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NCN

Improved TMD factorization and production of forward jets

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Based on
Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren,
JHEP 1612 (2016) 034
JHEP 1612 (2016) 034

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

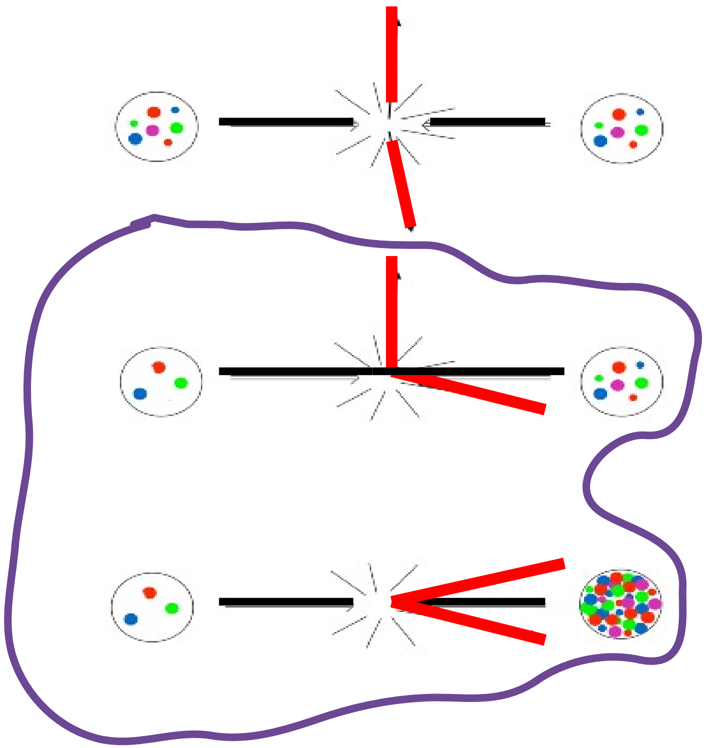
Forward jets can be used to study so called low x phenomena i.e. saturation of gluon density

Jets can be used to perform tomography of QGP

In this talk I am going to address di-jets and single inclusive jet

4-jet production → Mirko Serino

LHC and tomography of partons → di-jet example



central-central i.e. dilute dilute

$$x \sim 10^{-1}$$

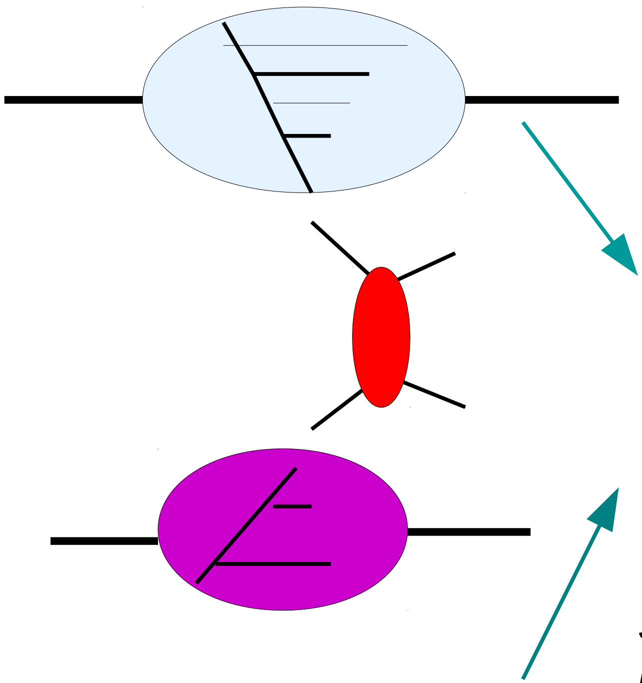
forward-central

$$x \sim 10^{-4}$$

forward-forward i.e. dilute - dense

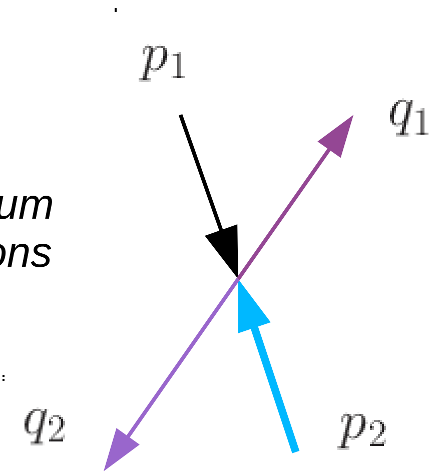
$$x \sim 10^{-5}$$

hybrid High Energy Factorization

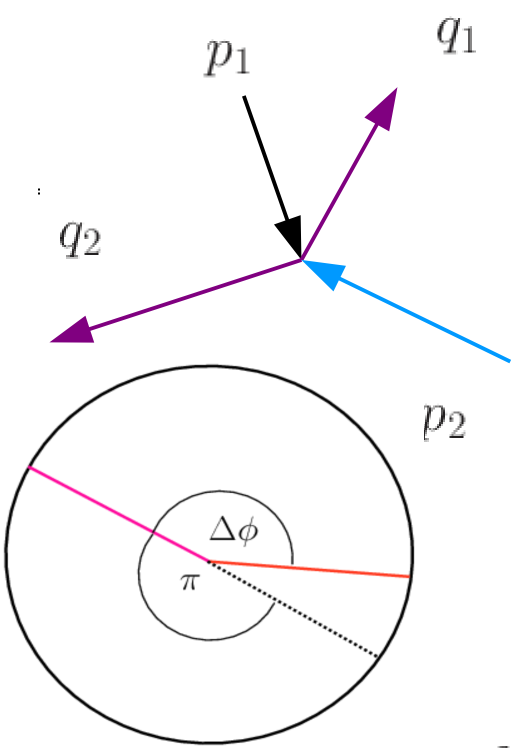


Strongly decreasing transversal momentum of DGLAP like partons

Strongly decreasing Longitudinal momentum fractions of off-shell partons



$$p_1 + p_2 = q_1 + q_2$$



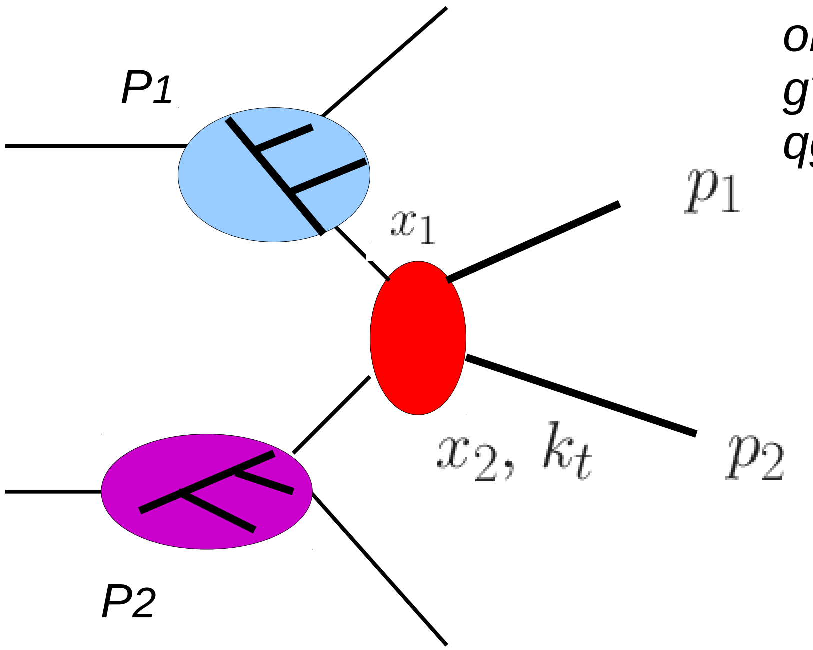
$$p_1 + p_2 = q_1 + q_2 + k$$

First attempt: hybrid factorization and dijets

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

conjecture

Deak, Jung, Kutak, Hautmann '09



obtained from CGC after neglecting all nonlinearities

*g*g → gg Iancu,Laidet*

qg → qg Van Hameren, Kotko, Kutak, Marquet, Petreska, Sapeta*

resummation of logs of x

logs of hard scale

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

$$x_1 = \frac{1}{\sqrt{s}}\left(|\vec{p}_{1t}|e^{y_1} + |\vec{p}_{2t}|e^{y_2}\right) \qquad \xrightarrow{y_1,y_2\gg 0} \qquad x_1 \sim 1$$

$$x_2 = \frac{1}{\sqrt{s}}\left(|\vec{p}_{1t}|e^{-y_1} + |\vec{p}_{2t}|e^{-y_2}\right) \qquad\qquad x_2 \ll 1$$

Inbalance momentum:

$$|\vec{k}_t|^2 = |\vec{p}_{1t}+\vec{p}_{2t}|^2 = |\vec{p}_{1t}|^2 + |\vec{p}_{2t}|^2 + 2|\vec{p}_{1t}||\vec{p}_{2t}|\cos\Delta\phi$$

Relevant scales and factorization

P_t average transverse momentum of dijets

k_t target gluon's transverse momentum

Q_s scale at which gluon recombination nonlinear effects at the target start to be relevant

$P_t \sim k_t$ High Energy Factorization → partons carry some k_t

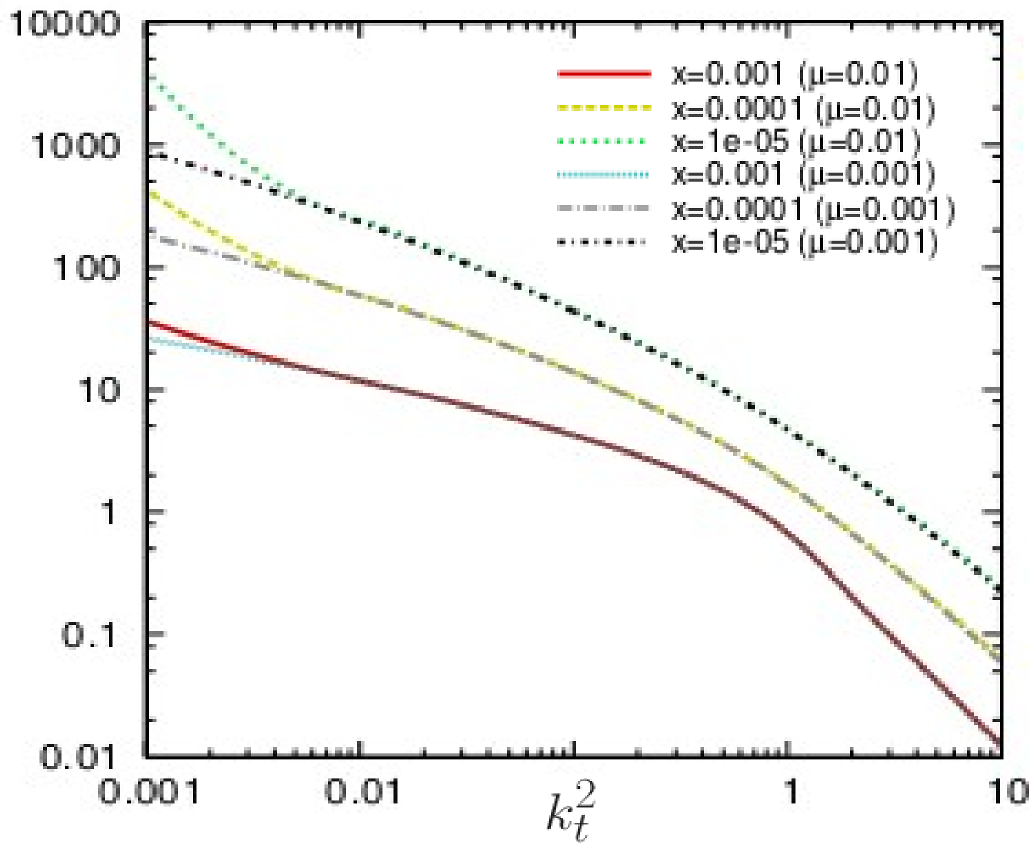
$k_t \ll P_t$ Collinear Factorization → partons in one of hadrons are just collinear with hadron
k_t is neglected

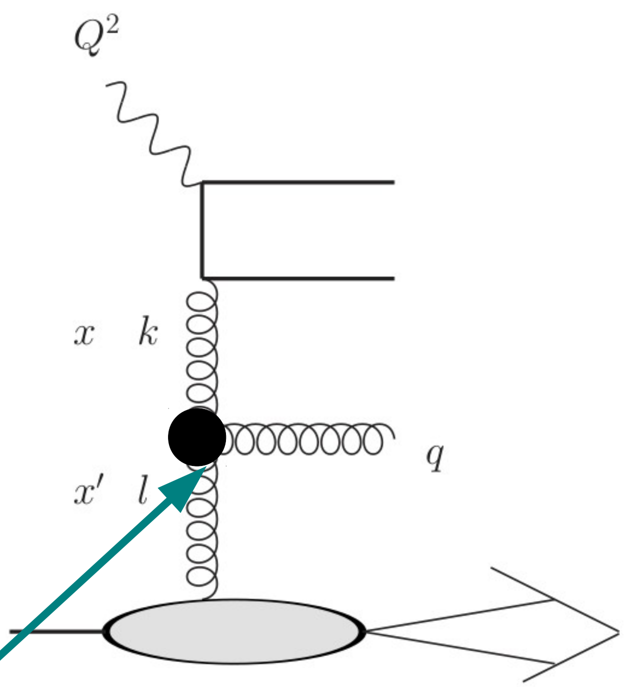
$Q_s \sim k_t \ll P_t$ generalized Transverse Momentum Dependent Factorization → rescatterings
formal treatment of nonlinearities but does not allow for calculation of decorelations

Q_s, k_t, P_t Improved Transverse Momentum Dependent Factorization

The saturation problem: sensitivity to gluons at small k_t

Solution of BFKL equation

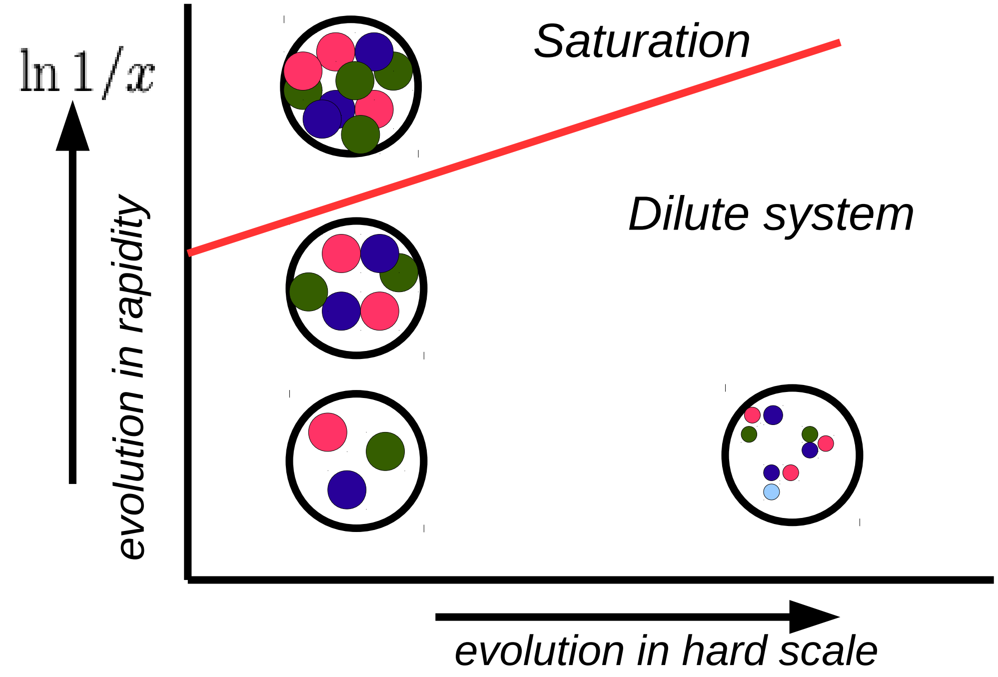




$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F}$$

High energy factorization and saturation

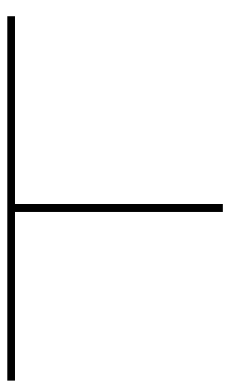
Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.



On microscopic level it means that
gluon apart splitting recombine

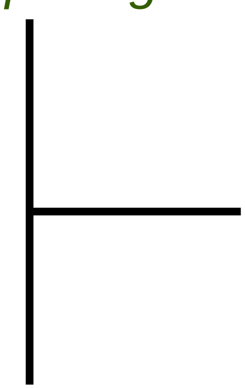
splitting

Linear evolution equation



Nonlinear evolution equations

splitting



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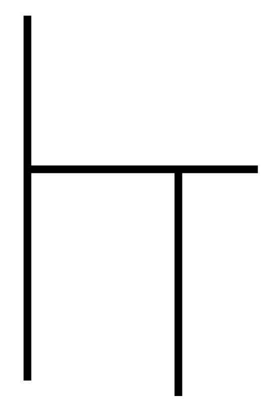
recombination



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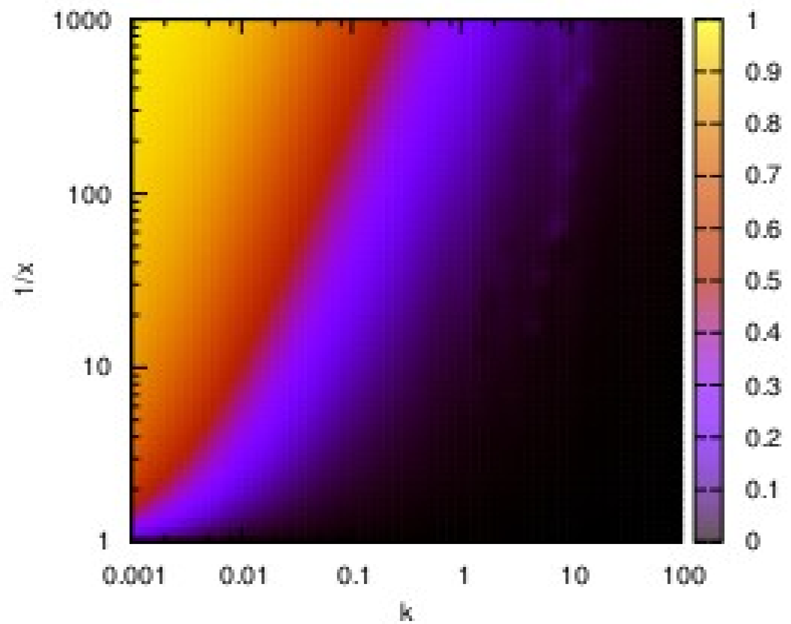

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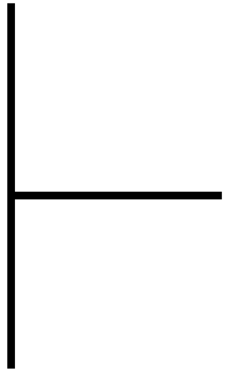
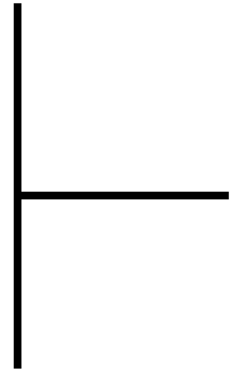


splitting

recombination

Nonlinear evolution equations



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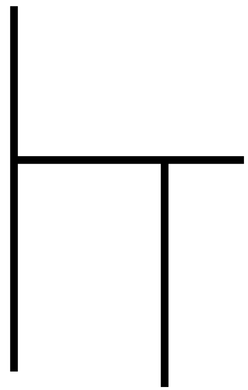


The saturation problem: supressing gluons at small k_t

Originally formulated in coordinate space

Balitsky '96, Kovchegov '99

Now at NLO accuracy

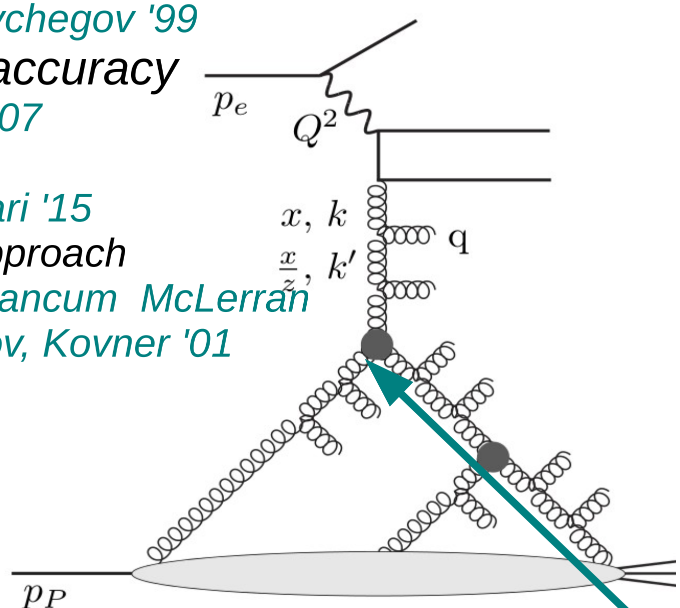
Balitsky, Chirilli '07

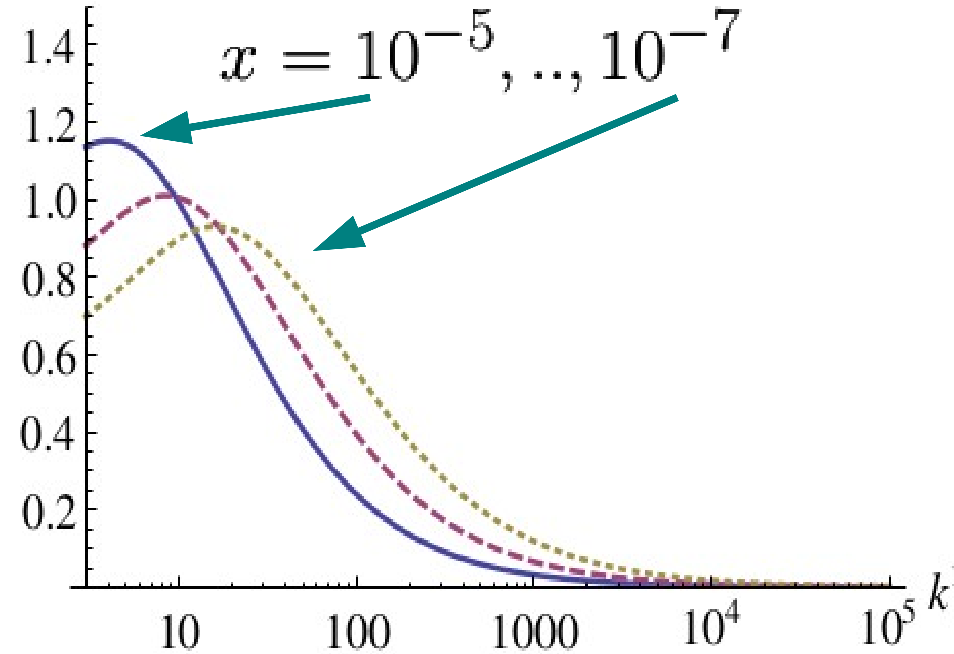
and solved

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

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

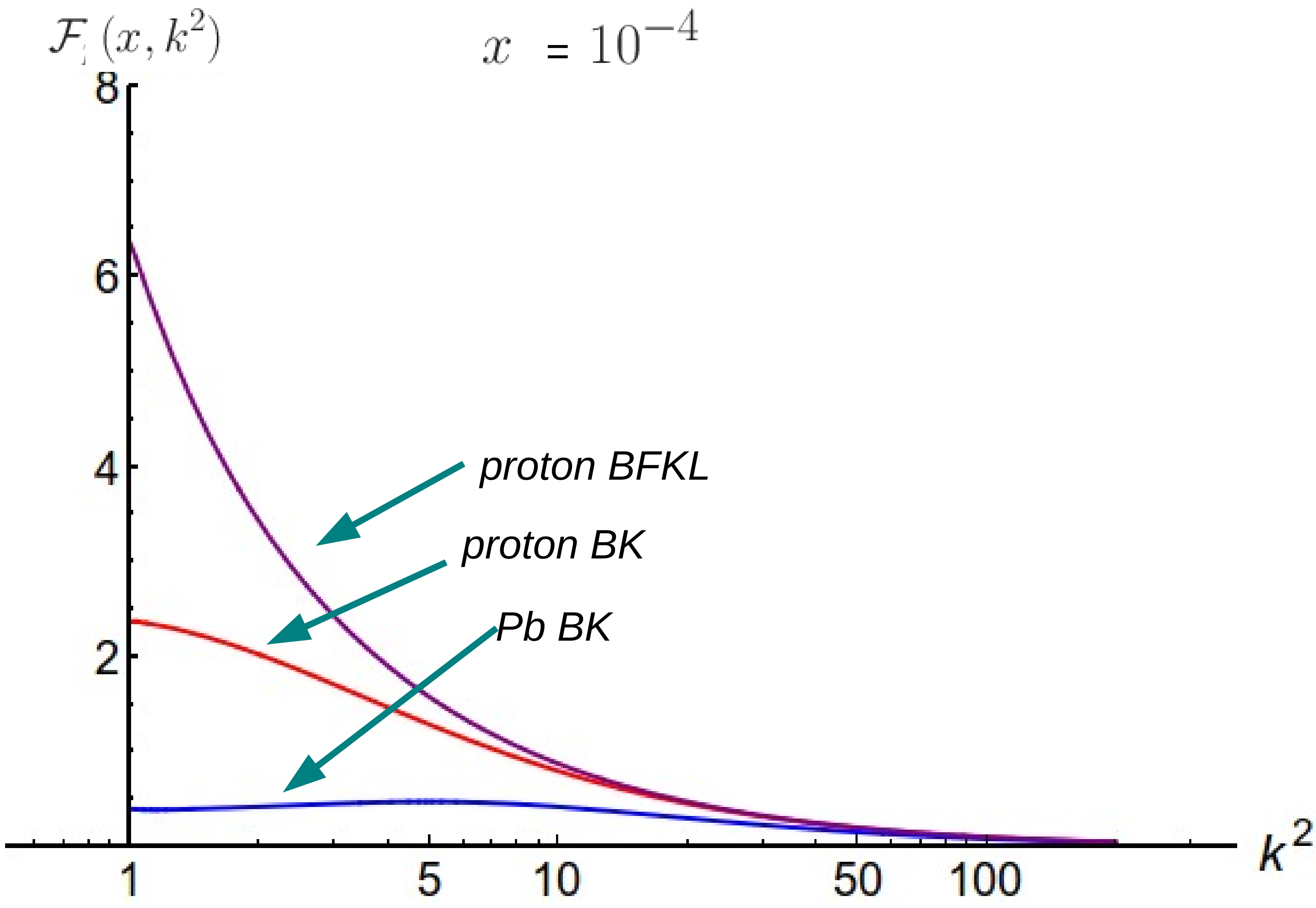
Momentum space

Kwiecinski, Kutak '02

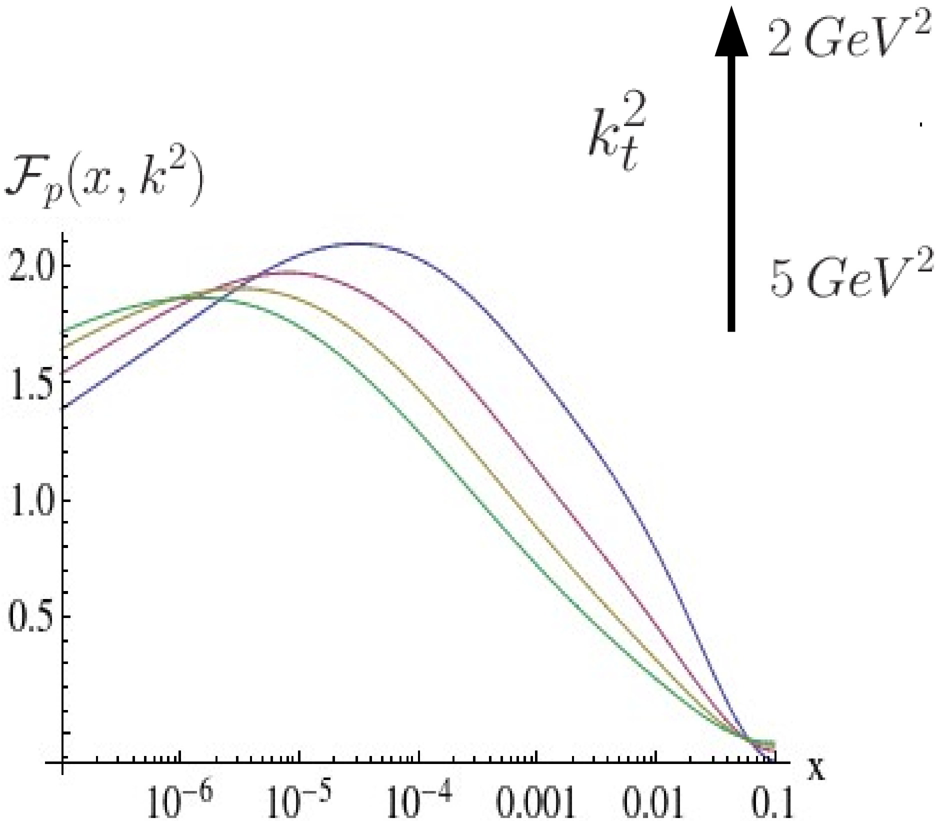
Nikolaev, Schafer '06

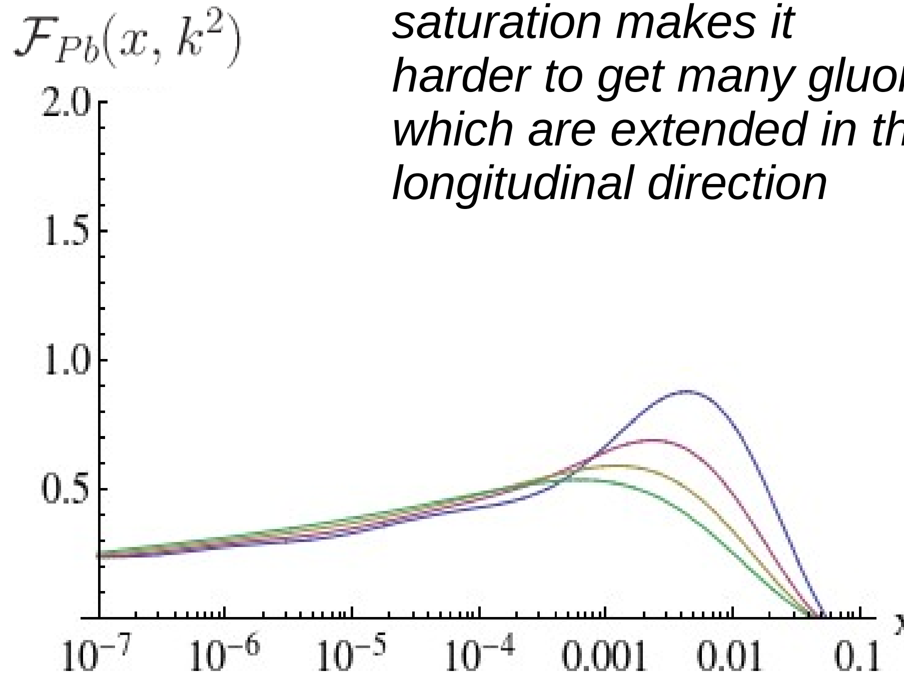
hadron's radius

Glue in p vs. glue in Pb vs. linear - kt dependence



Only nonlinear - glue in p vs. glue in Pb

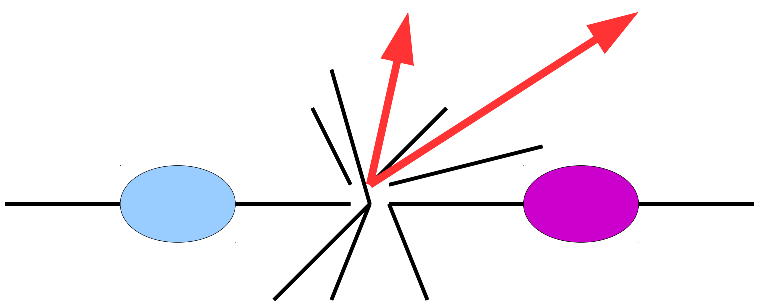




Innvoking uncerainity principle. The plots show that saturation makes it harder to get many gluons which are extended in the longitudinal direction

Maximum signalize emergence of saturation scale

Central-forward di-jets



PDF we use at present

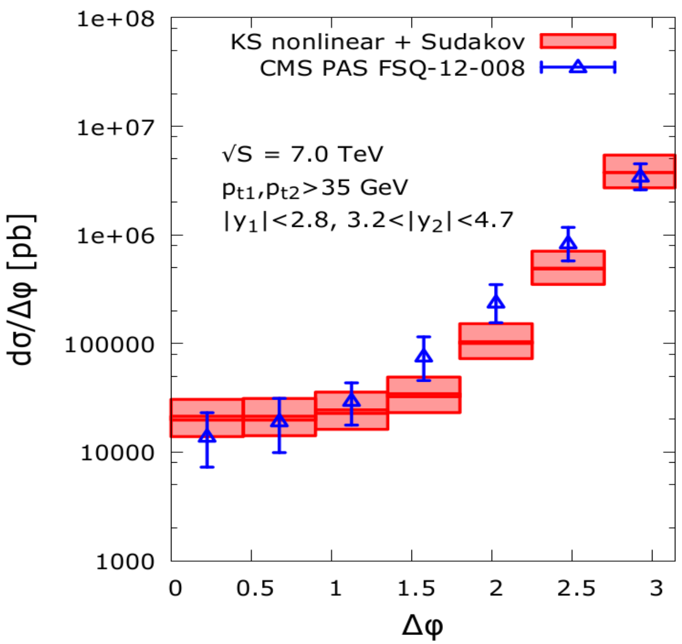
KS (Kutak-Sapeta) nonlinear → gluon density from extension of momentum space version of BK equation to include:

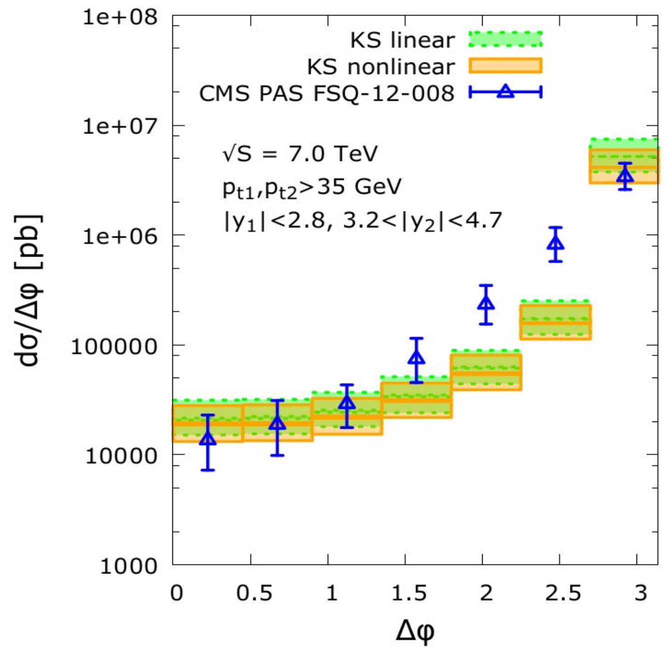
- *kinematical constraint*
- *complete splitting function,*
- *running coupling*
- *quarks*

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

Decorelations inclusive scenario forward-central

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



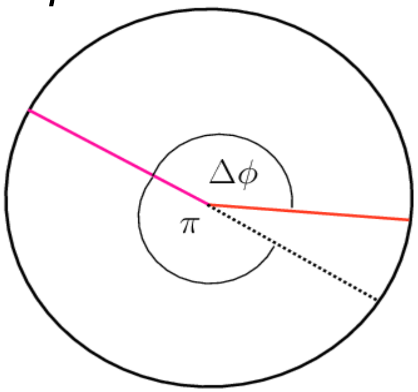


$$p_{t1},\, p_{t2} > 35\, GeV$$

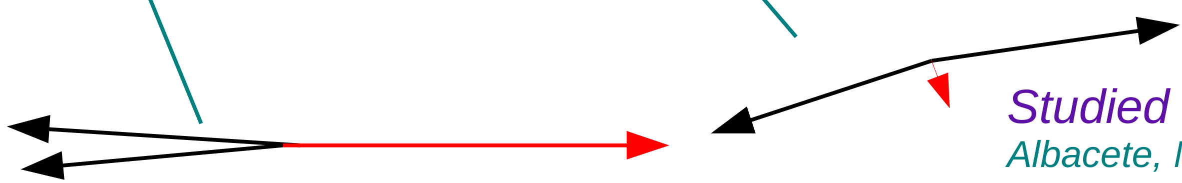
$$3.2 < |y_2| < 4.7$$

$$|y_1| < 2.8$$

Leading jets, no further requirement



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



Observable suggested to study BFKL effects

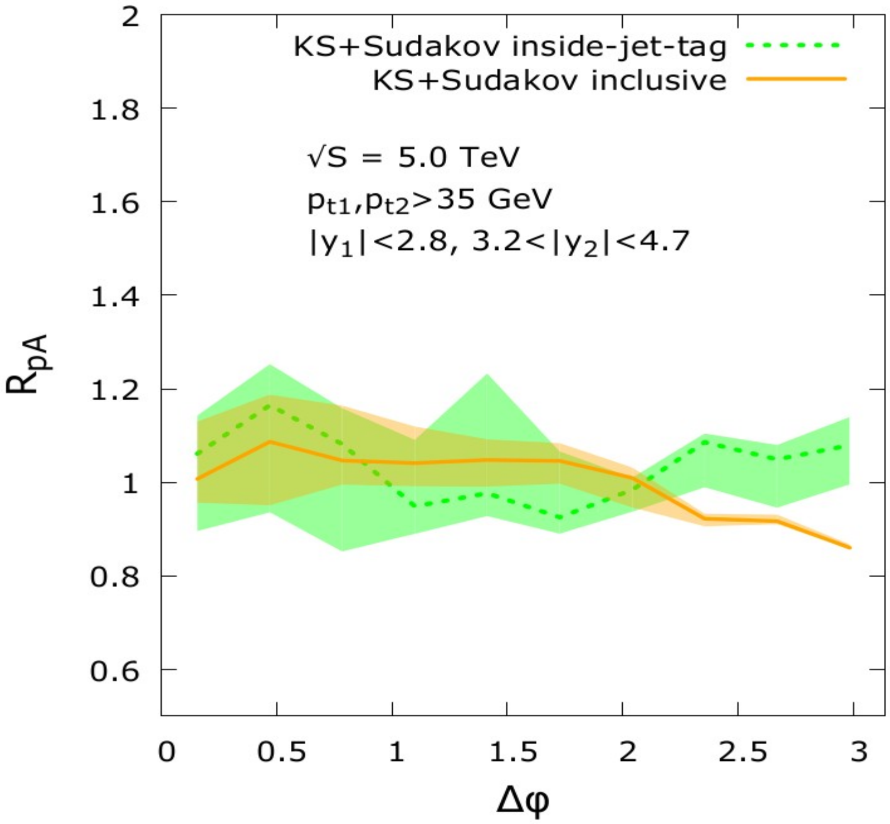
Sabio-Vera, Schwensen '06

Studied also context of RHIC

Albacete, Marquet '10

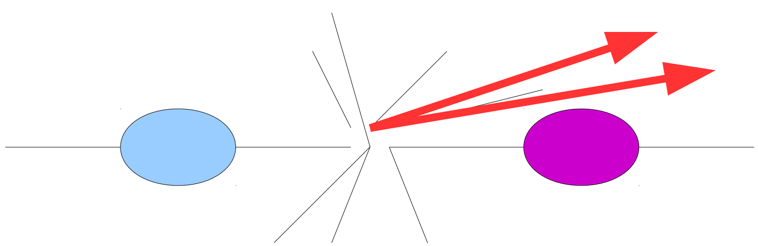
Predictions for p-Pb for forward-central

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



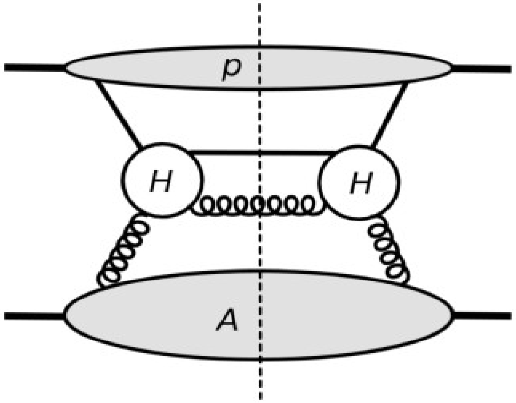
saturation effects are rather weak for forward-central jets

Forward-forward di-jets



Towards TMD for dijets in pA

The used factorization formula for dijets is strictly valid in linear regime and was calculated In a specific gauge. Results for dijets based on it with usage of gluon density coming from nonlinear equation can estimate of strength of saturation. We want to go beyond this



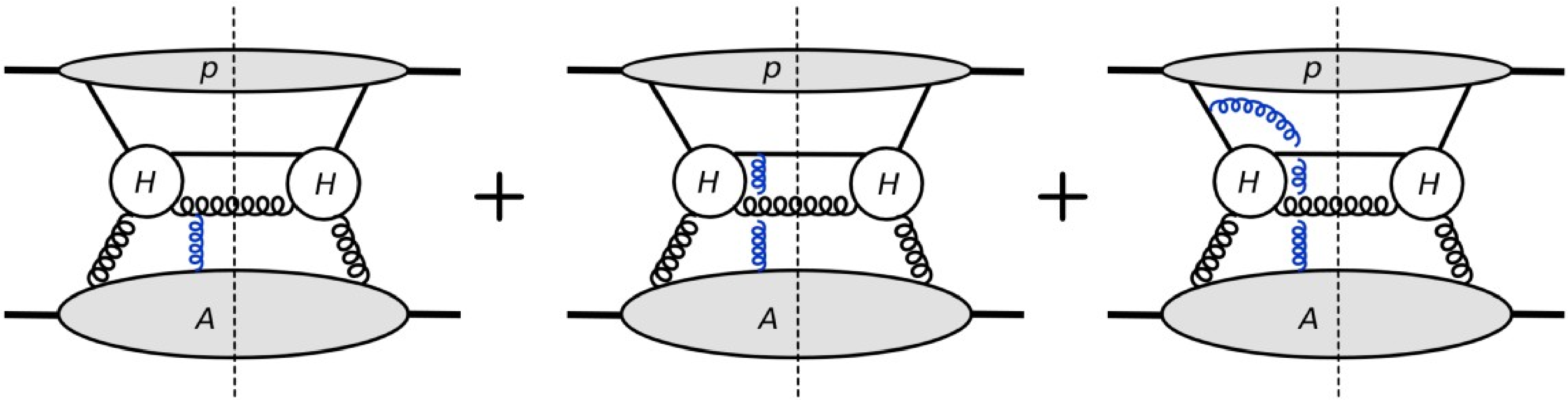
$$\frac{d\sigma^{pA\to\text{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{1}{16\pi^3(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2)\,|\overline{\mathcal{M}_{ag^*\to cd}}|^2 \mathcal{F}_{g/A}(x_2,k_t)\frac{1}{1+\delta_{cd}}$$

$$\mathcal{F}_{g/A}(x_2,k_t) \overset{\text{naive}}{=} 2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ix_2 p_A^- \xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \left\langle A\right|\mathrm{Tr}\left[F^{i-}\left(\xi^+,\boldsymbol{\xi}_t\right)F^{i-}(0)\right]\left|A\right\rangle$$

Taking all complexity into account leads to following generalization of formula above...

Bomhof, Mulders and Pijlman '16.

Towards TMD for dijets in pA – gauge link



+ similar diagrams with 2,3,….gluon exchanges.

All this need to be resummed

Bomhof, Mulders, Pijlman 06

This is achieved via gauge link which renders the gluon density gauge invariant

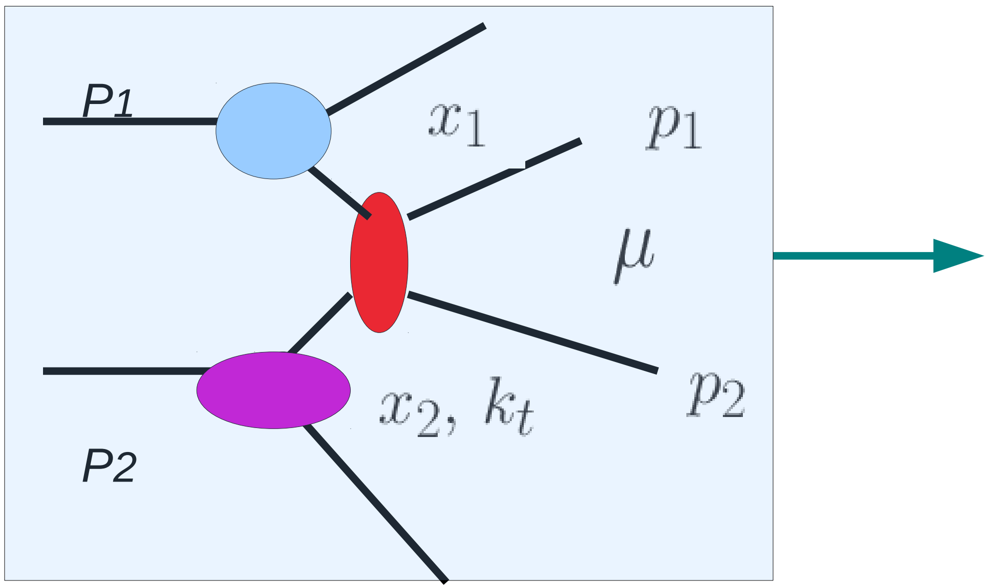
$$\mathcal{P}\exp\left[-ig\int_{\alpha}^{\beta} d\eta^{\mu} A^{a}(\eta) T^{a}\right]$$

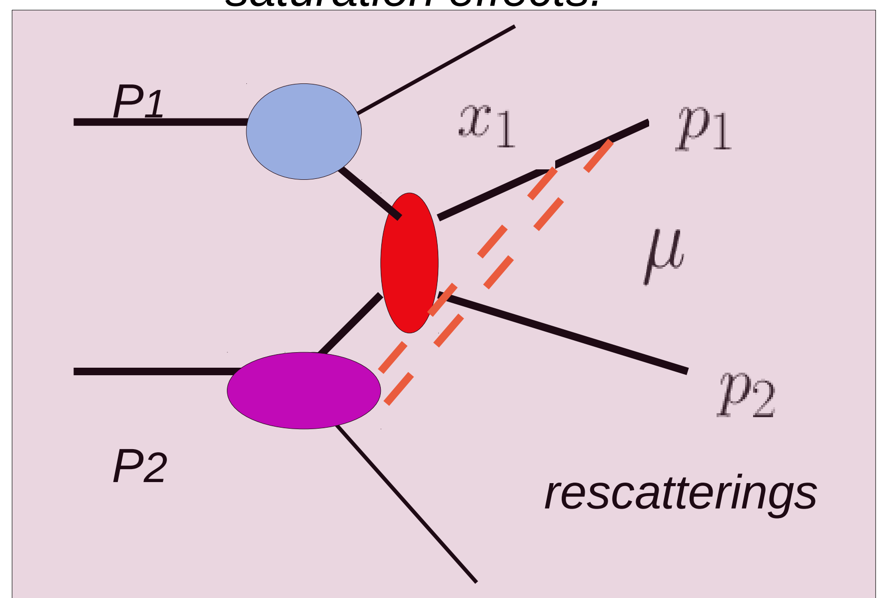
$$\mathcal{F}_{g/A}(x_2, k_t) = 2\int \frac{d\xi^{+} d^{2}\boldsymbol{\xi}_t}{(2\pi)^3 p_A^{-}} e^{ix_2 p_A^{-}\xi^{+} - ik_t\cdot\boldsymbol{\xi}_t} \langle A|\mathrm{Tr}\left[F^{i-}\left(\xi^{+},\boldsymbol{\xi}_t\right) U_{[\xi,0]} F^{i-}(0)\right]|A\rangle$$

Improved TMD for dijets

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

can be be used for estimates of saturation effects.





Color structure defines gauge links, different for any sub process

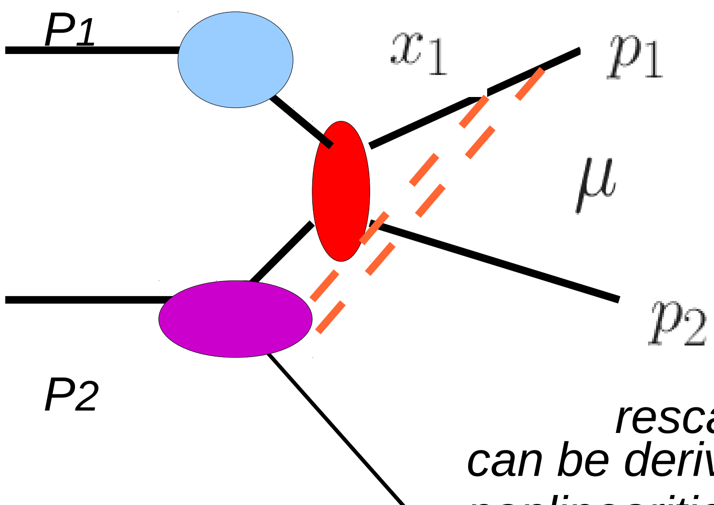
Generalization but no possibility to calculate decorelations since no kt in ME
Dominguez, Marquet, Xiao, Yuan '11

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

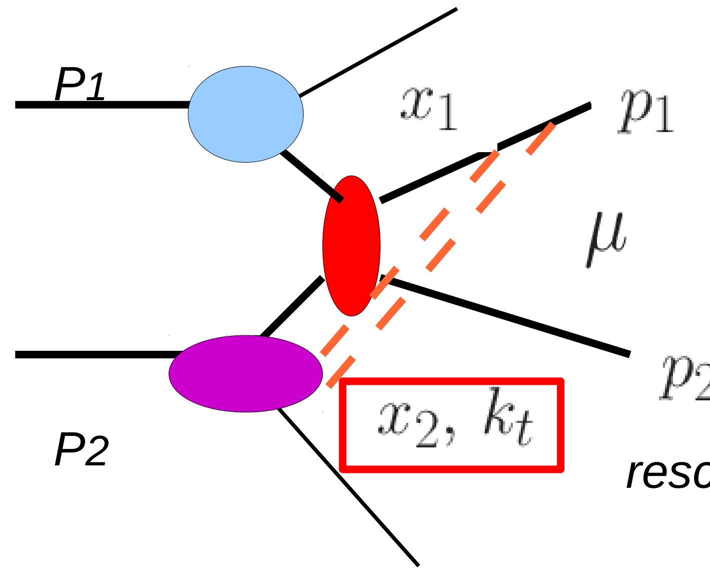
$$\frac{d\sigma^{pA\to cdX}}{d^2P_td^2k_tdy_1dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\, x_1f_{q/p}(x_1,\mu^2)\sum_{i=1}^{n}\mathcal{F}_{ag}^{(i)}H_{ag\to cd}^{(i)}\frac{1}{1+\delta_{cd}}$$

Improved TMD for dijets

can be be used for estimates of saturation effects



rescatterings
can be derived but no nonlinearities



rescatterings

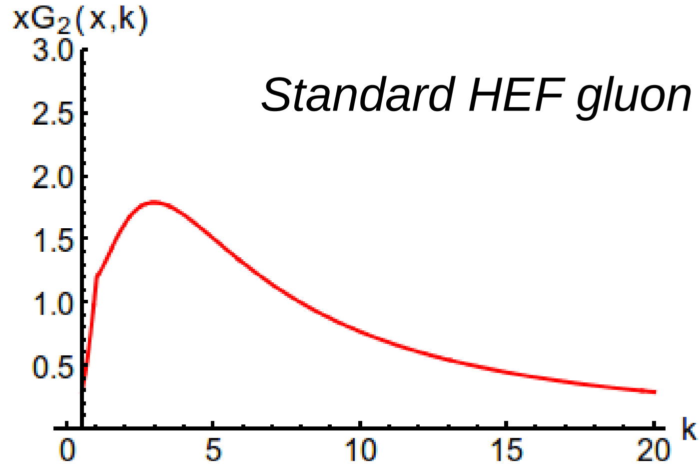
We found a method to include kt in ME and express the factorization fprmula in terms of gauge invariant sub amplitudes → more direct relation to two fundamental gluon densities: dipole gluon density and Weizacker-Williams gluon density

Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '15

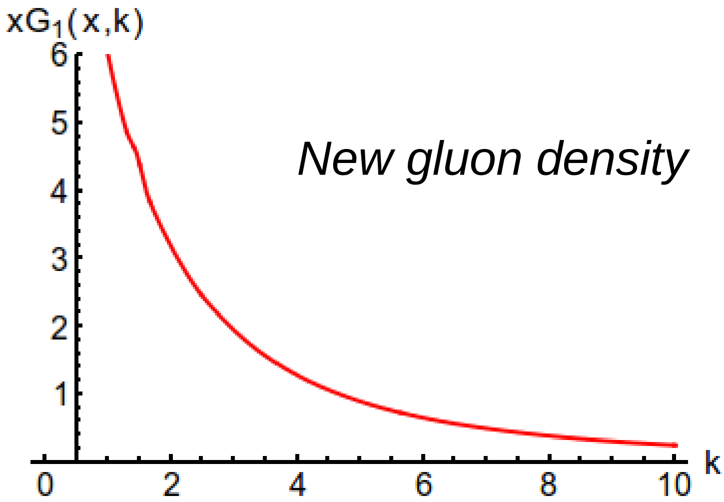
$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2) \sum_{i=1}^{2} K^{(i)}_{ag^*\to cd} \Phi^{(i)}_{ag\to cd} \frac{1}{1+\delta_{cd}}$$

Glimpse on the first results – HEF vs. ITMD

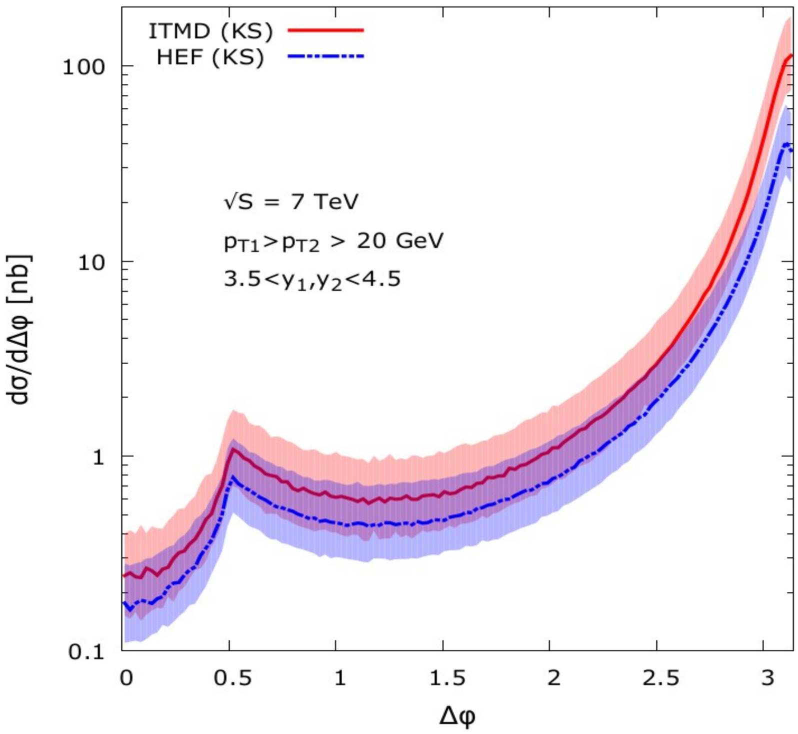
Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '16



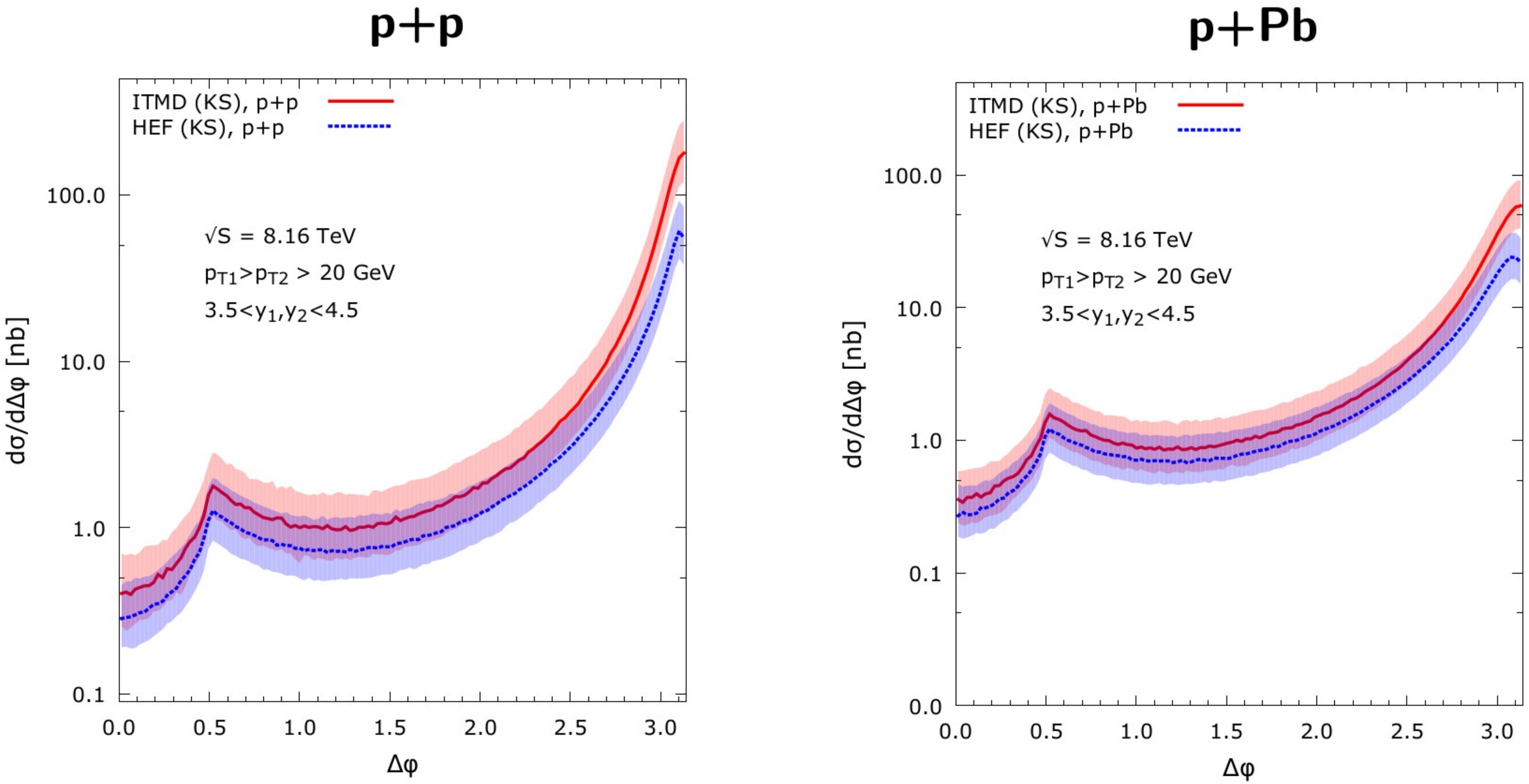
Standard HEF gluon density



New gluon density

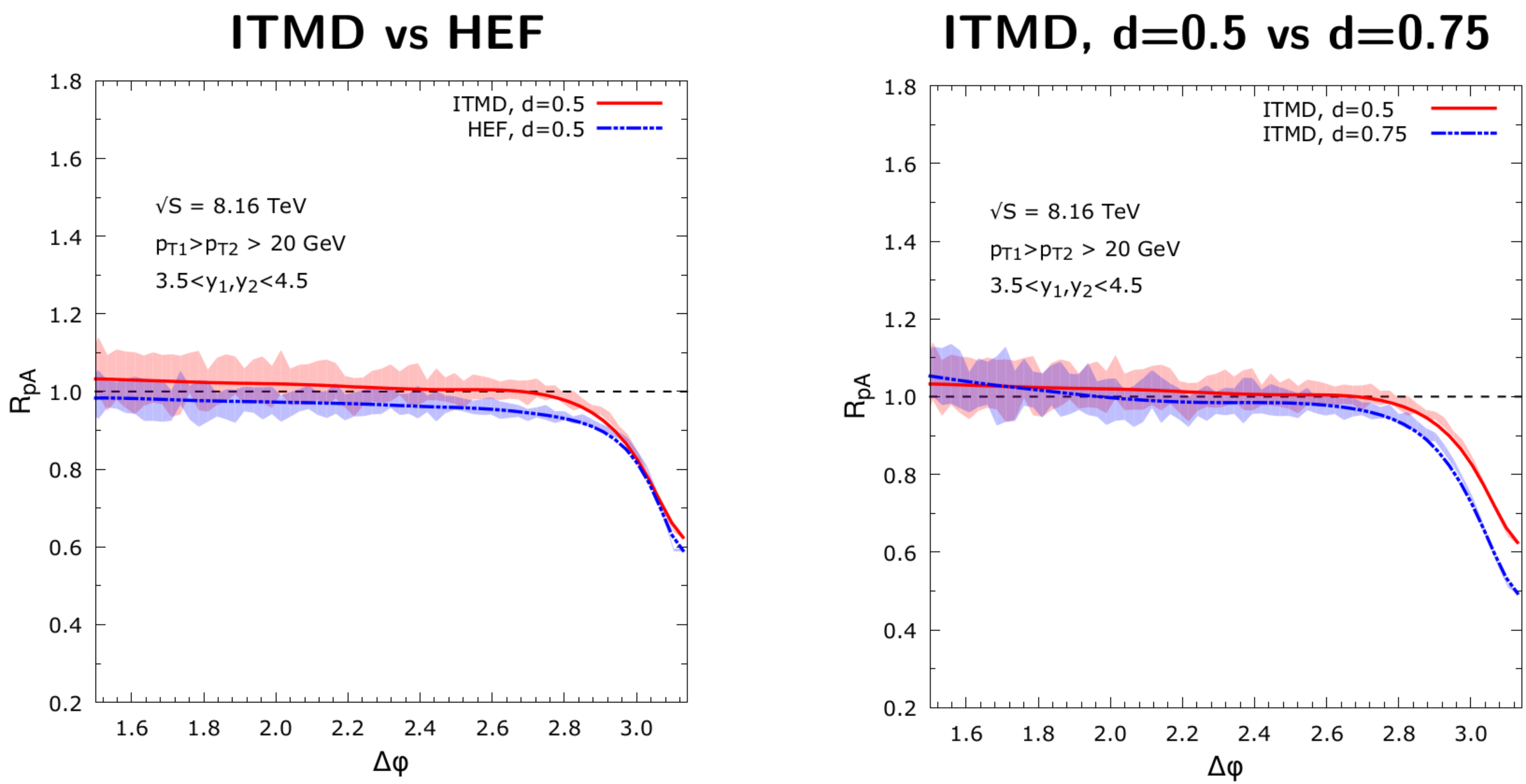


Azimuthal distance beetween jets



Differences in normalization but altogether similar behavior when switching from HEF to ITMD

R_{pA}: azimuthal distance beetween jets



RpA comes very similar since differences in the cross section effectively cancel out

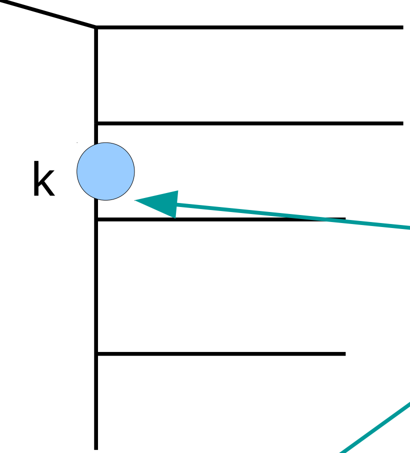
Conclusions and outlook

- *New framework ITMD for calculations of forward dijets has been developed*
- *The framework already gives phenomenological predictions for forward-forward dijets*
- *The results for di-jets are consistent with PYTHIA MC simulation. However, the results would agree better after implementing FSR into HEF*
- *Single inclusive jets in p+Pb at very forward rapidities*
- *Update the parton densities*

Backup

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

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

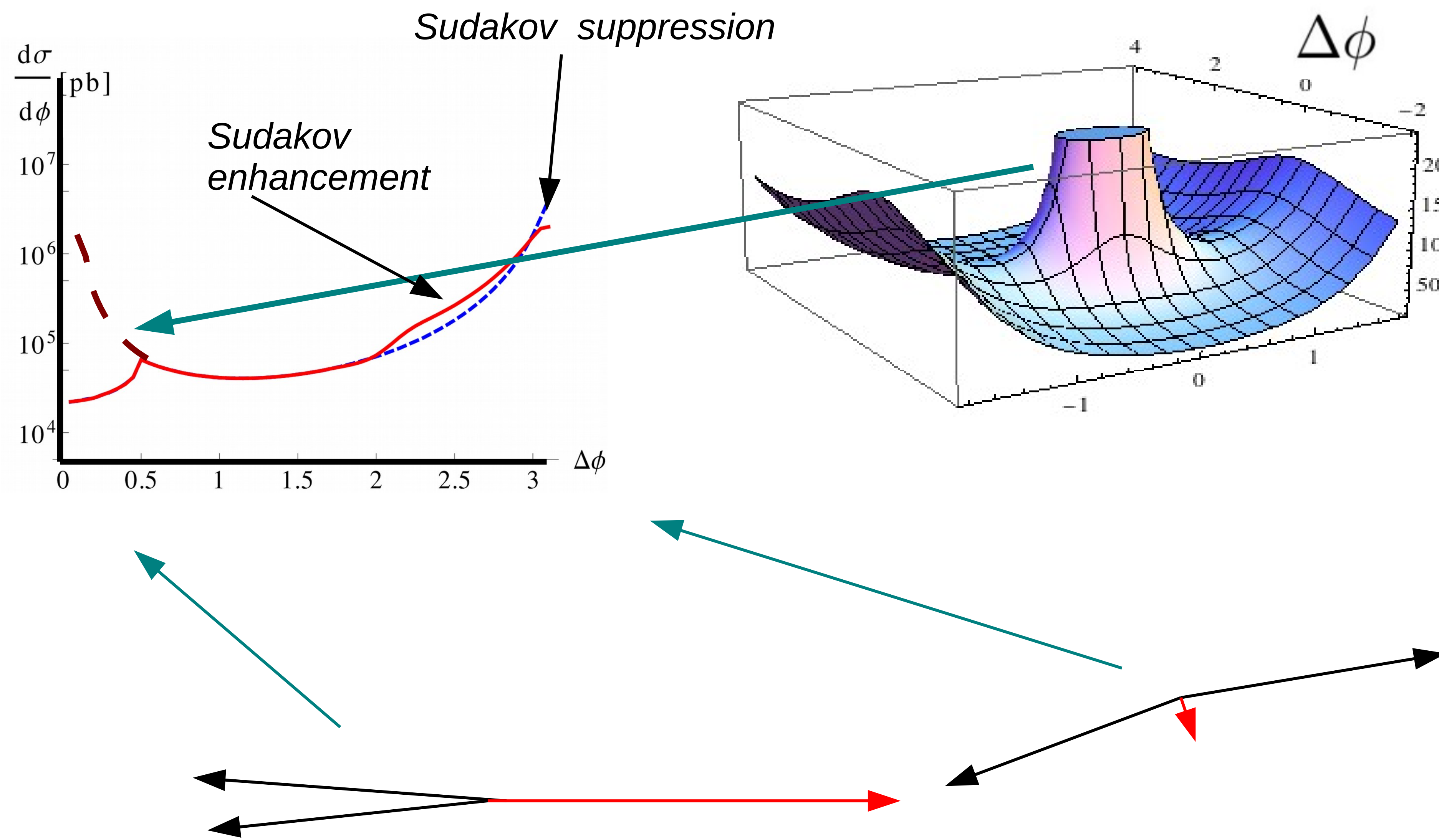
$$\mathcal{F}(x,k^2,\mu^2)\sim\partial_{\lambda^2}(T(\lambda^2,\mu^2)xg(x,\lambda^2))|_{\lambda^2=k^2}$$

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

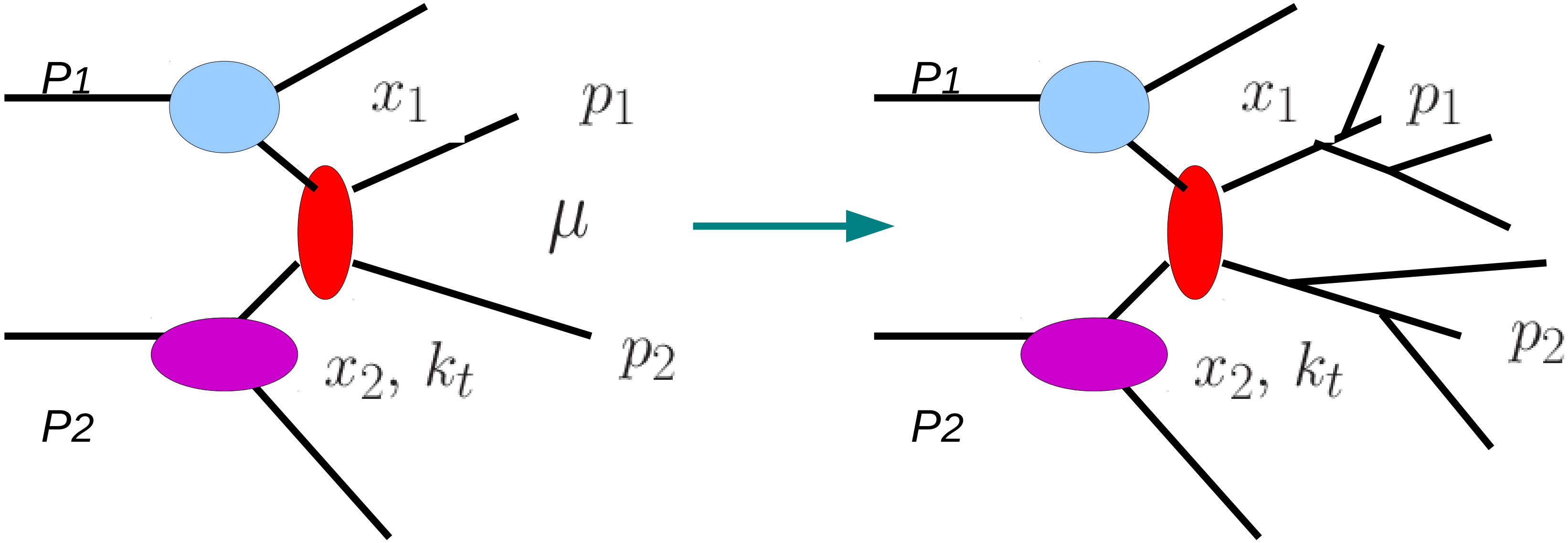
Other relevant effects – Sudakov form factor in ISR

Divergence regularized by jet algorithm

KK '14



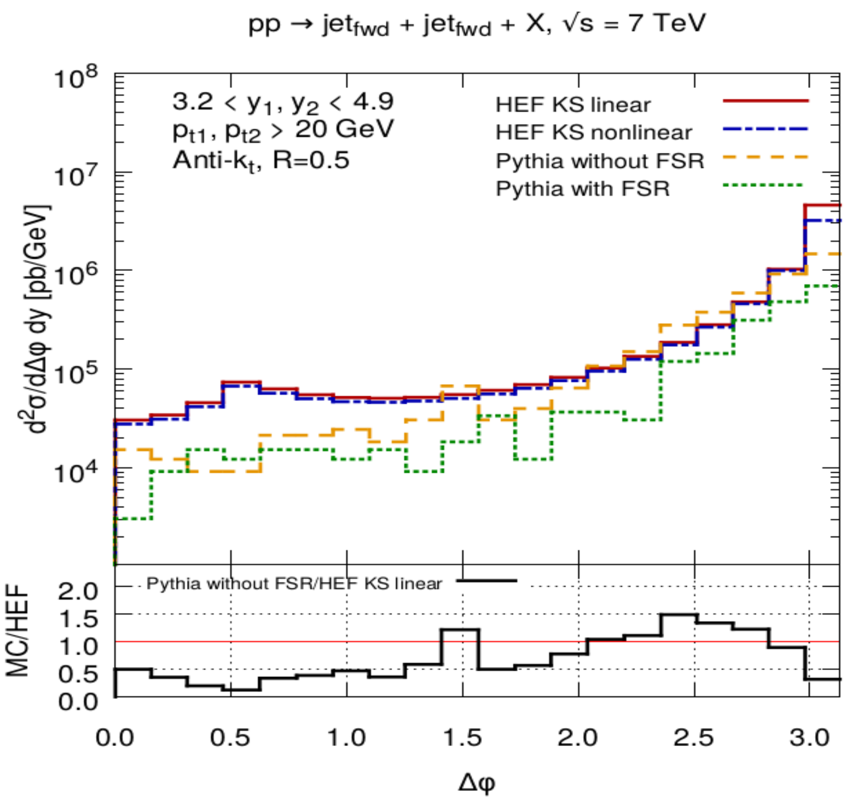
Other relevant effects – Final State Radiation

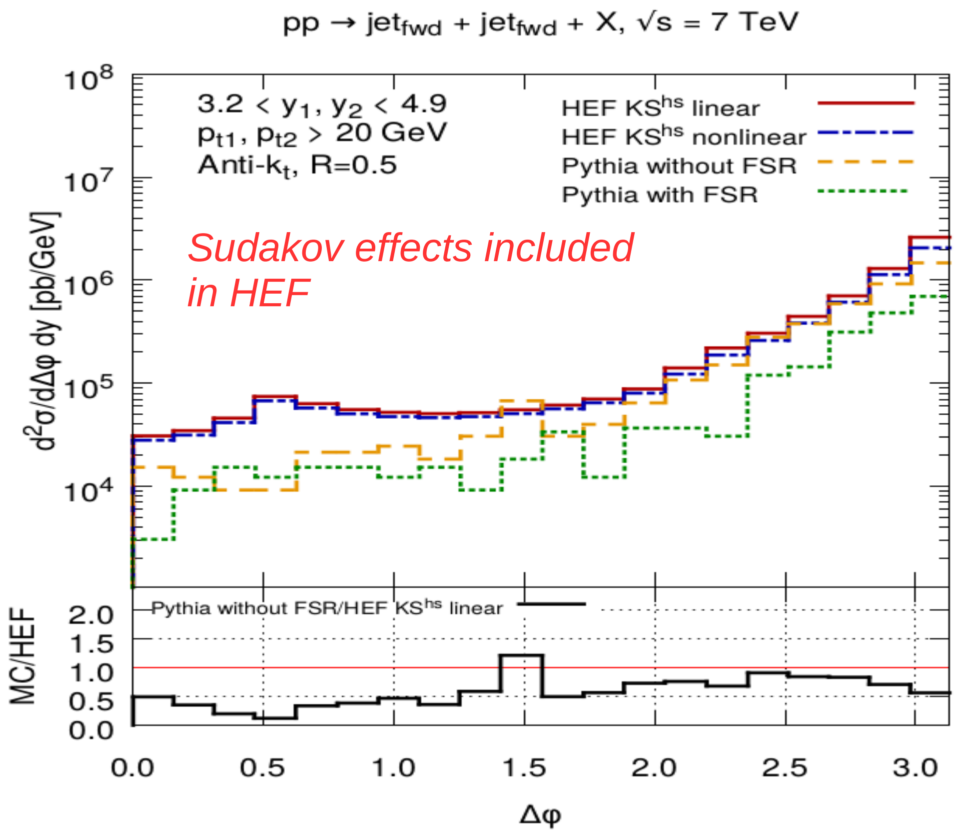


Wide angle soft emissions lower cross section for hard jets

Other relevant effects – final state parton shower with Pythia

Bury, Deak, Kutak, Sapeta '16





HEF framework with KShardsacle or DLC2016 → compatible with ISR in Pythia at moderate and large angles → importance of Sudakov resummation.