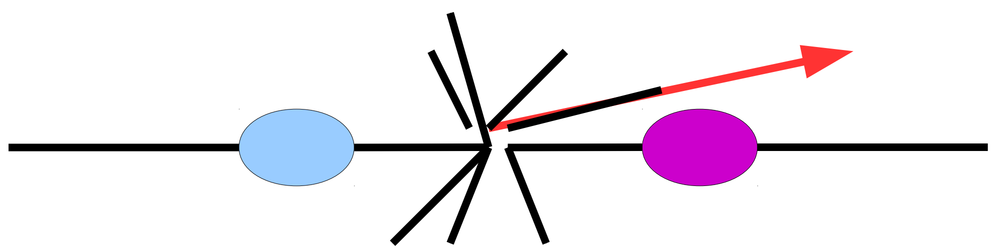
$$\mathcal{F}(x,k^2,\mu^2)\sim\partial_{\lambda^2}(T(\lambda^2,\mu^2)xg(x,\lambda^2))|_{\lambda^2=k^2}$$

One can apply similar procedure to include Sudakov effect In KS pdf → KS hs

Mueller, Xiao, Yan '12
Mueller, Xiao, Yan '13
Kutak '14

Inclusive-forward jet

$|3.2| < y < |4.7|$

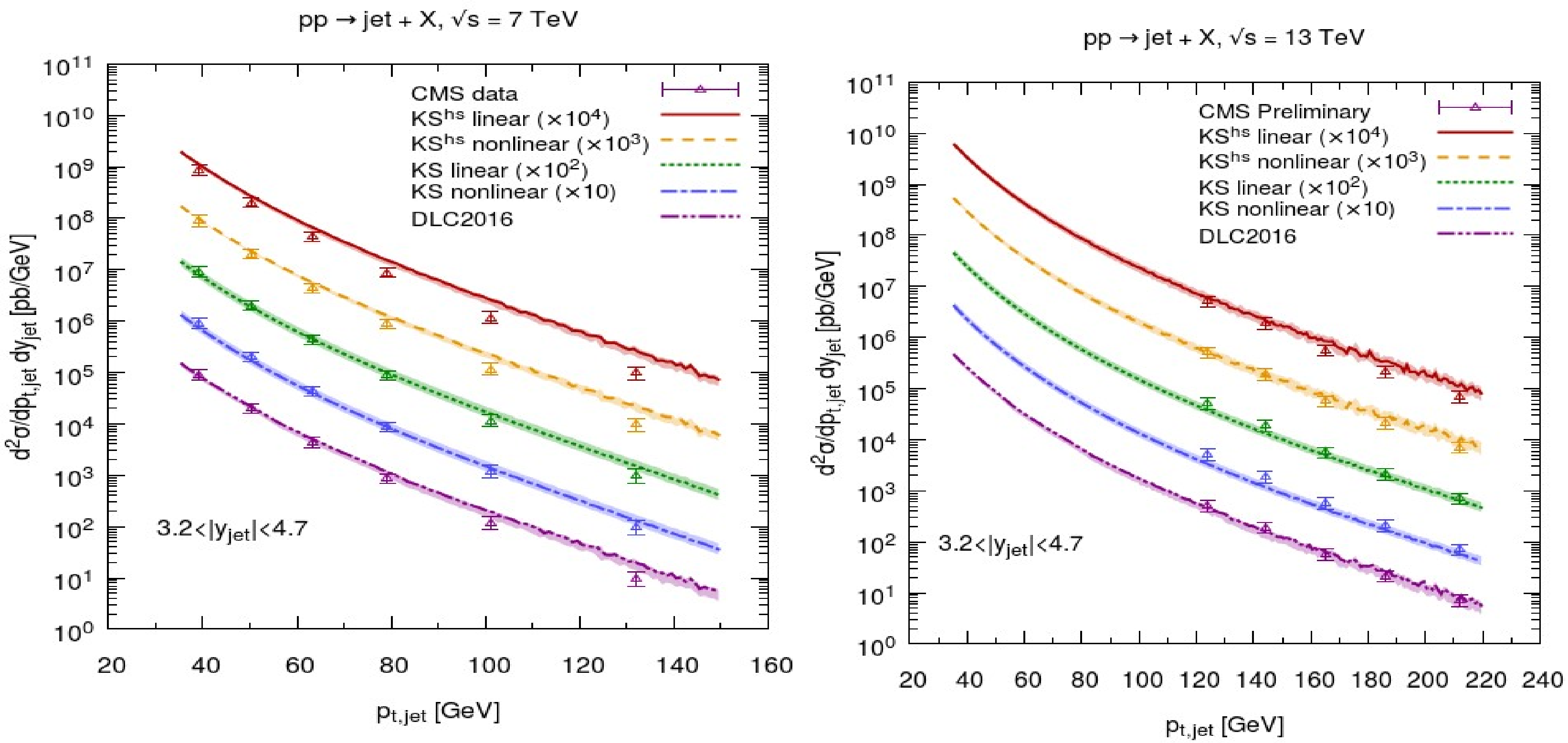


$x_{min} \sim 10^{-5}$

Single inclusive p_t jet spectra

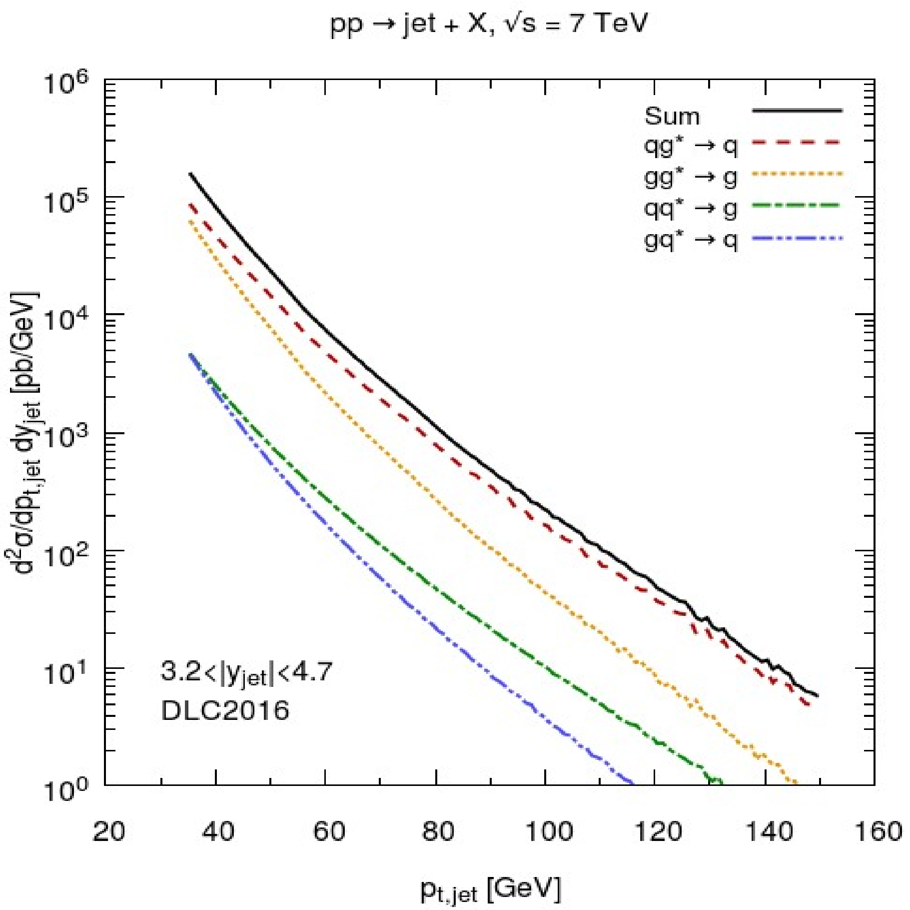
Bury, Deak , Kutak, Sapeta '16

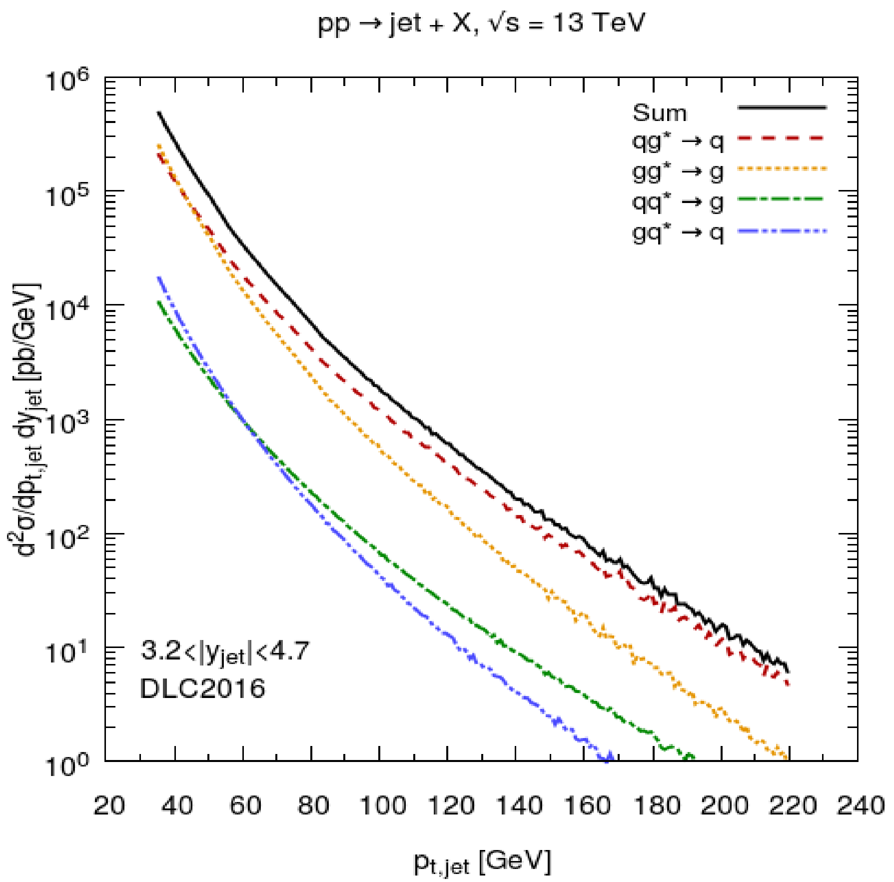
|3.2| < y <|4.7|



Reasonable description of data by KS, KS^{hs}, DLC2016. Not so good by KS^{hs} linear
In the calculation with hardscale dependent pdf hard scale was set to pt=kt therefore no Sudakov effect

Single inclusive p_t jet spectra – process decomposition

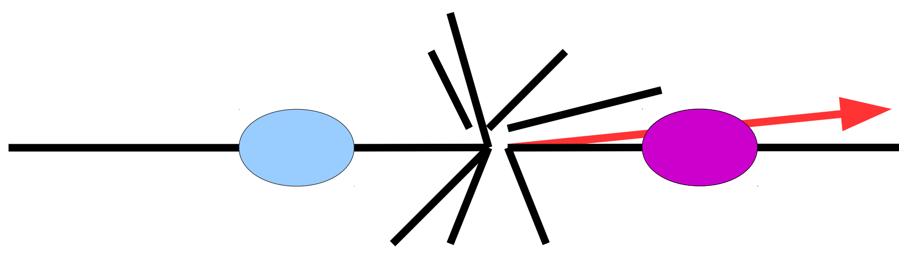




The dominant contribution comes from qg → q.*
This is due to steeper falling of gluon collinear pdf and sum over quark flavor number since ME qg → q and gg* → differ only by color factor.*

Inclusive-very forward jet

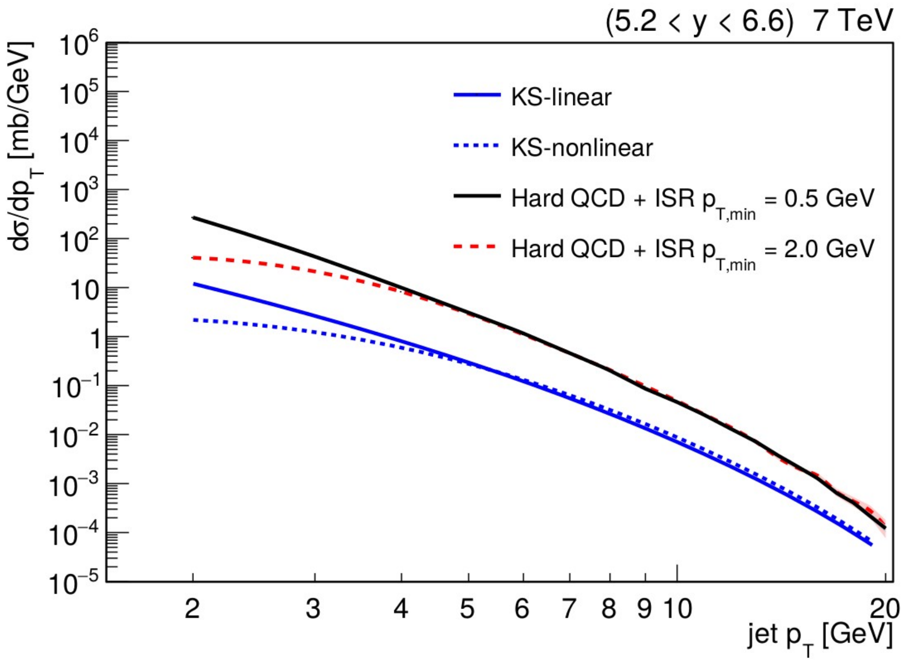
$5.2 < y < 6.6$

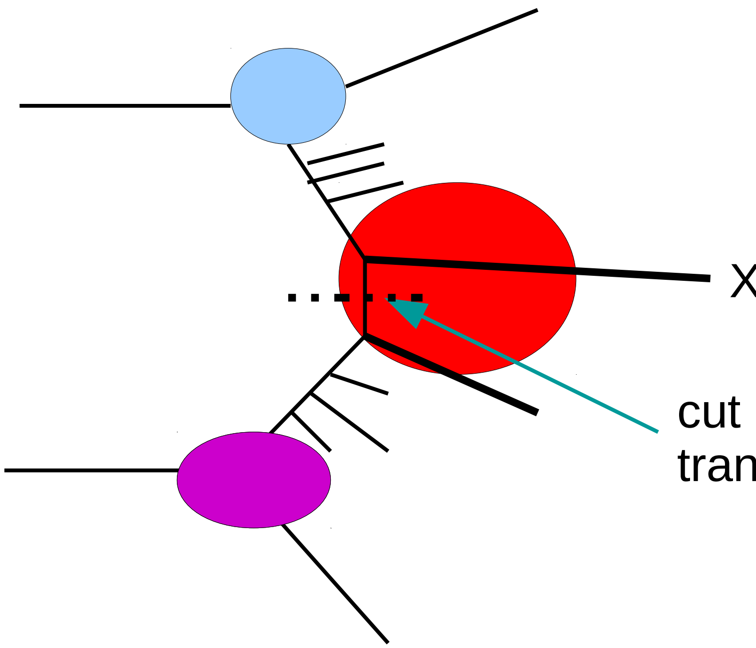


$x_{min} \sim 10^{-6}$

Saturation in PYTHIA ?

KK, H. van Havermaeth, P. van Mechelen





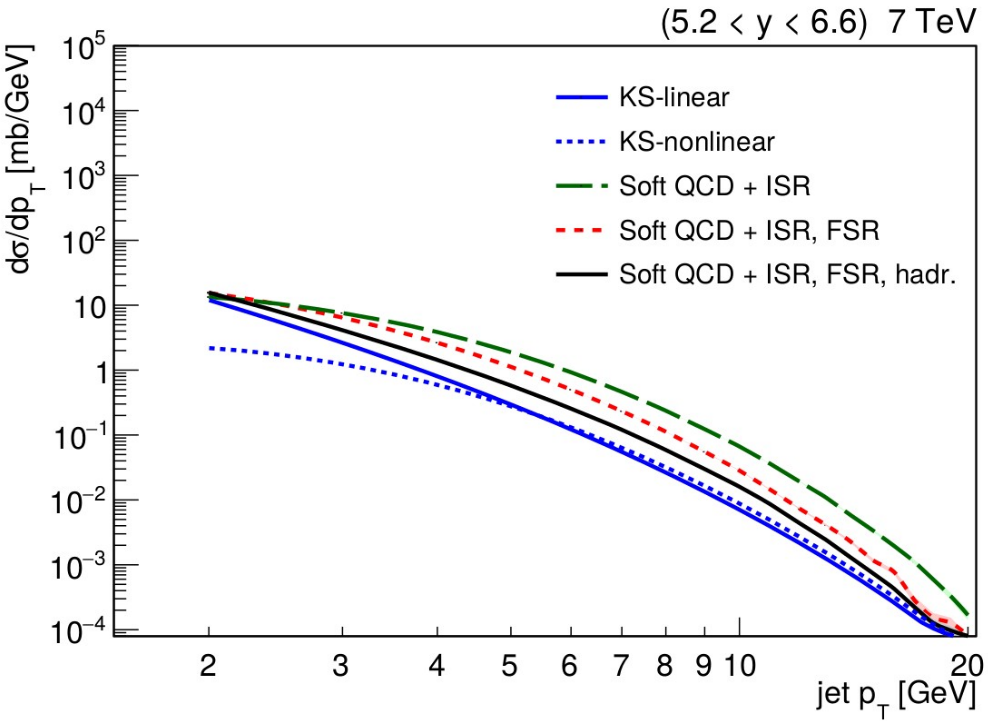
PTYHIA formally does not have low x resummation. It has many physics effects build in which could which allows one to include a range of potentially important physical effects, such as multi-parton interactions, final-state radiation and non-perturbative corrections, and the correct behaviour at low x is modelled by appropriate initial conditions . The comparison to it offers a hint of where the predicted phenomena are universal and where they differ.

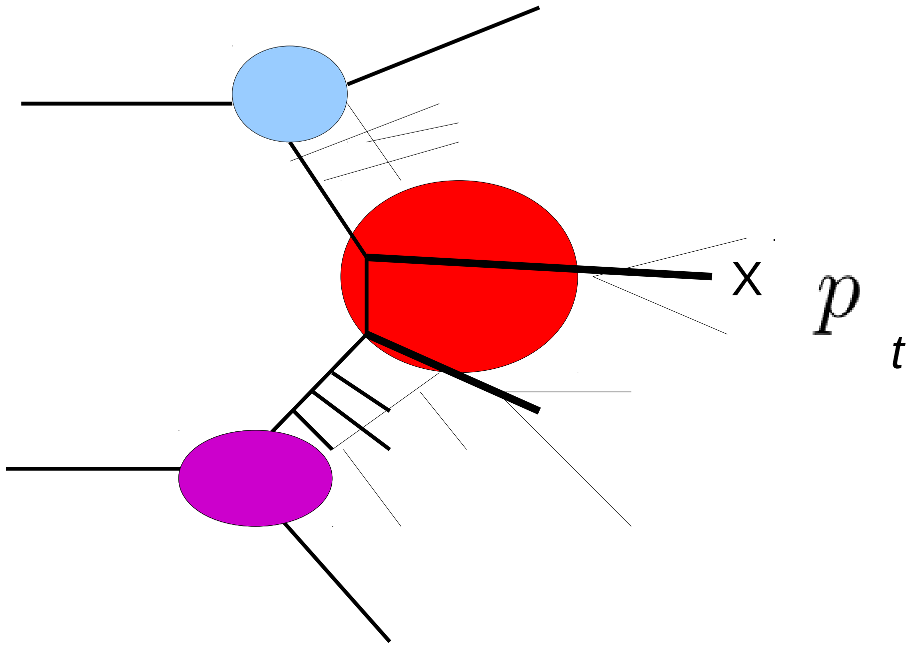
Remarkable similarity in shape between BK and PYTHIA (ME+ISR+cut) with hard cut

Remarkable similarity in shape between BFKL and PYTHIA (ME+ISR+cut) with soft cut

Single inclusive jet at VFR- p_t jet spectra

KK, H. van Haevermaet, P. van Mechelen

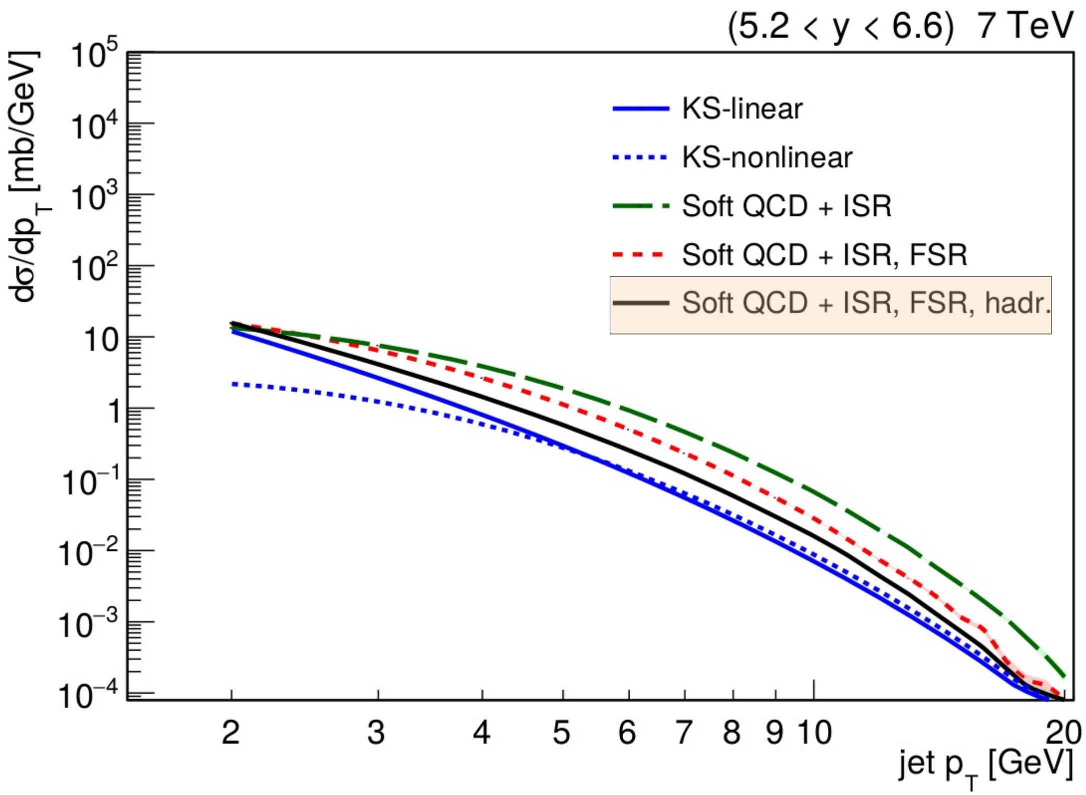


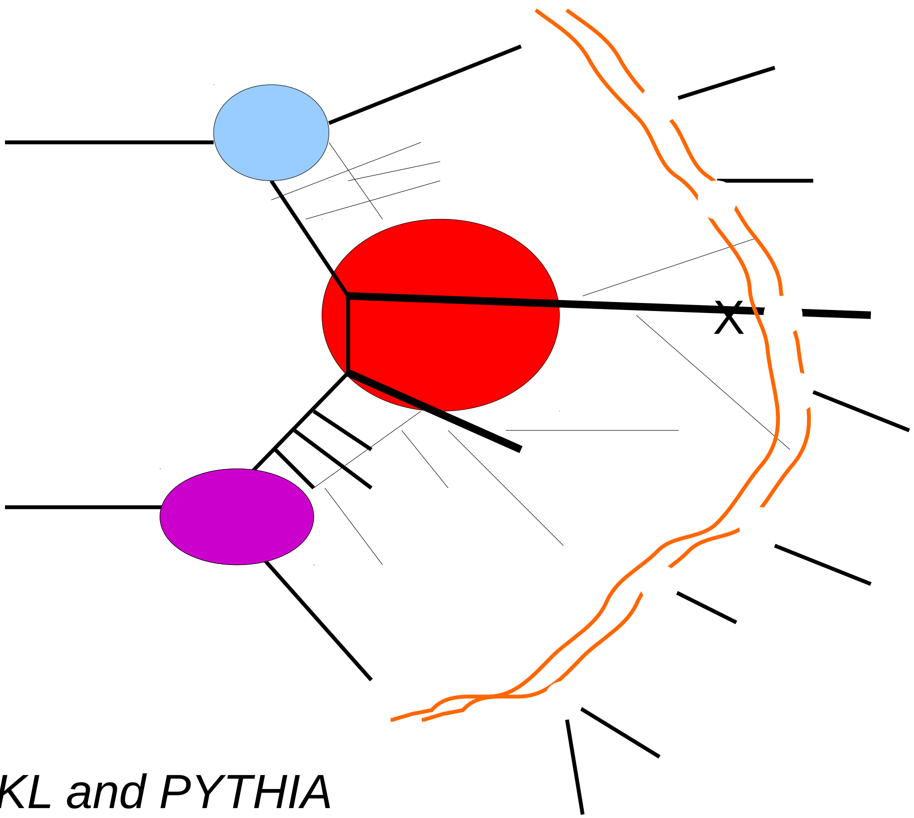


- *Saturation visible at low p_T*
- *At large values of p_T KS-linn and KS-nonlin give similar results*

Single inclusive jet at VFR - p_t jet spectra

KK, H. van Haevermaet, P. van Mechelen

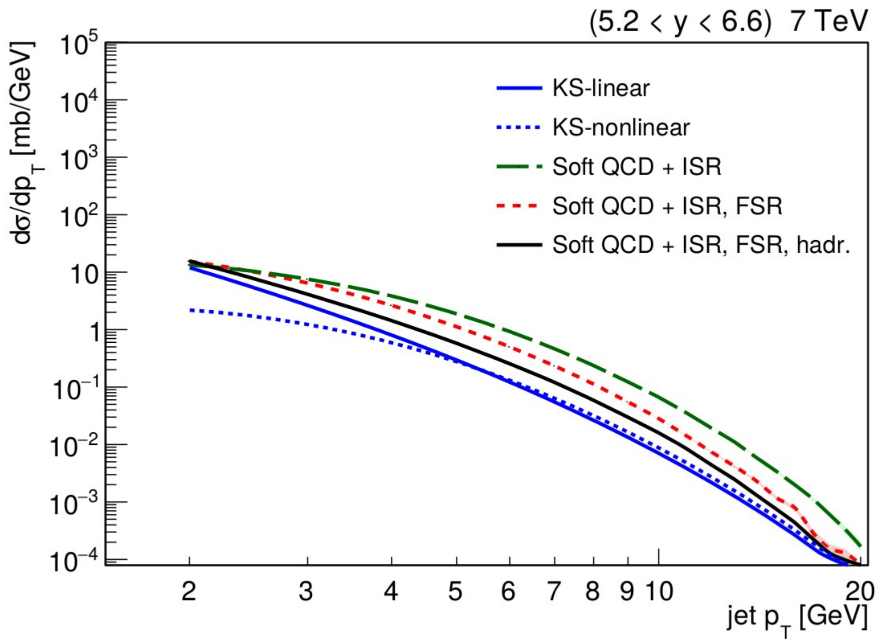


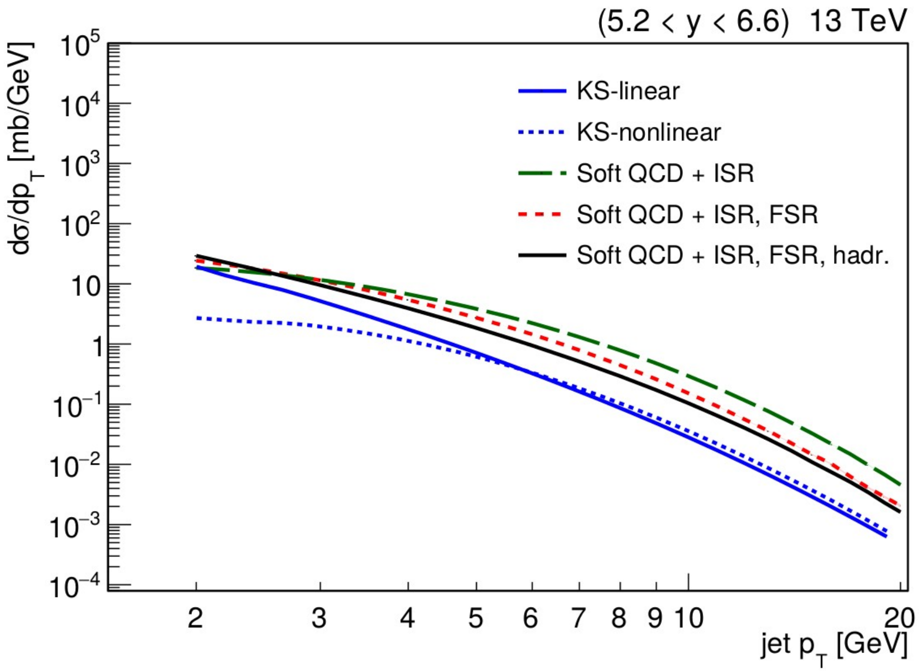


- *At lower energies better agreement between BFKL and PYTHIA*
- *Saturation visible at low p_T*
- *At large values of p_T BFKL and BK give similar results*
- *Hadronisation effects more important at 7 TeV*

Single inclusive jet at VFR - p_t jet spectra

KK, H. van Haevermaet, P. van Mechelen





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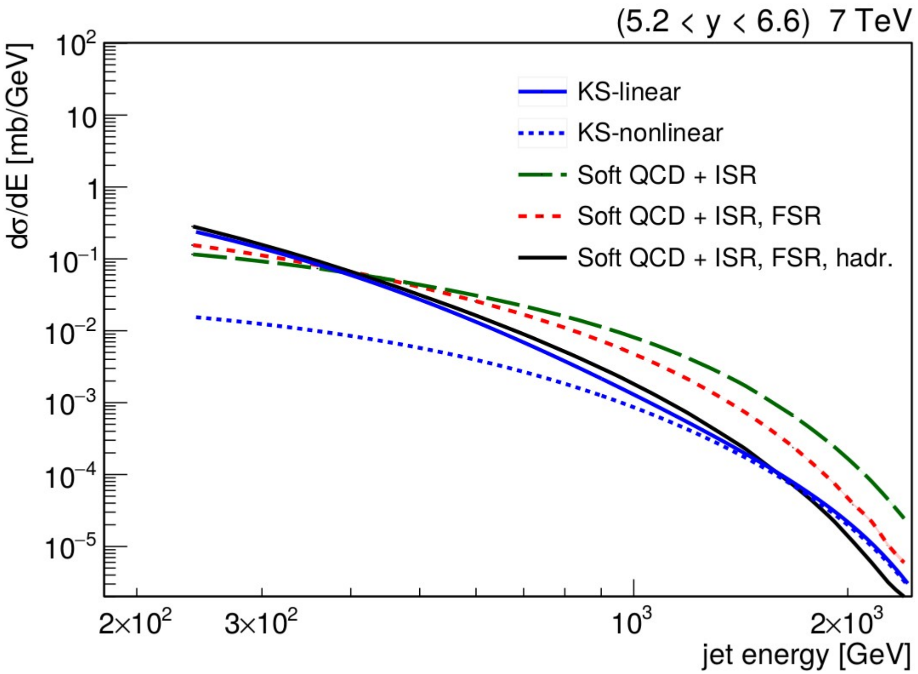
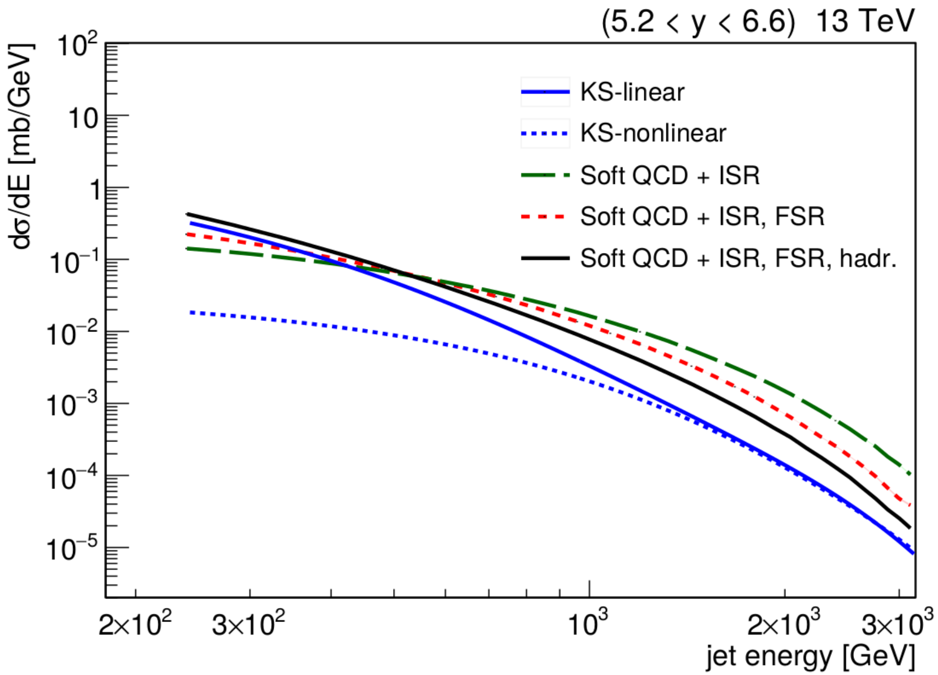
Single inclusive jet in CASTOR- energy spectra





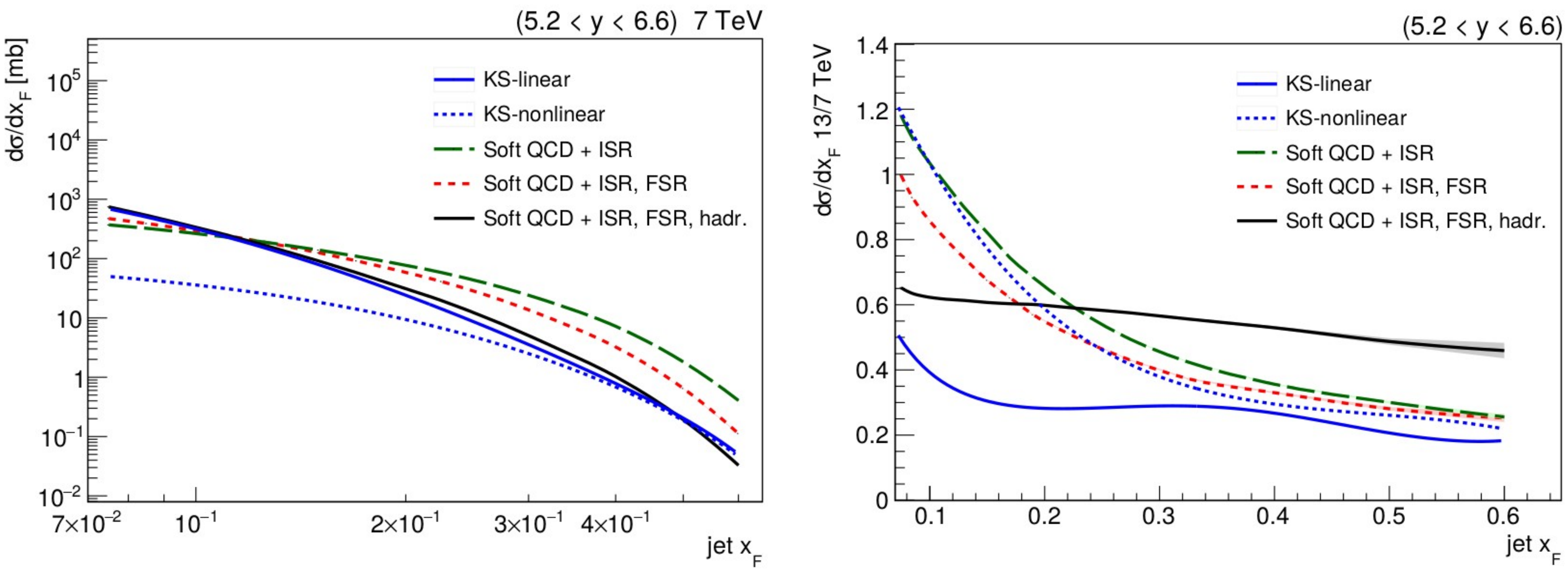
Result consistent with pT spectra.
Measurable in CASTOR

$$\frac{d\sigma}{dE} = \int_{y_{\min}}^{y_{\max}} dy \, \frac{d\sigma}{dy \, dp_T} \frac{1}{\cosh \, y}$$

At lower energies better agreement between KS-lin and PYTHIA

Single inclusive jet in CASTOR- x_F spectra

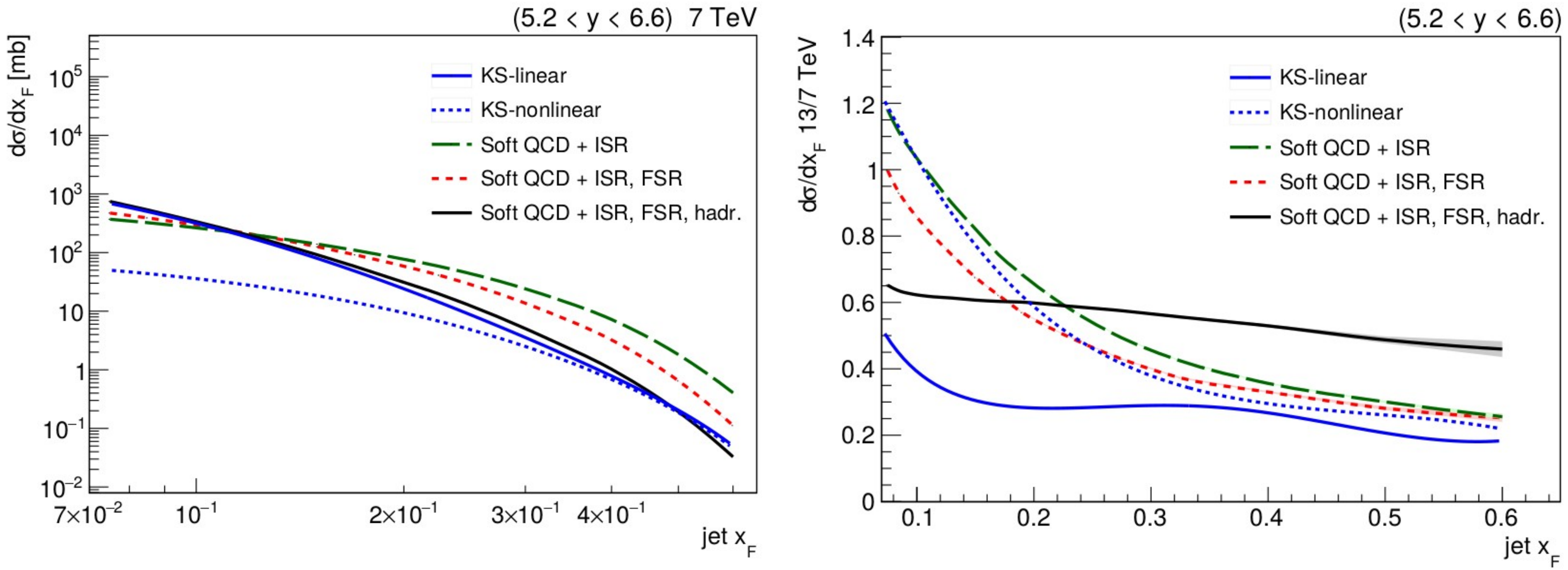
KK, H. van Haevermaet, P. van Mechelen



$$\frac{d\sigma}{dx_F} = \frac{\sqrt{s}}{2}\frac{d\sigma}{dp_L} = \frac{\sqrt{s}}{2}\int_{y_{\min}}^{y_{\max}} dy\, \frac{d\sigma}{dy\, dp_T}\frac{1}{\sinh y}$$

Single inclusive jet in CASTOR- x_F spectra

KK, H. van Haevermaet, P. van Mechelen



Measures asymetry in the longitudinal direction
cross section ratio → compare jets with different pT. For xF values below 0.3 → one compares the jet cross section at 7 TeV in the saturation/regularization domain to the jet cross section at 13 TeV at larger pt, hence the sharp increase of the ratio. This effect is smoothed out by hadronization.

The cross section ratio predicted by PYTHIA with all effects included is therefore again flat as a function of xF

Conclusions and outlook

- *Reasonable description of pt spectra of single inclusive forward jets at high p_t*
- *Predictions for spectra of single inclusive jets at very forward rapidity.*
- *Similarity of PYTHIA results to HEF results addressed → PYTHIA with hard cut similar to BK, PYTHIA with soft cut similar to BFKL.*
- *PYTHIA at 7 TeV with all effects turn on similar to BFKL*
- *Single inclusive jets in p+Pb at very forward rapidities*
- *Update the BK and BFKL parton densities*
- *Include FSR*