Jets at high energies

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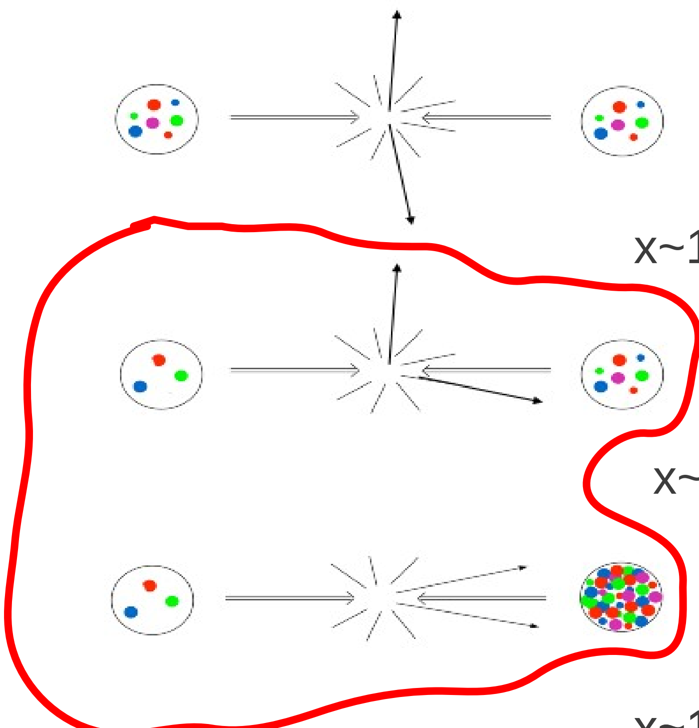
LHC as a scanner of gluon



central-central i.e.
not so dense-not so dense

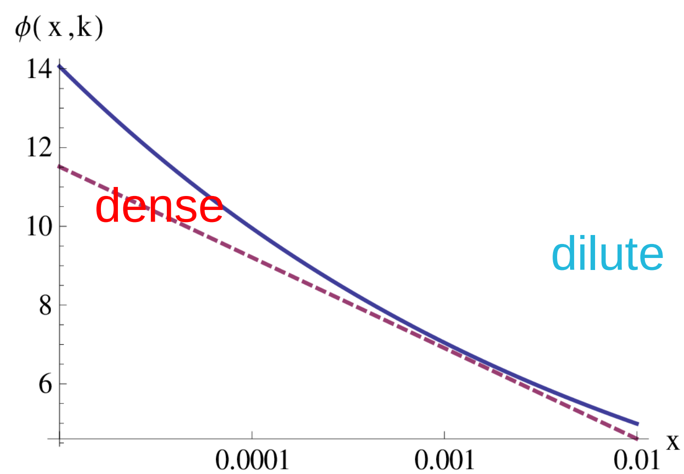
x~10 $^{-4}$

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

x~10 $^{-4}$

forward-forward i.e.
dilute -dense

x~10 $^{-6}$



QCD at high energies – high energy factorization

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{a,b,c,d} \int \frac{d^2k_{1t}}{\pi}\frac{d^2k_{2t}}{\pi}\frac{1}{16\pi^2(x_1x_2S)^2}\overline{|\mathcal{M}_{ab\to cd}|}^2 \delta^2(\vec{k}_{1t}+\vec{k}_{2t}-\vec{p}_{1t}-\vec{p}_{2t})$$
$$\times \mathcal{F}_{a/A}(x_1, k_{1t}^2, \mu^2)\, \mathcal{F}_{b/B}(x_2, k_{2t}^2, \mu^2)\, \frac{1}{1+\delta_{cd}}$$

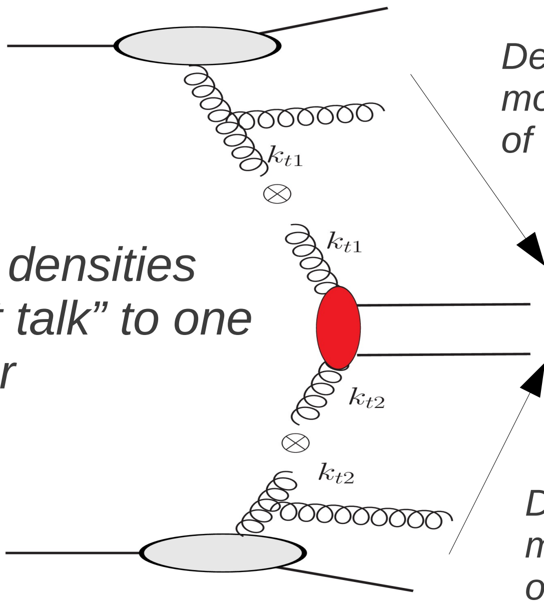
$$k_1^\mu = x_1 P_1^\mu + \bar{x}_1 P_2^\mu + k_{1t}^\mu \qquad k_2^\mu = x_2 P_2^\mu + \bar{x}_2 P_1^\mu + k_{2t}^\mu$$

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

Parton densities “do not talk” to one another

$$|\mathcal{M}_{ab\to cd}|^2 = \frac{2x_1 k_1^{\mu_1} k_1^{\nu_1}}{k_1^2}\frac{2x_2 k_2^{\mu_2} k_2^{\nu_2}}{k_2^2}\mathcal{M}_{ab\to cd\,\mu_1\nu_1}\mathcal{M}^*_{ab\to cd\,\mu_2\nu_2}$$

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. Possible double counting

Some trials to generalized to p-A
Dominguez, Huan, Marquet,Xiao '10

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

New helicitybased metods for ME
van Hameren, Kotko,KK '12

BCFW for offshell gluons

An n-gluon amplitude is a function of momenta $k_1, k_2, \ldots, k_n$ and directions $p_1, p_2, \ldots, p_n$, satisfying the conditions

$$k_1^\mu + k_2^\mu + \cdots + k_n^\mu = 0$$
$$p_1^2 = p_2^2 = \cdots = p_n^2 = 0$$
$$p_1 \cdot k_1 = p_2 \cdot k_2 = \cdots = p_n \cdot k_n = 0$$

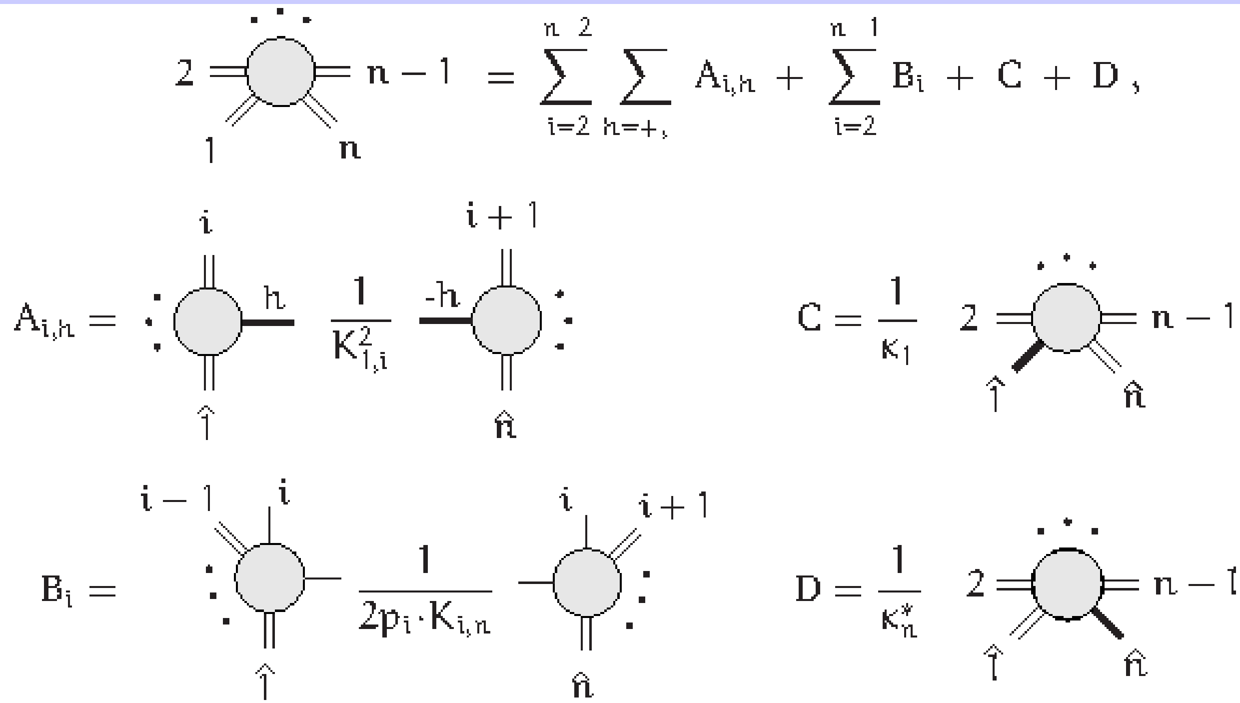
For each k^μ, k_T^μ is not unique, and may be defined using an auxiliary light-like q^μ:

$$k_T^\mu(q) = k^\mu - \frac{q \cdot k}{q \cdot p} p^\mu$$
$$= -\frac{\kappa}{2} \frac{\langle p|\gamma^\mu|q]}{[pq]} - \frac{\kappa^*}{2} \frac{\langle q|\gamma^\mu|p]}{\langle qp\rangle}$$

$$\kappa = \frac{\langle q|\not{k}|p]}{\langle qp\rangle} \quad , \quad \kappa^* = \frac{\langle p|\not{k}|q]}{[pq]}$$

$k^2 = -\kappa\kappa^*$ is independent of q^μ, but also individually κ and κ^* are independent of q^μ.

Shifting the k_T of pairs of gluons into complex space, the BCFW recursion formula for amplitudes with off-shell gluons can be derived, in which all building blocks are well-defined amplitudes with less (off-shell) legs.



With these one can easily derive compact expressions, e.g. the MHV formula for $\mathcal{A} \equiv \mathcal{A}(1^*, i^*, (\text{the rest})^+)$

$$\mathcal{A} = \frac{1}{\kappa_1^* \kappa_i^*} \frac{\langle p_1 p_i\rangle^4}{\langle p_1 p_2\rangle\langle p_2 p_3\rangle \cdots \langle p_{n-2} p_{n-1}\rangle\langle p_{n-1} p_n\rangle\langle p_n p_1\rangle}$$

From A. van Hameren

Off-shell amplitudes and Wilson lines

Off-shell gauge invariant amplitude $\tilde{\mathcal{M}}_{e_1\ldots e_n}(k_1,\ldots,k_n;X)$ for

$$g^*(k_1,e_1)\ldots g^*(k_n,e_n)\to X$$

where k_i, e_i are momentum and "polarization" vector of an off-shell gluon can be defined as [P. Kotko arXiv:1403.4824]

$$\langle 0|\,\mathfrak{R}^{c_1}_{e_1}(k_1)\ldots\mathfrak{R}^{c_n}_{e_n}(k_n)\,|X\rangle \stackrel{*}{=} \delta(k_1\cdot e_1)\ldots\delta(k_n\cdot e_n)$$
$$\delta^4(k_1+\ldots+k_n-X)\,\tilde{\mathcal{M}}_{e_1\ldots e_n}(k_1,\ldots,k_n;X)$$

where (almost-)infinite (almost-)straight Wilson lines are

$$\mathfrak{R}^{c_i}_{e_i}(k_i)=\int d^4y\, e^{iy\cdot k_i}\,\mathrm{Tr}\left\{\frac{1}{\pi g}\,t^{c_i}\,\mathcal{P}\exp\left[ig\int_{-\infty}^{\infty}ds\,\frac{dz_\mu(s)}{ds}\,A^\mu_b(z)\,t^b\right]\right\}$$

where t^a are color generators and the path is parametrized as

$$z^\mu(s)=y^\mu+\frac{2}{\epsilon}\tanh\left(\frac{\epsilon s}{2}\right)e^\mu_X,\quad s\in(-\infty,\infty)$$

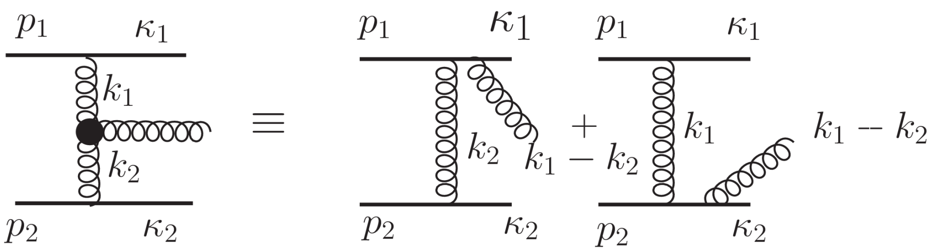
In the matrix element definition the limit $\epsilon\to 0$ is taken and only connected contributions are retained.

⋆ Used in FORM program `OGIME` = Off-shell Gauge Invariant Matrix Elements

From P. Kotko

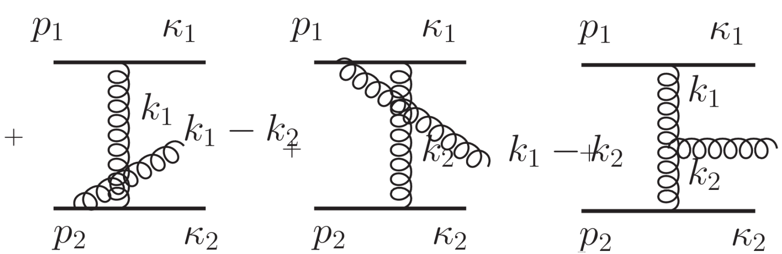
The BFKL evolution

Balitsky, Fadin, Kuraev, Lipatov '77



$$1 \gg \alpha_1 \gg \alpha_2$$

$$1 \gg |\beta_1| \gg |\beta_2|$$

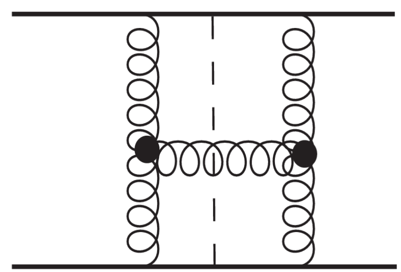


$$k_1 = \alpha_1 p_1 + \beta_1 p_2 + k_{1t}$$

$$k_2 = \alpha_2 p_1 + \beta_2 p_2 + k_{2t}$$

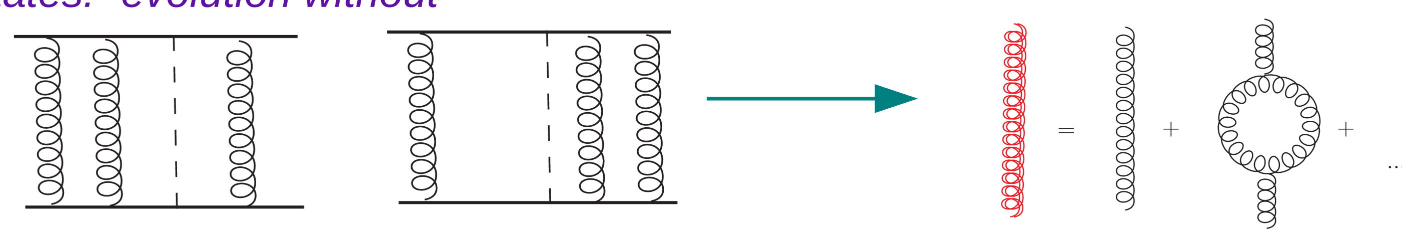
$$iA^{\rho}_{2\to 3} = (-2ig_2 p_1^{\mu}) t^{a}_{mj} \left(\frac{-i}{k_1^2}\right) f_{abc} g_s \Gamma^{\rho}_{\mu\nu}(k_1, k_2) \left(\frac{-i}{k_2^2}\right) (-2ig_s p_2^{\nu}) t^{b}_{nl}$$

- *Known also for SM YM*
- *Studied also in context of AdS/CFT*
- *Known up to NLO*
- *No saturation*
- *No applicable to final states: "evolution without observer"*



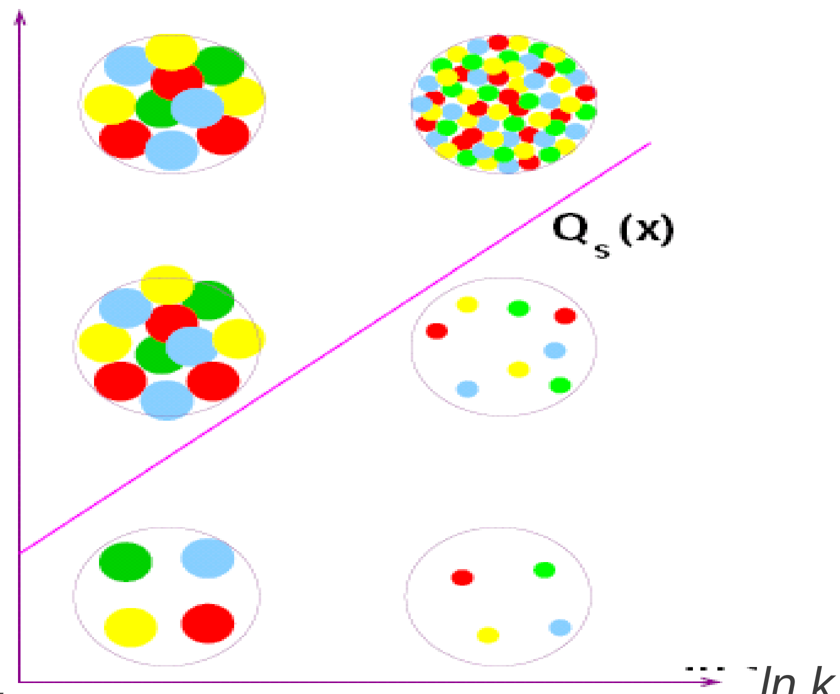
$$J^{\mu} = -ig\bar{u}(p_1 + q)\gamma^{\mu} u(p_1) \approx -2ig_s p_1^{\mu}$$

reggeized gluon



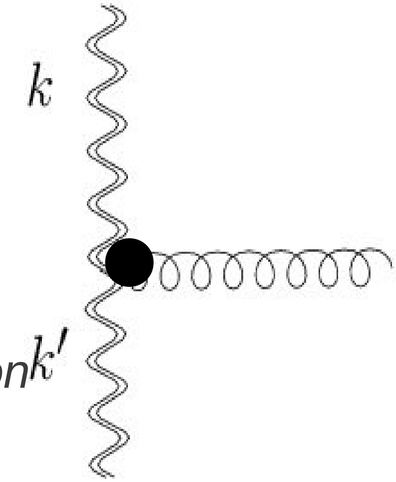
High energy factorization and saturation

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. F_2)change their behavior from power like to logarithmic like.



On microscopic level it means that gluon apart splitting recombine

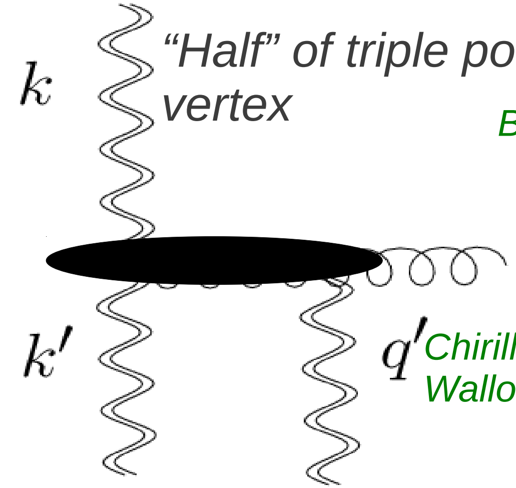
splitting



Linear evolution equation

recombination

Nonlinear evolution equations
BK, JIMWLK
CGC framework
DIPSY



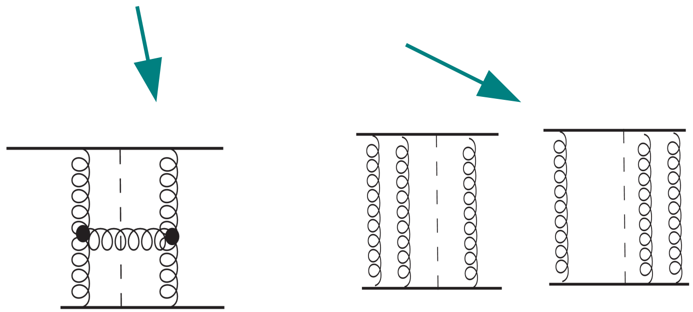
"Half" of triple pomeron vertex

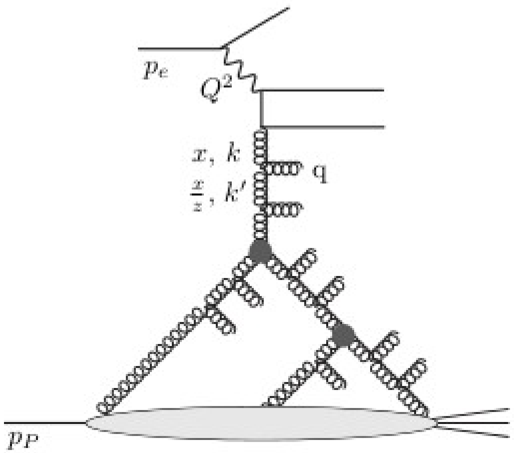
Bartels,Wusthoff '95

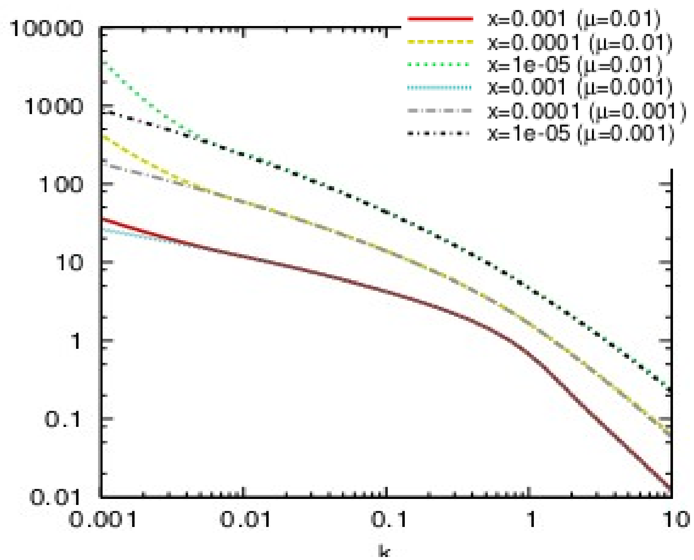
Chirilli,Szymanowski, Wallon '10

The BFKL and BK evolutions - solutions

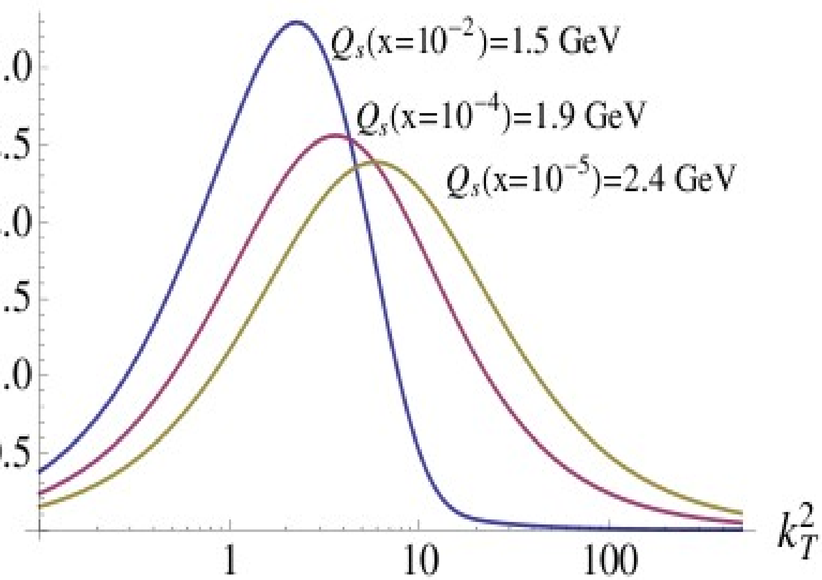
$$\mathcal{F}(x,k^2) = \mathcal{F}_0(x,k^2) + \overline{\alpha}_s \int_{x/x_0}^{1} \frac{dz}{z} \int_0^\infty \frac{dl^2}{l^2} \left[\frac{l^2\mathcal{F}(x/z,l^2) - k^2\mathcal{F}(x/z,k^2)}{|k^2-l^2|} + \frac{k^2\mathcal{F}(x/z,k^2)}{\sqrt{(4l^4+k^4)}} \right]$$







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



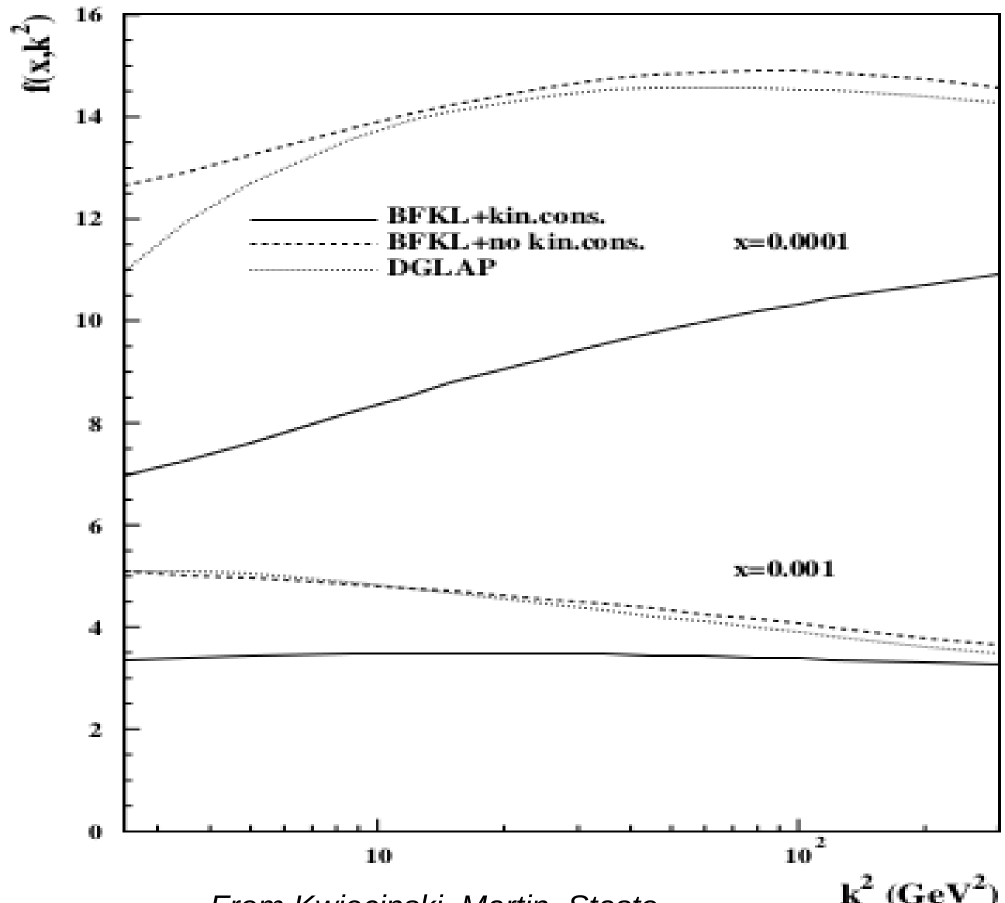
BFKL with subleading corrections
Kwiecinski, Martin, Staśto prescription

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

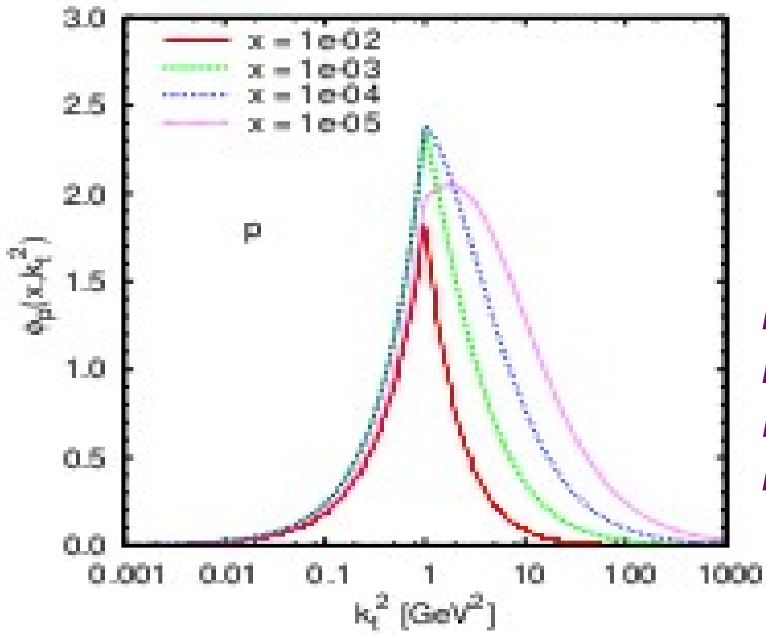


From Kwiecinski, Martin, Stasto
Phys.Rev. D56 (1997) 3991-4006

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

$$\begin{aligned}\mathcal{F}_p(x,k^2) &= \mathcal{F}_p^{(0)}(x,k^2) \\ &+ \frac{\alpha_s(k^2)N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_0^2}^{\infty}\frac{dl^2}{l^2}\left\{\frac{l^2\mathcal{F}_p(\frac{x}{z},l^2)\,\theta(\frac{k^2}{z}-l^2) - k^2\mathcal{F}_p(\frac{x}{z},k^2)}{|l^2-k^2|} + \frac{k^2\mathcal{F}_p(\frac{x}{z},k^2)}{|4l^4+k^4|^{\frac{1}{2}}}\right\} \\ &+ \frac{\alpha_s(k^2)}{2\pi k^2}\int_x^1 dz\left(P_{gg}(z) - \frac{2N_c}{z}\right)\int_{k_0^2}^{k^2} dl^2\,\mathcal{F}_p(\frac{x}{z},l^2)\end{aligned}$$

Unintegrated gluon density from BK with corrections



Nonlinear equation for unintegrated gluon density.
Related to BK via Fourier transform
Includes corrections of higher order KK, Kwiecincki, '02
Fitted to latest HERA data KK, Sapeta '11

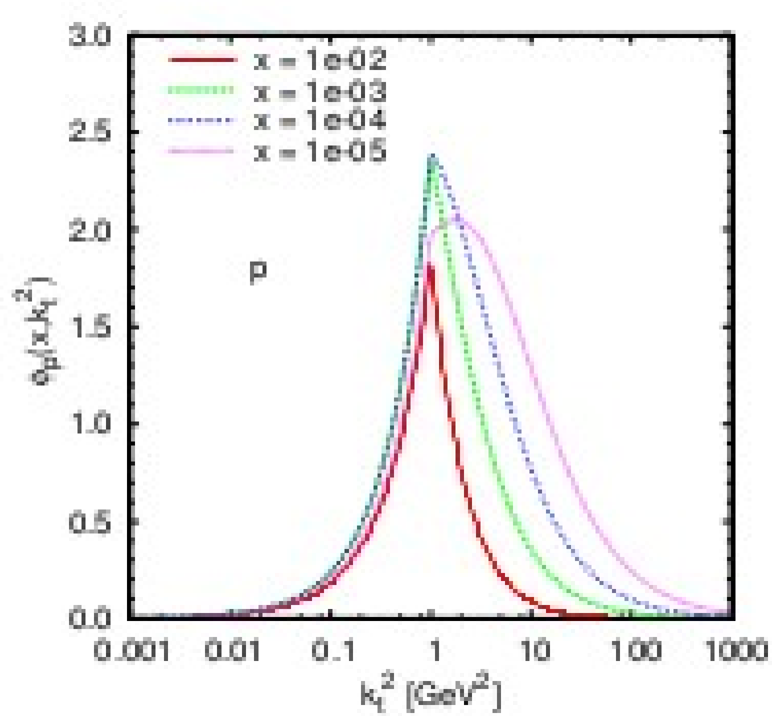
$$\mathcal{F}_p(x,k^2) = \mathcal{F}_p^{(0)}(x,k^2)$$
$$+ \frac{\alpha_s(k^2)N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_0^2}^{\infty}\frac{dl^2}{l^2}\left\{\frac{l^2\mathcal{F}_p(\frac{x}{z},l^2)\,\theta(\frac{k^2}{z}-l^2) - k^2\mathcal{F}_p(\frac{x}{z},k^2)}{|l^2-k^2|} + \frac{k^2\mathcal{F}_p(\frac{x}{z},k^2)}{|4l^4+k^4|^{\frac{1}{2}}}\right\}$$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

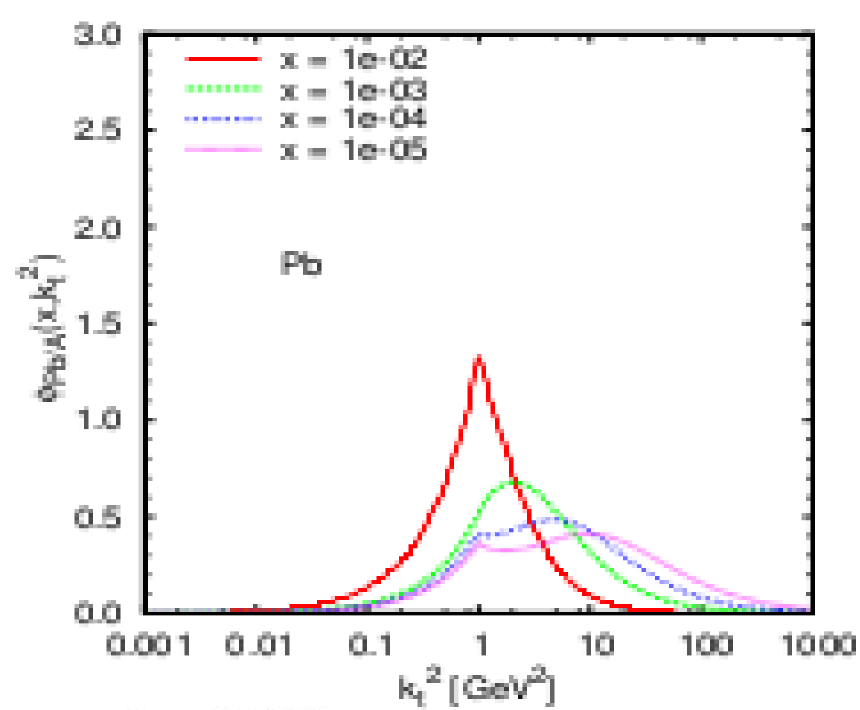
Kwiecinski, KK '03

Corrections
of higher orders
Included.
Kin. Constr
DGLAP spf

Andersson, Gustafson,Sammuelsson '96
Kwiecinski, Martin, Stasto '96,

Glue in p vs. glue in Pb





$R_A = R\,A^{1/3}$

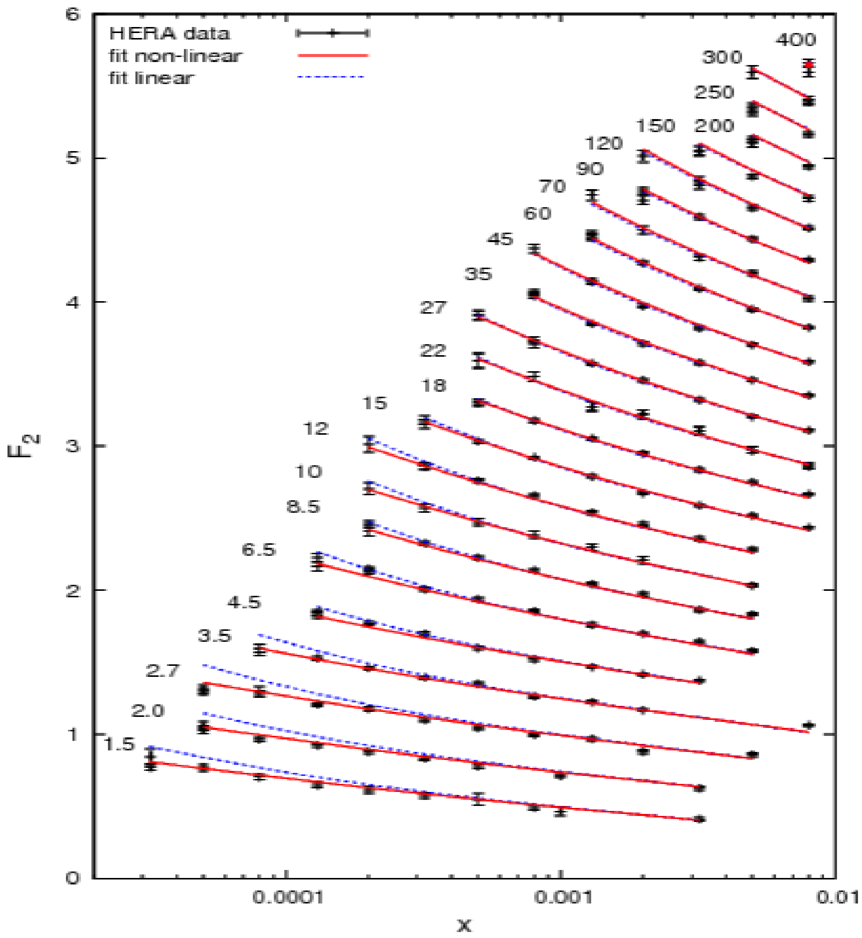
Nonlinear equation for unintegrated gluon density.

Related to BK via Fourier transform

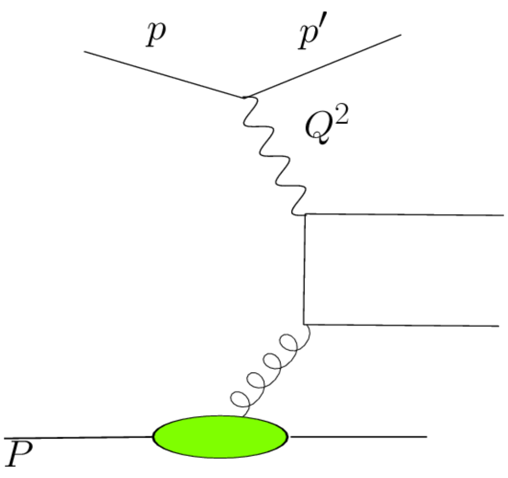
Includes corrections of higher order Kwiecincki, KK 2002

Fitted to latest HERA data Sapeta, KK 2011

BFKL applied to DIS - some recent results



Sapeta, KK '12

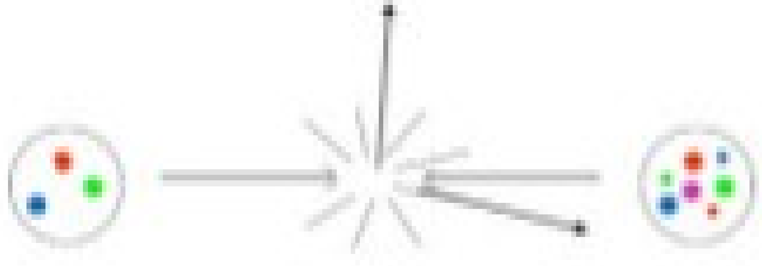


FromBK equation with corrections of higher order

Tools to be used

- *General tool for matrix elements within HEF based on spinor helicity method (A. van Hameren)*
- *Gauge link based tool to evaluate matrix elements (OGIME P. Kotko)*
- *Monte Carlo for production of dijets, trijets within HEF with Sudakov effect LxJet (P. Kotko)*
- *Tool for forward dijets Forward (S. Sapeta)*

Central-forward di-jets

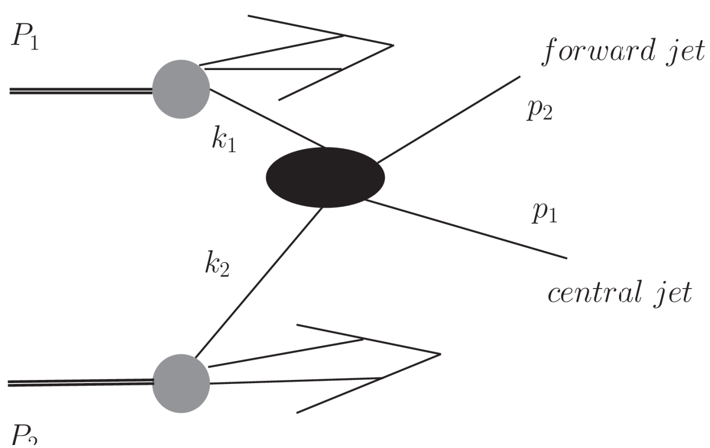


High energy prescription and forward-central di-jets

Deak, Jung, Hautmann Kutak
JHEP 0909:121,2009

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

$S = 2P_1 \cdot P_2$



- *Resummation of logs of x and logs of hard scale*
- *Knowing well parton densities at largr x one can get information about low x physics*
- *Framework goes recently under name “hybride framework”*

$$x_1 = \frac{1}{\sqrt{S}}\left(p_{t1}e^{y_1} + p_{t2}e^{y_2}\right) \xrightarrow{y_1\sim 0,\, y_2 \gg 0} \sim 1$$

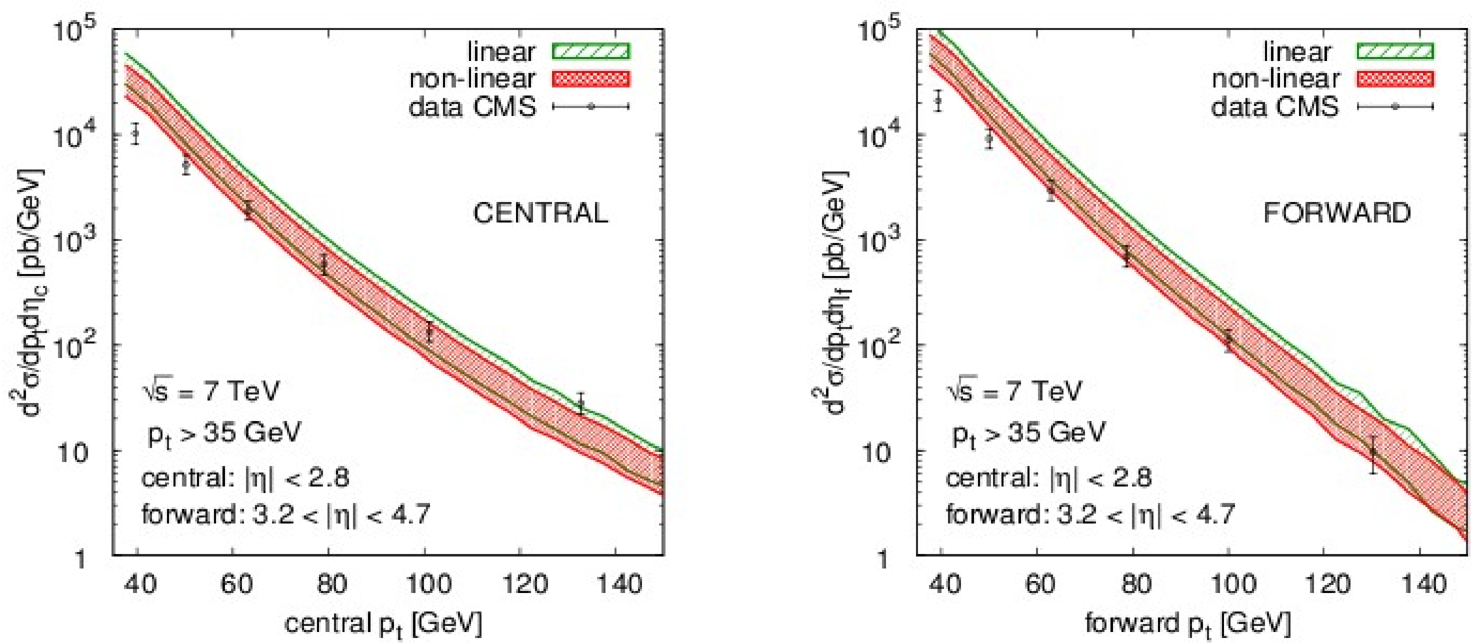
$$x_2 = \frac{1}{\sqrt{S}}\left(p_{t1}e^{-y_1} + p_{t2}e^{-y_2}\right) \qquad \ll 1$$

$$k_1^\mu = x_1 P_1^\mu$$

$$k_2^\mu = x_2 P_2^\mu + k_t^\mu$$

Di-jets p_t spectra

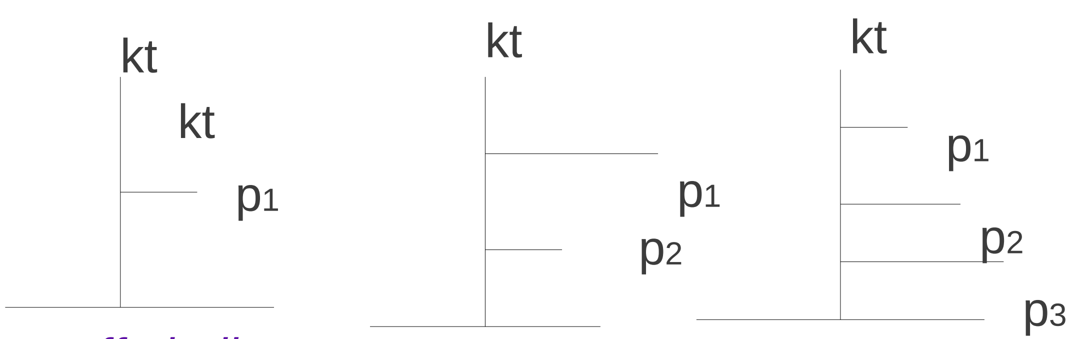
S.Sapeta. KK ,12



Reasonable agreement.

No usage of traditional parton shower

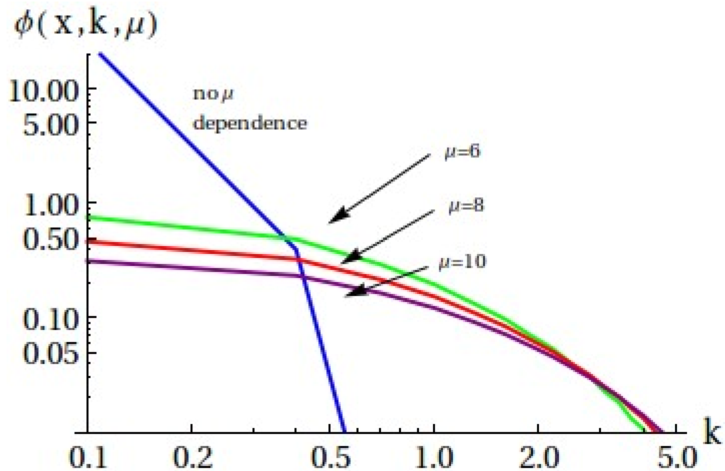
Gluon emissions are unordered in pt
and udd up to $k_t = |p_1+p_2+.....p_n|$



During evolution time incoming gluon becomes off-shell

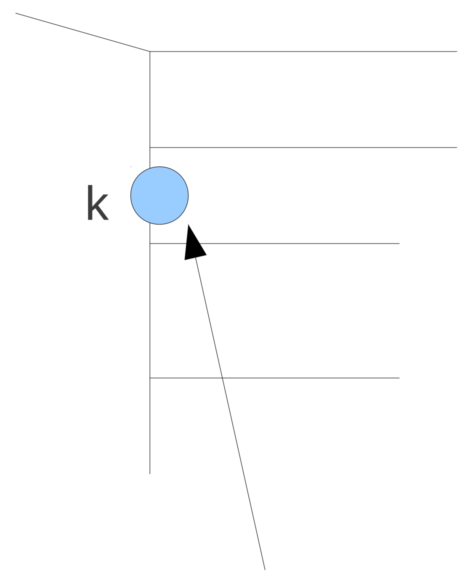
Crucial effect of higher order corrections

Final states via Sudakov effects - illustration



Two scale dependent gluon density vs. one scale dependent

Probability of finding no real gluon
Between scales μ



μ hard scale

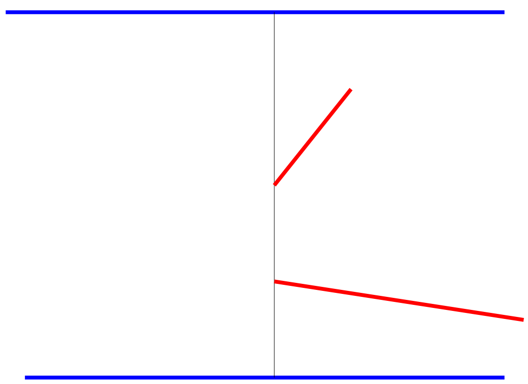
Survival probability of the gap without emissions

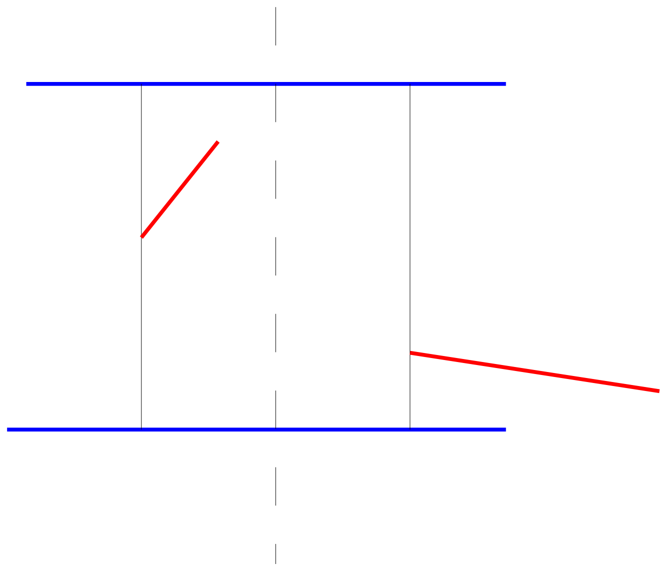
$$T_a(k_t,\mu) = \exp\left(-\int_{k_t^2}^{\mu^2} \frac{\alpha_s(p_t^2)}{2\pi}\,\frac{dp_t^2}{p_t^2} \sum_{a'} \int_0^{1-\Delta} P_{a'a}(z')\,dz'\right)$$

Kimber, Martin, Ryskin framework '01

Mueller, Xiao, Huan ;13

Things potentially to be added in the future

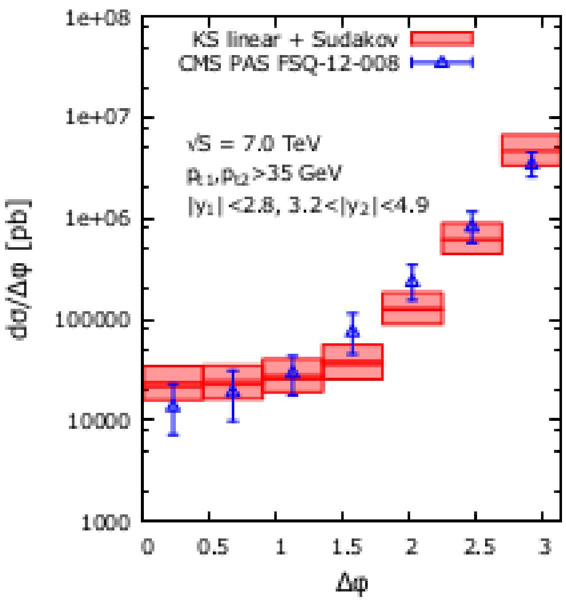


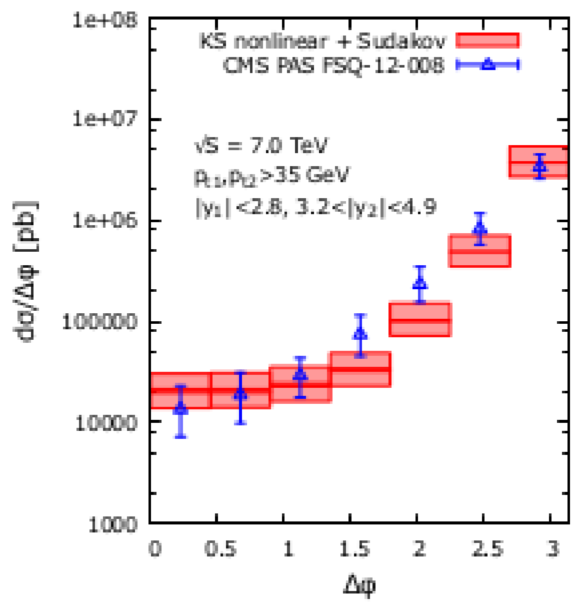


Missing MPI contributions

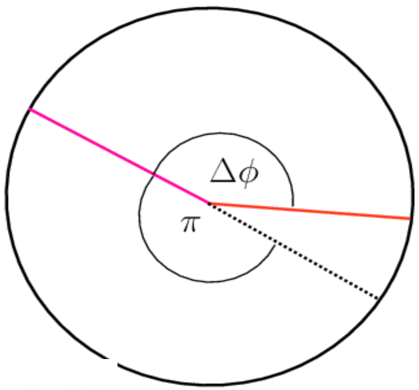
Decorelations inclusive scenario

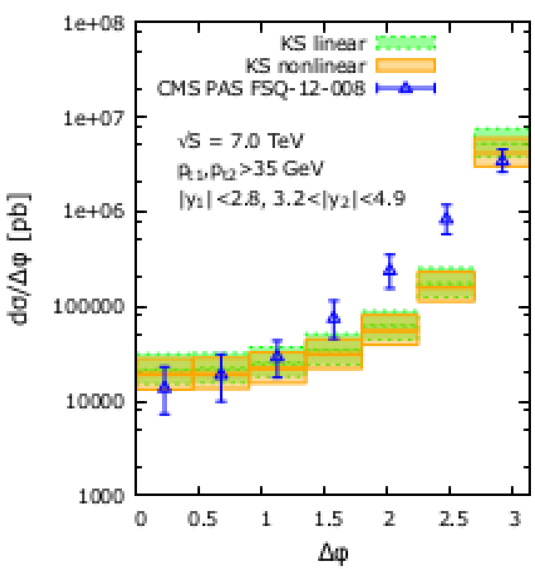
A.v.Hameren, P.Kotko, KK, S.Sapeta '14





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

$$\Delta\phi = \pi$$

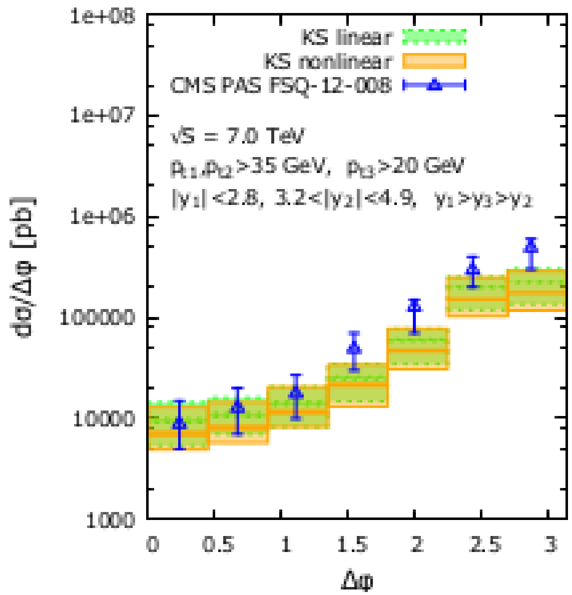
Sudakov effects by reweighting implemented in LxJet Monte Carlo
P. Kotko

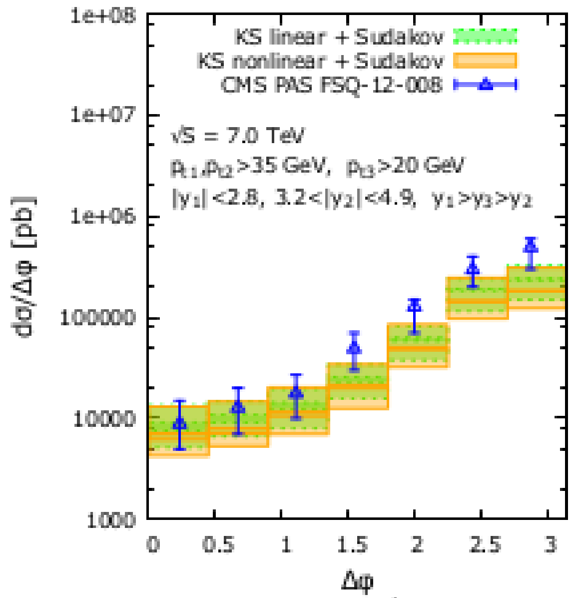
Observable suggested to study BFKL effects
Sabio-Vera, Schwensen '06

Studied also context of RHIC
Albacete, Marquet '10

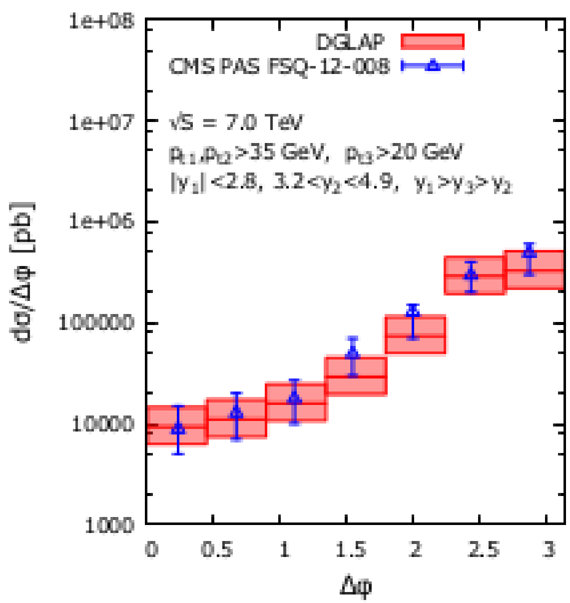
Decorelations inside jet tag scenario

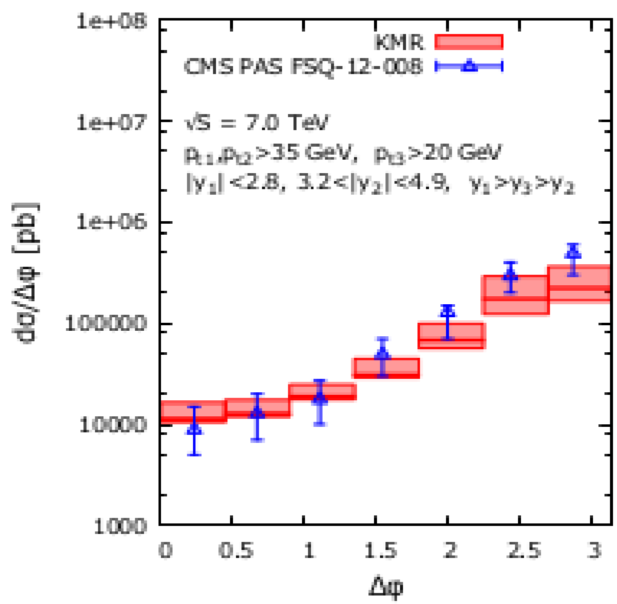
A.v.Hameren, P.Kotko, KK, S.Sapeta '14

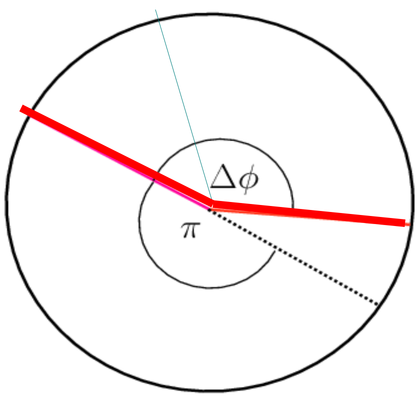




pt1, pt2 >35 GeV, leading jets |y1|<2.8, 3.2<|y2|<4.7 Third jet pt>20GeV. Between the forward and central region



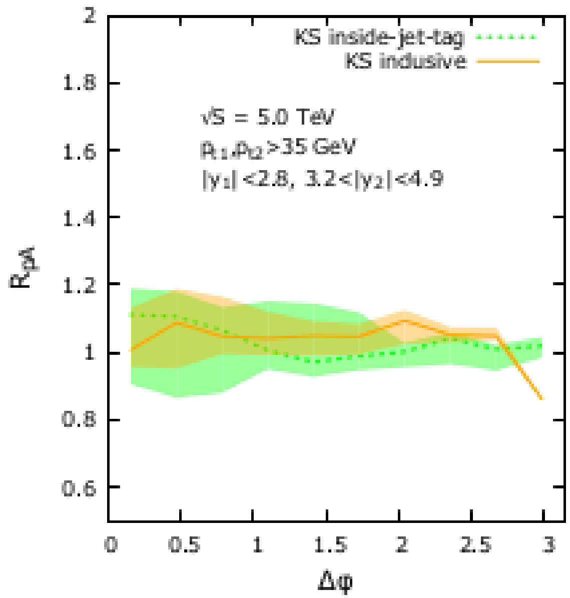


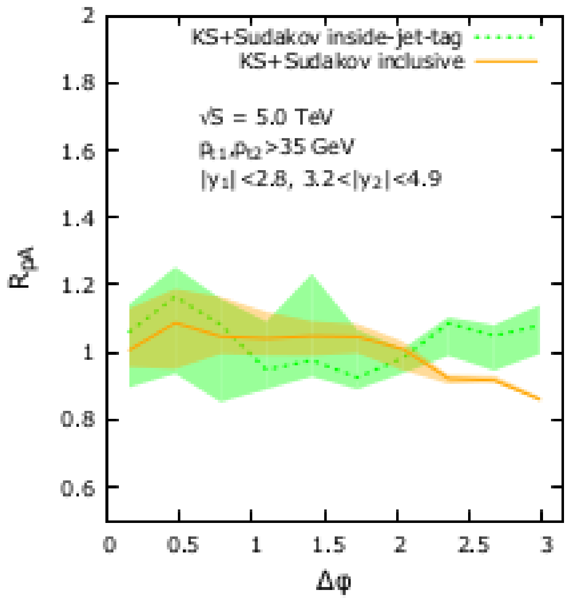


Sudakov effects by reweighting implemented in LxJet Monte Carlo P. Kotko

Predictions for p-Pb

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



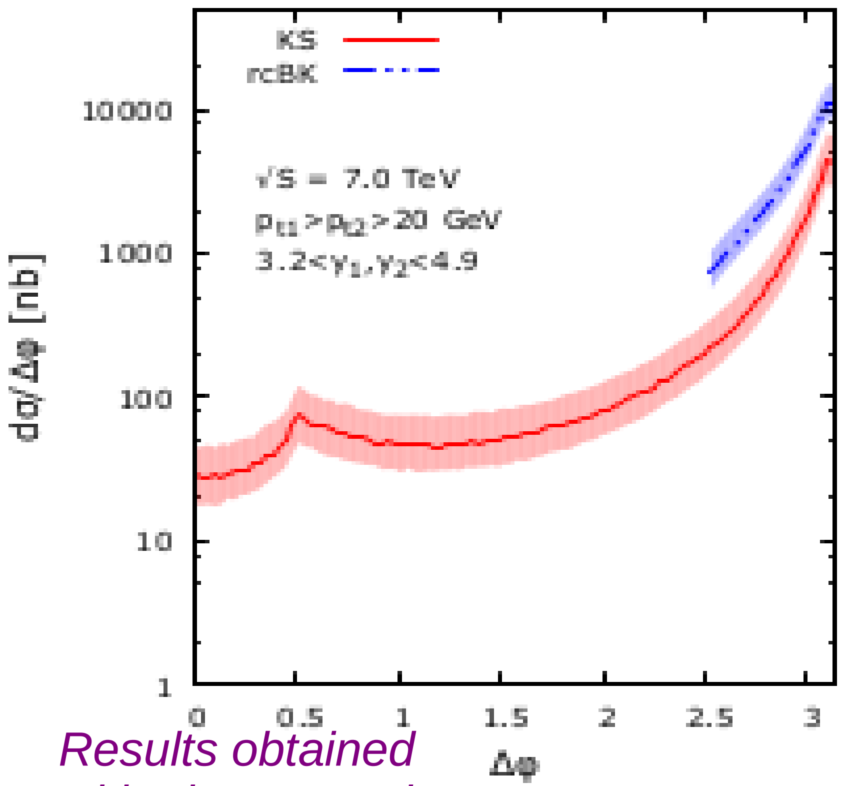


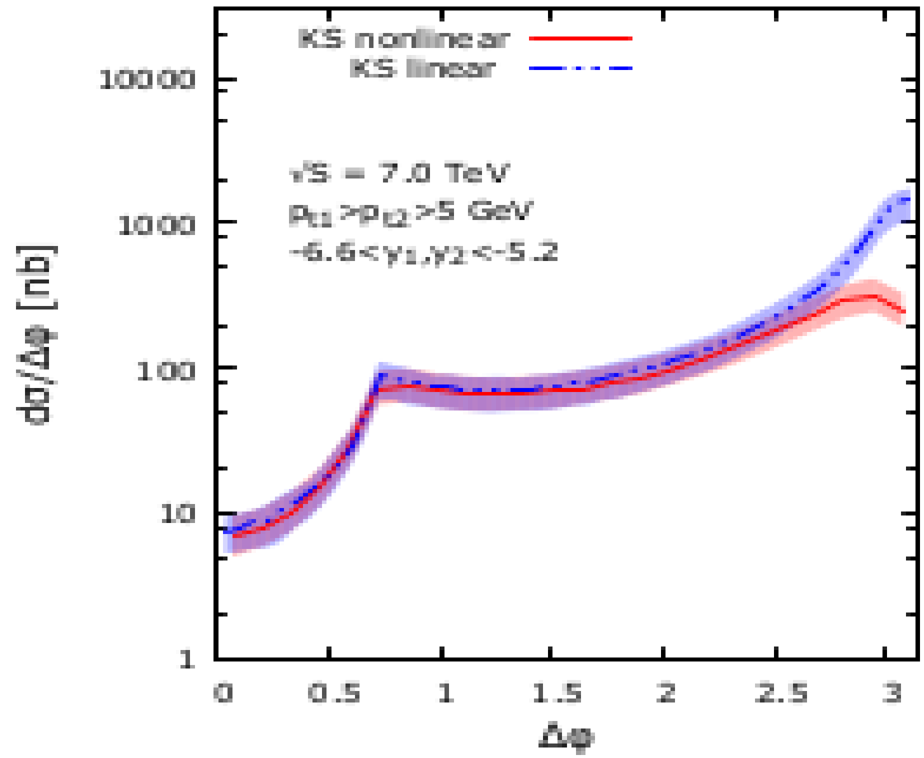
- *Sudakov enhance saturation effects*
- *Hawever, satuartion effects are rather weak*

Forward-forward di-jets

Results for decorelations

Van Hameren, Kotko, KK ,Marquet, Sapeta' 13



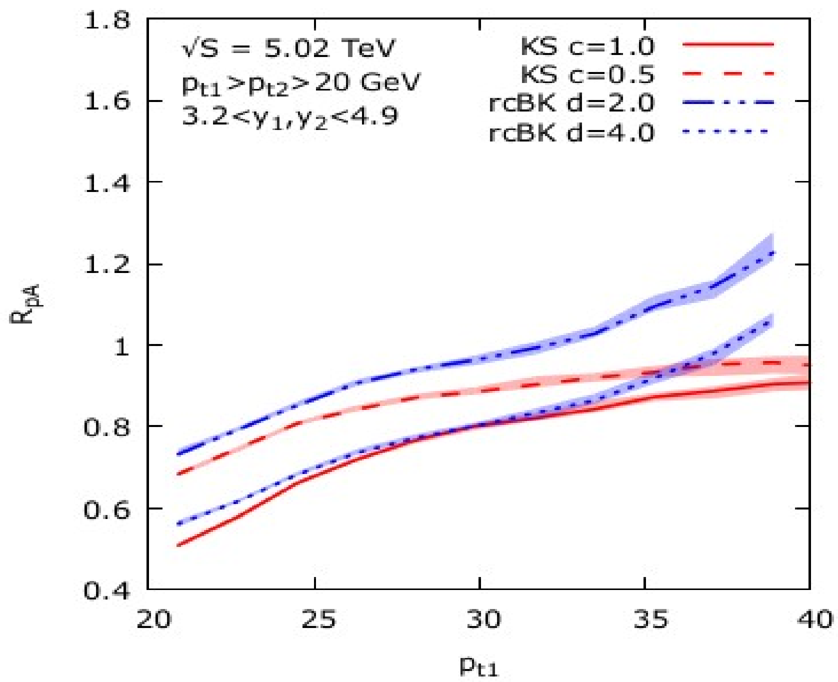


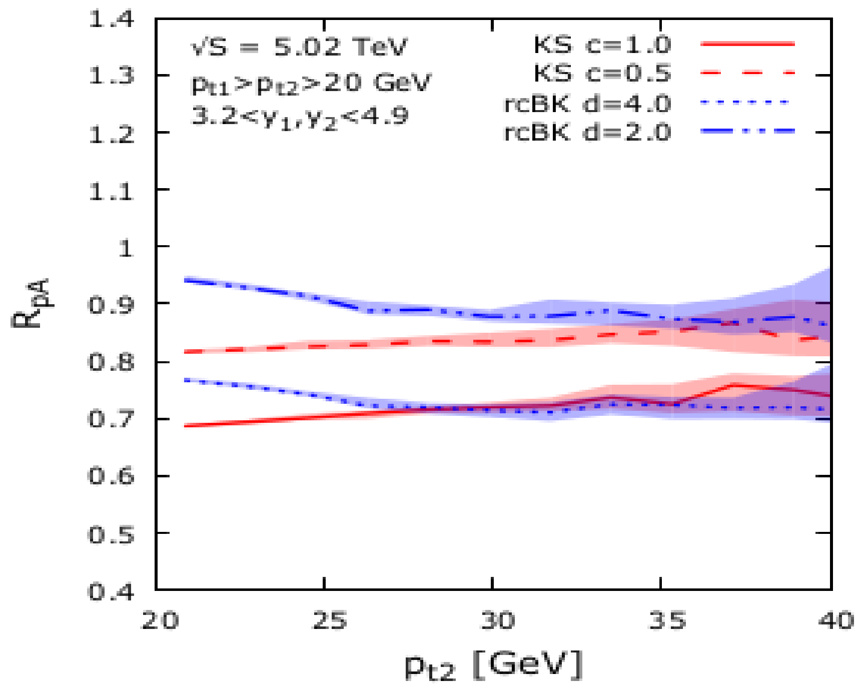
Results obtained with gluons coming from rcBK and BK with corrections of higher orders

Importance of corrections of higher orders

Forward-forward di-jets

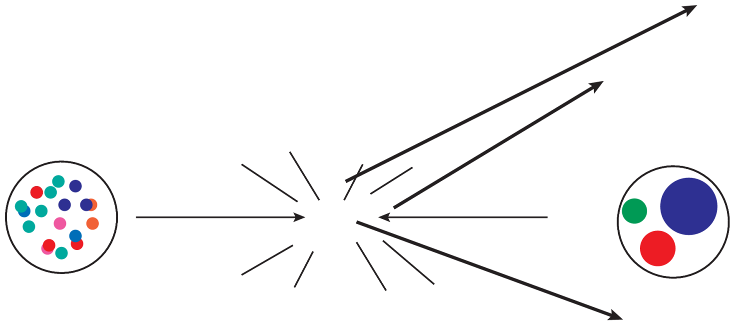
A. van Hameren:,KK, Kotko,Marquet, Sapeta '14





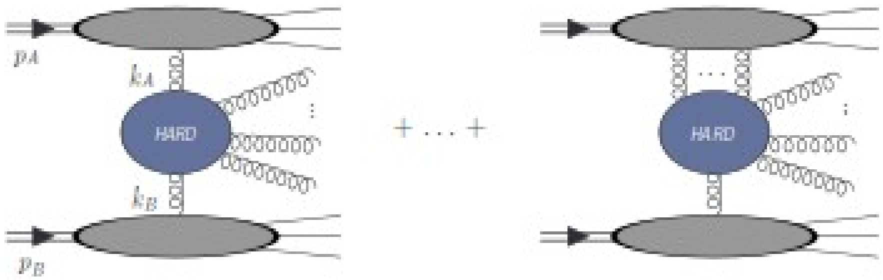
Studies of subleading jet gives more pronounced signal of suppression. Details of that are still to be understood

Forward tri-jets



HEF applied to three jets

Van Hameren, Kotko, KK ,13



p-p and p-Pb collisions

CM energy 5 TeV and 7 TeV

$p_{T\,1} > p_{T\,2} > p_{T\,3} > p_{T\,\mathrm{cut}}$

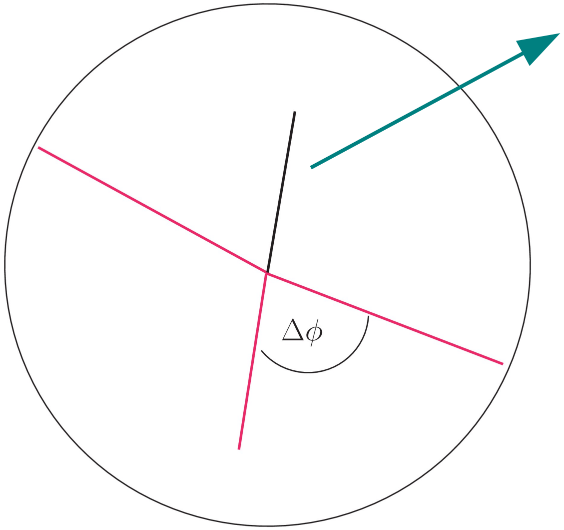
$$d\sigma_{AB\to X} = \int \frac{d^2k_{T\,A}}{\pi} \int \frac{dx_A}{x_A} \int dx_B \quad \sum_b \mathcal{F}_{g^*/A}\left(x_A, k_{T\,A}\right) f_{b/B}\left(x_B\right) d\hat{\sigma}_{g^*b\to X}\left(x_A, x_B, k_{T\,A}\right)$$

$$x_A = \sum_i \frac{|\vec{p}_{T\,i}|}{\sqrt{S}}\, e^{\eta_i}, \quad x_B = \sum_i \frac{|\vec{p}_{T\,i}|}{\sqrt{S}}\, e^{-\eta_i}$$

$$\eta_{f\,0} \leq \eta_i \leq \eta_{f\,1} \qquad\qquad |\eta_j| \leq \eta_c$$

central   *forward*

$$|\vec{p}_{T\,i}| > p_{T\,\mathrm{cut}}, \quad i = 1, 2, 3.$$

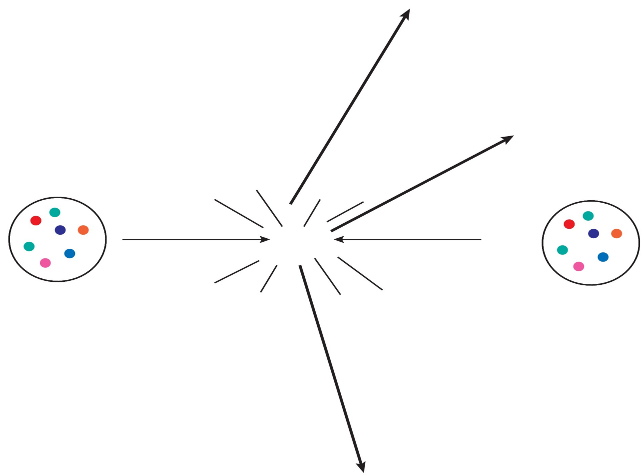


Incoming Reggon i.e. off-shell gluon

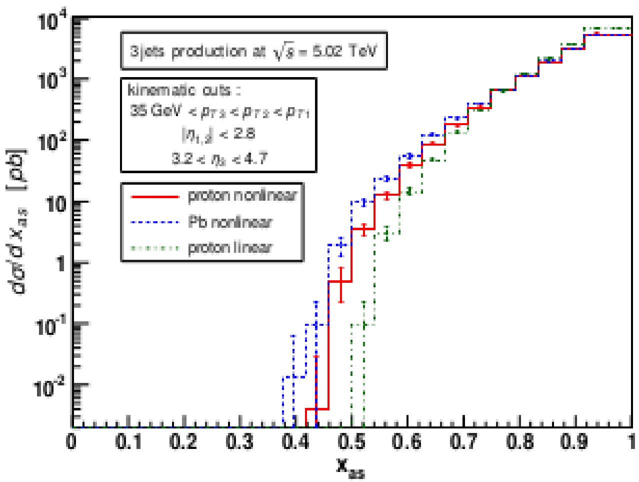
[1] http://annapurna.ifj.edu.pl/~pkotko/LxJet.html

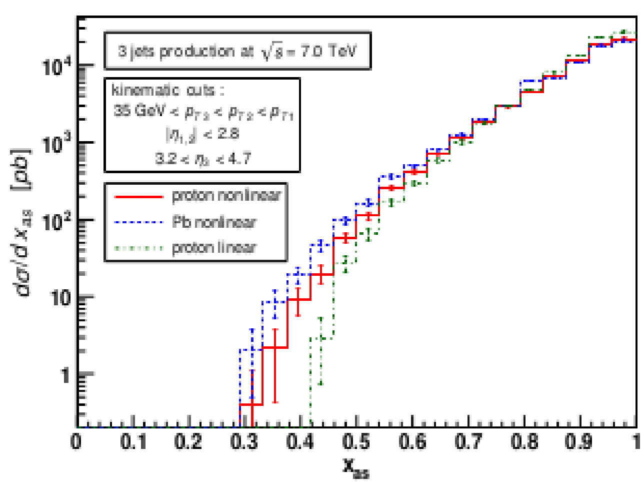
Central-central-forward configuration

Van Hameren, Kotko, KK ,13



two leading jets are in the central region with $|\eta_{1,2}| < 2.8$
the softest jet is in the forward region $3.2 < \eta_3 < 4.7$
$p_{T\,\mathrm{cut}} = 35\,\mathrm{GeV}$
we may restrict additional cuts on the central jets, e.g. $|\vec{p}_{T\,1} + \vec{p}_{T\,2}| < D_{\mathrm{cut}}$



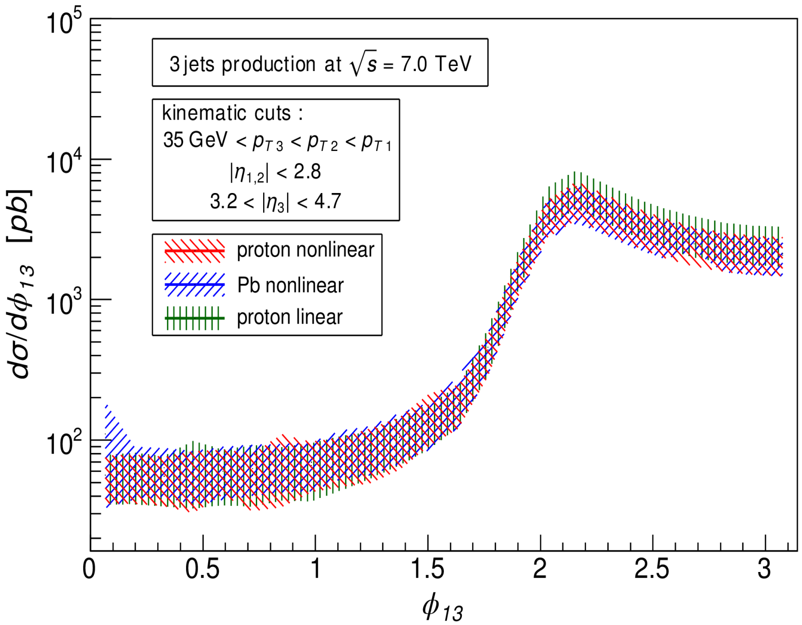


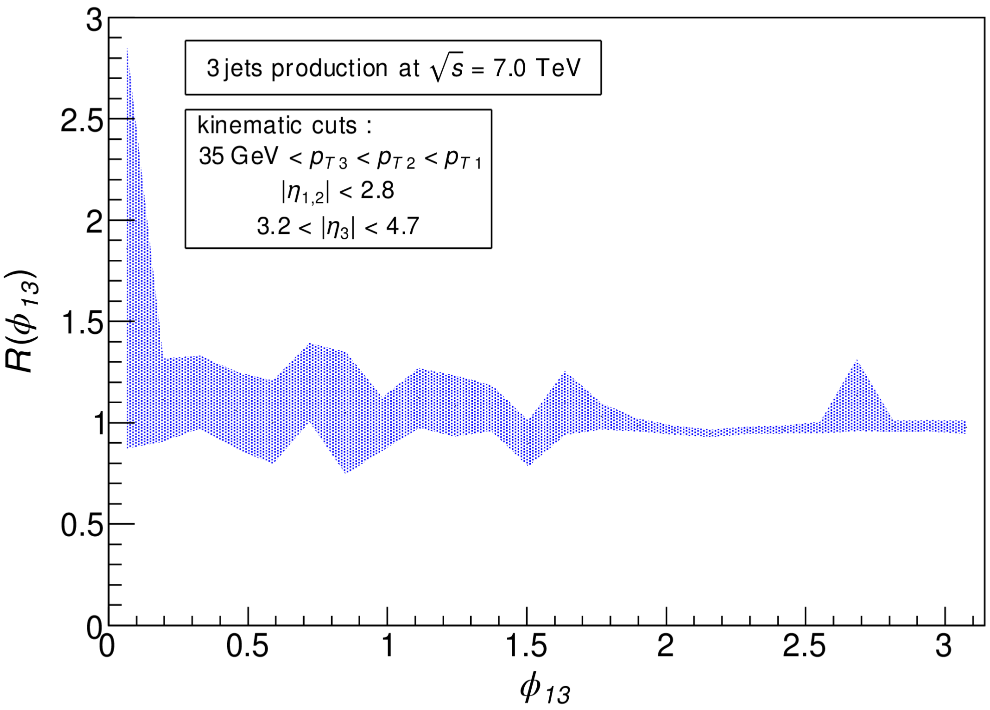
$$x_{\mathrm{as}} = \frac{|x_A - x_B|}{x_A + x_B}$$

Many symmetric events

Central-central-forward configuration

Van Hameren, Kotko, KK ,13

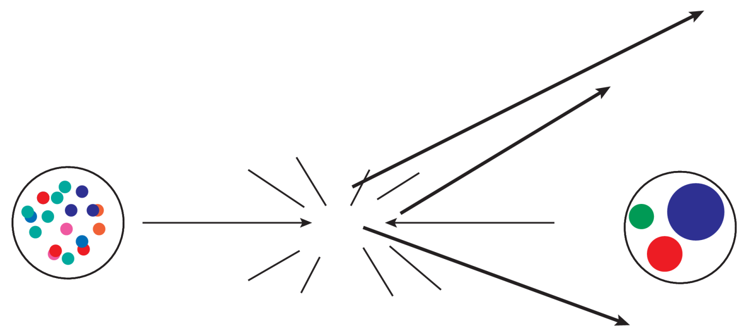


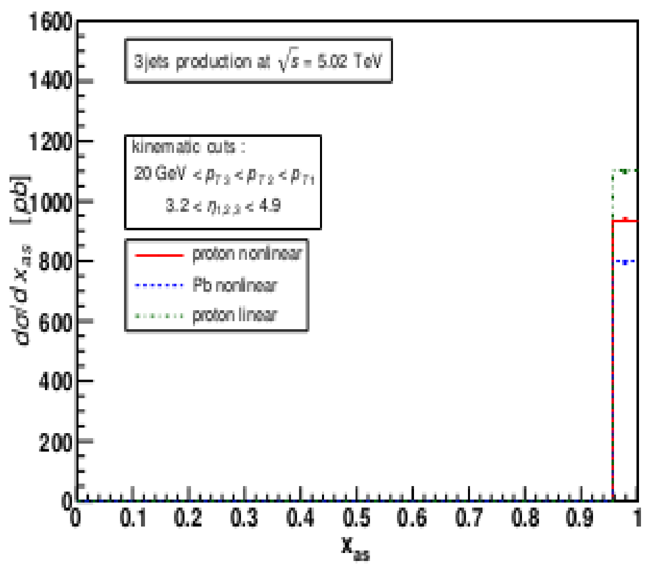


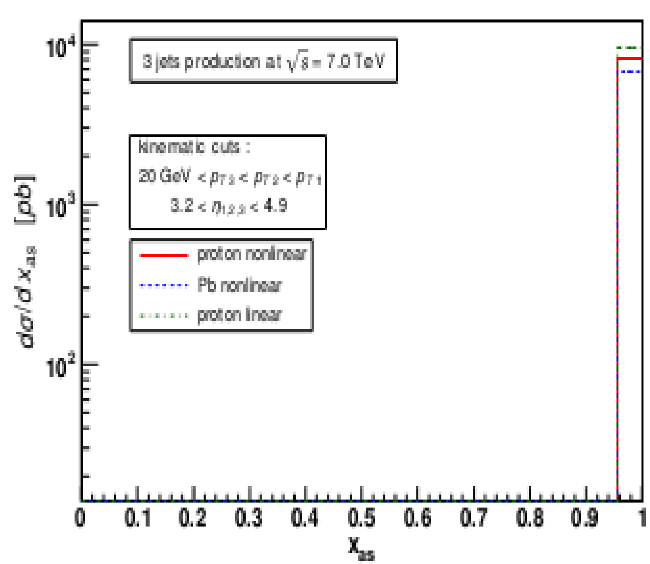
No noticeable saturation effects

Forward-forward-forward configuration

Van Hameren, Kotko, KK ,13







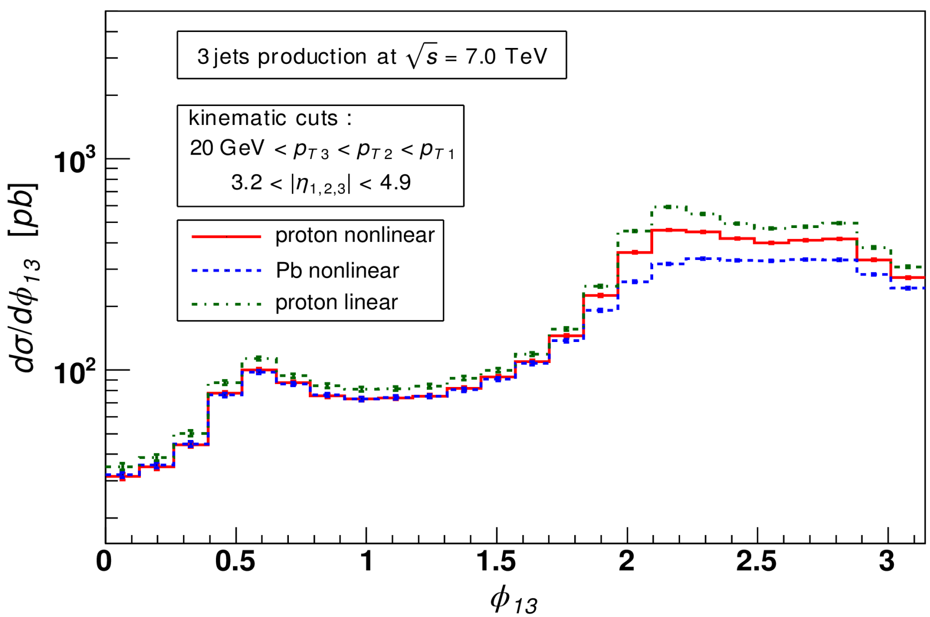
$$x_{as} = \frac{|x_A - x_B|}{x_A + x_B}$$

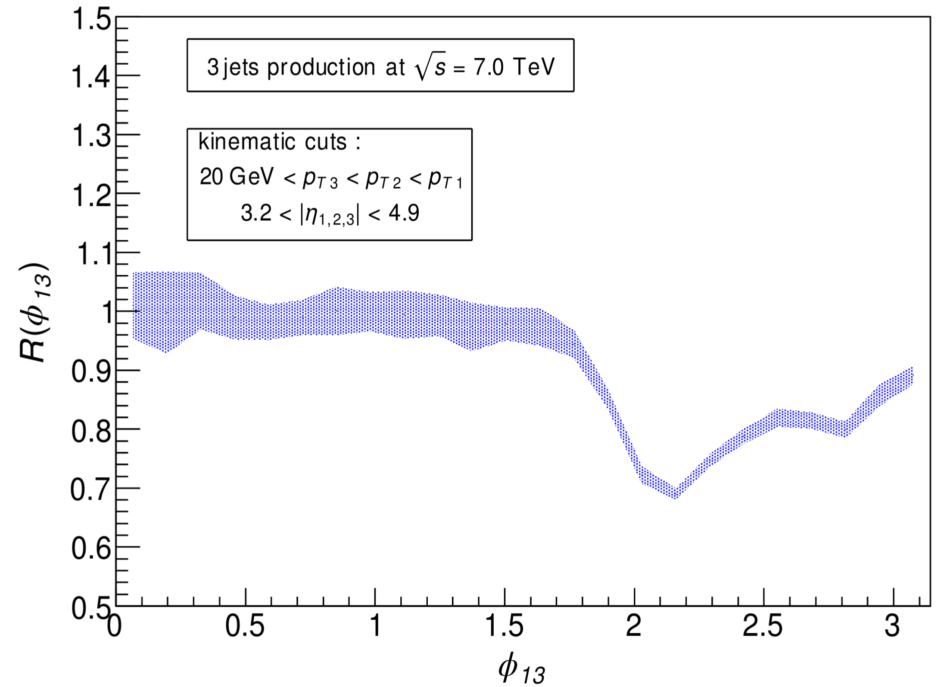
1

totally assymetric

Forward-forward-forward configuration

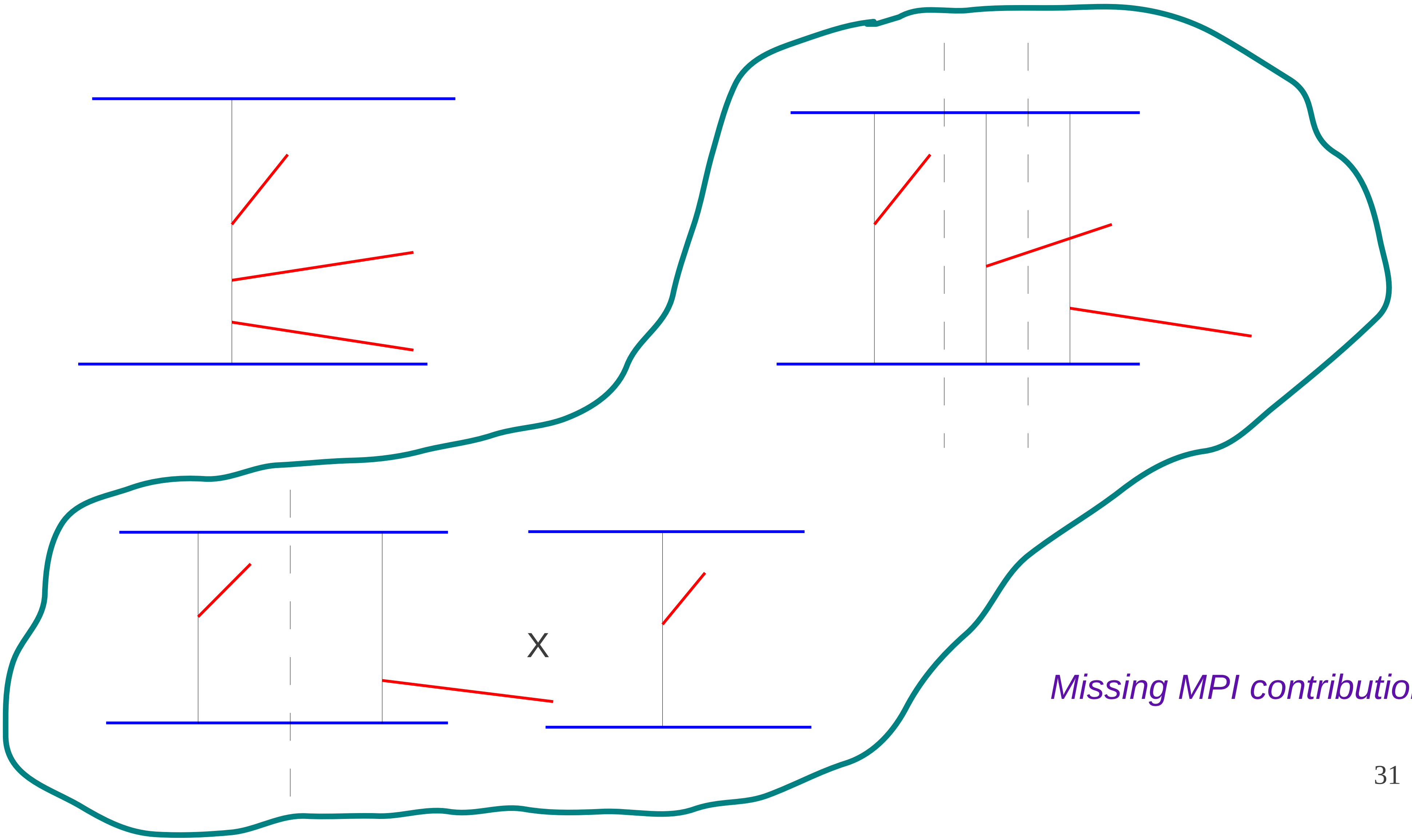
Van Hameren, Kotko, KK ,13





Saturation effects show up

Things eventually to be added in the future



Missing MPI contributions

Conclusions and outlook

- *Achieved very good description of forward-central jet measurement*
- *Predictions for pPb are robust*
- *Evidence for low x dynamics*
- *Open questions – description of the decorelations within CCFM and KGBJS. It includes Sudakov, and low x dynamics.*