Predictions for saturation in forward final states at the LHC

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NCN

The results are based on

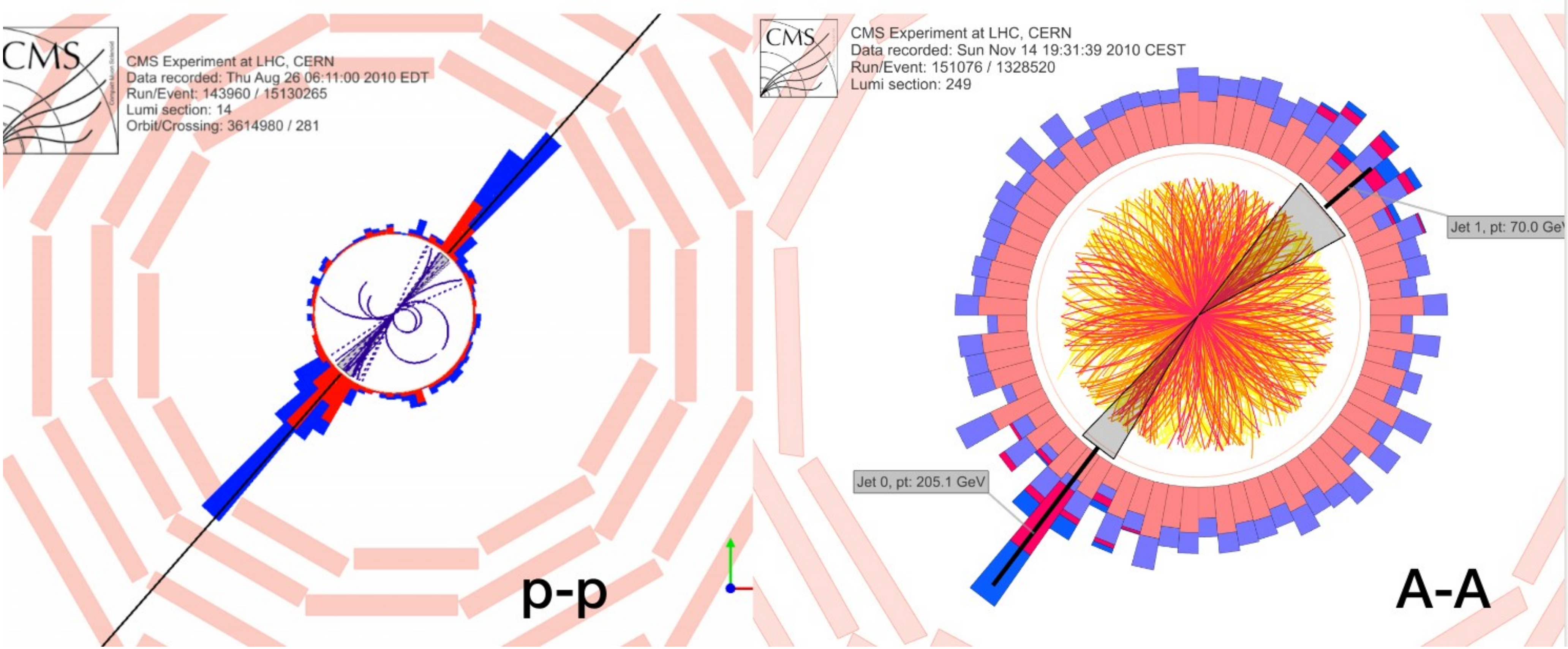
JHEP12(2022)131
M. Abdullah Al-Mashad, A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, P. Van Mechelen, S. Sapeta

Eur. Phys. J. C 83, 947 (2023)
A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, S. Sapeta

Eur. Phys. J. C 83 (2023)
I. Ganguli, A. van Hameren, P.Kotko, K. Kutak

2409.06675
S. Adhya, K. Kutak, W. Płaczek, M. Rohrmoser, K. Tywoniuk

Vacuum and medium processes



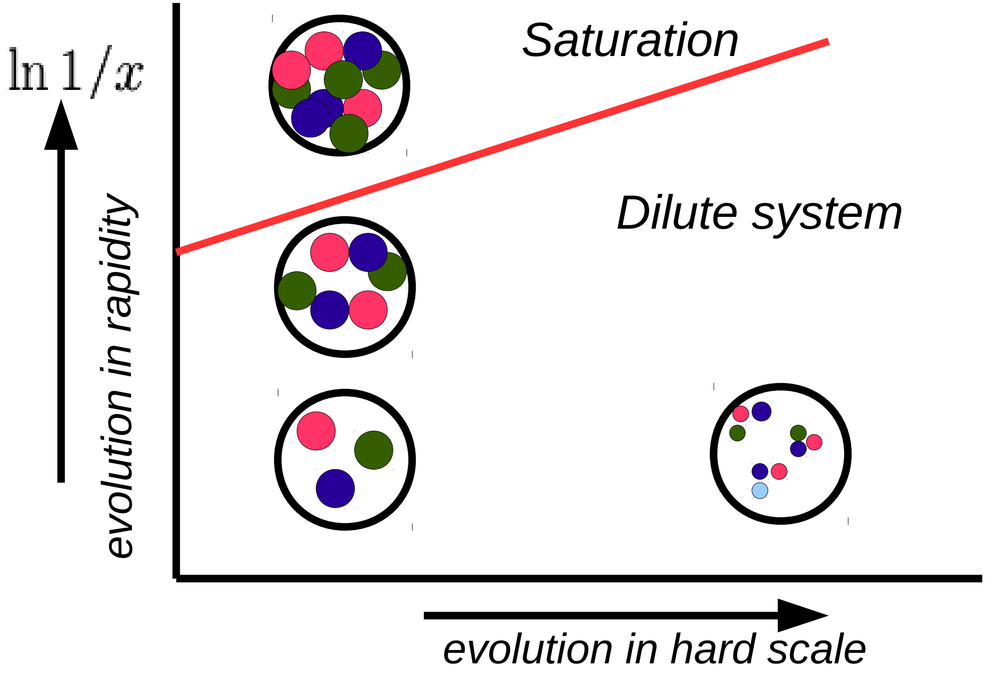
and **p - Pb**

Gluons at high energies

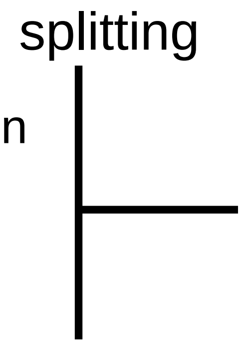
Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.

L.V. Gribov, E.M. Levin, M.G. Ryskin
Phys.Rept. 100 (1983) 1-150

Larry D. McLerran, Raju Venugopalan
Phys.Rev. D49 (1994) 3352-3355



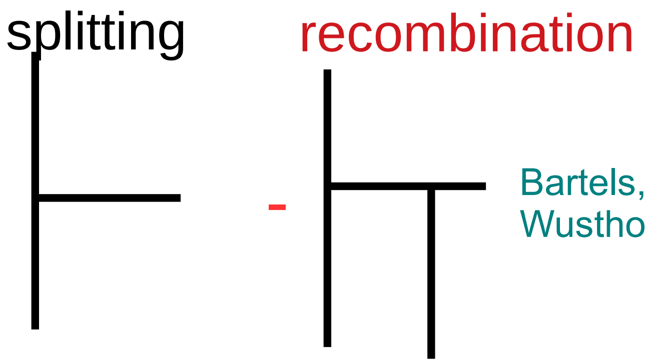
On microscopic level it means that
gluon apart splitting recombine



Linear evolution
Equation
BFKL

Nonlinear evolution equations
BK, JIMWLK
Balitcky-Kovchegov,

Jailian-Marian,Iancu
McLerran,Weigert,Leonidov,Kovner



Bartels,
Wusthoff ‘93

Gluons at high energies

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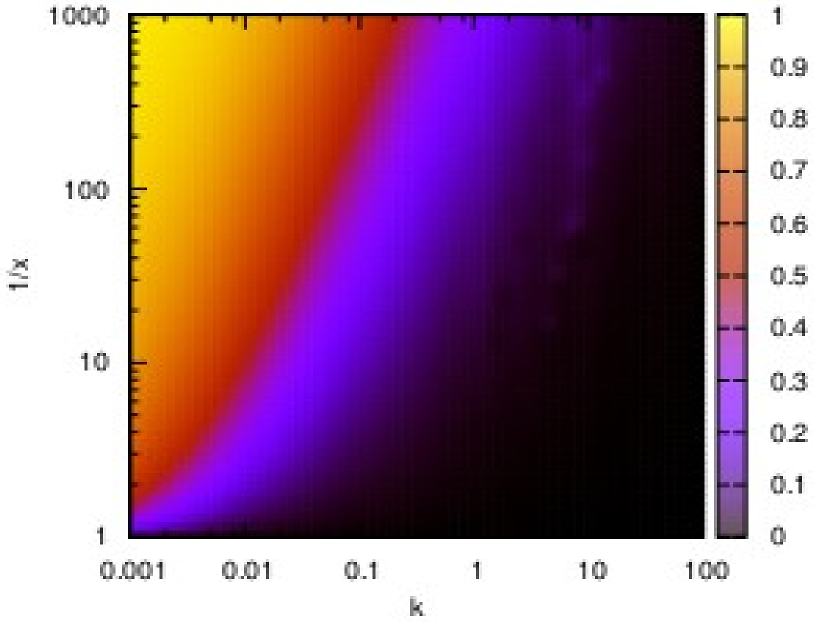

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splitting

Linear evolution
Equation
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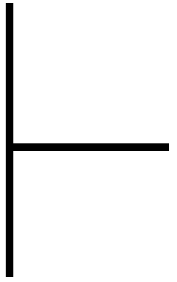

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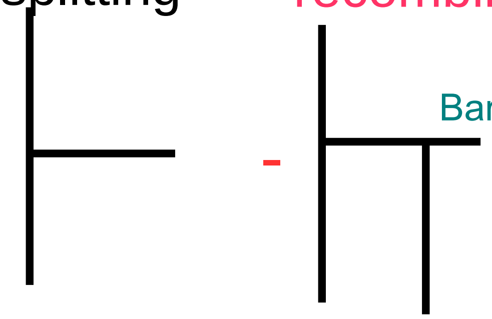
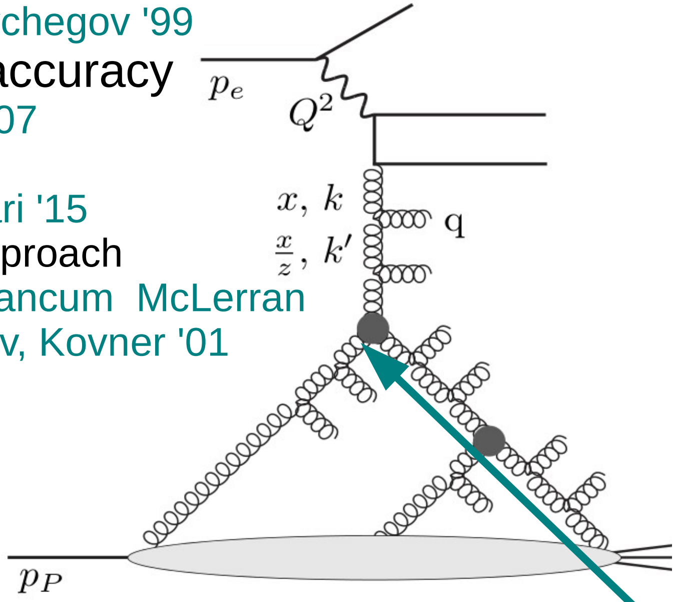
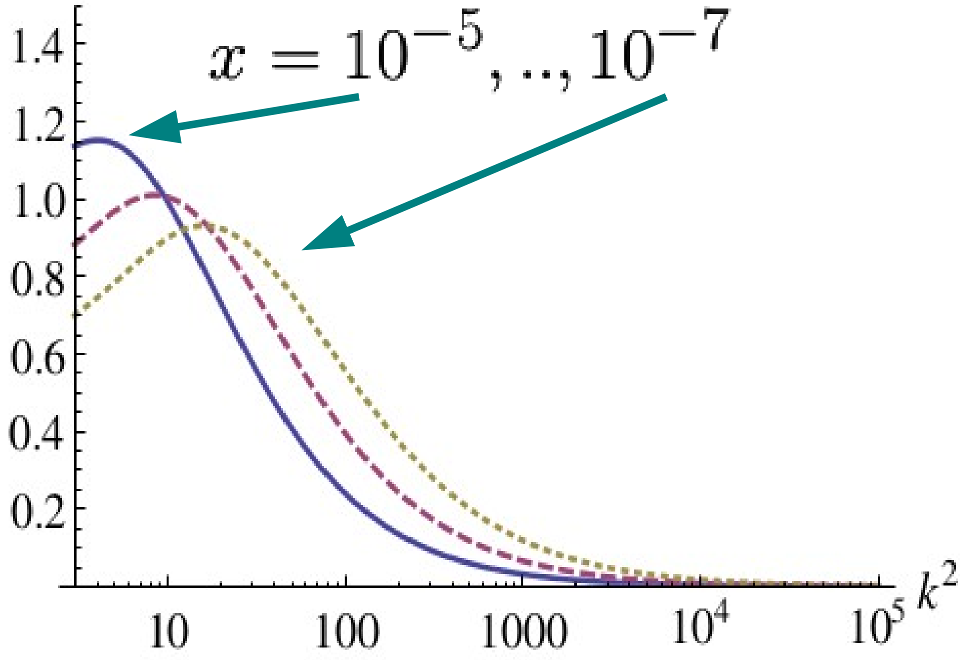


Bartels, Wusthoff’93

The saturation problem: supressing gluons at small kt

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 Balitsky Kovchegov equation

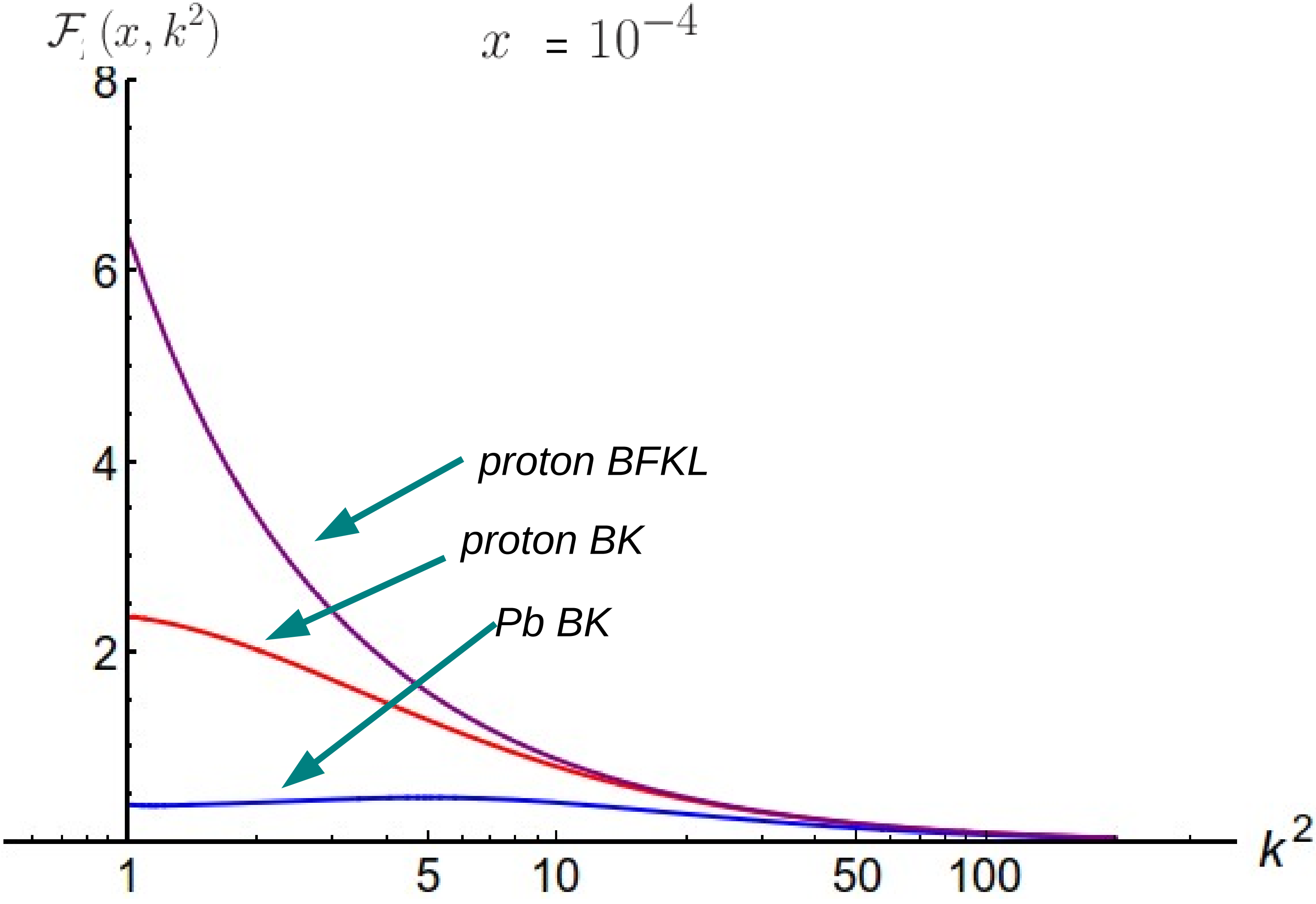
The BK equation for dipole gluon density

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

hadron's radius

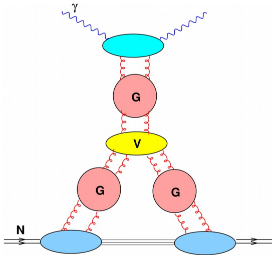
Kwiecinski, Kutak '02
Nikolaev, Schafer '06

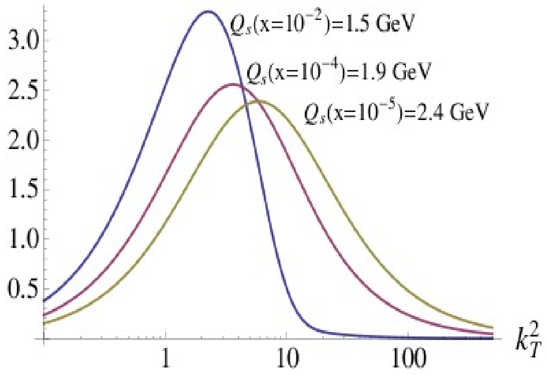
Glue in p vs. glue in Pb vs. linear - kt dependence



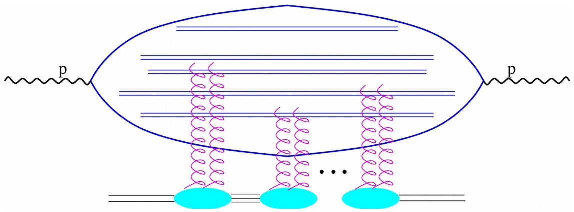
Momentum space vs. coordinate space

momentum space - Bjorken frame

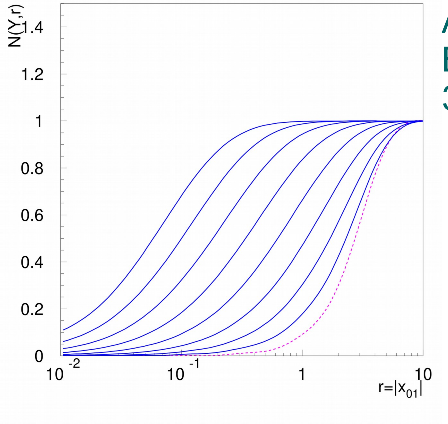




position space - Mueller frame



gluon ~ color dipole



from A. Stasto Acta Phys.Polon. B35 (2004) 3069-3102

$$\mathcal{F}(x,k) = \mathcal{F} + K_{m\,s}\otimes\mathcal{F}(x,k) - \frac{1}{R^2}TPV\otimes\mathcal{F}(x,k)^2$$

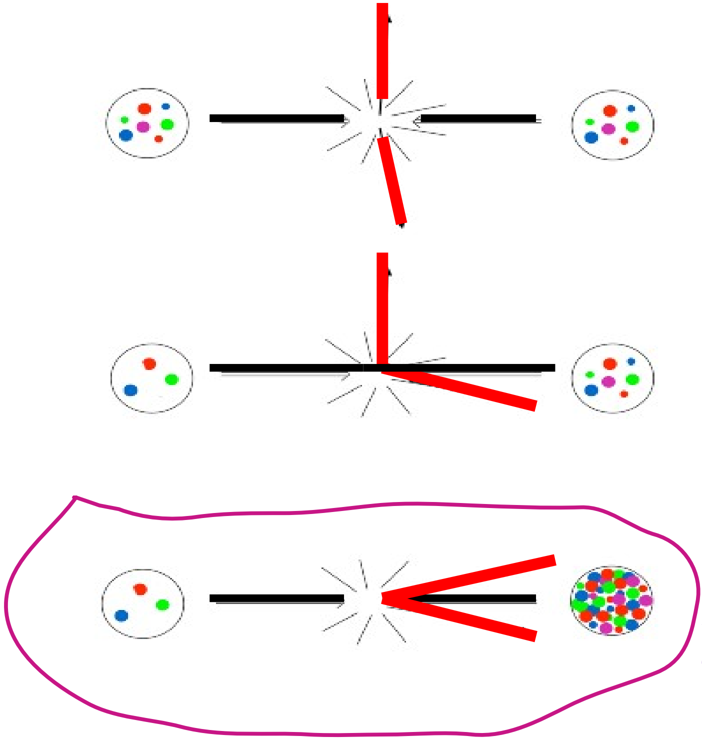
$$N(x,r,b) = N_0 + K_{p\,s}\otimes\left(N(x,r,b) - N(x,r,b)^2\right)$$

dipole unintegrated gluon density

dipole amplitude (one can integrate out b)

related by Fourier transform

Why forward final states?



central-central i.e.
dilute dilute

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

forward-central

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

forward-forward i.e.
dilute - dense

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

ITMD

ITMD = small x Improved Transverse Momentum Dependent factorization

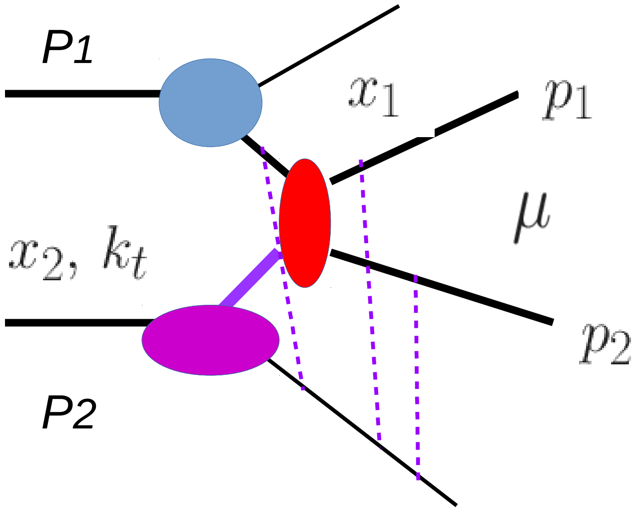
- accounts for saturation
- correct gauge structure i.e. uses gauge links to define TMD's
- takes into account kinematical effects – the whole phase space is available at LO
- valid in region $p_T > Q_s$, k_T can by any. p_T is hard final state momentum, k_T is inbalance

Generic structure: transverse momentum enters hard factors and gluon distributions gluon distribution depends on color flow

P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta, A. van Hamere
JHEP 1509 (2015) 106

P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren
JHEP 12 (2016) 034

The ITMD factorization for di-jets



- The color structure is separated from kinematic part of the amplitude by means of the color decomposition.
- The TMD gluon distributions are derived for the color structures following

P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska JHEP 12 (2016) 034

For CGC derivation see
Altinoluk, Bussarie, Kotko ‘19

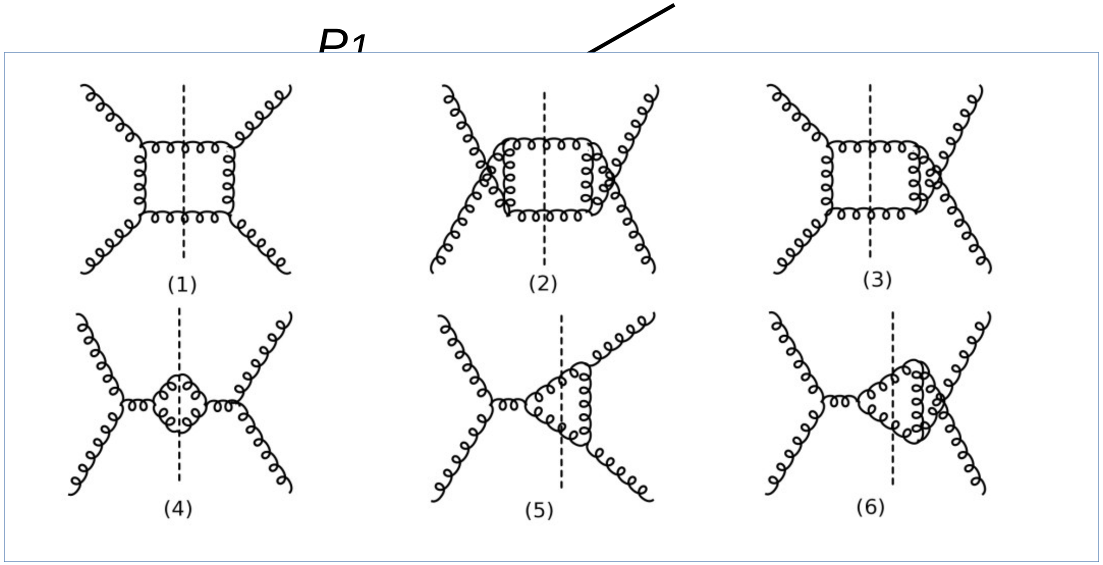
Formalism implemented in Monte Carlo programs KaTie by A. van Hameren

gauge invariant amplitudes with k_t and TMDs

Example for g* g → g g

$$\frac{d\sigma^{pA\to ggX}}{d^2P_t\, d^2k_t\, dy_1\, dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\, x_1 f_{g/p}(x_1,\mu^2)\sum_{i=1}^{6}\mathcal{F}_{gg}^{(i)} H_{gg\to gg}^{(i)}$$

ITMD - hard factors



from

F. Dominguez, C. Marquet,
Bo-Wen Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

The same gauge link and as in TMD ’s

Fabio Dominguez, Bo-Wen Xiao, Feng Yuan
Phys.Rev.Lett. 106 (2011) 022301

F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan
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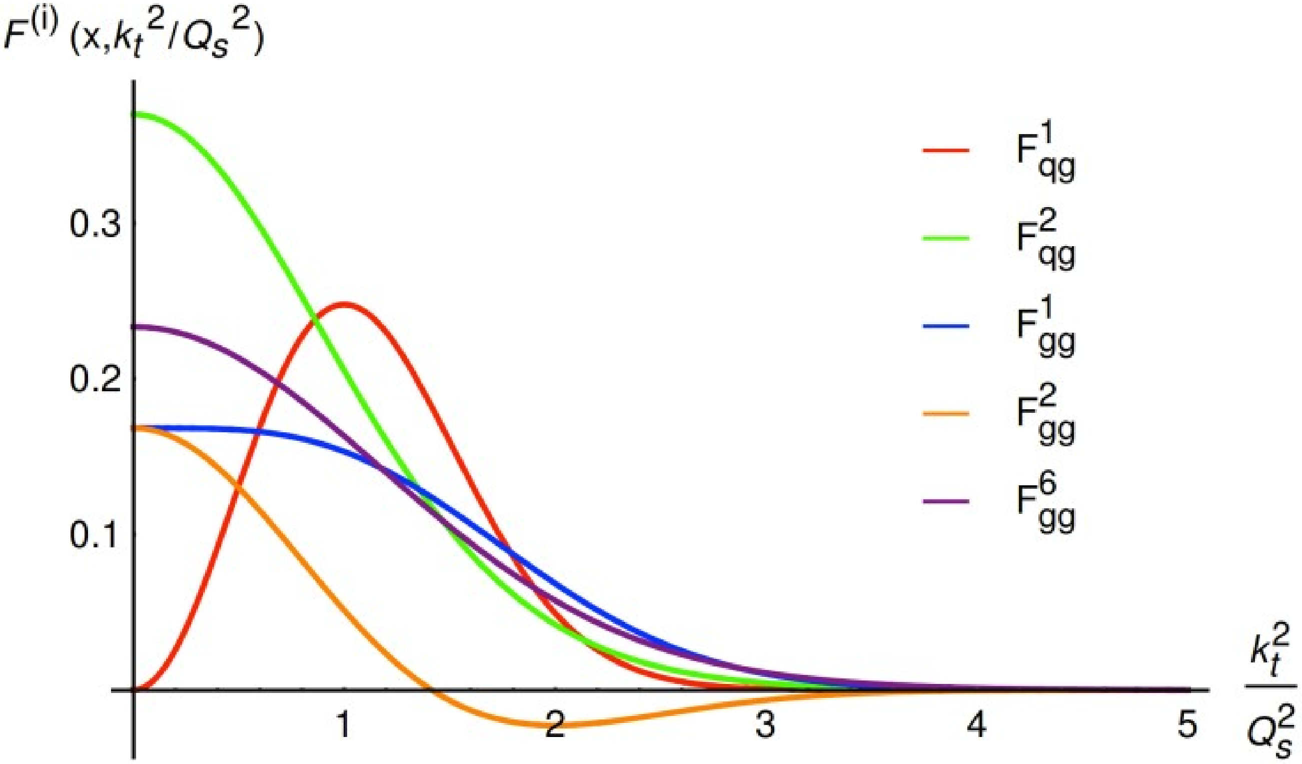
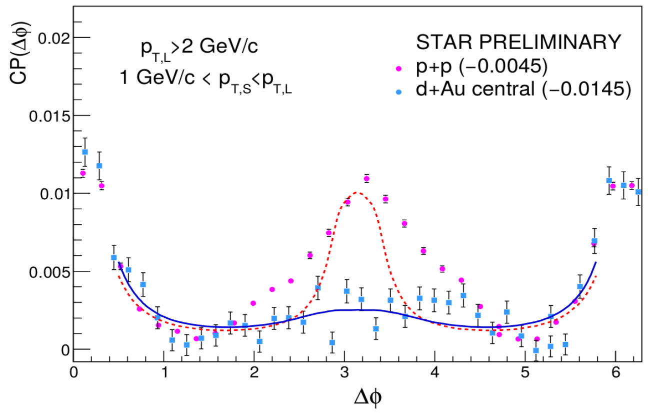
Set of basic TMD’s relevant here

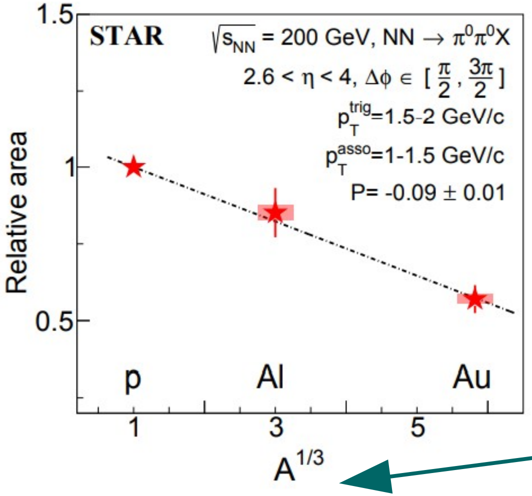


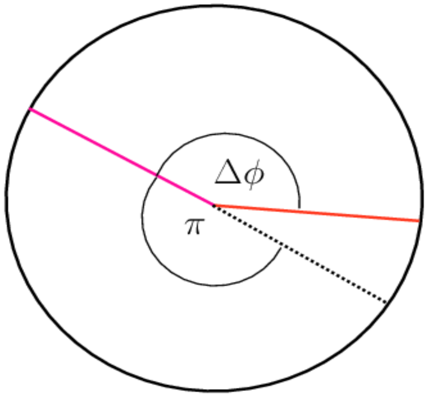
Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '16 JHEP 1612 (2016) 034

Selected hints of saturation



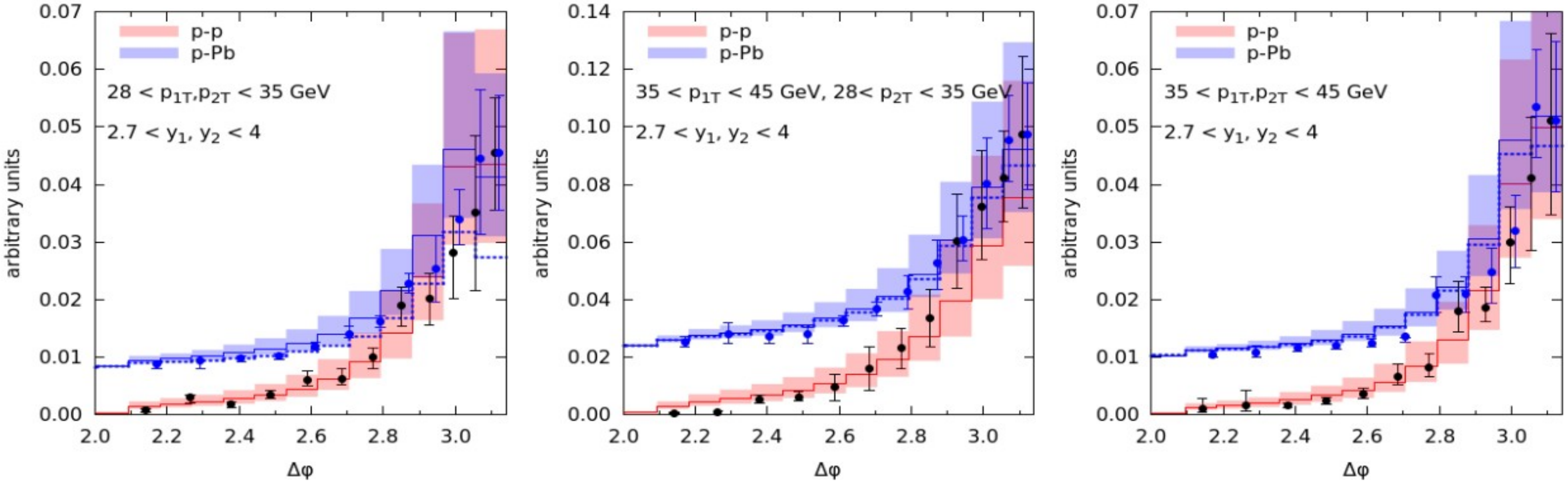
J. Albacete, C, Marquet
Phys.Rev.Lett. 105 (2010) 162301





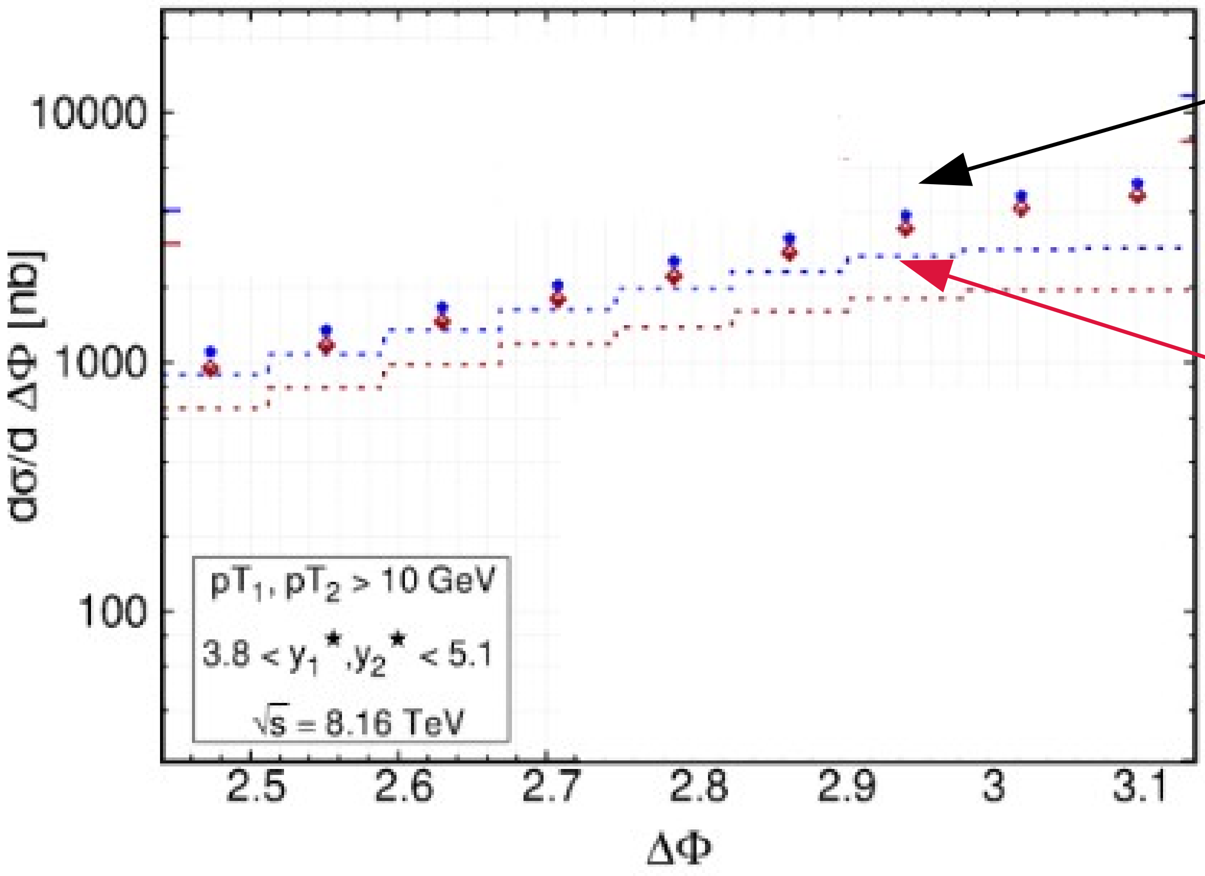
prediction of
saturation

PRL A 129 (2022) 9, 092501



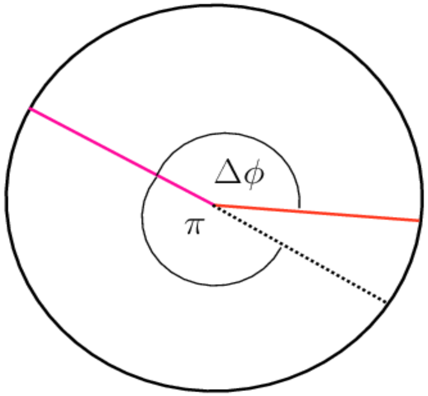
A. Hameren, P. Kotko, K. Kutak, S. Sapeta
Phys.Lett. B795 (2019) 511-515

Dijets in FoCal - azimuthal angle dependence



PYTHIA
p-p
p-Pb

ITMD + FSR+had
p-p
p-Pb

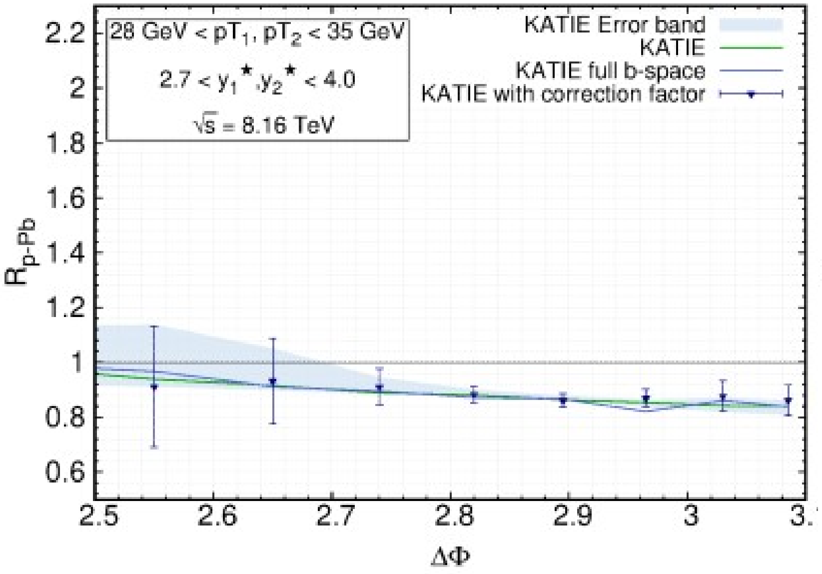


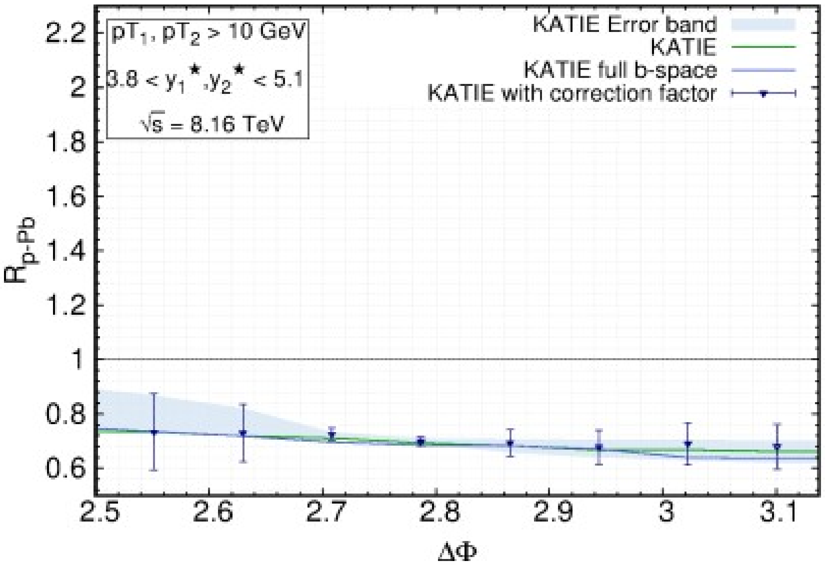
Larger suppression in ITMD factorization.

JHEP12(2022)131
M. Abdullah Al-Mashad, A. van Hameren,
H. Kakkad, P. Kotko, K. Kutak, P. Van Mechelen, S. Sapeta

ITMD calculation using KaTie
Comput.Phys.Commun. 224 (2018) 371-380
A. van Hameren

Nuclear modification ratio





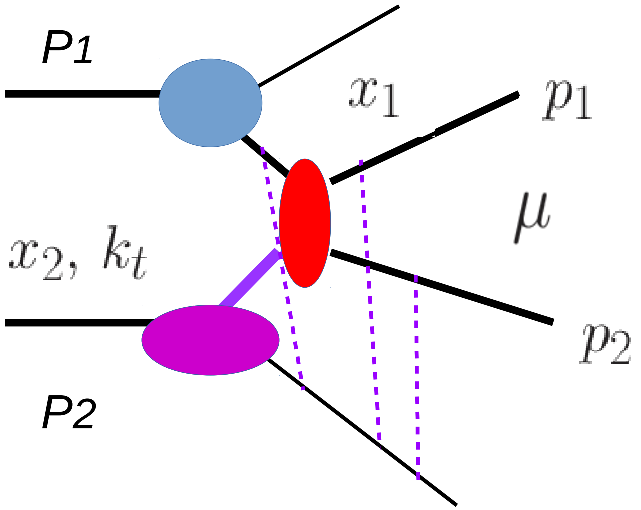
Visible suppression in both ATLAS and ALICE kinematical setup.

$$R_{\mathrm{p-Pb}} = \frac{\frac{d\sigma^{p+Pb}}{d\mathcal{O}}}{A\frac{d\sigma^{p+p}}{d\mathcal{O}}}$$

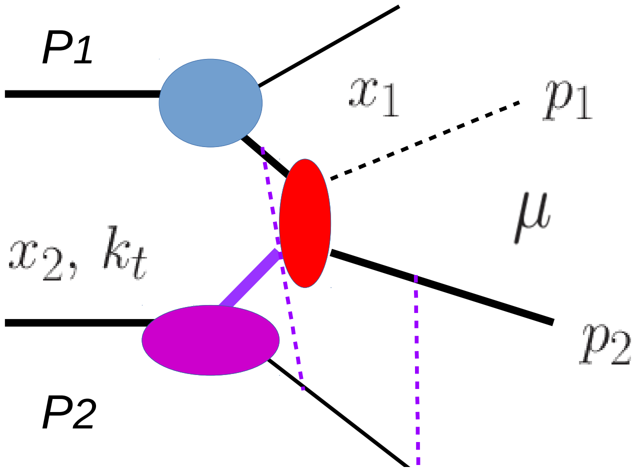
KaTie
Comput.Phys.Commun. 224 (2018) 371-380
A. van Hameren

Photon – jet final state

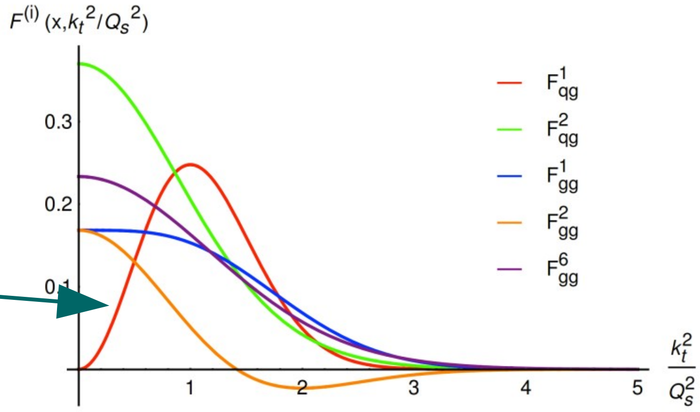
FS: Jet – Jet



FS: Jet – Photon

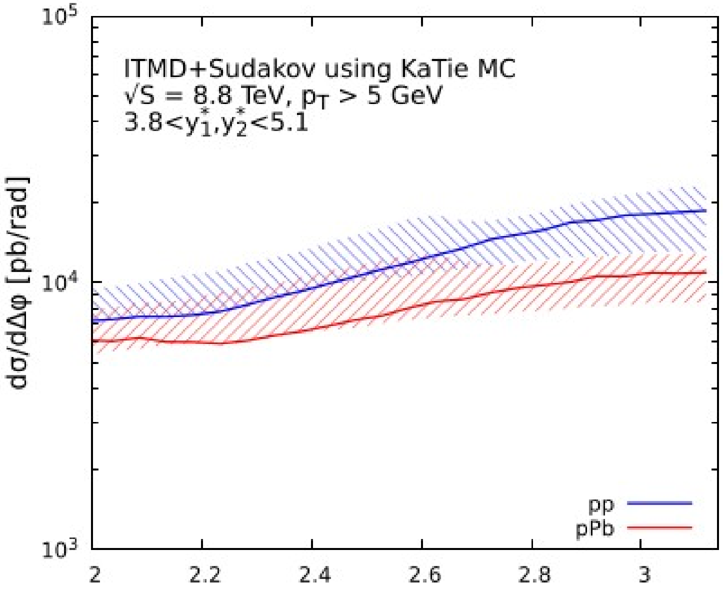


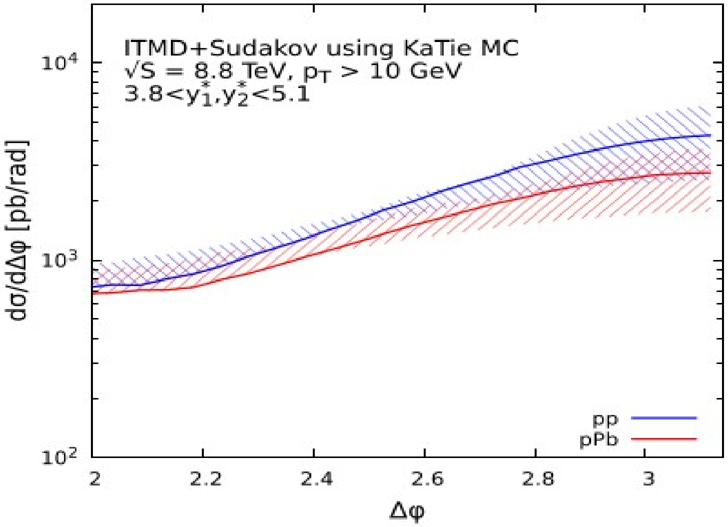
- Photon does not interact with remnant
- Factorization simplifies
- Only one type of TMD contributes
- It gives maximal saturation

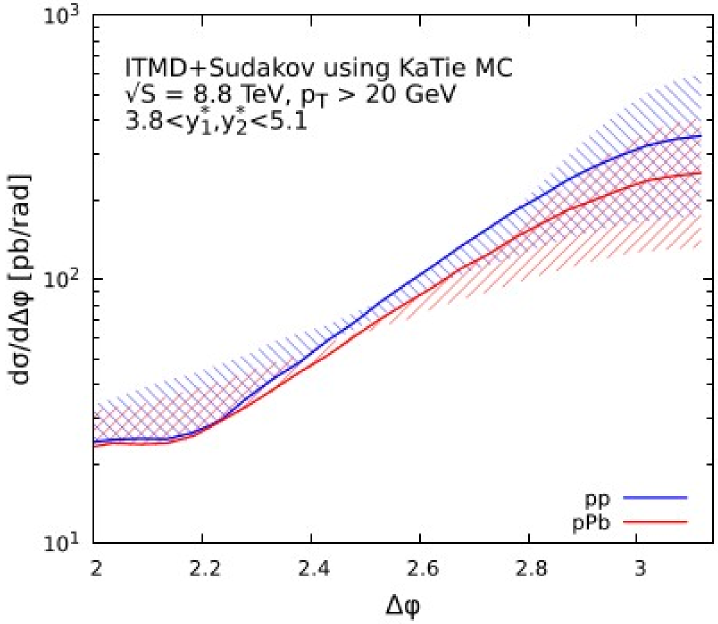


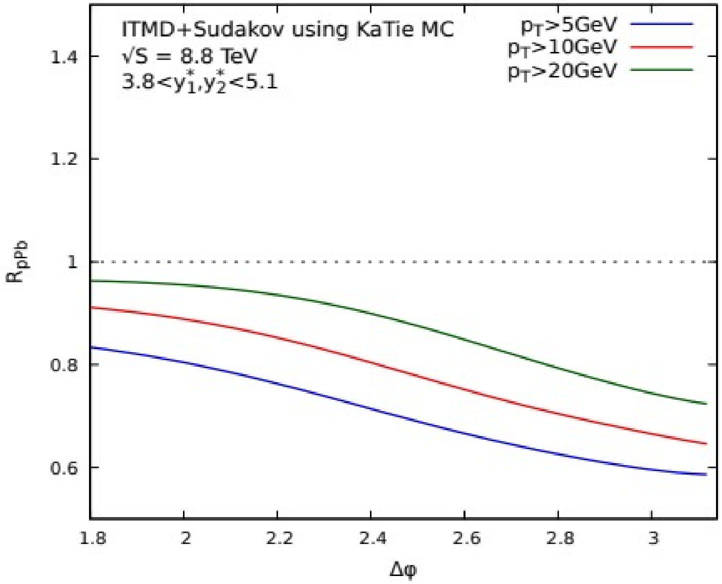
Photon and jet at LHC

Ganguli, van Hameren, Kotko, Kutak ‘24



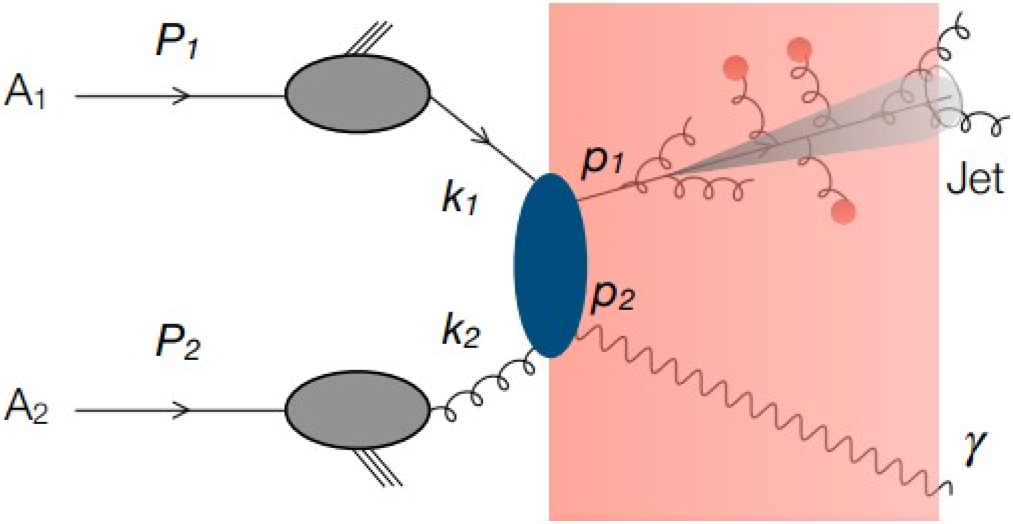






At small $p_{T\ \mathrm{clearly}}$ visible suppression. The bands do not overlap

Photon jet final state in Pb-Pb



Process where one can study:

- relevance of vacuum like emissions at forward rapidities.
- rapidity dependence of medium
- saturation effects

Estimate of multiplicity

$$N^{\rm in}_{\rm DLA} = 2\bar{\alpha} \log \frac{R}{\theta_c} \left(\log \frac{E}{\omega_c} + \frac{2}{3} \log \frac{R}{\theta_c} \right)$$

$$\sigma_{Pb-Pb} = D_{frag} \otimes \sigma_{Pb-Pb\, no-med}$$

At central rapidities

$$E = p_T$$

At forward rapidities

$$E \sim p_T e^{\eta}$$

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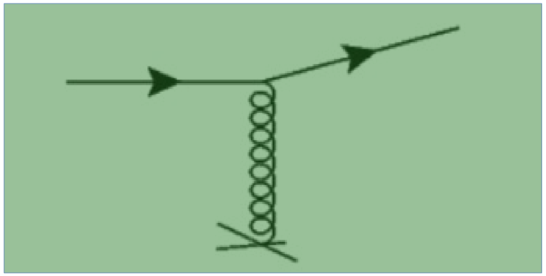
S. Adhya, K. Kutak, W. Płaczek, M. Rohrmoser, K. Tywoniuk

Jet medium interaction

scattering...

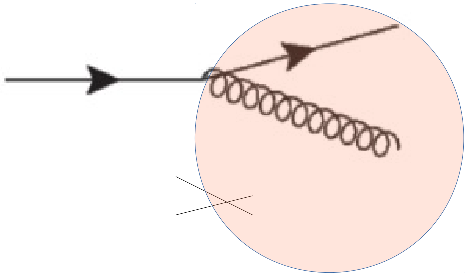


Transverse momentum transfer!

$p \to p + k_T$

Scattering Kernel: $C(k_T)$

...splitting...

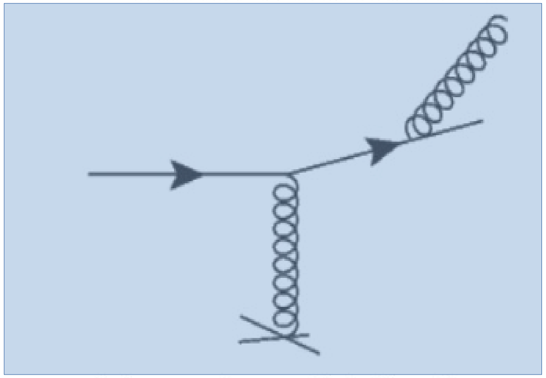


Bremsstrahlung as in vacuum.

Individual colors of partons may not be

resolvable by medium particles

...induced radiation



Momentum distribution:

$p \to zp$

Blaizot, Dominguez, Iancu, Mehtar-Tani ’12

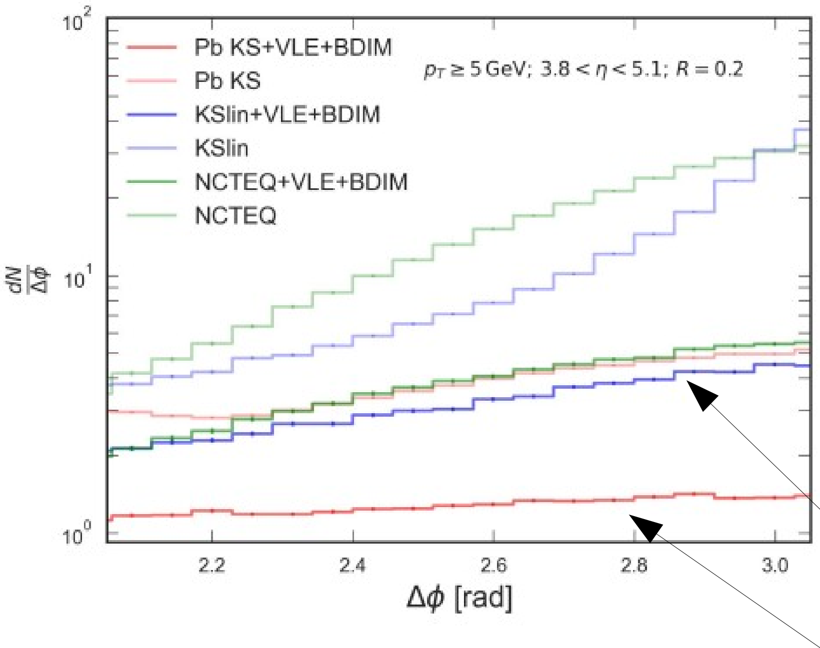
Average transfer: $\hat{q}$

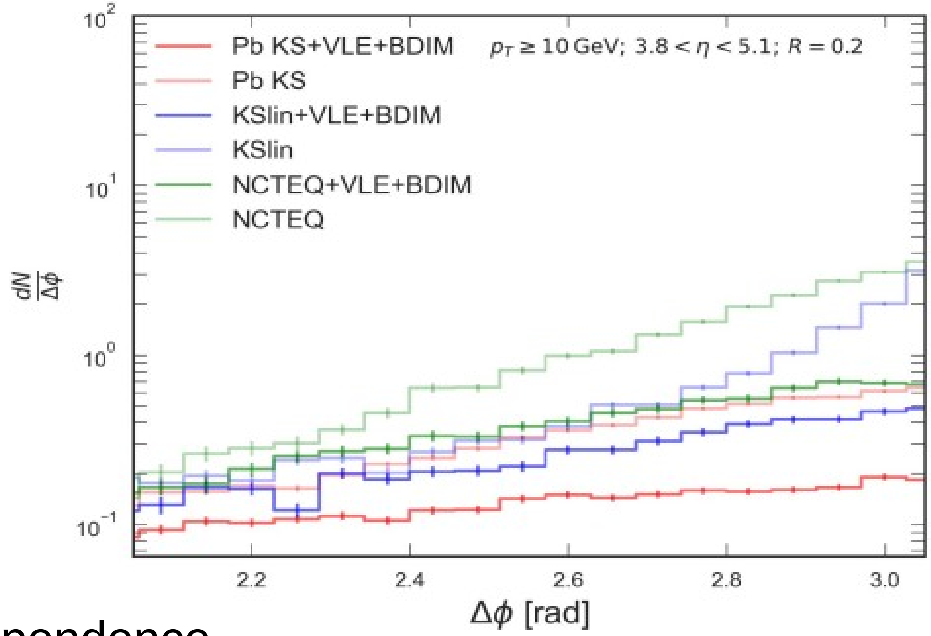
$$\frac{\partial}{\partial t} D(x,\mathbf{k},t) = \frac{1}{t^*}\int_0^1 dz\,\mathcal{K}(z)\left[\frac{1}{z^2}\sqrt{\frac{z}{x}}\,D\left(\frac{x}{z},\frac{\mathbf{k}}{z},t\right)\theta(z-x) - \frac{z}{\sqrt{x}}D(x,\mathbf{k},t)\right]$$

$$+\int \frac{d^2\mathbf{q}}{(2\pi)^2}\,C(\mathbf{q})\,D(x,\mathbf{k}-\mathbf{q},t)$$

Equation describes interplay of rescatterings and branching.
This particular equation has k_t independent kernel.
This is an approximation. The whole broadening comes
from rescattering. Energy of emitted gluon is much larger than its transverse momentum

Azimuthal angle decorelations





p_T dependence

clearly visible supression due to saturation (and Sudakov)

temperature and saturation dependence

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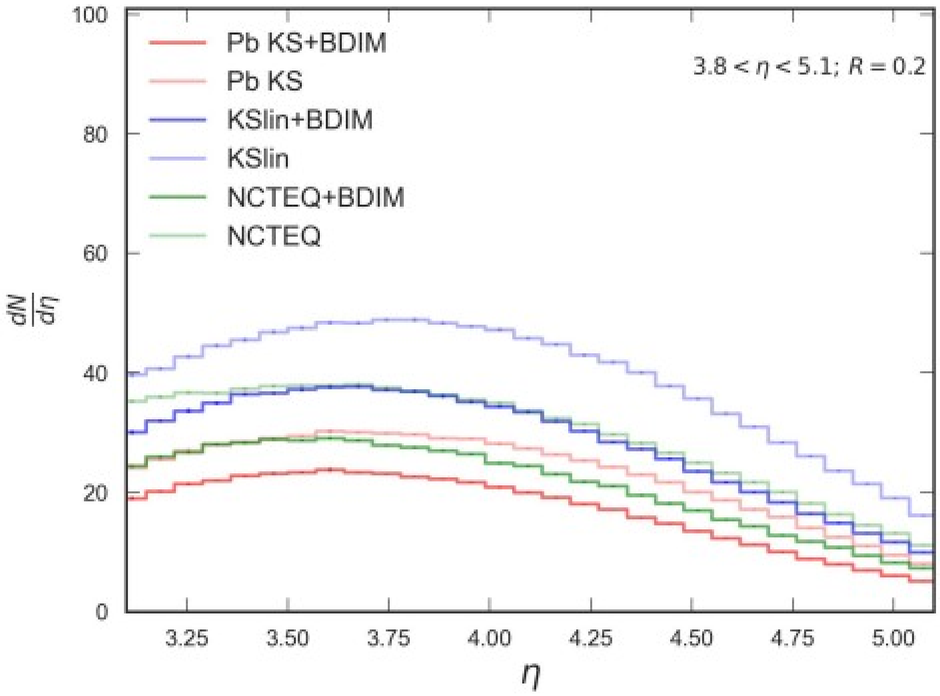
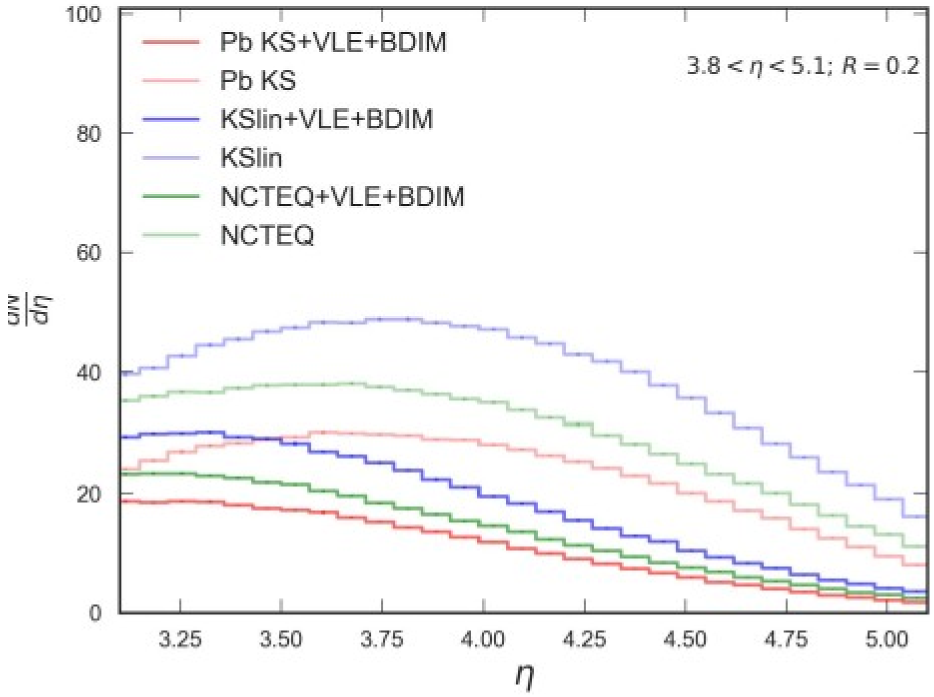
Rapidity spectra





VLE emissions accounted for

Large supression due to VLE

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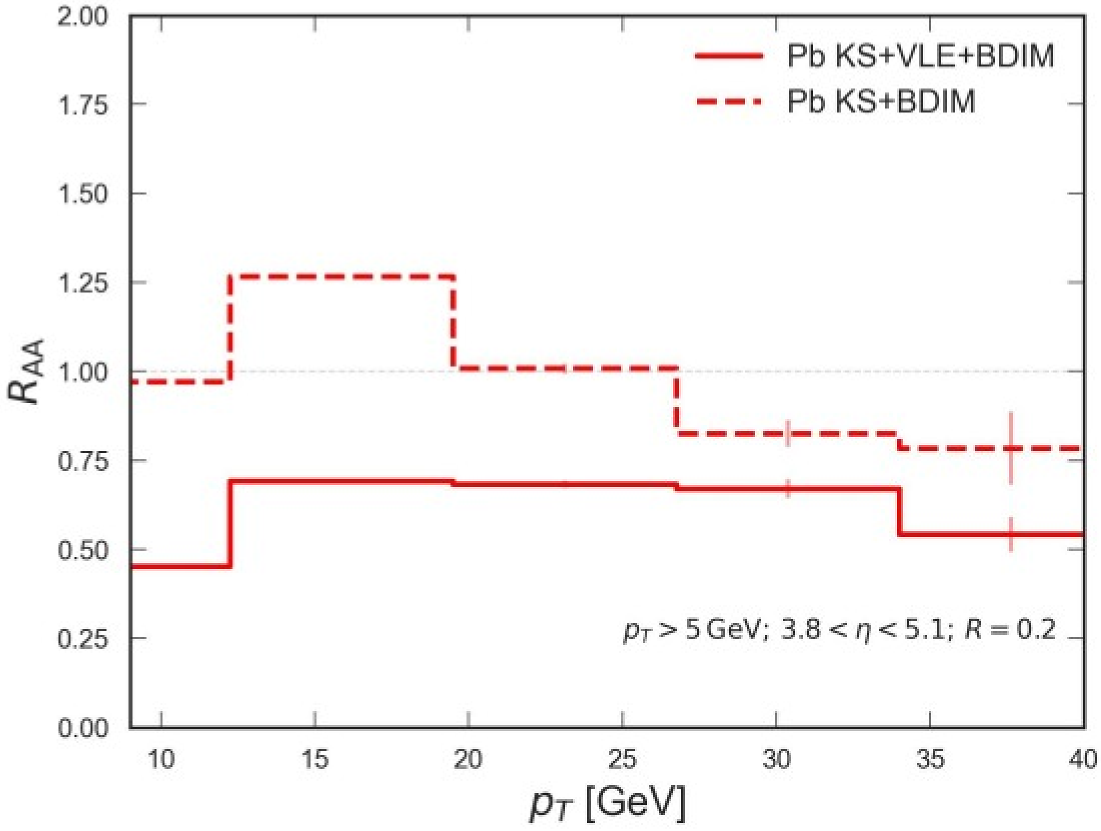
Nuclear modification ratio – relevance of VLE



suppression due to quenching

suppression due to saturation

Summary and future plans

- QCD is very well explored at LHC however saturation is sill an open problem

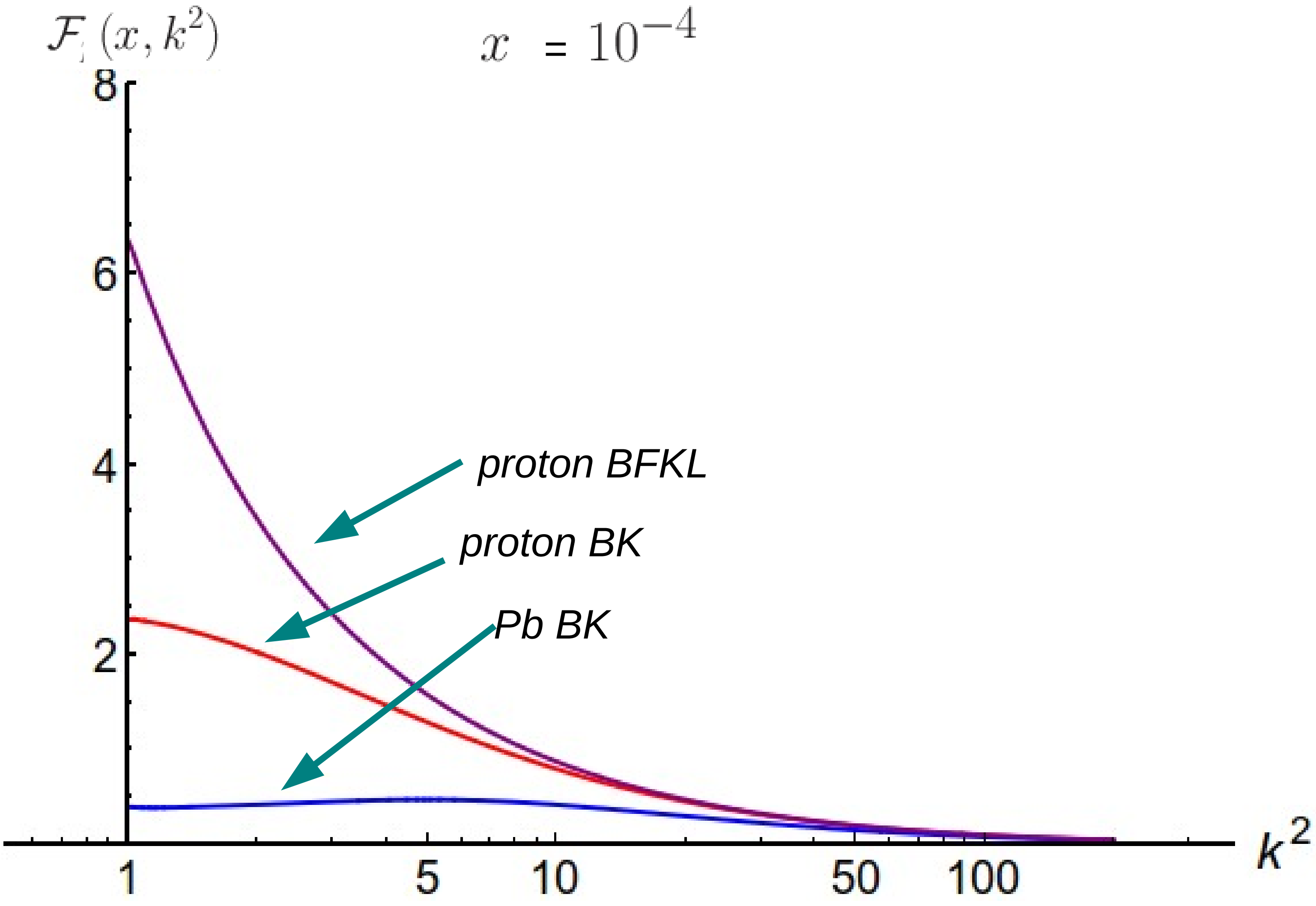
- ITMD/CGC predict that saturation will be visible in dijet and photon-jet decorelations in p-Pb

- Another option is to look for saturation effects in Pb-Pb. Preliminary results show that saturation is visible even after accounting for jet quenching

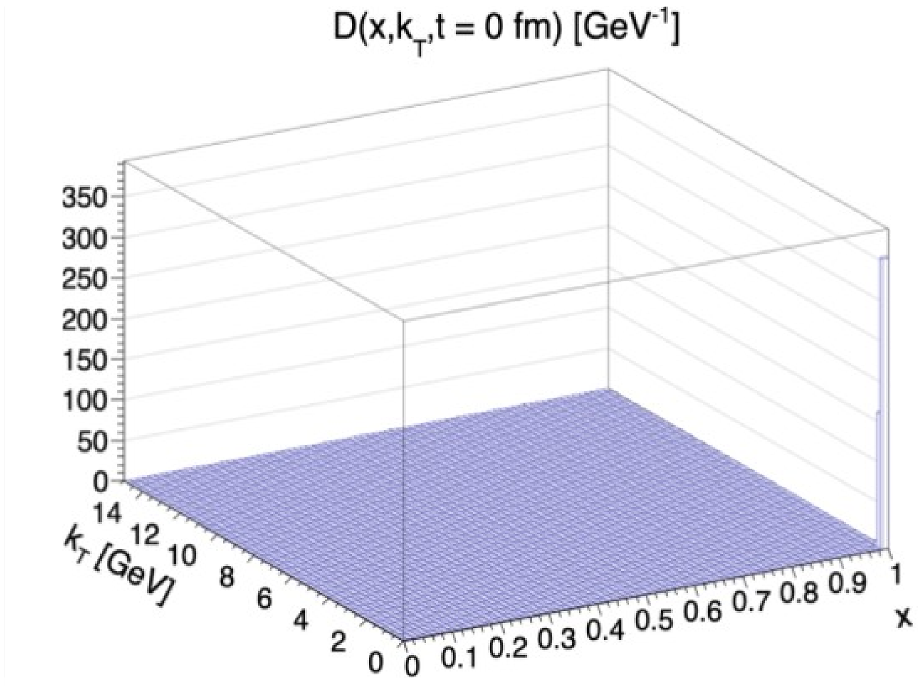
- The presented results are not definite. The plans include accounting for higher order corrections, new fits of TMD, accounting for expansion of medium and rapidity dependent medium

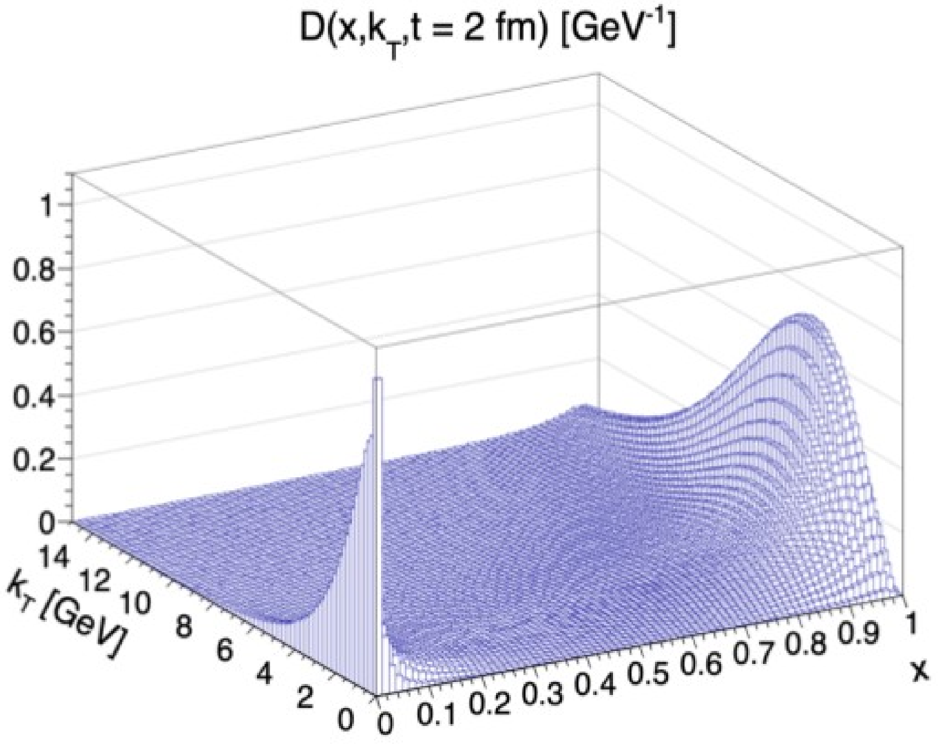
BACKUP

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



Jet medium interaction and turbulence





$$D(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} \exp\left(-\pi \frac{\tau^2}{1-x}\right)$$

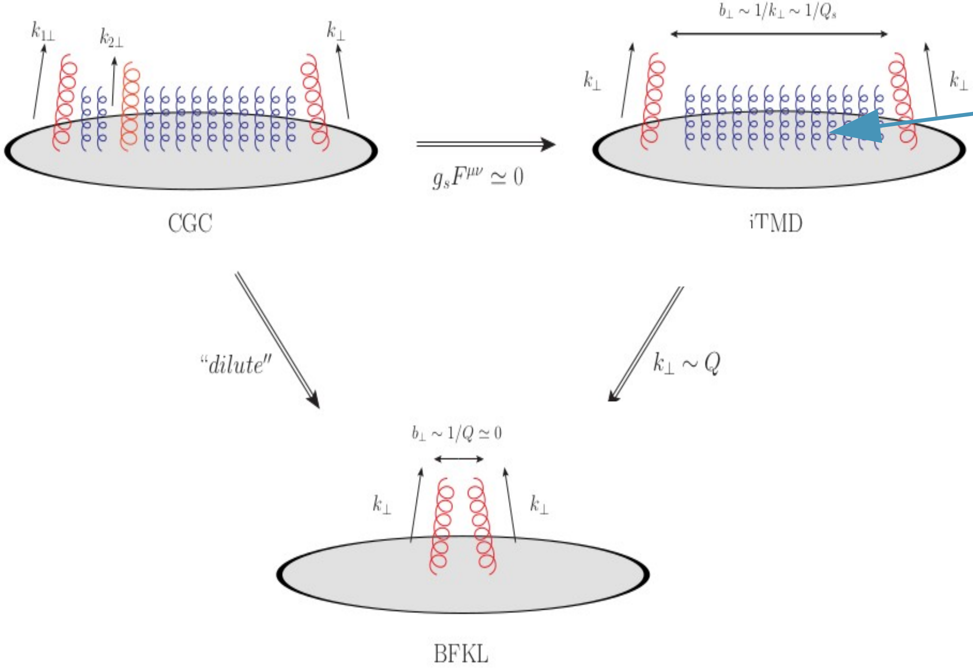
The solution features so called turbulent behavior. Here that means that at low x the solution factorizes into x and t dependent distributions.

The fact that the spectrum keeps the same x-dependence when t keeps increasing reflects the fact that the energy flows to x = 0 without accumulating at any finite value of x
→ wave turbulence

ITMD from CGC

T. Altinoluk, R. Boussarie, P. Kotko JHEP 1905 (2019) 156
T. Altinoluk, R. Boussarie, JHEP10(2019)208

Expansion in distance - parameter entering as argument Wilson lines appearing in generic CGC amplitude i.e. amplitude for propagation in strong color field of target



Multiple soft emissions

from R. Boussarie
Initial Stages 2019

Wandzura-Wilczek approximmation ITMD neglects higher genuine twist contributions i.e. hard gluon exchanges between the target and the amplitude, while it resums all kinematic twist