Supported by Narodowe Centrum Nauki (NCN)
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NCN

Forward-forward dijets at LHC

Krzysztof Kutak

Instytut Fizyki Jądrowej
im. Henryka Niewodniczańskiego
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Forward-forward dijets at LHC
and perspectives for finding gluon saturation

Krzysztof Kutak

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Polskiej Akademii Nauk

Talked based on

Ongoing research M. Bury, KK, S. Sapeta

Phys.Rev. D91 (2015) 3, 034021 K.Kutak

Arxiv: 1503.03421 P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren,

Phys.Lett. B737 (2014) 335-340, A. van Hameren, P. Kotko, K. Kutak, S. Sapeta

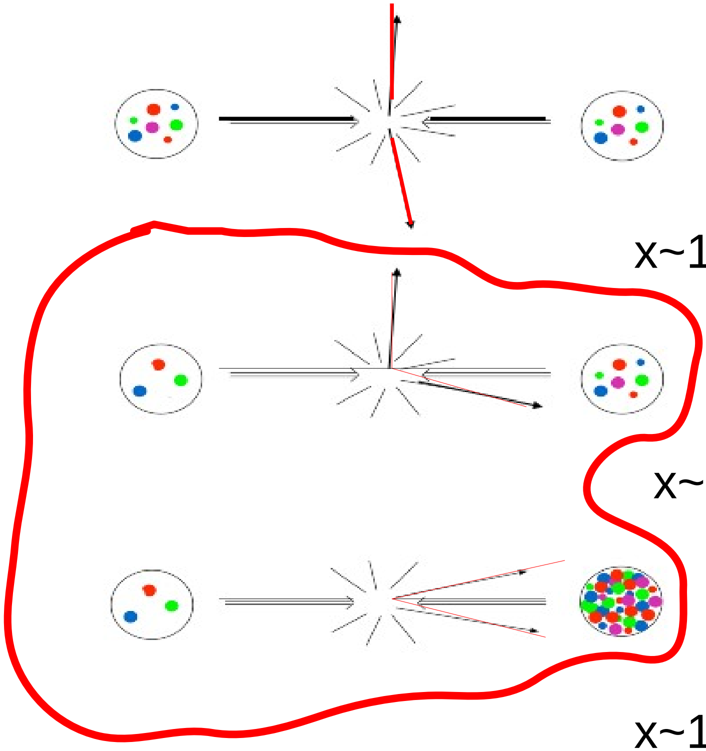
Phys. Rev. D 89, 094014 (2014), A. van Hameren, P. Kotko, K. Kutak, C. Marquet, S. Sapeta

Phys. Rev. D 86, 094043 (2012), Krzysztof Kutak, Sebastian Sapeta

Outline

- *Motivation*
- *Basics of theory*
- *Central-forward jets*
- *Forward-jets*
- *Z+jet*
- *Conclusions and oultlook*

LHC as a scanner of gluon



central-central i.e.
dilute dilute

$x \sim 10^{-4}$

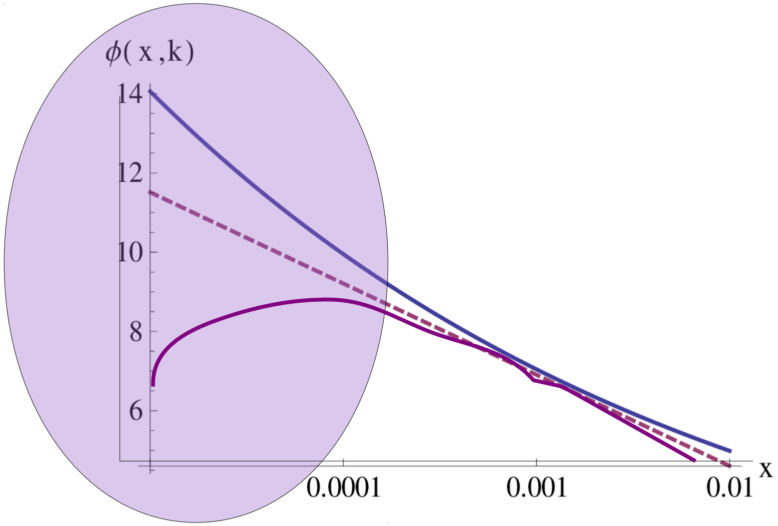
forward-central i.e.
dilute – not so dense

$x \sim 10^{-4}$

forward-forward i.e.
dilute -dense

$x \sim 10^{-5}$

Gluon density

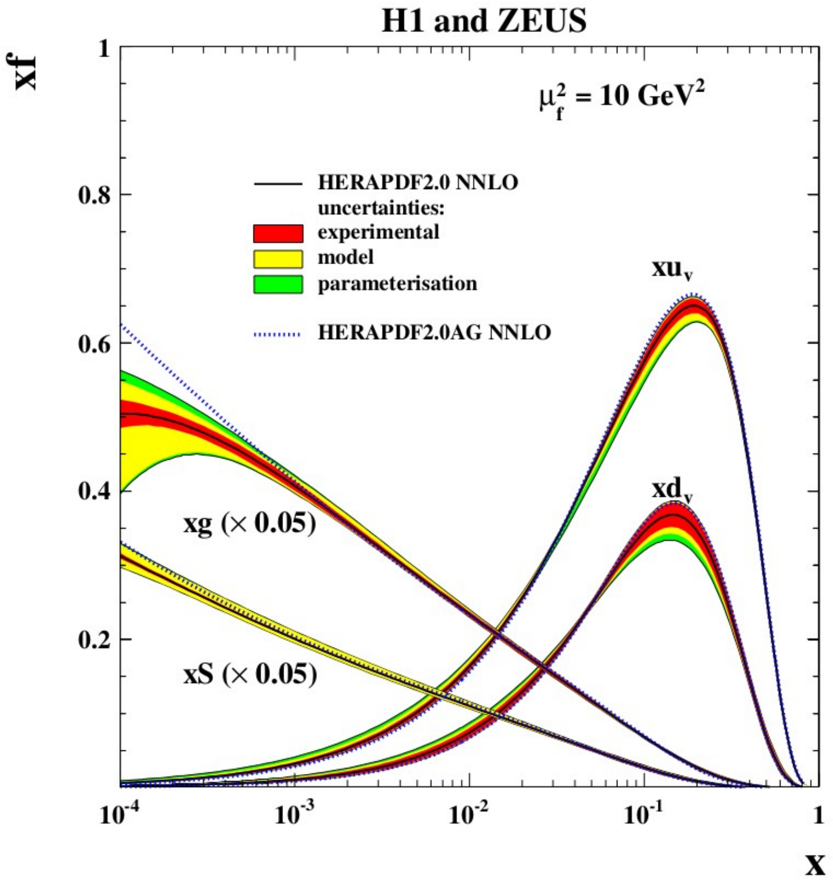


dense

dilute

Structure of the proton

For example: DIS experiments at DESY



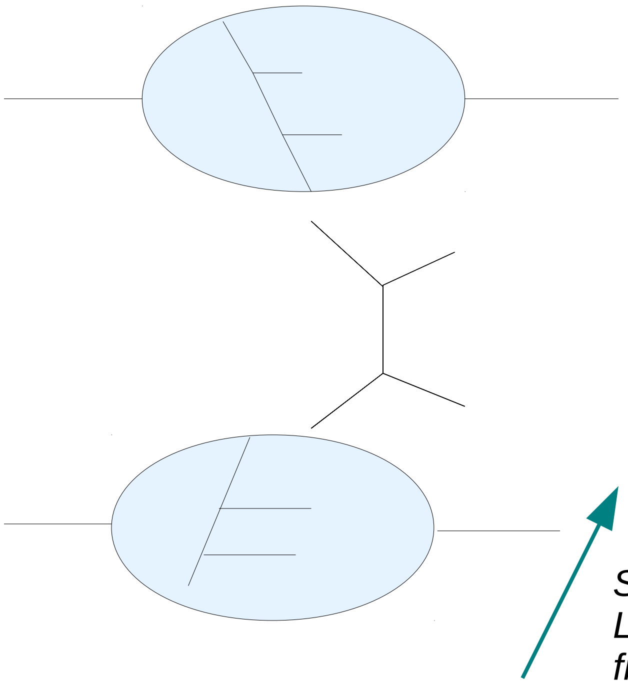
1506.06042

There are processes for which the accuracy of evaluation of matrix elements is higher than evaluation of pdfs.

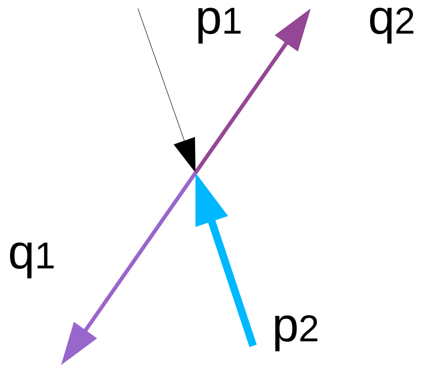
Example is total cross section for Higgs N^3LO theoretical uncertinity is 4% and uncertainity due to pdf choice is 10 % talk at "Parton showers and resummations 2015". Sven Olaf-Moch

Note the uncertainity of gluon.
Even valence like shape allowed

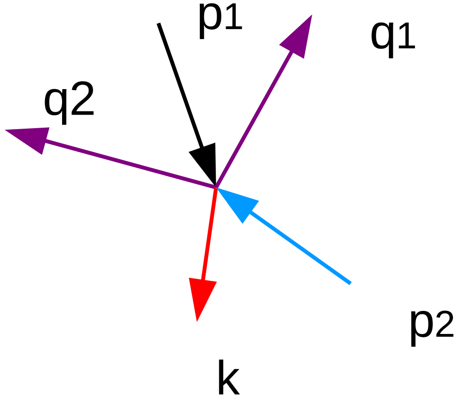
QCD at high energies – high energy factorization



Strongly decreasing
Longitudinal momentum
fractions of off-shell partons



$p_1+p_2=q_1+q_2$



$p_1+p_2=q_1+q_2+k$

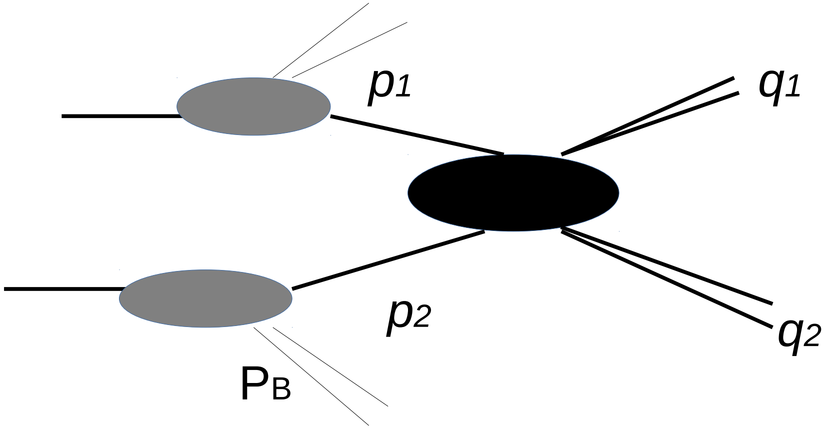
Monte Carlo generators → aim to describe fully processes
In general many parameters → tunings
My point of view → ME + parton densities in kt factorization
Gain: less parameters.
Physics motivated approach to dense system

New helicity based methods for ME
Kotko, K.K, van Hameren, '12

Theory
Gribov, Levin, Ryskin '81
Ciafaloni, Catani, Hautman '93
Collins, Ellis '93

Phenomenology
Jung, Hautmann; Szczurek, Maciuła; KK, Kotko, van Hameren Staśto...

Didjet production – collinear formalism



In collinear framework initial state partons are collinear with the hadron's momentum.

Final state jets are always back-to-back.

To overcome this problem One uses Monte Carlo Generators to apply parton showers. to modify kinematics of initial state

$$d\hat{\sigma}_{ij} = \frac{(2\pi)^4 \delta^4(p_1 + p_2 - q_1 - q_2)}{2\hat{s}} \frac{dy_1\, d^2q_{1\perp}}{4\pi\,(2\pi)^2} \frac{dy_2\, d^2q_{2\perp}}{4\pi\,(2\pi)^2} |M_{ij}|^2$$

$$\frac{d\sigma}{d^2q_{1\perp} d^2q_{2\perp} dy_1 dy_2} = \sum_{ij} \int dx_1 x_2\, f_{i/1}(x_1, \mu^2) f_{j/2}(x_2, \mu^2) \frac{d\hat{\sigma}_{ij}}{d^2q_{1\perp} d^2q_{2\perp} dy_1 dy_2}$$

$$\mu = (q_{1\perp} + q_{2\perp})/2$$

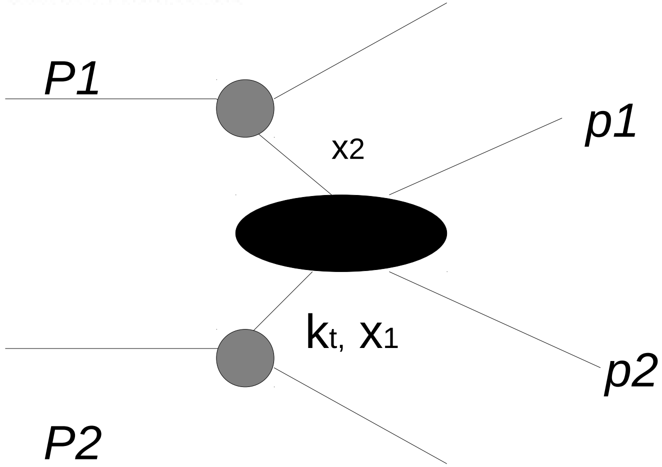
Hybrid factorization and dijets

$$\frac{d\sigma}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \sum_{a,c,d} \frac{p_{t1} p_{t2}}{8\pi^2 (x_1 x_2 S)^2} \overline{|\mathcal{M}_{ag\to cd}|}^2 x_1 f_{a/A}(x_1,\mu^2)\, \mathcal{F}_{g/B}(x_2,k^2,\mu^2) \frac{1}{1+\delta_{cd}}$$

Can be obtained from CGC after neglecting nonlinearities
In that limit gluon density is just the dipole gluon density

Deak, Jung, KK, Hautmann '09

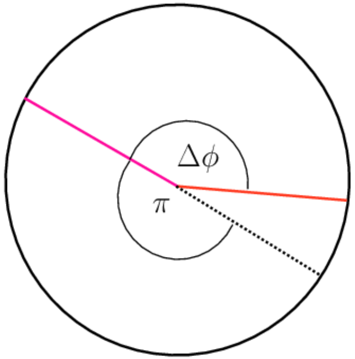
$$S = 2P_1 \cdot P_2$$



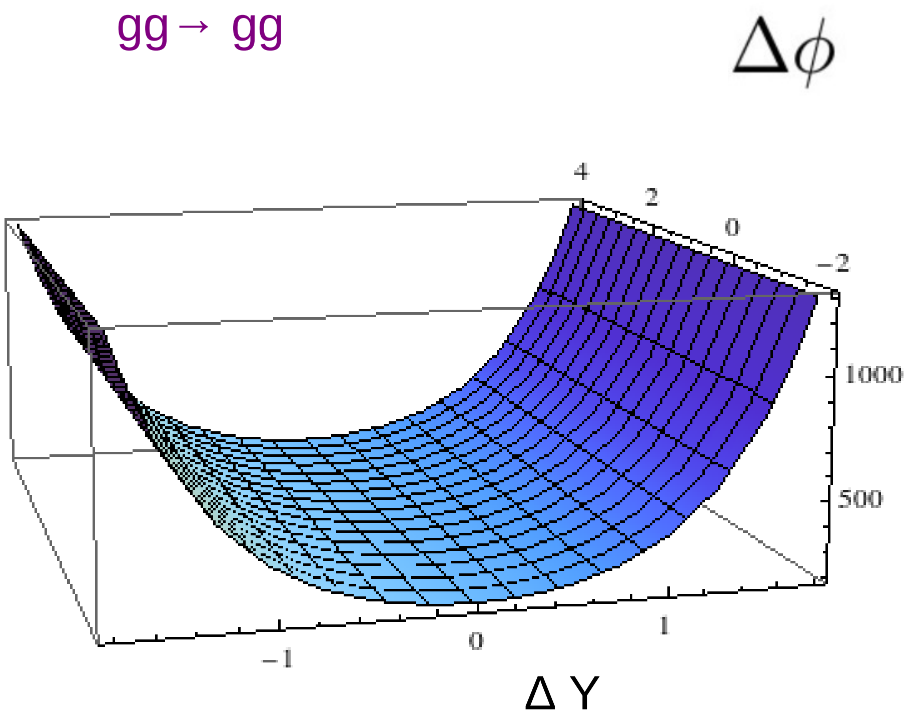
$$\mathcal{F}(x,k^2) = \frac{C_F}{\alpha_s (2\pi)^3} \int d^2\mathbf{b}\, d^2\mathbf{r}\, e^{-i\mathbf{k}\cdot\mathbf{r}} \nabla_r^2 N(\mathbf{r},\mathbf{b},x)$$

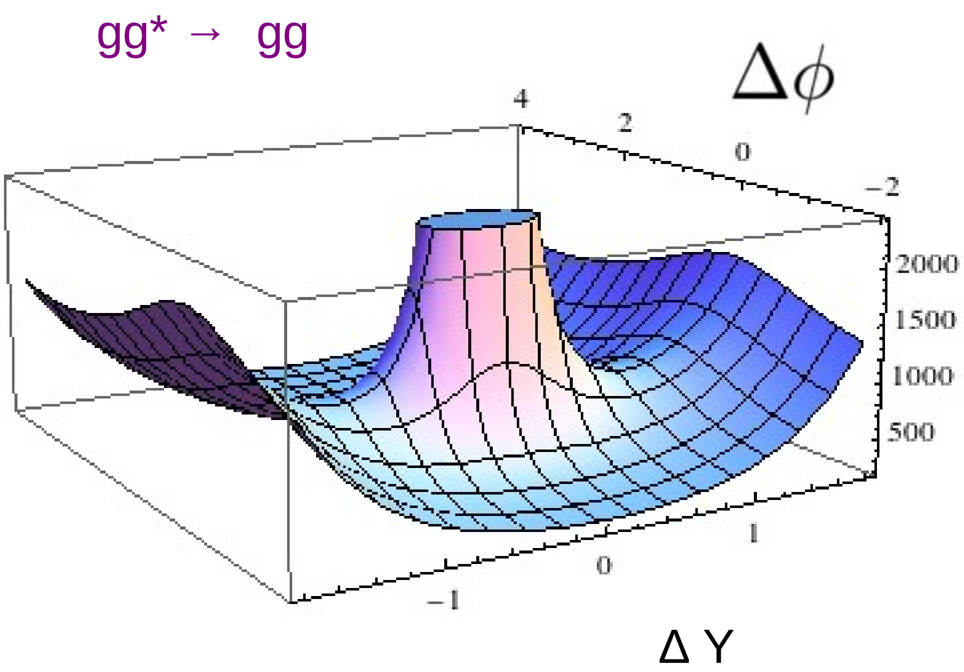
Consistent with definition of gluon density from
Dominguez, Marquet, Xiao, Yuan '10

- *Resummation of logs of x and logs of hard scale*
- *Knowing well parton densities at large x one can get information about low x physics*



Collinear vs. off-shell ME





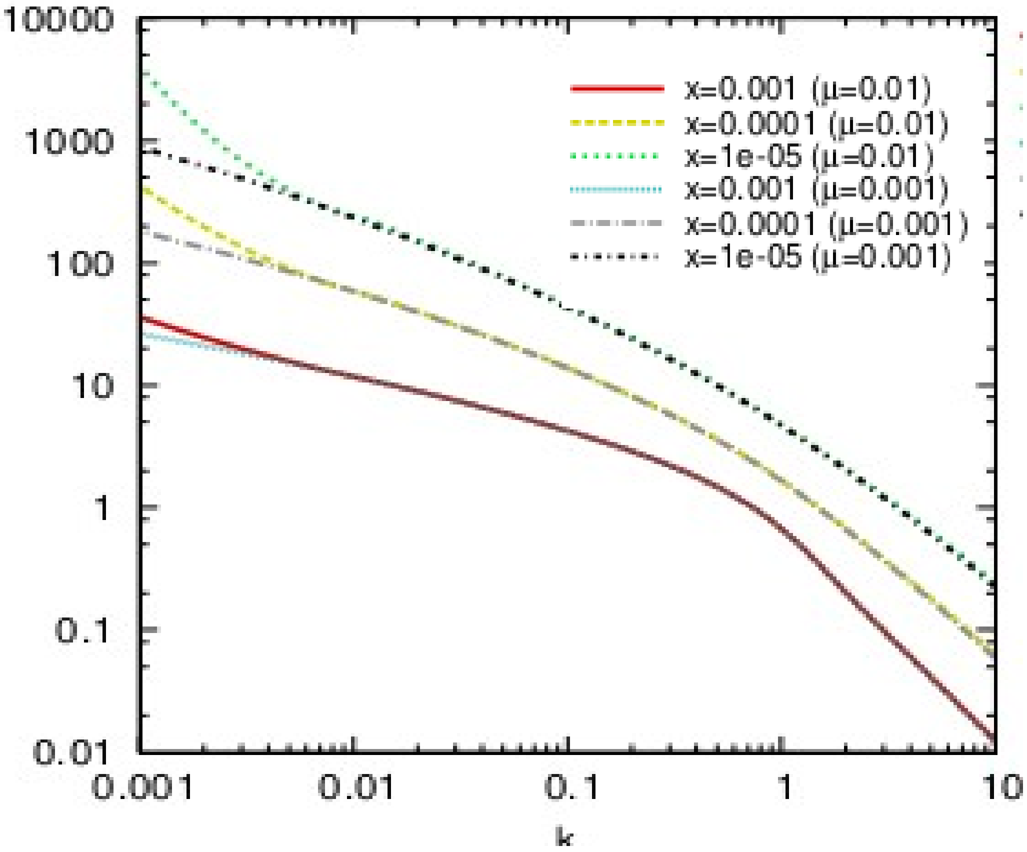
Collinear 2 → 2 ME

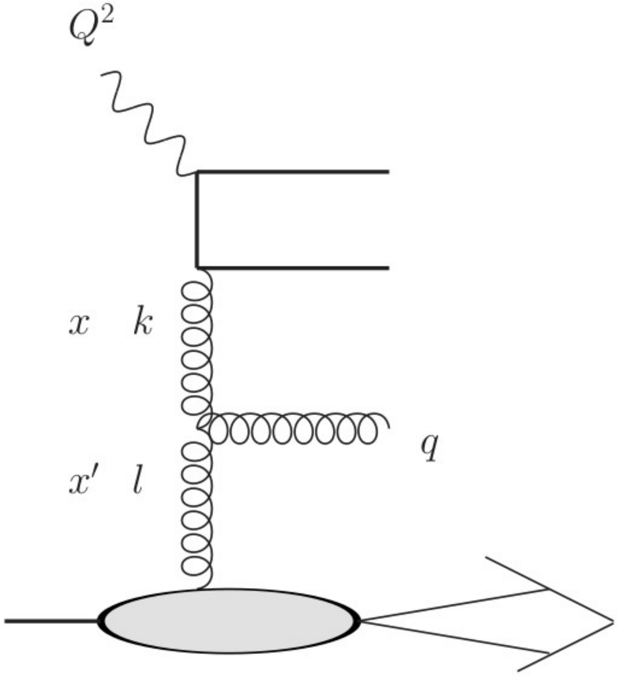
$$M=\frac{32\,\pi^2\,\alpha^2\,(e^{-\Delta y}+1)^2\,(e^{\Delta y}\,(e^{\Delta y}+1)+1)^2\,\mathrm{Nc}^2\,(-2\cosh(\Delta y)-1)}{(e^{\Delta y}+1)^2\,(\mathrm{Nc}^2-1)\,(-\cosh(\Delta y)-1)}$$

One off-shell parton 2 → 2 ME

$$M=\frac{32\,\pi^2\,\alpha^2\,e^{-2\,\Delta y}\,\mathrm{Nc}^2\,(\mathrm{pt1}+e^{\Delta y}\,\mathrm{pt2})^2\,(e^{2\,\Delta y}\,\mathrm{pt1}^2+e^{\Delta y}\,\mathrm{pt1}\,\mathrm{pt2}+\mathrm{pt2}^2)^2\,(\cos(\Delta\mathrm{phi})-2\cosh(\Delta y))}{(\mathrm{Nc}^2-1)\,\mathrm{pt1}^2\,\mathrm{pt2}^2\,(e^{\Delta y}\,\mathrm{pt1}+\mathrm{pt2})^2\,(\cos(\Delta\mathrm{phi})-\cosh(\Delta y))}$$

The LO BFKL equation



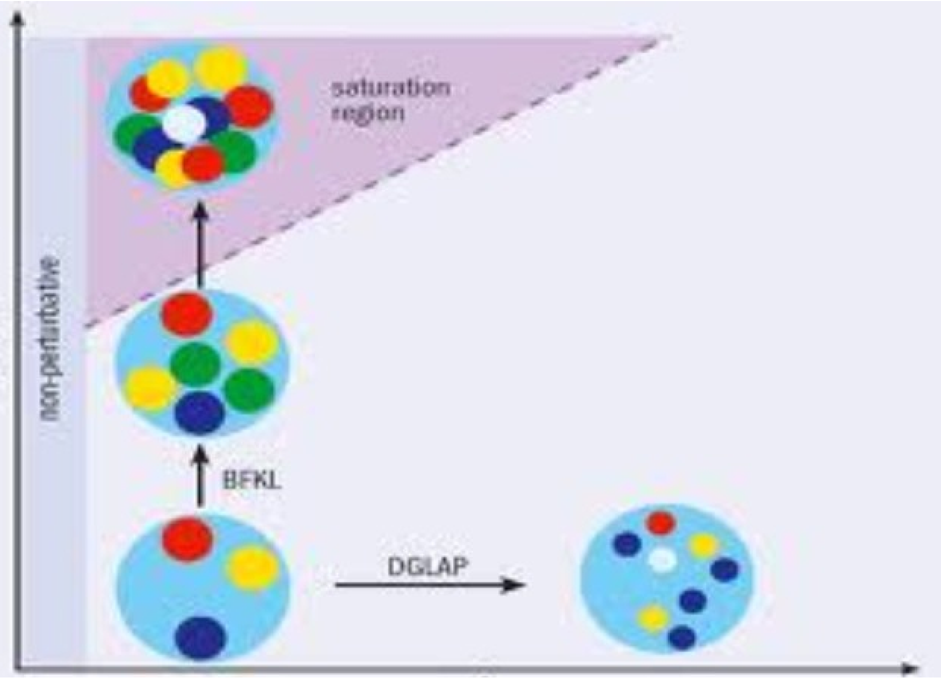


$$\mathcal{F}(x,k^2) = \mathcal{F}_0(x,k^2) + \overline{\alpha}_s \int_{x/x_0}^{1} \frac{dz}{z} \int_0^{\infty} \frac{dl^2}{l^2} \left[\frac{l^2 \mathcal{F}(x/z,l^2) - k^2 \mathcal{F}(x/z,k^2)}{|k^2 - l^2|} + \frac{k^2 \mathcal{F}(x/z,k^2)}{\sqrt{(4l^4 + k^4)}} \right]$$

No hard scale dependence

High energy factorization and saturation

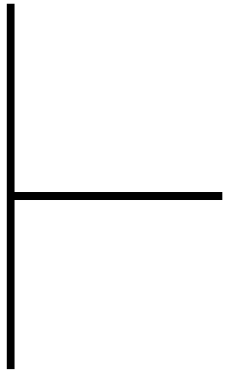
Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.
More generally saturation is an example of percolation which has chance to happen since partons have size 1/k_t and hadron has finite size. Cross sections (e.g. F2) change their behavior from power like to logarithmic like.



On microscopic level it means that gluon apart splitting recombine

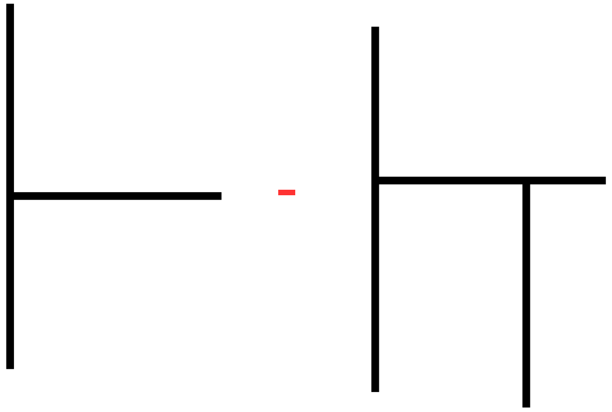
splitting

Linear evolution equation



recombination

Nonlinear evolution equations
BK, JIMWLK
CGC framework
DIPSY



Comment on Color Glass Condensate

General name for frameworks which address problem of saturation

Color → color degrees of freedom,
Glass → typical scale smaller compared to hard scale
Condensate → saturation

- *GLR equation → outdated equation for gluon density including nonlinearities*
- *BK equation → equation for multiple scattering of color dipole → gluon density with nonlinearities*
- *JIMWLK equation → generalization of BK equation → can provide gluon density*
- *GBW model → model for dipole amplitude → gluon density → falls like* k^2 *at small k*
- *KLN model → old model for gluon density with saturation scale → constant at small k*
- *MV model → model for dipole amplitude → gluon density → falls like k^2 at small k*
- *IP-Sat →saturation model with target which has nouniform geometry*
- *Glasma – some version of lassical YM equations*

The nonlinear equation for unintegrated gluon density

Originally formulated in coordinate space

Balitsky '96, Kovchegov'99

Now at NLO accuracy

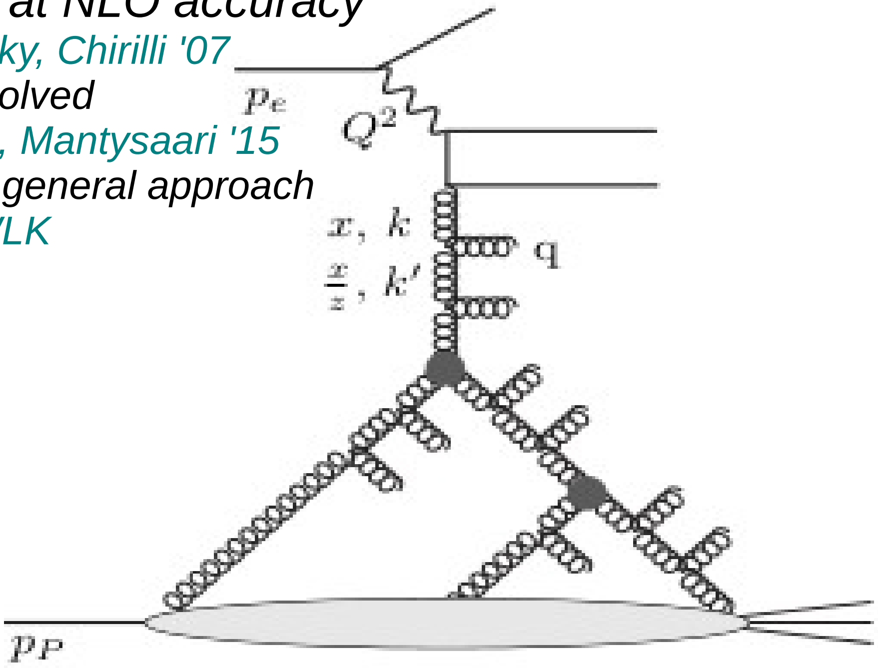
Balitsky, Chirilli '07

and solved

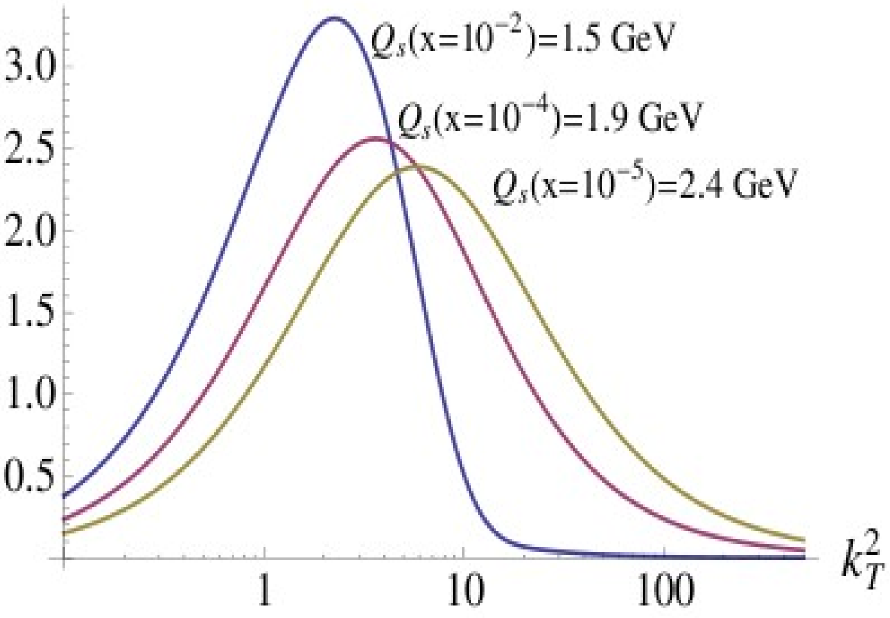
Lappi, Mantysaari '15

More general approach

JIMWLK



the CGC I use



$$\mathcal{F}(x,k^2) = \mathcal{F}_0(x,k^2) + \overline{\alpha}_s \int_{x/x_0}^{1} \frac{dz}{z} \int_0^\infty \frac{dl^2}{l^2} \left[\frac{l^2 \mathcal{F}(x/z,l^2) - k^2 \mathcal{F}(x/z,k^2)}{|k^2 - l^2|} + \frac{k^2 \mathcal{F}(x/z,k^2)}{\sqrt{(4l^4 + k^4)}} \right]$$

$$- \frac{\pi \alpha_s^2 k^2}{4 N_c R^2} \nabla_k^2 \int_{x/x_0}^{1} \frac{dz}{z} \left[\int_{k^2}^{\infty} \frac{dl^2}{l^2} \ln \frac{l^2}{k^2} \mathcal{F}(x/z,l^2) \right]^2$$

Applications also in coordinate space:

Gotsman, Levin, Lublinsky, Naftali,Maor 03

Albacete, Armesto, Milhano, Salgado, Wiedemann '03 ,

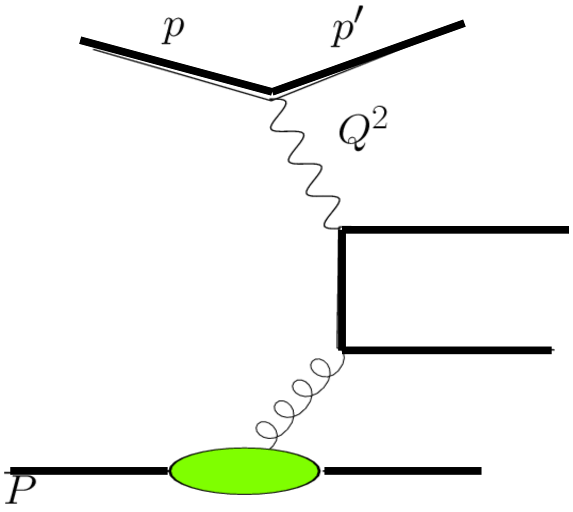
Berger, Stasto 12; Marquet, Soyez '07,…..

Kwiecinski, KK '02

Stasto, KK '05

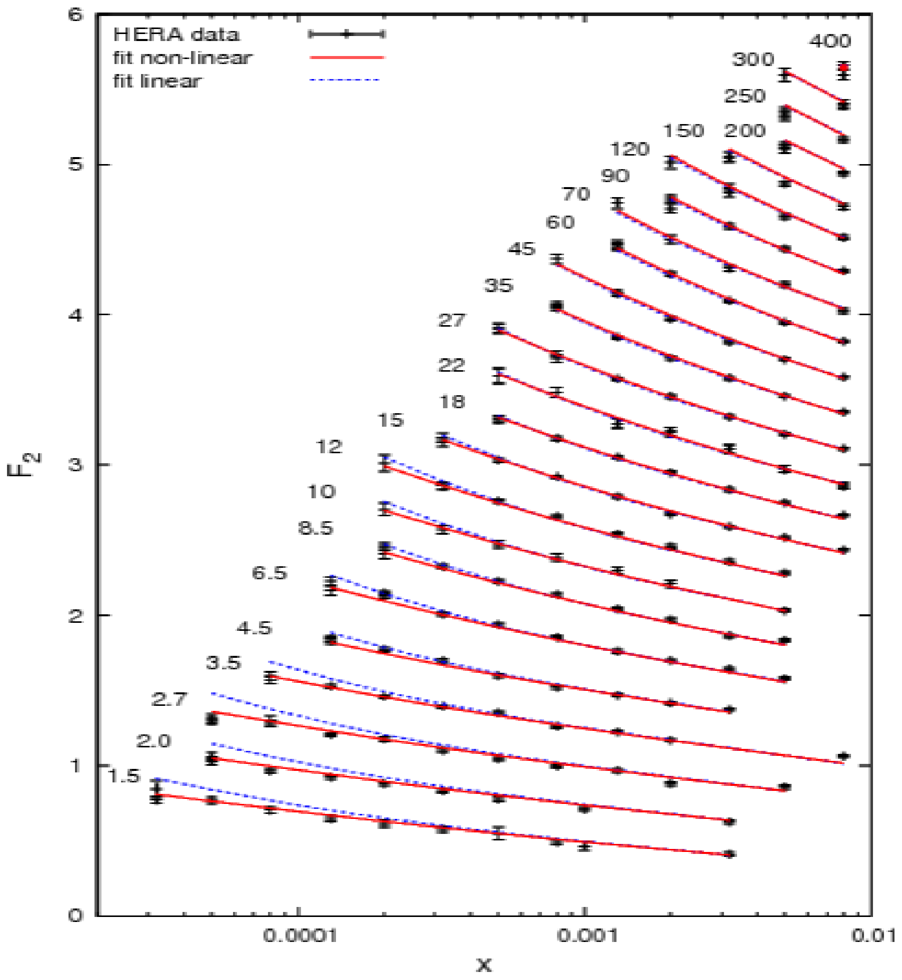
Nikolaev, Schafer '06

HEF framework applied to DIS



$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2}\alpha_s \sum_q e_q^2 \int d^2k\, \mathcal{F}(x,k^2)\left(S_L(k^2,Q^2,m_q^2) + S_T(k^2,Q^2,m_q^2)\right)$$

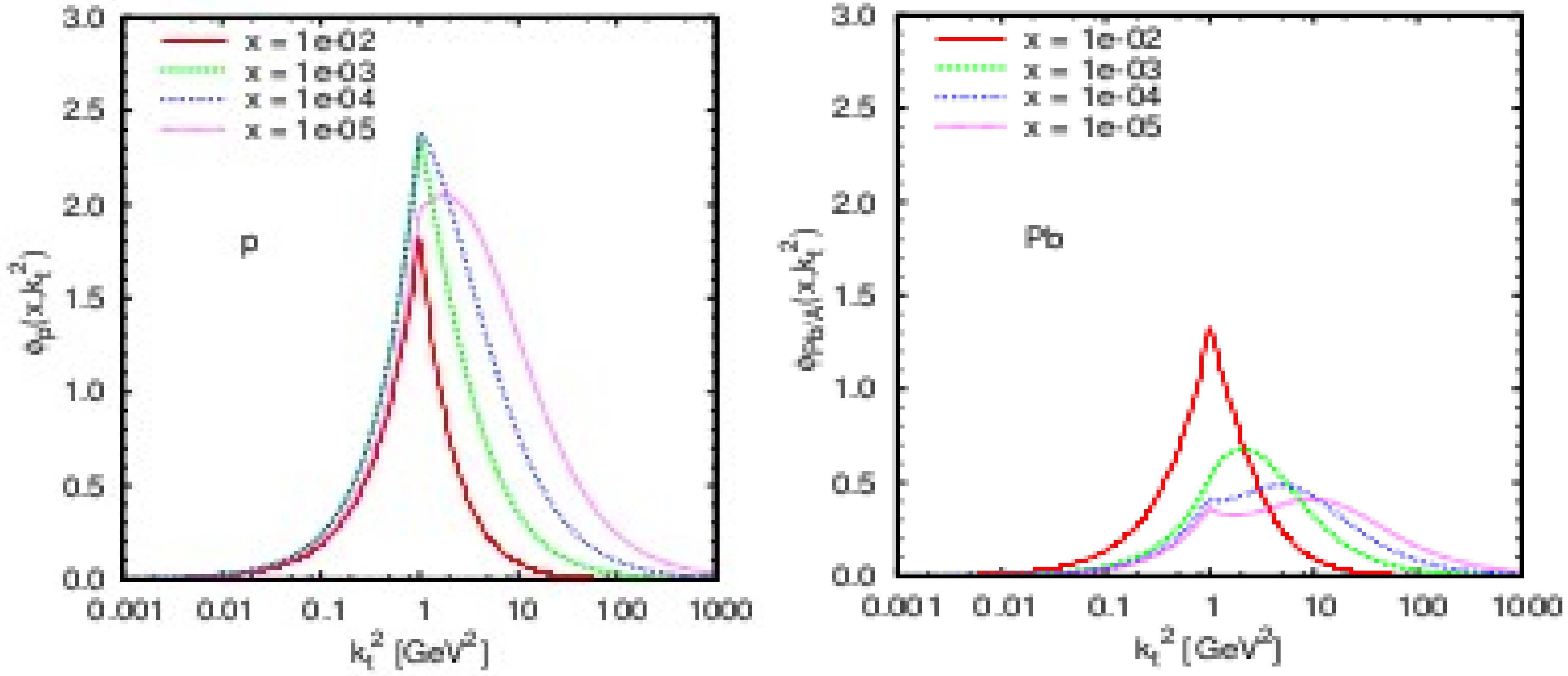
HEF framework applied to DIS



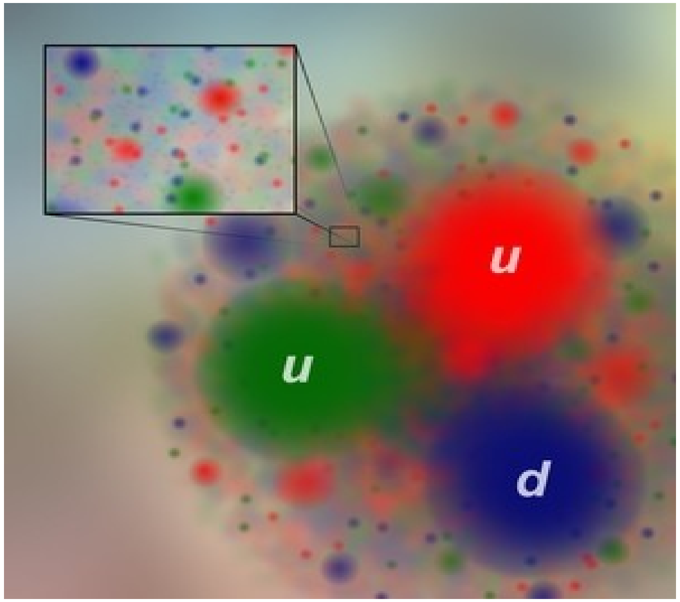
BK vs. BFKL equation with resummed corrections of higher order

Sapeta, KK '12

Glue in p vs. glue in Pb



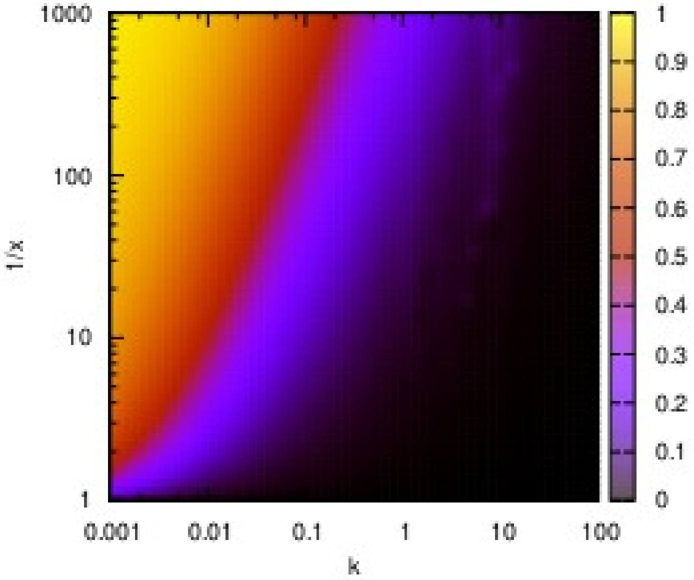
Hard scale dependence



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

Saturation scale in equation with coherence

BK

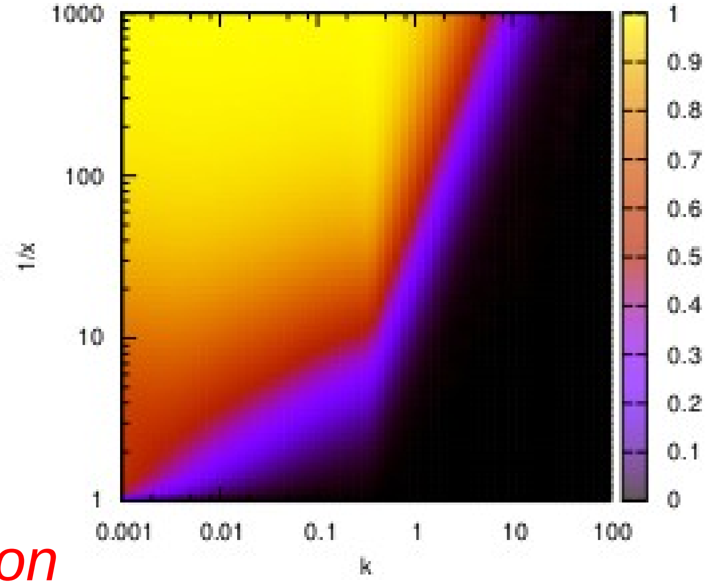


Avsar, Stasto '10
(absorbtive boundary method)

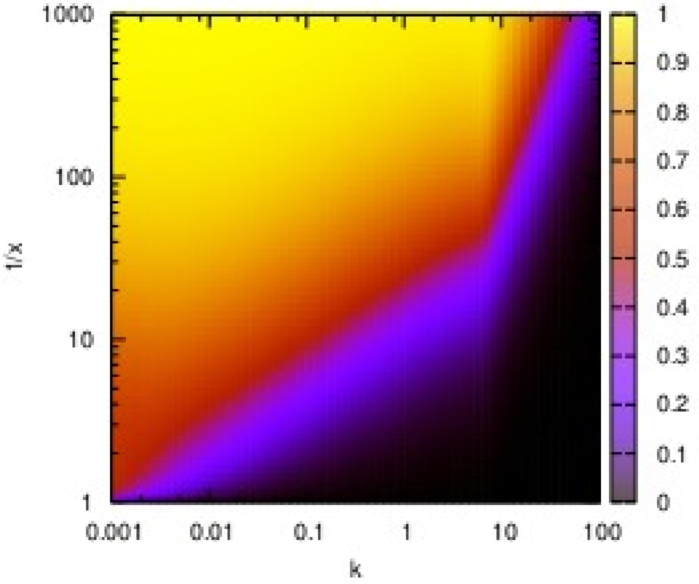
KK, Toton '13
(nonlinear equation)

CCFM – NL/R^2

R radius of proton

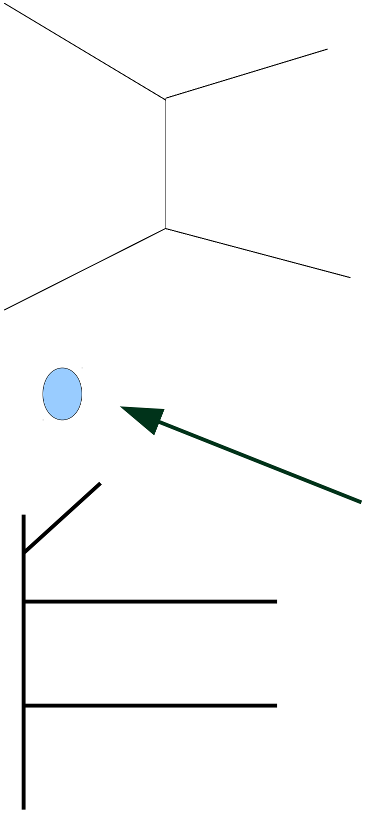


Hard scale=1GeV



Hard scale =10 GeV

Introducing hard scale dependence



Nonlinear extension of CCFM not applied so far to phenomenology

hard matrix element provides hard scale

Probability of finding no real gluon between scales Sudakov formfactor

Include the effect in the last step of evolution of BK nonlinear evolution equation

KK '14

Motivated by KMR framework

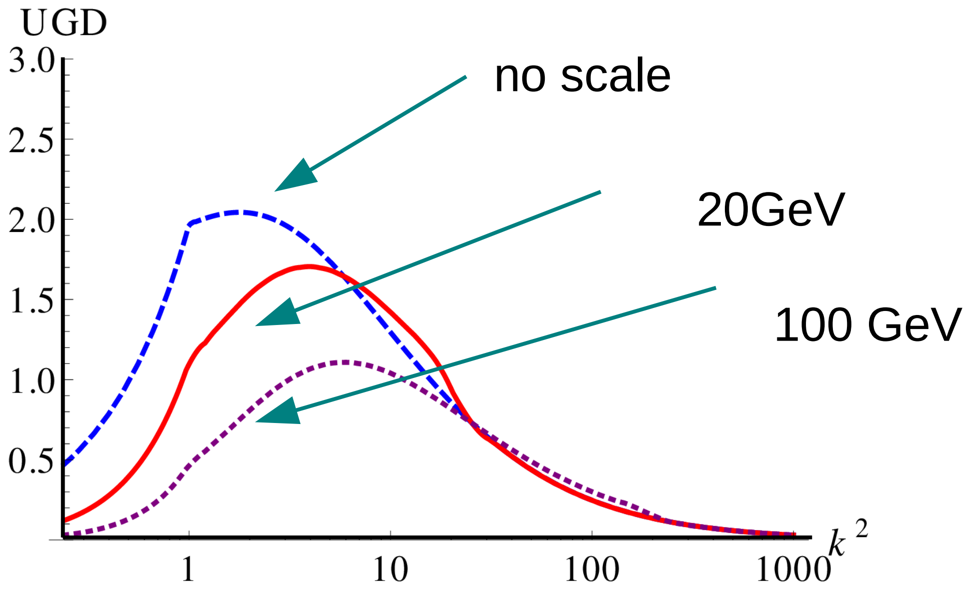
Kimber, Martin, Ryskin '01

Another approach by

Mueller, Yuan, Xiao '13

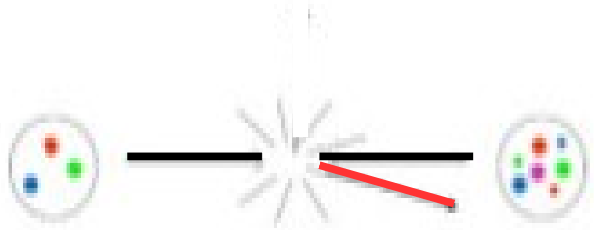
Saturation scale in equation with coherence forward-forward jets

K.K. '14

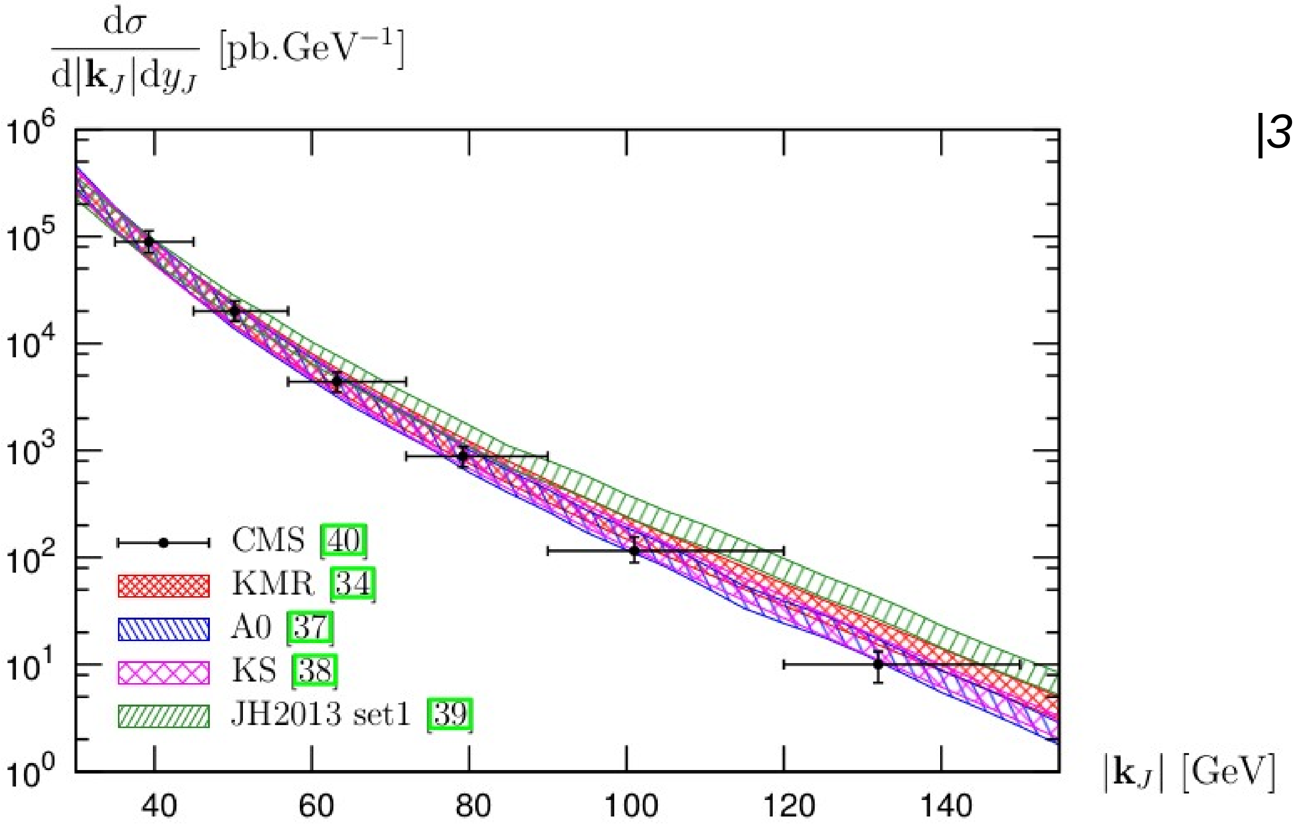


Low kt gluons are suppressed. The conservation of probability leads to change of shape of gluon density which depends on the hard scale

Inclusive-forward jet



Single inclusive p_t jet spectra



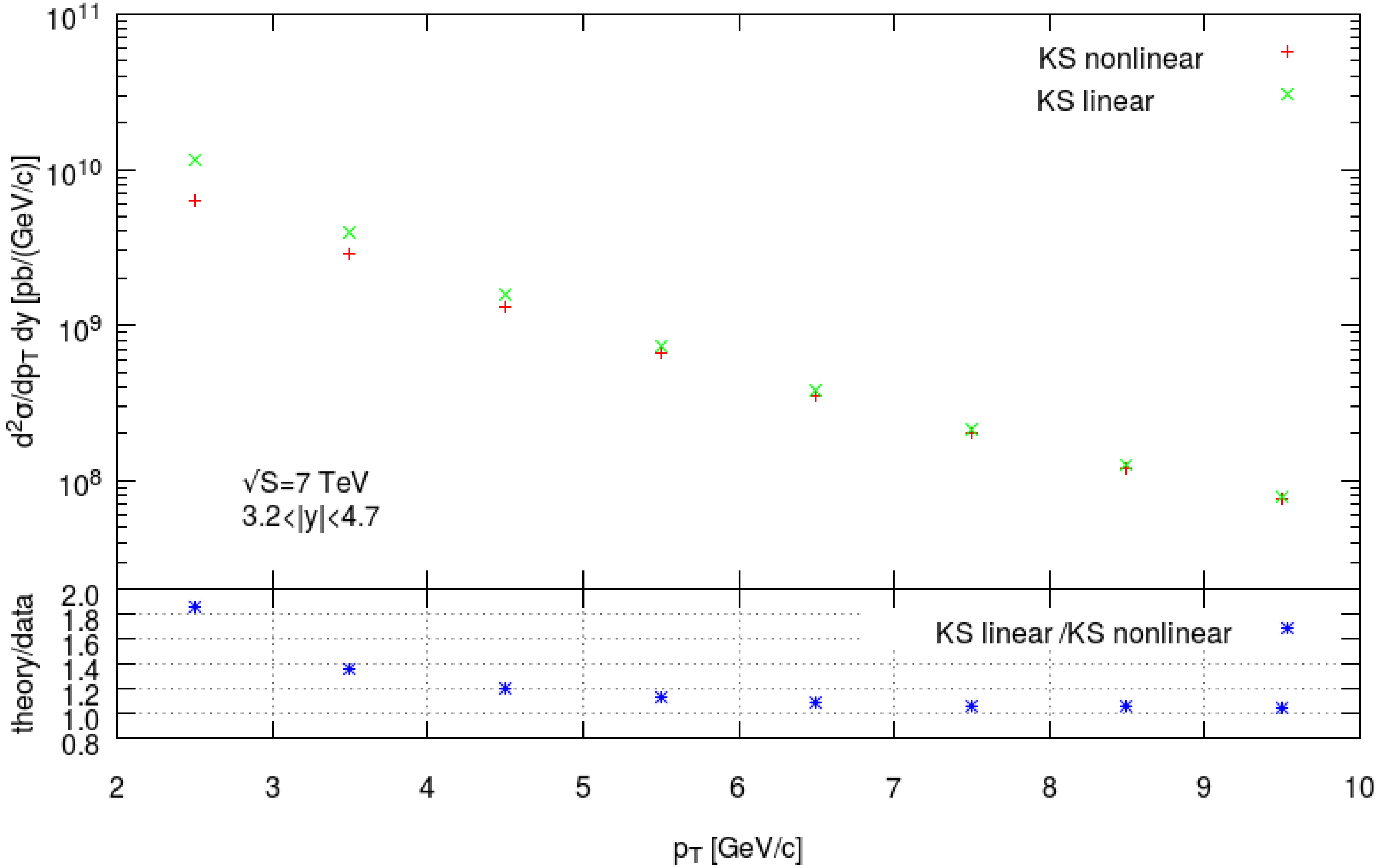
$|3.2| < y < |4.7|$

Decloue, Szymanowski, Wallon '15

$$\frac{d\sigma}{dy_1 dp_{1t}} = \frac{1}{2}\frac{\pi\, p_{1,t}}{(x_1 x_2 S)^2}\sum_{a,b,c}\overline{|\mathcal{M}_{ab\to c}|}^2 x_1 f_{a/A}(x_1,\mu^2)\,\mathcal{F}_{b/B}(x_2,p_{1t}^2,\mu^2)$$

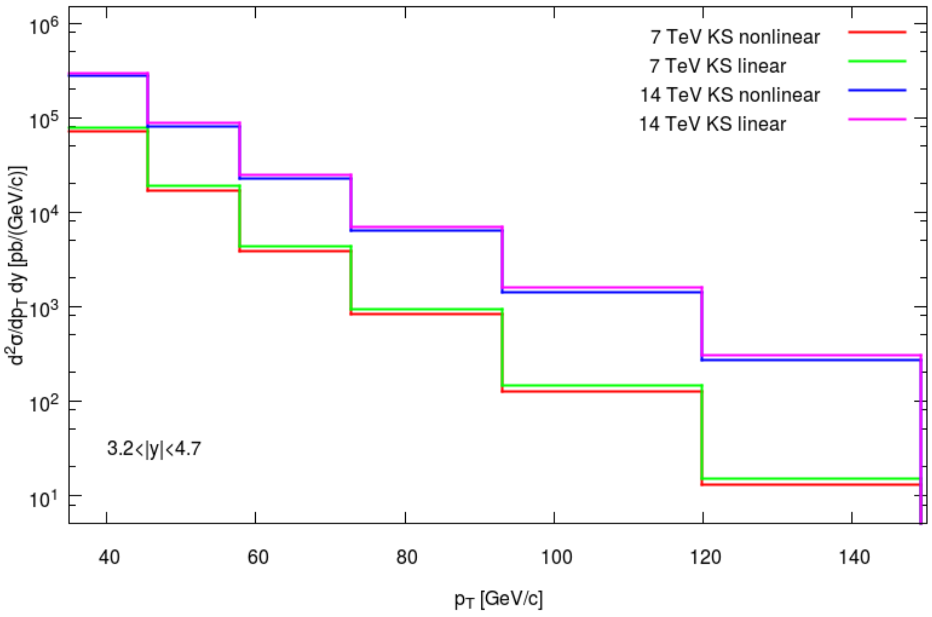
Extension to lower p_t jet spectra

Single inclusive forward jet

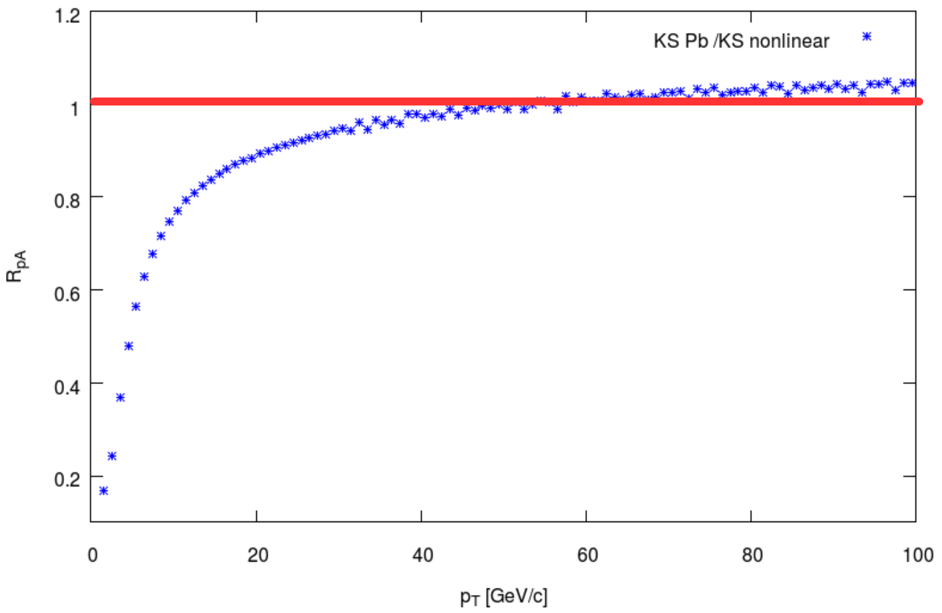


Di-jets p_t spectra at 14 TeV and RpA

Single inclusive forward jet

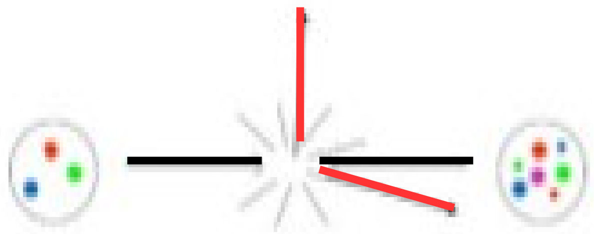


Nuclear modification ratio



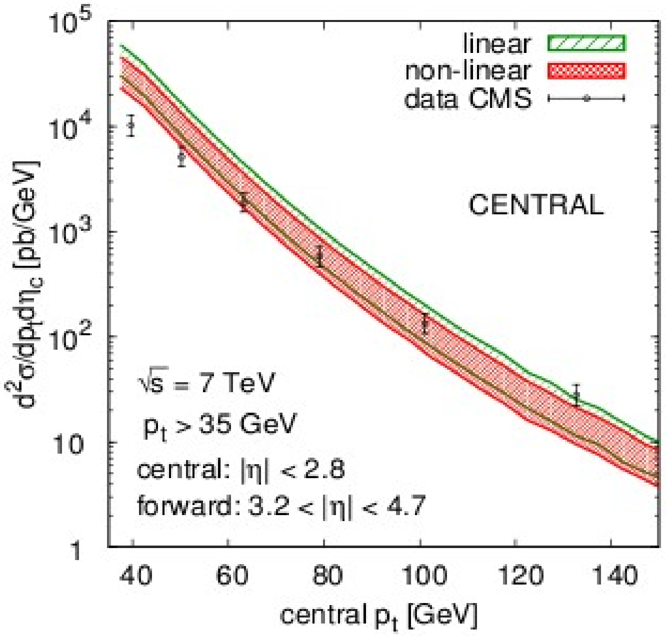
Bury, KK, Sapeta, to appear soon

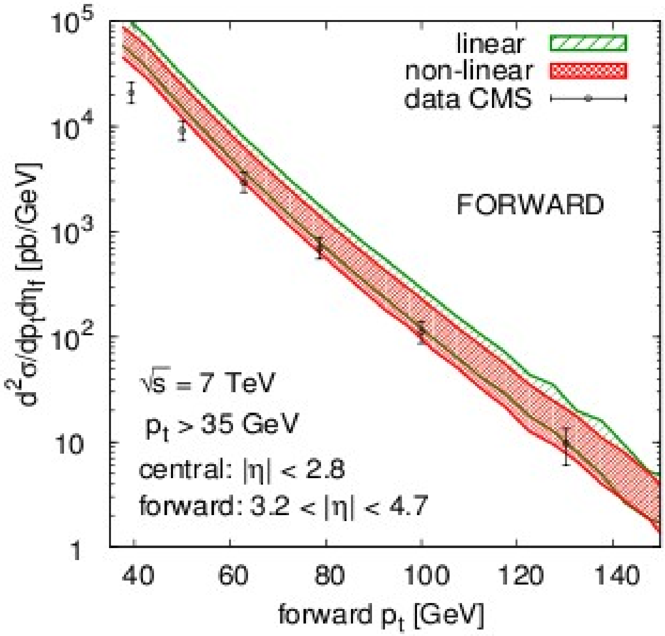
Central-forward di-jets



Di-jets p_t spectra

S.Sapeta. KK ,12

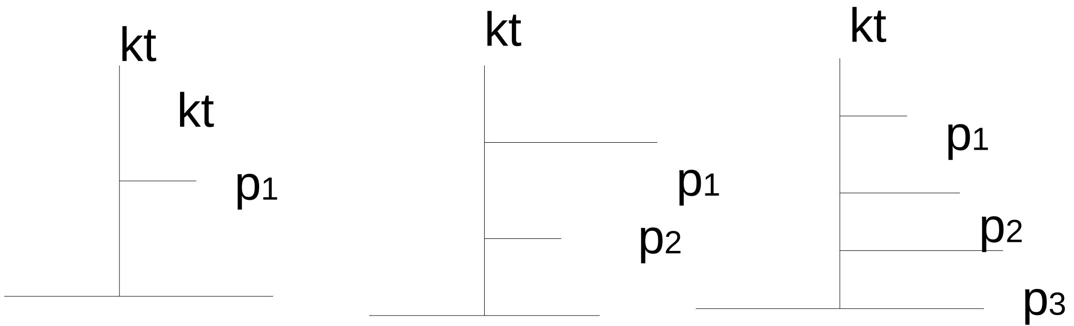




Reasonable agreement.

No usage of traditional parton shower

Gluon emissions are unordered in pt
and udd up to $k_t = |p_1+p_2+.....p_n|$

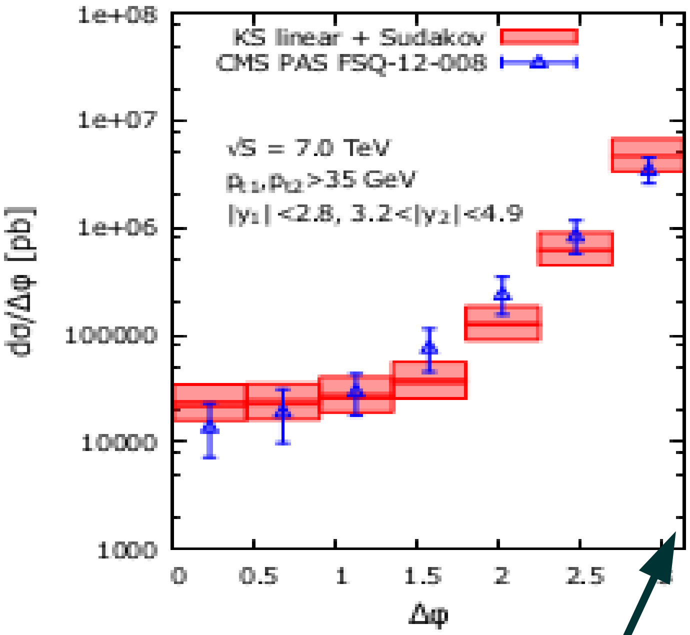


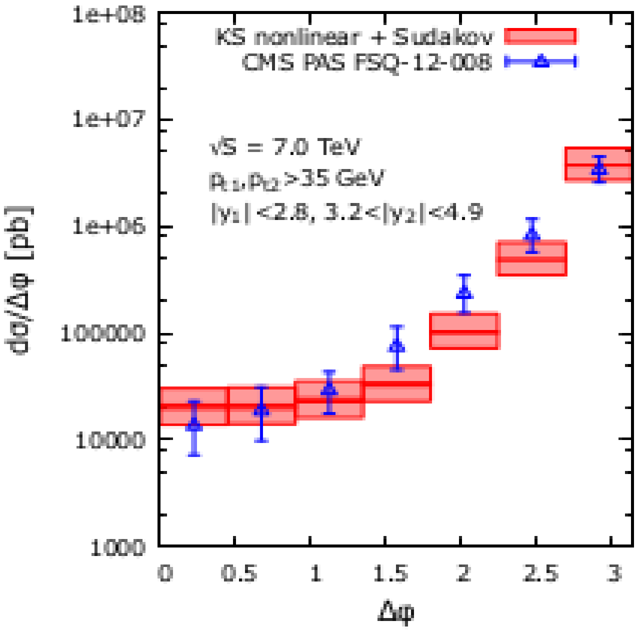
During evolution time incoming gluon becomes off-shell

Crucial effect of higher order corrections

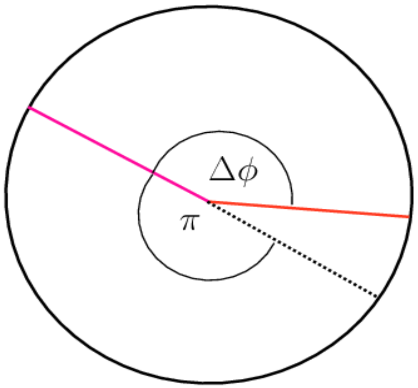
Decorelations inclusive scenario forward-central

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





pt1,pt2 >35, leading jets
|y1|<2.8, 3.2<|y2|<4.7
No further requirement on jets



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

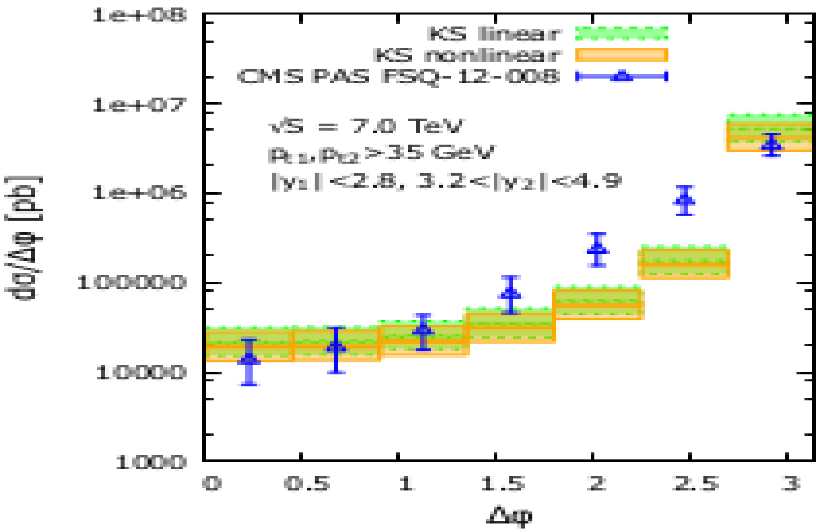
Sudakov effects by reweighing
implemented in LxJet Monte Carlo
P. Kotko

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

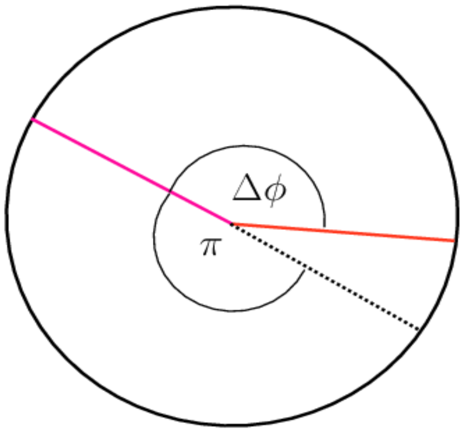
Studied also context of RHIC
Albacete, Marquet '10

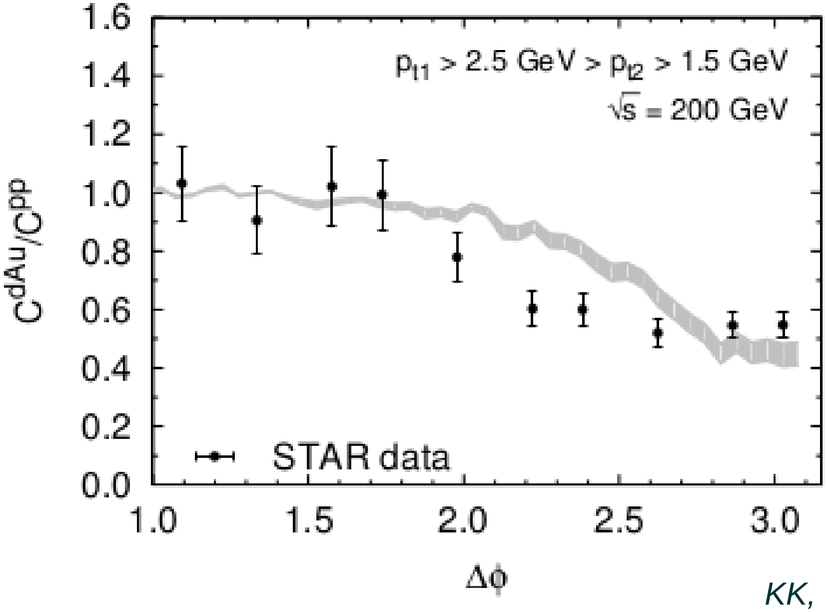
Forward-central decorelations inclusive scenario

A.van Hameren, P.Kotko, KK, S.Sapeta '14



pt_1,pt_2 > 35 GeV, leading jets
$|y_1| < 2.8$, $3.2 < |y_2| < 4.7$
No further requirement on jets



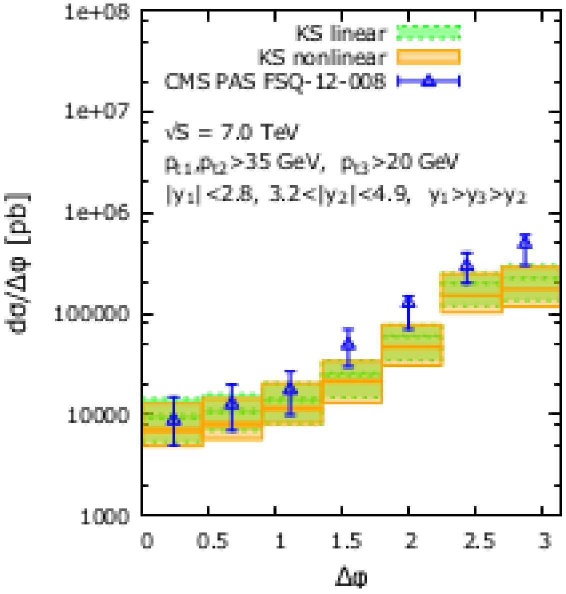


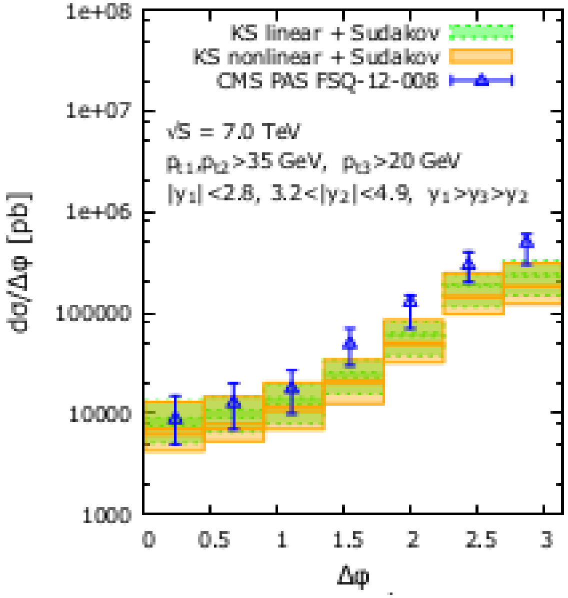
KK, Sapeta 12

No usage of fragmentation function.
just divided cross section for jets in d+Au by p+p

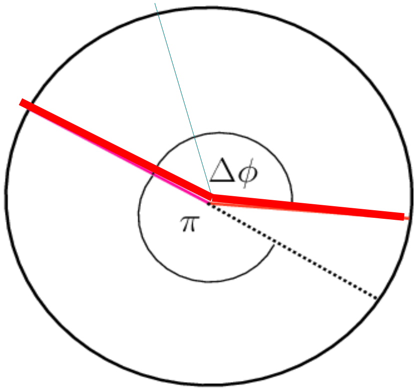
Decorelations inside jet tag scenario

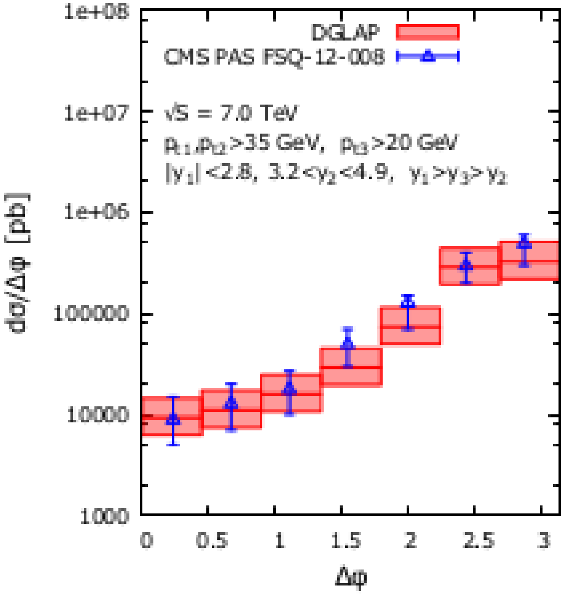
A.v.Hameren, P.Kotko, KK, S.Sapeta '14

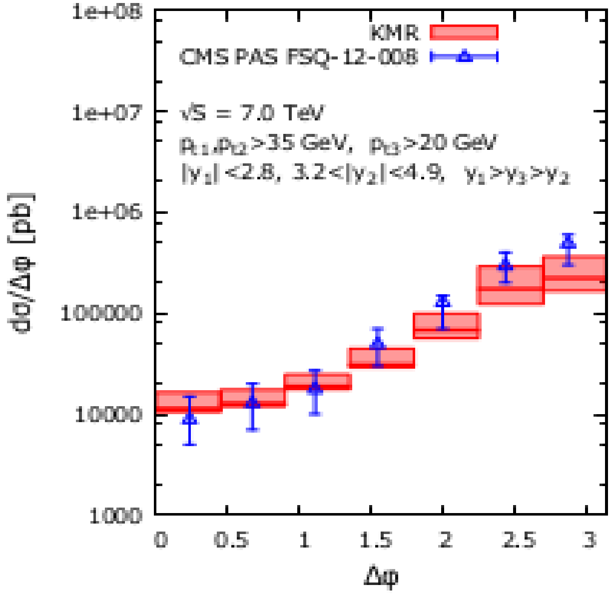




pt1, pt2 >35 GeV, leading jets |y1|<2.8, 3.2<|y2|<4.7 Third jet pt>20GeV. Between the forward and central region



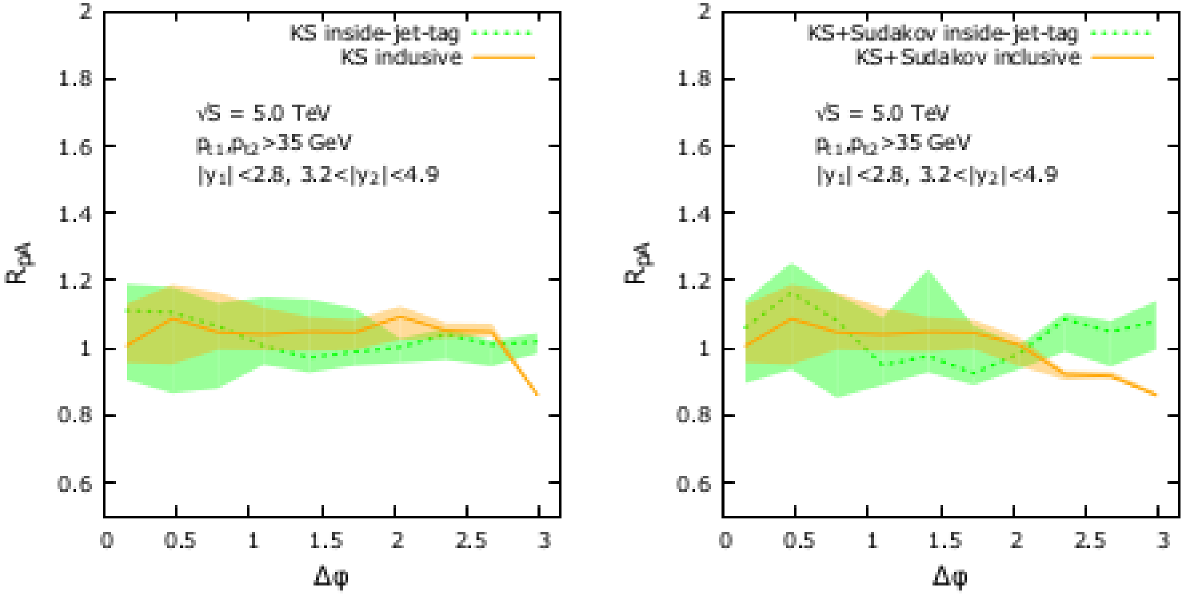




Sudakov effects by reweighting implemented in LxJet Monte Carlo P. Kotko

Predictions for p-Pb for forward-central

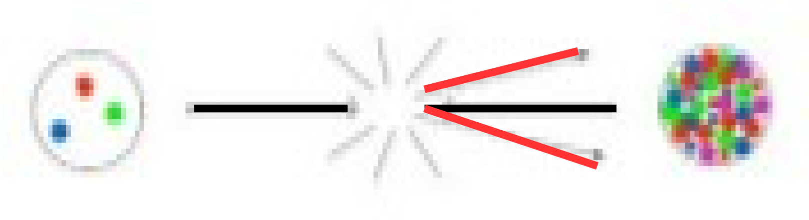
A.v.Hameren, P.Kotko, KK, S.Sapeta '14



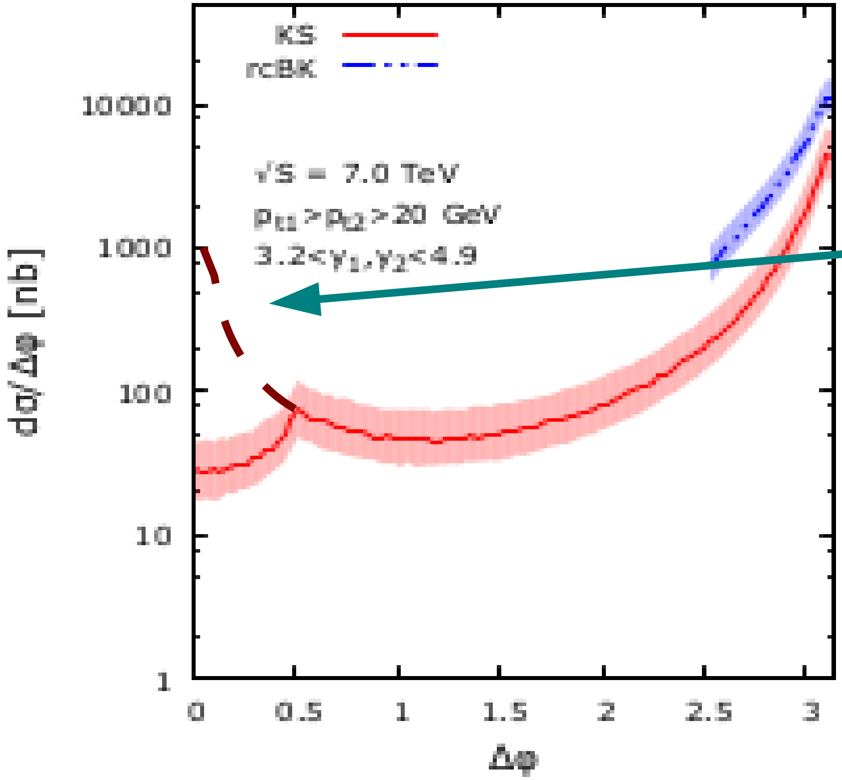
- *Sudakov enhances saturation effects*

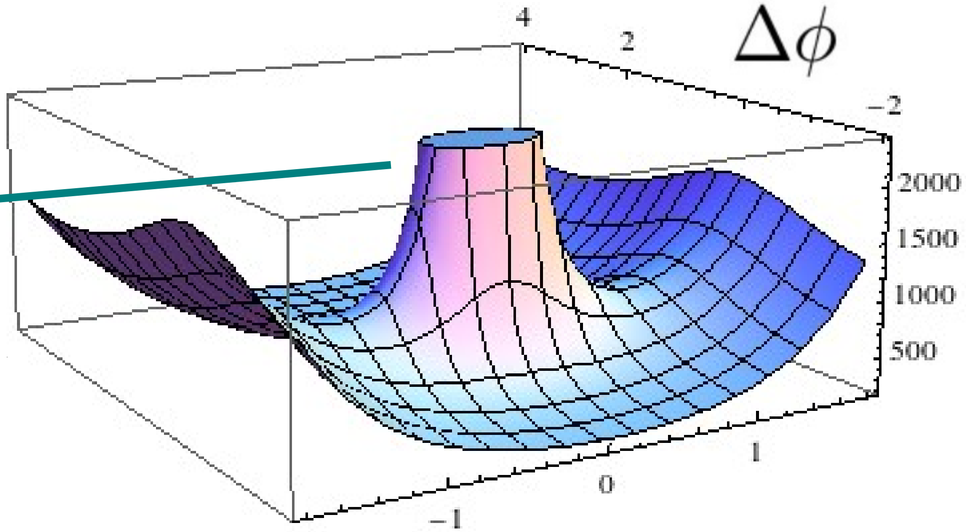
- *However, saturation effects are rather weak for forward-central jets*

Forward-forward di-jets

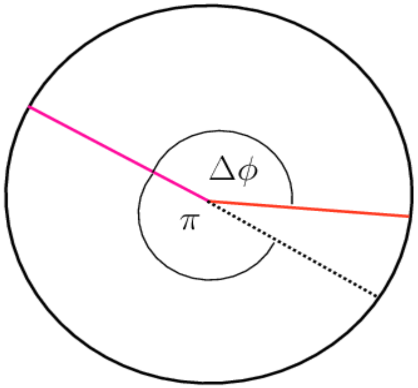


Results for decorelations



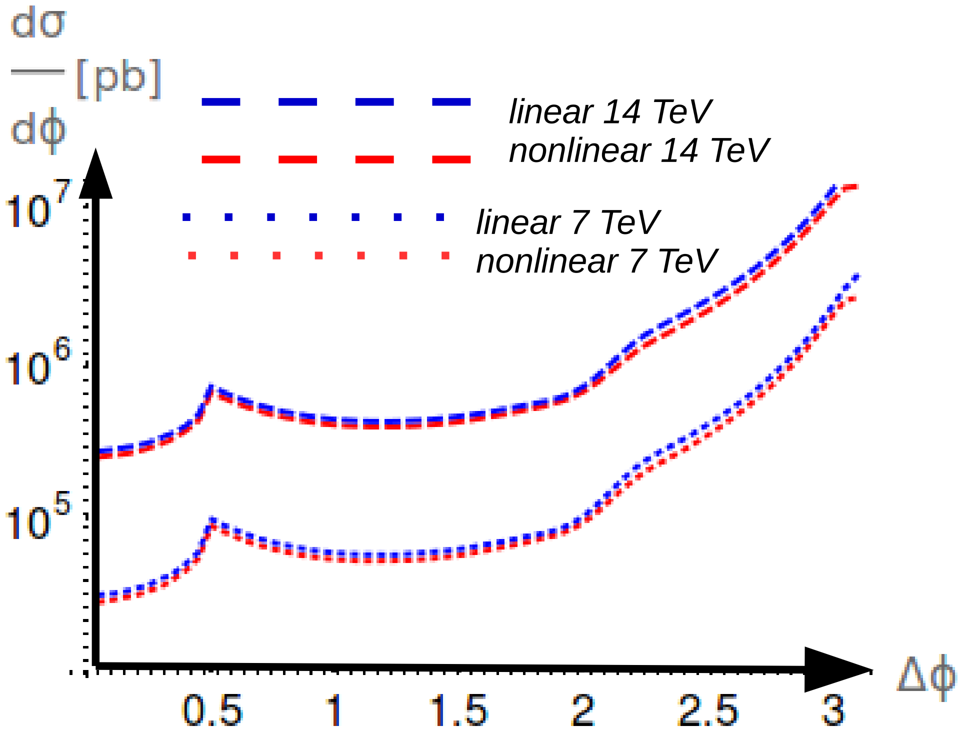


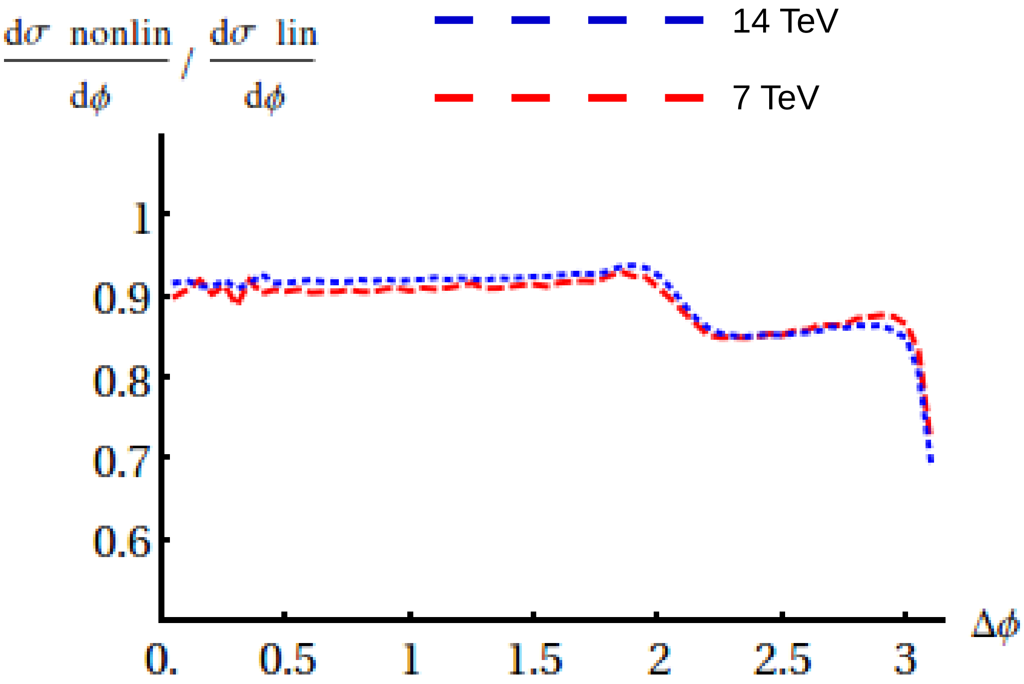
Divergence regularized by jet algorithm



Predictions for p-Pb for forward-forward

KK '14

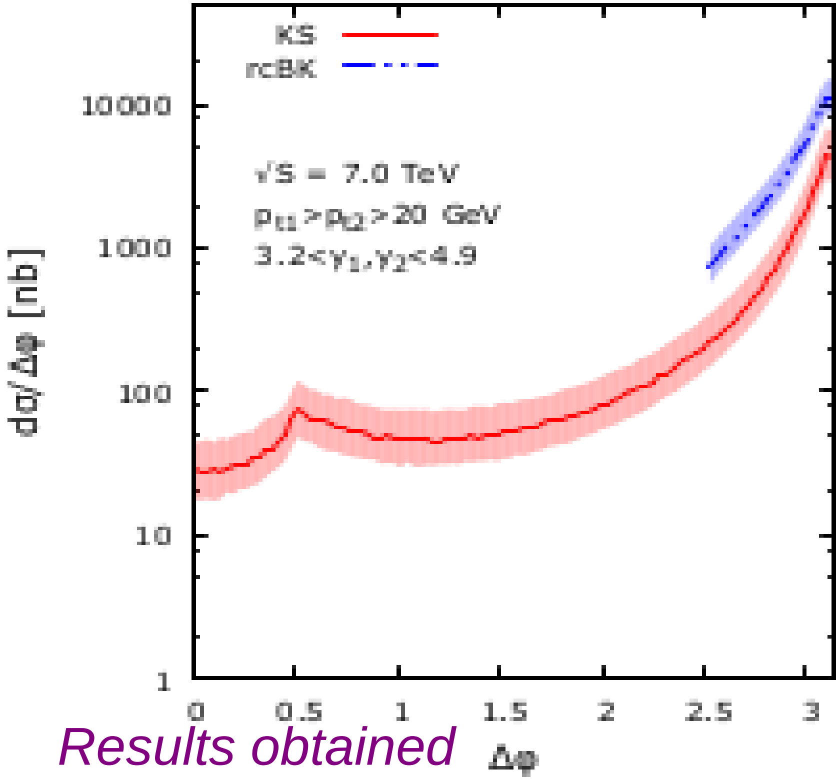




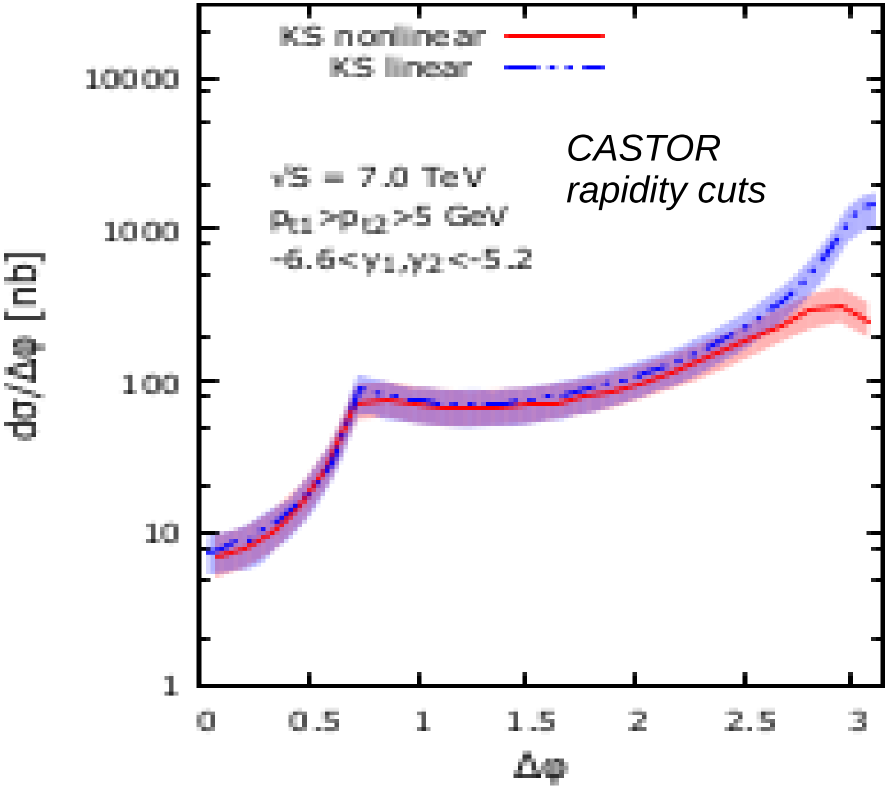
- *No significant change in shape after increasing energy from 7 TeV to 14 TeV*
- *Noticeable difference between linear and nonlinear scenario*

Results for decorelations

A. van Hameren, Kotko,KK,Marquet, Sapeta '14



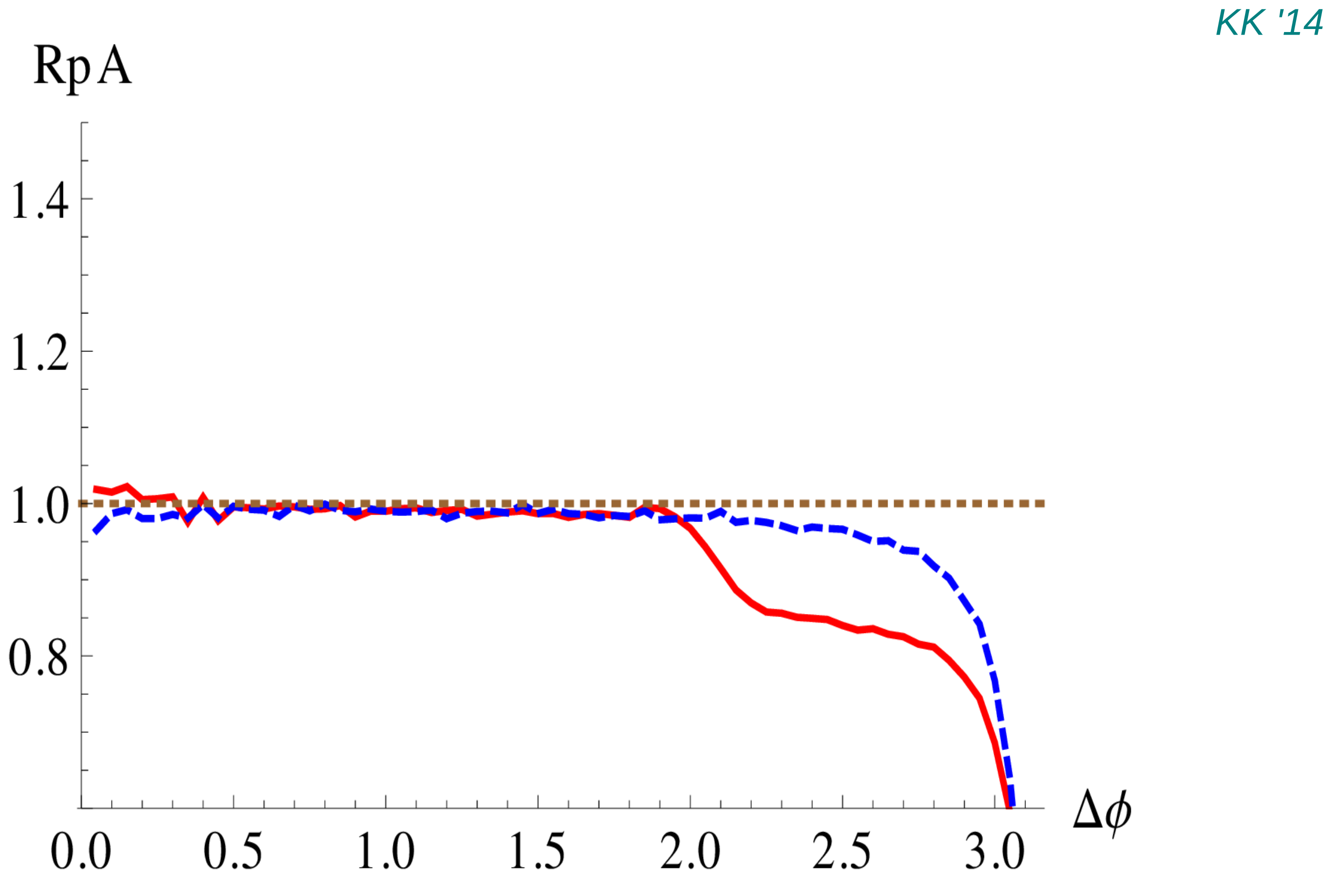
Results obtained with gluons coming from rcBK and BK with corrections of higher orders



CASTOR rapidity cuts

Kotko, KK ' 14

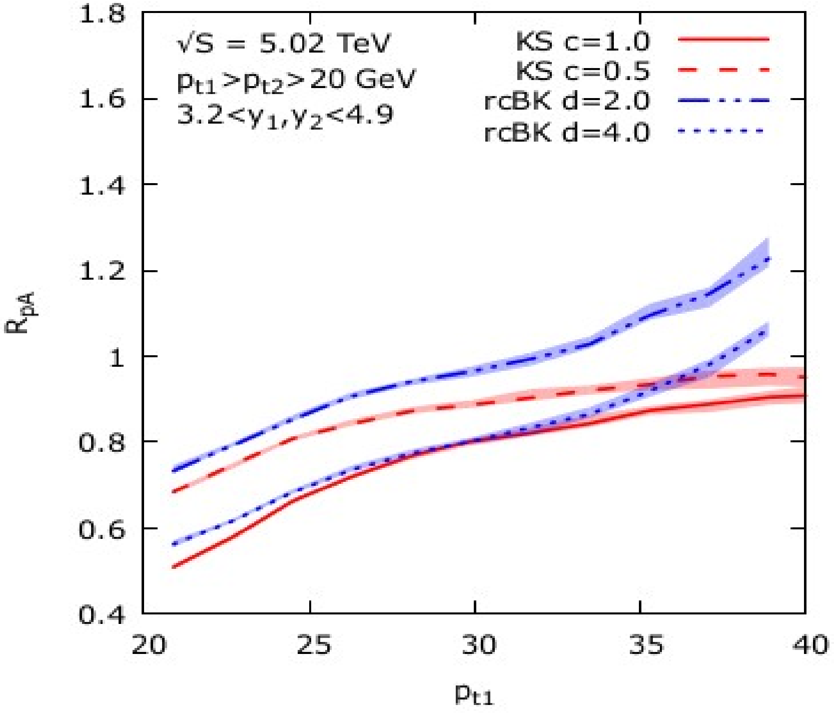
Predictions for p-Pb for forward-forward



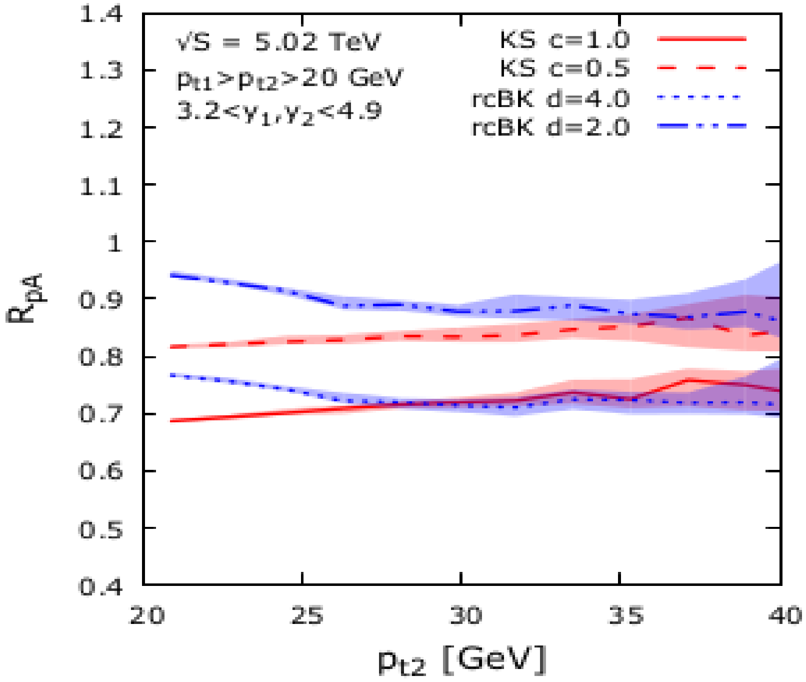
- *The hard scale effects make the potential signatures of saturation more pronounced.*
- *“p+Pb” affected more by saturation than “p+p” therefore we see more significant effect.*

Forward-forward dijets

A. van Hameren, Kotko,KK,Marquet, Sapeta '14



rcBK: above unity at large pt
KS: reaches unity at large pt



Studies of sub-leading jet gives more pronounced signal of nonlinear effects.

Recent theoretical developments

The used formula for dijets is valid in linear regime. Reults for dijets based on it with usage of gluon density coming from nonlinear equation give estimate of strength of saturation.

$$\frac{d\sigma}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \sum_{a,c,d} \frac{p_{t1}p_{t2}}{8\pi^2 (x_1 x_2 S)^2} \overline{|\mathcal{M}_{ag\to cd}|}^2 x_1 f_{a/A}(x_1,\mu^2)\,\mathcal{F}_{g/B}(x_2,k^2,\mu^2)\frac{1}{1+\delta_{cd}}$$

Gauge invariant operator based definition of parton densities and specific color structure of particular hard process leads leads to following generalization of formula above. This follows from papers of *Bomhof, Mulders and Pijlman 2006.*

$$\frac{d\sigma^{pA\to qgX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\, x_1 f_{q/p}(x_1,\mu^2) \sum_{i=1}^{2} \mathcal{F}_{qg}^{(i)} H_{qg\to qg}^{(i)}$$

$$\frac{d\sigma^{pA\to q\bar{q}X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\, x_1 f_{g/p}(x_1,\mu^2) \sum_{i=1}^{3} \mathcal{F}_{gg}^{(i)} H_{gg\to q\bar{q}}^{(i)}$$

$$\frac{d\sigma^{pA\to ggX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\, x_1 f_{g/p}(x_1,\mu^2) \sum_{i=1}^{6} \mathcal{F}_{gg}^{(i)} H_{gg\to gg}^{(i)}$$

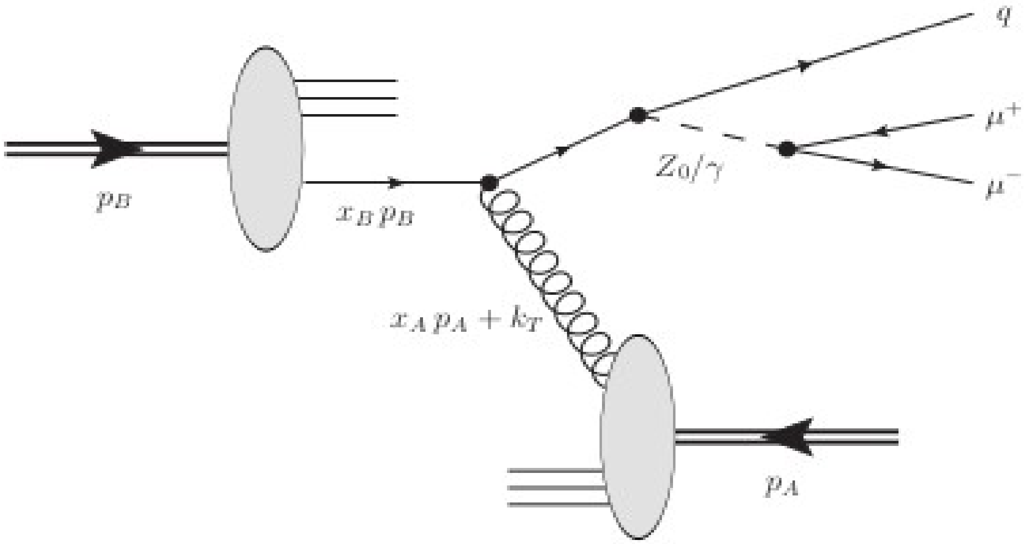
$$P_t = (1-z)p_{1t} - zp_{2t} \qquad z = \frac{p_1^+}{p_1^+ + p_2^+}$$

No kt in ME, finite Nc
Dominguez, Marquet, Xiao, Yuan '11

Application to differential distributions in d+Au
Stasto, Xiao, Yuan '11

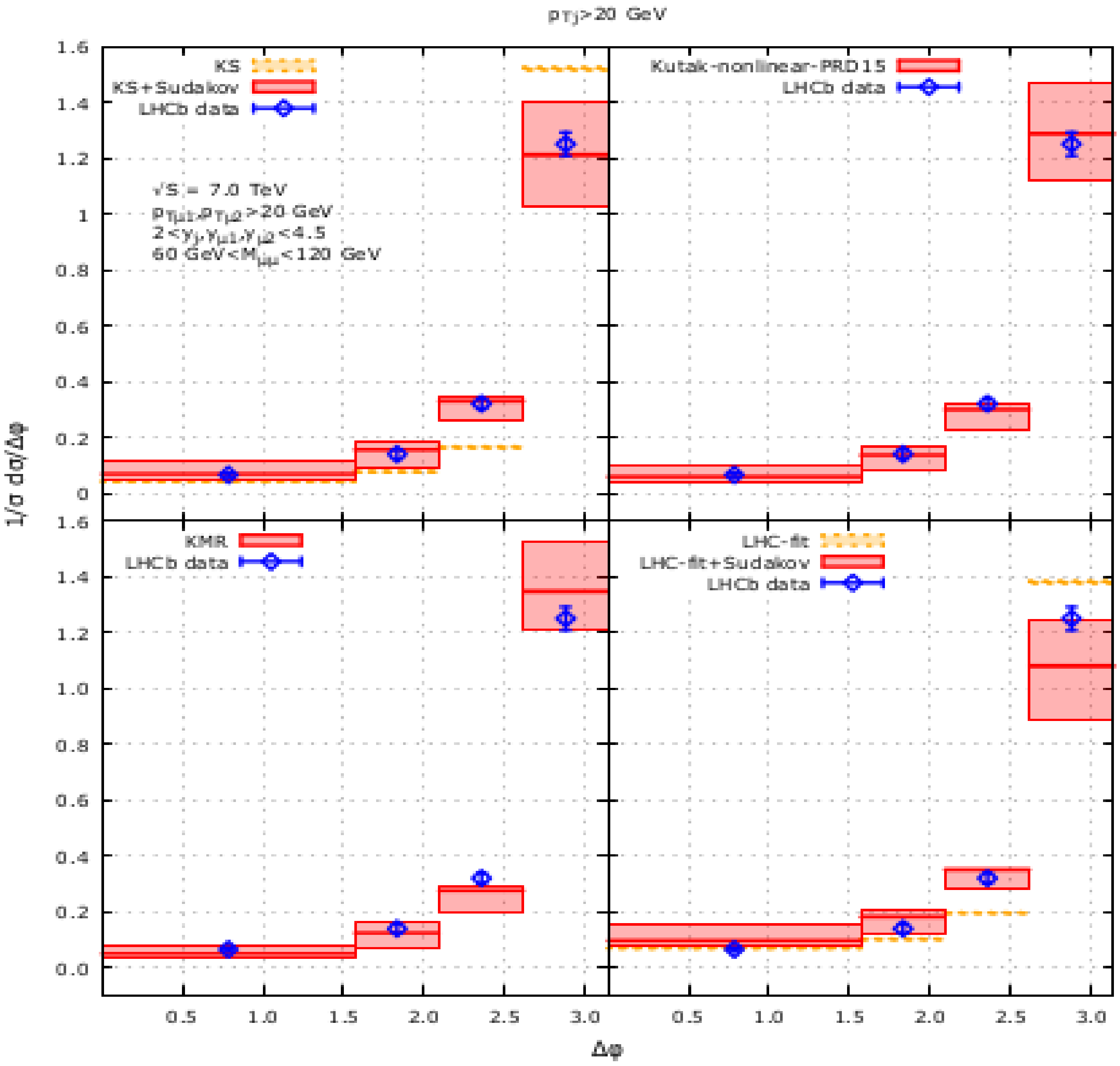
kt in ME finite Nc
Kotko, KK, van Hameren, Marquet, Petreska, Sapeta '15 (kt in ME, finite Nc)

Production of Z + jet

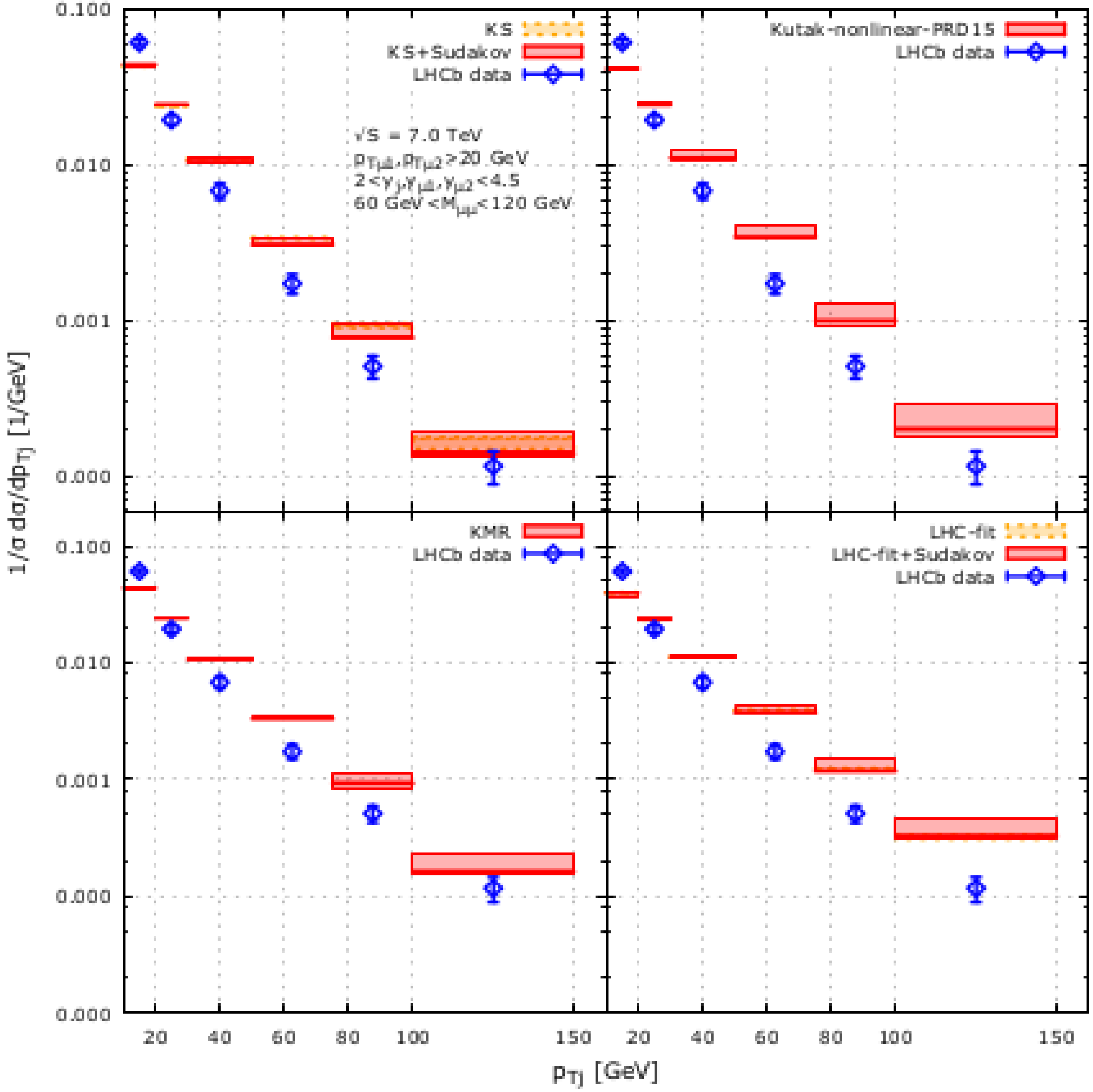


Van Hameren, KK, Kotko '15

Decorelations

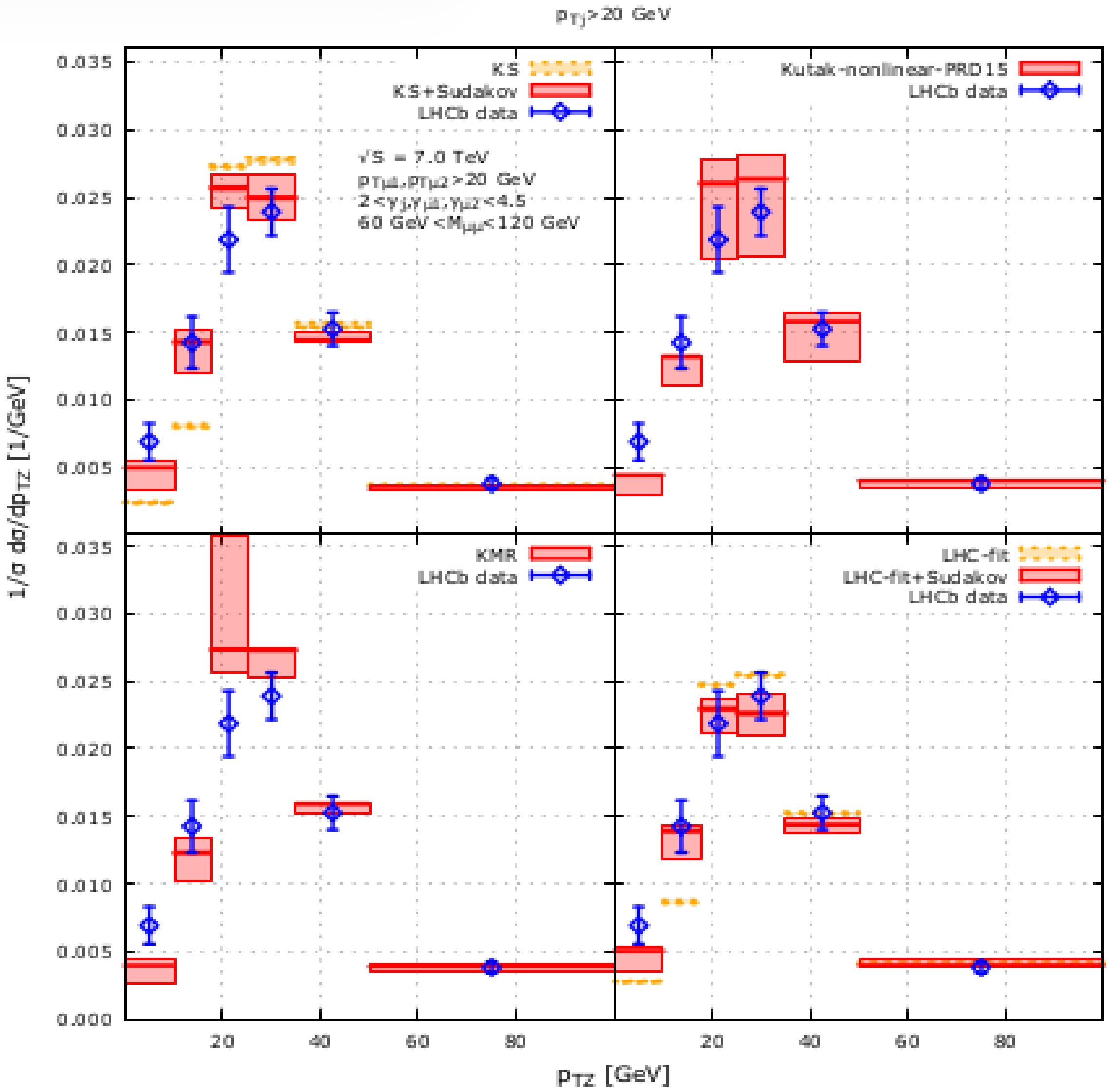


Pt of jet



Tendency in agreement
but not too good description
Possible effects of
final state interactions.
Color recombination.

Pt of Z



Colorless final state.
No color rescatterings.
Description OK

Conclusions and outlook

- *Our framework describes well:*

    F_2, single inclusive jet production, Z0 + jet

- *Predictions for forward-forward dijets in pPb are provided*

- *Spectrum of subleading jet from dijets might provide strong signal of suppression due to initial state effect*

- *Necessary to calculate spectra using recent theoretical advancements*