Supported by Narodowe Centrum Nauki (NCN)
with Sonata BIS grant

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Estimating nonlinear effects in forward di-jet production in UPC at the LHC

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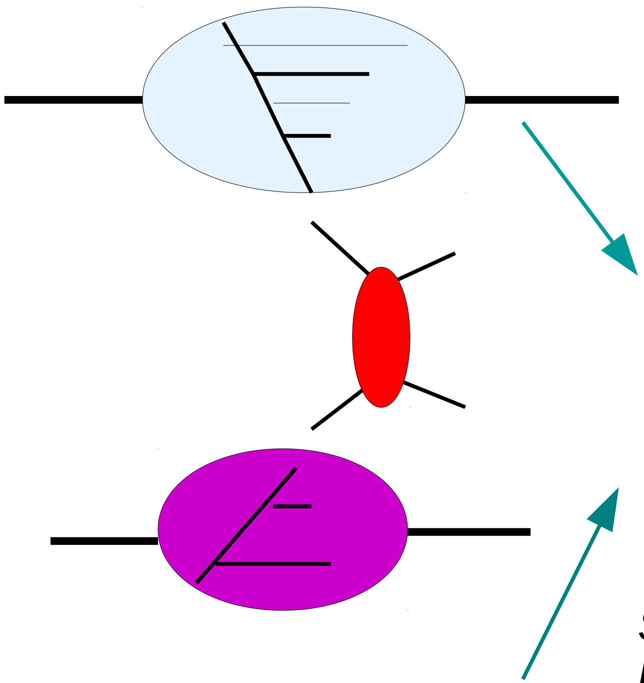
Why jets in UPC?

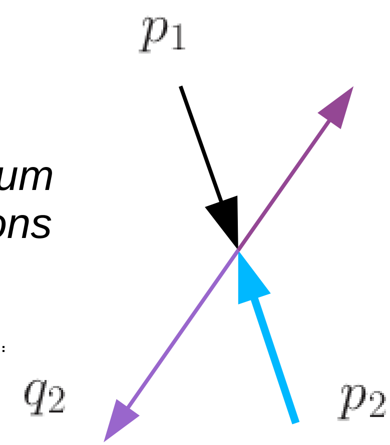
- *$\gamma A \to 2$ jets is sensitive to the Weizsacker-Williams (WW) unintegrated gluon distribution (UGD), whereas other processes like J/ψ or inclusive jets are sensitive to the dipole UGD*
- *$pA \to 2$ jets is sensitive to both UGDs (directly to the dipole UGD and indirectly to WW)*
- *Dipole UGD for proton is relatively well constrained from HERA; this not the case for the WW UGD*
- *Goal: calculate nuclear modification ratios and see how much saturation one gets for dijets in UPC for the current LHC setup*

hybrid High Energy Factorization

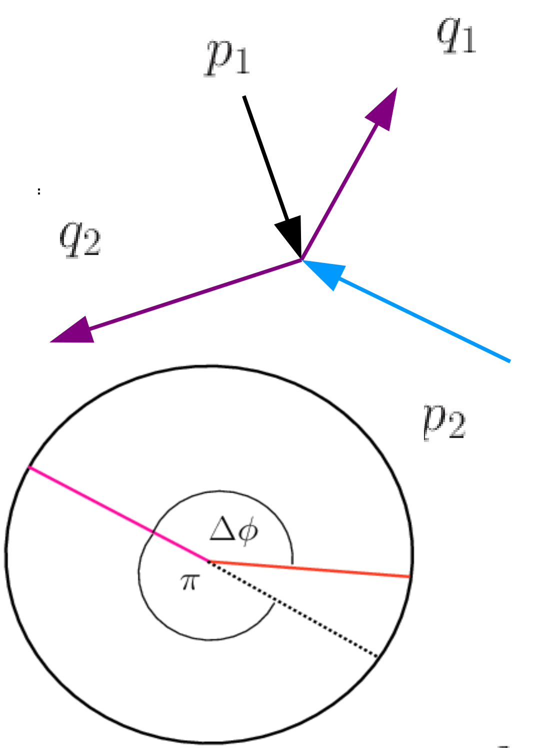


Strongly decreasing transversal momentum of DGLAP like partons

Strongly decreasing Longitudinal momentum fractions of off-shell partons



$$p_1 + p_2 = q_1 + q_2$$

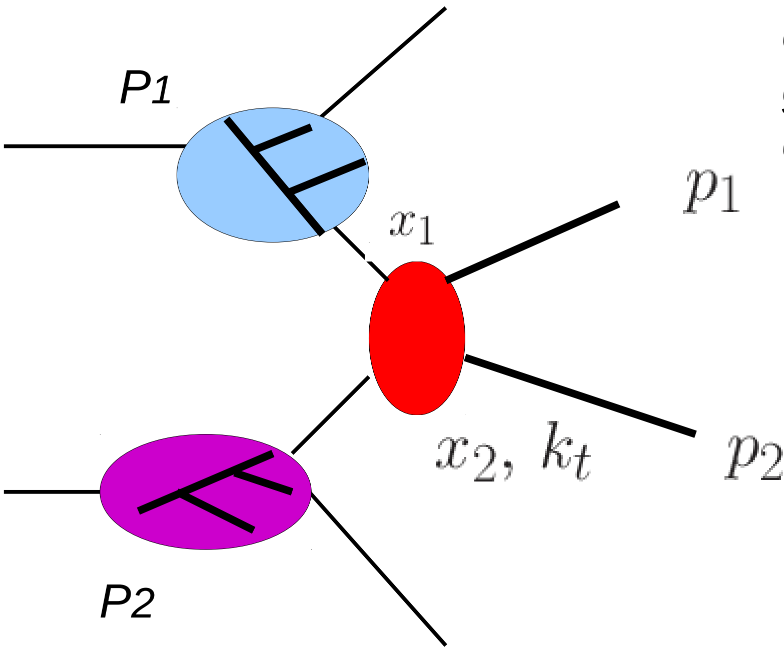


$$p_1 + p_2 = q_1 + q_2 + k$$

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
$g^*g \to gg$ Iancu,Laidet
$qg^* \to qg$ 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

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

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

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

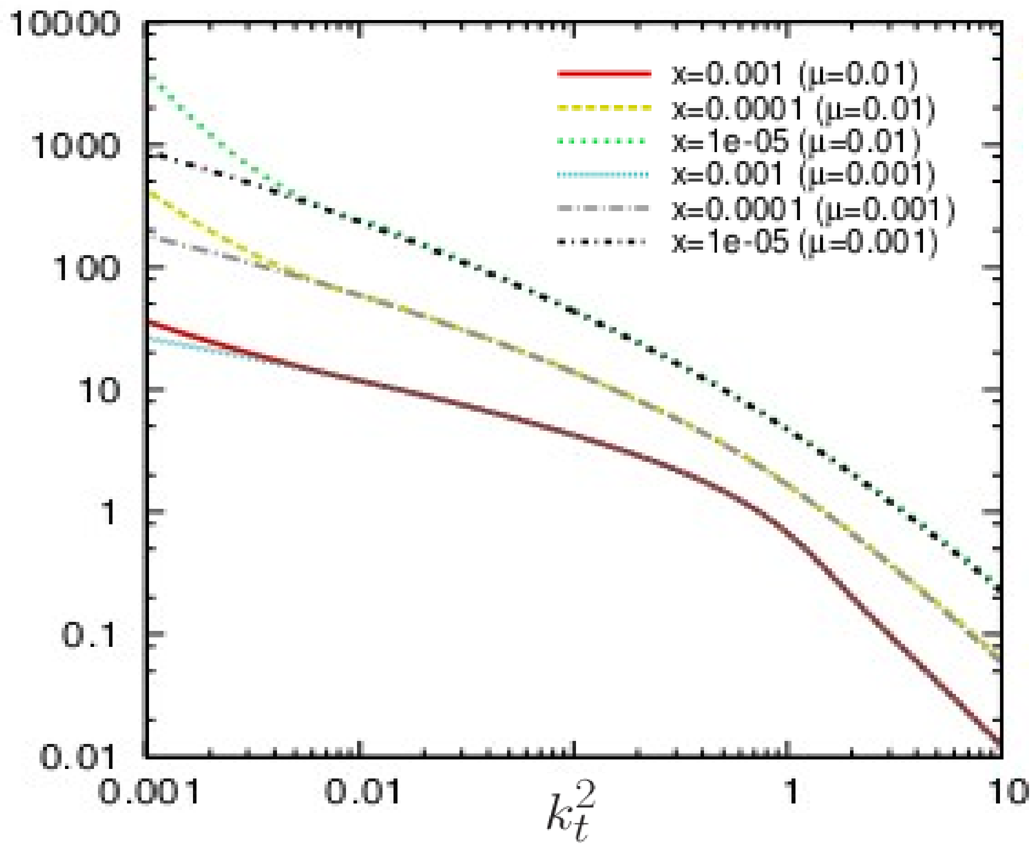
$k_t \ll P_t$ Collinear Factorization → partons in one of hadrons are just collinear with hadron k_t is neglected

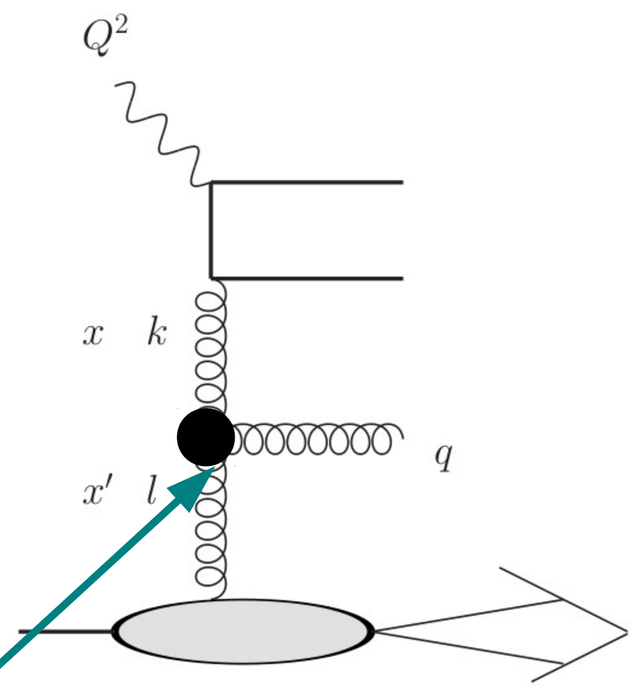
$Q_s \sim k_t \ll P_t$ generalized Transverse Momentum Dependent Factorization → rescatterings formal treatment of nonlinearities but does not allow for calculation of decorelations

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

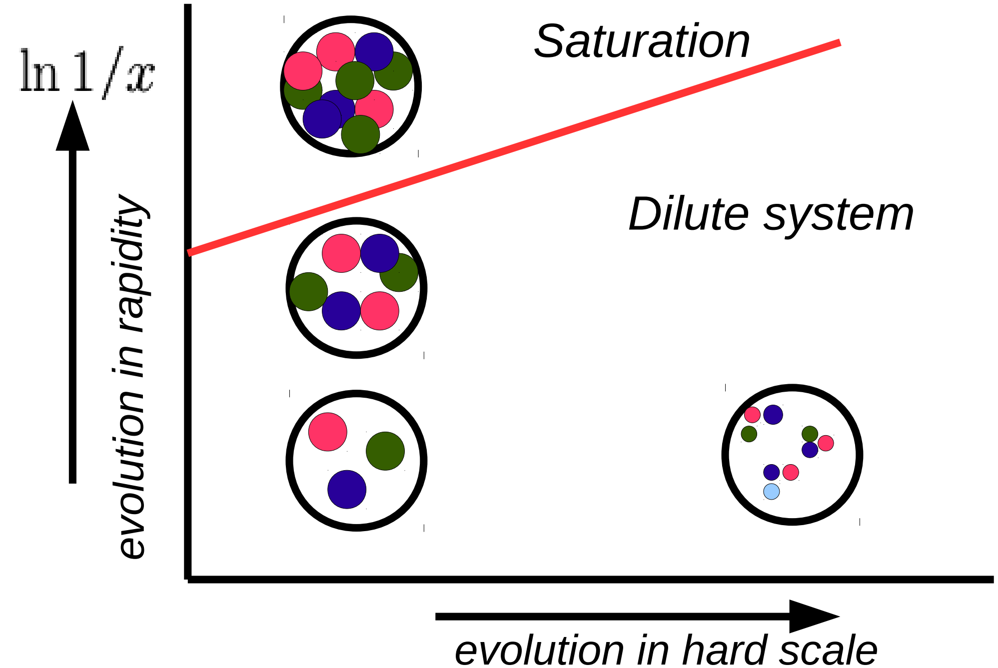




$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F}$$

High energy factorization and saturation

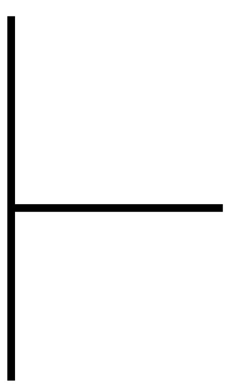
Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.



On microscopic level it means that gluon apart splitting recombine

splitting

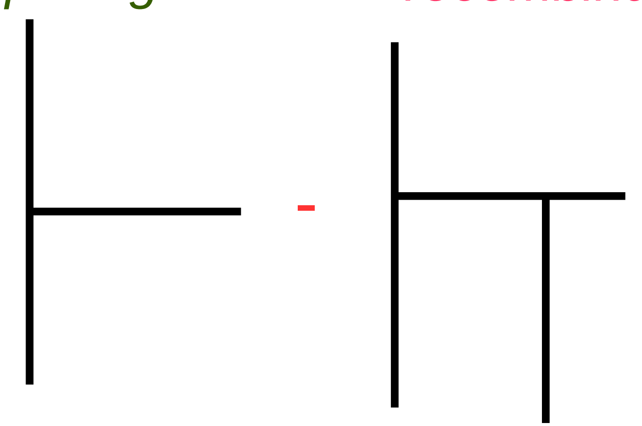
Linear evolution equation



Nonlinear evolution equations

splitting

recombination



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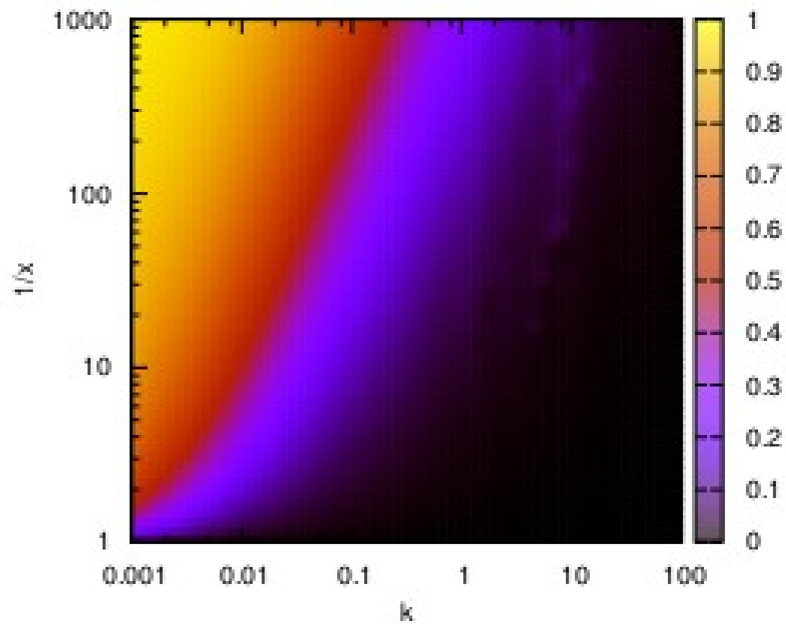

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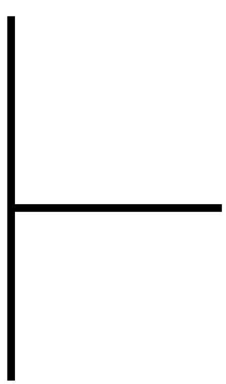
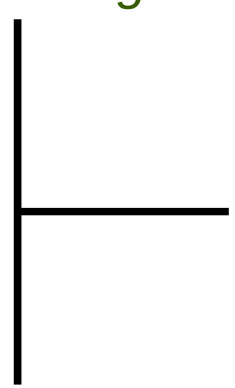


splitting

recombination

Nonlinear evolution equations



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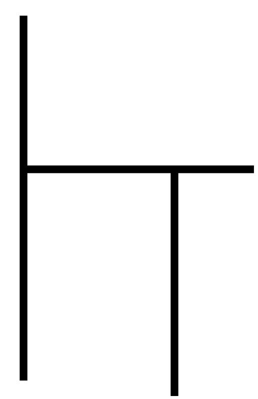


The saturation problem: supressing gluons at small k_t

Originally formulated in coordinate space

Balitsky '96, Kovchegov '99

Now at NLO accuracy

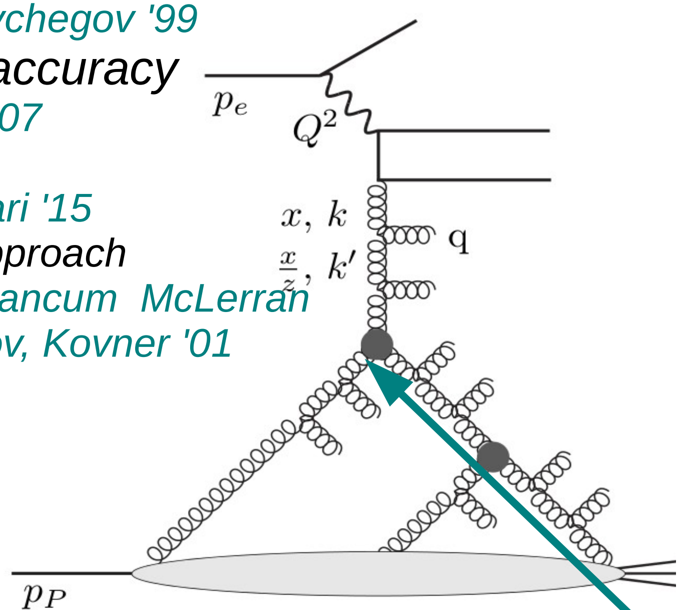
Balitsky, Chirilli '07

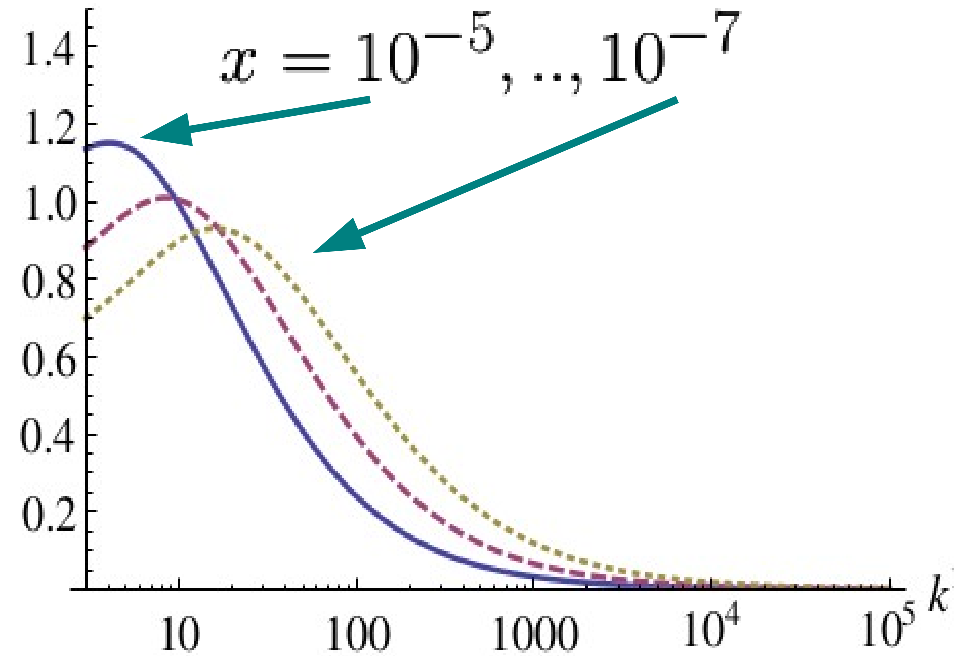
and solved

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

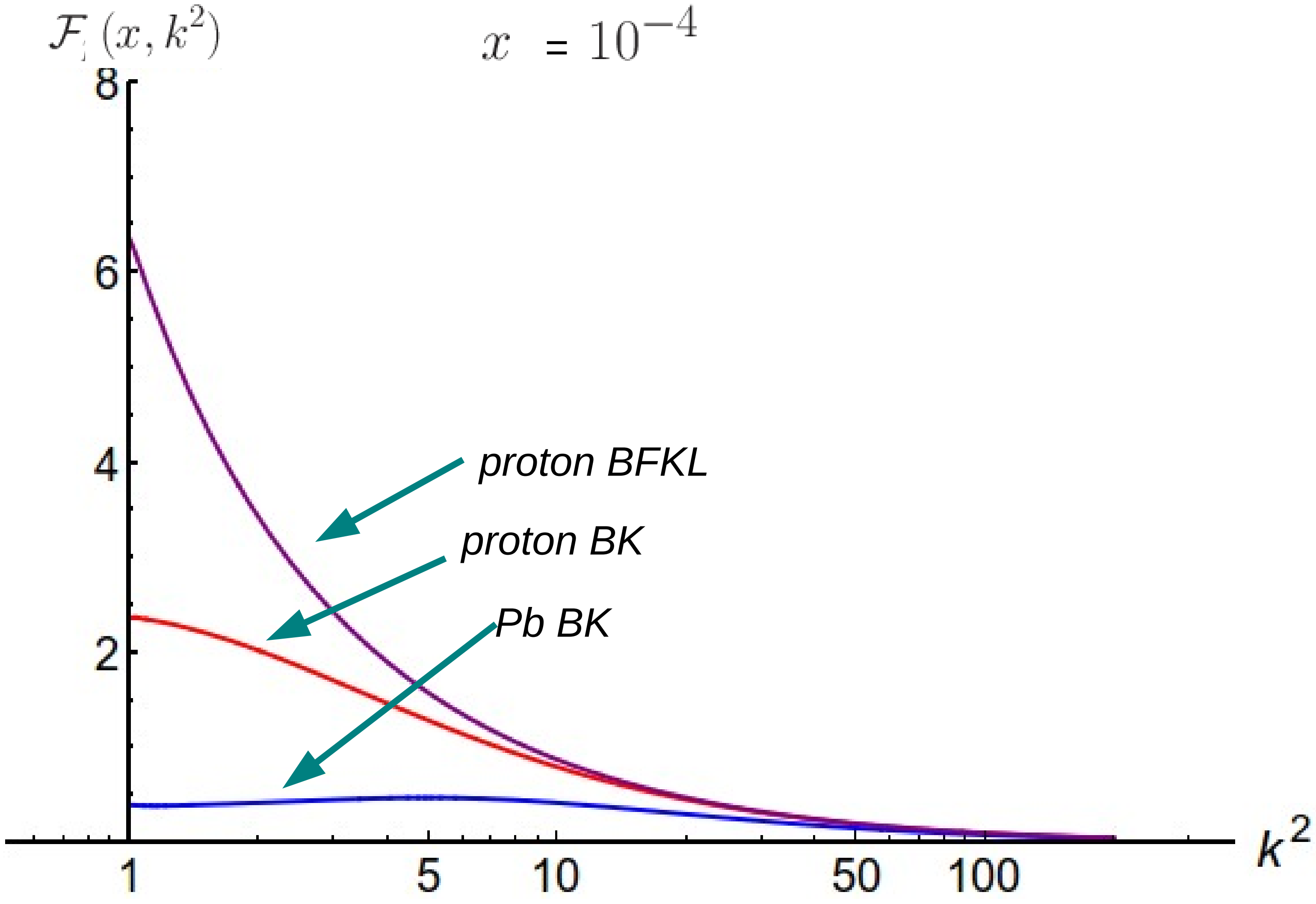
$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} - \frac{1}{R^2} V \otimes \mathcal{F}^2$$

hadron's radius

Momentum space

Kwiecinski, Kutak '02
Nikolaev, Schafer '06

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



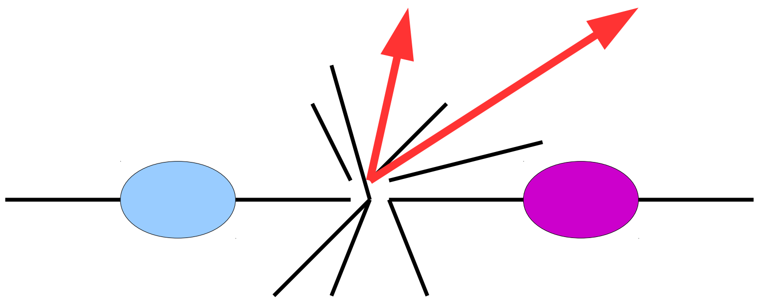
PDF we use at present

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*

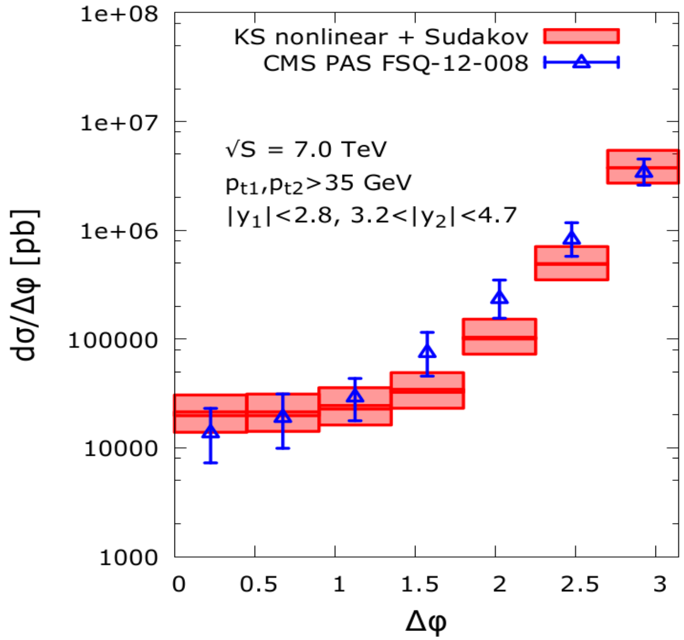
KK, Kwiecinski '03 fitted to '10 HERA data KK, Sapeta '12,nonlinear extension of unified BFKL+DGLAP Kwiecinski, Martin, Staśto framework '97.

Central-forward di-jets



Decorelations inclusive scenario forward-central

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

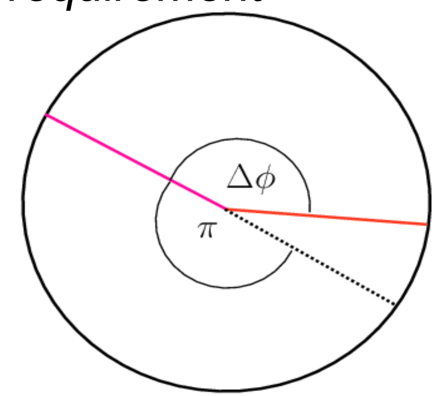


$$p_{t1}, p_{t2} > 35\, GeV$$

$$3.2 < |y_2| < 4.7$$

$$|y_1| < 2.8$$

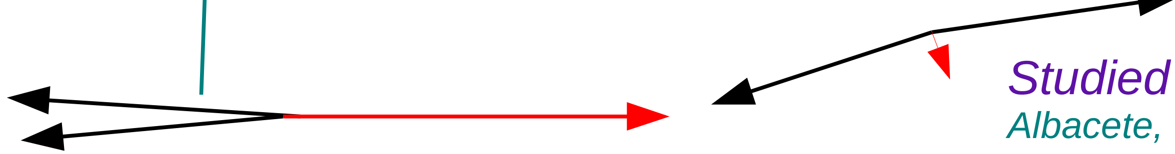
Leading jets, no further requirement



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

Observable suggested to study BFKL effects

Sabio-Vera, Schwensen '06

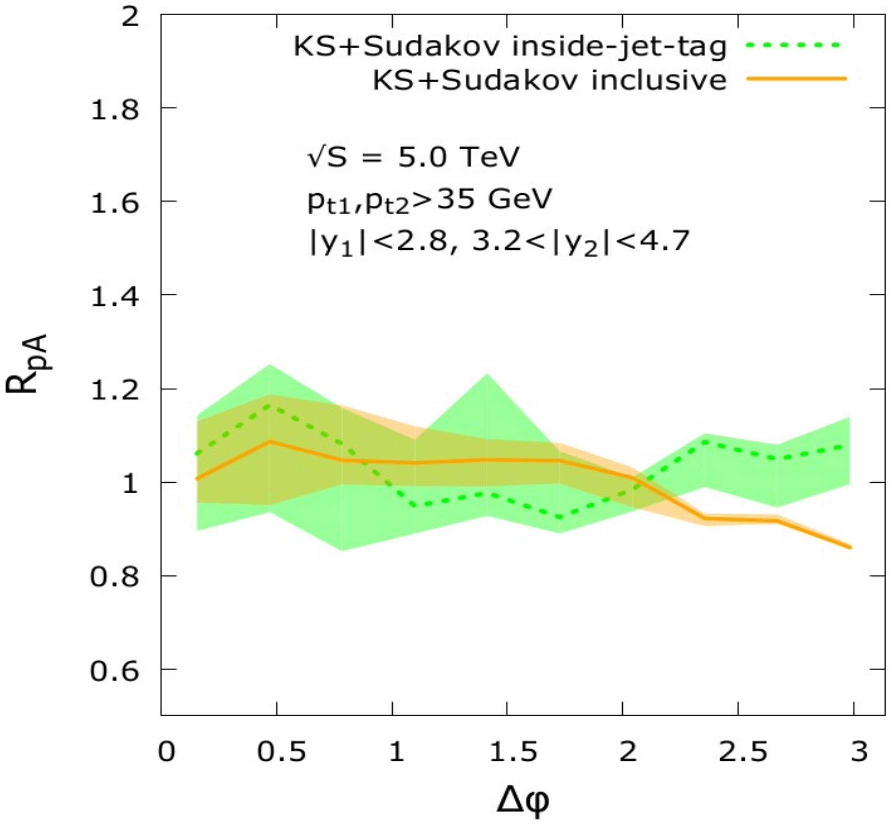


Studied also context of RHIC

Albacete, Marquet '10

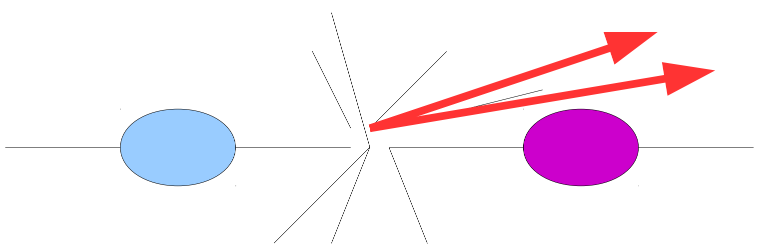
Predictions for p-Pb for forward-central

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



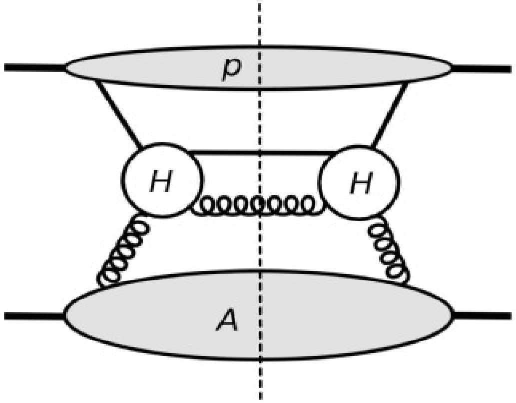
saturation effects are rather weak for forward-central jets

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



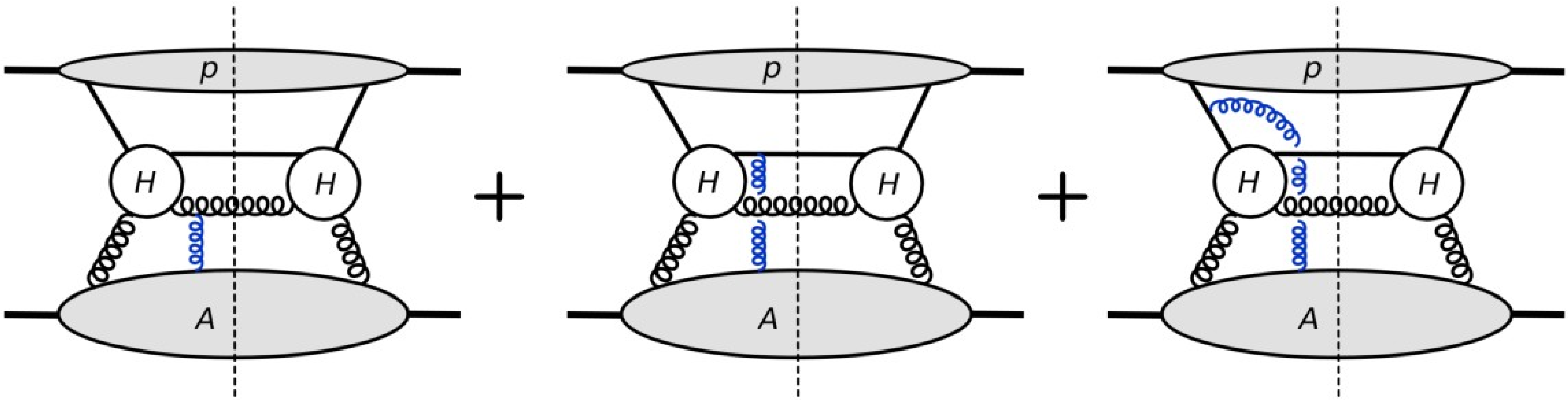
$$\frac{d\sigma^{pA\to\text{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{1}{16\pi^3 (x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2)\, |\overline{\mathcal{M}_{ag^*\to cd}}|^2 \mathcal{F}_{g/A}(x_2,k_t) \frac{1}{1+\delta_{cd}}$$

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

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.

Bomhof, Mulders, Pijlman 06

All this need to be resummed

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

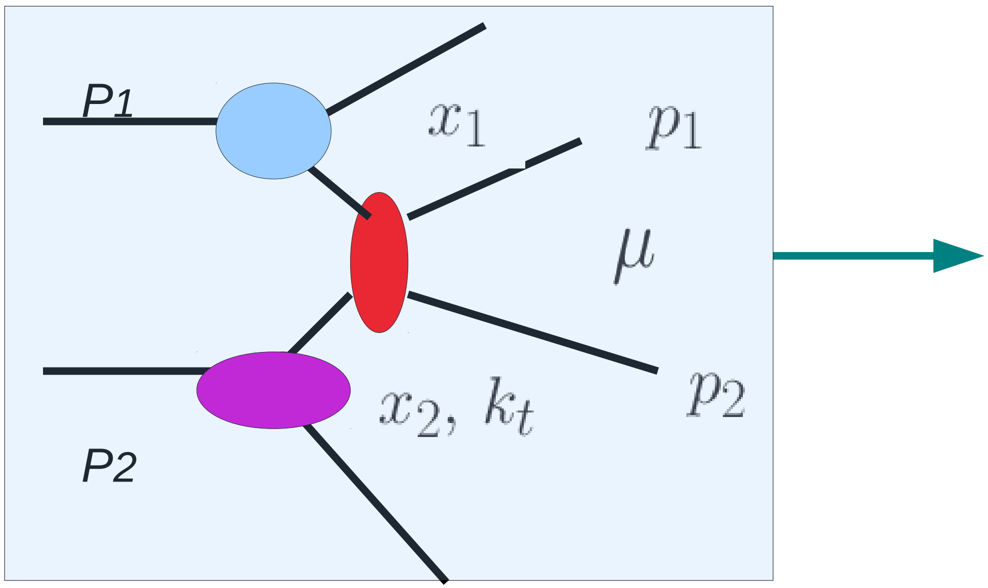
$$\mathcal{P}\exp\left[-ig\int_{\alpha}^{\beta} d\eta^{\mu} A^{a}(\eta) T^{a}\right]$$

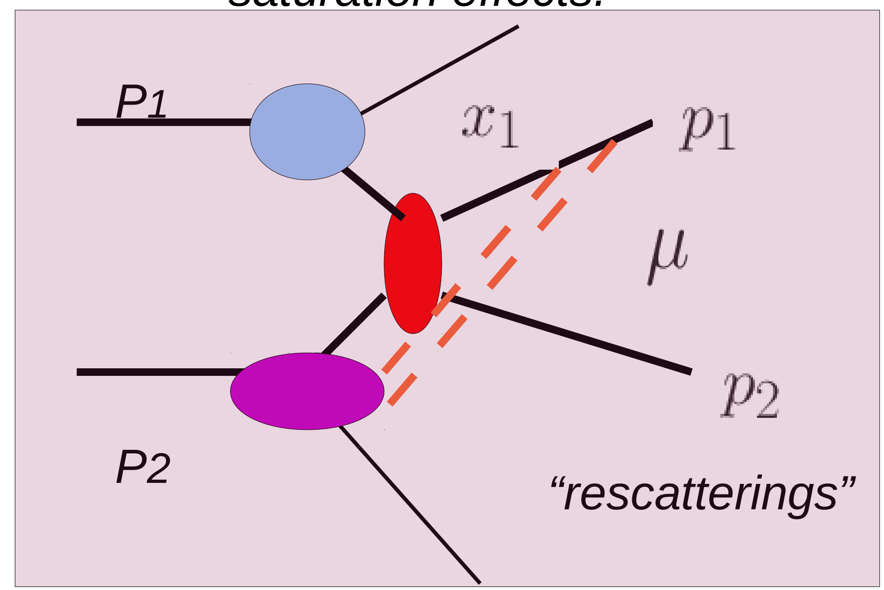
$$\mathcal{F}_{g/A}(x_2, k_t) = 2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ix_2 p_A^- \xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \langle A|\mathrm{Tr}\left[F^{i-}\left(\xi^+, \boldsymbol{\xi}_t\right) U_{[\xi,0]} F^{i-}(0)\right]|A\rangle$$

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.



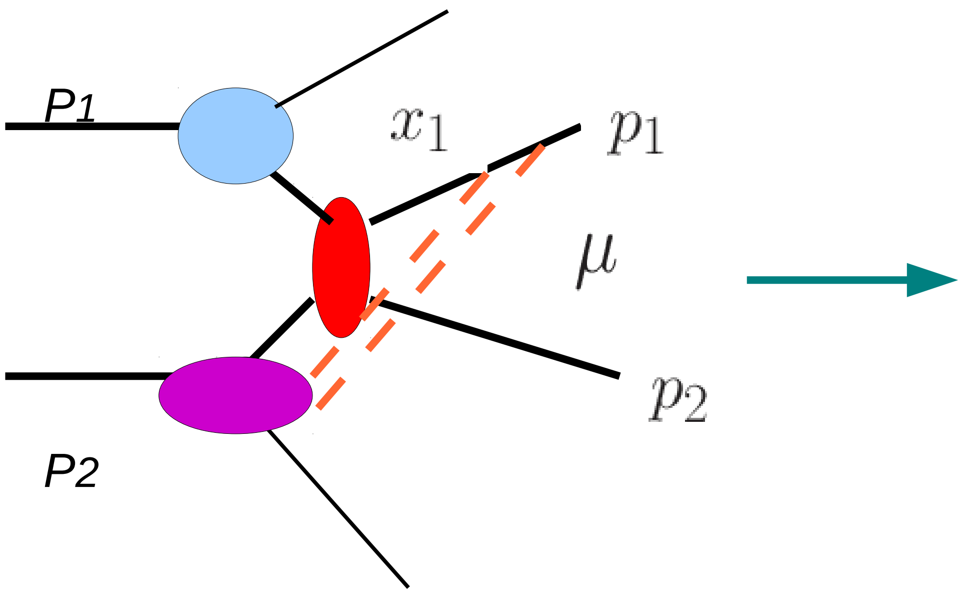


Generalization but no possibility to calculate decorelations since no kt in ME
Dominguez, Marquet, Xiao, Yuan '11

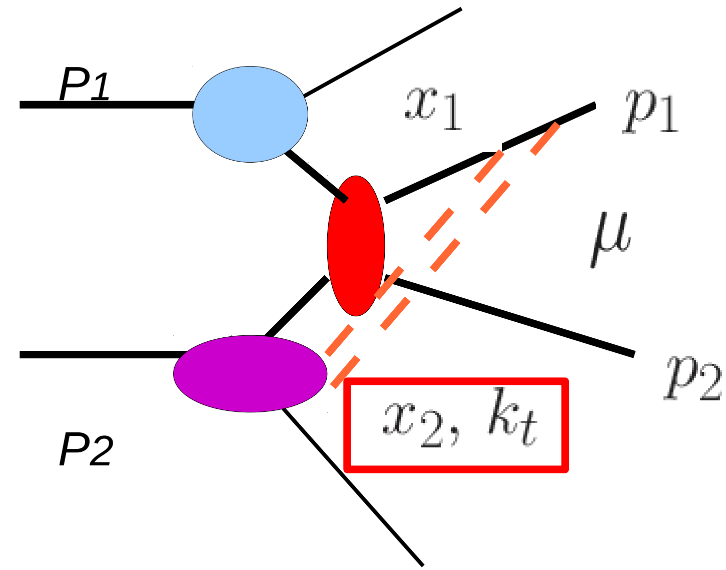
Application to differential distributions in d+Au
Stasto, Xiao, Yuan '11

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

Improved TMD for dijets



can be be used for estimates of saturation effects



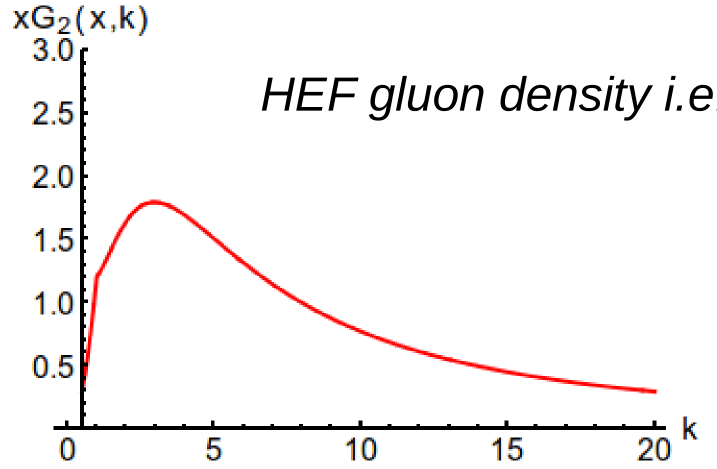
We found a method to include kt in ME and express the factorization fprmula in terms of gauge invariant sub amplitudes → more direct relation to two fundamental gluon densities: dipole gluon density and Weizacker-Williams gluon density

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

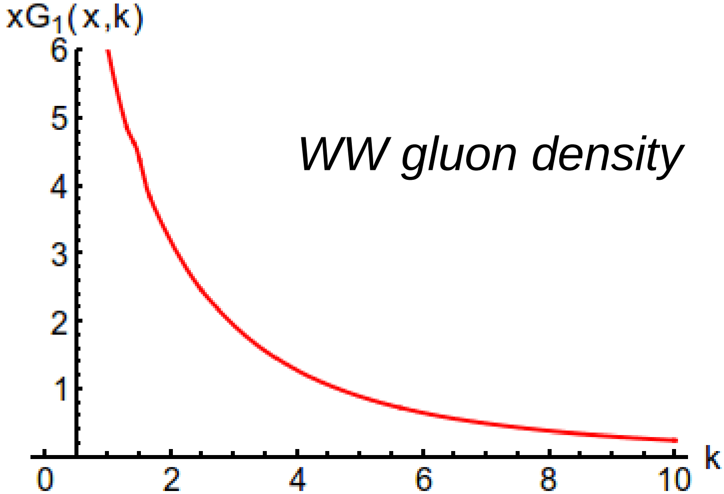
$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2) \sum_{i=1}^{2} K^{(i)}_{ag^*\to cd} \Phi^{(i)}_{ag\to cd} \frac{1}{1+\delta_{cd}}$$

Glimpse on the first results – HEF vs. ITMD

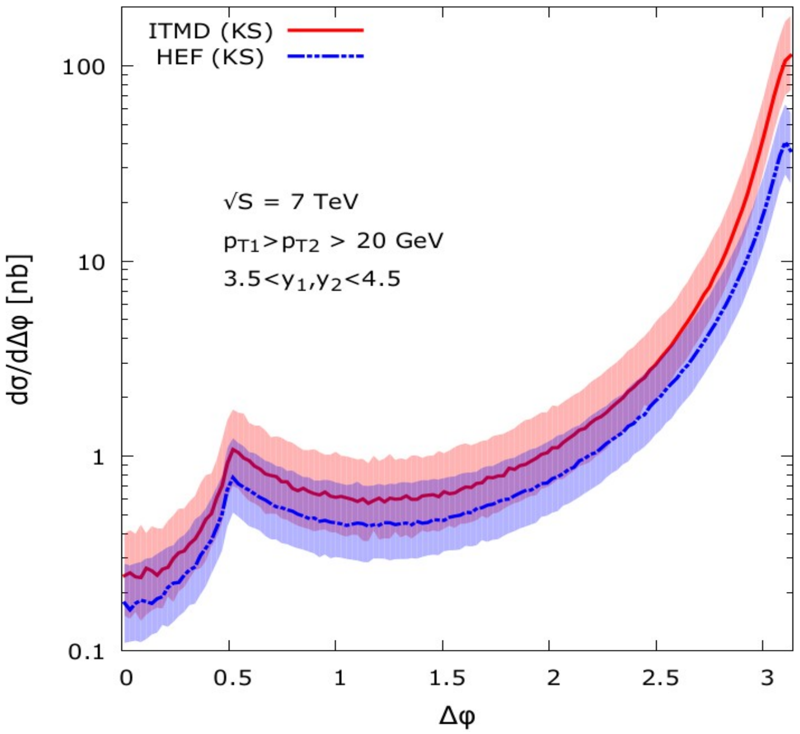
Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren '16



HEF gluon density i.e. dipole UGD

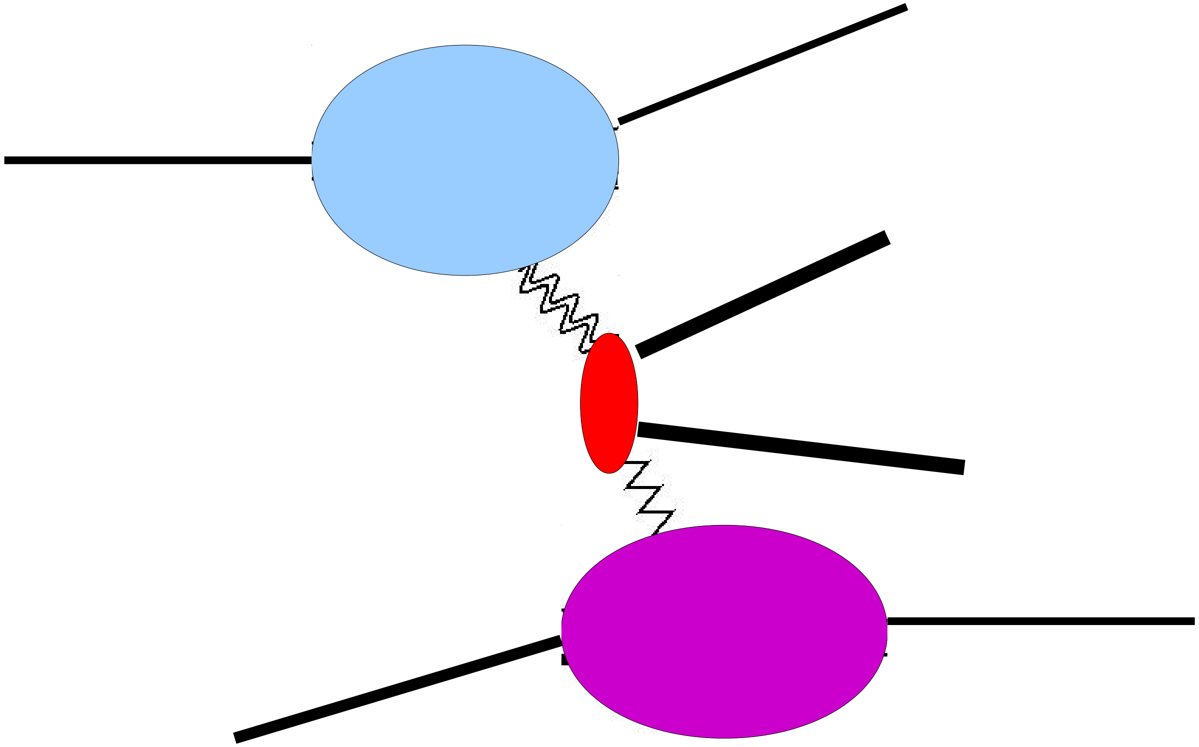


WW gluon density



In large Nc on can express WW UGD in terms of dipole UGD. We use this approximation

UPC collision of Pb-Pb

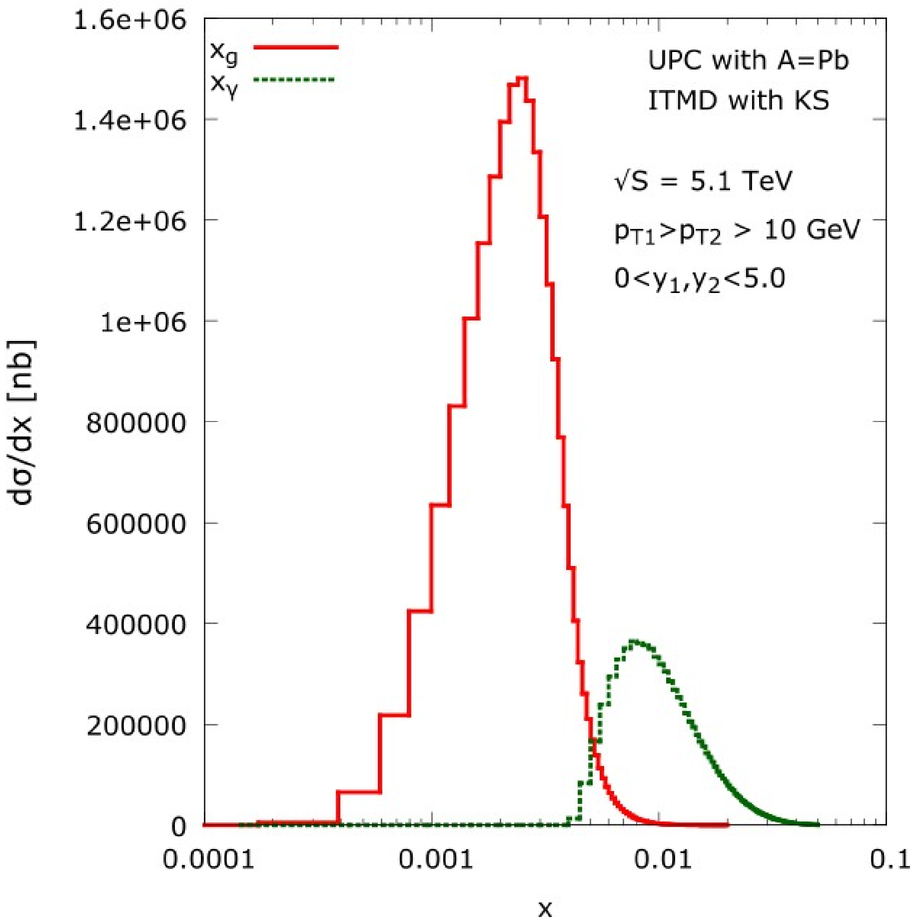


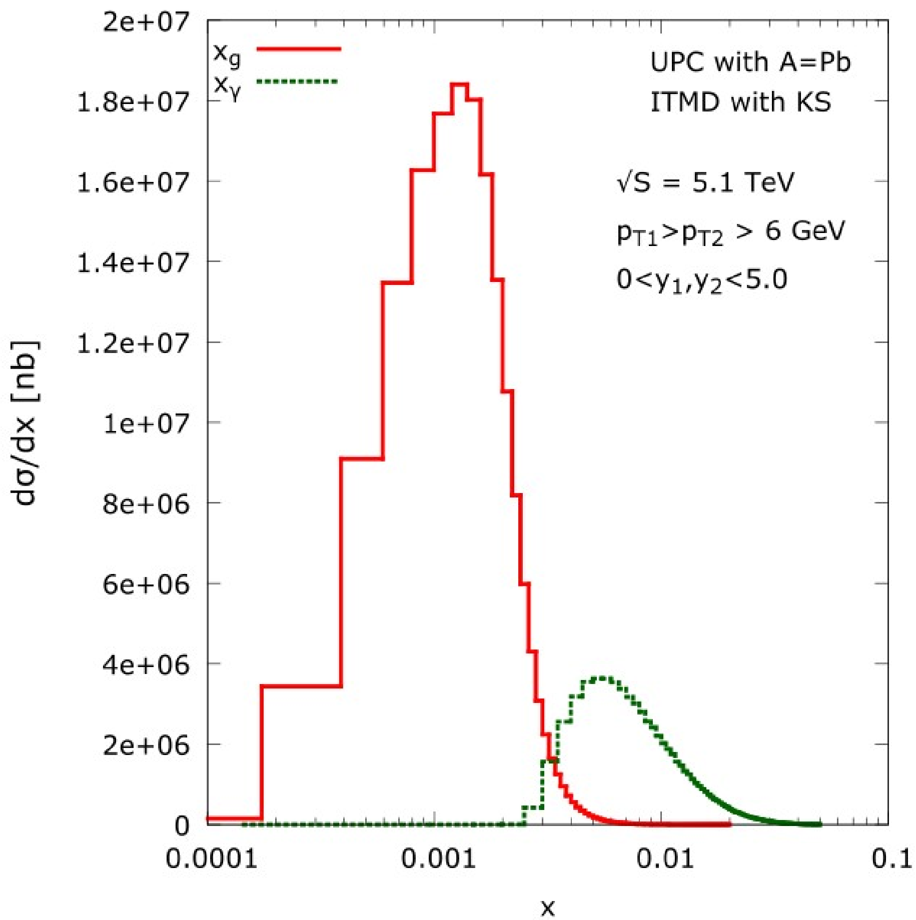
$$d\sigma^{\mathrm{UPC}}_{AA\to 2\,\mathrm{jet}+X} = \int \mathrm{d}x_\gamma \, \frac{\mathrm{d}N_\gamma}{\mathrm{d}x_\gamma} \, \mathrm{d}\sigma_{\gamma A\to 2\,\mathrm{jet}+X}$$

$$\frac{d\sigma_{\gamma A\to 2j}}{dy_1 d^2 p_{T1} dy_2 d^2 p_{T1}} \sim x_A G_1\left(x_A, k_T^2\right) \otimes K_{\gamma g^* \to q\bar{q}}\left(k_T\right)$$

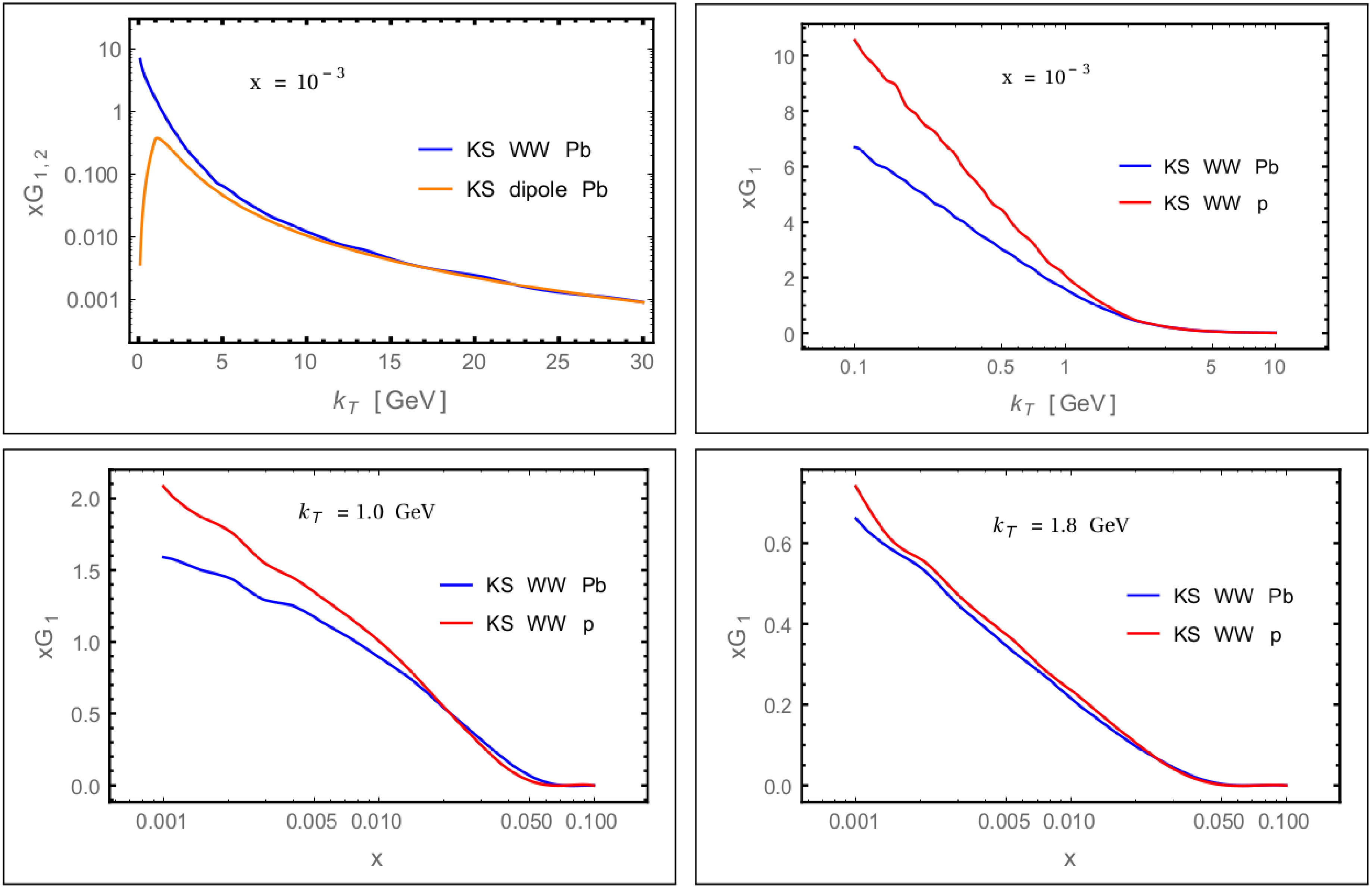
Longitudinal momentum fraction distributions – different cuts scenario

Kotko, Kutak, Sapeta, Stasto, Strikman '16

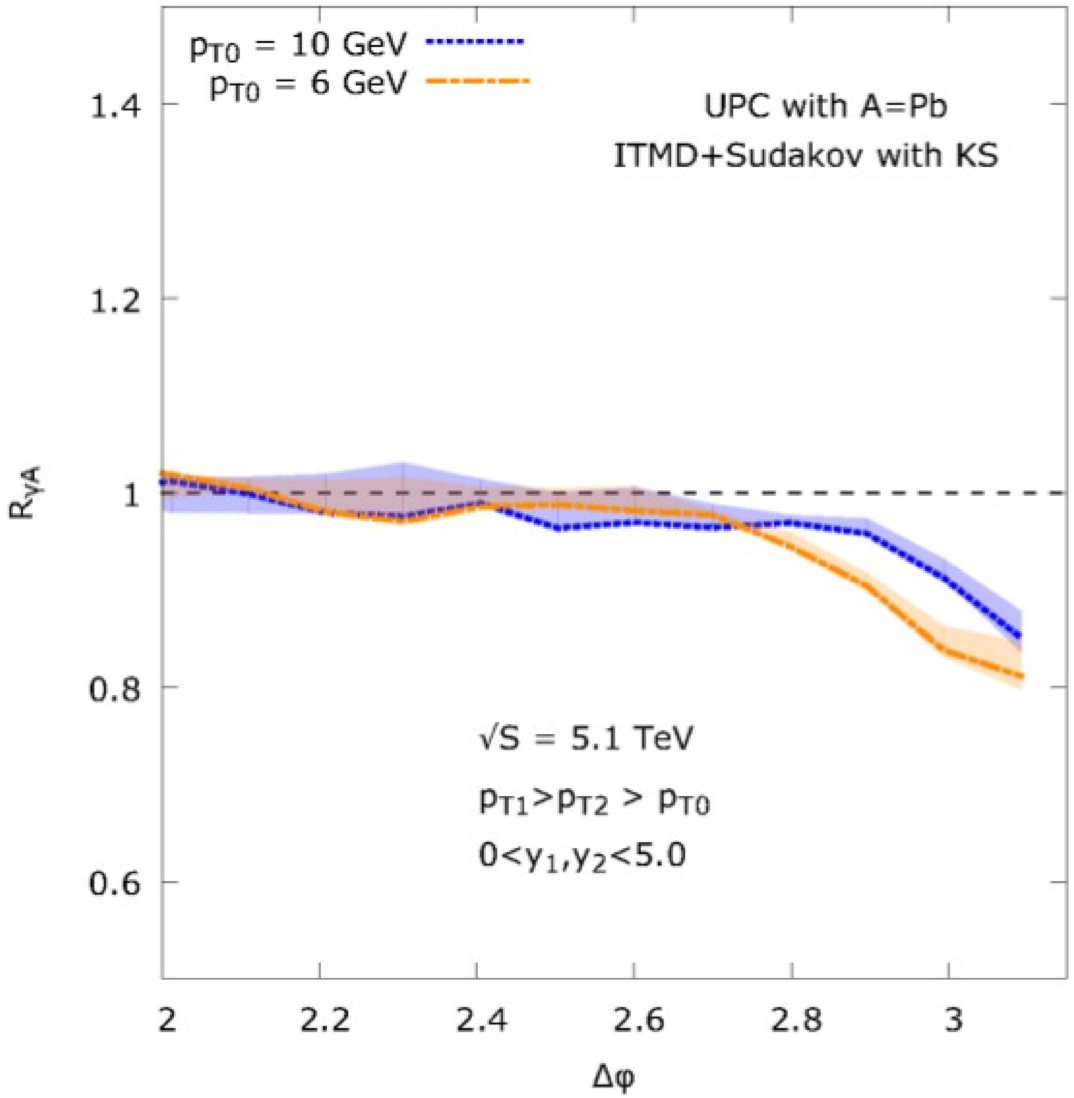




WW vs. dipole gluon density

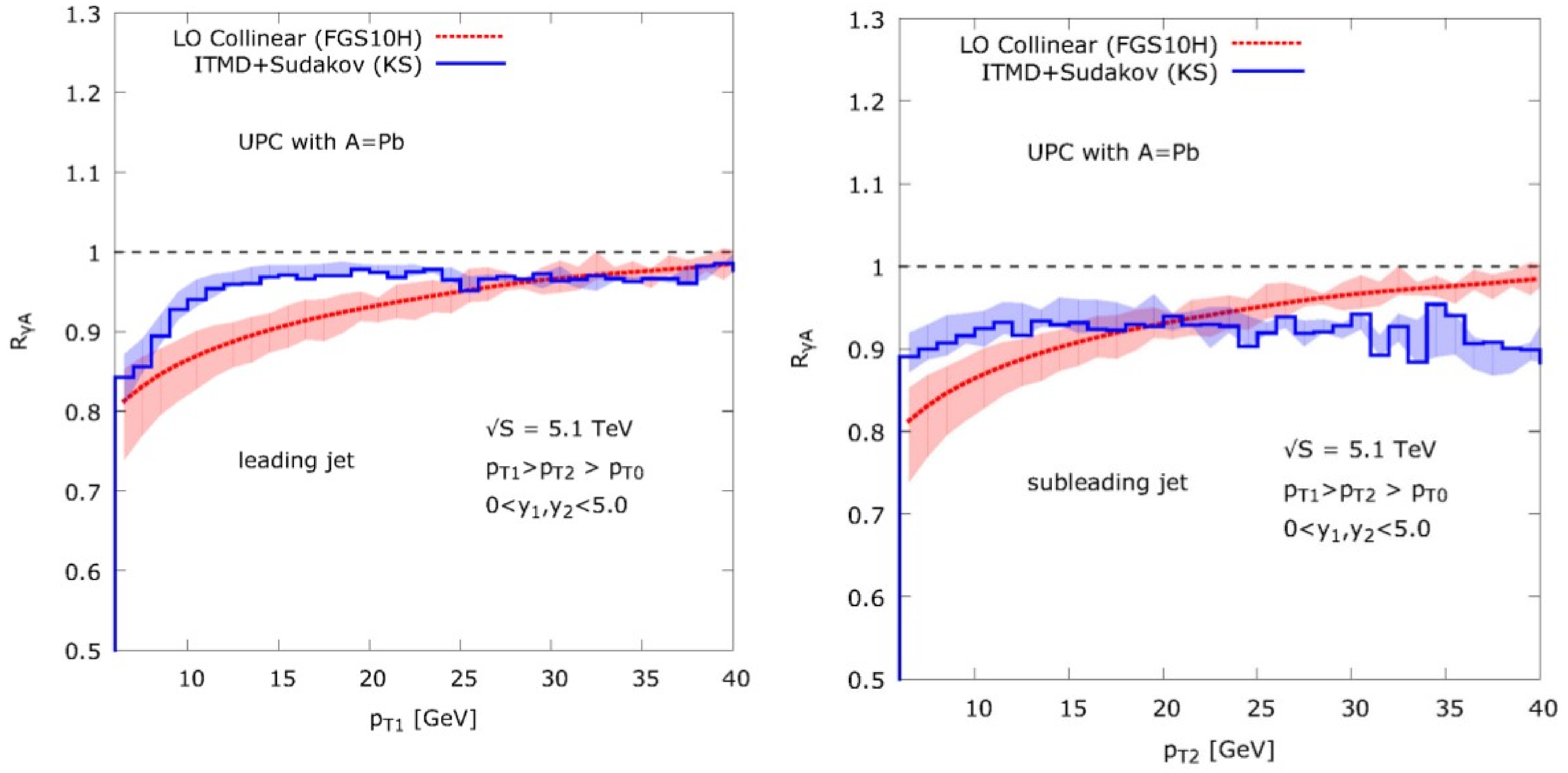


Nuclear modification factor - azimuthal decorelations



$$R_{\gamma A} = \frac{d\sigma_{AA}^{\mathrm{UPC}}}{A d\sigma_{Ap}^{\mathrm{UPC}}}$$

Nuclear modification factor - pt spectra



Conclusions

- *New framework ITMD for calculations of forward dijets has been developed*

- *Direct component of dijet production in UPC is directly sensitive to Weizsacker-Williams (WW) gluon distribution; this is the only 'true' gluon distribution at small x*

- *Present calculations use WW obtained from the 'dipole' gluon distribution fitted to data; no experimental information about WW is available*

- *Within the kinematics allowed by the present formalism the suppression factor is 10-20% depending on the transverse momentum cut*