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NCN

Aspects of forward di-jet production at the LHC

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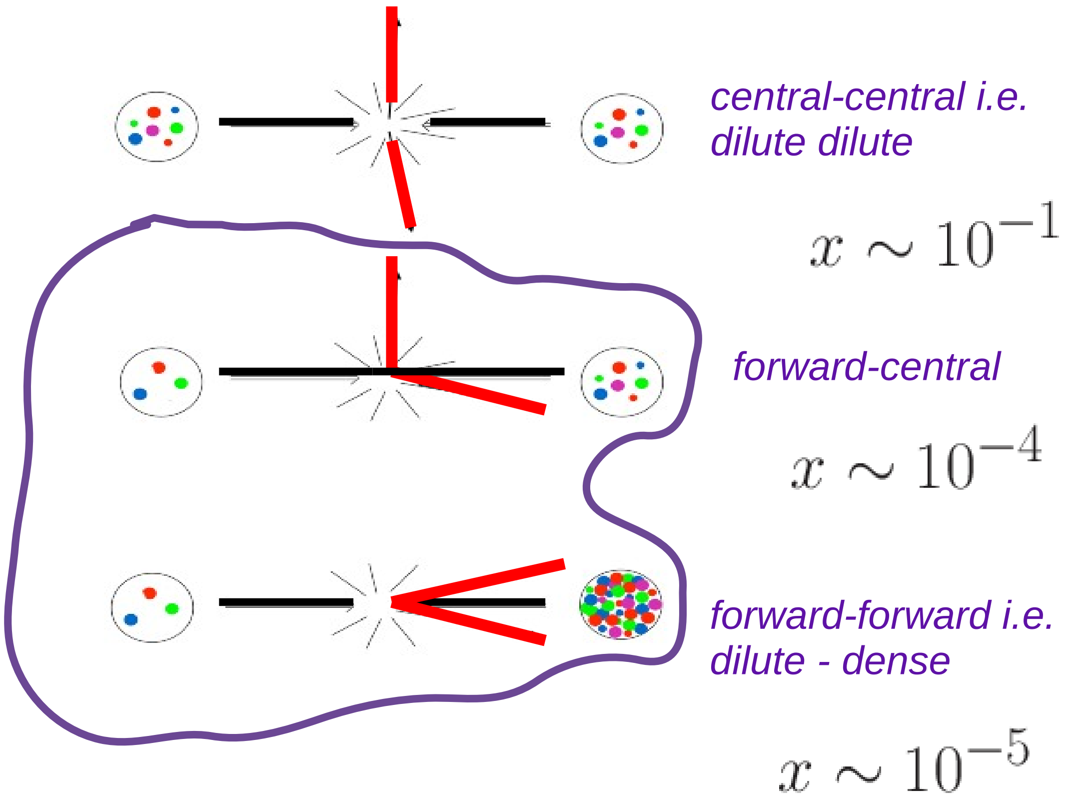
Polskiej Akademii Nauk

Why jets?

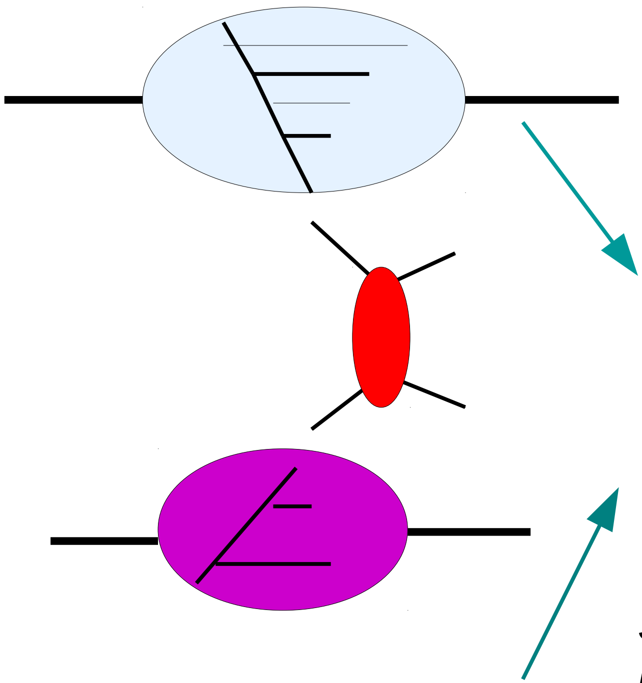
- *jets are direct manifestation of partonic structure of hadrons*
- *jets are challenging to get good description of their properties and especially to find saturation*
- *Tomography of QGP*
- *One can test different types of PDFS*
- *γ A → 2 jets is sensitive to the Weizsacker-Williams (WW) unintegrated gluon distribution (UGD), whereas other processes like J /ψ or inclusive jets are sensitive to the dipole UGD*
- *pA → 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*

LHC and tomography of partons → di-jet example



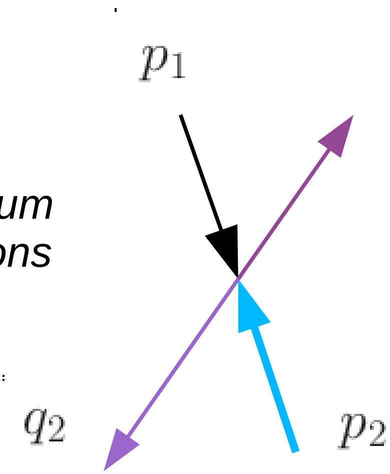
From Cyrille Marquet

hybrid High Energy Factorization

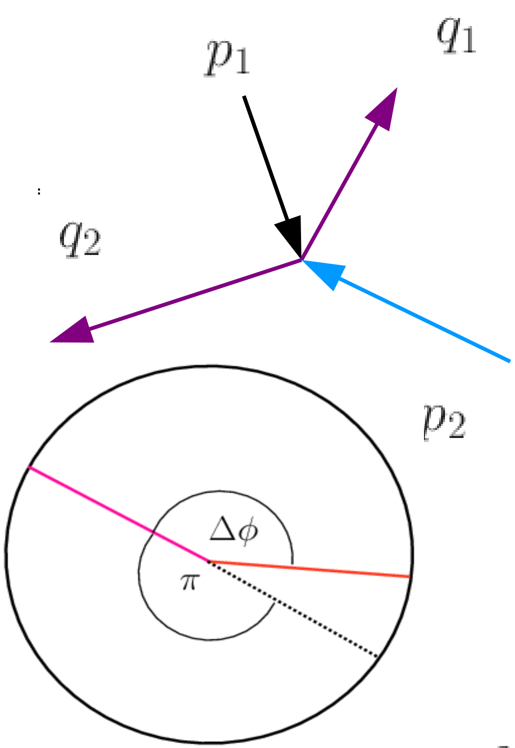


Strongly decreasing transversal momentum of DGLAP like partons

Strongly decreasing Longitudinal momentum fractions of off-shell partons



$$p_1 + p_2 = q_1 + q_2$$

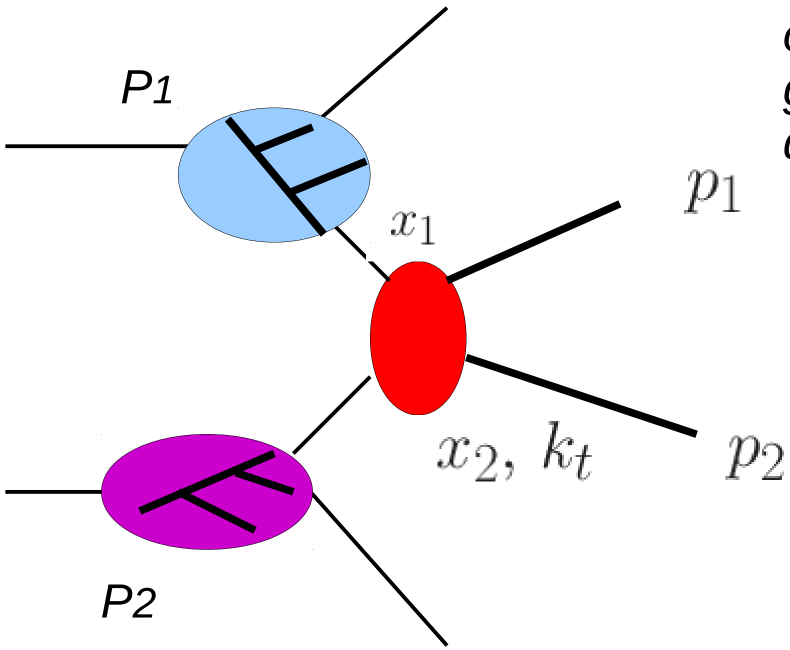


$$p_1 + p_2 = q_1 + q_2 + k$$

First attempt: hybrid factorization and dijets

$$\frac{d\sigma^{P_1P_2\to \text{dijets}+X}_{\text{SPS}}}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \frac{p_{1t}p_{2t}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/P_1}(x_1,\mu^2)\,|\overline{\mathcal{M}_{ag^*\to cd}}|^2 \quad \mathcal{F}_{g/P_2}(x_2,k_t^2)\frac{1}{1+\delta_{cd}}$$

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

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

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 → partons carry some k_t

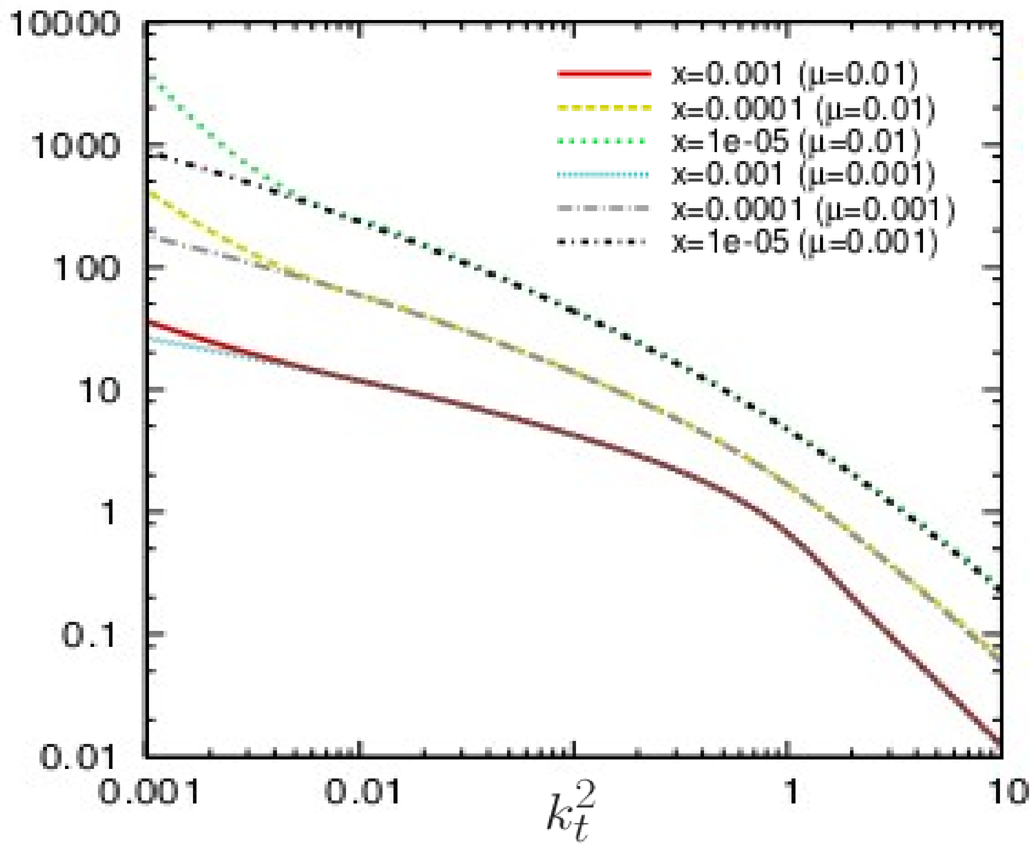
$k_t << P_t$ Collinear Factorization → partons in one of hadrons are just collinear with hadron
k_t is neglected

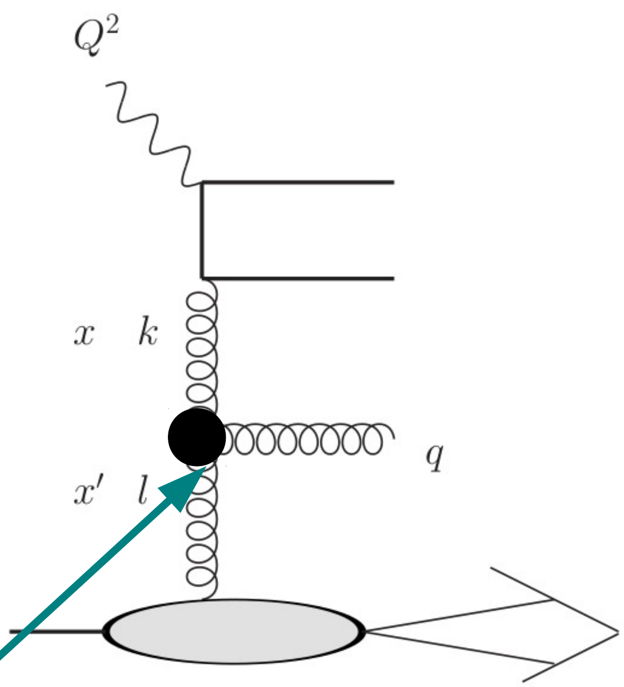
$Q_s \sim k_t << P_t$ generalized Transverse Momentum Dependent Factorization → rescatterings
formal treatment of nonlinearities but does not allow for calculation of decorelations

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

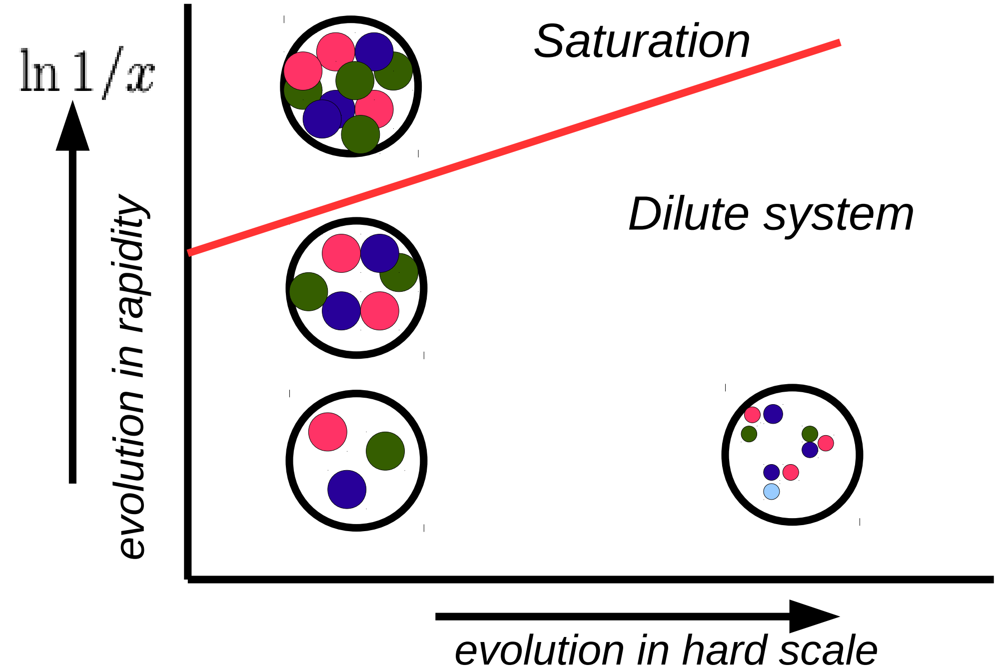




$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F}$$

High energy factorization and saturation

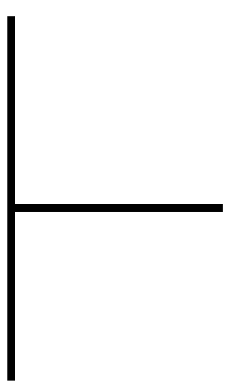
Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.



On microscopic level it means that gluon apart splitting recombine

splitting

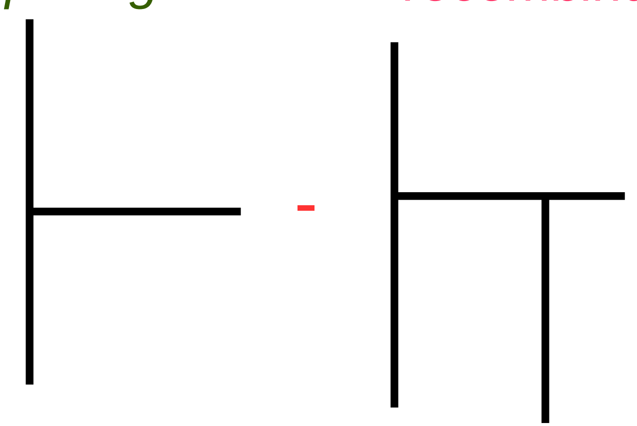
Linear evolution equation



Nonlinear evolution equations

splitting

recombination



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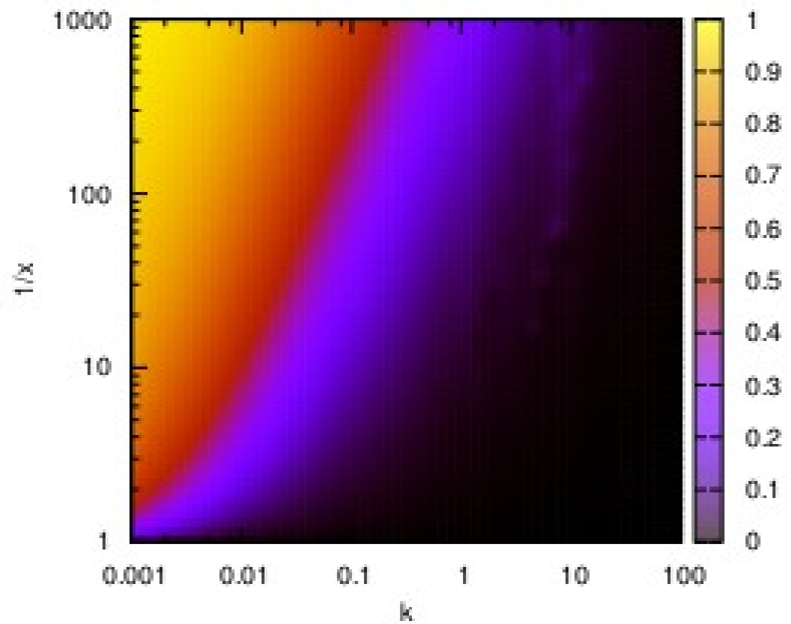

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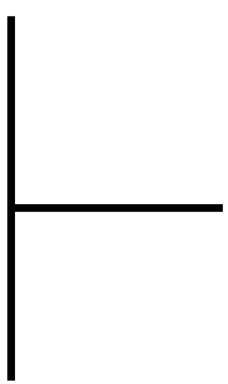
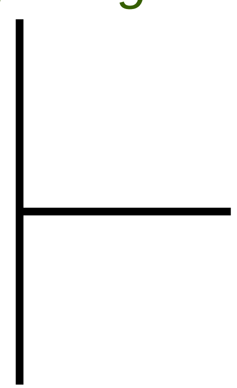


Linear evolution equation

splitting

recombination

Nonlinear evolution equations



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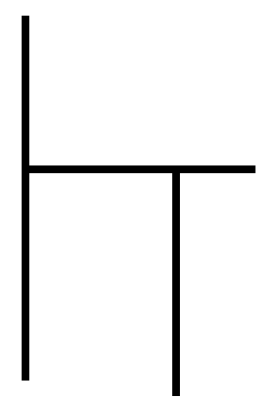
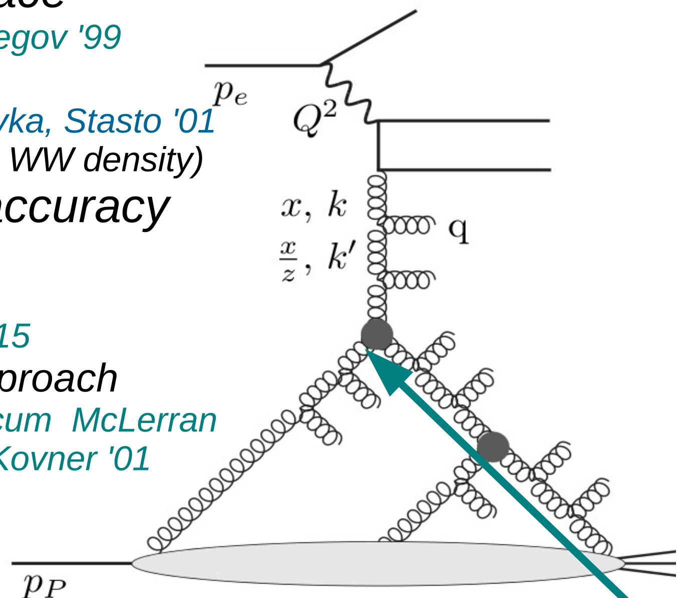
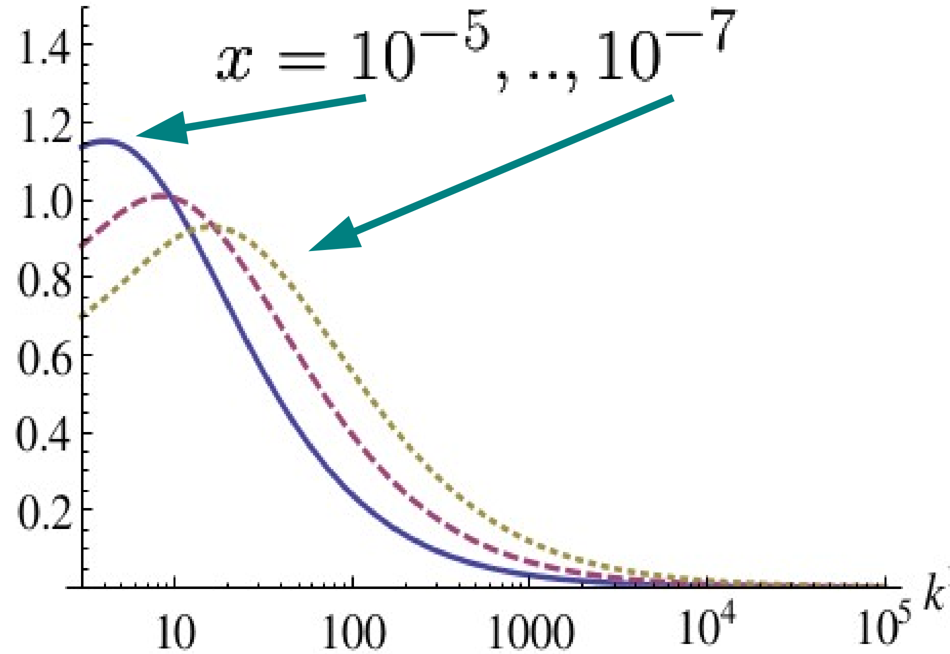


The saturation problem: supressing gluons at small k_t

Originally formulated in coordinate space
Balitsky '96, Kovchegov '99
first solved
Golec-Biernat, Motyka, Stasto '01
(momentum space, WW density)
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

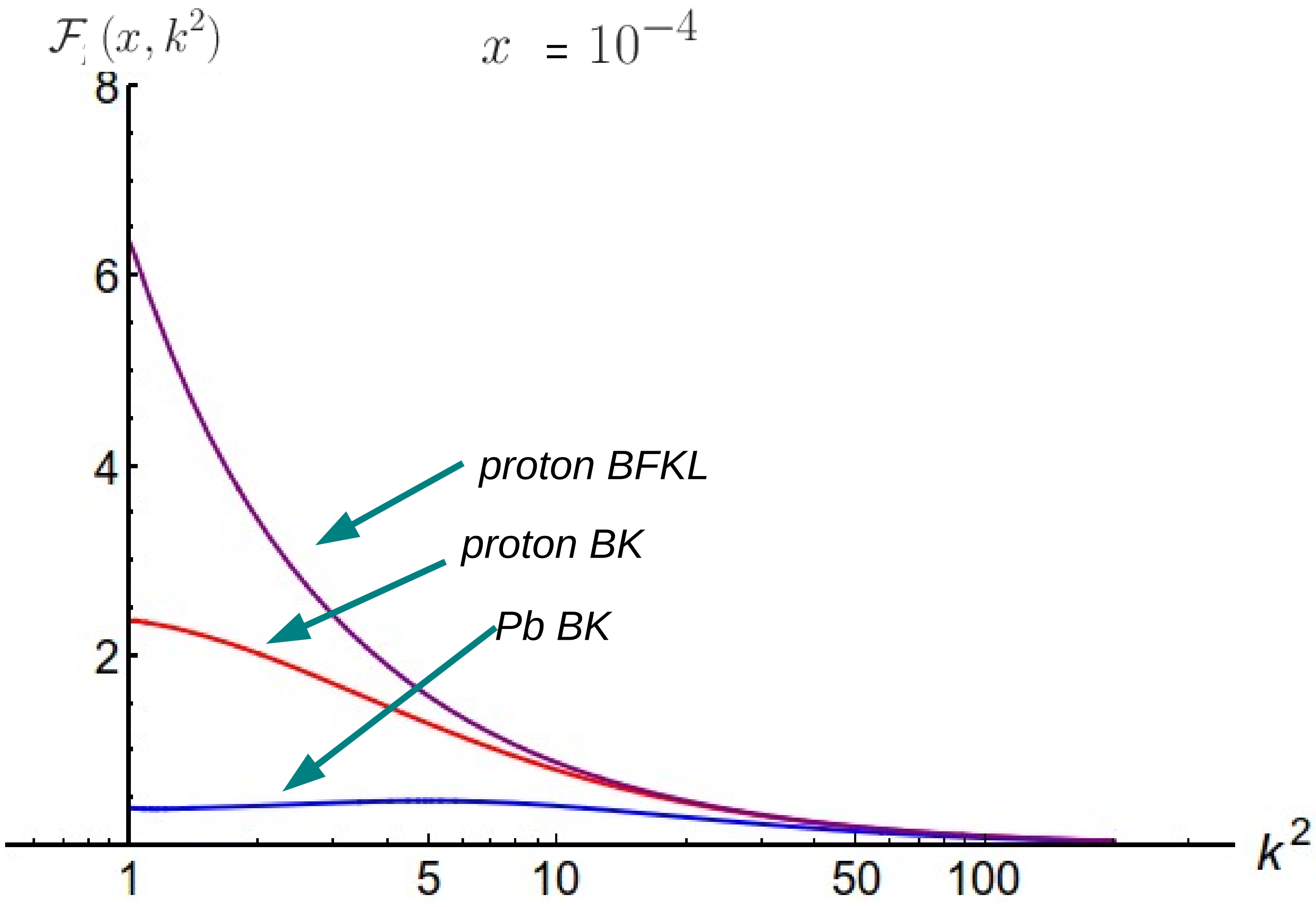
$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} - \frac{1}{R^2} V \otimes \mathcal{F}^2$$

Momentum space

Kwiecinski, Kutak '02
Nikolaev, Schafer '06

hadron's radius

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



Numerical clculations

Parton densities

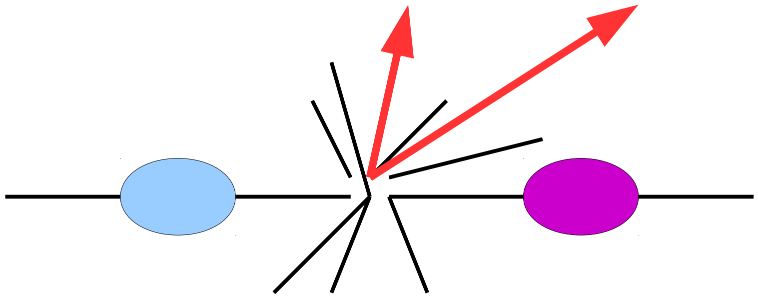
KS (Kutak-Sapeta) nonlinear → gluon density from extension of momentum space version of BK equation to include:
- *kinematical constraint*
- *complete splitting function,*
- *running coupling*
- *quarks*

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

KMRW (Kimber, Martin Ryskin, Watt) → full set of pdfs obtained fron unfolding collinear pdfs and imposing angular ordering. LO and NLO formulation available

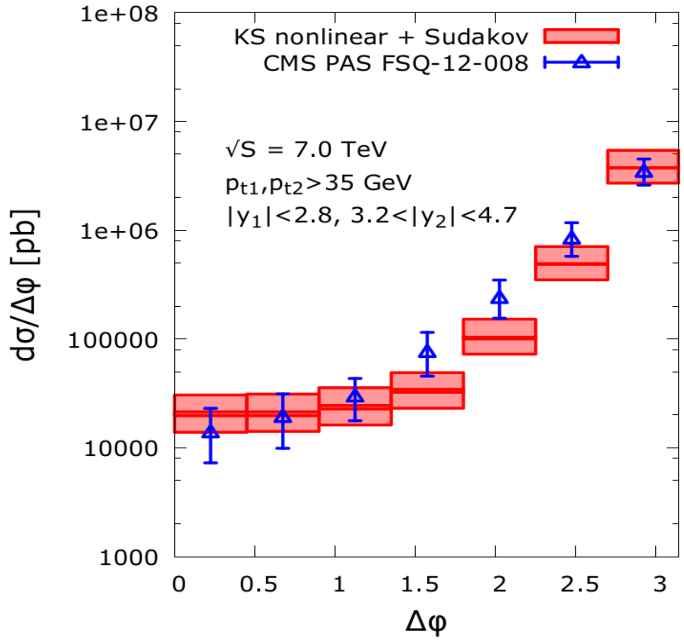
Monte Carlo KaTie by Andreas van Hameren, *arXiv:1611.00680*
- *complete Monte Carlo program for tree-level calculations in HEF (at present)*
- *any process within the Standard Model*
- *any initial-state partons on-shell or off-shell*
- *employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes*
- *automatic phase space optimization*

Central-forward di-jets



Decorelations inclusive scenario forward-central

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

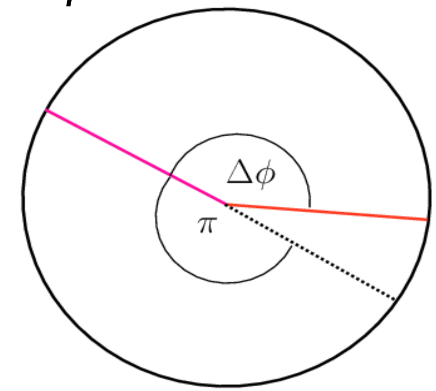


$$p_{t1},\, p_{t2} > 35\, GeV$$

$$3.2 < |y_2| < 4.7$$

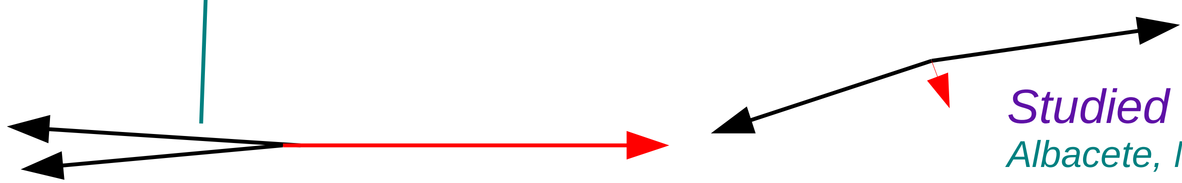
$$|y_1| < 2.8$$

Leading jets, no further requirement



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

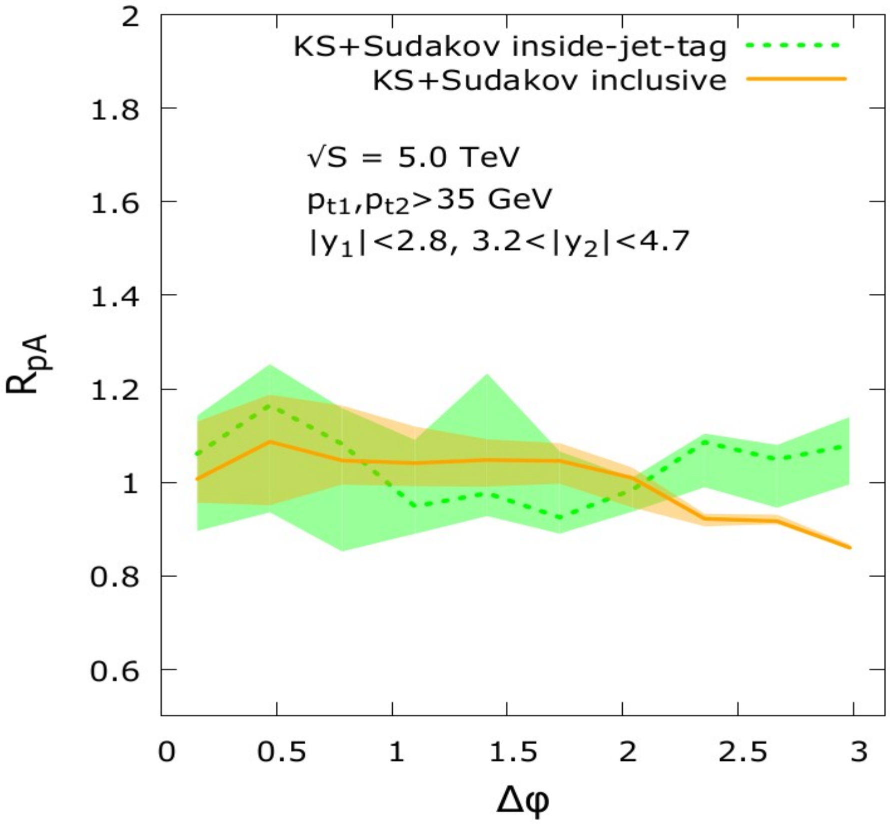
Observable suggested to study BFKL effects
Sabio-Vera, Schwensen '06



Studied also context of RHIC
Albacete, Marquet '10

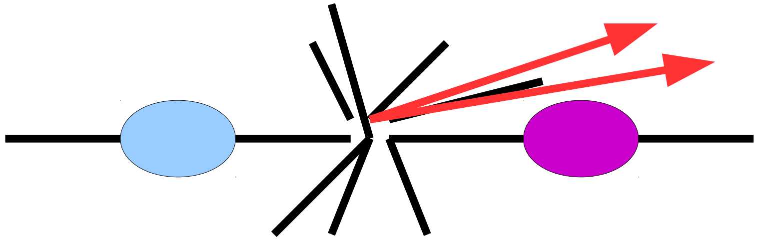
Predictions for p-Pb for forward-central

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



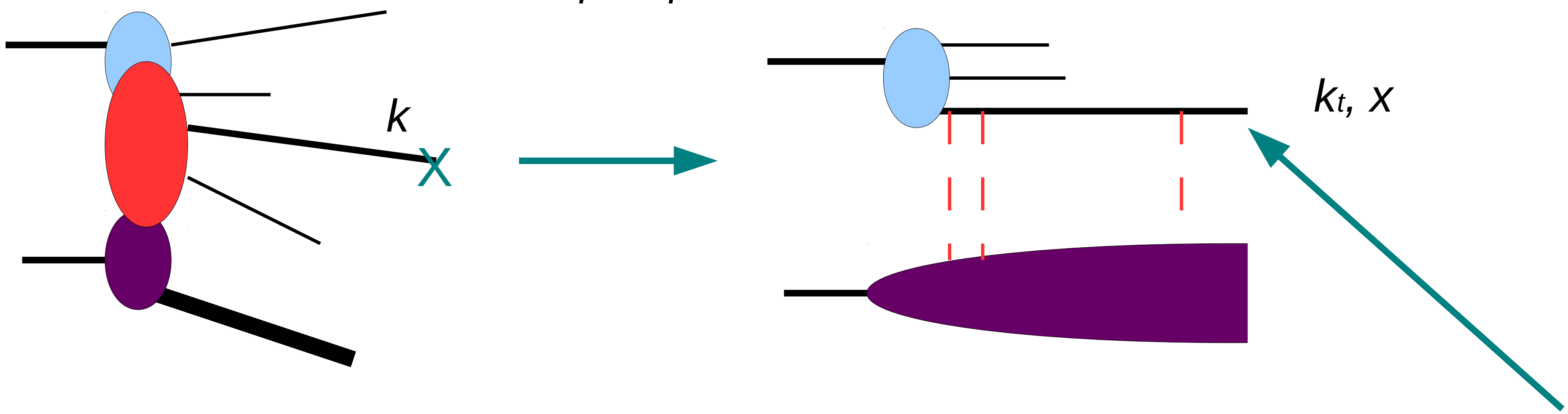
saturation effects are rather weak for forward-central jets

Forward-forward di-jets



Dipole gluon density

In dipole picture



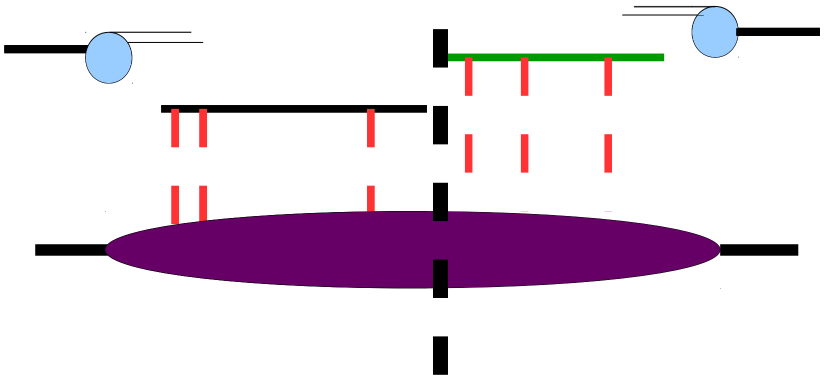
initial state $t = -\infty$

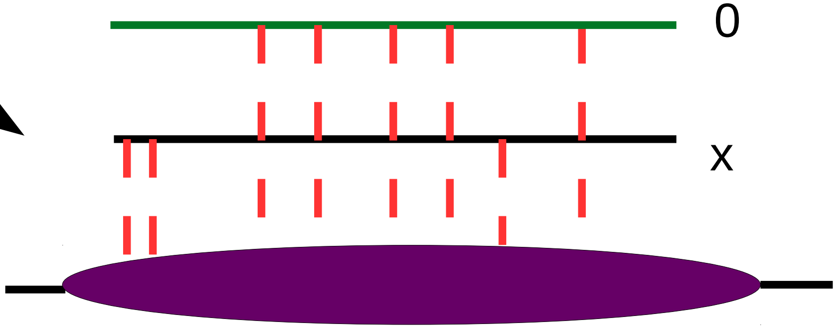
final state $t = \infty$

Wilson line U_x

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.

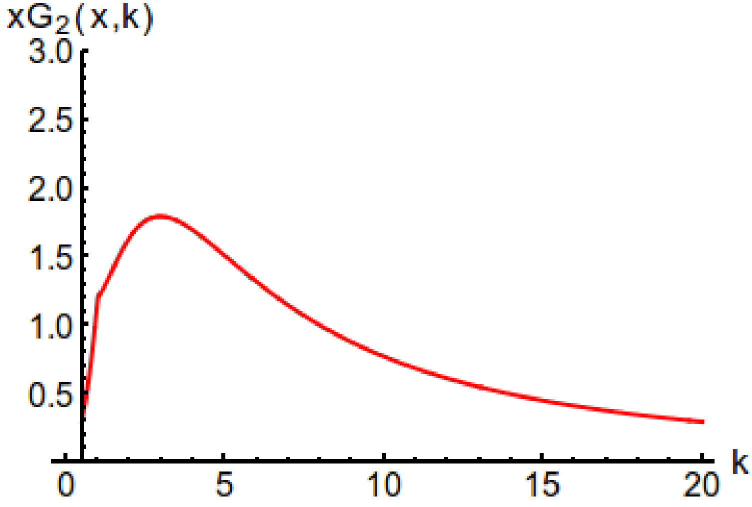
$$\mathcal{F}(x, \mathbf{k}_t^2) \propto \mathbf{k}_t^2 \int \frac{d^2\mathbf{x}}{(2\pi)^2} e^{-i\mathbf{k}_t \cdot \mathbf{x}} S(x, \mathbf{x})$$

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*

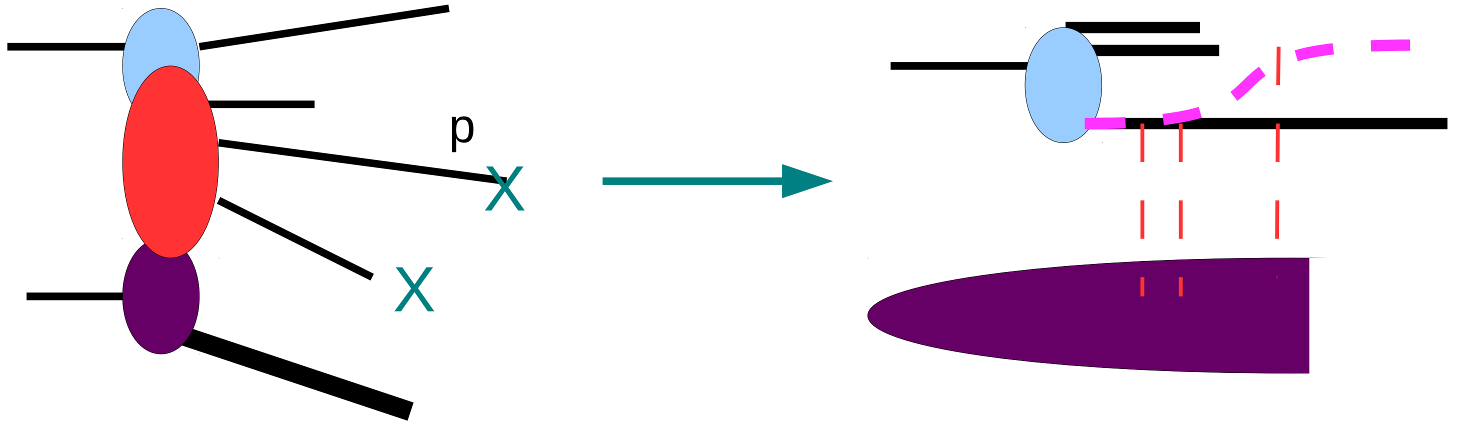
- *One can write BK equaion in the momentum space which as a solution gives dipole gluon density*



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

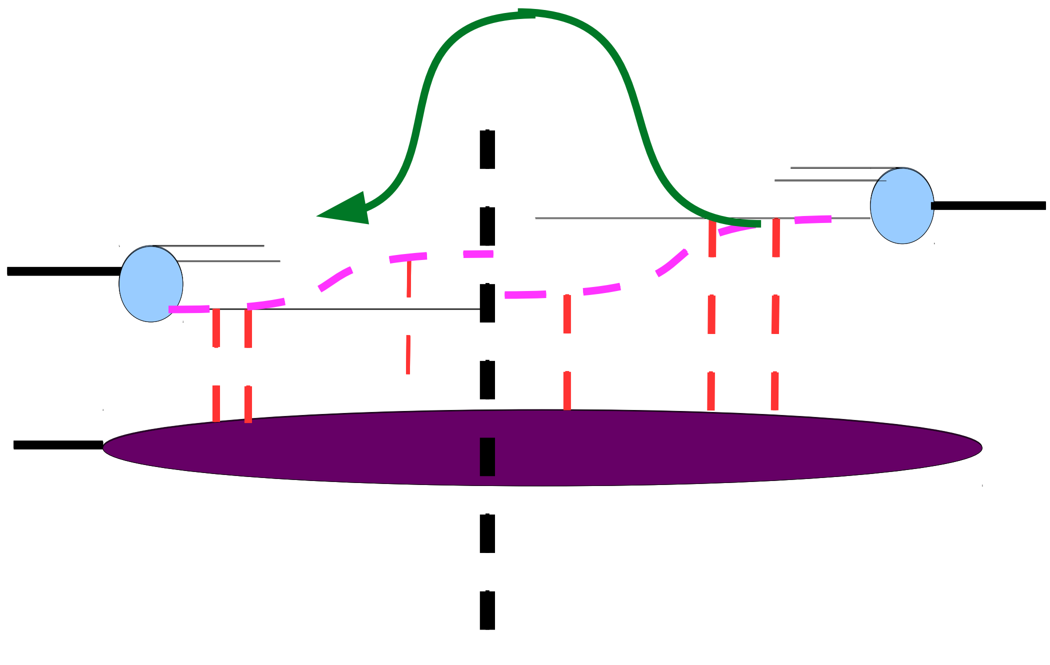
$$xG^{(1)}(x, \mathbf{k}_t^2) \equiv \mathcal{F}(x, \mathbf{k}_t^2)$$

Weizacker-Williams gluon density

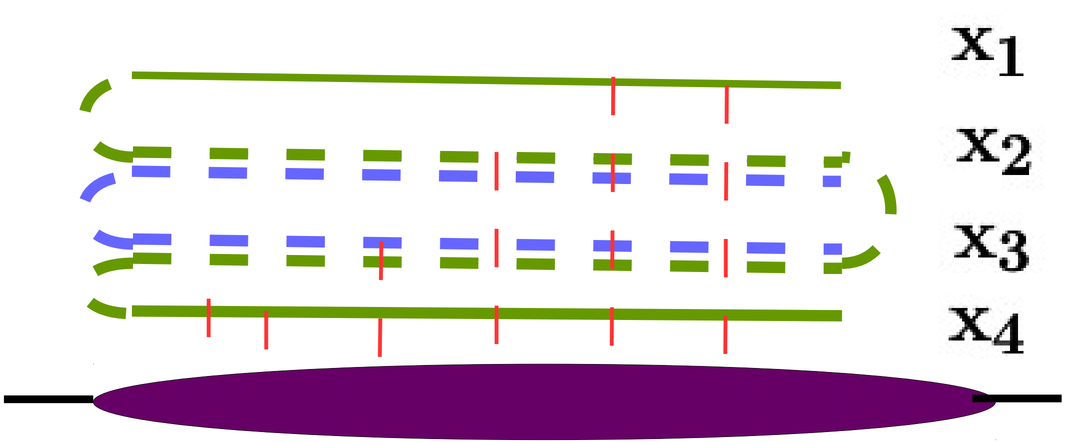


Double inclusive production $q + g \to gq$

Weizacker-Williams gluon density



Large number of color limit



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

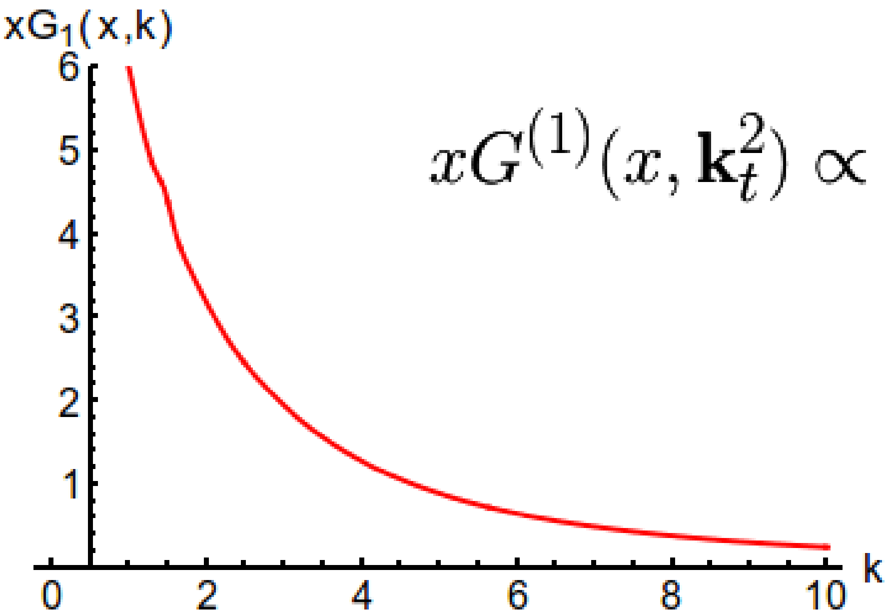
$$Q \propto \langle Tr(U^\dagger(x_1)U(x_2)U^\dagger(x_3)U(x_4))\rangle$$

Weizacker-Williams gluon density

- Can be determined from dijet productionin 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



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

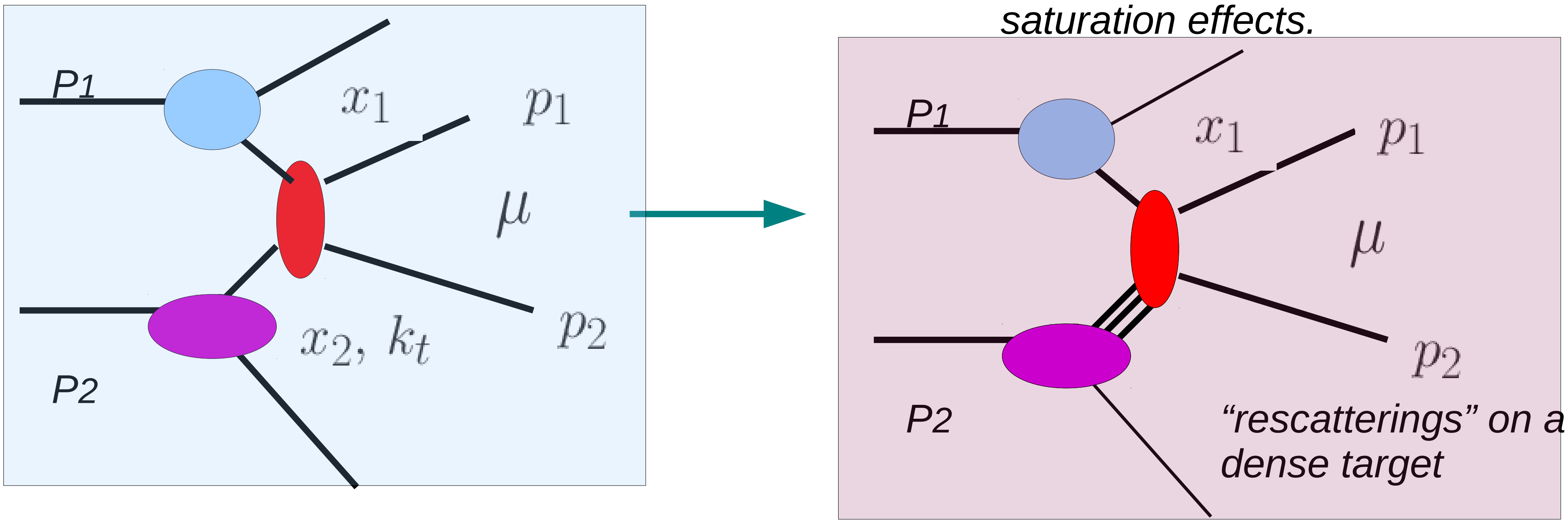
In approximation

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

Improved TMD for dijets

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

can be be used for estimates of saturation effects.



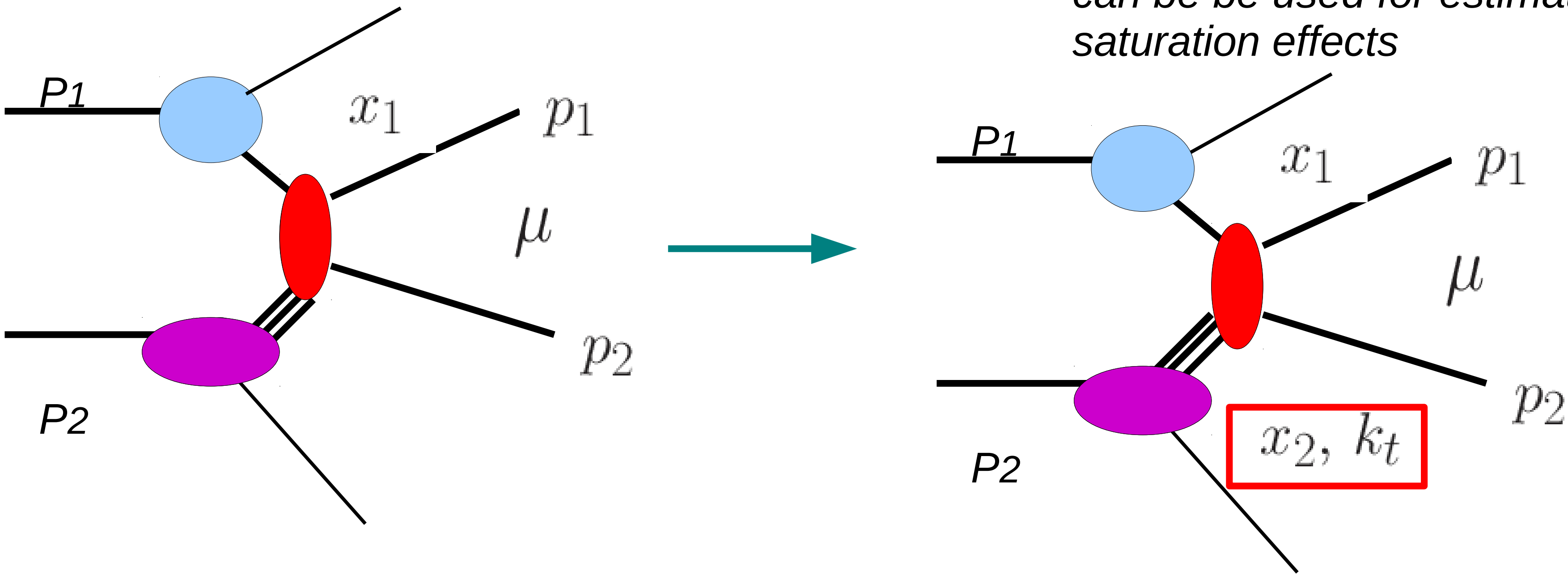
Generalization but no possibility to calculate decorelations since no kt in ME so called correlation limit
Dominguez, Marquet, Xiao, Yuan '11

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

$$\frac{d\sigma^{pA\to cdX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\, x_1 f_{q/p}(x_1,\mu^2)\sum_{i=1}^{n}\mathcal{F}_{ag}^{(i)} H_{ag\to cd}^{(i)}\frac{1}{1+\delta_{cd}}$$

Improved TMD for dijets

can be be used for estimates of saturation effects



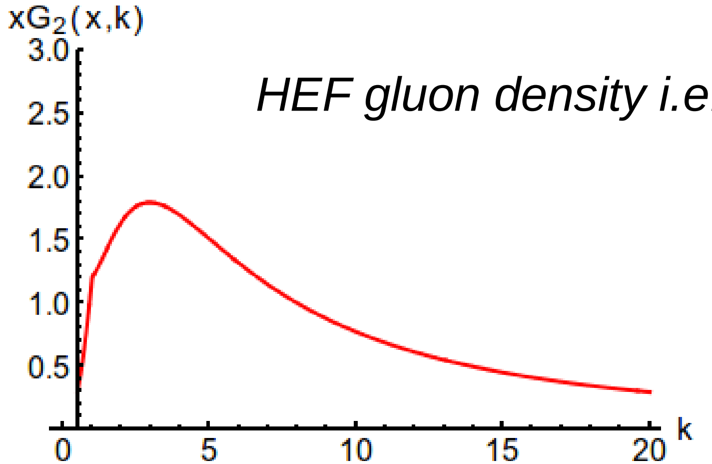
We found a method to include kt in ME and express the factorization fprmula in terms of gauge invariant sub amplitudes → more direct relation to two fundamental gluon densities: dipole gluon density and Weizacker-Williams gluon density

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

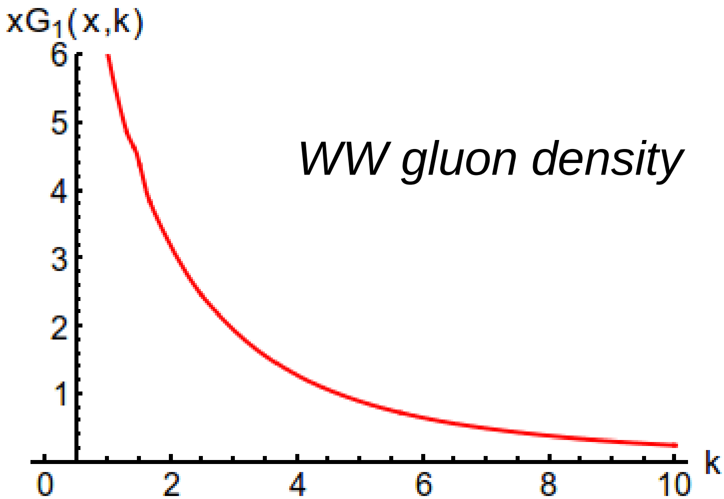
$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2)\sum_{i=1}^{2} K^{(i)}_{ag^*\to cd}\Phi^{(i)}_{ag\to cd}\,\frac{1}{1+\delta_{cd}}$$

Glimpse on the first results – HEF vs. ITMD

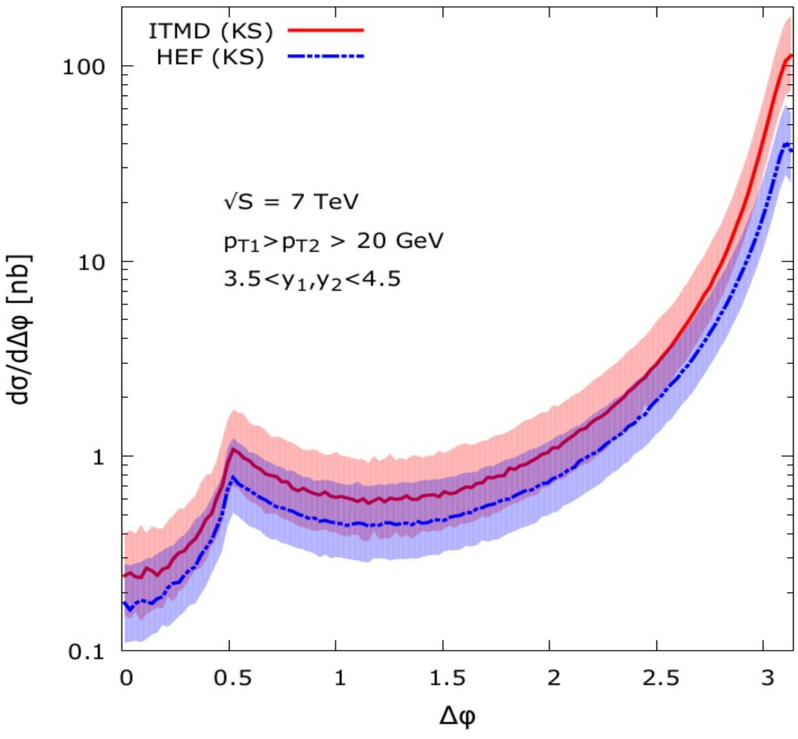
Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren '16



HEF gluon density i.e. dipole UGD



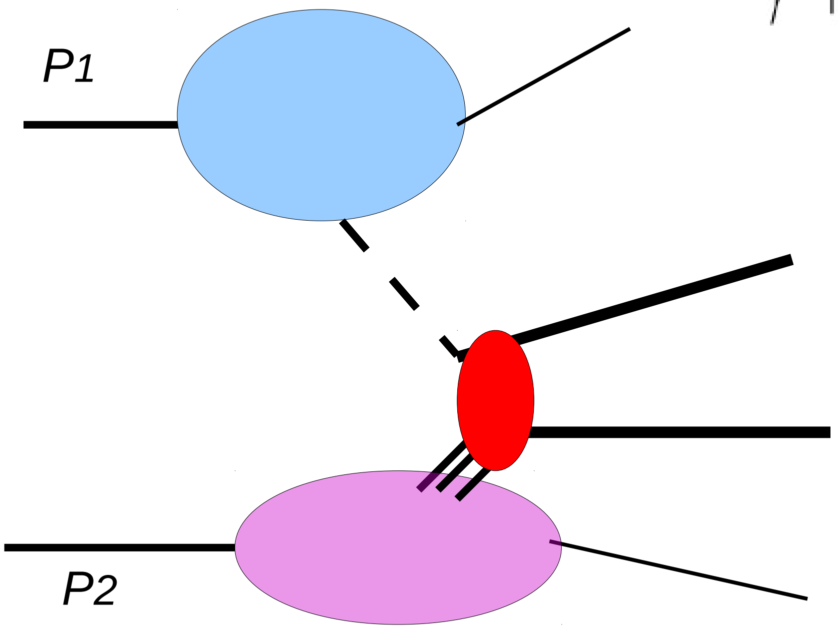
WW gluon density

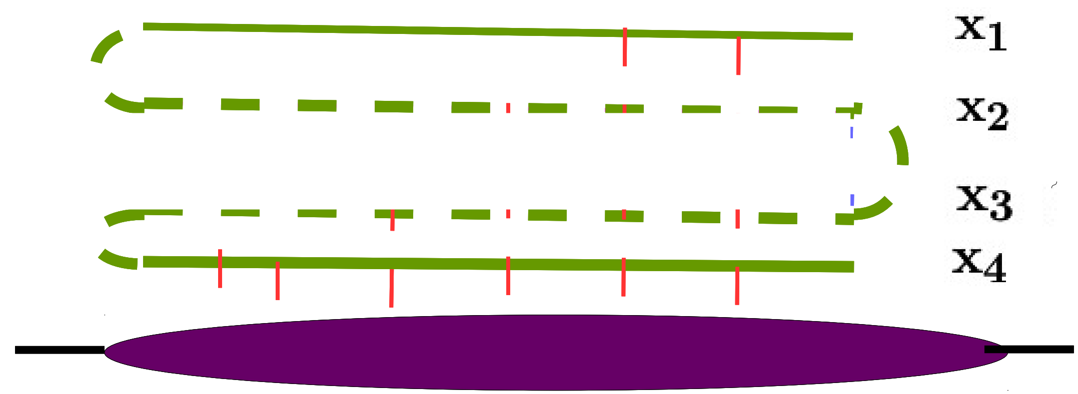


In large Nc on can express WW UGD in terms of dipole UGD. We use this approximation

UPC collision of Pb-Pb

$$\gamma + g \to \bar{q}q$$





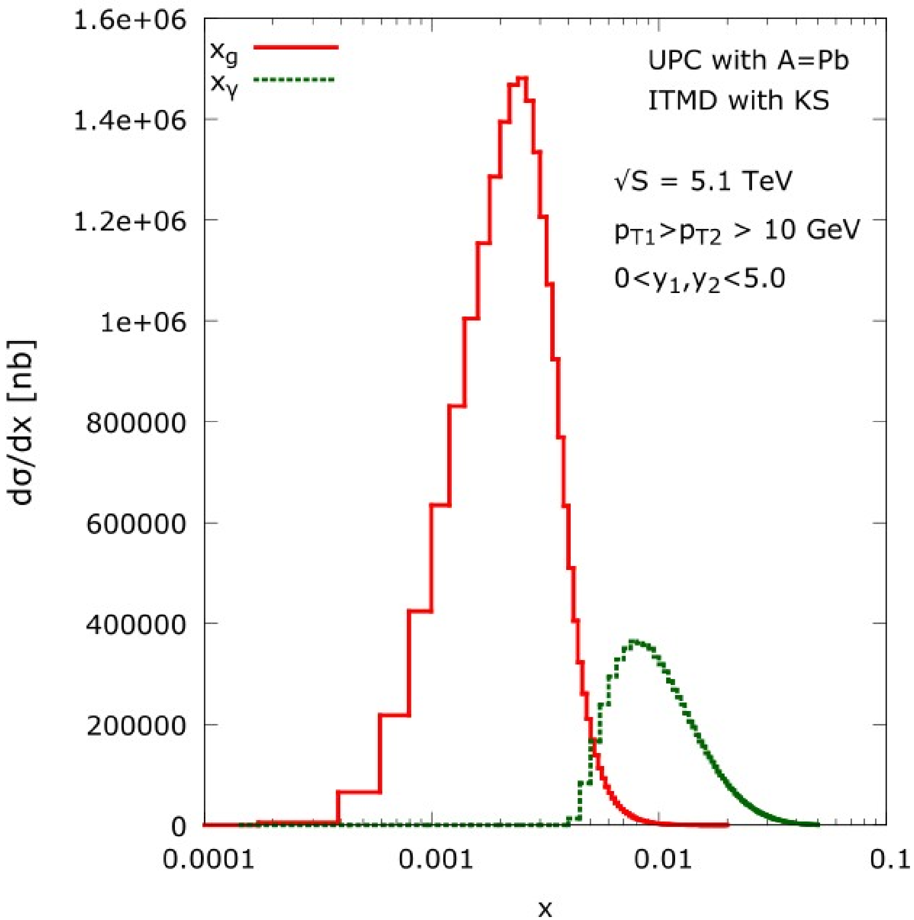
$$d\sigma_{AA\to 2jet+X} = \int dx_\gamma \frac{dN_\gamma}{dx_\gamma} d\sigma_{\gamma A\to 2jet+X}$$

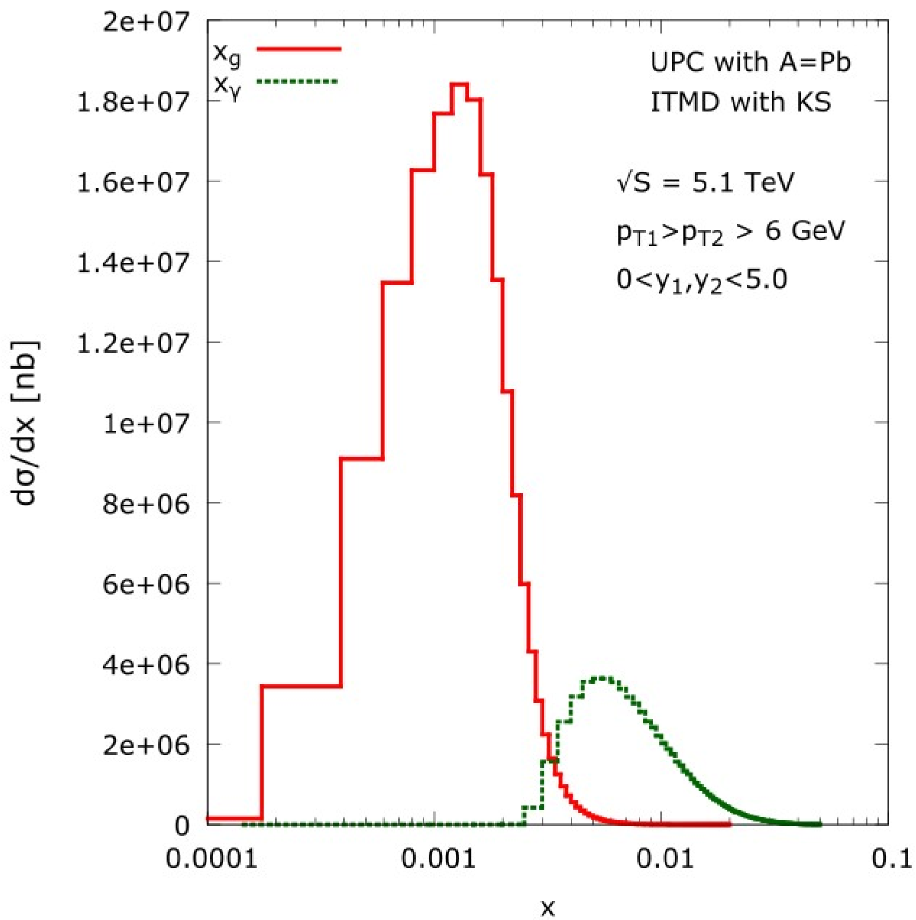
$$\frac{d\sigma_{\gamma A\to 2j}}{dy_1 d^2p_{T_1} dy_2 d^2 p_{T_2}} \sim x_A G_1(x_A, k_T^2) \otimes K_{\gamma g^*\to q\bar{q}}(k_T)$$

Kotko, Kutak, Sapeta, Stasto, Strikman '16

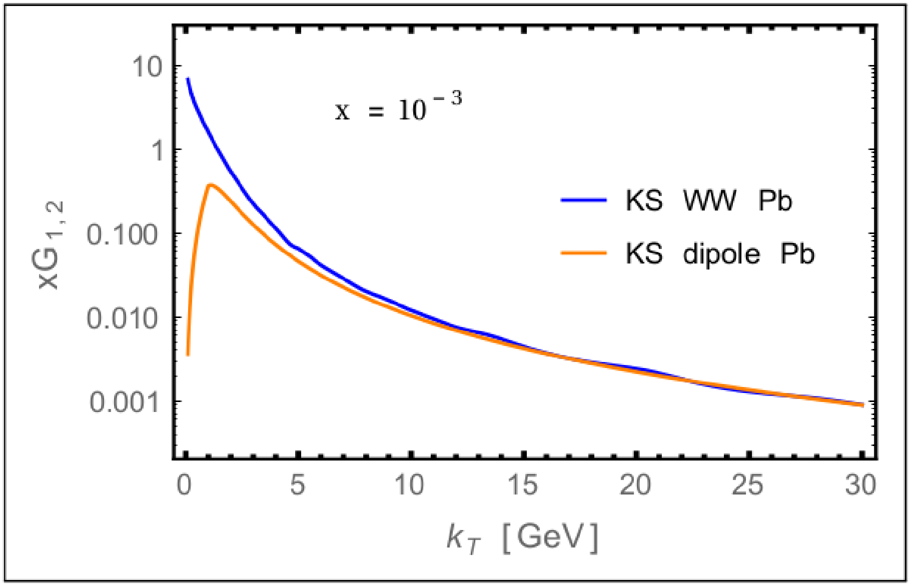
Longitudinal momentum fraction distributions – different cuts scenario

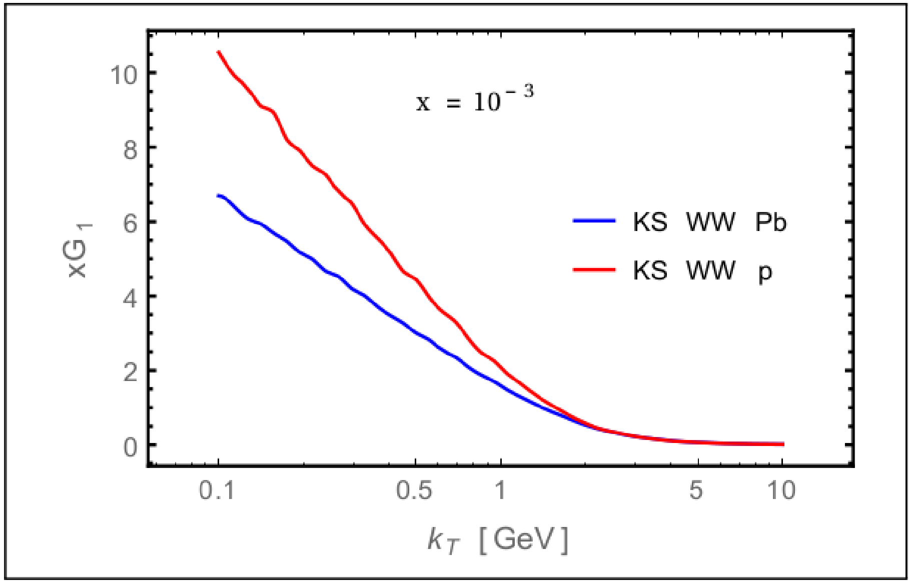
Kotko, Kutak, Sapeta, Stasto, Strikman '16

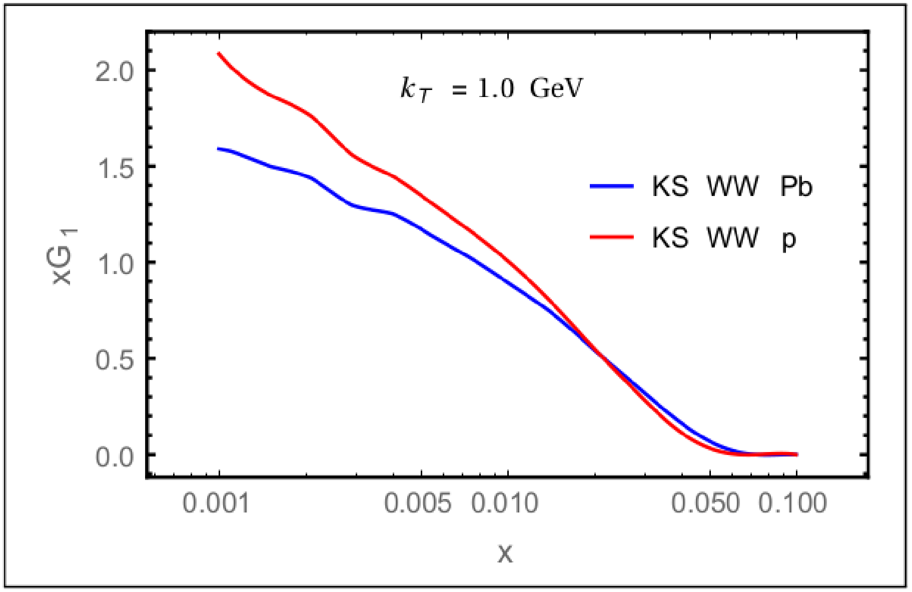


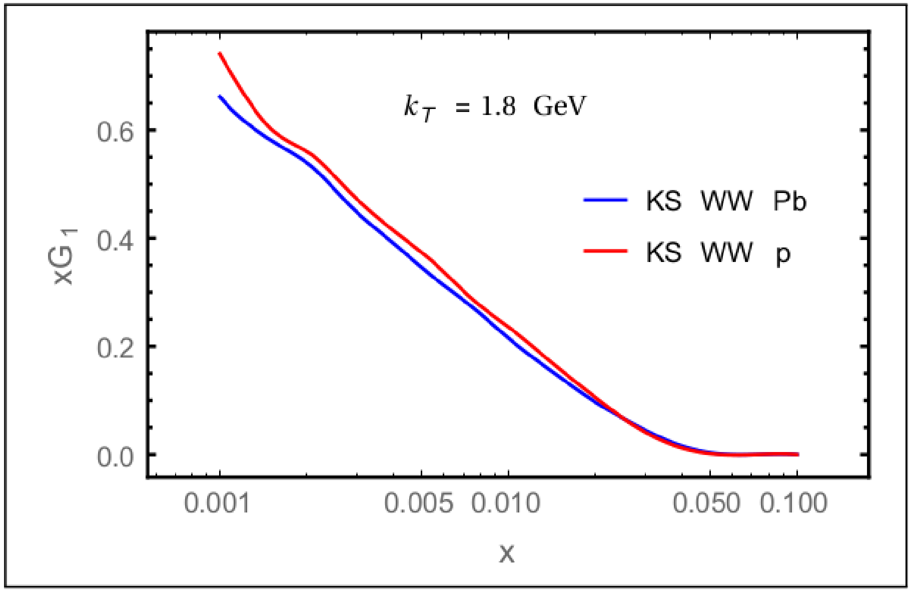


WW vs. dipole gluon density

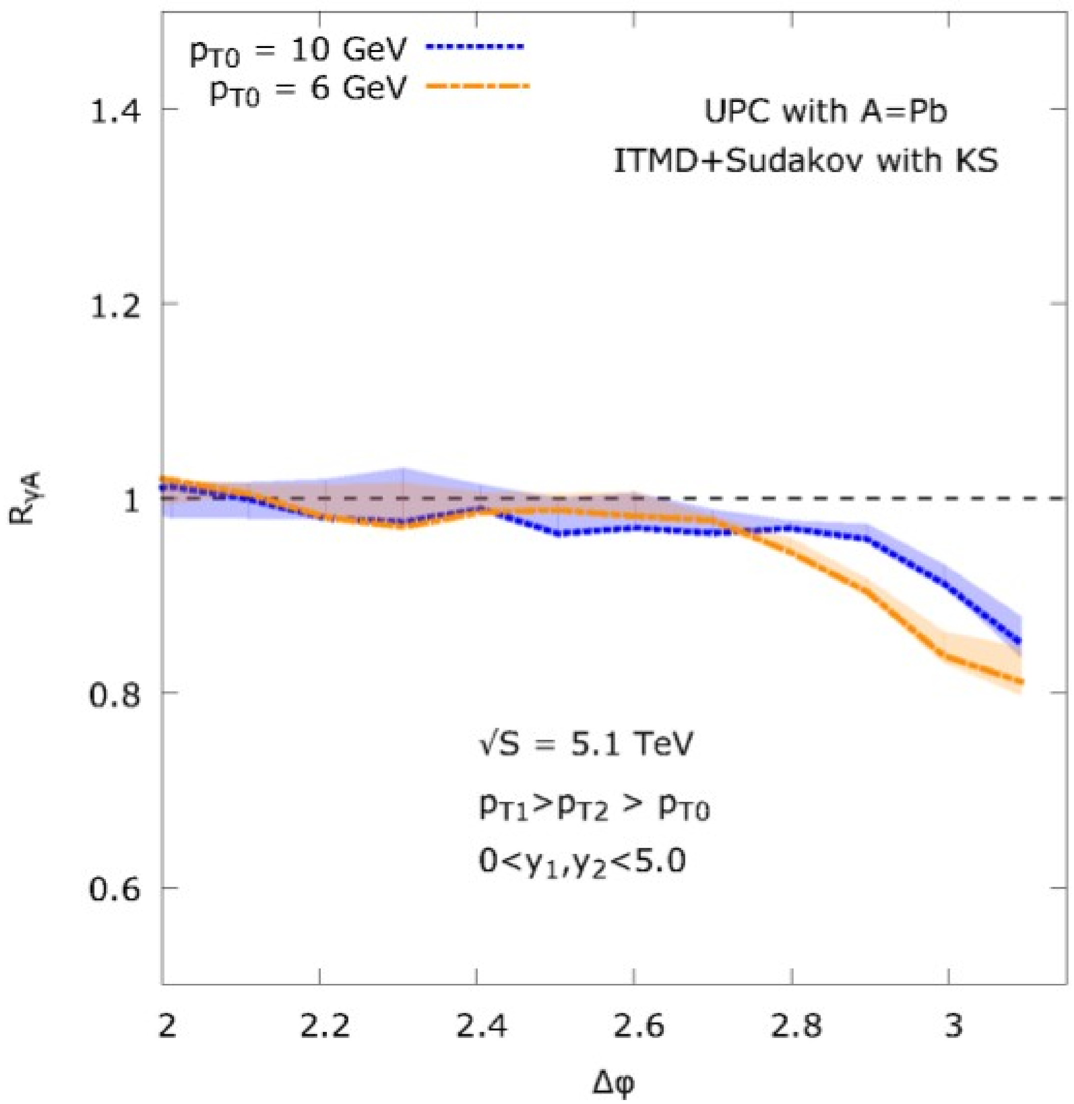






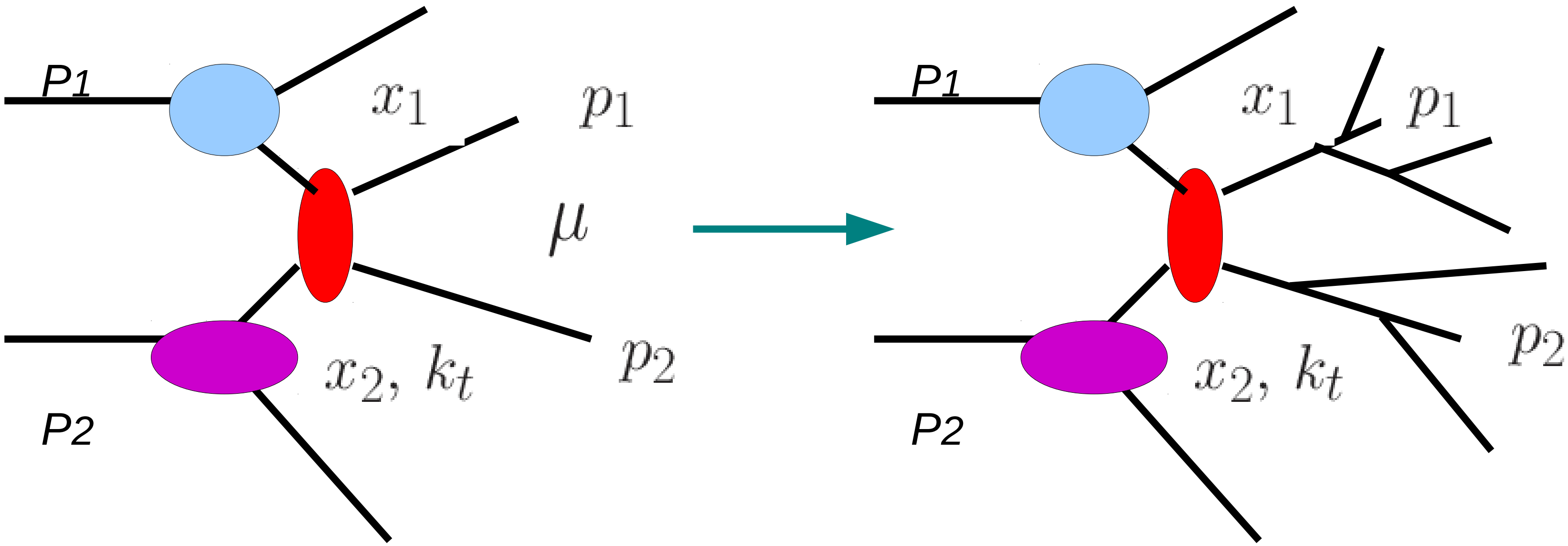


Nuclear modification factor - azimuthal decorelations



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

Other relevant effects – Final State Radiation



Final state emissions and hadronization.

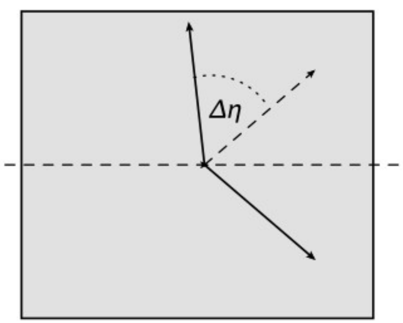
Work in progress with IFJ PAN team: Bury, Jung, van Hameren, Sapeta, Serino

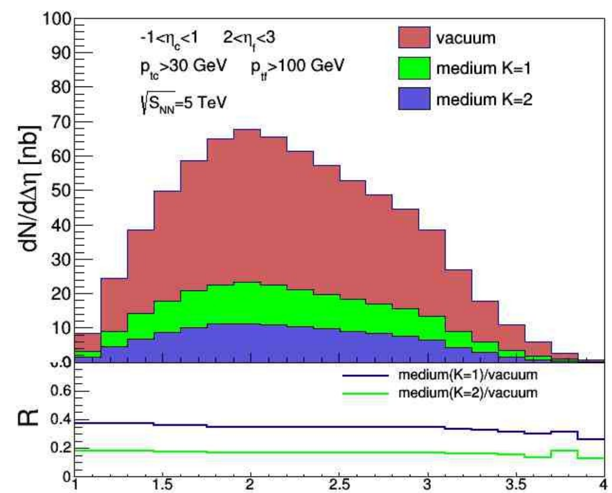
Jets in Pb-Pb using HEF

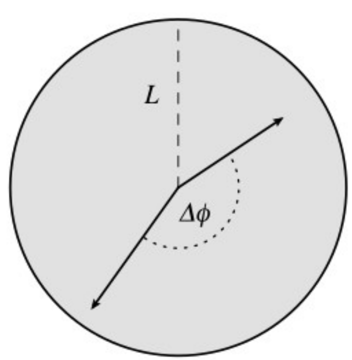
Deak, Kutak, Tywoniuk 1706.08434

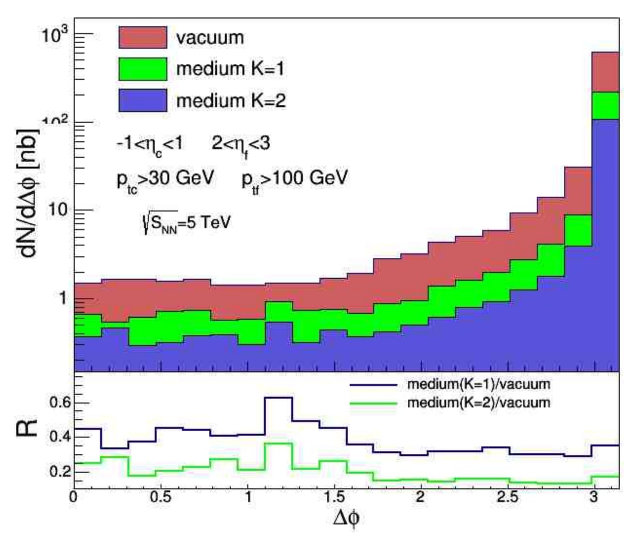
$$\frac{d\sigma}{dy_1 dy_2 dp_{t1} dp_{t2} d\Delta\phi} = \sum_{a,c,d} \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 \, P_a(\epsilon_1) P_g(\epsilon_2) \left. \frac{d\sigma_{acd}}{dy_1 \mathrm{d}y_2 dp'_{t1} dp'_{t2} d\Delta\phi} \right|_{\substack{p'_{1t}=p_{1t}+\epsilon_1 \\ p'_{2t}=p_{2t}+\epsilon_2}}$$

quenching wights | *vacuum Pb-Pb scattering*









Conclusions and outlook

- *New framework ITMD for calculations of forward dijets has been developed*
- *The framework is applicable for UPC collisions too*
- *It seems that saturation effects are relevant for forward-forward jet configuration*
- *New Monte Carlo tool has been developed KaTie. It allows for calculation of any process in SM with exact kinematics and low x resummation.*

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