

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



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

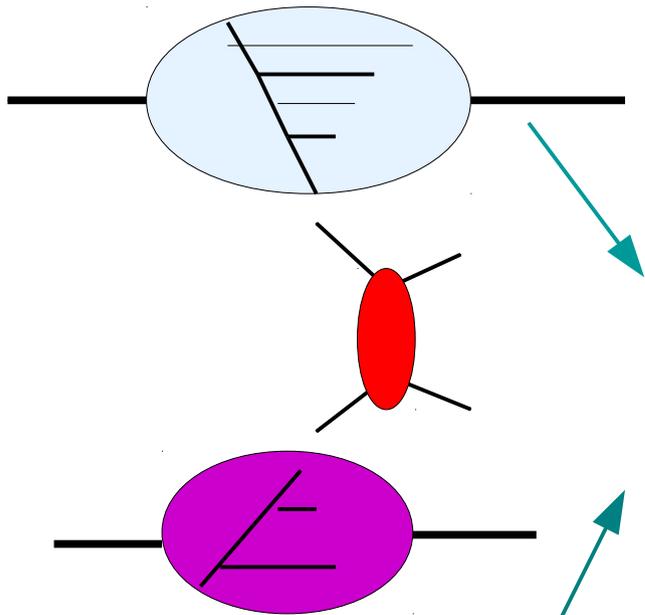
Krzysztof Kutak



Why jets in UPC?

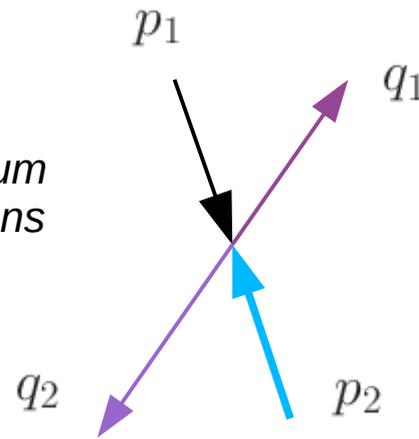
- jets are difficult observables.....but we should not give them up
- $\gamma A \rightarrow 2 \text{ jets}$ is sensitive to the Weizsacker-Williams (WW) unintegrated gluon distribution (UGD), whereas other processes like J/ψ or inclusive jets are sensitive to the dipole UGD
- $pA \rightarrow 2 \text{ jets}$ 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

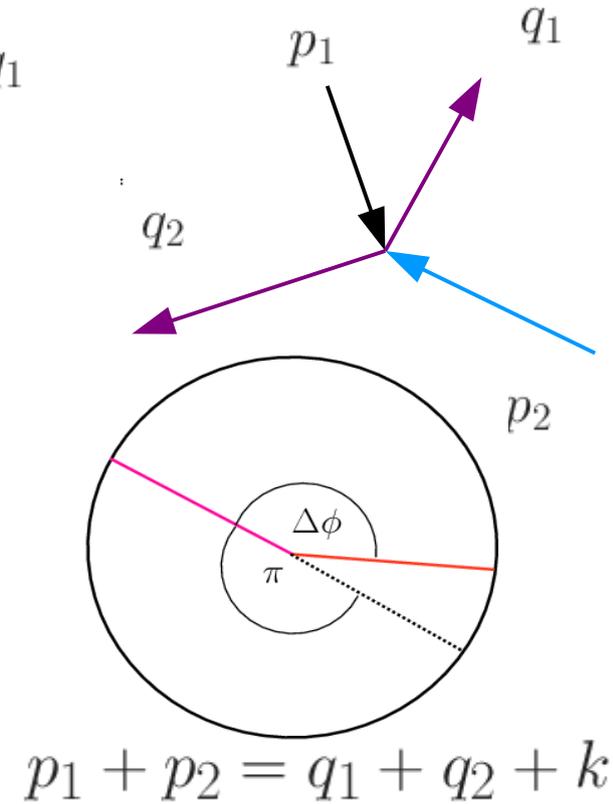


Strongly decreasing transversal momentum of DGLAP like partons

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

$$\frac{d\sigma_{SPS}^{P_1 P_2 \rightarrow \text{dijets} + X}}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \frac{p_{1t} p_{2t}}{8\pi^2 (x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/P_1}(x_1, \mu^2) |\overline{\mathcal{M}_{ag^* \rightarrow cd}}|^2 \mathcal{F}_{g/P_2}(x_2, k_t^2) \frac{1}{1 + \delta_{cd}}$$

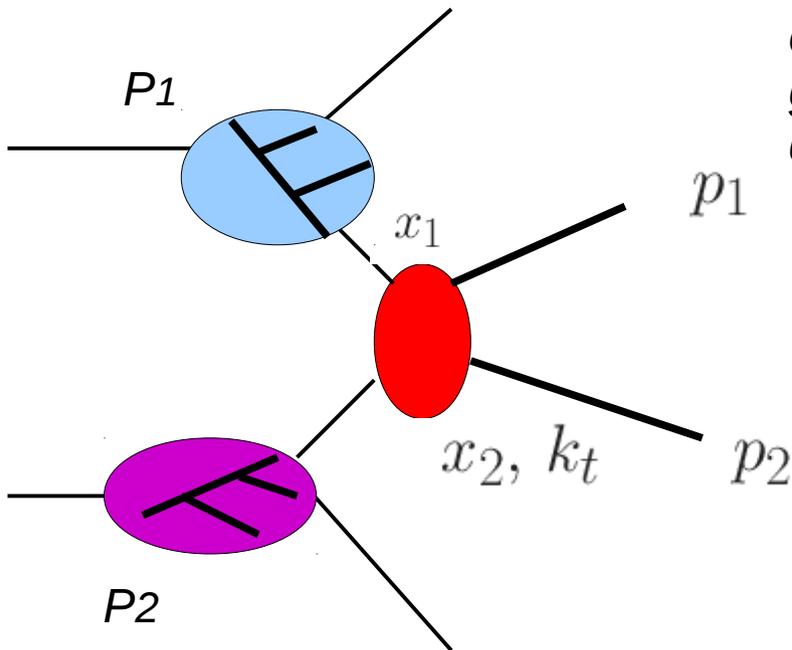
conjecture

Deak, Jung, Kutak, Hautmann '09

obtained from CGC after neglecting all nonlinearities

*$g^*g \rightarrow gg$ [Iancu, Laidet](#)*

$qg^ \rightarrow qg$ [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

$$\begin{aligned} x_1 &= \frac{1}{\sqrt{s}} (|\vec{p}_{1t}| e^{y_1} + |\vec{p}_{2t}| e^{y_2}) & \xrightarrow{y_1, y_2 \gg 0} & x_1 \sim 1 \\ x_2 &= \frac{1}{\sqrt{s}} (|\vec{p}_{1t}| e^{-y_1} + |\vec{p}_{2t}| e^{-y_2}) & & x_2 \ll 1 \end{aligned}$$

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 \rightarrow partons carry some k_t

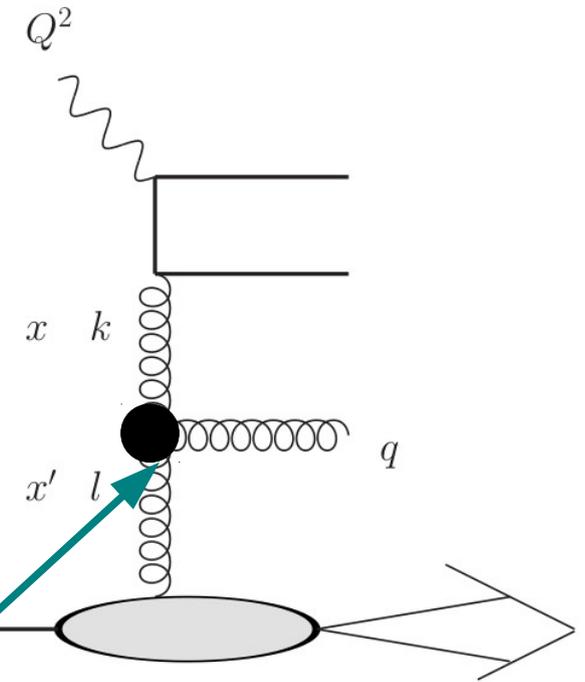
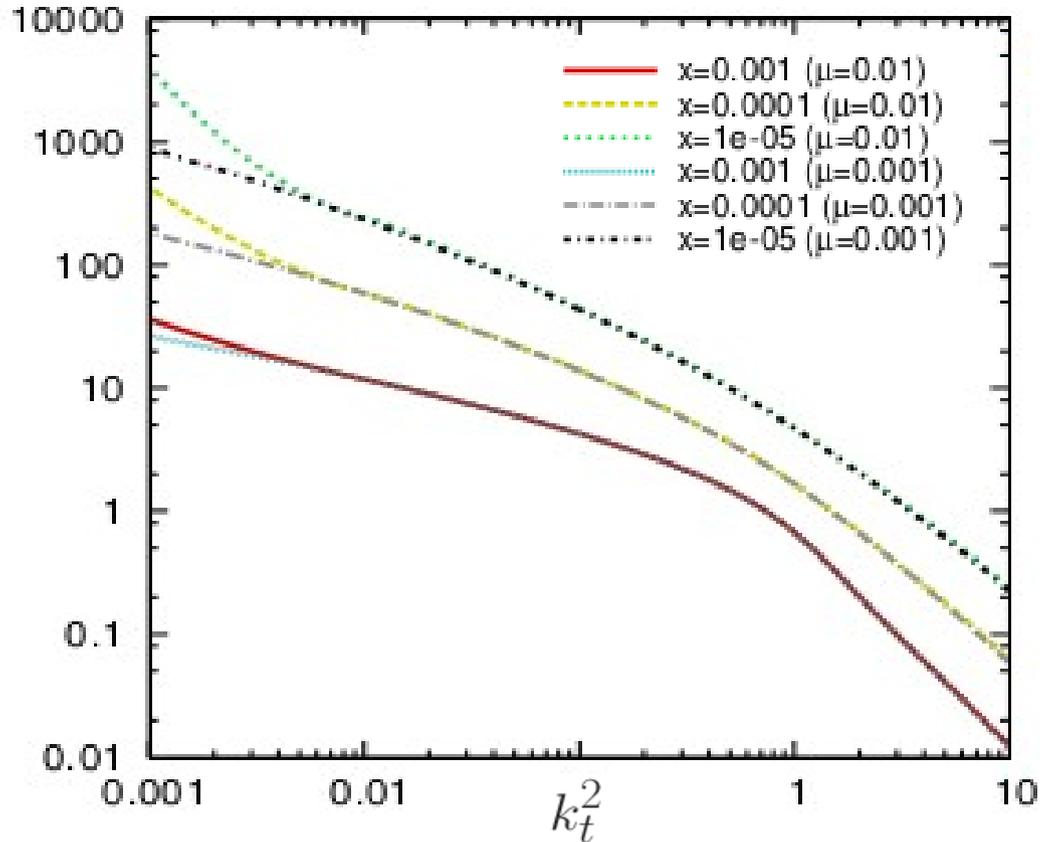
$k_t \ll P_t$ Collinear Factorization \rightarrow partons in one of hadrons are just collinear with hadron
 k_t is neglected

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

Q_s, k_t, P_t Improved Transverse Momentum Dependent Factorization

The saturation problem: sensitivity to gluons at small k_t

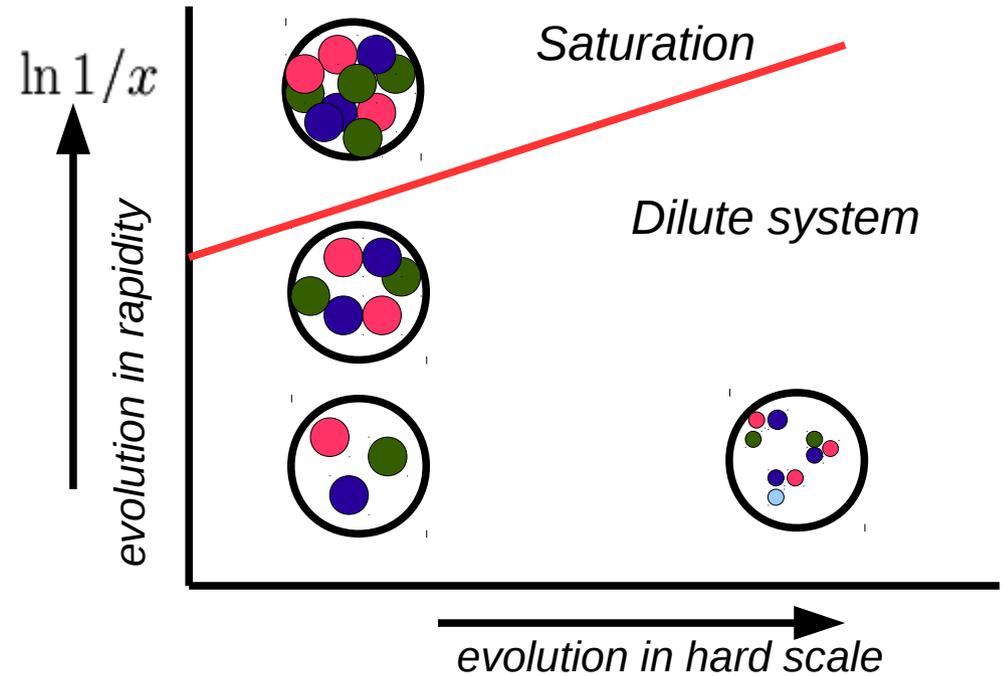
Solution of BFKL equation



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

High energy factorization and saturation

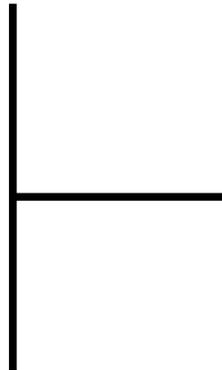
Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.



On microscopic level it means that gluon apart splitting recombine

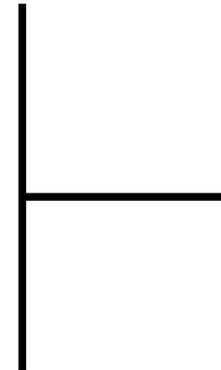
splitting

Linear evolution equation

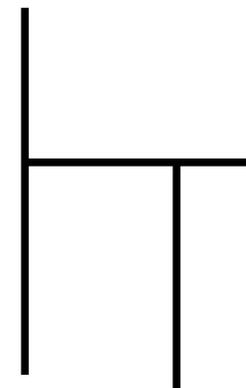


Nonlinear evolution equations

splitting

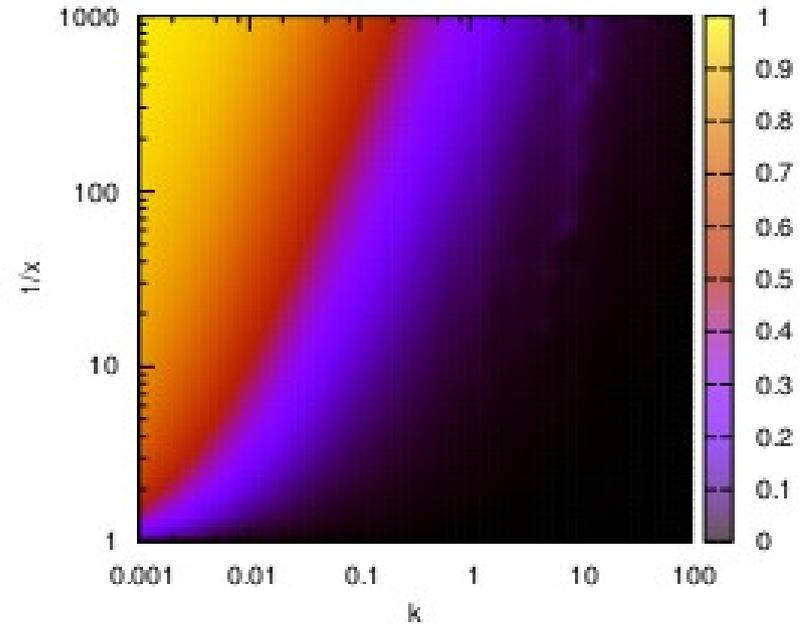


recombination



High energy factorization and saturation

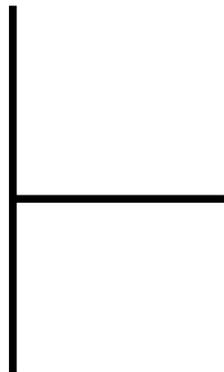
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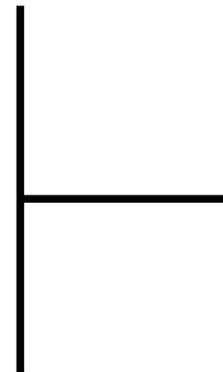
splitting

Linear evolution equation

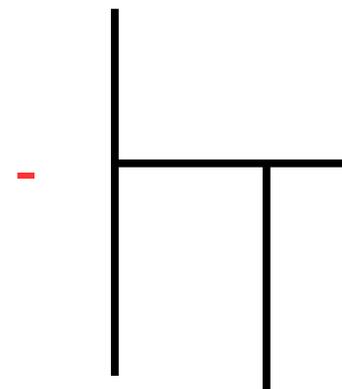


Nonlinear evolution equations

splitting



recombination



The saturation problem: suppressing gluons at small k_t

Originally formulated in coordinate space

Balitsky '96, Kovchegov '99

Now at NLO accuracy

Balitsky, Chirilli '07

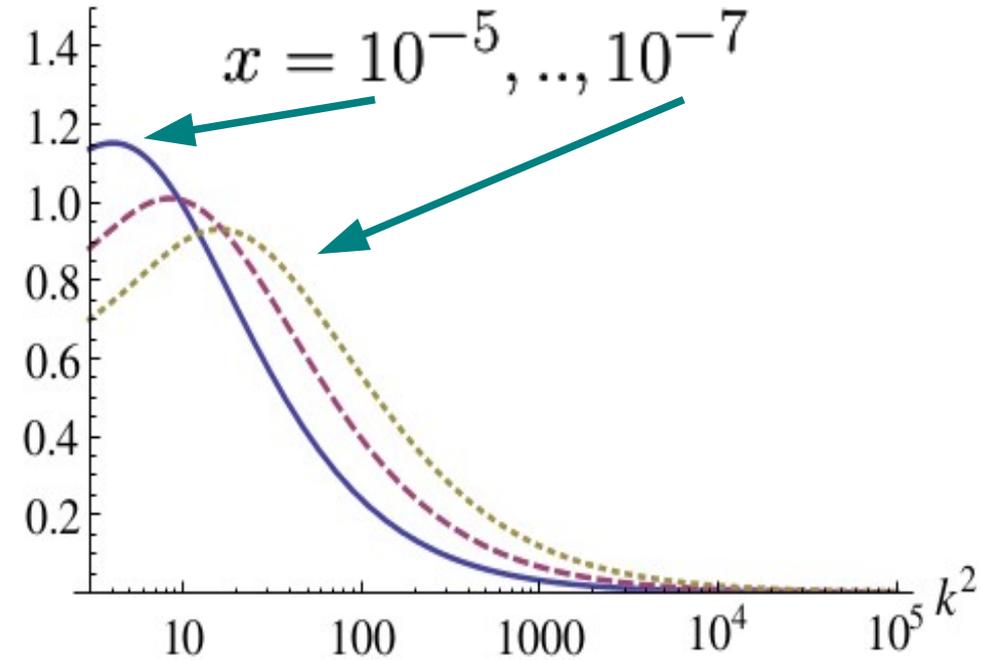
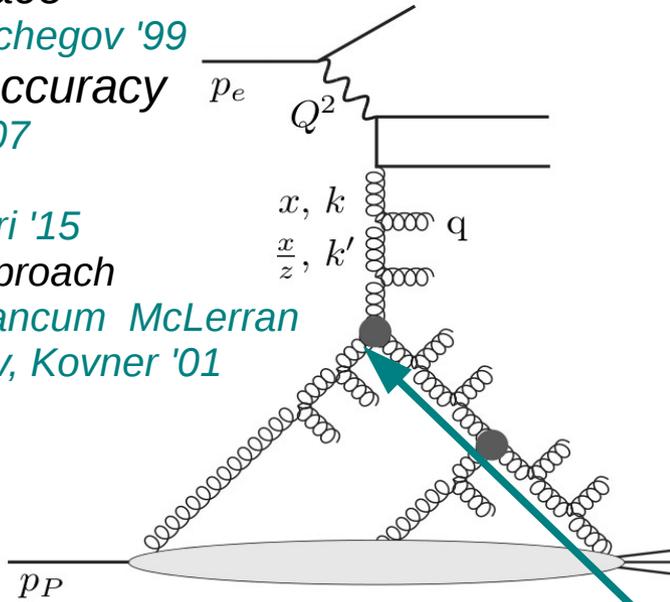
and solved

Lappi, Mantysaari '15

More general approach

Jalilian-MarianI, Iancu McLerran

Weigert Leonidov, Kovner '01



Solution of the equation

The BK equation for dipole gluon density

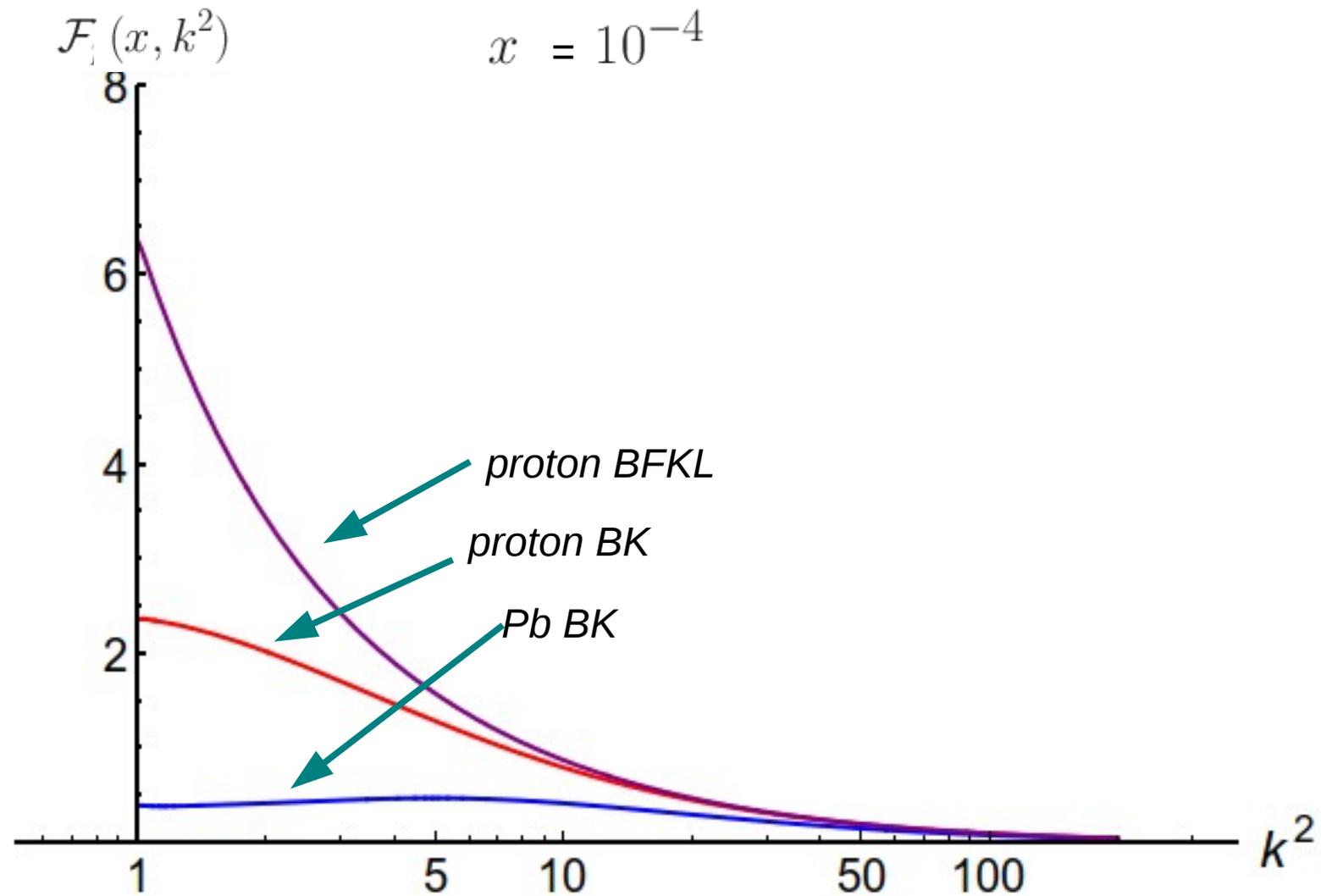
$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} - \frac{1}{R^2} V \otimes \mathcal{F}^2$$

hadron's radius

Momentum space

Kwiecinski, Kutak '02
Nikolaev, Schafer '06¹⁰

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



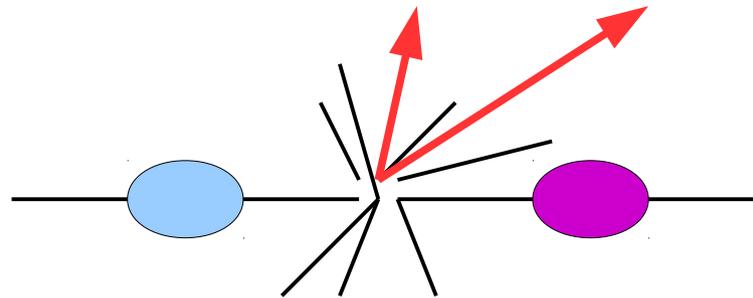
PDF we use at present

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*

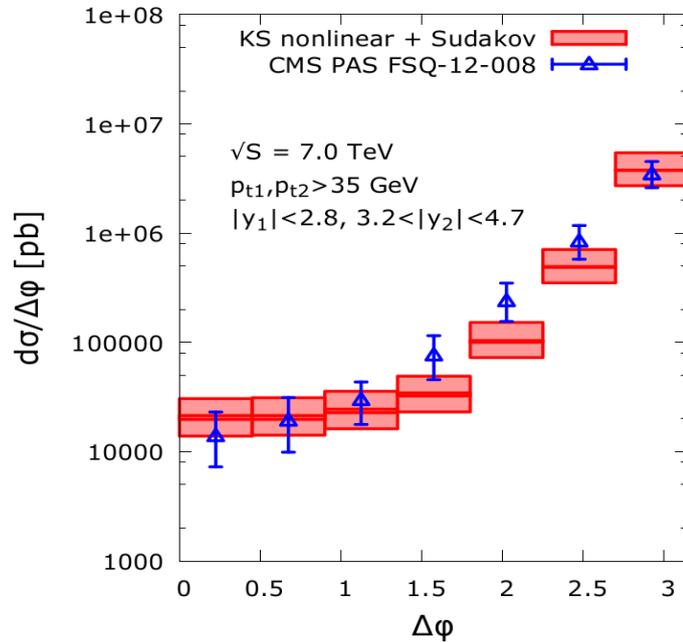
KK, Kwiecinski '03 fitted to '10 HERA data KK, Sapeta '12, nonlinear extension of unified BFKL+DGLAP Kwiecinski, Martin, Staśto framework '97.

Central-forward di-jets



Decorelations inclusive scenario forward-central

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

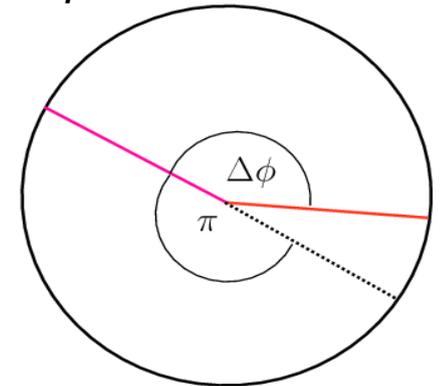


$$p_{t1}, p_{t2} > 35 \text{ GeV}$$

$$3.2 < |y_2| < 4.7$$

$$|y_1| < 2.8$$

Leading jets, no further requirement



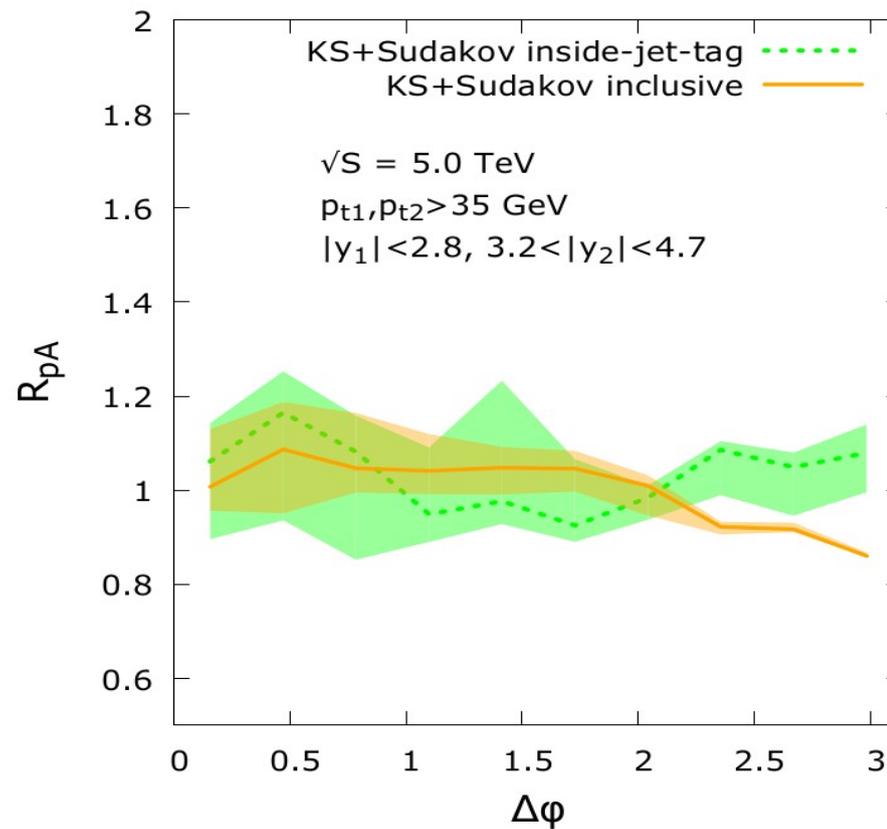
In DGLAP approach
i.e $2 \rightarrow 2$ + pdf one would get delta function

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

Studied also context of RHIC
Albacete, Marquet '10

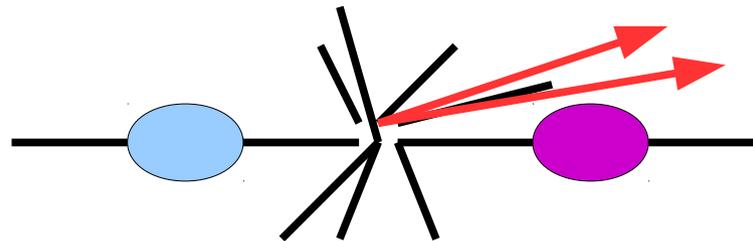
Predictions for p -Pb for forward-central

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



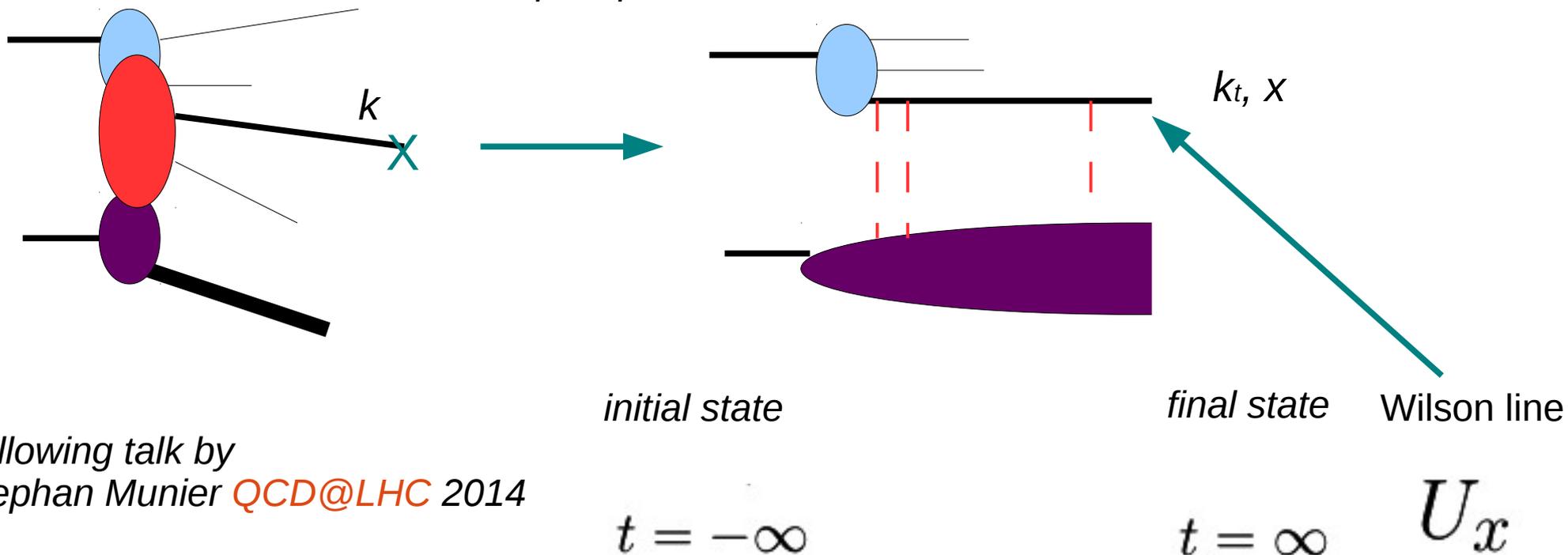
saturation effects are rather weak for forward-central jets

Forward-forward di-jets



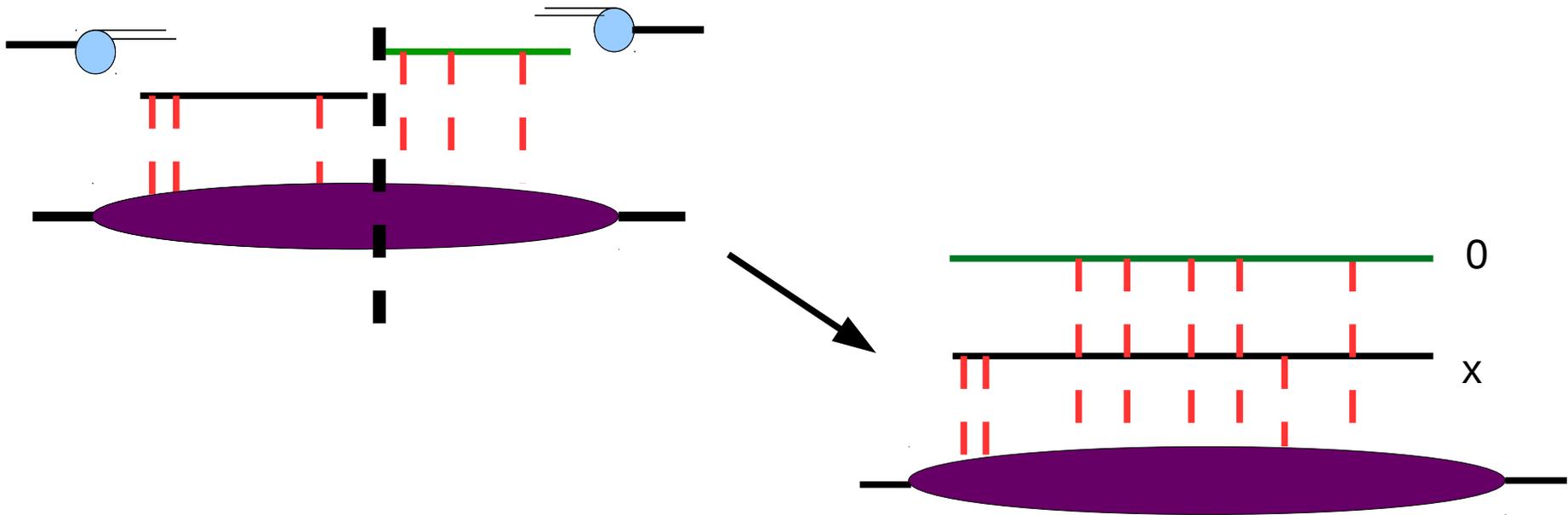
Dipole gluon density

In dipole picture



Following talk by
Stephan Munier **QCD@LHC** 2014

Dipole gluon density



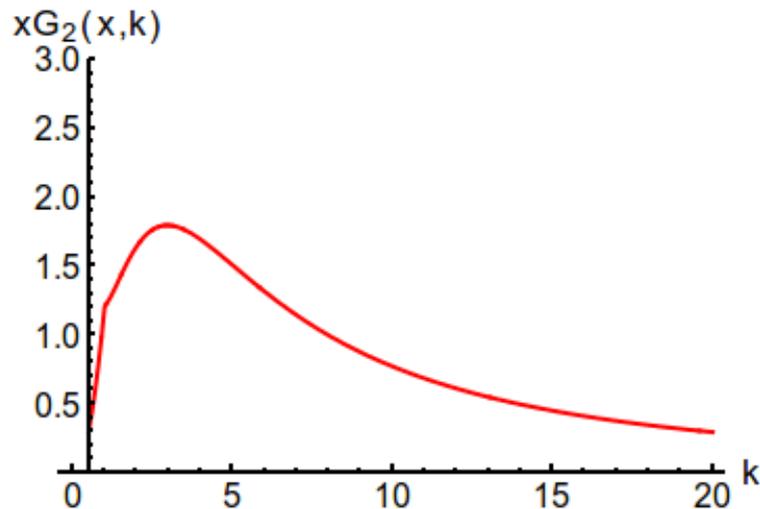
We factor out wave function.

We multiply the amplitude by it's hermitian conjugate.

$$\mathcal{F}(x, \mathbf{k}_t^2) \propto \mathbf{k}_t^2 \int \frac{d^2 \mathbf{x}}{(2\pi)^2} e^{-i\mathbf{k}_t \cdot \mathbf{x}} S(x, \mathbf{x})$$

Dipole gluon density

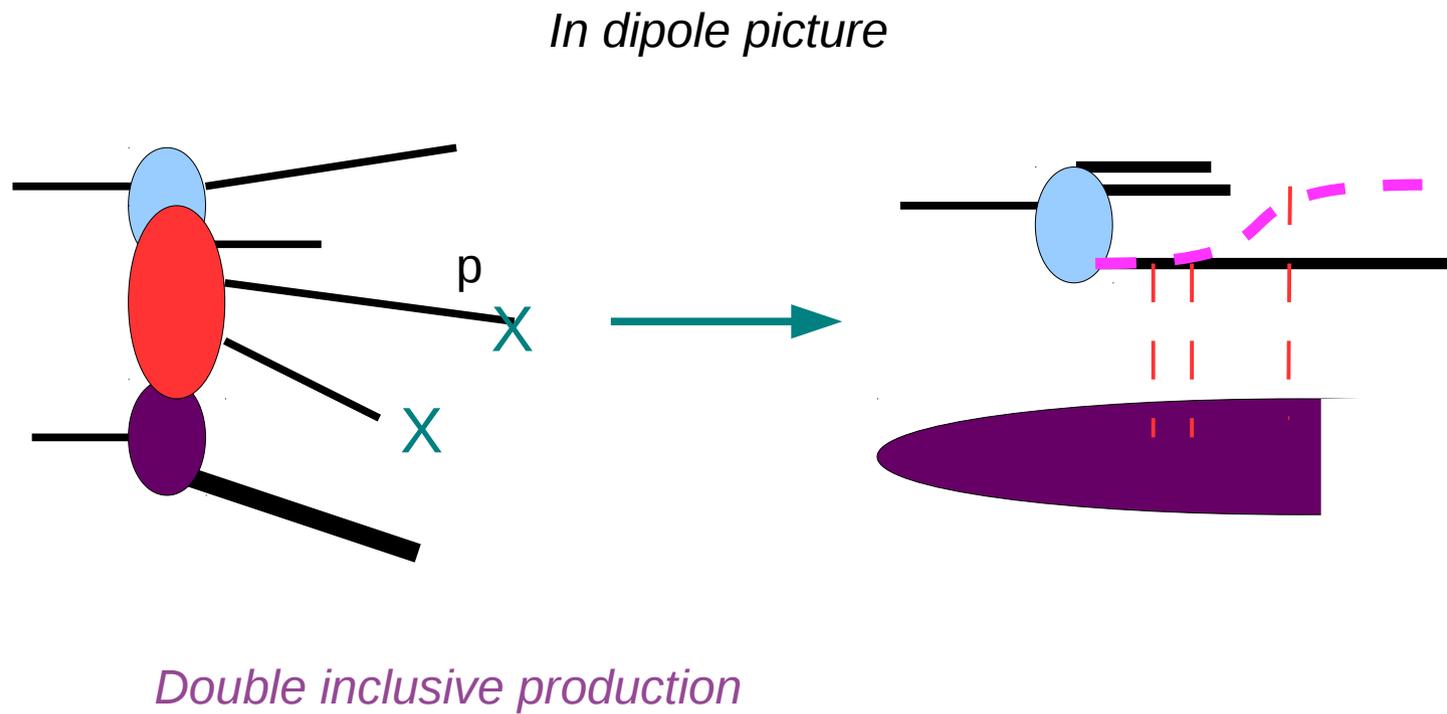
- Enters directly into DIS structure function and DY cross section
- Can be expressed in terms of the expectation value of the S – matrix for scattering of a qq dipole off a dense target, SF
- One can write BK equation in the momentum space which as a solution gives dipole gluon density



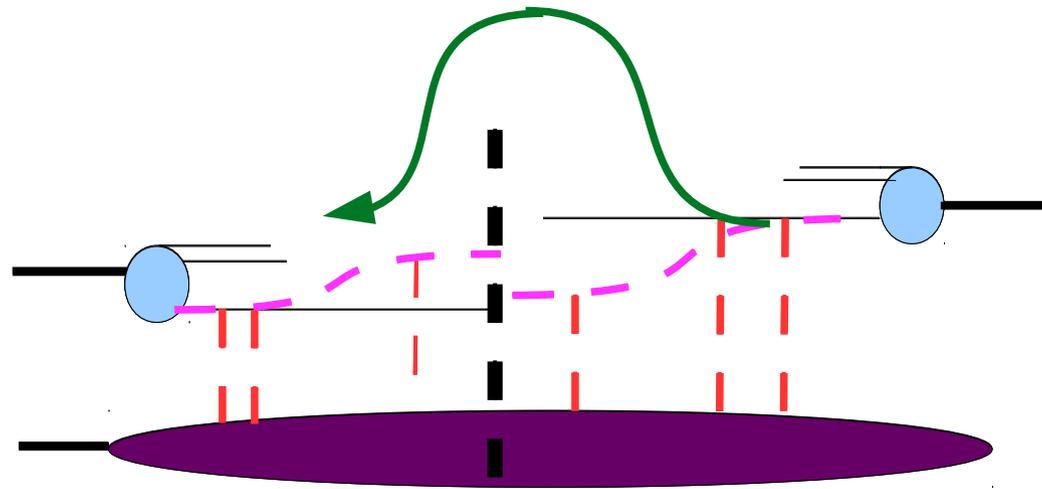
$$\mathcal{F}(x, \mathbf{k}_t^2) \propto \mathbf{k}_t^2 \int \frac{d^2\mathbf{x}}{(2\pi)^2} e^{-i\mathbf{k}_t \cdot \mathbf{x}} S(x, \mathbf{x})$$

$$xG^{(1)}(x, \mathbf{k}_t^2) \equiv \mathcal{F}(x, \mathbf{k}_t^2)$$

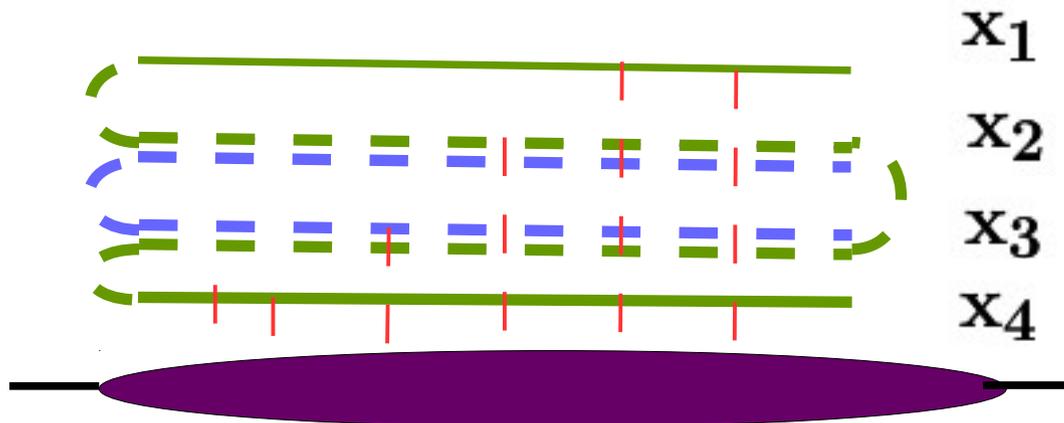
Weizacker-Williams gluon density



Weizacker-Williams gluon density



Large number of color limit

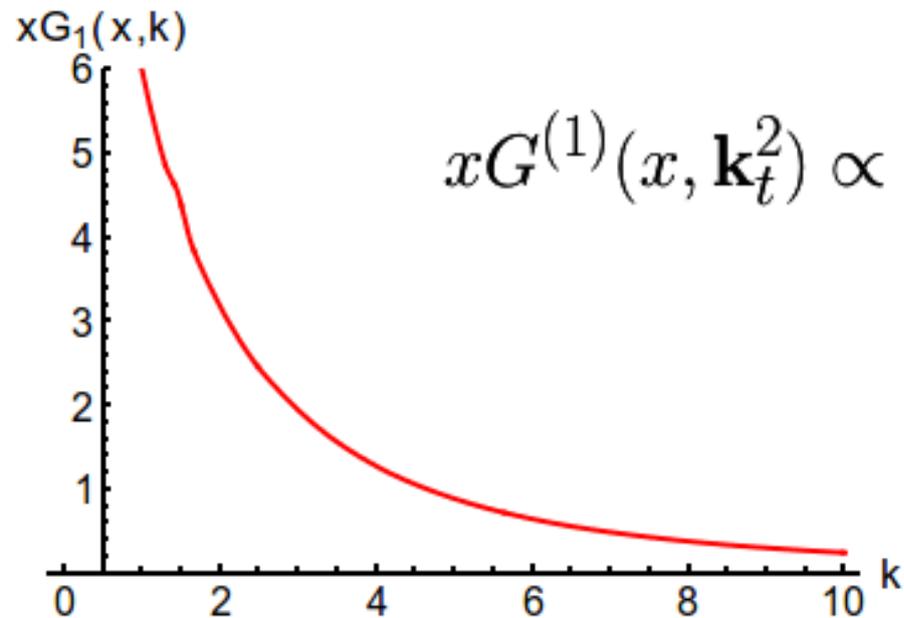


$$S \propto \langle \text{Tr}(U^\dagger(x_2)U(x_3)) \rangle$$

$$Q \propto \langle \text{Tr}(U^\dagger(x_1)U(x_2)U^\dagger(x_3)U(x_4)) \rangle$$

Weizacker-Williams gluon density

- Can be determined from dijet production in DIS
- In general can be obtained from a quadrupole operator
- For Gaussian distribution of sources one can express it through the expectation value of the S – matrix for scattering of a gg dipole



$$xG^{(1)}(x, \mathbf{k}_t^2) \propto \int \frac{d^2\mathbf{x}}{(2\pi)^2} e^{-i\mathbf{k}_t \cdot \mathbf{x}} \frac{(1 - S_A(x, \mathbf{x}))}{\mathbf{x}^2}$$

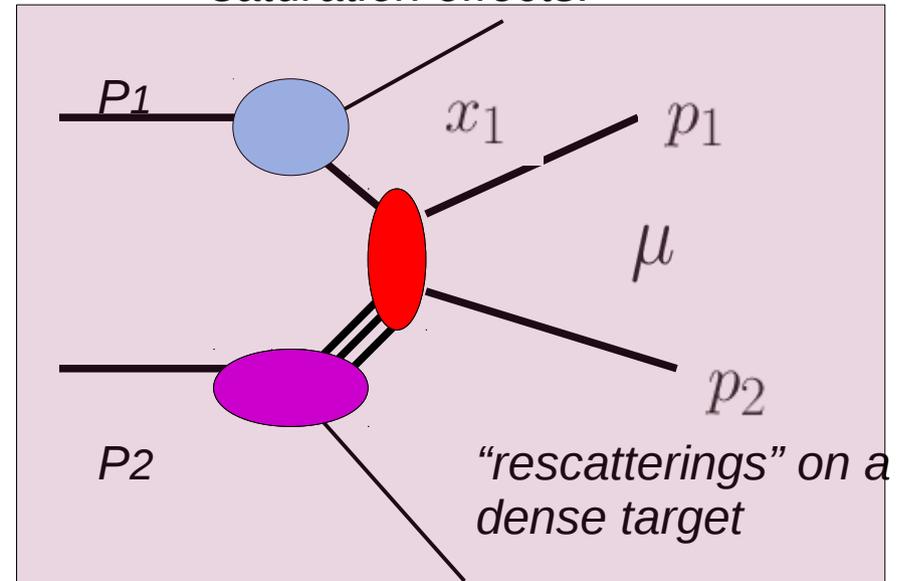
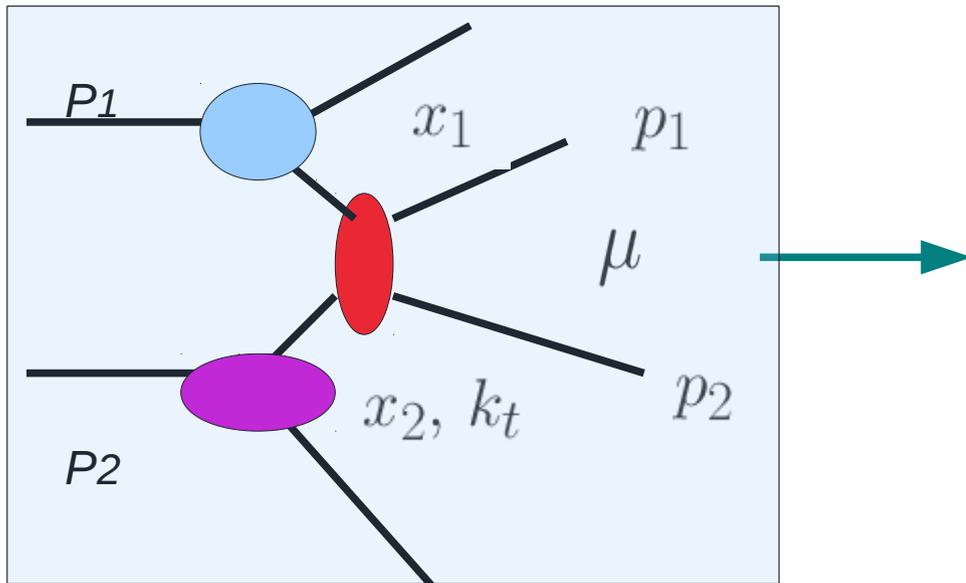
In approximation

$$S_A(x, \mathbf{x}) = [S(x, \mathbf{x})]^2$$

Improved TMD for dijets

$$\frac{d\sigma_{SPS}^{P_1 P_2 \rightarrow \text{dijets} + X}}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \frac{p_{1t} p_{2t}}{8\pi^2 (x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/P_1}(x_1, \mu^2) |\overline{\mathcal{M}}_{ag^* \rightarrow cd}|^2 \mathcal{F}_{g/P_2}(x_2, k_t^2) \frac{1}{1 + \delta_{cd}}$$

can be used for estimates of saturation effects.

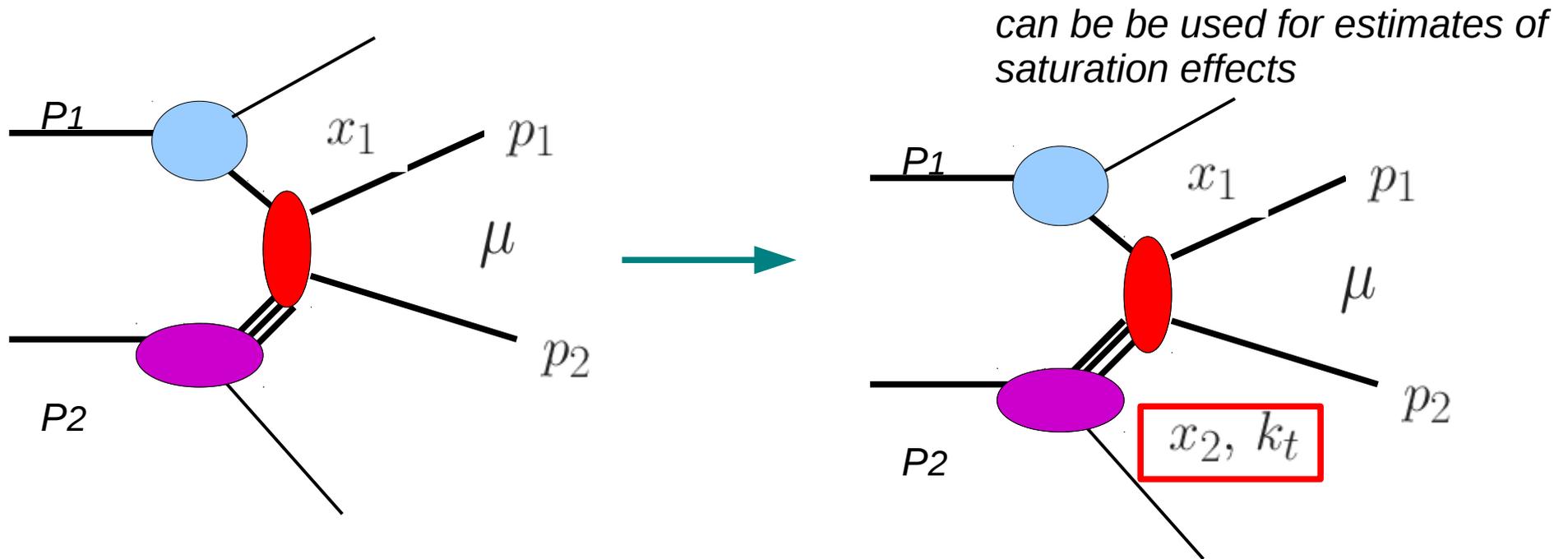


Generalization but *no possibility to calculate decorrelations* since no k_t in ME
 Dominguez, Marquet, Xiao, Yuan '11

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

$$\frac{d\sigma^{pA \rightarrow cdX}}{d^2 P_t d^2 k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} x_1 f_{q/p}(x_1, \mu^2) \sum_{i=1}^n \mathcal{F}_{ag}^{(i)} H_{ag \rightarrow cd}^{(i)} \frac{1}{1 + \delta_{cd}}$$

Improved TMD for dijets

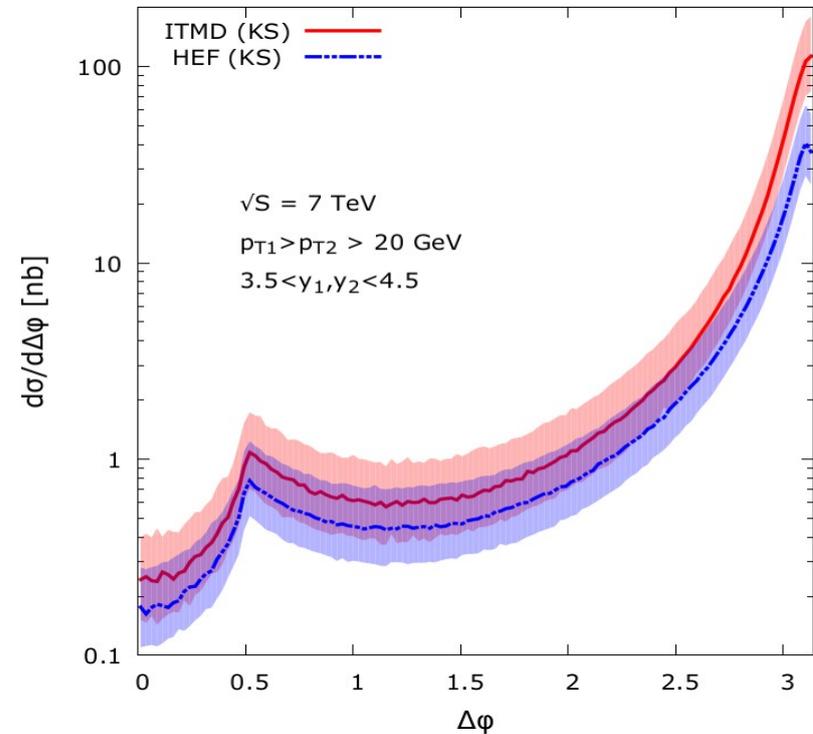
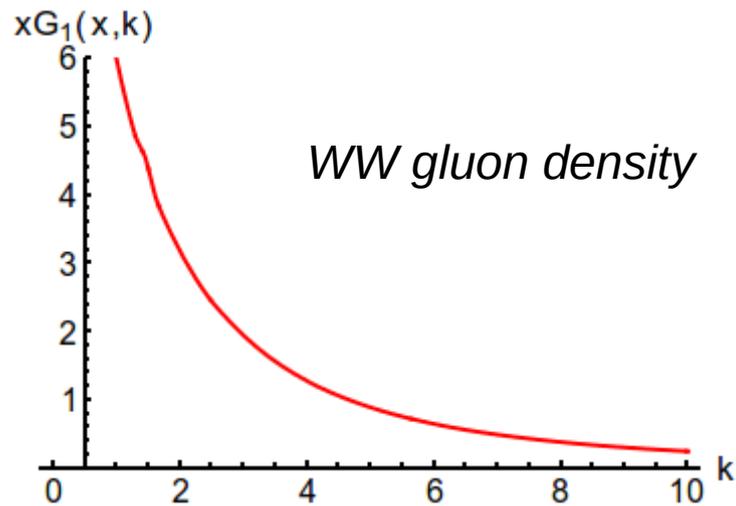
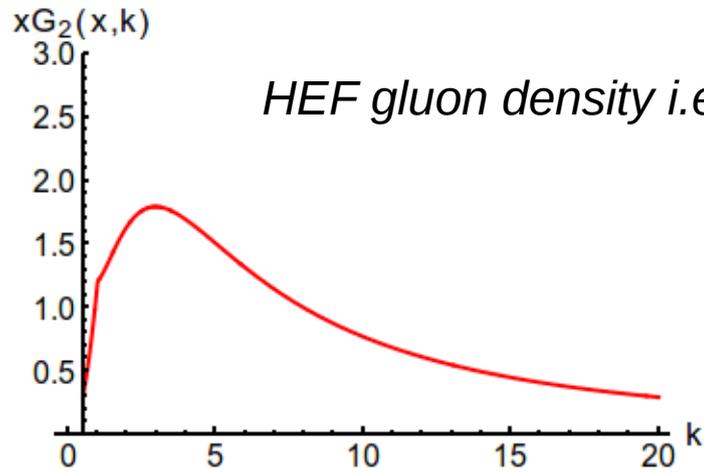


We found a method to include k_t in ME and express the factorization formula in terms of gauge invariant sub amplitudes \rightarrow more direct relation to two fundamental gluon densities: **dipole gluon density** and **Weizacker-Williams gluon density**
 Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '15

$$\frac{d\sigma^{pA \rightarrow \text{dijets} + X}}{d^2 P_t d^2 k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1, \mu^2) \sum_{i=1}^2 K_{ag^* \rightarrow cd}^{(i)} \Phi_{ag \rightarrow cd}^{(i)} \frac{1}{1 + \delta_{cd}} \quad 26$$

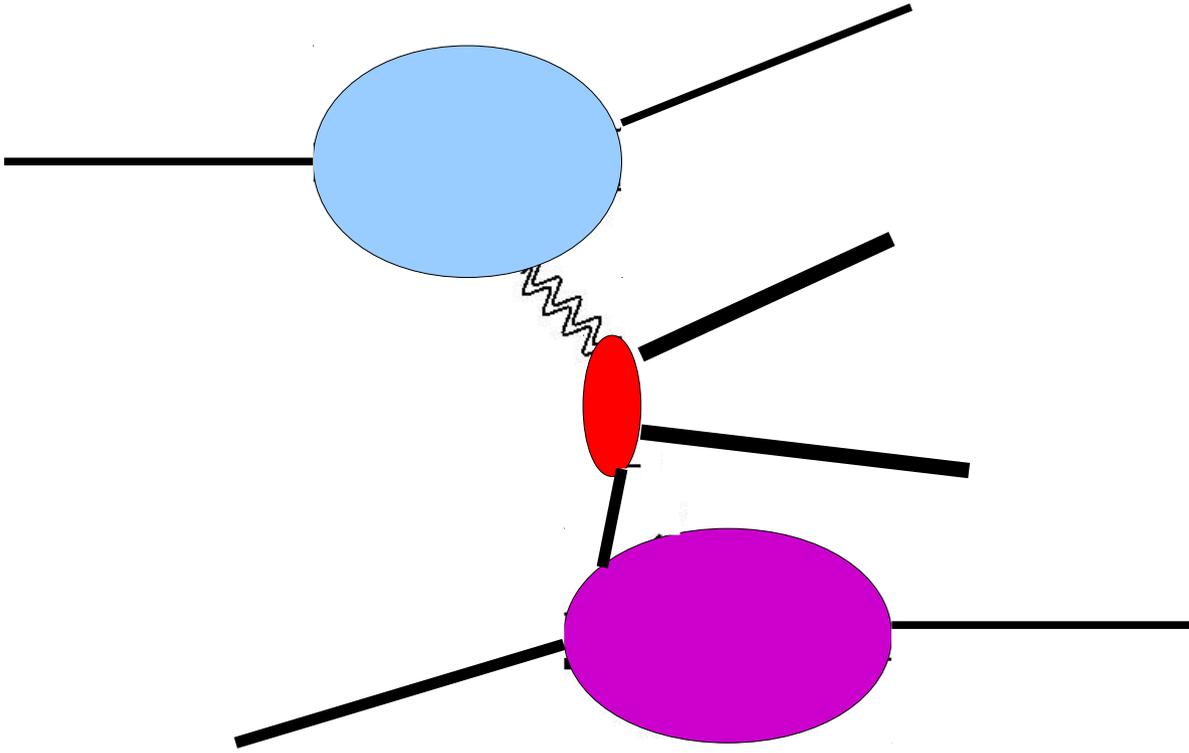
Glimpse on the first results – HEF vs. ITMD

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



In large N_c one can express WW UGD in terms of dipole UGD. We use this approximation

UPC collision of Pb-Pb

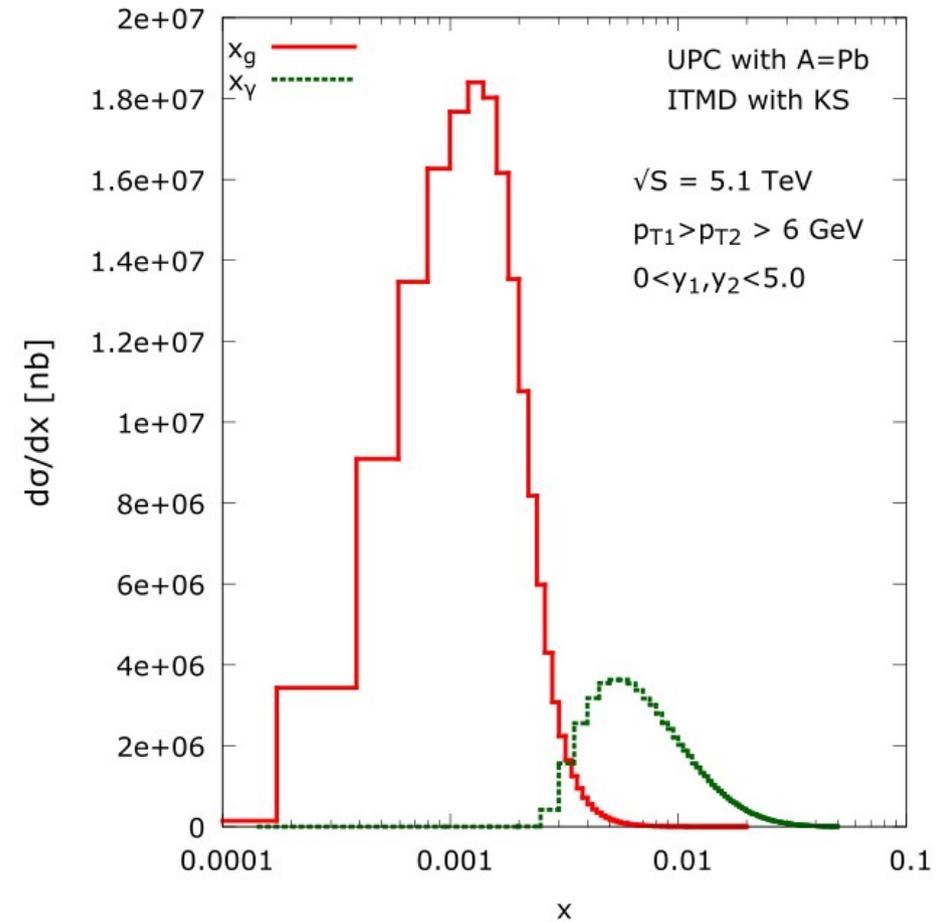
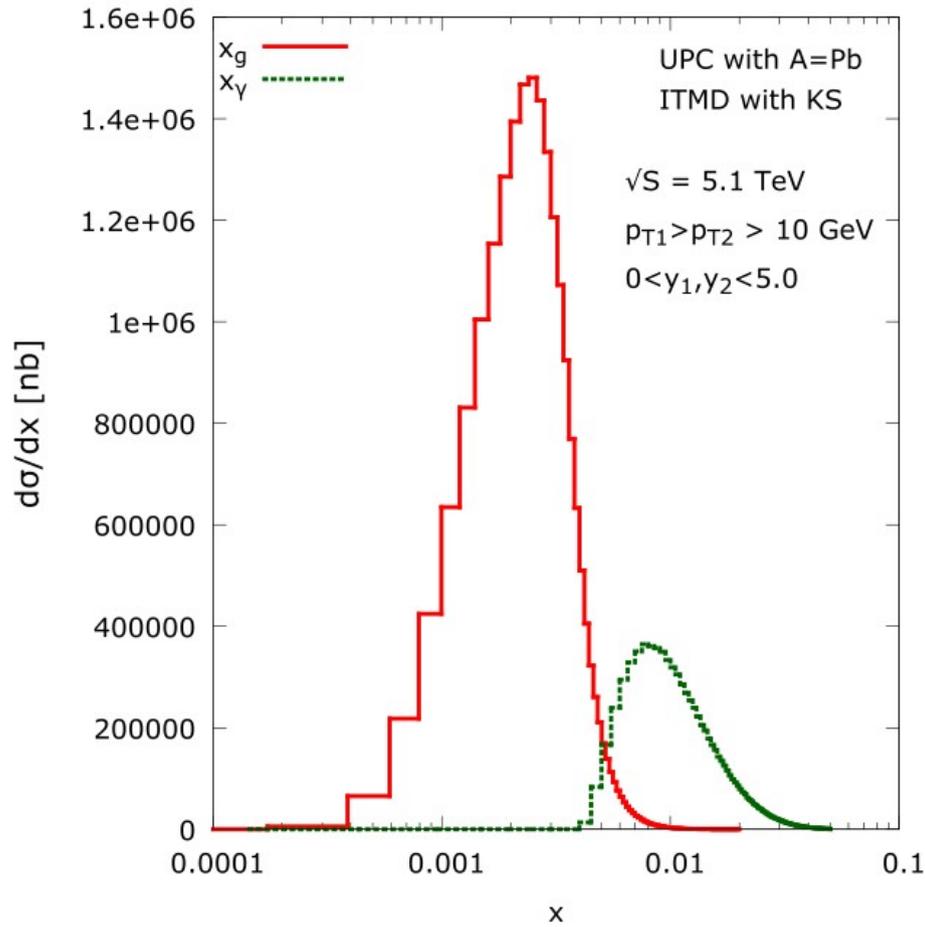


$$d\sigma_{AA \rightarrow 2\text{jet}+X}^{\text{UPC}} = \int dx_\gamma \frac{dN_\gamma}{dx_\gamma} d\sigma_{\gamma A \rightarrow 2\text{jet}+X}$$

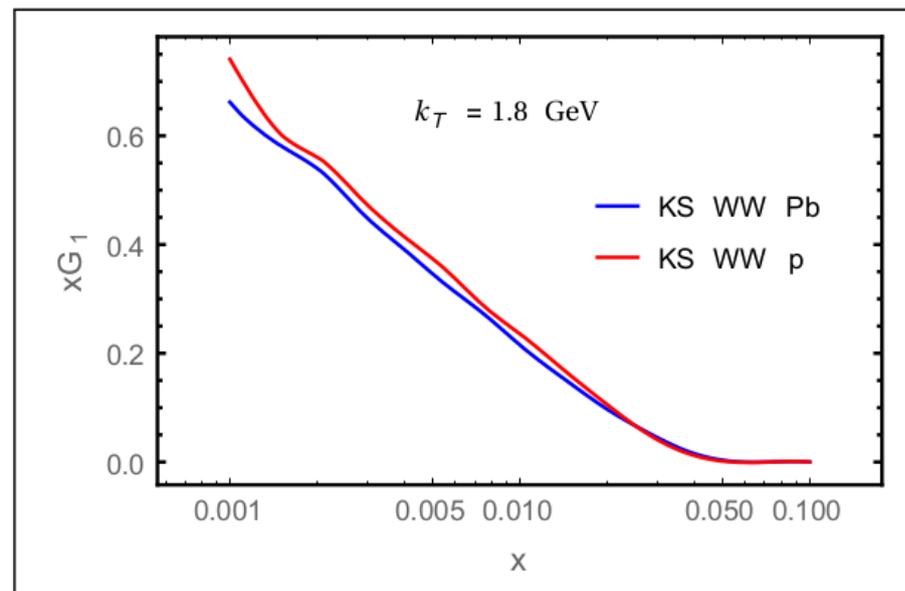
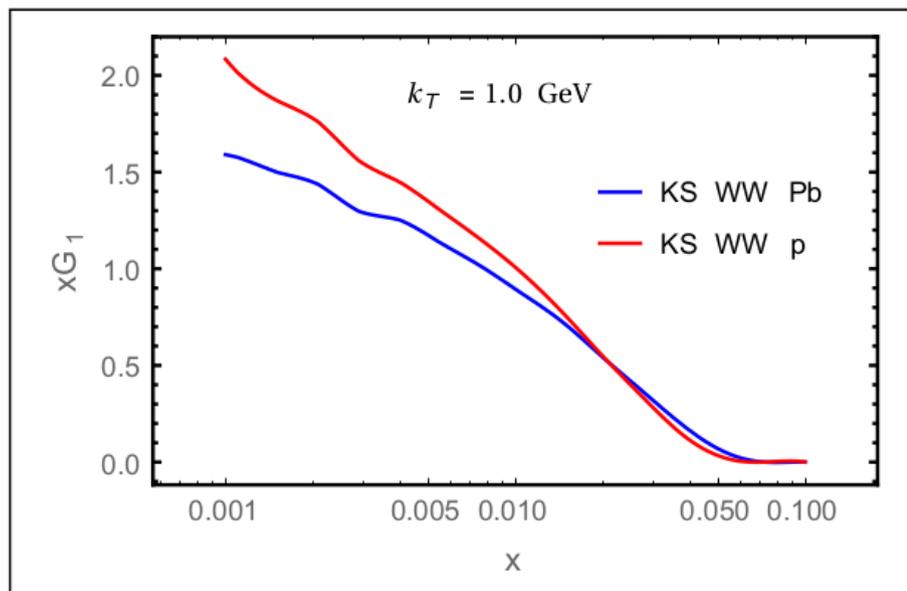
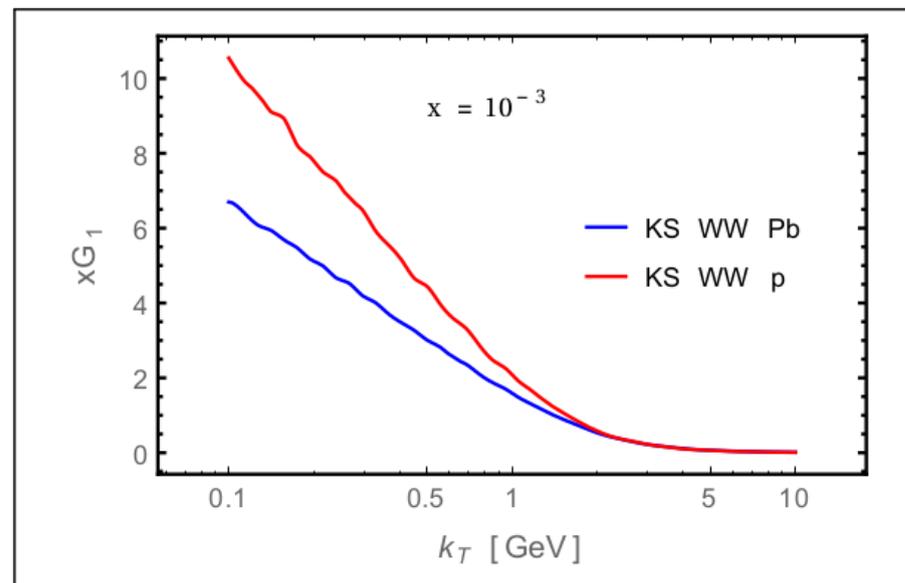
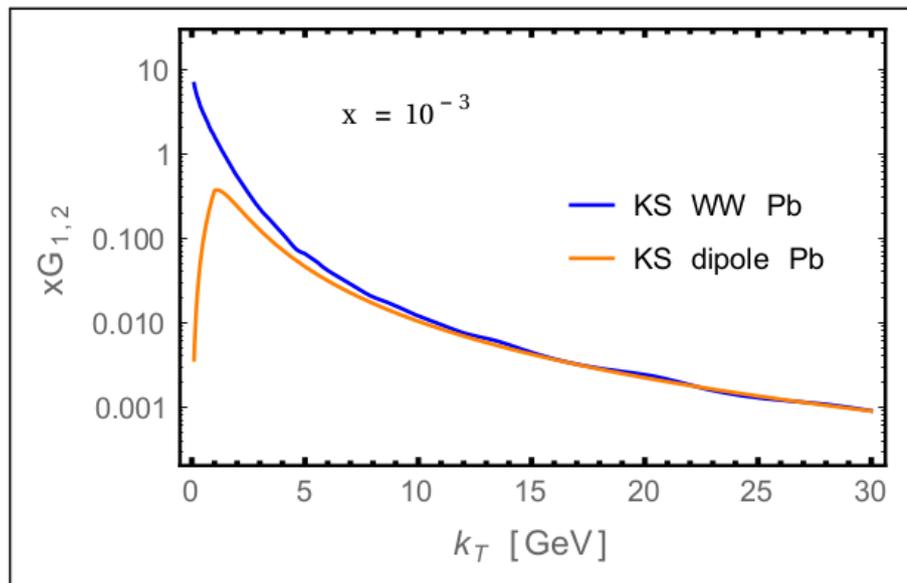
$$\frac{d\sigma_{\gamma A \rightarrow 2j}}{dy_1 d^2 p_{T1} dy_2 d^2 p_{T1}} \sim x_A G_1(x_A, k_T^2) \otimes K_{\gamma g^* \rightarrow q\bar{q}}(k_T)$$

Longitudinal momentum fraction distributions – different cuts scenario

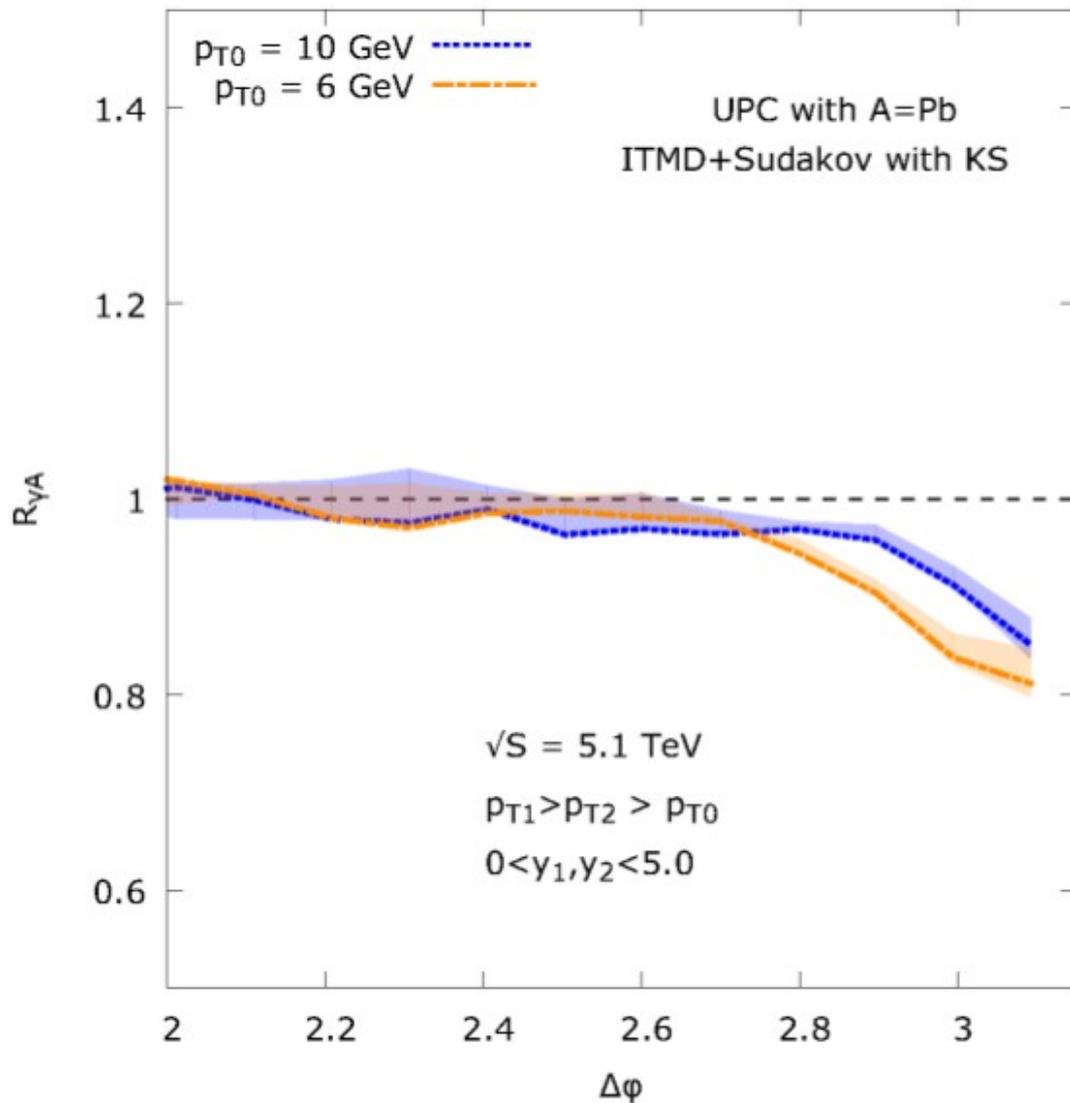
Kotko, Kutak, Sapeta, Stasto, Strikman '16



WW vs. dipole gluon density

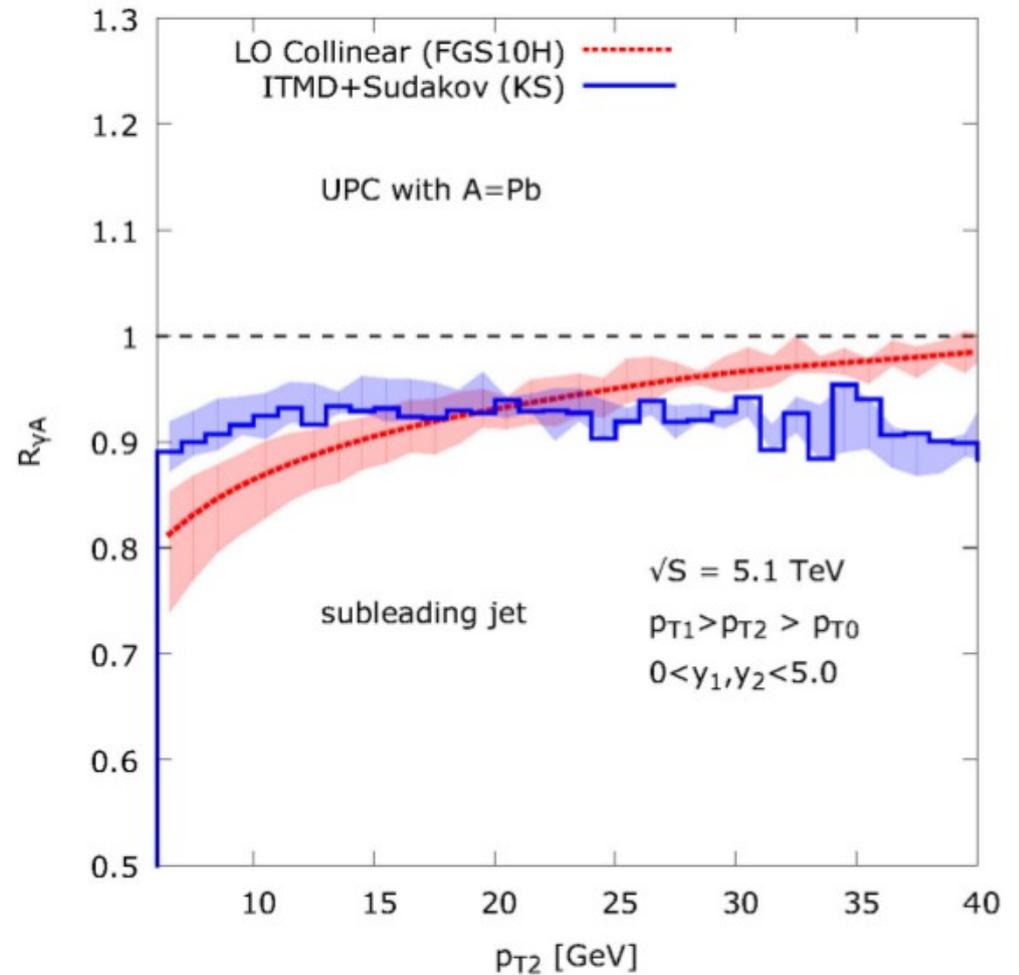
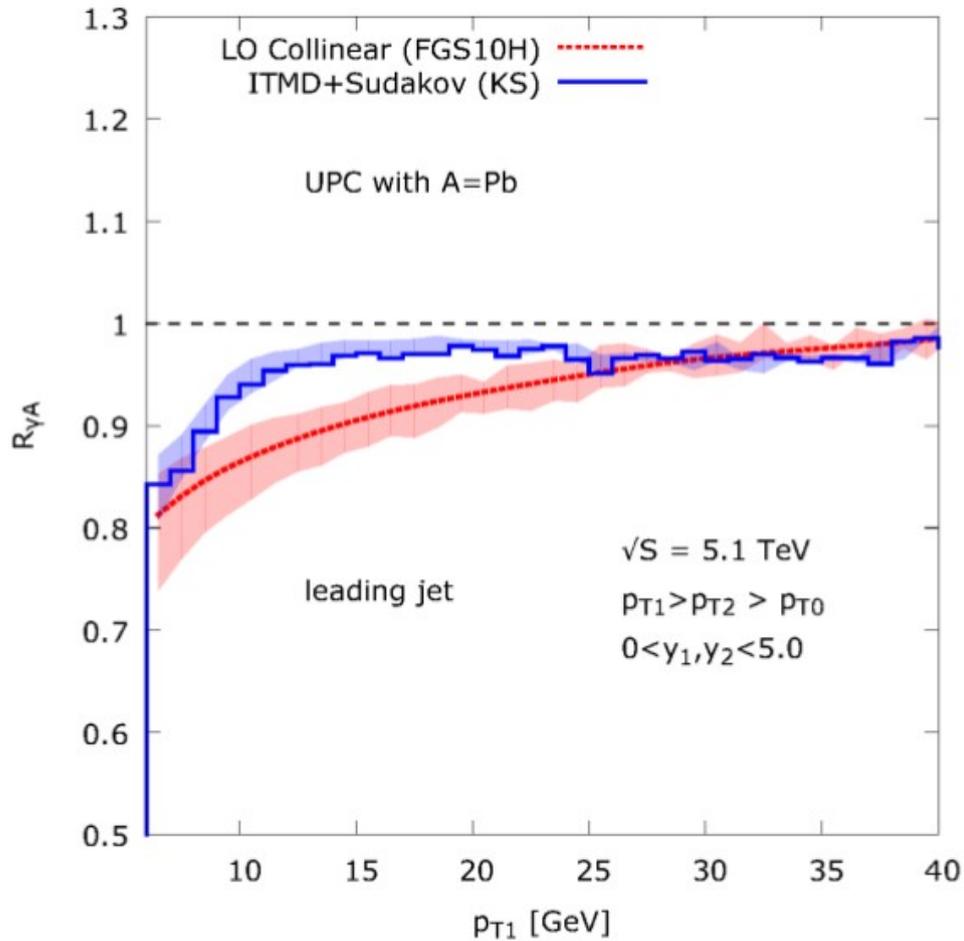


Nuclear modification factor - azimuthal decorrelations

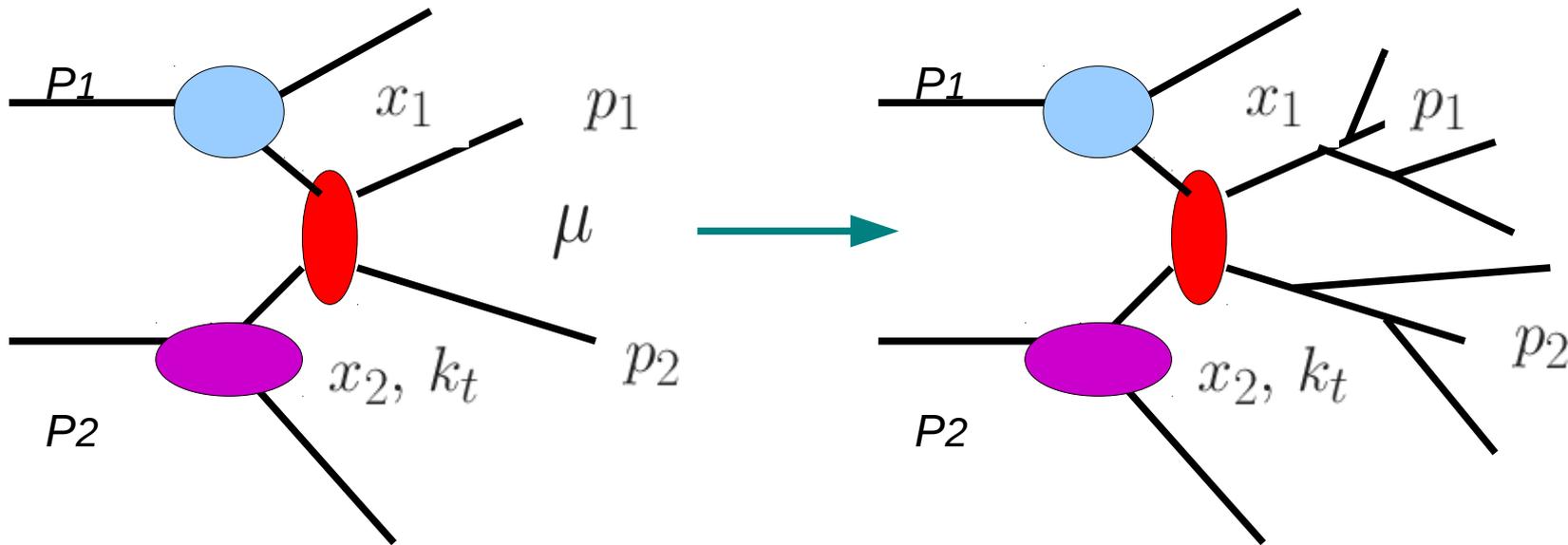


$$R_{\gamma A} = \frac{d\sigma_{AA}^{\text{UPC}}}{A d\sigma_{Ap}^{\text{UPC}}}$$

Nuclear modification factor - p_T spectra



Other relevant effects – Final State Radiation



Final state emissions and hadronization.

Work in progress with IFJ PAN team: Bury, Jung, van Hameren, Sapeta, Serino

Conclusions and outlook

- *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*
- *Update the pdfs used.*
- *Include FSR, hadronization*