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NCN

Perspectives for finding signatures of saturation with forward-forward dijets at LHC

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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,

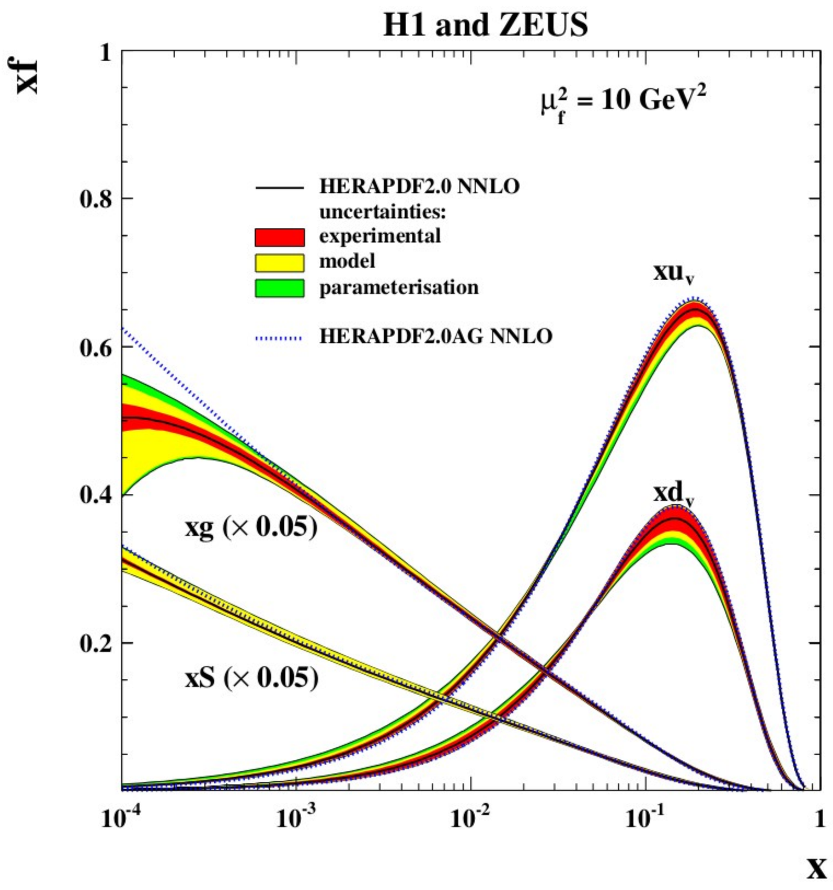
Phys.Lett. B737 (2014) 335-340, A. van Hameren, P. Kotko, K. Kutak, S. Sapeta

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

Structure of the proton

For example: DIS experiments at DESY



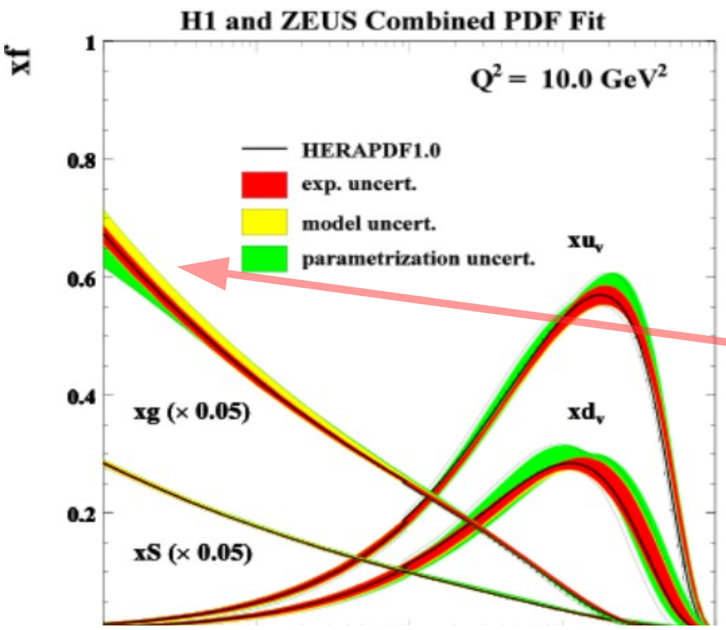
1506.06042

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

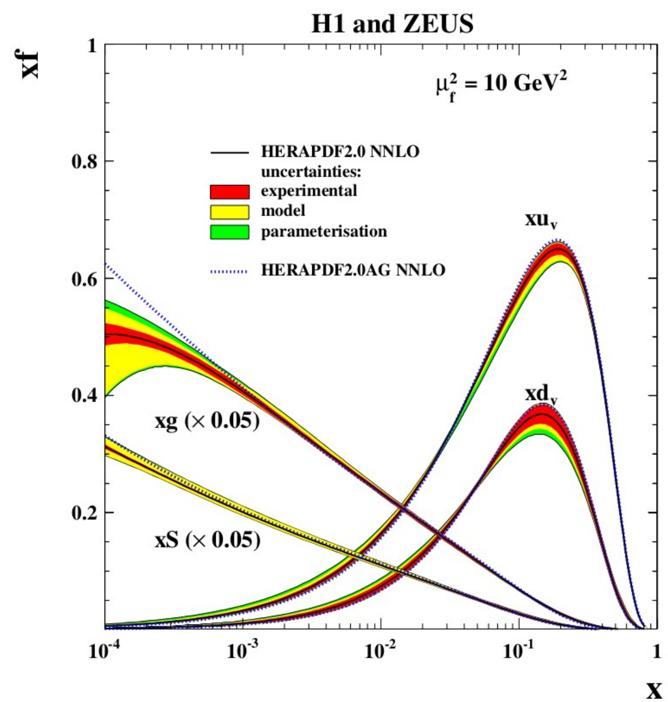
Unitarity problem arises



0911.0884

Original motivation → power like growth of gluon density which may lead to violation of unitarity bound.

Another possible motivation → corrections which introduce saturation follow from certain order of diagrams in perturbation theory when energy ordering is applied



kt in ME, finite Nc

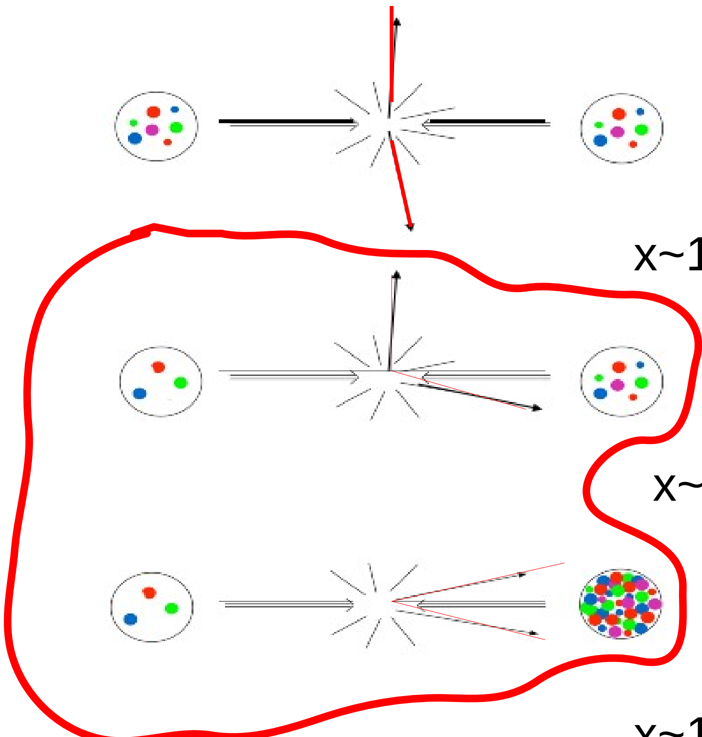
1506.06042

NNLO collinear effects have large impact on gluon

Recently the valence quarks PDF has been calculated directly on lattice.
Idea by Ji '14

Numerical results ETMC 1504.07455

LHC as a scanner of gluon



central-central i.e. dilute dilute

$x \sim 10^{-4}$

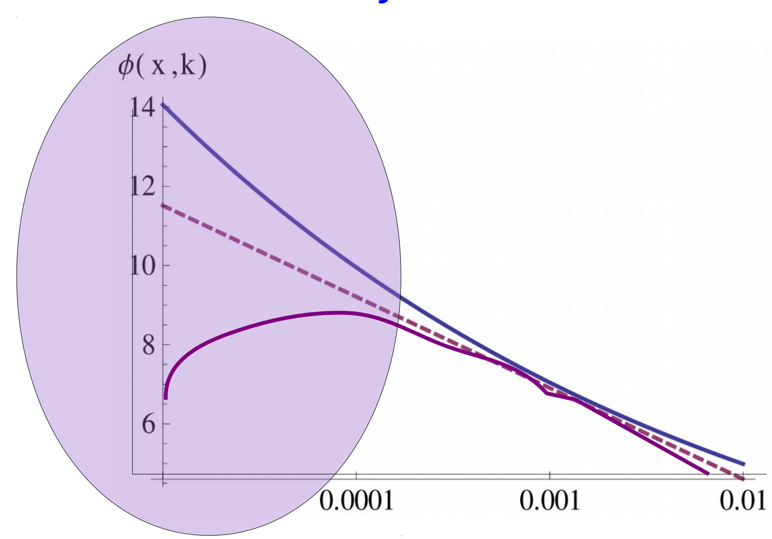
forward-central i.e. dilute – not so dense

$x \sim 10^{-4}$

forward-forward i.e. dilute -dense

$x \sim 10^{-5}$

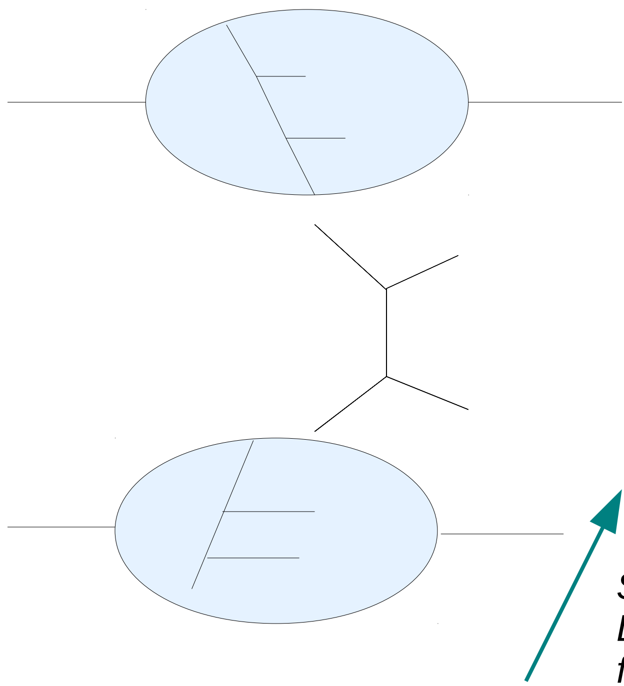
Gluon density



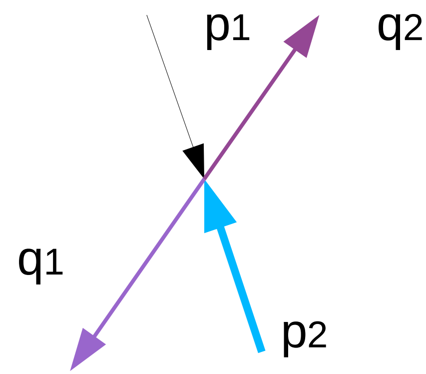
dense

dilute

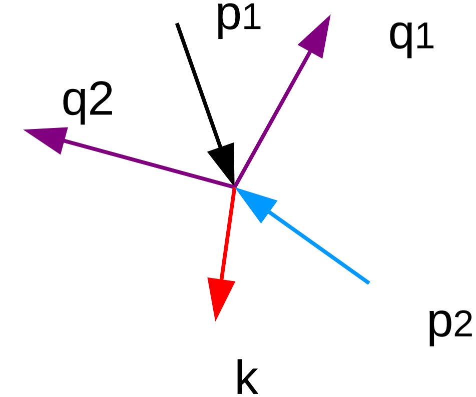
QCD at high energies – high energy factorization



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...

QCD at high energies – high energy factorization

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{a,b,c,d} \int \frac{d^2k_{1t}}{\pi}\frac{d^2k_{2t}}{\pi}\frac{1}{16\pi^2(x_1x_2S)^2}\overline{|\mathcal{M}_{ab\to cd}|}^2 \delta^2(\vec{k}_{1t}+\vec{k}_{2t}-\vec{p}_{1t}-\vec{p}_{2t})$$

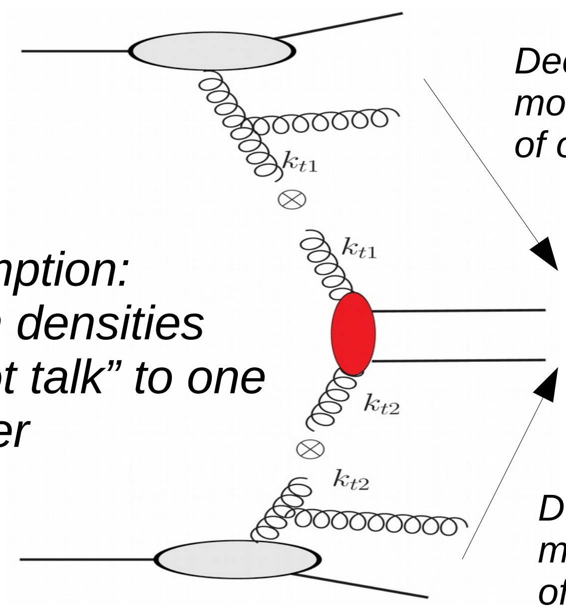
$$\times \mathcal{F}_{a/A}(x_1,k_{1t}^2,\mu^2)\,\mathcal{F}_{b/B}(x_2,k_{2t}^2,\mu^2)\,\frac{1}{1+\delta_{cd}}$$

$$k_1^\mu = x_1 P_1^\mu + \bar{x}_1 P_2^\mu + k_{1t}^\mu \qquad k_2^\mu = x_2 P_2^\mu + \bar{x}_2 P_1^\mu + k_{2t}^\mu$$

$$\bar{x}_1 = \frac{k_1^2+\mathbf{k}^2}{Sx_1} \qquad \bar{x}_2 = \frac{k_2^2+\mathbf{k}^2}{Sx_2}$$

$$|\mathcal{M}_{ab\to cd}|^2 = \frac{2x_1k_1^{\mu_1}k_1^{\nu_1}}{k_1^2}\frac{2x_2k_2^{\mu_2}k_2^{\nu_2}}{k_2^2}\mathcal{M}_{ab\to cd\,\mu_1\nu_1}\mathcal{M}^*_{ab\to cd\,\mu_2\nu_2}$$

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



Decreasing longitudianl momentum fractions of off-shell partons

Decreasing longitudianl momentum fractions of off-shell partons

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

Originally derived for heavy quarks in final state.
Therefore no problem of division into density and ME
gluons more tricky.

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

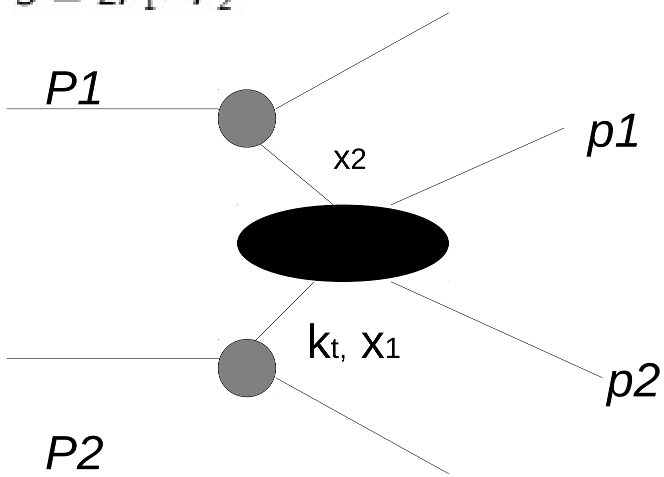
Hybrid factorization and dijets

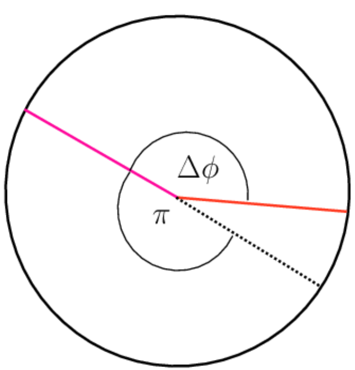
$$\frac{d\sigma}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \sum_{a,c,d} \frac{p_{t1} p_{t2}}{8\pi^2 (x_1 x_2 S)^2} \overline{|\mathcal{M}_{ag\to cd}|}^2 x_1 f_{a/A}(x_1, \mu^2)\, \mathcal{F}_{g/B}(x_2, k^2, \mu^2) \frac{1}{1+\delta_{cd}}$$

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

Deak, Jung, KK, Hautmann '09

$S = 2P_1 \cdot P_2$





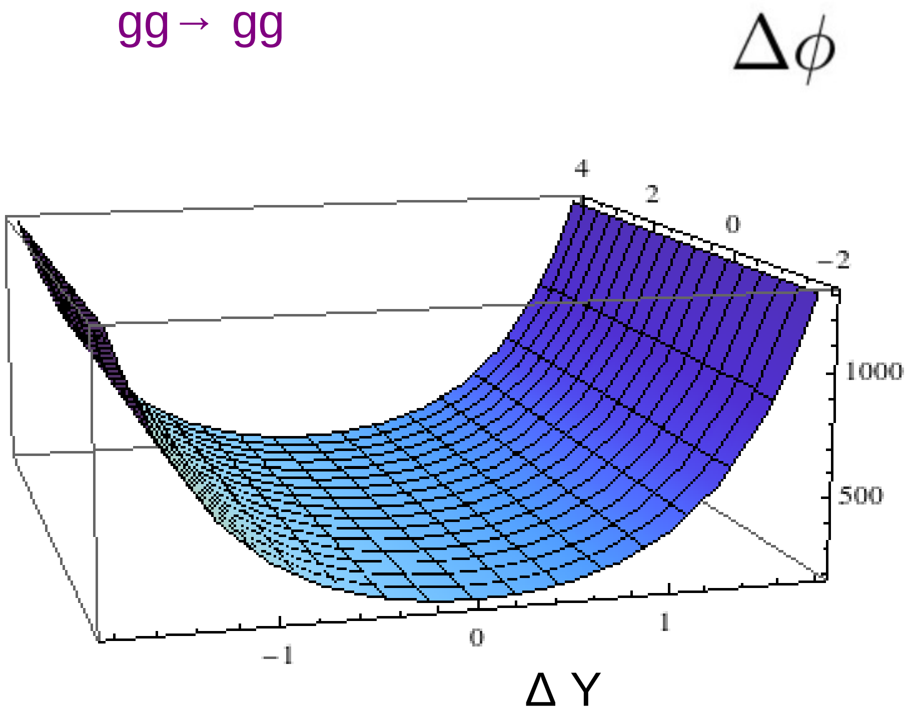
$$\mathcal{F}(x, k^2) = \frac{C_F}{\alpha_s (2\pi)^3} \int d^2\mathbf{b}\, d^2\mathbf{r}\, e^{-i\mathbf{k}\cdot\mathbf{r}} \nabla_r^2 N(\mathbf{r}, \mathbf{b}, x)$$

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

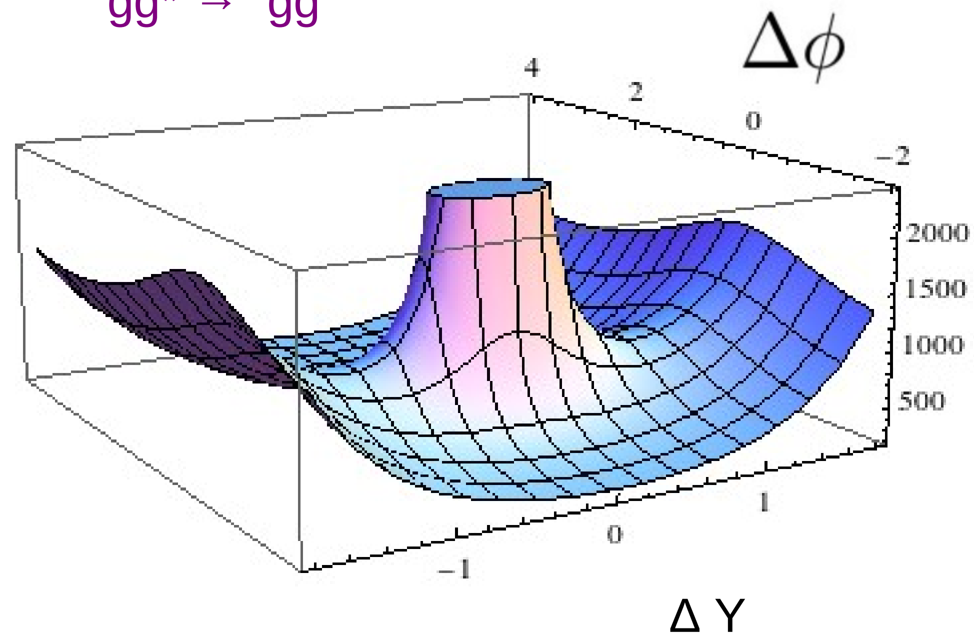
- *Resummation of logs of x and logs of hard scale*
- *Knowing well parton densities at large x one can get information about low x physics*

Collinear vs. off-shell ME

gg → gg



gg* → gg



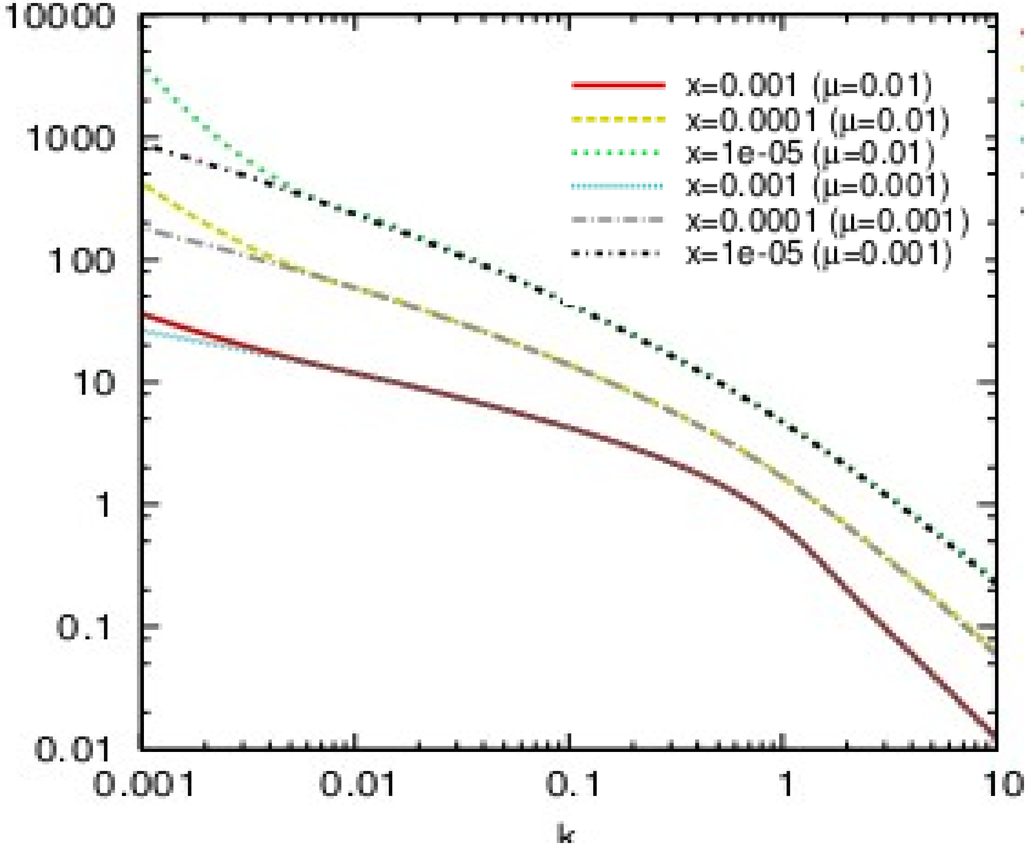
Collinear 2 → 2 ME

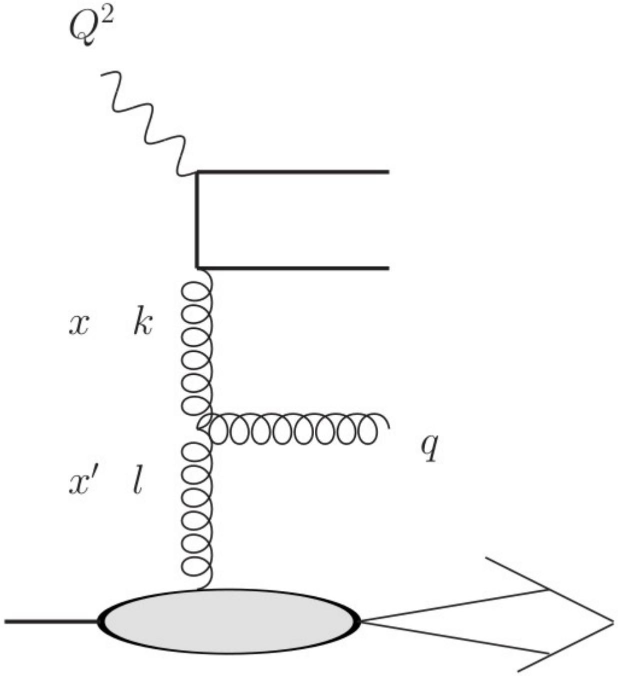
$$M = \frac{32\,\pi^2\,\alpha^2\,\left(e^{-\Delta y}+1\right)^2\left(e^{\Delta y}\left(e^{\Delta y}+1\right)+1\right)^2 \mathrm{Nc}^2\,\left(-2\cosh(\Delta y)-1\right)}{\left(e^{\Delta y}+1\right)^2\left(\mathrm{Nc}^2-1\right)\left(-\cosh(\Delta y)-1\right)}$$

One off-shell parton 2 → ME

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

The LO BFKL equation





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

when k >> l →

$$\mathcal{F}(x,k^2) = \mathcal{F}_0(x,k^2) + \bar{\alpha}_s \int_{x/x_0}^{1} \frac{dz}{z} \int_{k_0^2}^{k^2} dl^2 \frac{\mathcal{F}(x/z,l^2)}{k^2}$$

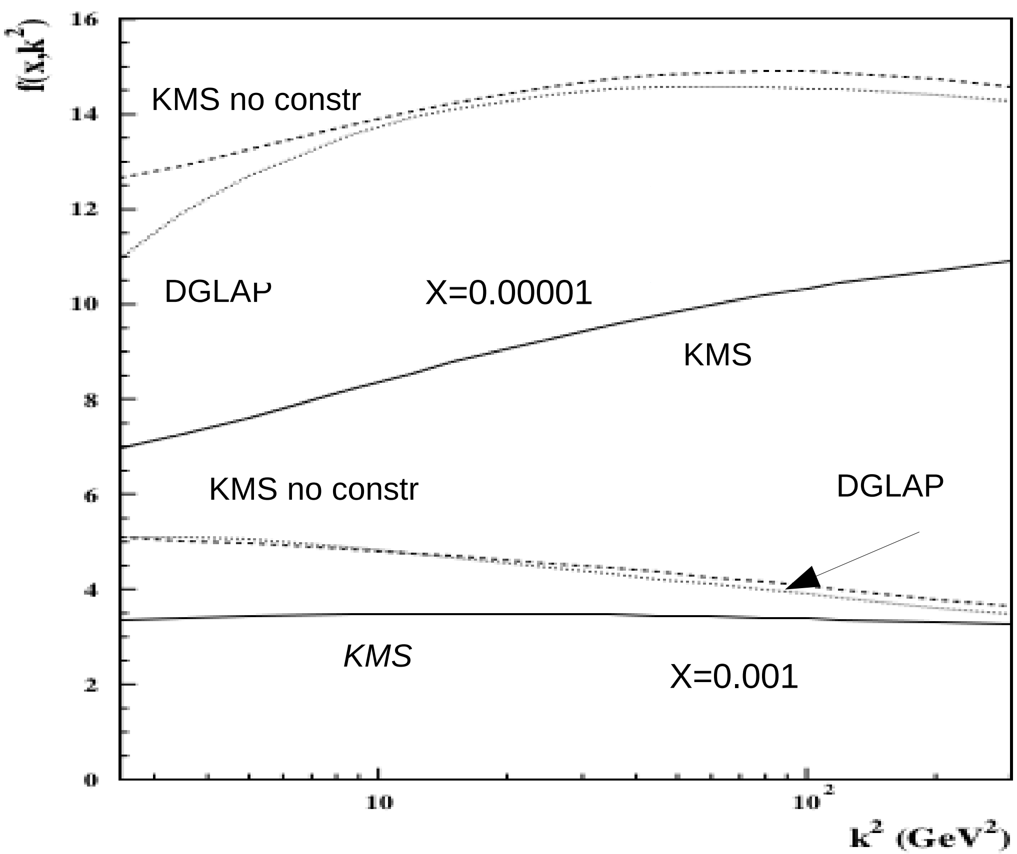
Very usefull: low x eq with subleading corrections Kwiecinski, Martin, Staśto prescription

Nonsingular pieces of splitting function

Kinematical effects i.e. momentum of gluon dominated by it's transversal component

Running coupling

In principle not applicable to final states since no hard scale dependence



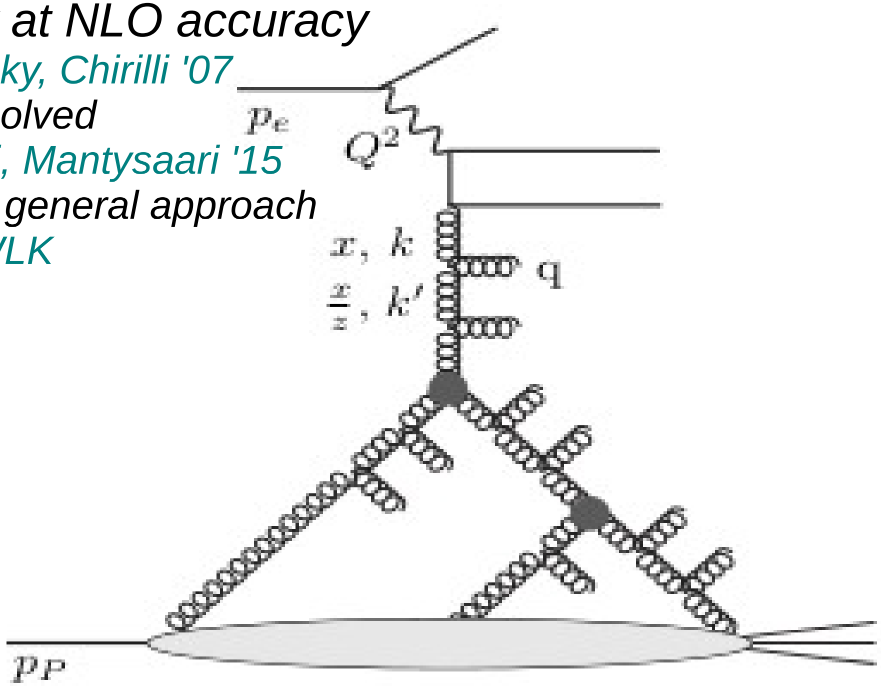
$$\mathcal{F}(x,k^2) = \mathcal{F}^{(0)}(x,k^2)$$
$$+ \frac{\alpha_s(k^2)N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_0^2}^{\infty}\frac{dl^2}{l^2}\left\{\frac{l^2\mathcal{F}(\frac{x}{z},l^2)\,\theta(\frac{k^2}{z}-l^2) - k^2\mathcal{F}(\frac{x}{z},k^2)}{|l^2-k^2|} + \frac{k^2\mathcal{F}(\frac{x}{z},k^2)}{|4l^4+k^4|^{\frac{1}{2}}}\right\}$$
$$+ \frac{\alpha_s(k^2)}{2\pi k^2}\int_x^1 dz\left[\left(P_{gg}(z) - \frac{2N_c}{z}\right)\int_{k_0^2}^{k^2} dl^2\,\mathcal{F}\left(\frac{x}{z},l^2\right) + zP_{gq}(z)\Sigma\left(\frac{x}{z},k^2\right)\right]$$

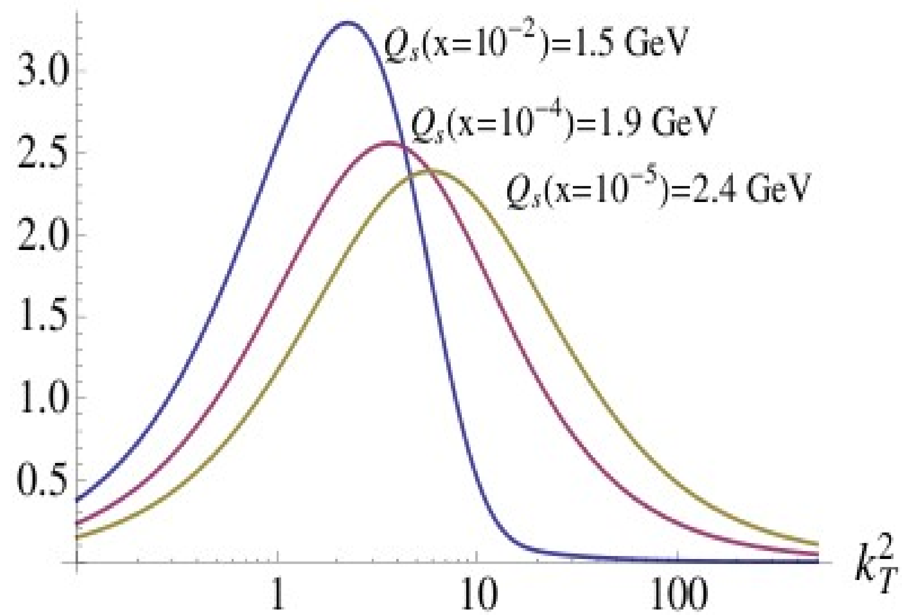
From Kwiecinski, Martin, Stasto Phys.Rev. D56 (1997) 3991-4006

$$f(x,k^2) = k^2\mathcal{F}(x,k^2)$$

The BK equation for unintegrated gluon density

Originally formulated in "x" space
Balitsky '96, Kovchegov'99
Now at NLO accuracy
Balitsky, Chirilli '07
and solved
Lappi, Mantysaari '15
More general approach
JIMWLK





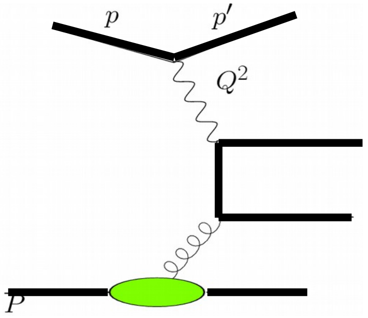
$$\mathcal{F}(x,k^2) = \mathcal{F}_0(x,k^2) + \overline{\alpha}_s \int_{x/x_0}^{1} \frac{dz}{z} \int_0^\infty \frac{dl^2}{l^2} \left[\frac{l^2 \mathcal{F}(x/z,l^2) - k^2 \mathcal{F}(x/z,k^2)}{|k^2 - l^2|} + \frac{k^2 \mathcal{F}(x/z,k^2)}{\sqrt{(4l^4 + k^4)}} \right]$$
$$- \frac{\pi \alpha_s^2 k^2}{4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

Applications also in coordinate space:
Gotsman, Levin, Lublinsky, Naftali,Maor 03
Albacete, Armesto, Milhano, Salgado, Wiedemann '03 ,
Berger, Stasto 12; Marquet, Soyez '07,…..

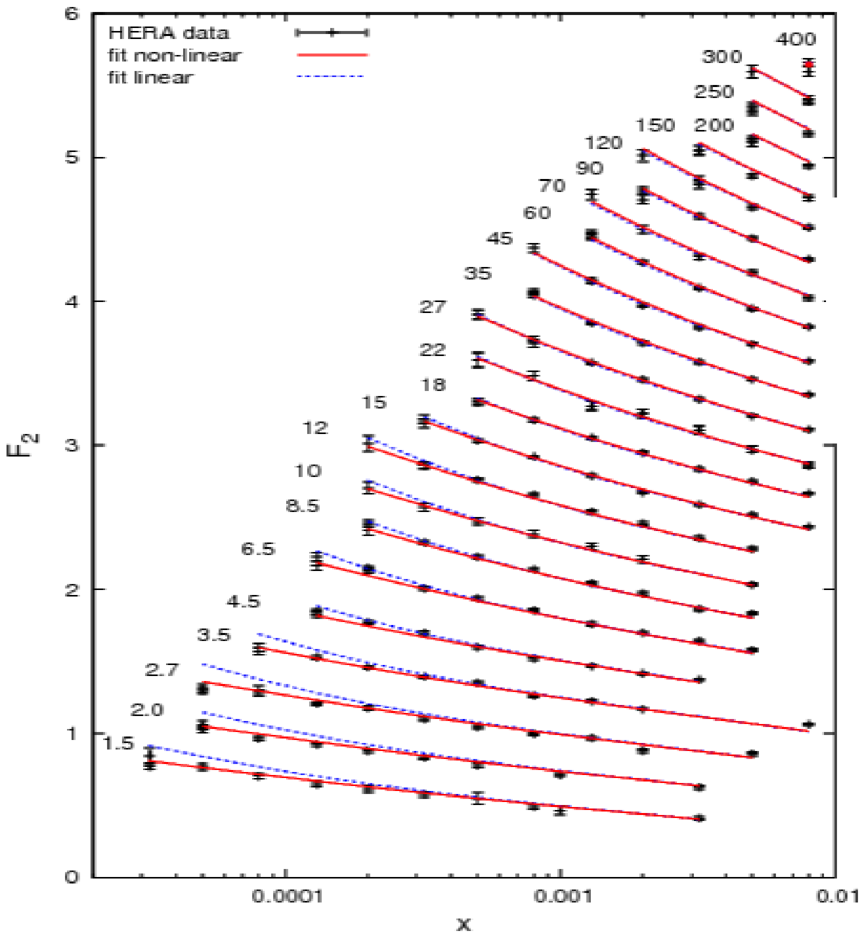
Kwiecinski, KK '02
Stasto, KK '05
Nikolaev, Schafer '06

HEF framework applied to DIS

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



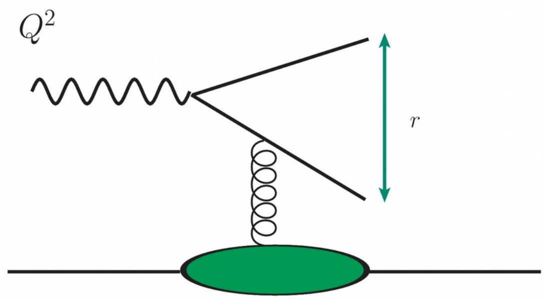
In the dipole formalism



$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}} \int d^2b \int_0^1 dz \int d^2r \left(|\psi_L(z,r)|^2 + |\psi_T(z,r)|^2\right) N(x,r,b)$$

Mueller, Patel '95

Forward scttering amplitude

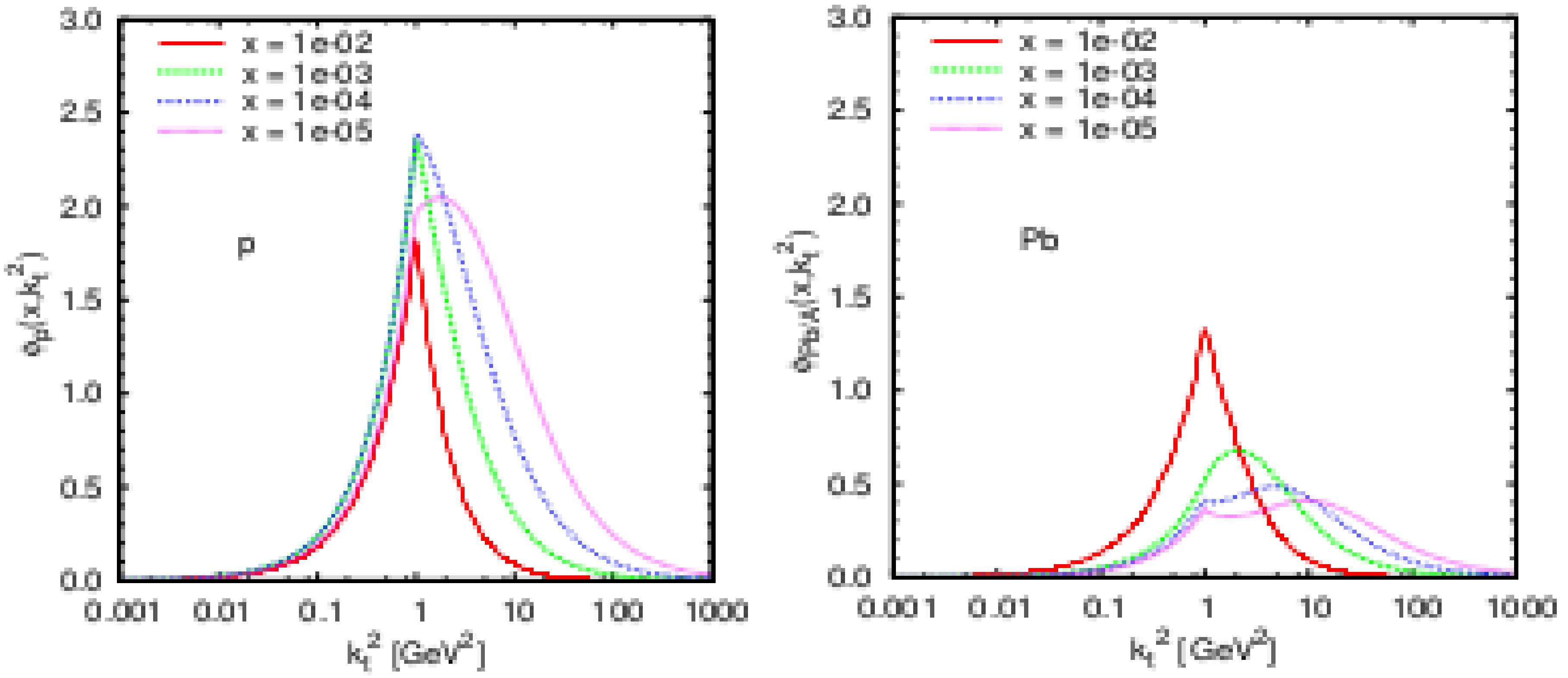


$$\mathcal{F}(x,k^2) = \frac{C_F}{\alpha_s(2\pi)^3} \int d^2\mathbf{b}\, d^2\mathbf{r}\, e^{-i\mathbf{k}\cdot\mathbf{r}} \nabla_r^2 N(\mathbf{r},\mathbf{b},x)$$

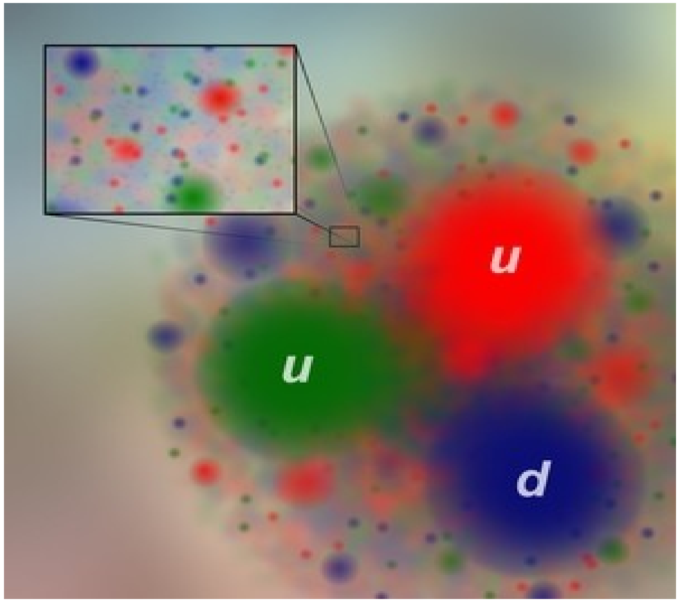
Sapeta, KK '12

BK equation with resummed corrections of higher order

Glue in p vs. glue in Pb



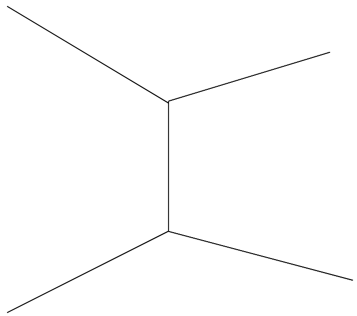
Hard scale dependence



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

CCFM evolution equation - evolution with observer

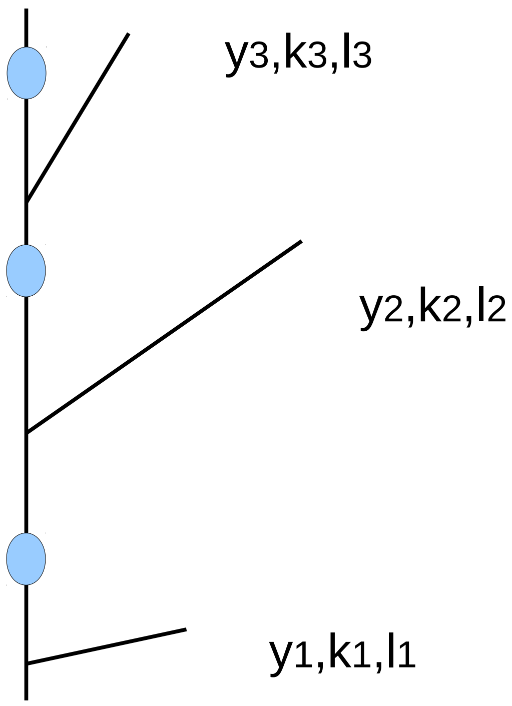
Catani,Ciafaloni, Fiorani, Marchesini '88



Constraint $l_i < L$

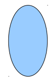
$L \sim pt1 + pt2$

L given by the scale of the hard process



There is a region where emitted gluons are soft the the dominant contribution to the amplitude comes from the angular ordered region.

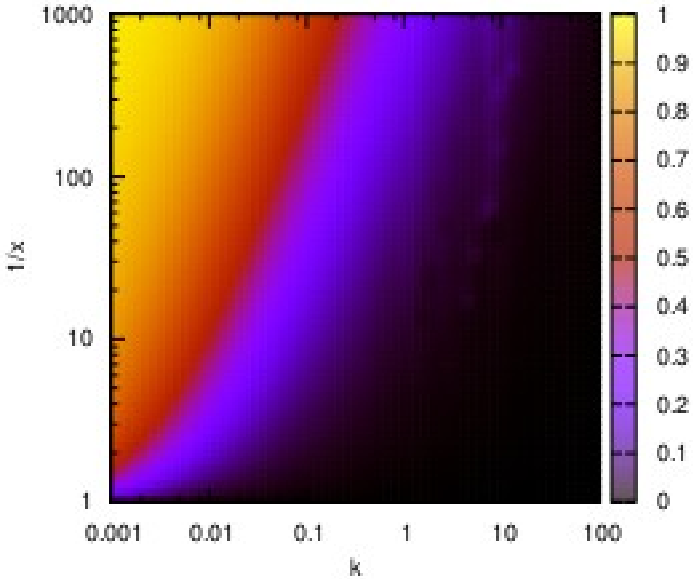
The same structure for $x \to 0$ *although the softest emitted gluons are harder than internal.*



Probability of finding no real gluon between hard emissions

Saturation scale in equation with coherence

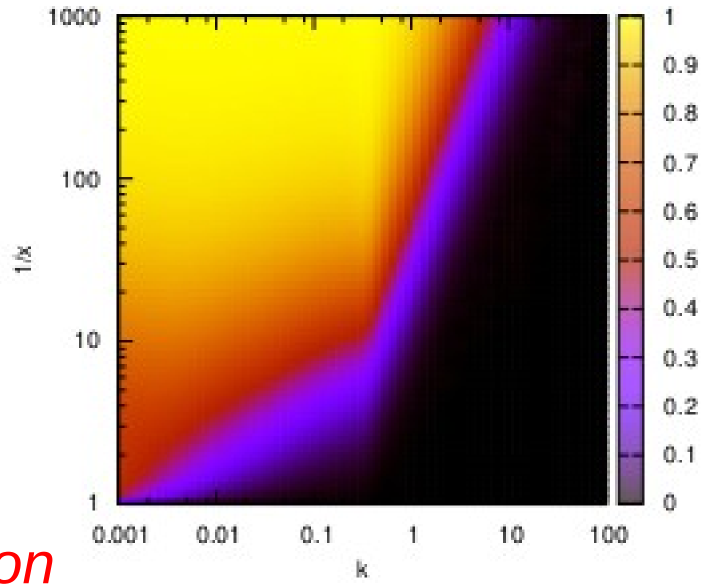
BK

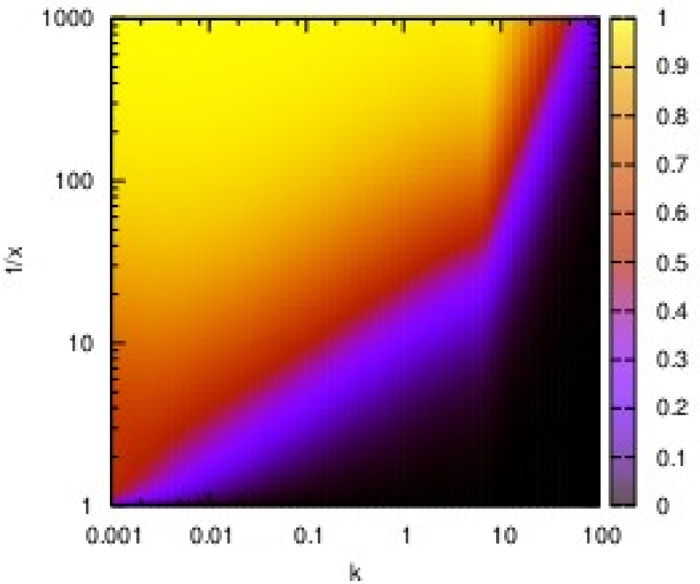


Avsar, Stasto '10
(absorbtive boundary method)

KK, Toton '13
(nonlinear equation)

CCFM – NL/R^2





R radius of proton

Hard scale=1GeV

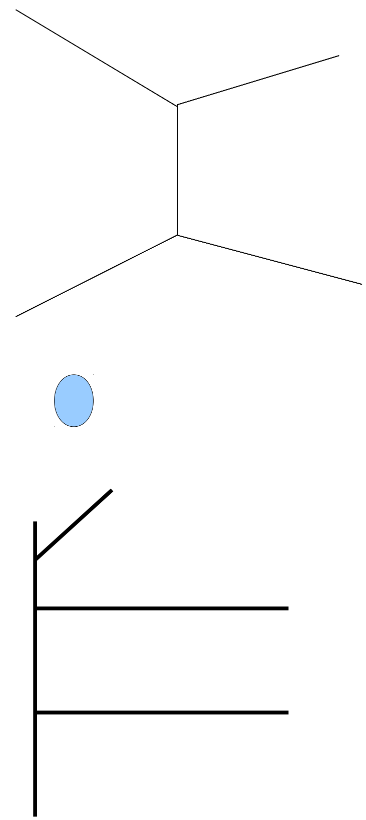
Hard scale =10 GeV

Introducing hard scale dependence

Nonlinear extension of CCFM not applied so far to phenomenology

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

KK '14



hard matrix element provides hard scale

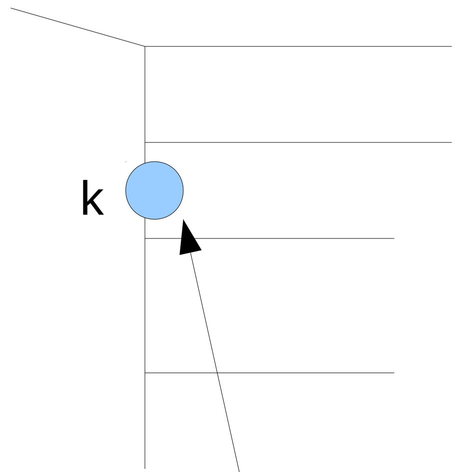
Probability of finding no real gluon between scales

Motivated by KMR framework

Kimber, Martin, Ryskin '01

Introducing hard scale dependence

Probability of finding no real gluon
Between scales μ and k



μ hard scale

Survival probability of the gap without emissions

Kutak '14

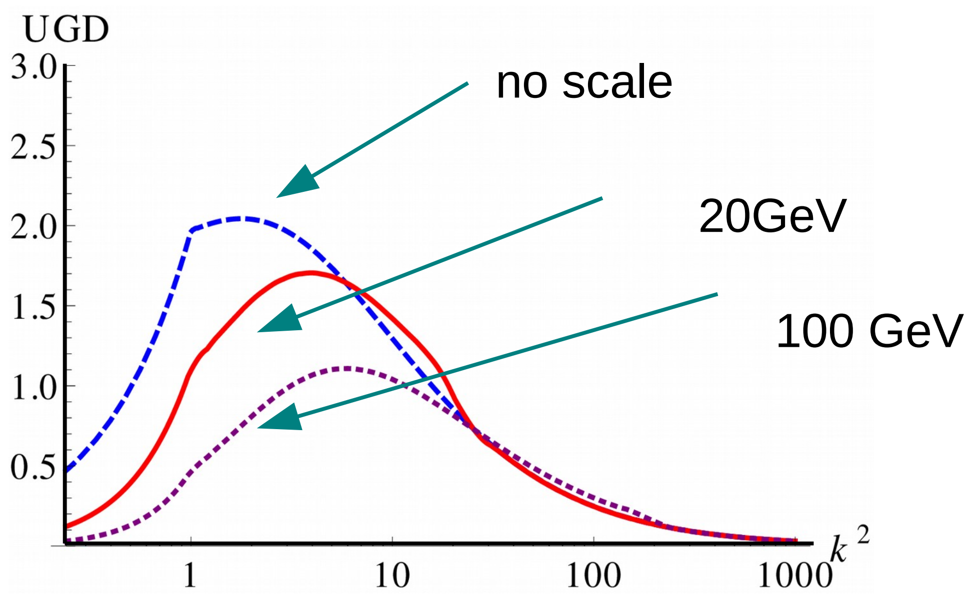
$$T_a(k_t,\mu) = \exp\left(- \int_{k_t^2}^{\mu^2} \frac{\alpha_s(p_t^2)}{2\pi} \frac{dp_t^2}{p_t^2} \sum_{a'} \int_0^{1-\Delta} P_{a'a}(z')\, dz' \right)$$

$$\mathcal{A}(x,k^2,\mu^2) = \theta(\mu^2 - k^2) T_s(\mu^2,k^2) \frac{xg(x,\mu^2)}{xg_{hs}(x,\mu^2)} \mathcal{F}(x,k^2) + \theta(k^2-\mu^2)\mathcal{F}(x,k^2).$$

$$xg_{hs}(x,\mu^2) = \int^{\mu^2} dk^2 T_s(\mu^2,k^2)\mathcal{F}(x,k^2), \;\; xg(x,\mu^2) = \int^{\mu^2} dk^2 \mathcal{F}(x,k^2)$$

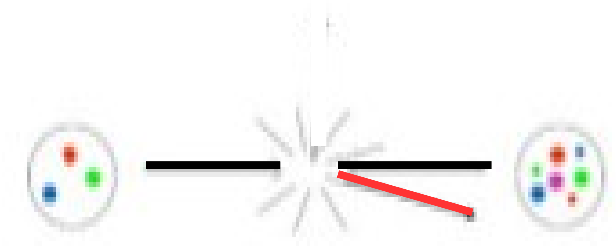
Saturation scale in equation with coherence forward-forward jets

K.K. '14

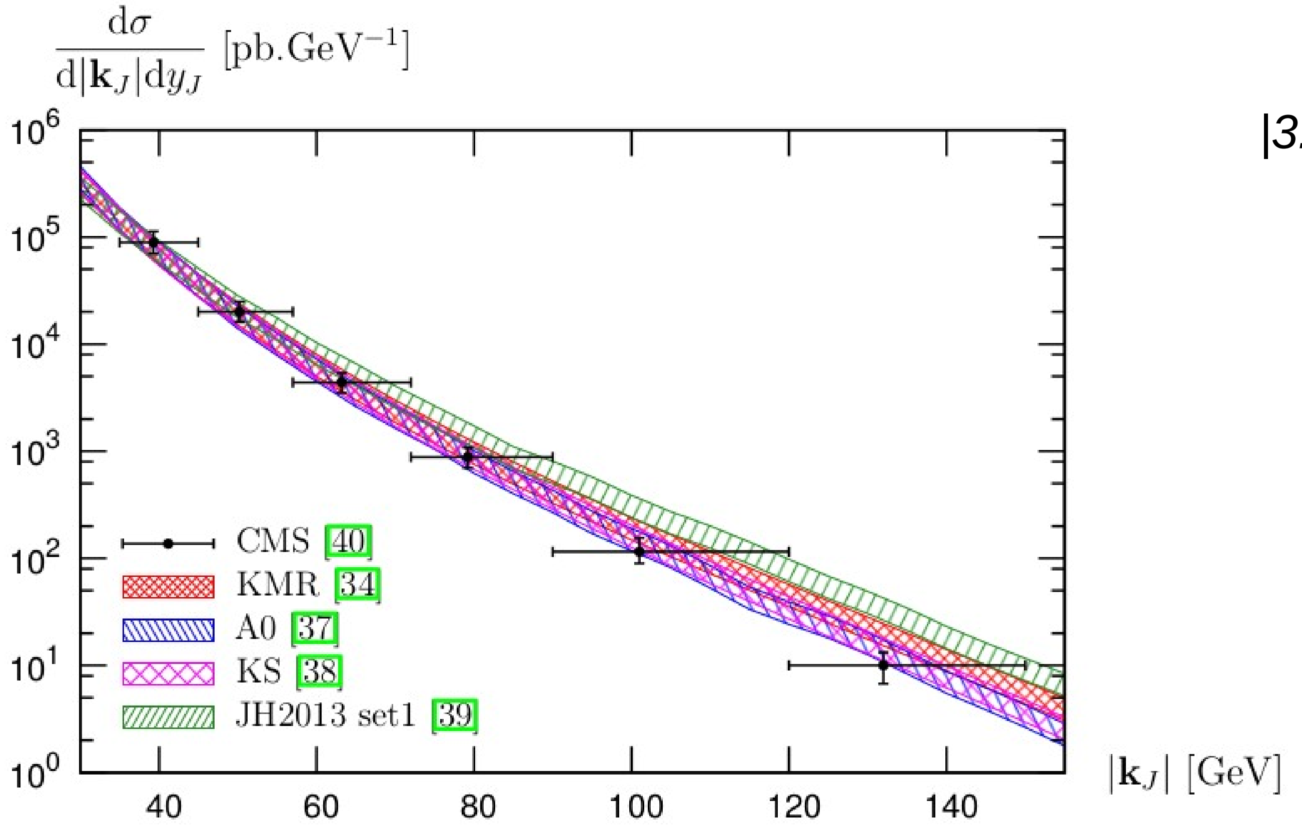


Low kt gluons are suppressed. The conservation of probability leads to change of shape of gluon density which depends on the hard scale

Inclusive-forward jet



Single inclusive p_t jet spectra



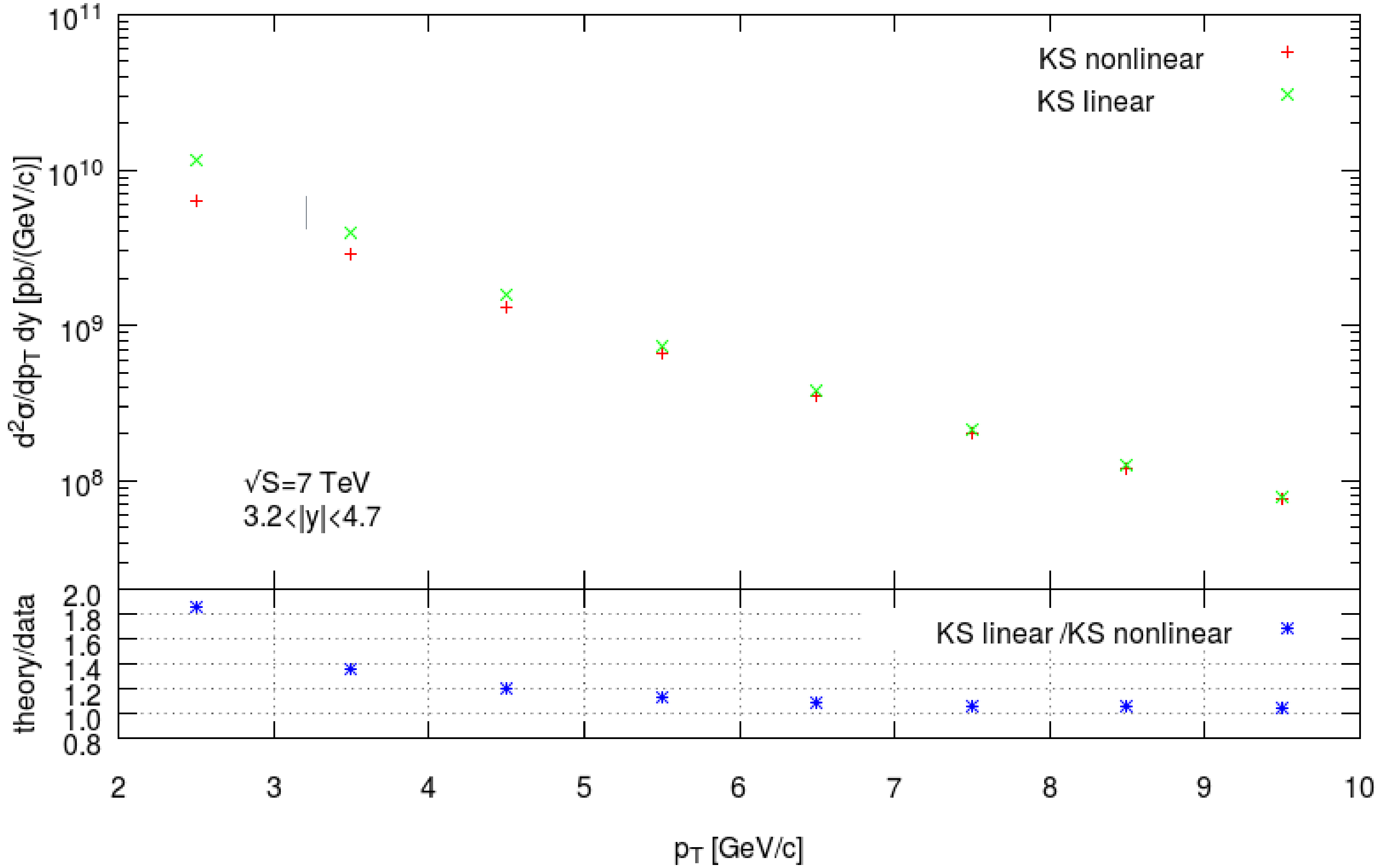
|3.2| < y <|4.7|

Decloue, Szymanowski, Wallon '15

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

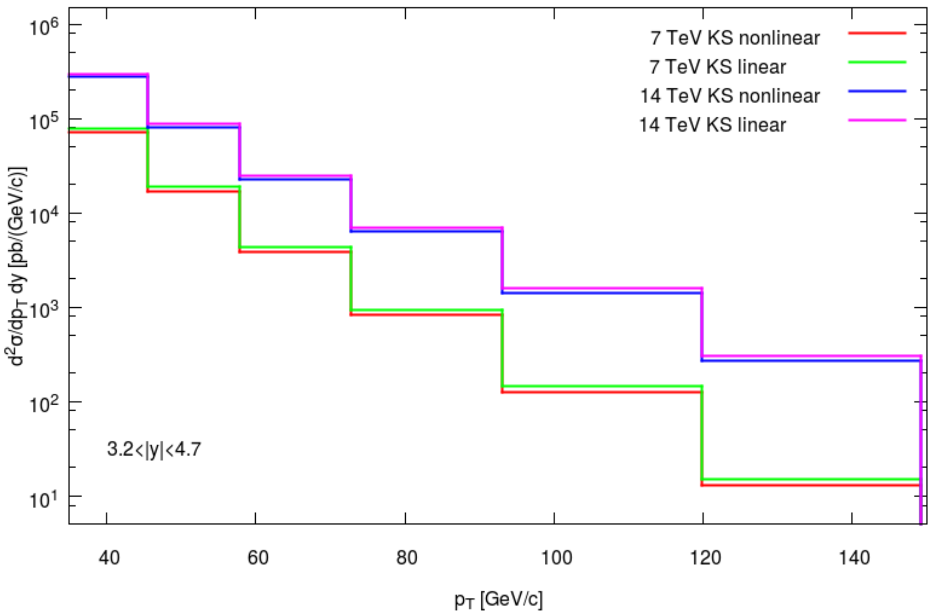
Extension to lower p_t jet spectra

Single inclusive forward jet

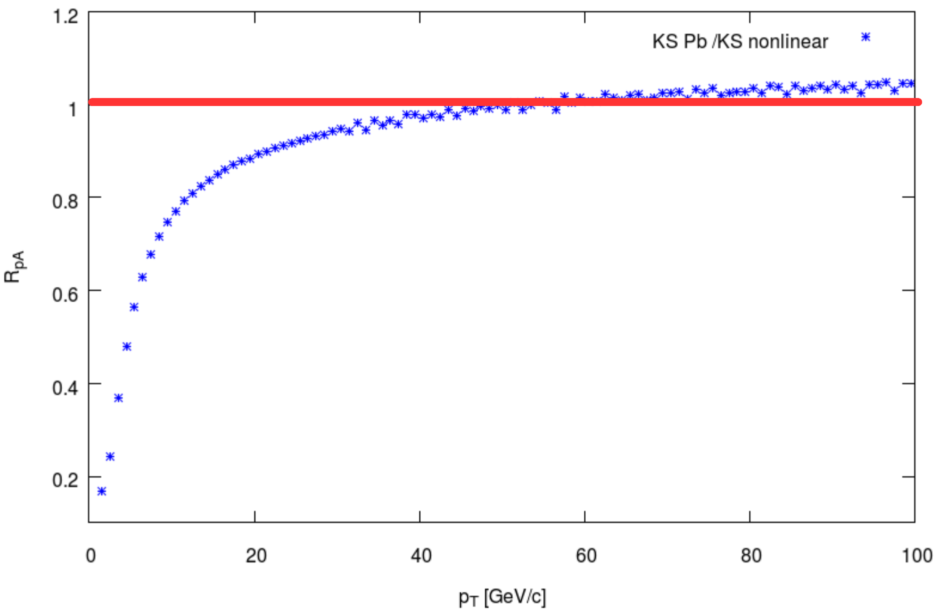


Di-jets p_t spectra at 14 TeV and RpA

Single inclusive forward jet

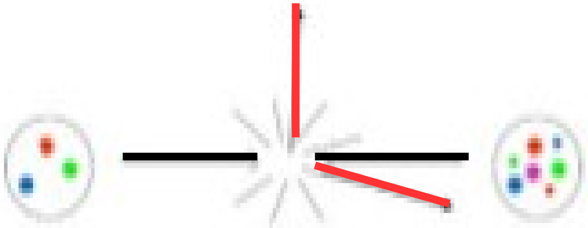


Nuclear modification ratio



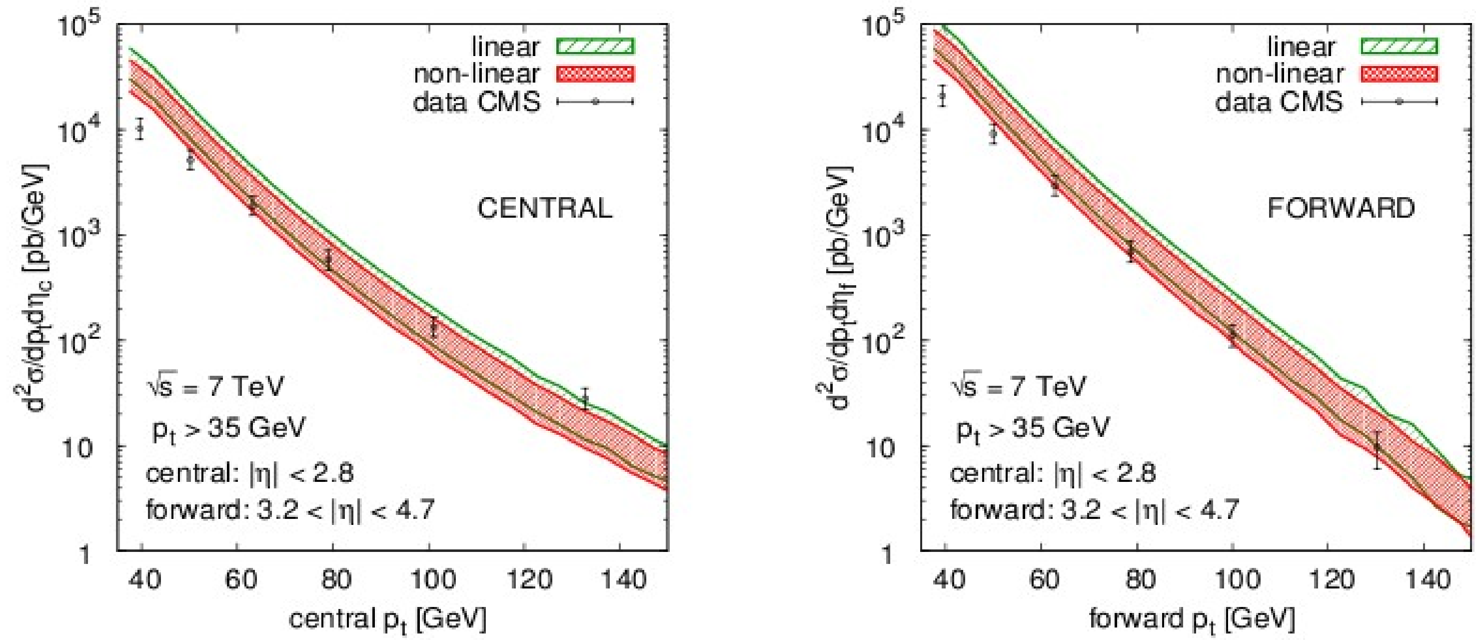
Bury, KK, Sapeta, to appear soon

Central-forward di-jets



Di-jets p_t spectra

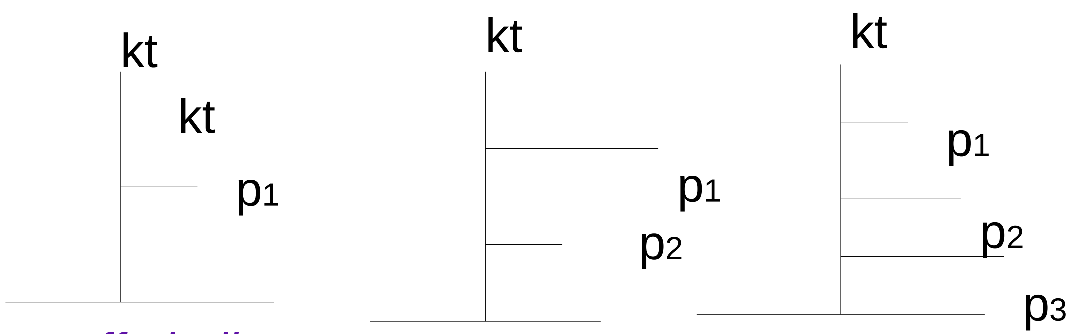
S.Sapeta. KK ,12



Reasonable agreement.

No usage of traditional parton shower

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

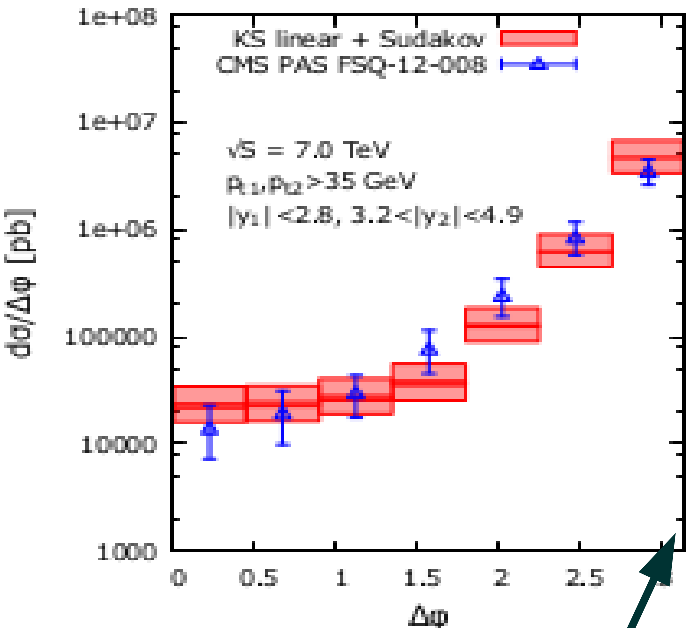


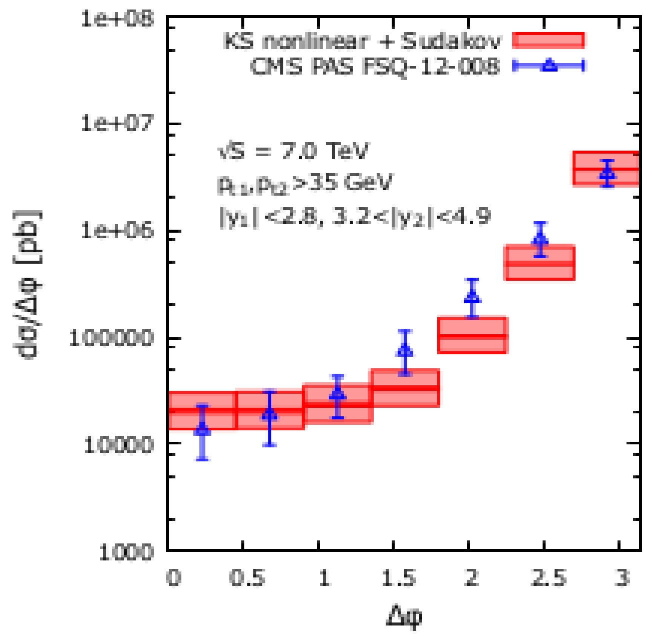
During evolution time incoming gluon becomes off-shell

Crucial effect of higher order corrections

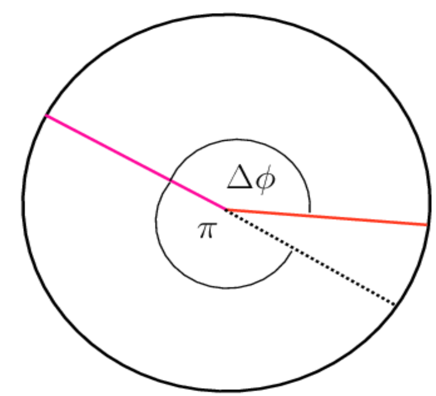
Decorelations inclusive scenario forward-central

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

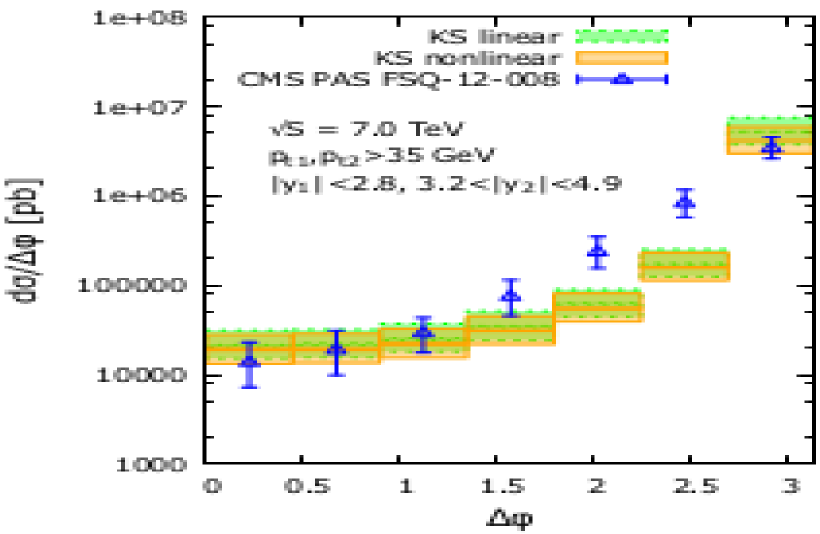
Sudakov effects by reweighing
implemented in LxJet Monte Carlo
P. Kotko

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

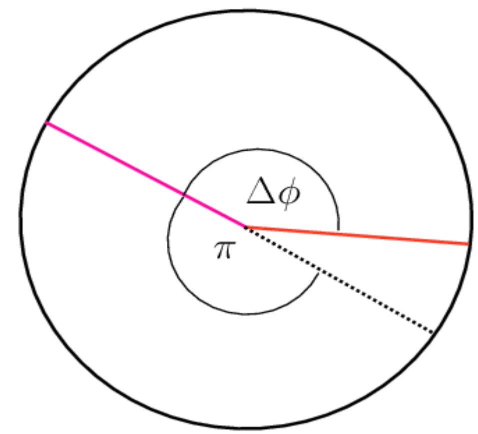
Studied also context of RHIC
Albacete, Marquet '10

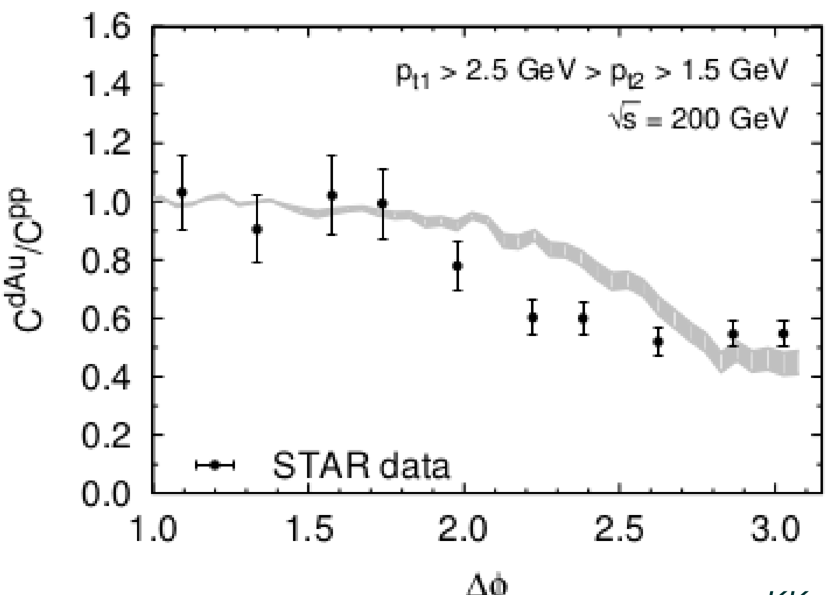
Forward-central decorelations inclusive scenario

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



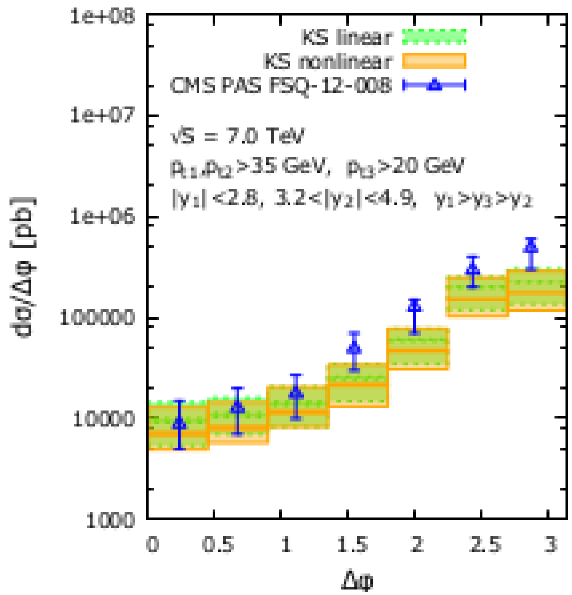


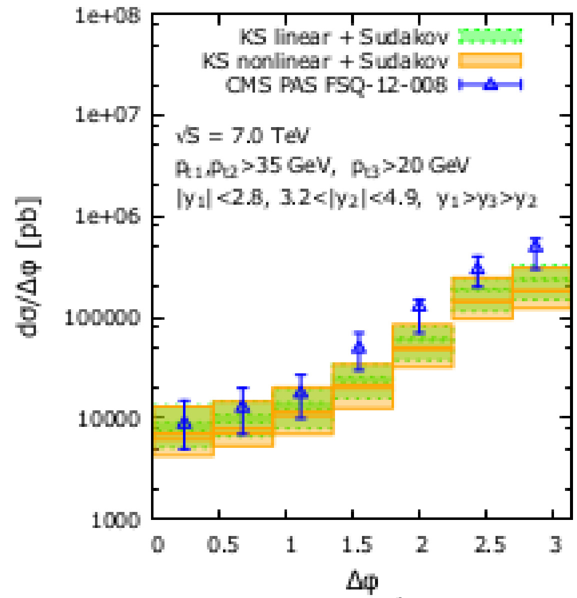
No usage of fragmentation function.
just divided cross section for jets in d+Au by p+p

KK, Sapeta 12

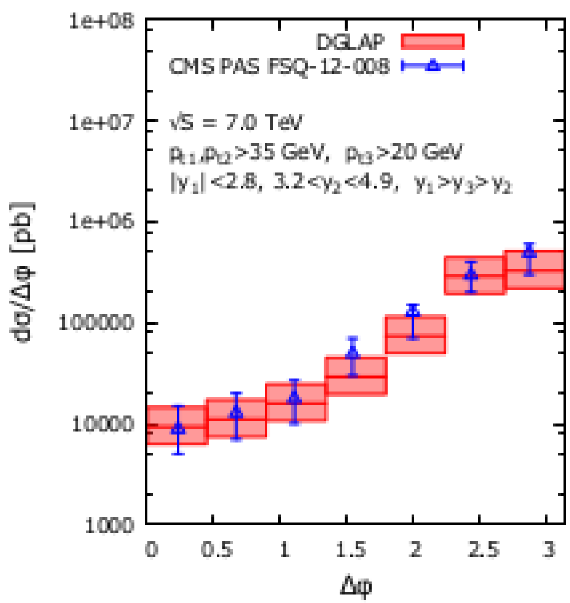
Decorelations inside jet tag scenario

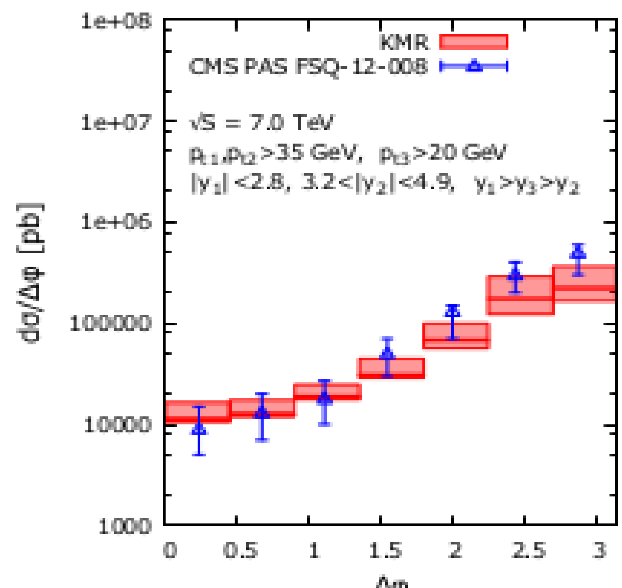
A.v.Hameren, P.Kotko, KK, S.Sapeta '14

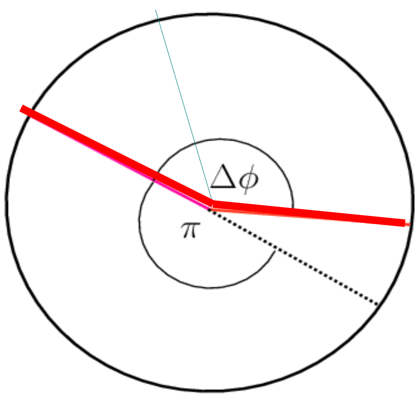




pt1, pt2 >35 GeV, leading jets |y1|<2.8, 3.2<|y2|<4.7 Third jet pt>20GeV. Between the forward and central region



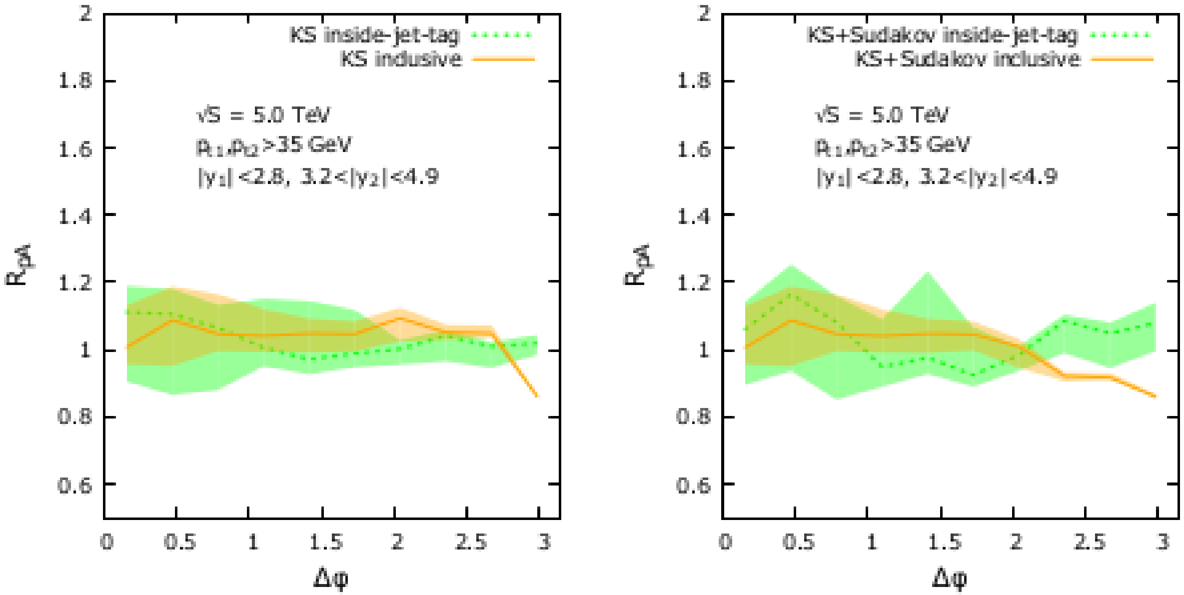




Sudakov effects by reweighting implemented in LxJet Monte Carlo P. Kotko

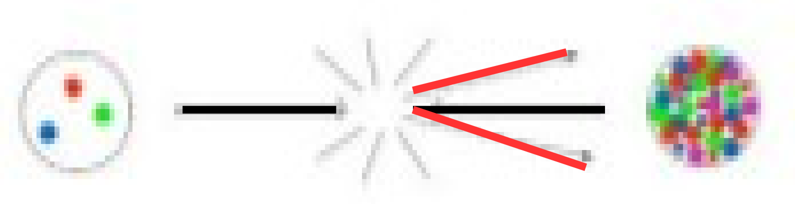
Predictions for p-Pb for forward-central

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

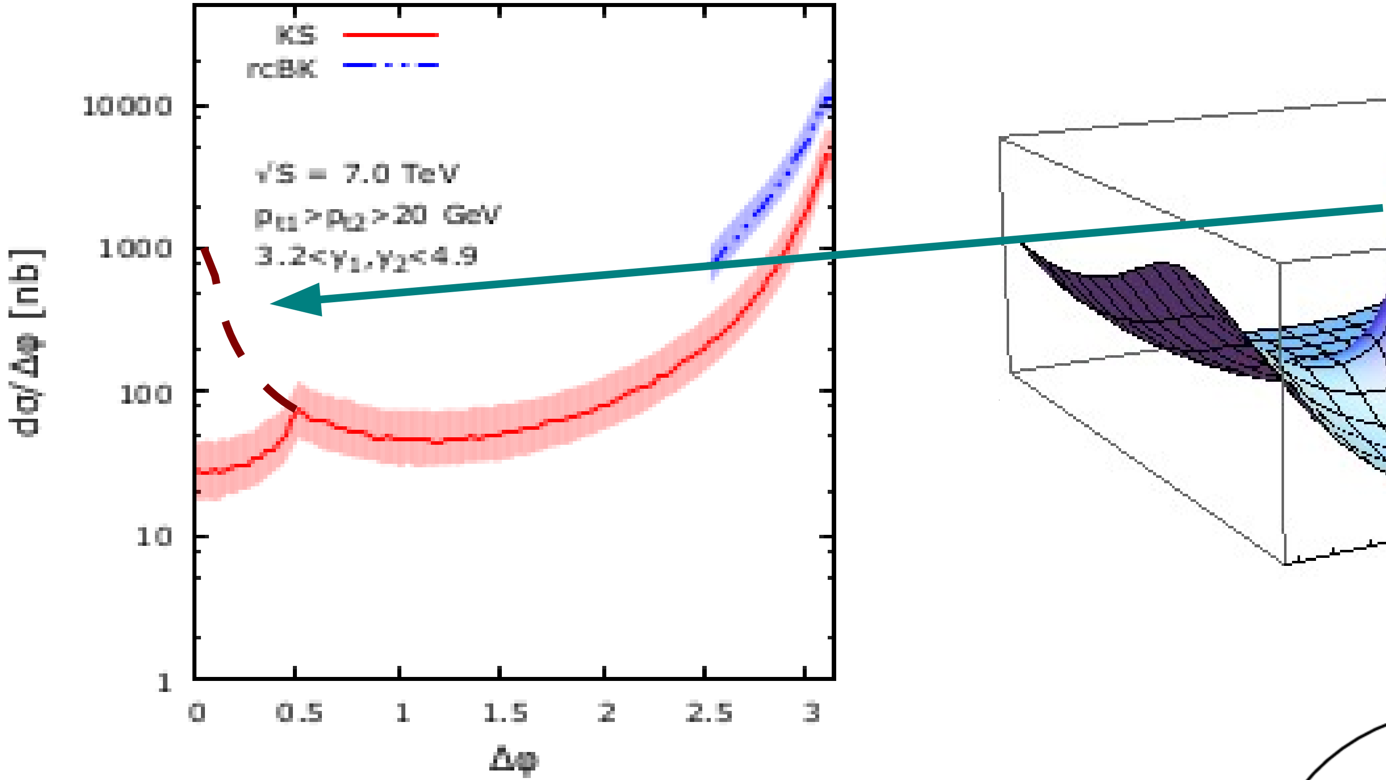


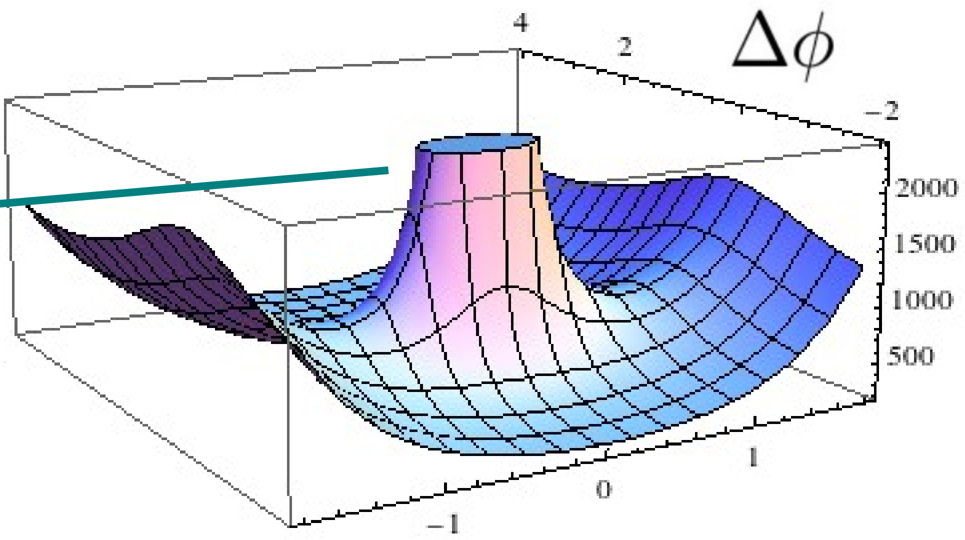
- *Sudakov enhances saturation effects*
- *However, saturation effects are rather weak for forward-central jets*

Forward-forward di-jets

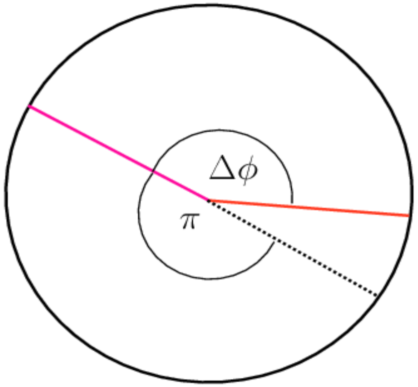


Results for decorelations





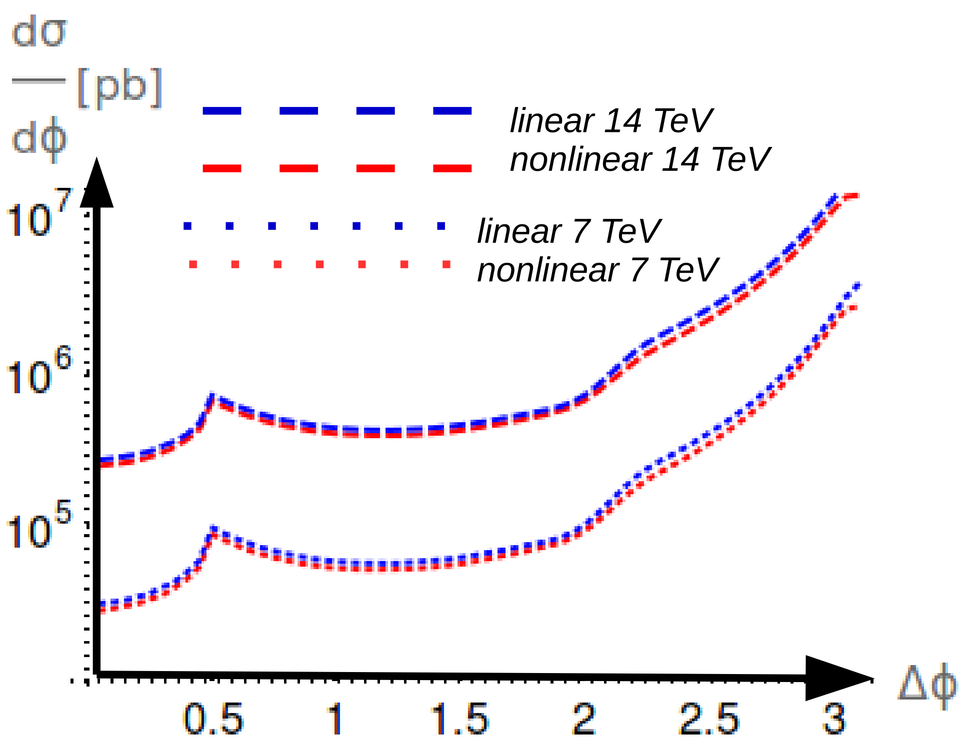
Divergence regularized by jet algorithm

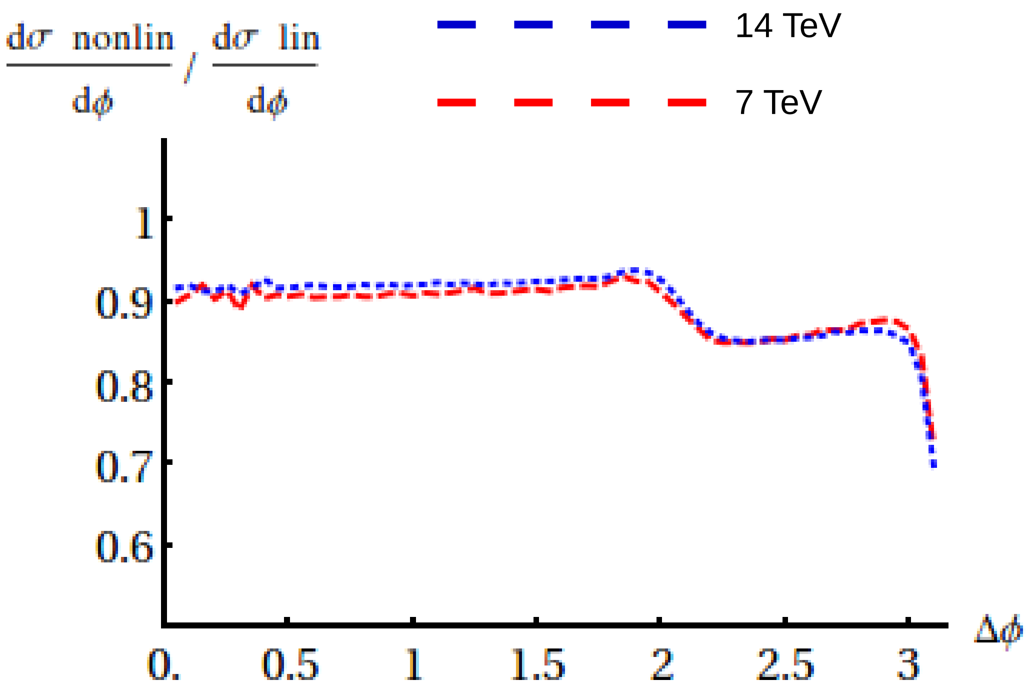


Any relation to the ridge effect ??

Predictions for p-Pb for forward-forward

KK '14

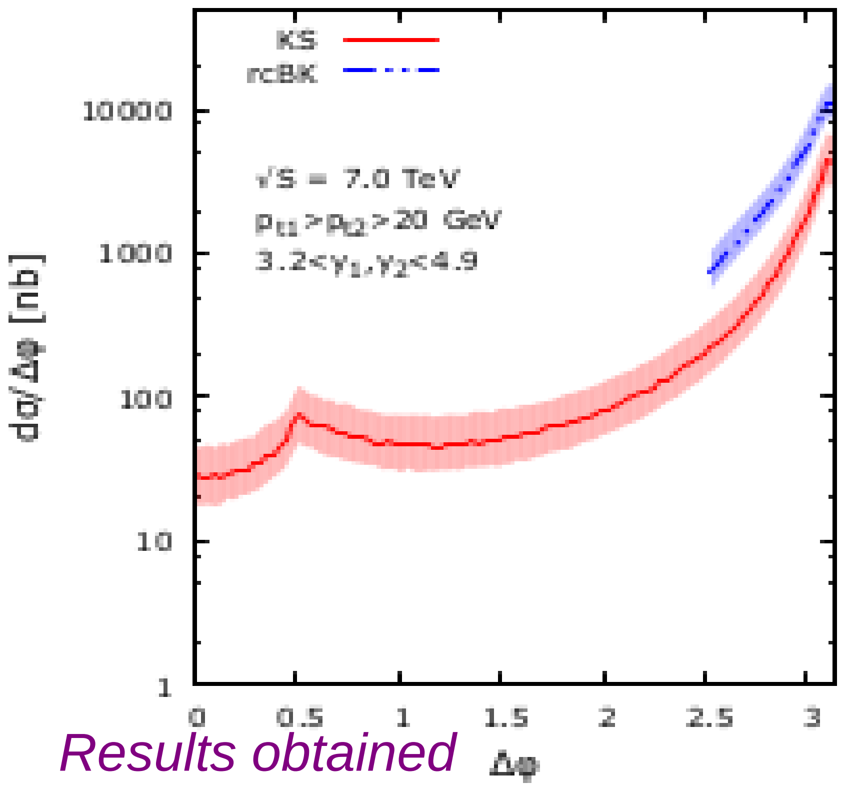




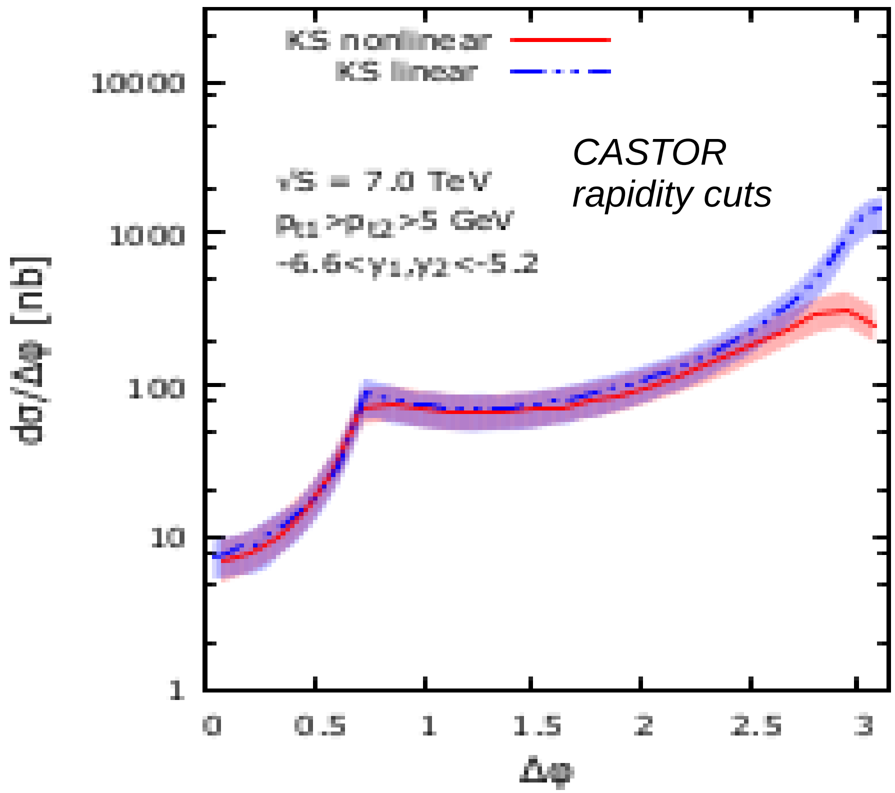
- No significant change in shape after increasing energy from 7 TeV to 14 TeV
- Noticeable difference between linear and nonlinear scenario

Results for decorelations

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



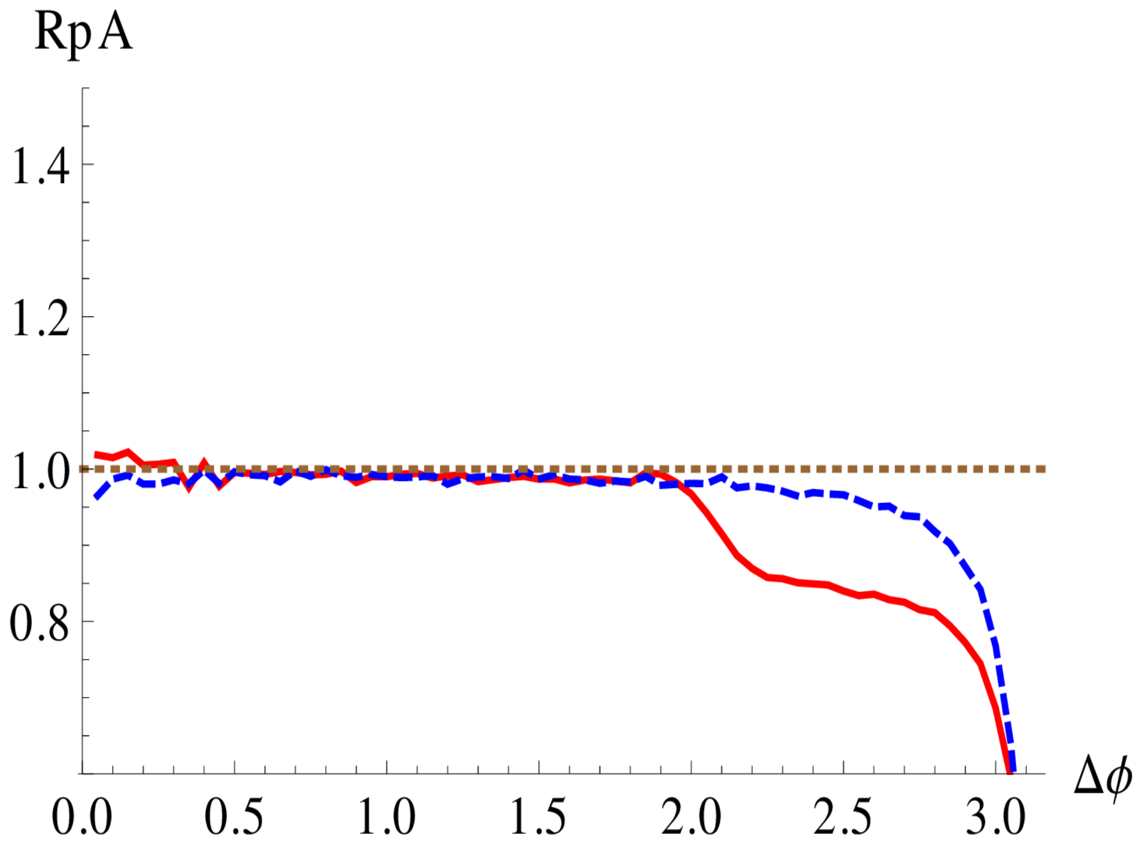
Results obtained with gluons coming from rcBK and BK with corrections of higher orders



Kotko, KK ' 14

Predictions for p-Pb for forward-forward

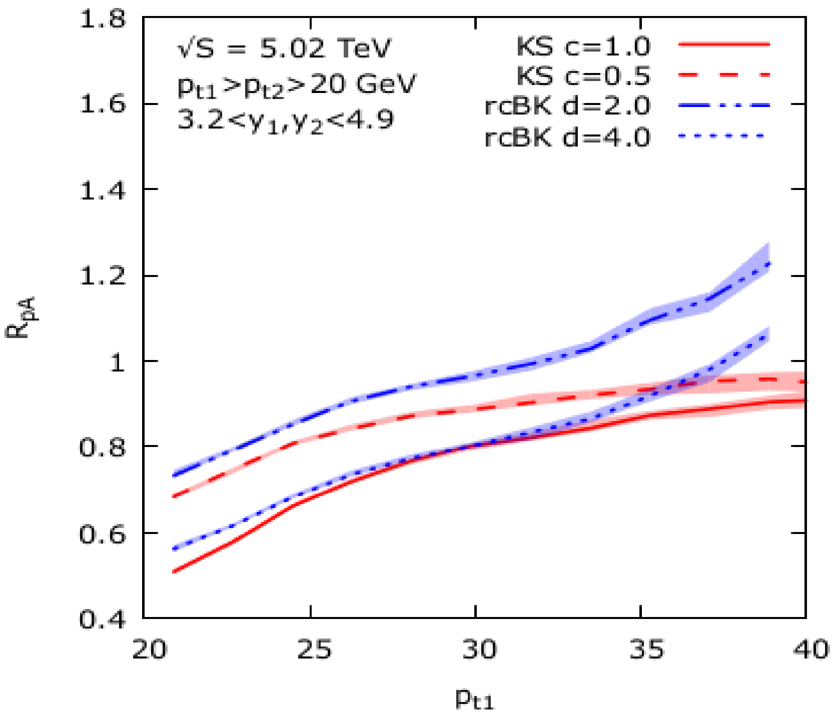
KK '14

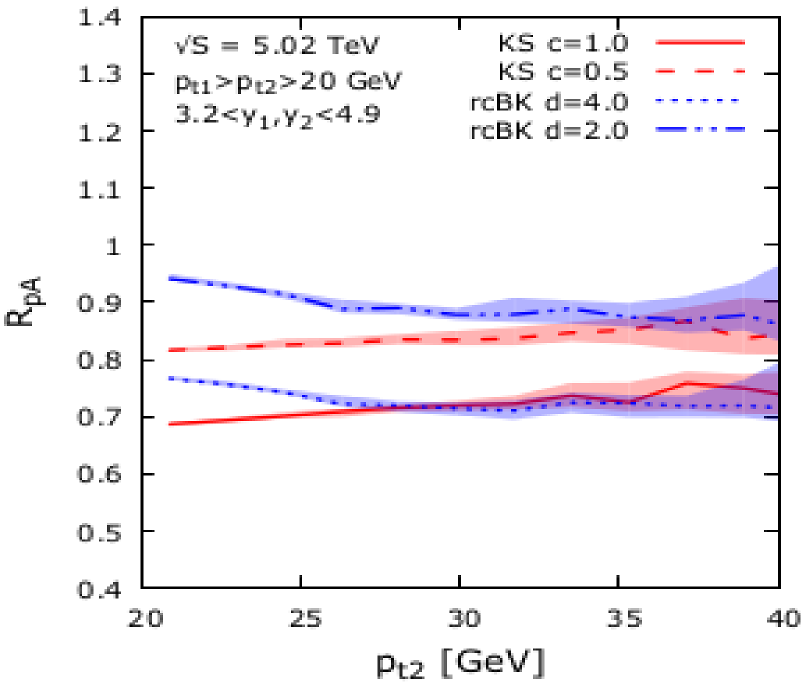


- *The hard scale effects make the potential signatures of saturation more pronounced.*
- *“p+Pb” affected more by saturation than “p+p” therefore we see more significant effect.*

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.

$$\frac{d\sigma^{pA\to qgX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2}\, x_1 f_{q/p}(x_1, \mu^2) \sum_{i=1}^{2} \mathcal{F}_{qg}^{(i)} H_{qg\to qg}^{(i)}$$

$$\frac{d\sigma^{pA\to q\bar{q}X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2}\, x_1 f_{g/p}(x_1, \mu^2) \sum_{i=1}^{3} \mathcal{F}_{gg}^{(i)} H_{gg\to q\bar{q}}^{(i)}$$

$$\frac{d\sigma^{pA\to ggX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2}\, x_1 f_{g/p}(x_1, \mu^2) \sum_{i=1}^{6} \mathcal{F}_{gg}^{(i)} H_{gg\to gg}^{(i)}$$

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

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)

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*