Saturation and forward jets in p-Pb and Pb-Pb

The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Krzysztof Kutak

The results are based on

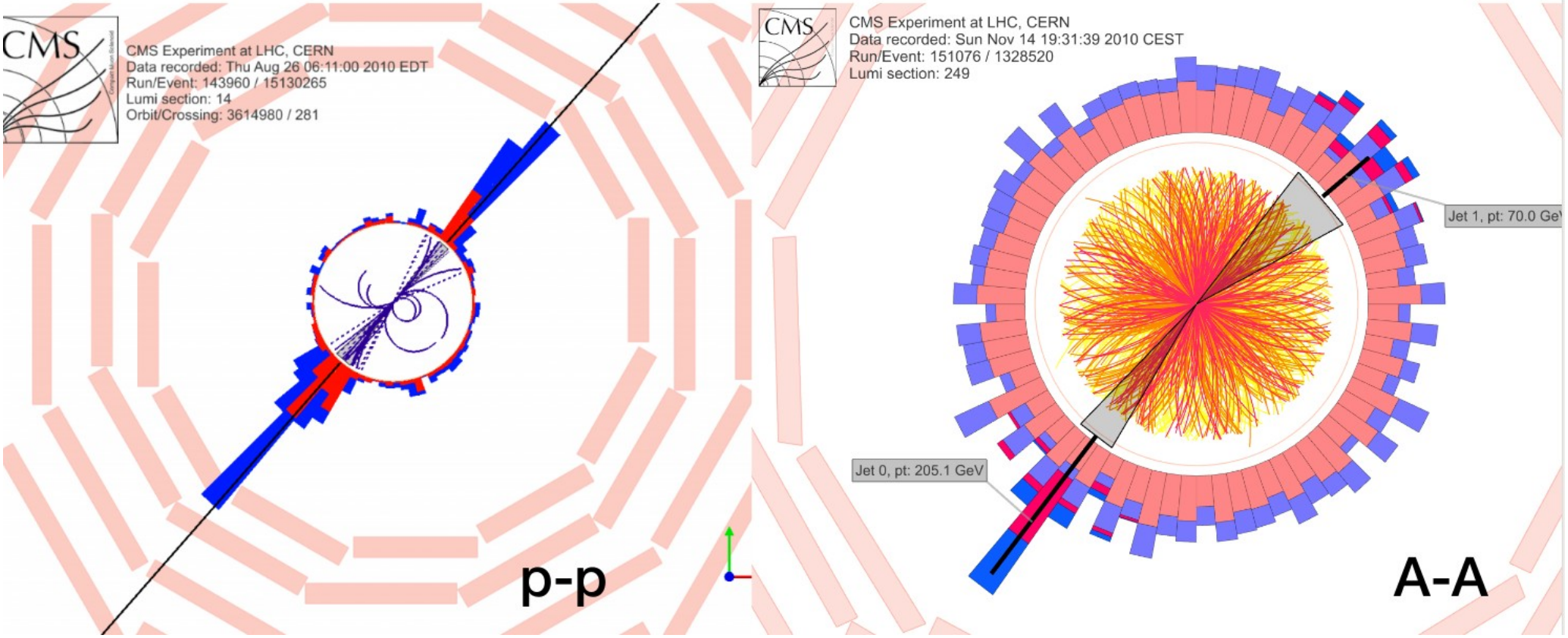
JHEP12(2022)131
M. Abdullah Al-Mashad, A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, P. Van Mechelen, S. Sapeta

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



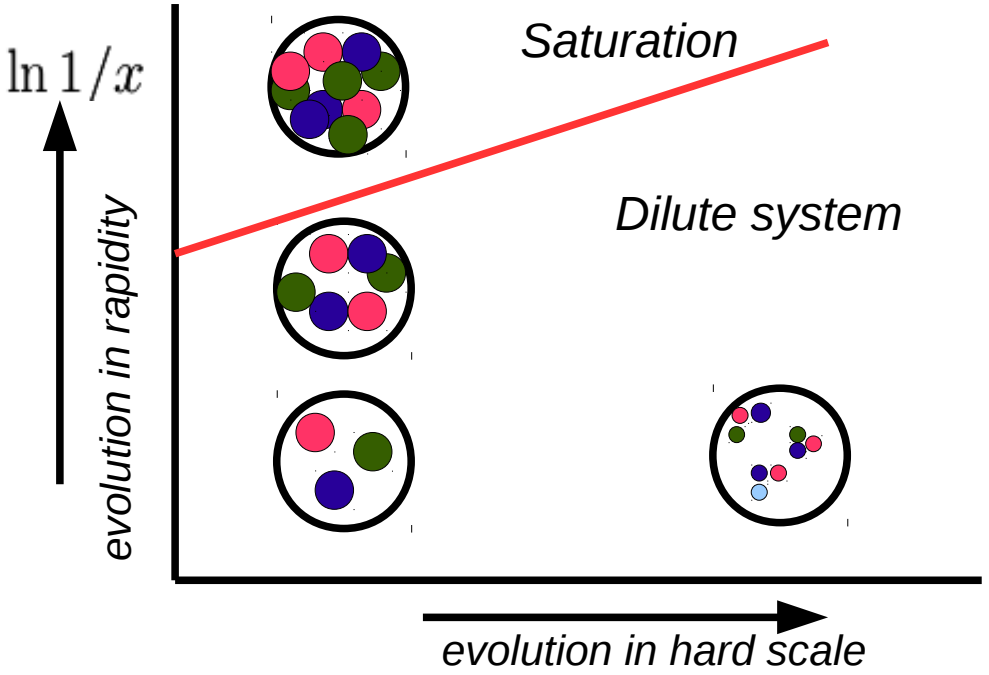
and **p - Pb**

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

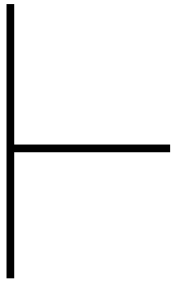
Larry D. McLerran, Raju Venugopalan
Phys.Rev. D49 (1994) 3352-3355



On microscopic level it means that gluon apart splitting recombine

splitting

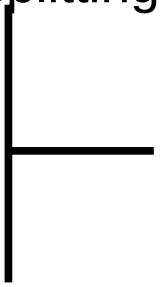
Linear evolution Equation BFKL



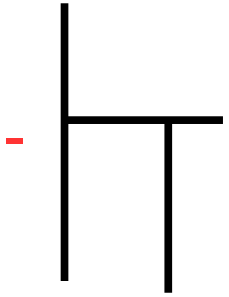
Nonlinear evolution equations
BK, JIMWLK
Balitcky-Kovchegov,

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

splitting



recombination



Bartels, Wusthoff '93

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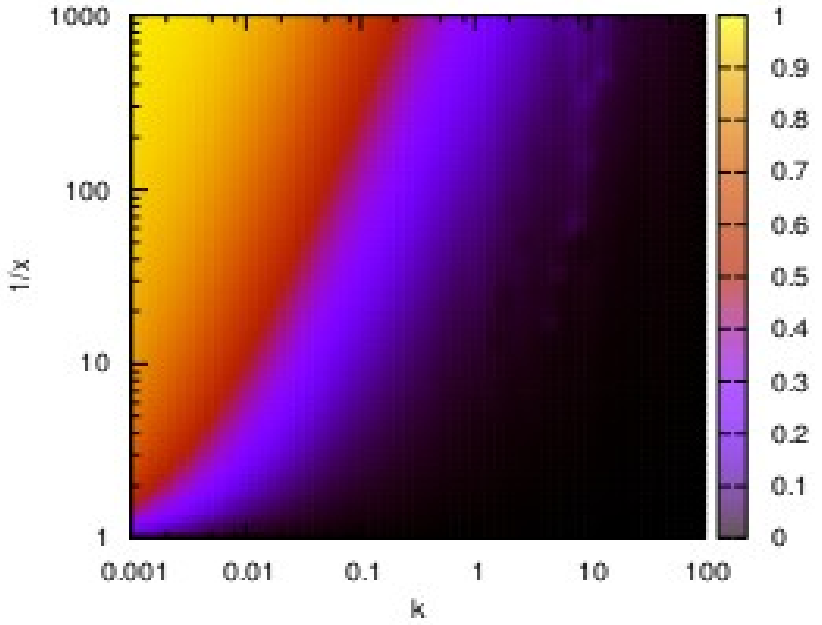

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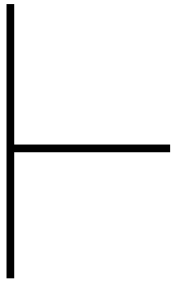
Linear evolution
Equation
BFKL



splitting

Nonlinear evolution equations
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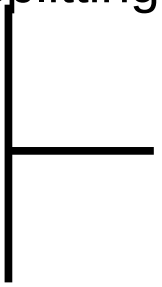
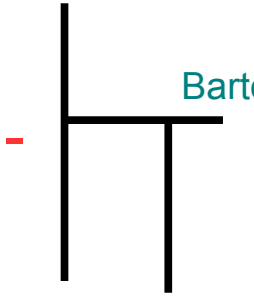


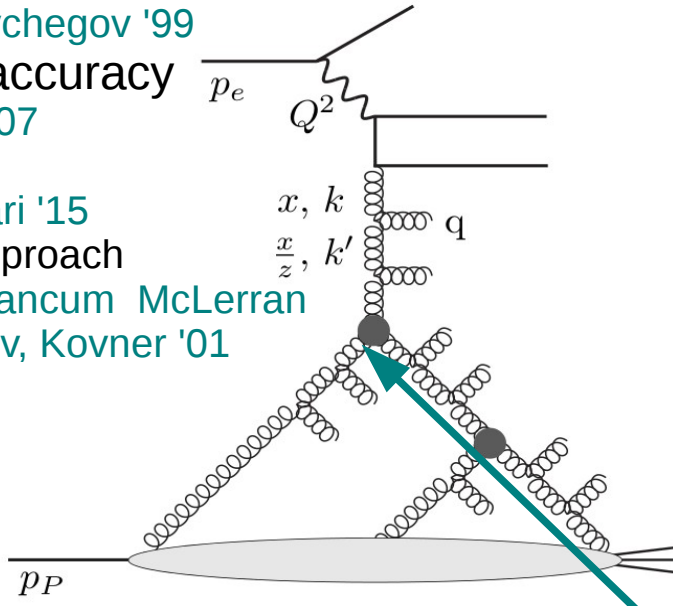
recombination

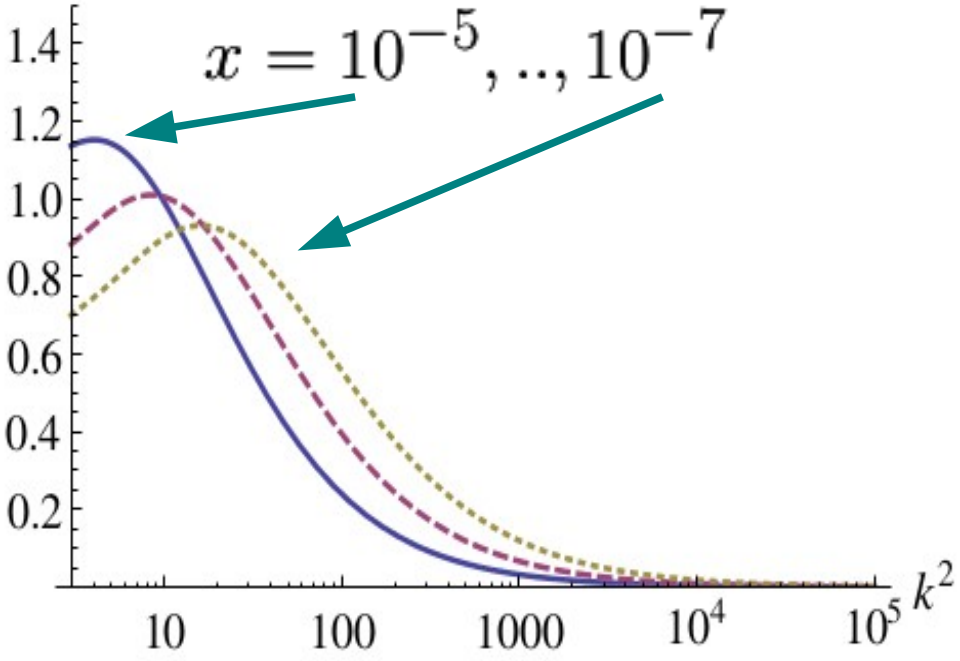


Bartels, Wusthoff'93

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 Balitsky Kovchegov equation

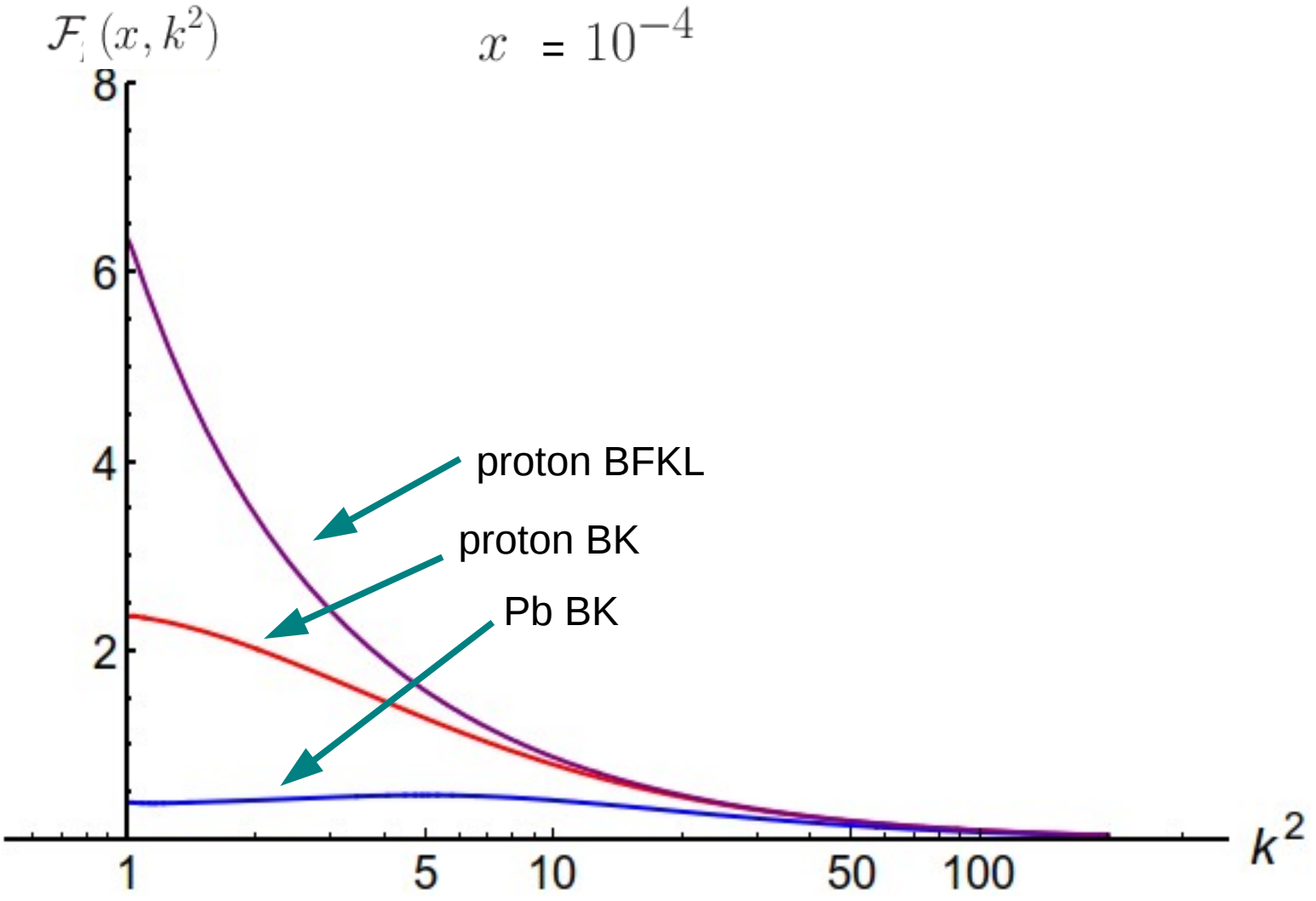
The BK equation for dipole gluon density

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

hadron's radius

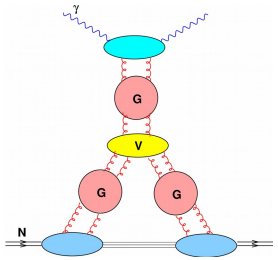
Kwiecinski, Kutak '02
Nikolaev, Schafer '06

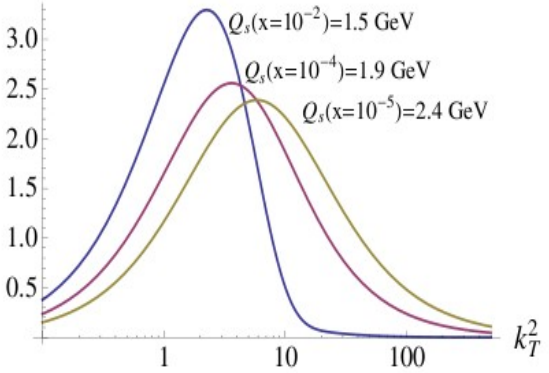
Glue in p vs. glue in Pb vs. linear - kt dependence



Momentum space vs. coordinate space

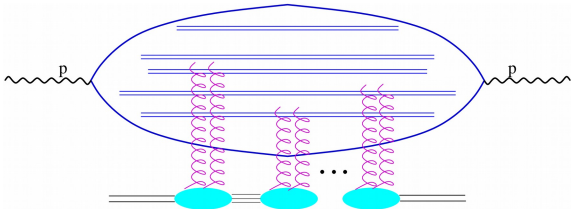
momentum space - Bjorken frame

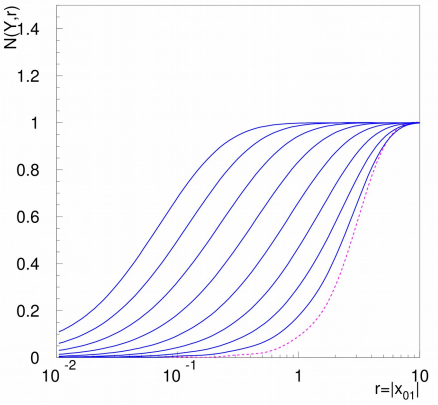




gluon ~ color dipole

position space - Mueller frame





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

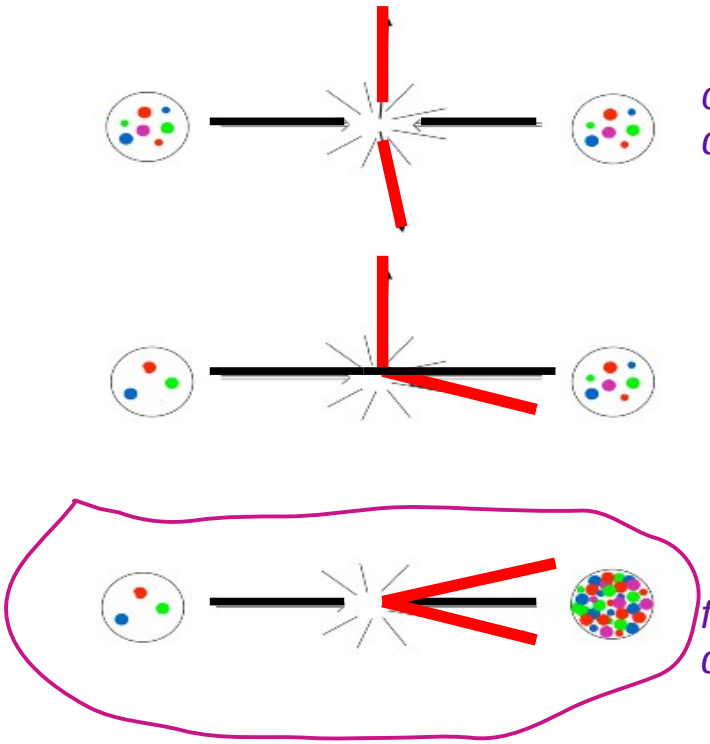
$$\mathcal{F}(x,k) = \mathcal{F} + K_{ms} \otimes \mathcal{F}(x,k) - \frac{1}{R^2} TPV \otimes \mathcal{F}(x,k)^2 \qquad N(x,r,b) = N_0 + K_{ps} \otimes (N(x,r,b) - N(x,r,b)^2)$$

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

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

From C. Marquet

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
- Implemented in Monte Carlo generator KaTie

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

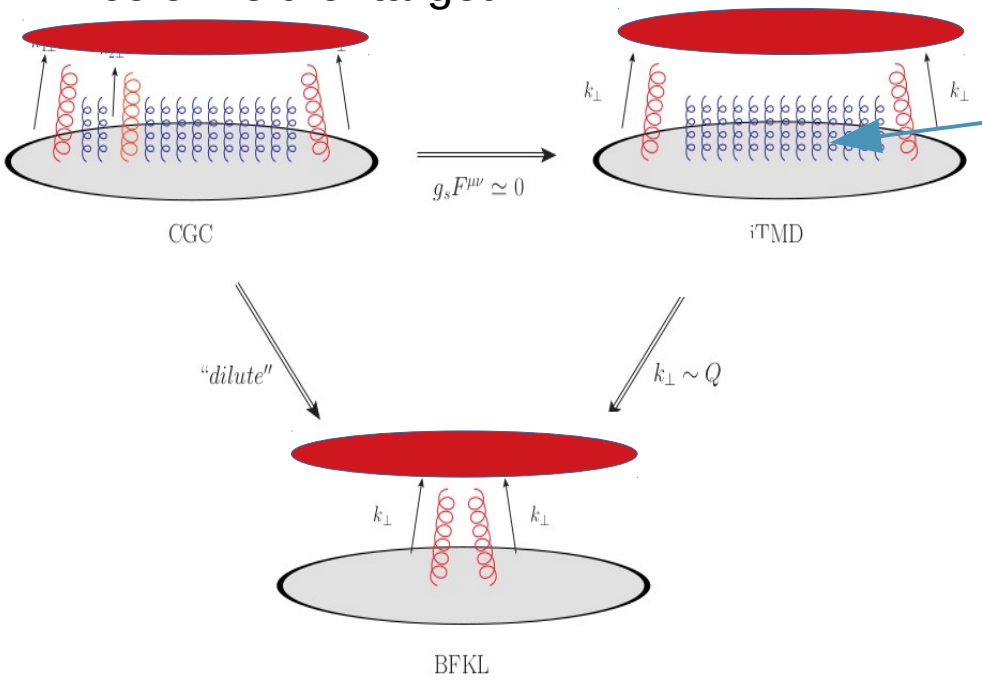
P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta, A. van Hamere
JHEP 1509 (2015) 106

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

ITMD from Color Glass Condensate

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

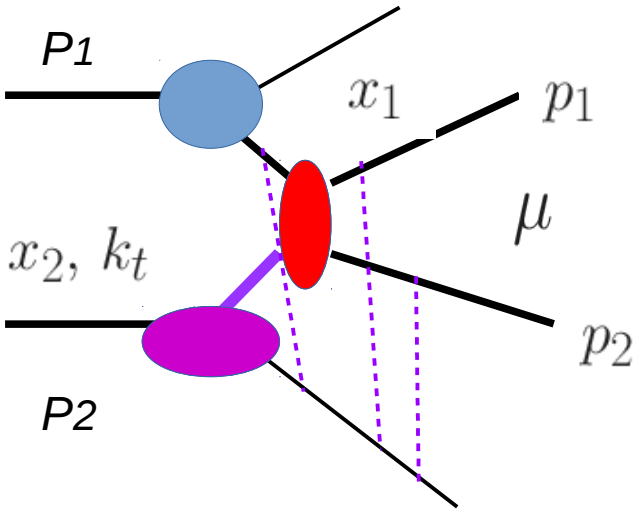


Multiple soft emissions

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

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

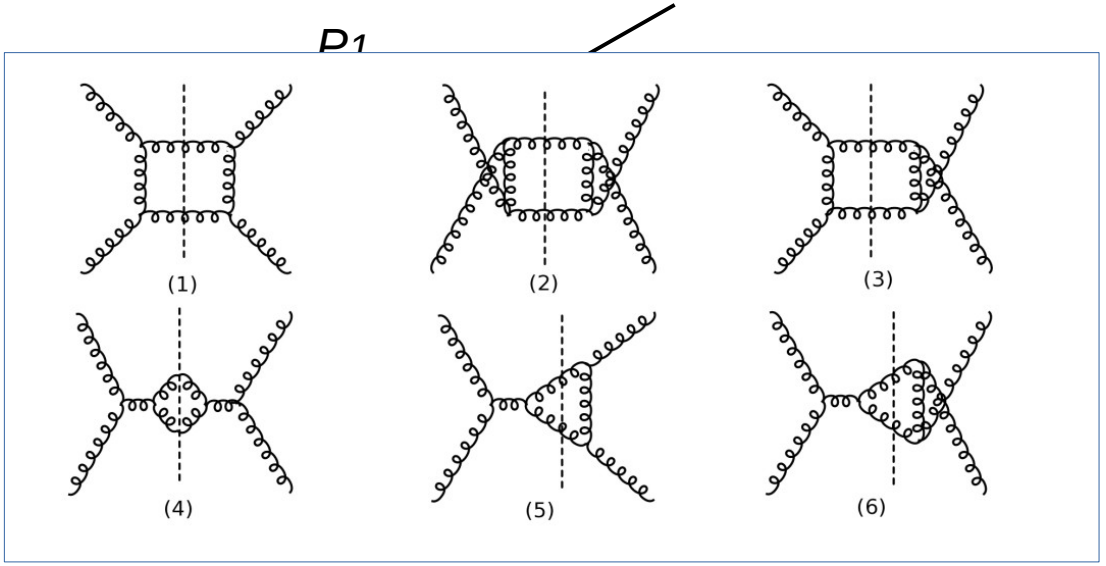
Formalism implemented in Monte Carlo programs KaTie by A. van Hameren

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

F. Dominguez, B. Xiao, F. Yuan
Phys.Rev.Lett. 106 (2011) 022301

F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan
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gauge invariant amplitudes with k_t and TMDs

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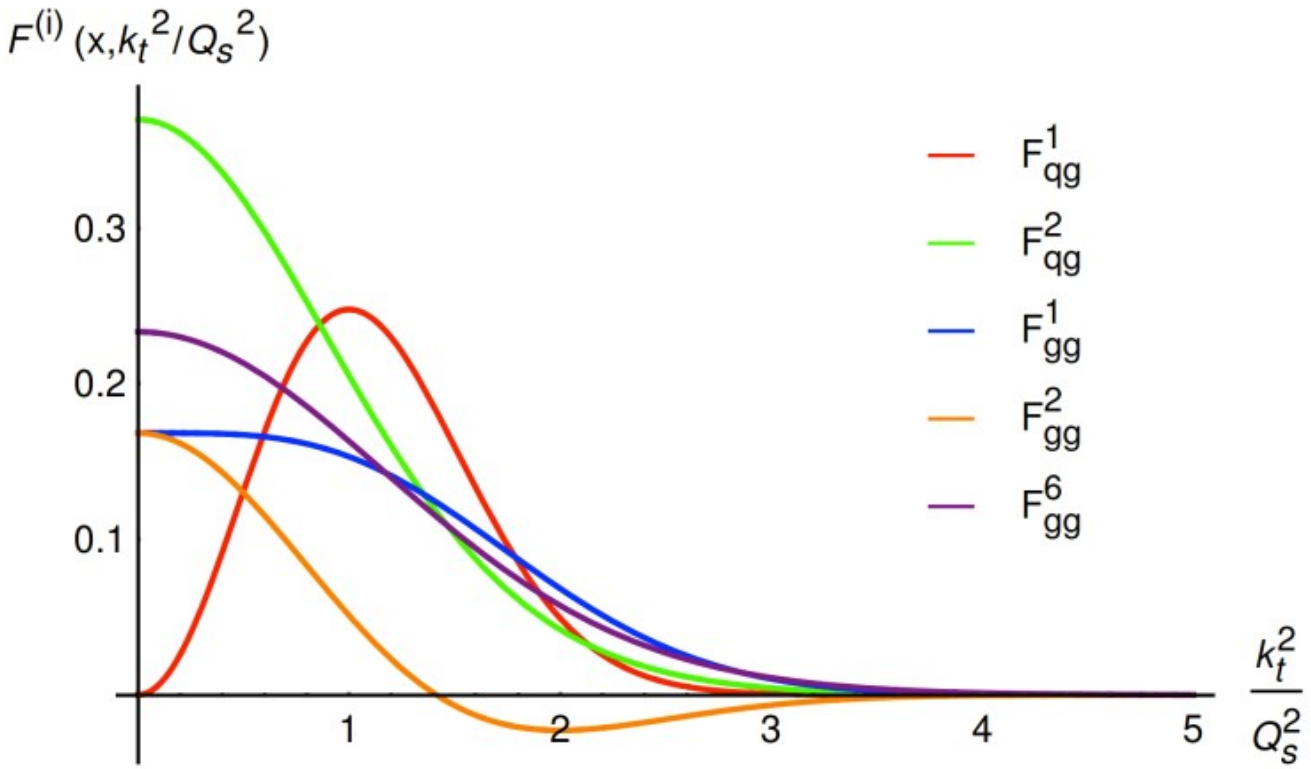
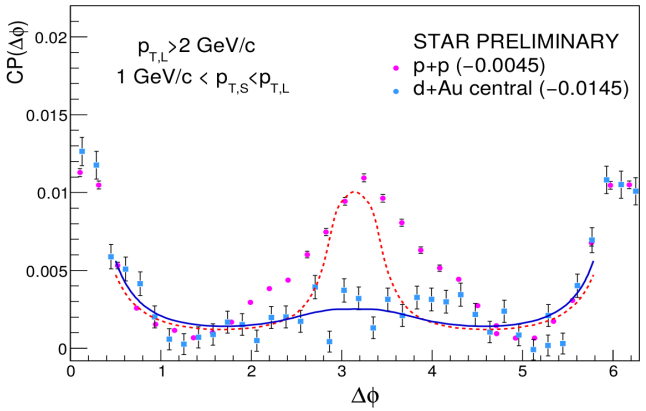
Set of basic TMD's relevant here

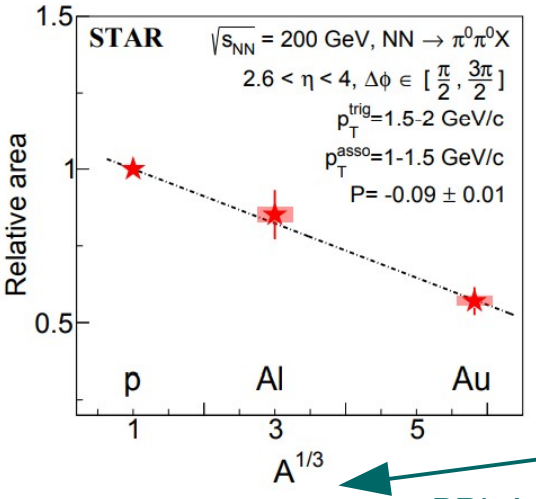


Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren '16 JHEP 1612 (2016) 034

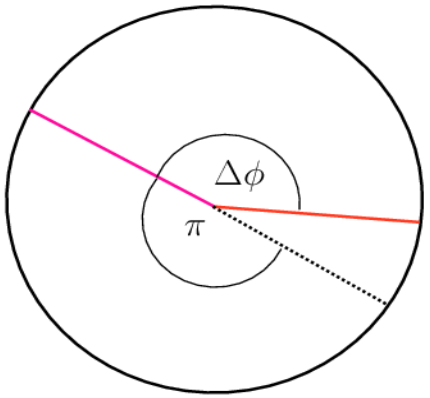
Selected hints of saturation



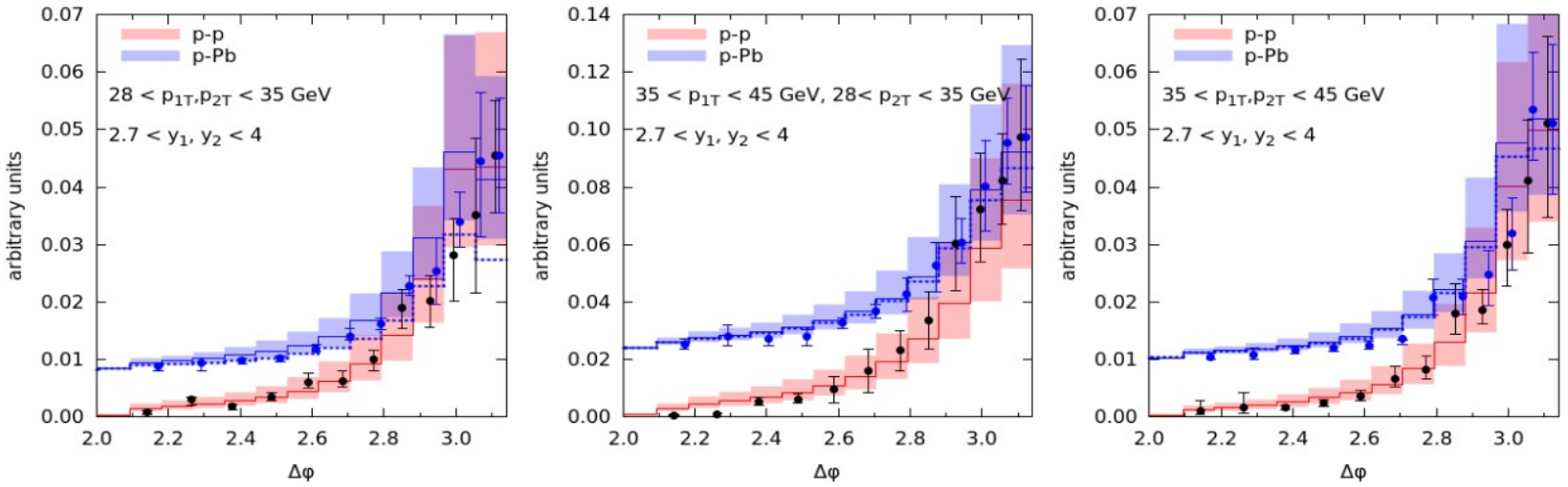
J. Albacete, C, Marquet
Phys.Rev.Lett. 105 (2010) 162301



PRL A 129 (2022) 9, 092501



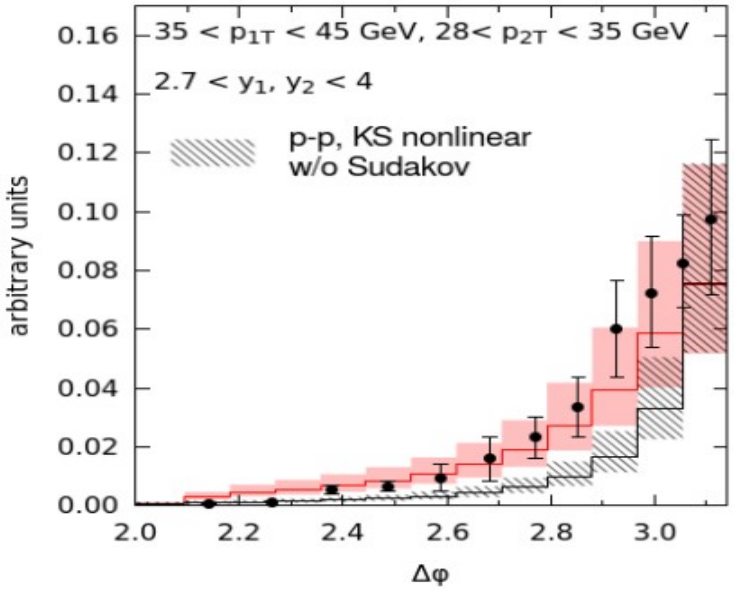
prediction of saturation

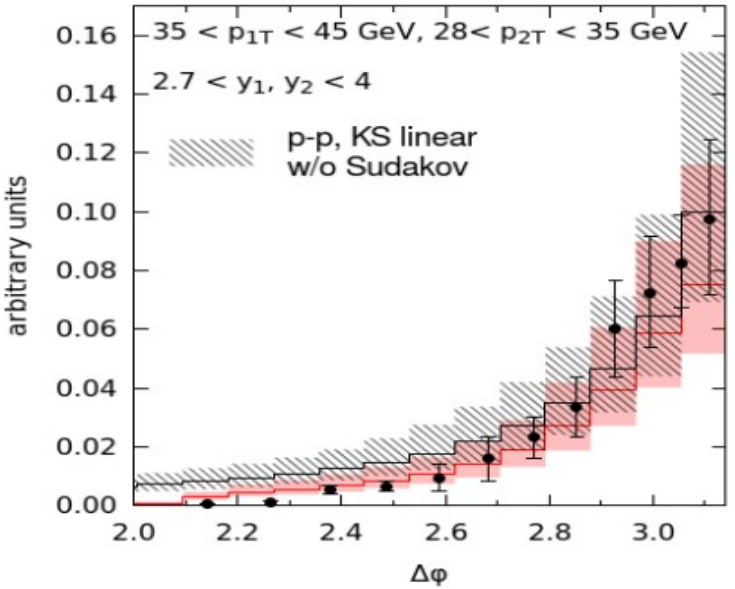


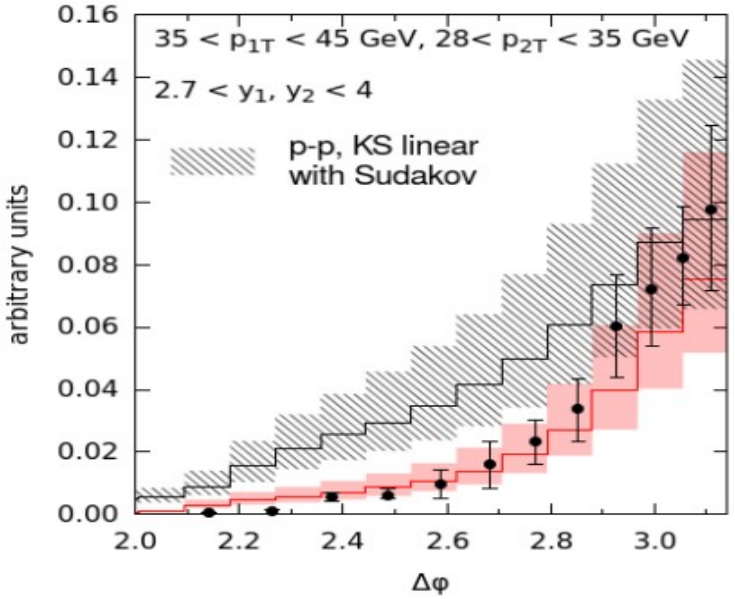
A. Hameren, P. Kotko, K. Kutak, S. Sapeta
Phys.Lett. B795 (2019) 511-515

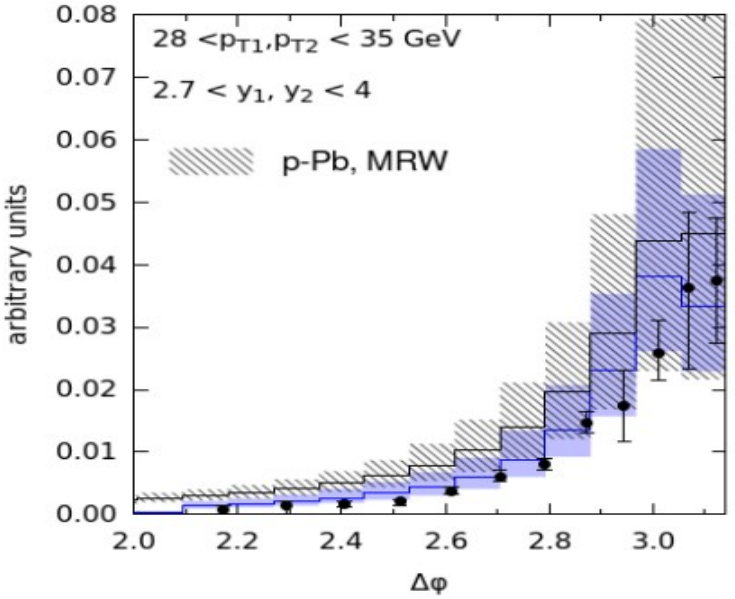
Other approaches

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

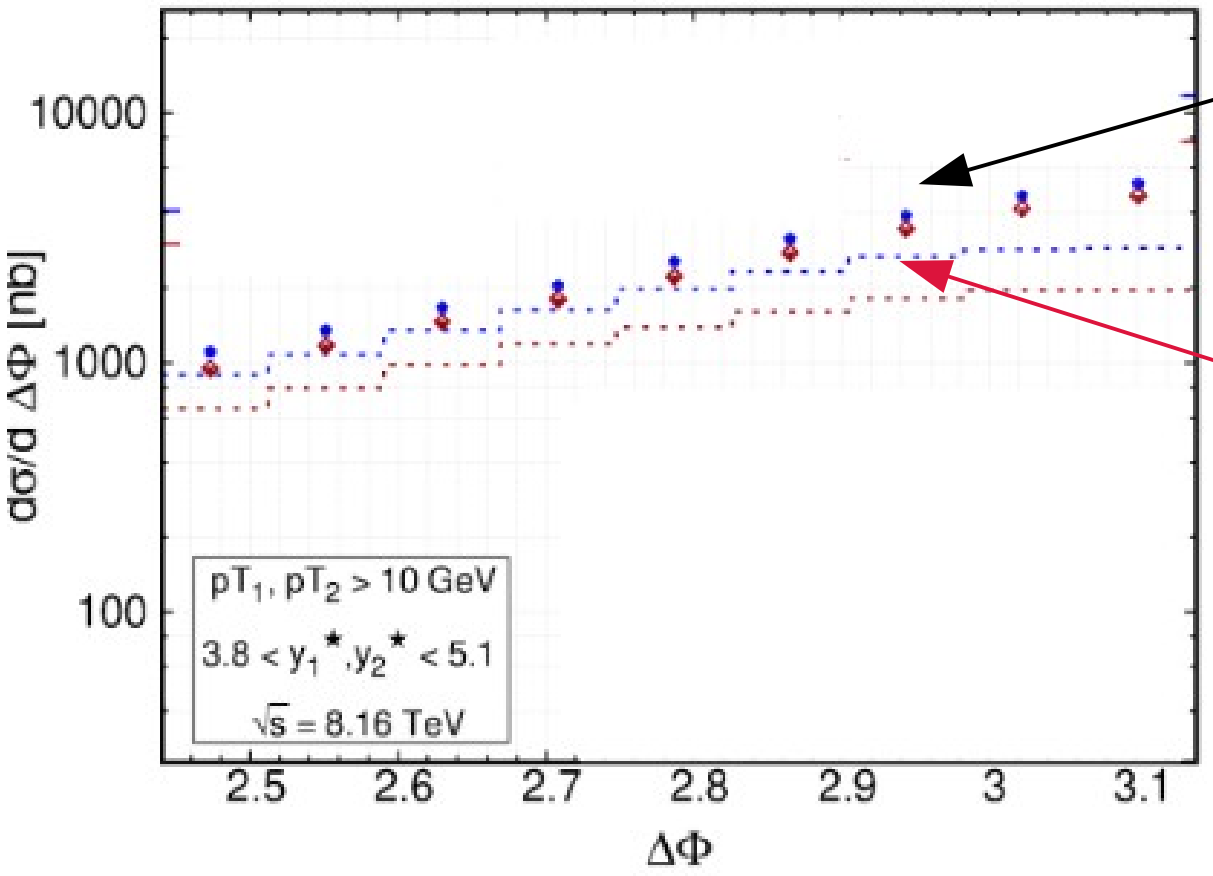






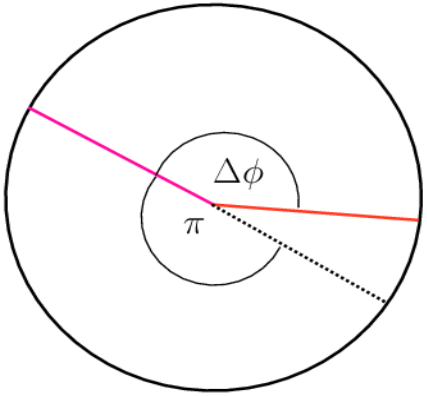


Dijets in FoCal - azimuthal angle dependence



PYTHIA
p-p
p-Pb

ITMD + FSR+had
p-p
p-Pb

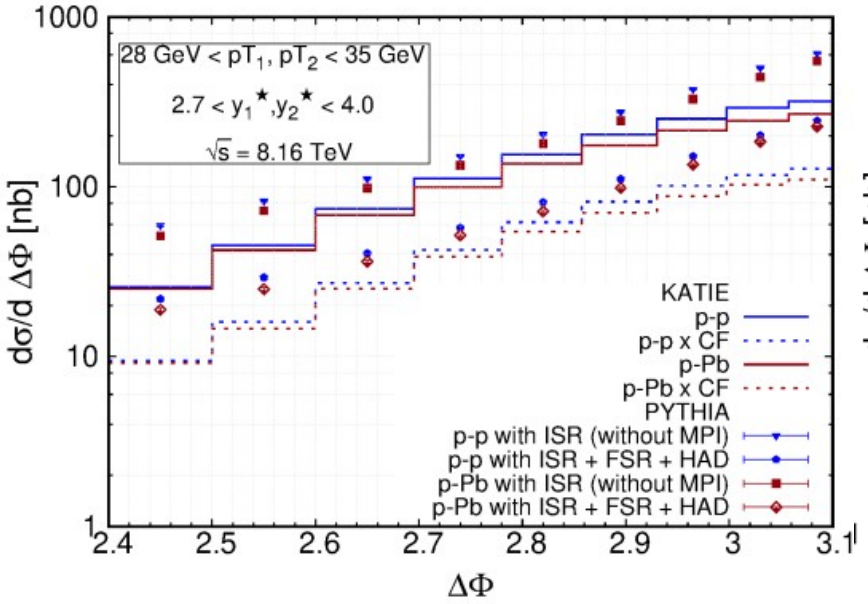


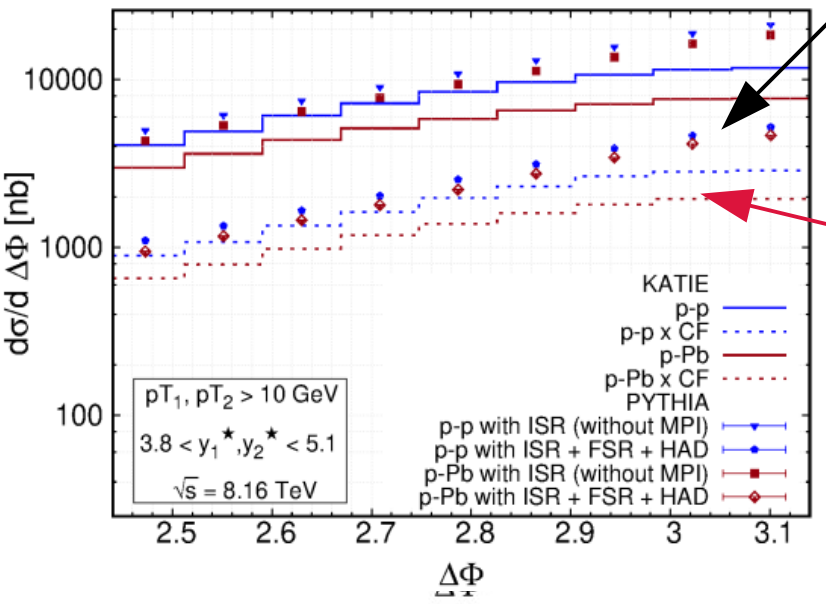
Larger suppression in ITMD factorization.

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

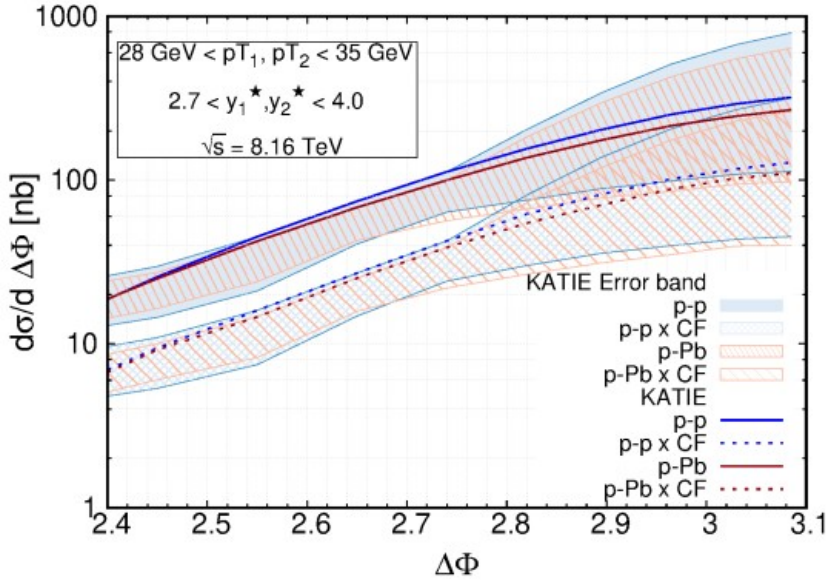
Azimuthal angle dependence ATLAS and ALICE

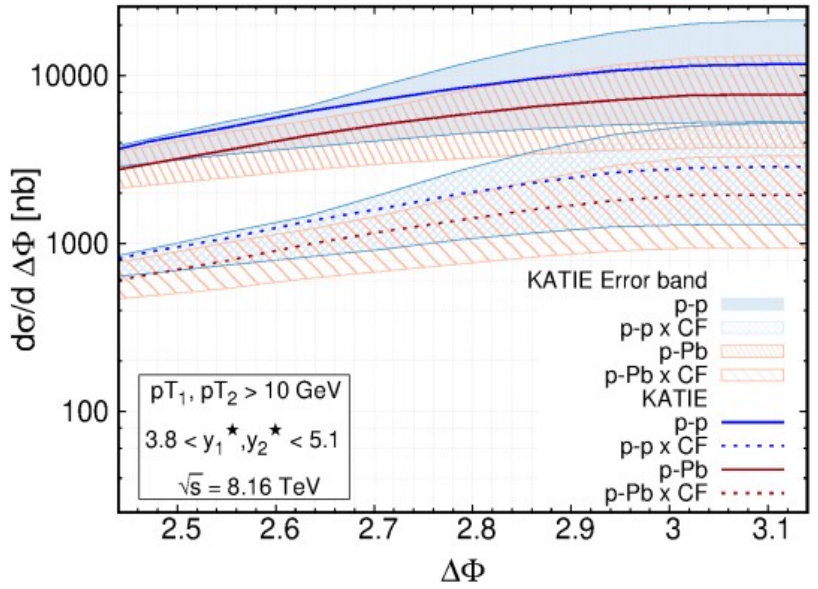




PYTHIA complete results
p-p
p-Pb

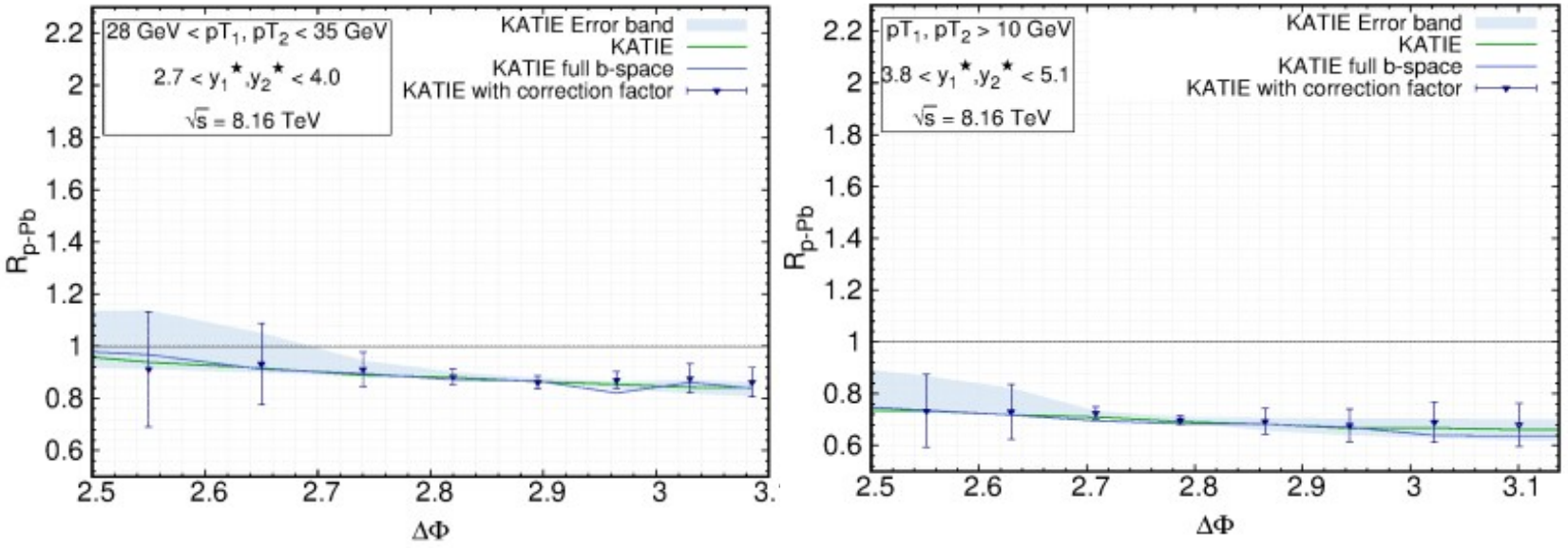
our complete results
p – p
p – Pb





our complete results with scale variation
p – p
p – Pb

Nuclear modification ratio



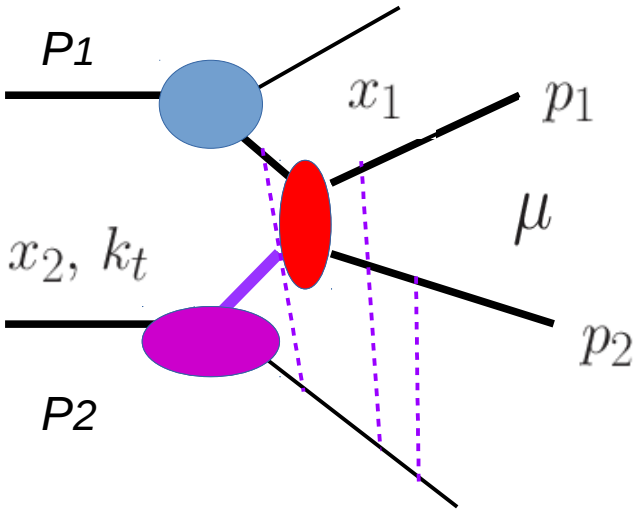
Visible suppression in both ATLAS and ALICE kinematical setup.

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

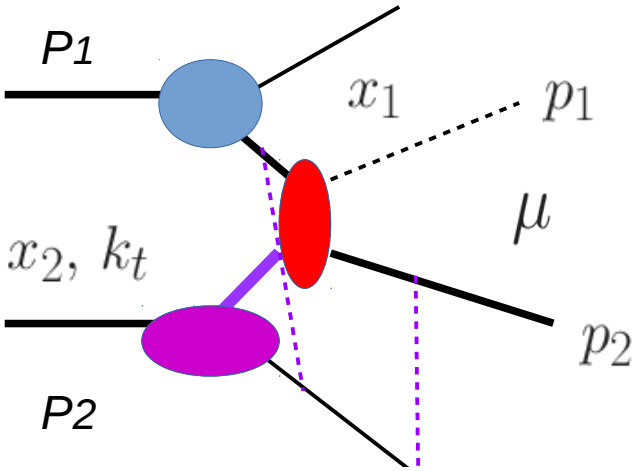
KaTie
Comput.Phys.Commun. 224 (2018) 371-380
A. van Hameren

Photon – jet final state

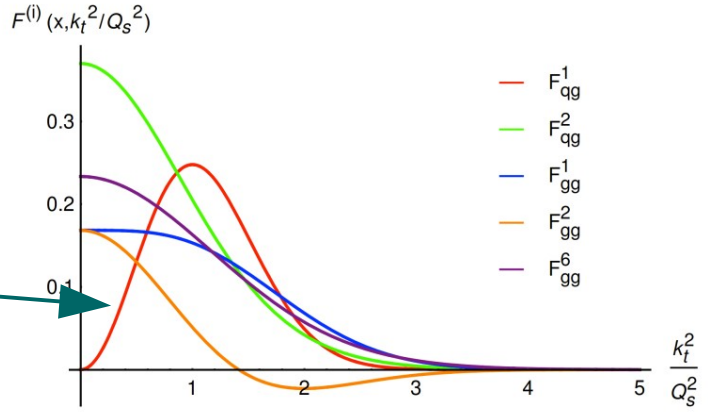
FS: Jet – Jet



FS: Jet – Photon

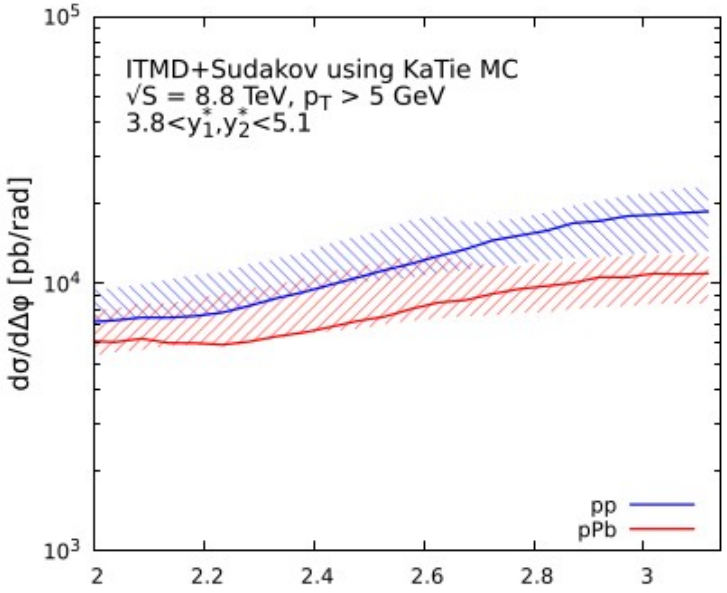


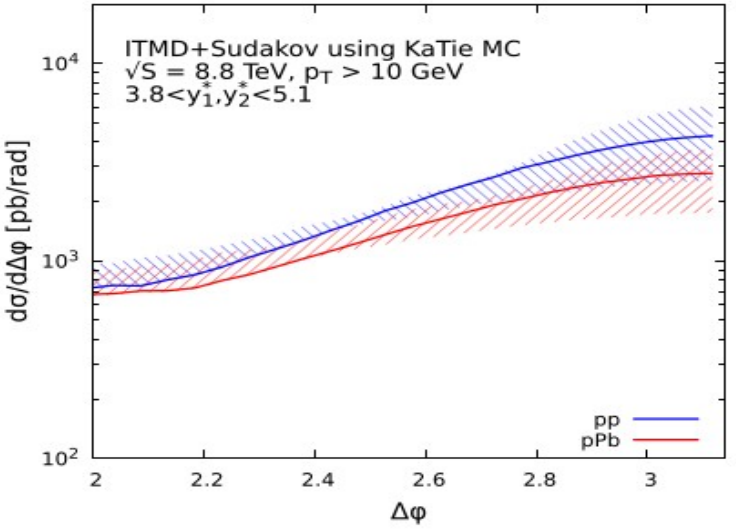
- Photon does not interact with remnant
- Factorization simplifies
- Only one type of TMD contributes
- It gives maximal saturation

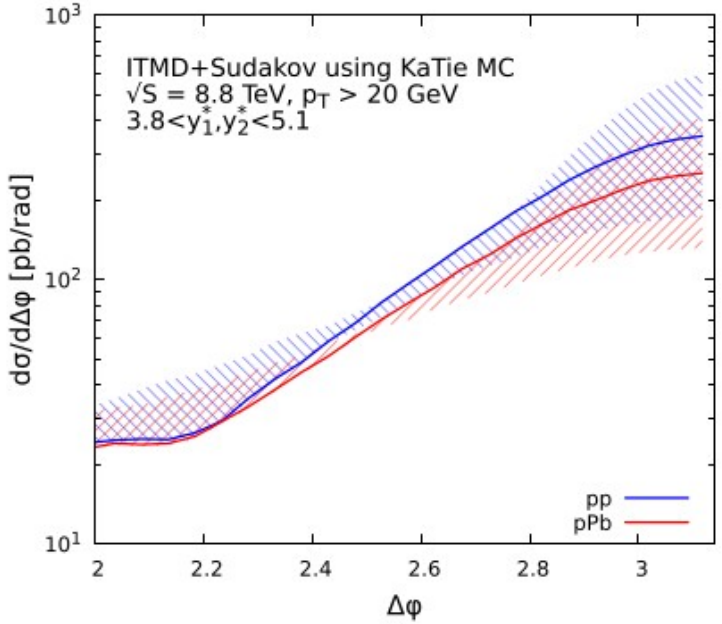


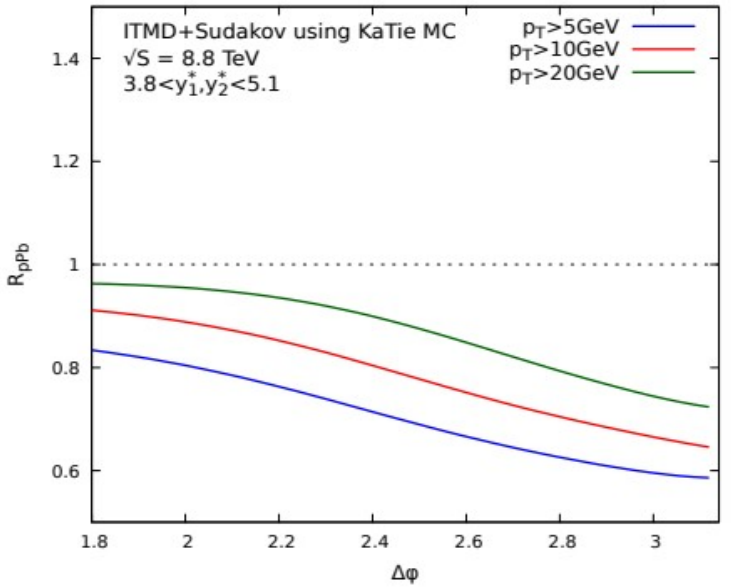
Photon and jet at LHC

Ganguli, van Hameren, Kotko, Kutak ‘24



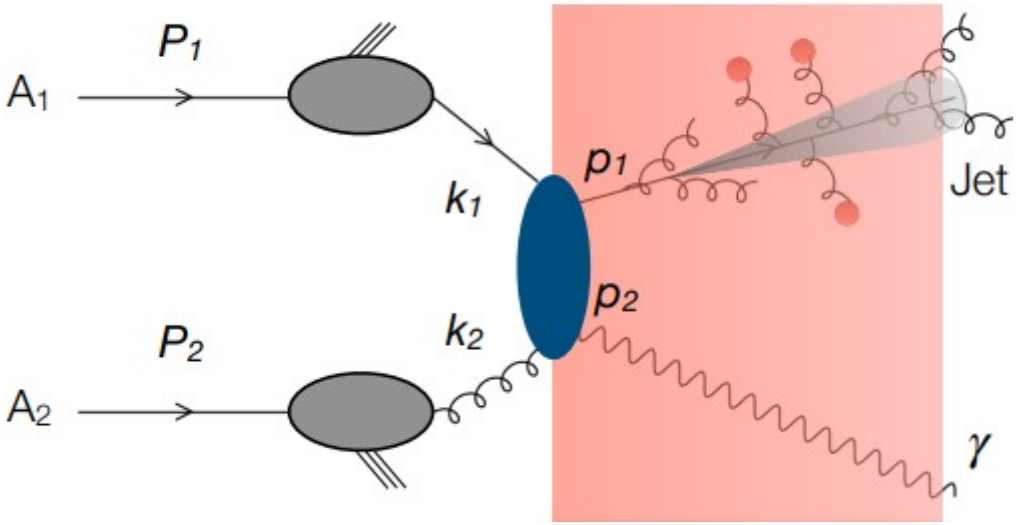






At small $p_{T\ clearly}$ visible suppression. The bands do not overlap

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

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

2409.06675
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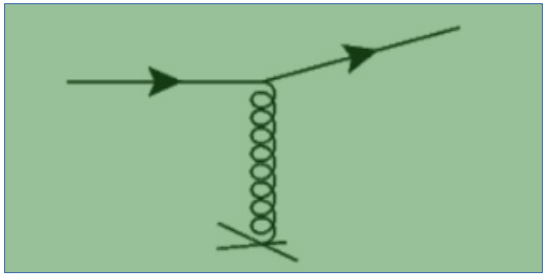
Jet medium interaction

scattering...

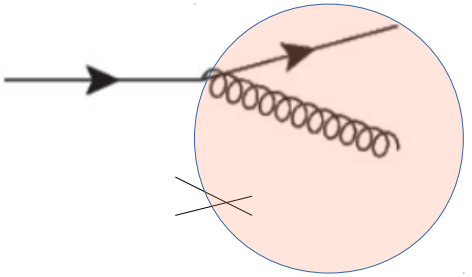


Transverse momentum transfer!

$p \to p + k_T$

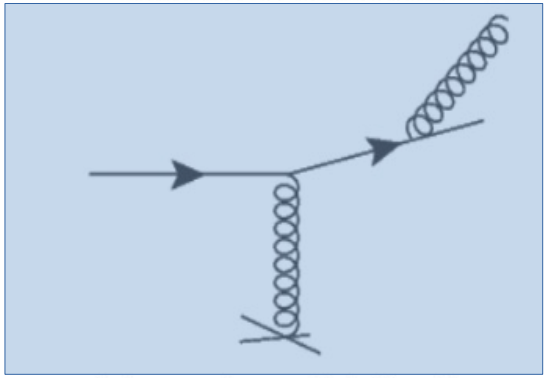
Scattering Kernel: $C(k_T)$

...splitting...



Bremsstrahlung as in vacuum.

...induced radiation



Momentum distribution:

$p \to zp$

Individual colors of partons may not be resolvable by medium particles

Blaizot, Dominguez, Iancu, Mehtar-Tani '12

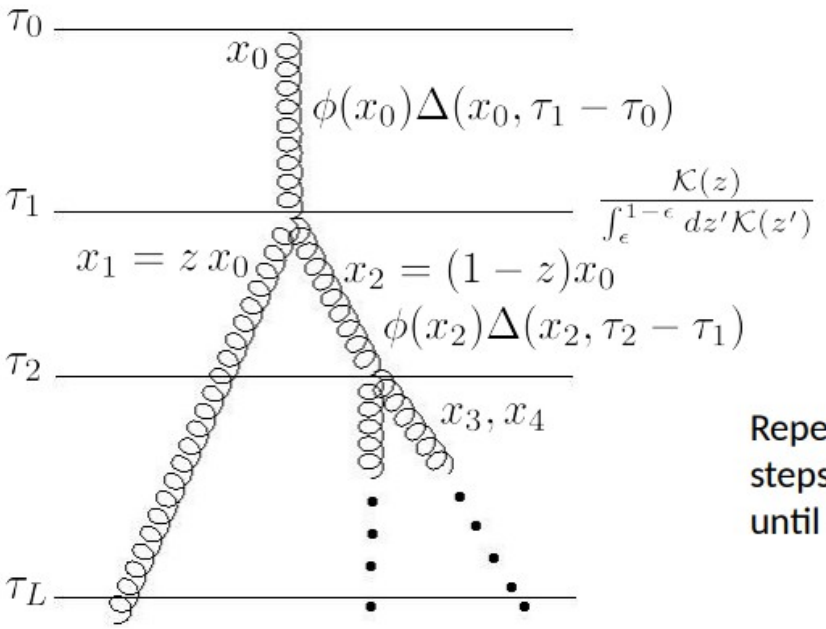
Average transfer: $\hat{q}$

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

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

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

Monte Carlo - TMDICE

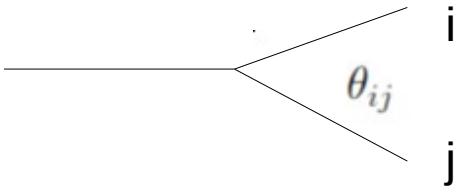


Repeat for all steps in τ and x until $\tau > \tau_L$

Other codes implementing BDMPS-Z spectra
MARTINI, JedMed,...

TMDICE code: [MR, arxiv: 2111.00323]
- Written in C++
- Source code available at

https://github.com/Rohrmoser/TMDICE



Individual colors of partons may not be resolvable by medium particles

No color resolution if

$t_{br} < t_{decoh}$

time of formation of radiation

Branching as in vacuum

See
Caucal, Iancu, Soyez, Mueller ‘18

Azimuthal angle decorelations – importance of vacuum like emissions and saturation

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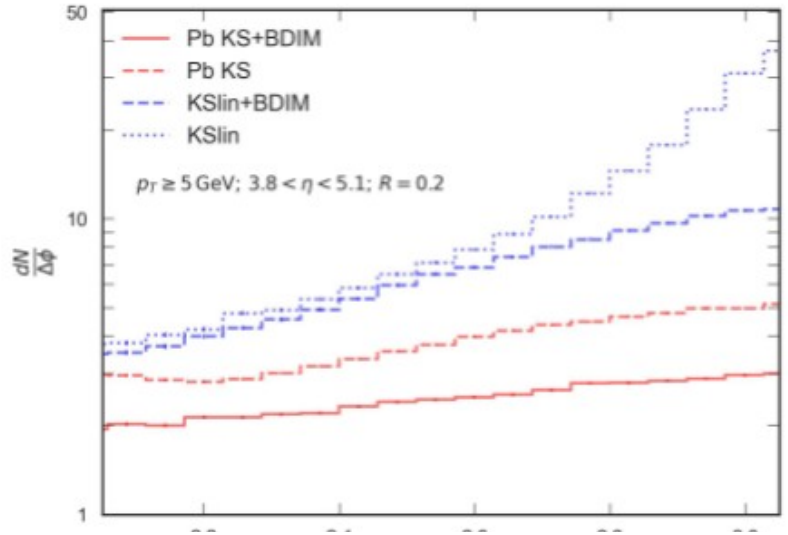
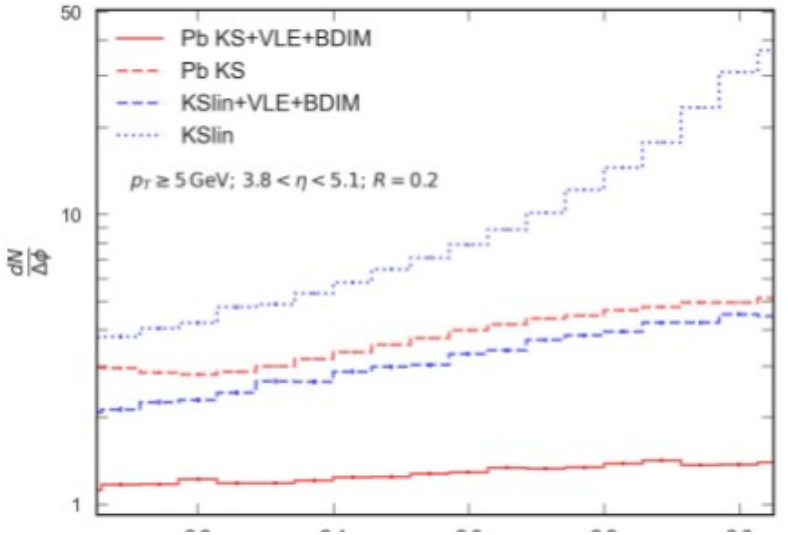
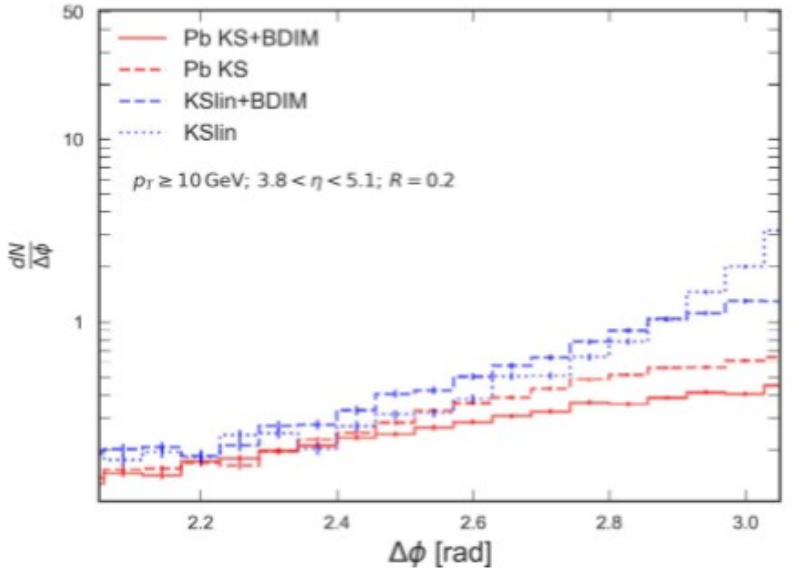
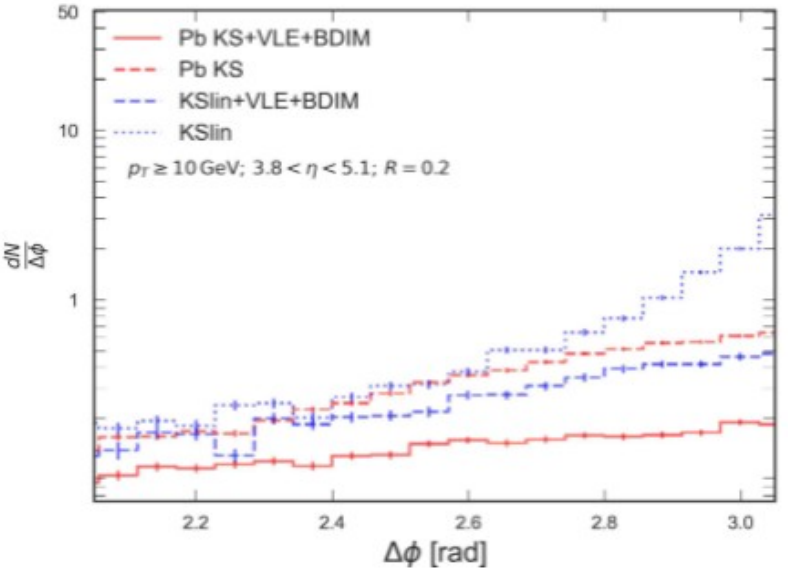
S. Adhya, K. Kutak, W. Płaczek,
M. Rohrmoser, K. Tywoniuk



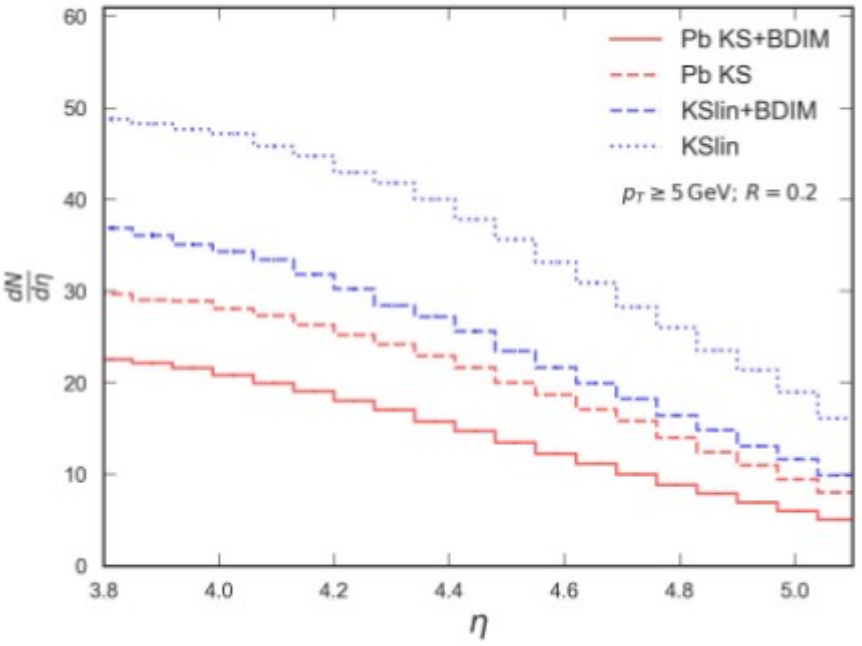


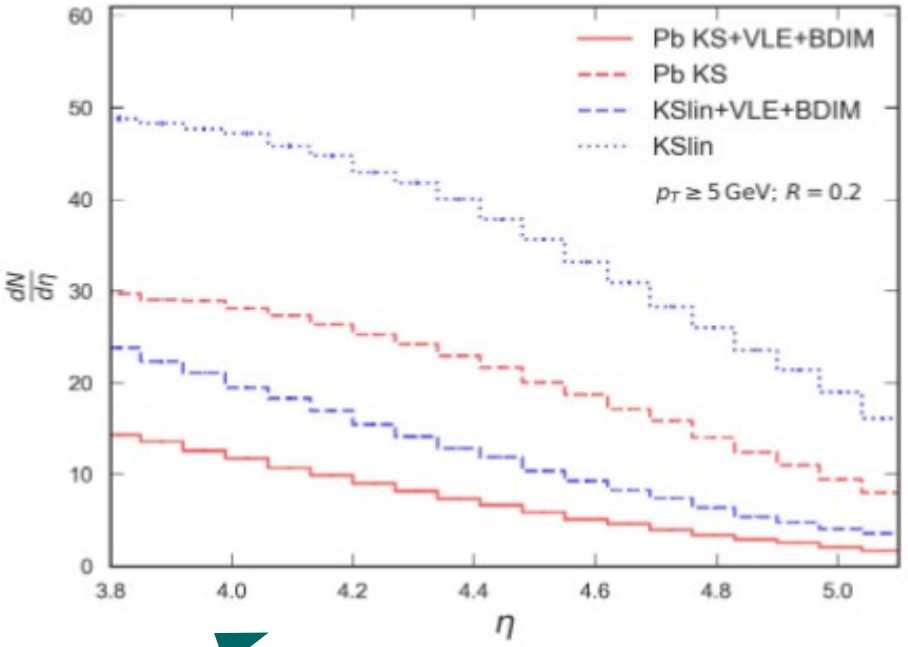
VLE





Rapidity spectra

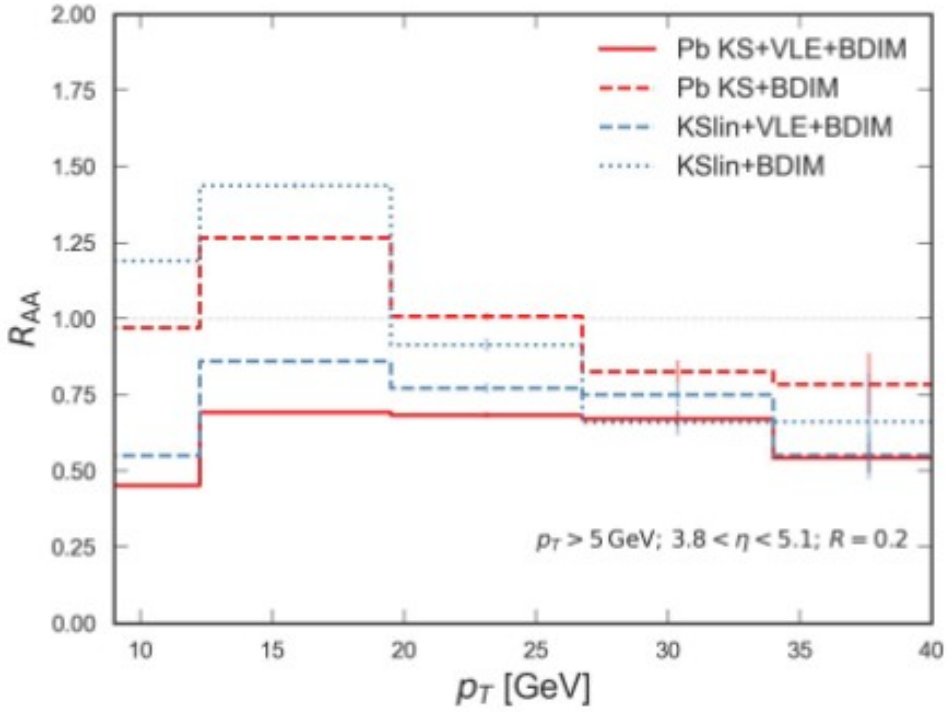




- VLE emissions accounted for
- large supression due to VLE

S. Adhya, K. Kutak, W. Płaczek, M. Rohrmoser, K. Tywoniuk ‘24

Nuclear modification ratio – relevance of VLE



- suppression due to quenching
- suppression due to saturation

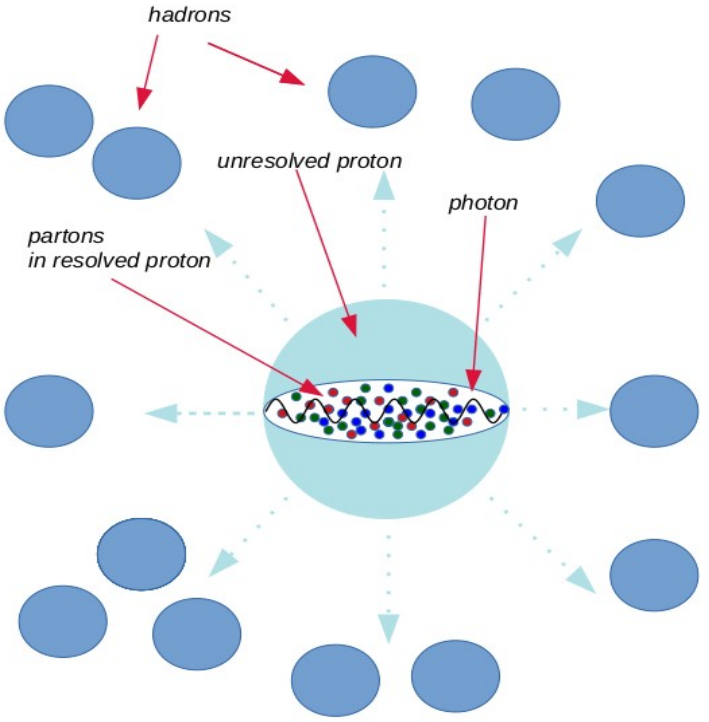
Entanglement entropy

Entanglement entropy – calculation and measurement

For DIS at high energies, this entanglement entropy can be calculated using

$$S(x,Q^2) = \ln \left\langle n\left(\ln\frac{1}{x}, Q\right)\right\rangle$$

Calculated using parton/dipole density



Conjecture that these entropies are the same

$$S_{hadron} = \sum P(N) \ln P(N)$$

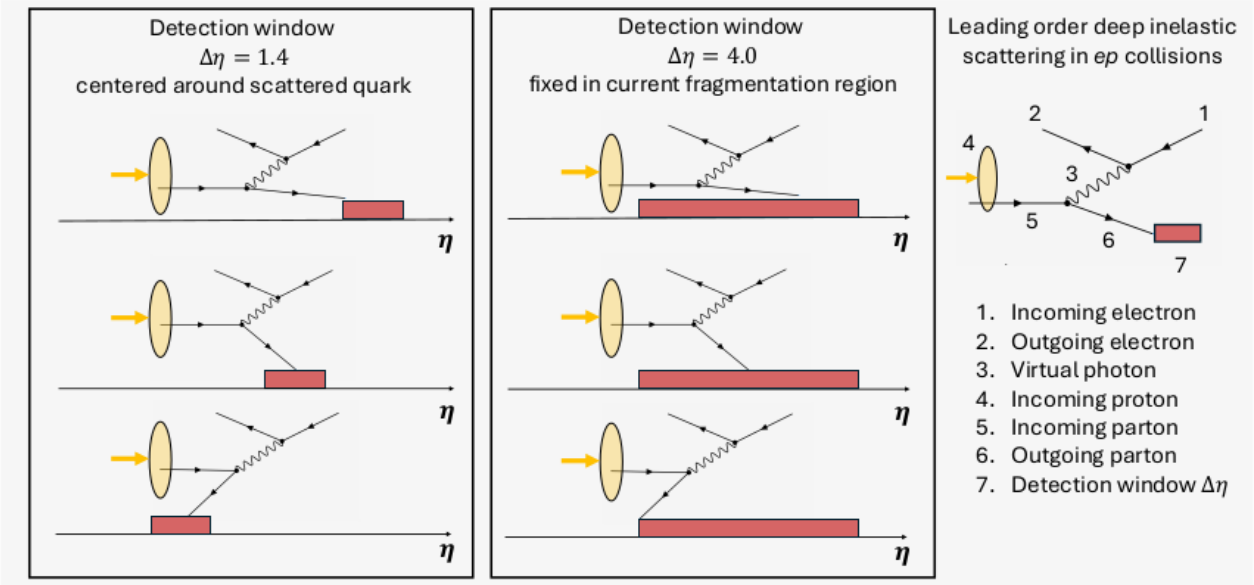
Measured by counting hadrons

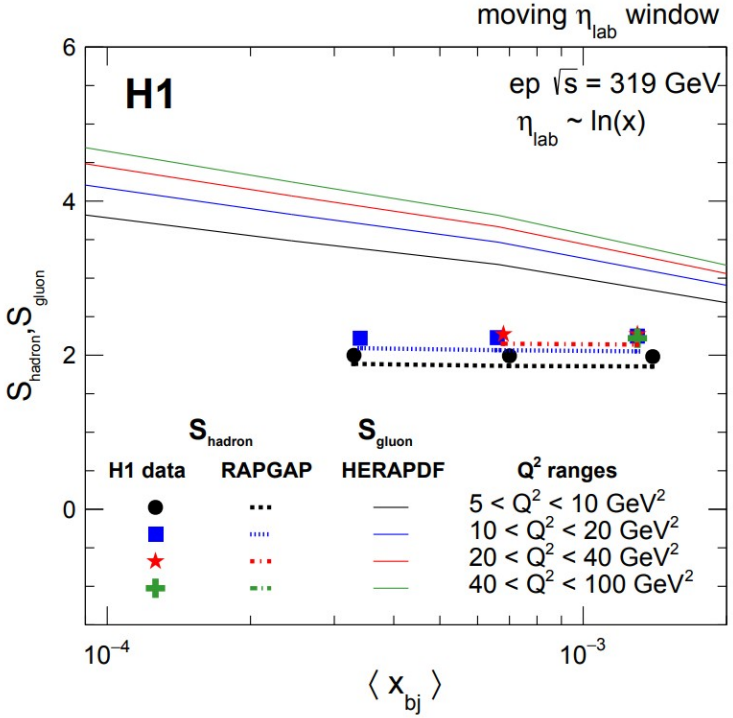
number of measured hadrons

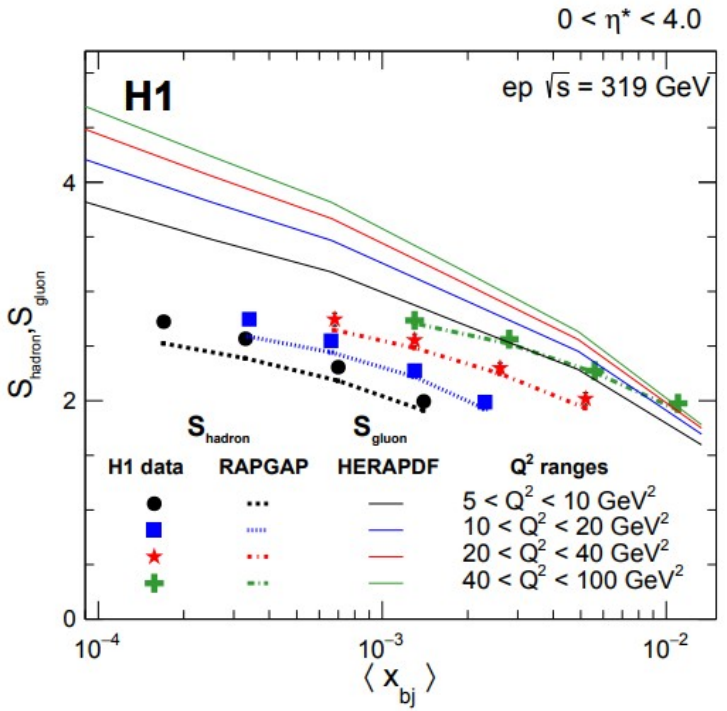
The charged particle multiplicity distribution measured in either the current fragmentation region or the target fragmentation region.

Fraction of events with charged hadron

Entropy measurements

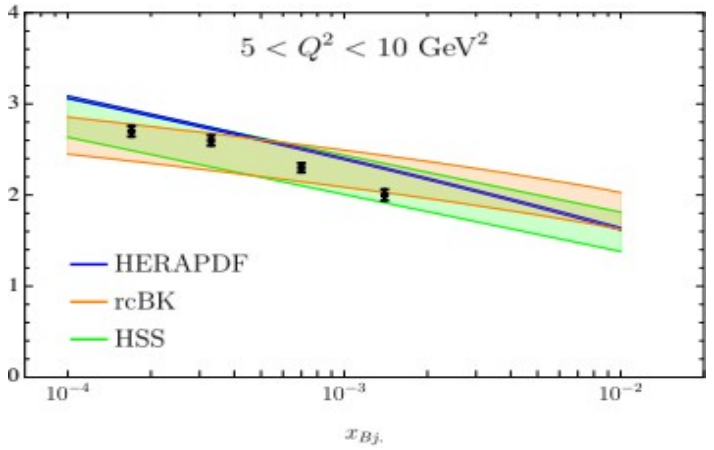


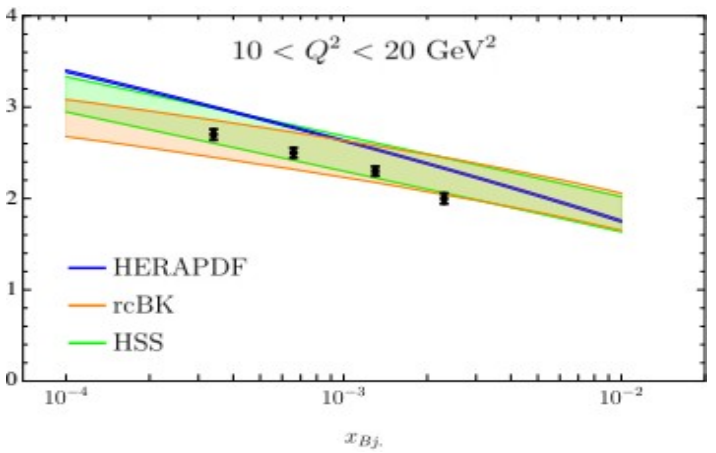


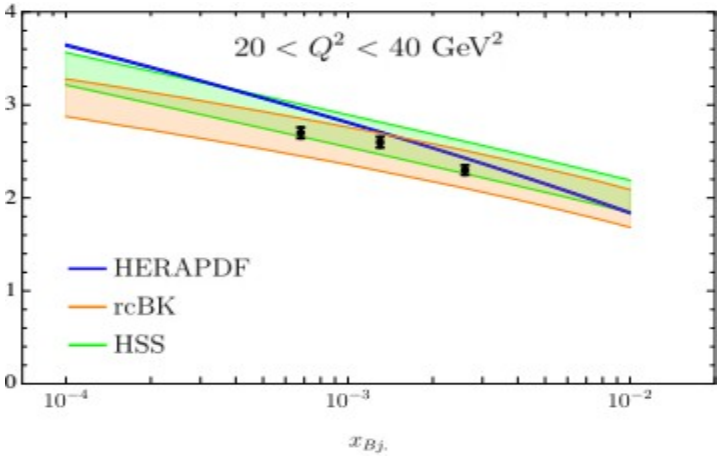


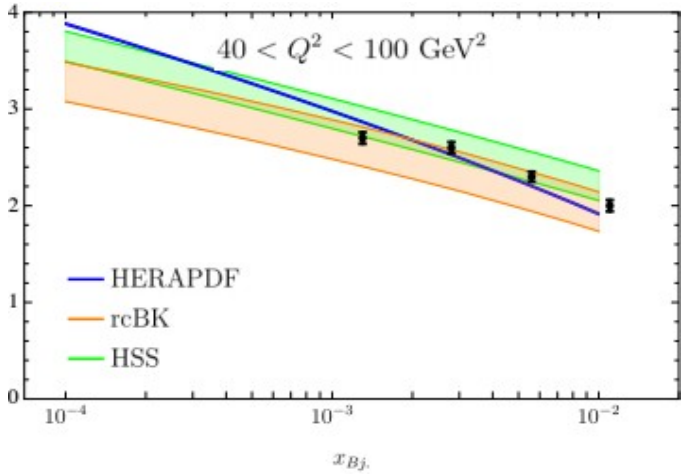
Large scales - description

Martin Hentschinski, KK, Robert Straka ‘23

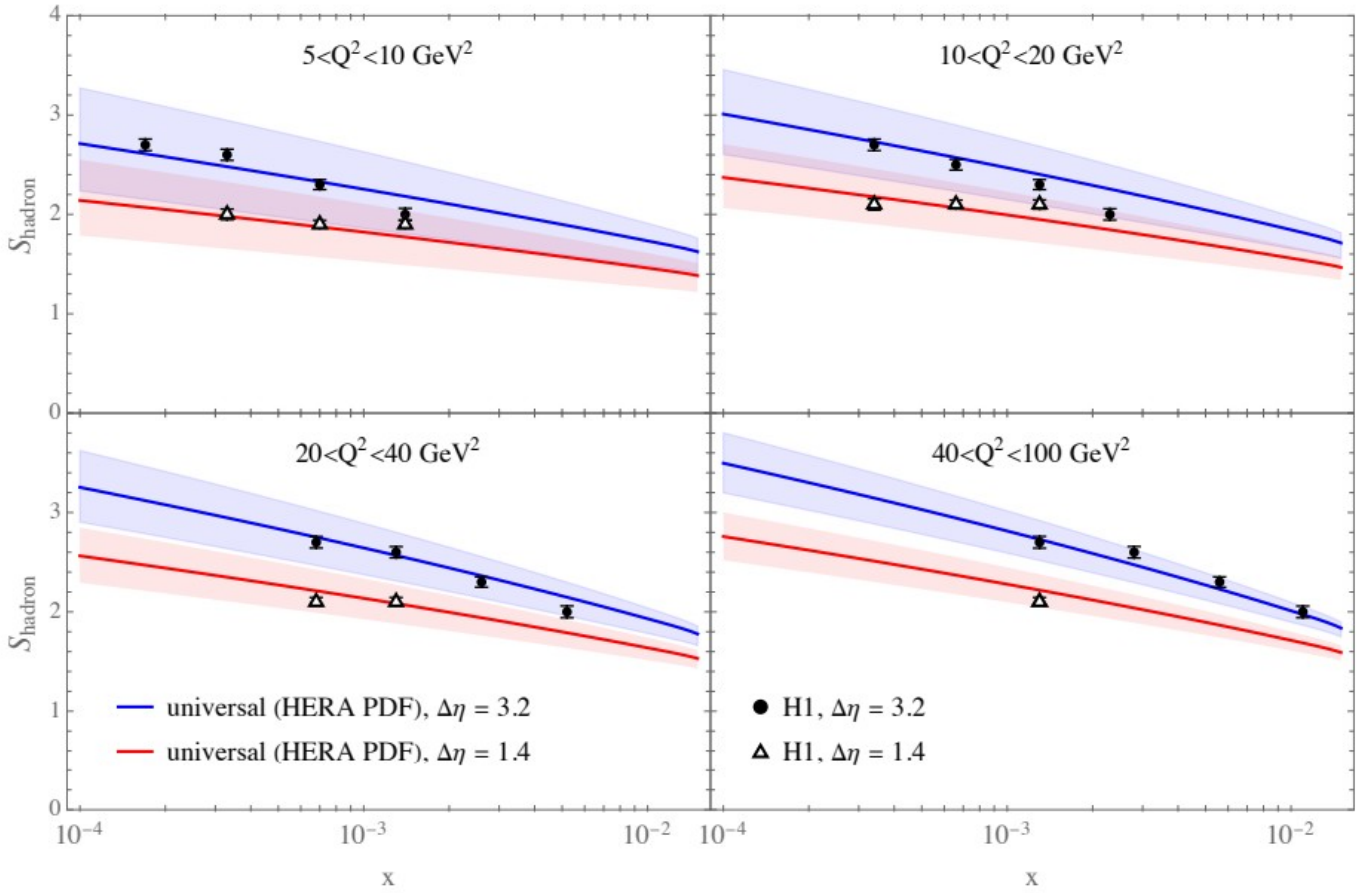






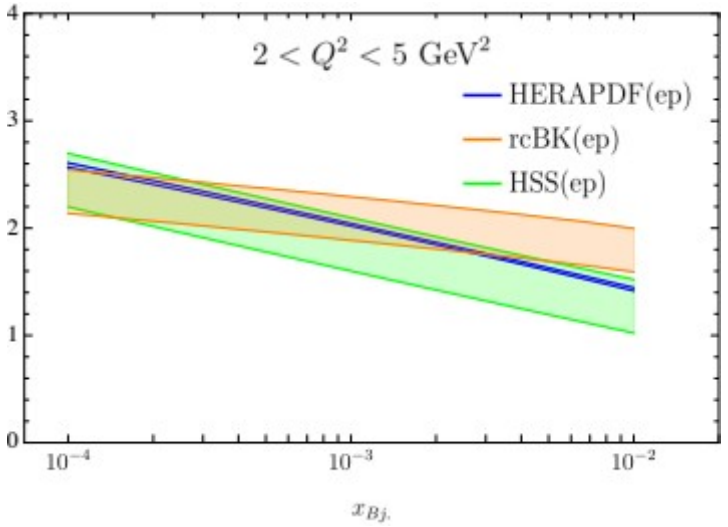


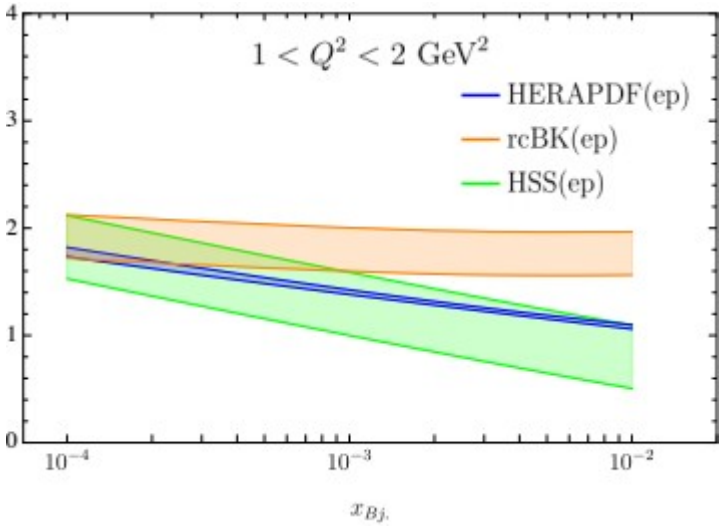
Fixed and moving rapidity window



Rept.Prog.Phys. 87 (2024) 12, 120501
M. Hentschinski, D. Kharzeev, K. Kutak, Z. Tu

Small scales - prediction





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M. Hentschinski, K. Kutak
PRL'23
M. Hentschinski, D. Kharzeev, K. Kutak, Z. Tu
PRD '24
P. Caputa, K. Kutak
Rept.Prog.Phys. 87 (2024) 12, 120501
M. Hentschinski, D. Kharzeev, K. Kutak, Z. Tu

It would be very interesting to study the EE at forward rapidities at LHC

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 final. The plans include accounting for higher order corrections, new fits of TMD, accounting for expansion of medium and rapidity dependent medium