Predictions for photon-jet correlations at forward rapidities in heavy-ion collisions

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

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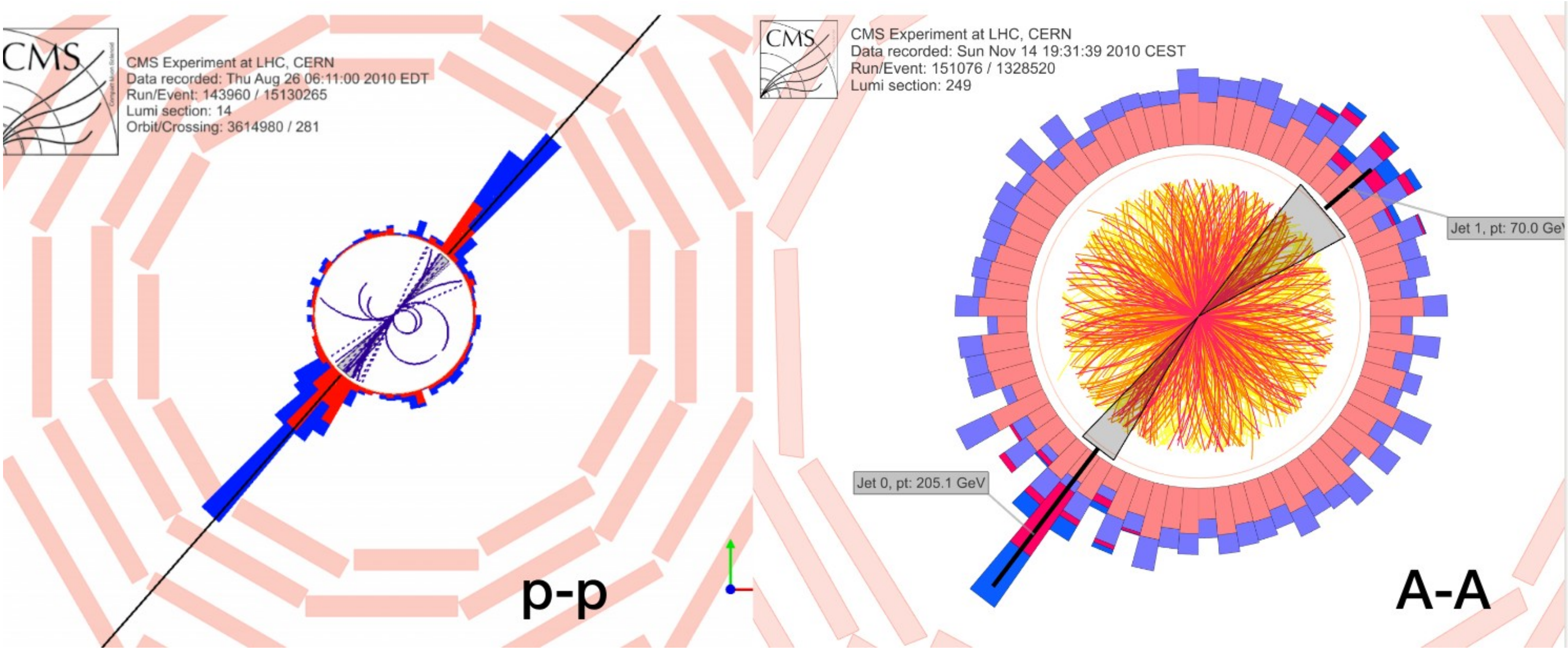
NCN

The results are based on

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

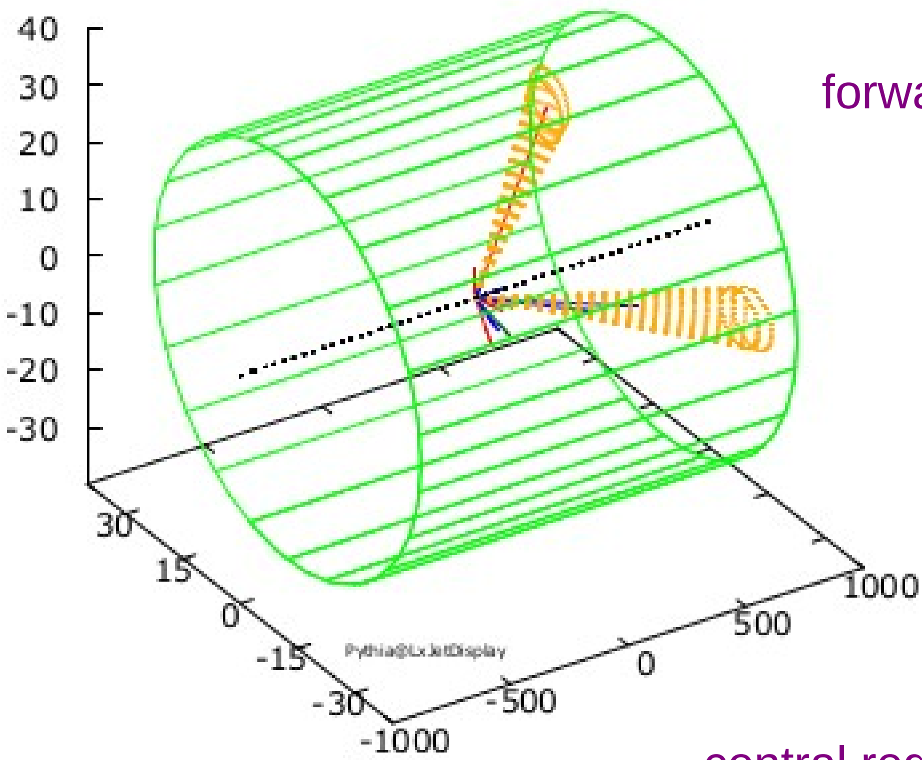
2409.06675
S. Adhya, K. Kutak, W. Płaczek, M. Rohrmoser, K. Tywoniuk

Vacuum and medium processes



and **p - Pb**

Dilute-dense: forward-forward



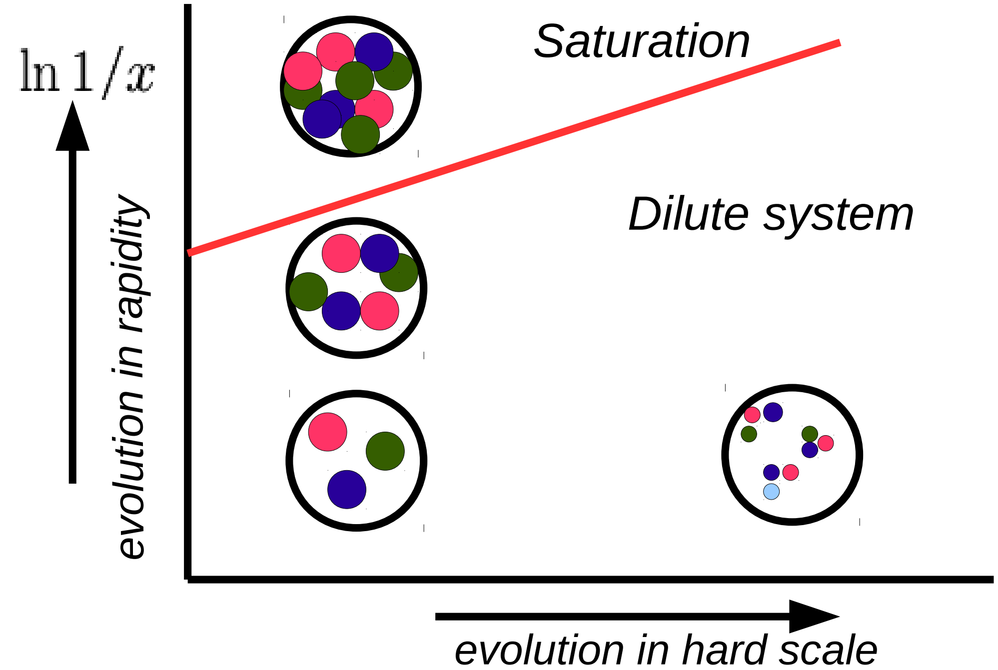
forward region

central region

From: Piotr Kotko

There is certain class of processes where one can assume that partons in one of hadrons are just collinear with hadron and in other are not

Gluons at high energies 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.

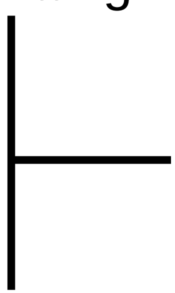
L.V. Gribov, E.M. Levin, M.G. Ryskin
Phys.Rept. 100 (1983) 1-150

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

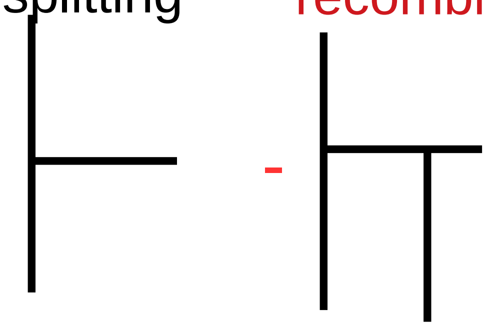
splitting



Nonlinear evolution equations
BK, JIMWLK
Balitcky-Kovchegov,

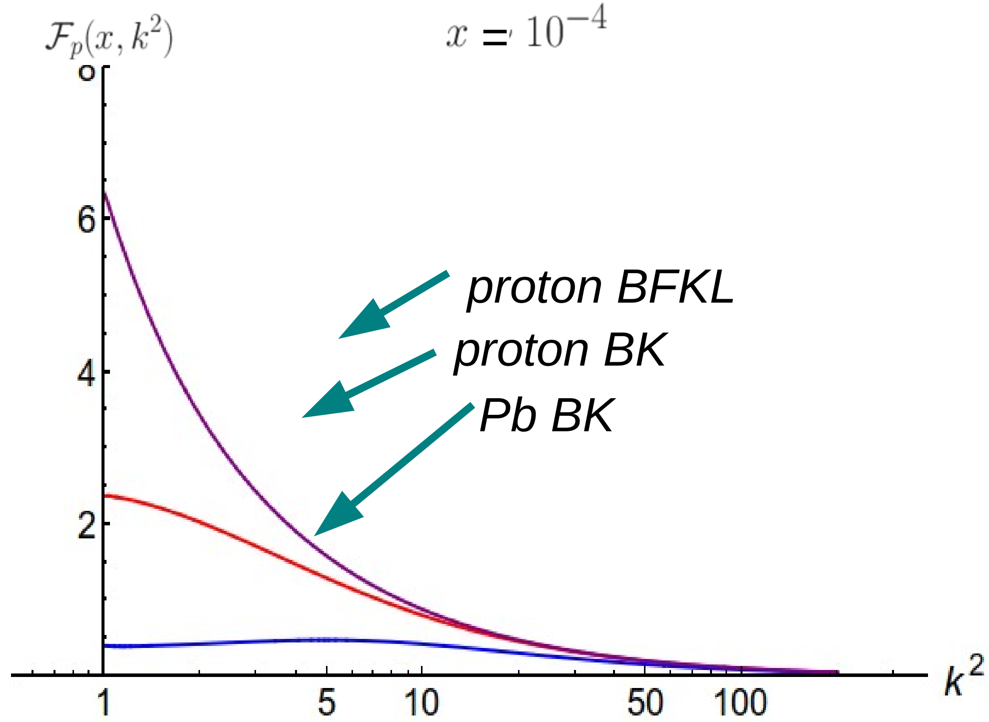
Jailian-Marian,Iancu
McLerran,Weigert,Leonidov,Kovner

splitting recombination



Bartels,
Wusthoff ‘93

Gluons at high energies and saturation



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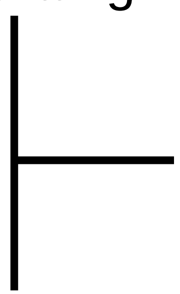
Momentum space picture:

splitting

Linear evolution
Equation
BFKL



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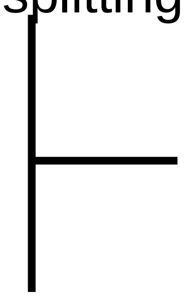

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Bartels, Wusthoff'93

Framework to be used

ITMD = small x Improved Transverse Momentum Dependent factorization

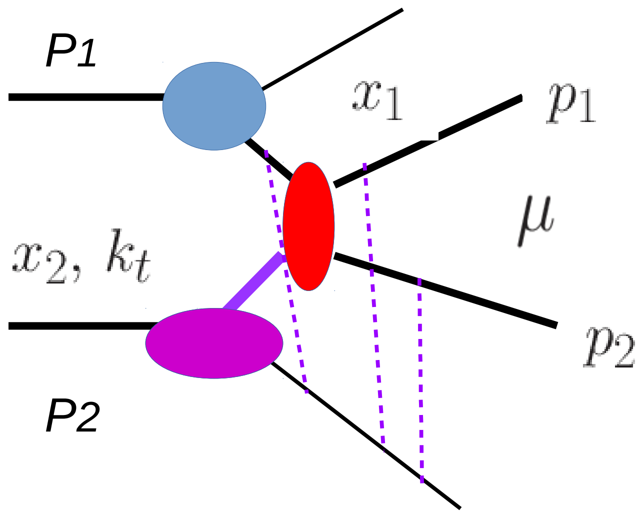
- accounts for saturation
- correct gauge structure i.e. uses gauge links to define TMD's
- takes into account kinematical effects – the whole phase space is available at LO
- valid in region $p_T > Q_s$, k_T can by any. p_T is hard final state momentum, k_T is inbalance

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 Hameren, JHEP 1509 (2015) 106

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

The ITMD factorization



- 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

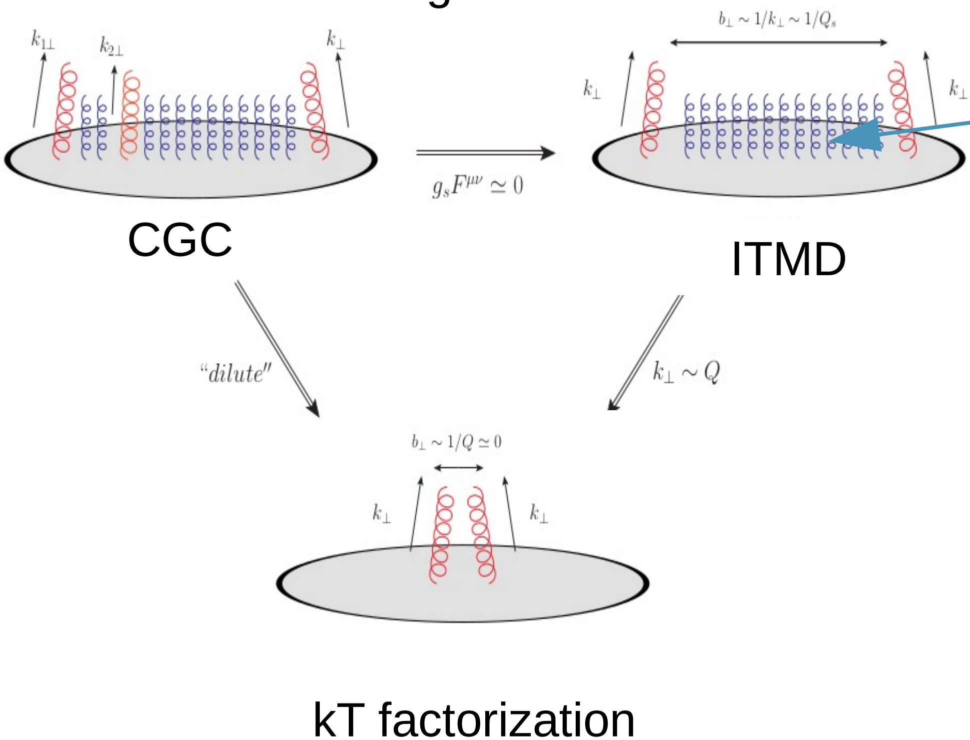
Example for g* g → g g

$$\frac{d\sigma^{pA\to ggX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2}\, x_1 f_{g/p}(x_1,\mu^2) \sum_{i=1}^{6} \mathcal{F}_{gg}^{(i)} H_{gg\to gg}^{(i)}$$

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

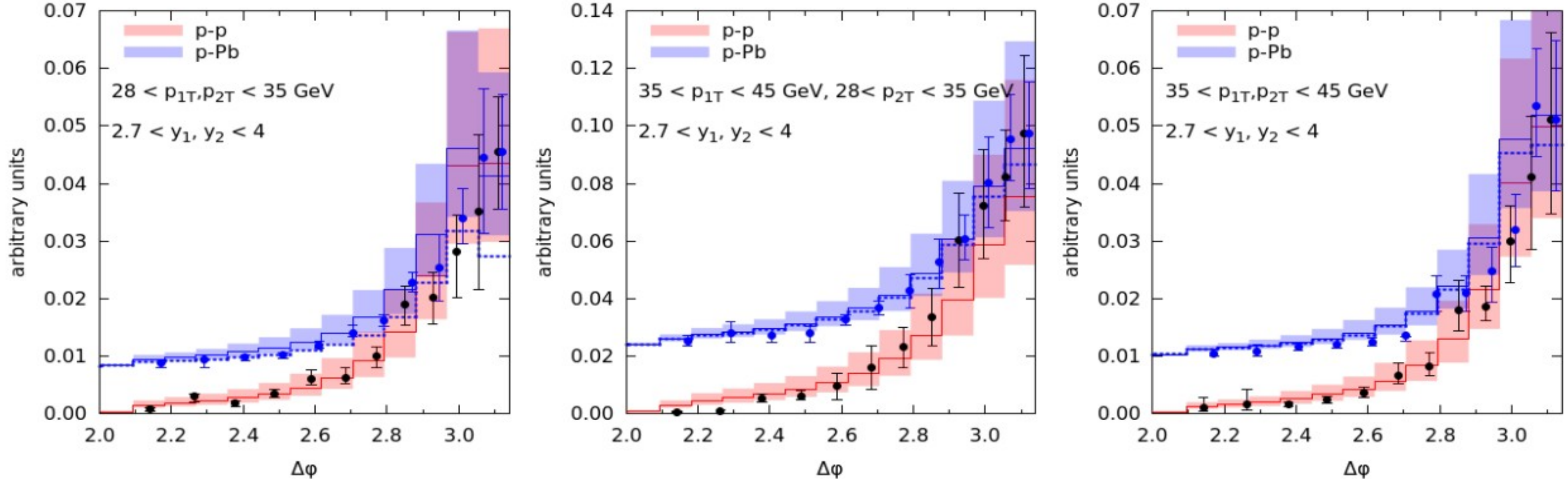


Multiple soft emissions

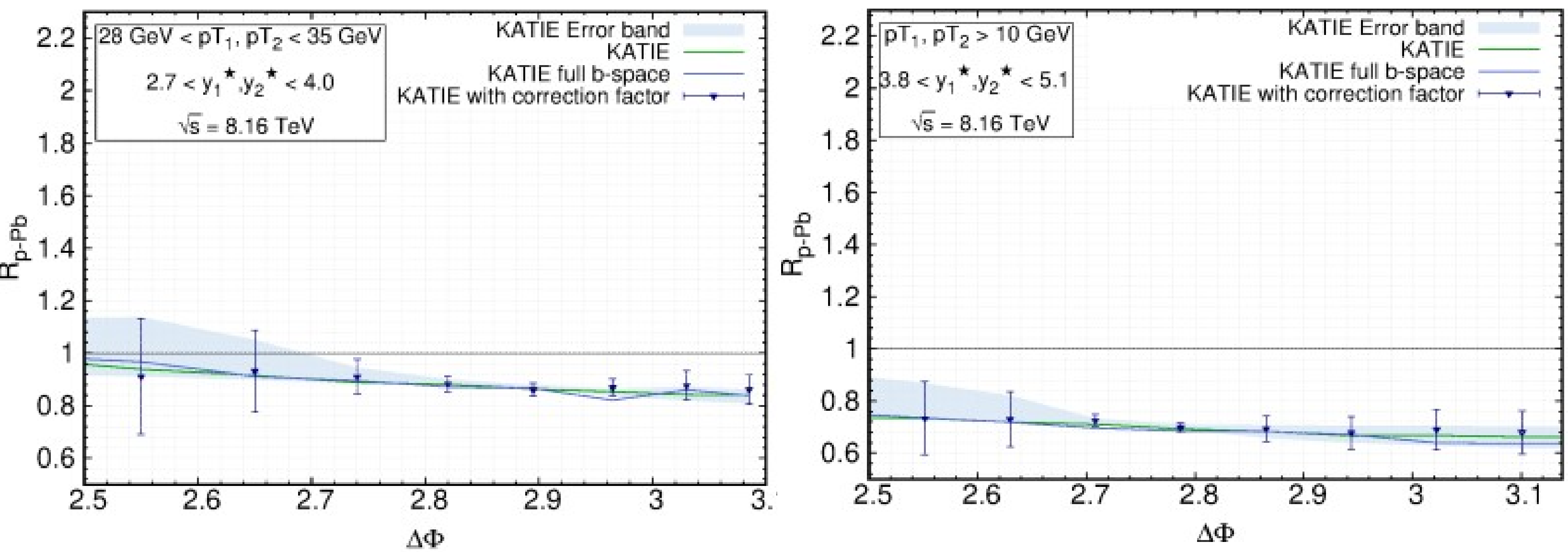
from R. Boussarie
Initial Stages 2019

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

ITMD - and di-jets



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

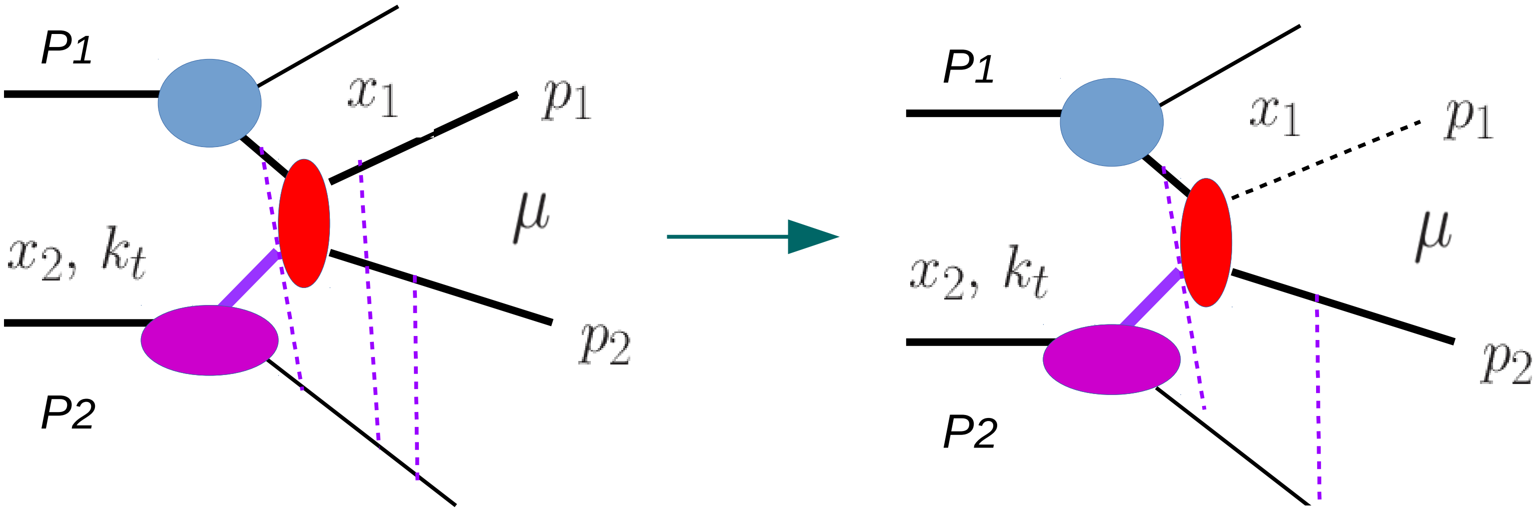


$$R_{\mathrm{p-Pb}} = \frac{\frac{d\sigma^{p+Pb}}{d\mathcal{O}}}{A\frac{d\sigma^{p+p}}{d\mathcal{O}}}$$

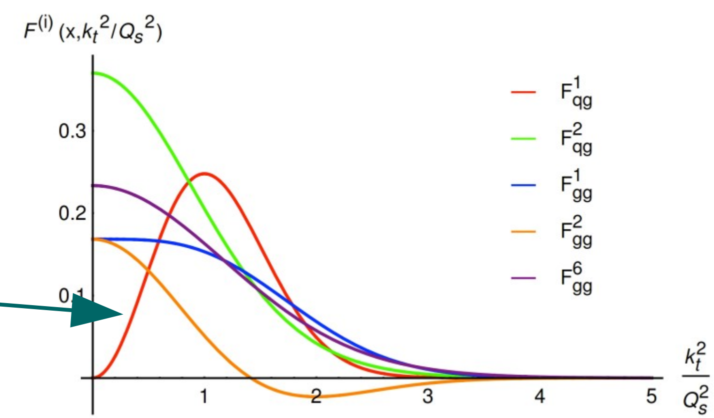
Photon – jet final state

FS: Jet – Jet

FS: Jet – Photon



- Photon does not interact with remnant
- Factorization simplifies ITMD and CGC are equivalent for this final state
- Only one type of TMD contributes
- In CGC language this means that quadrupole does not contribute
- It gives maximal saturation

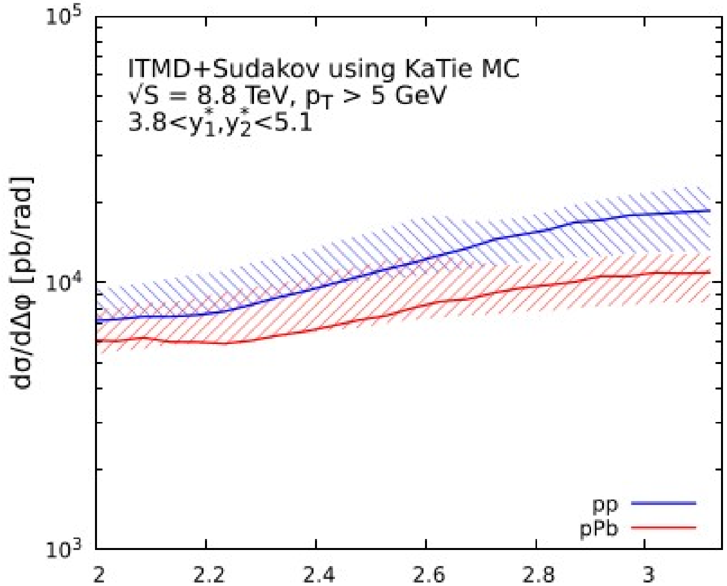


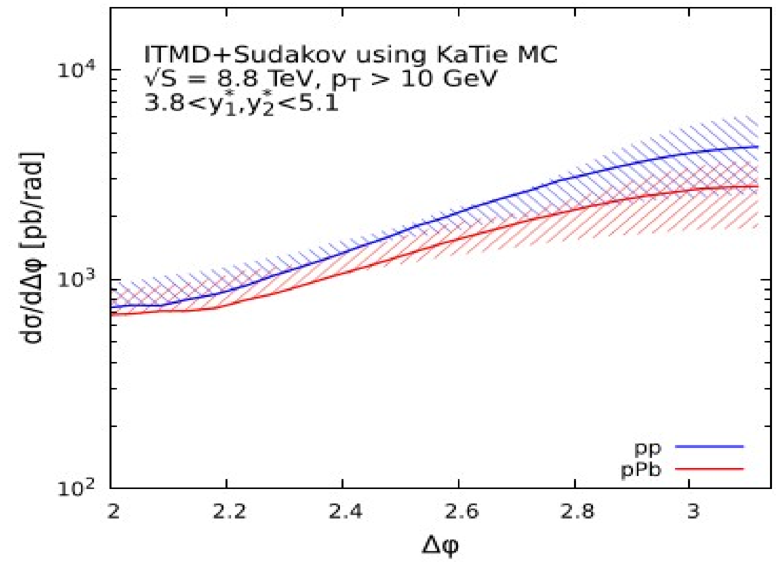
$$\frac{d\sigma^{AA\to\gamma+\mathrm{jet}+X}}{dy_1 dy_2 dp_{1T} dp_{2T} d\Delta\phi} = \frac{p_{1T}p_{2T}}{8\pi^2(x_1x_2s)^2}\sum_a x_1 f_{a/A}(x_1,\mu_F^2)|\mathcal{M}^{\mathrm{off-shell}}_{ag^*\to\gamma a}|^2\mathcal{F}(x_2,k_{2T}^2,\mu_F^2)$$

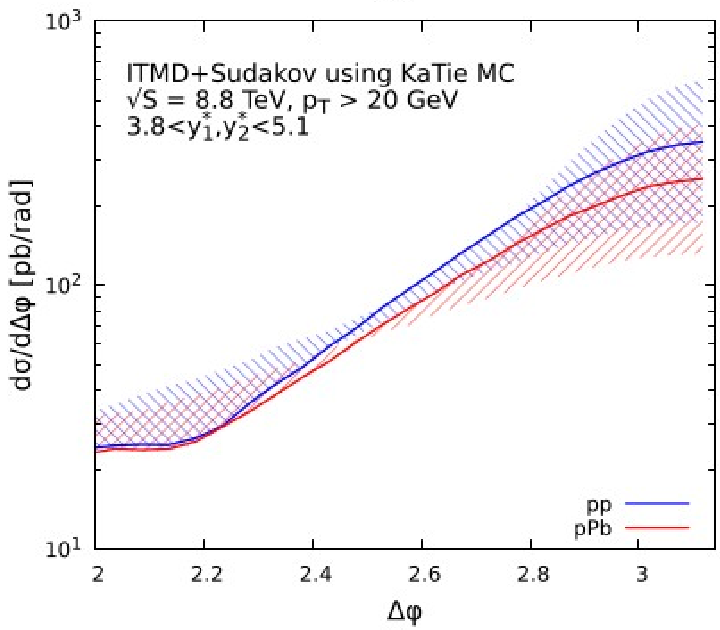
See also J. Jalilian-Marian and A. H. Rezaeian '12, Benic, Garcia-Montero, Perkov '22,...

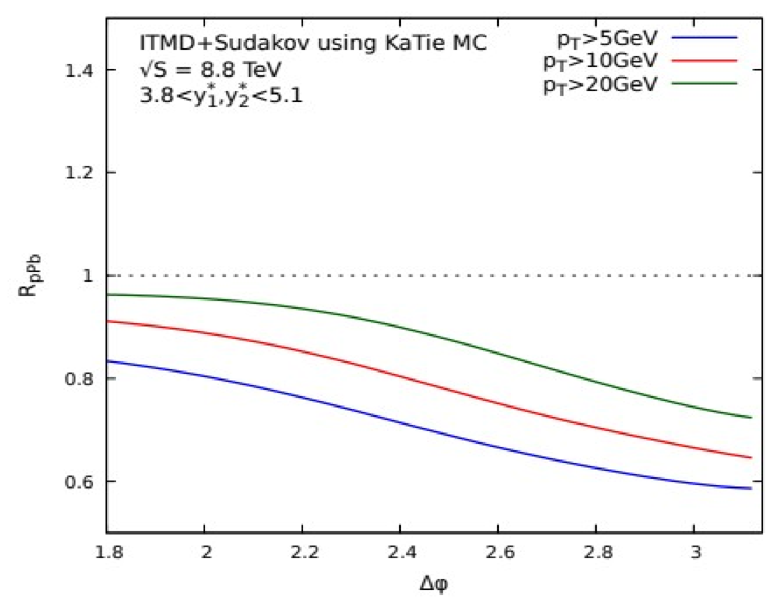
Photon and jet in FoCal

Ganguli, van Hameren, Kotko, Kutak ‘24



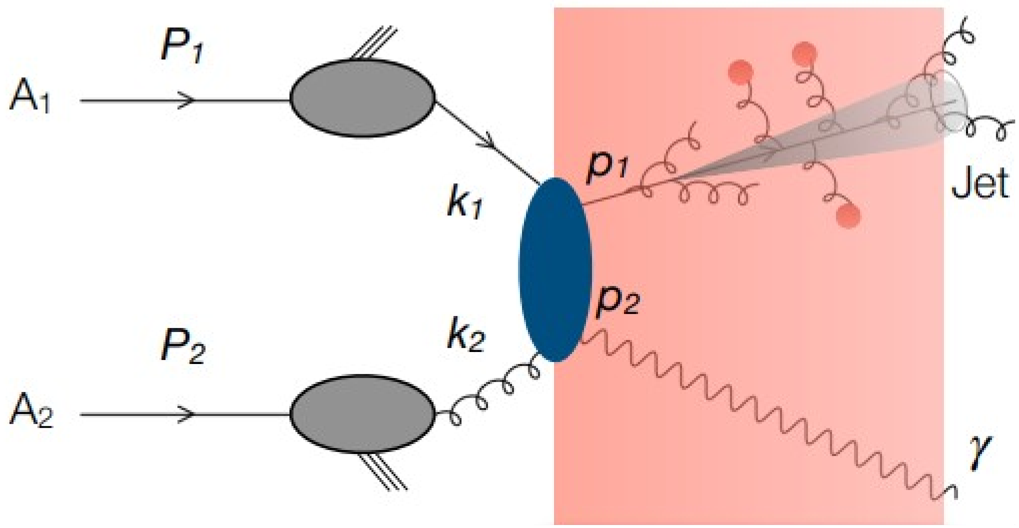






At small $p_{T\ \mathrm{clearly}}$ visible suppression.

Photon jet final state in Pb-Pb in FoCal



The data for this process will be there.
Possible measurement: ALICE 3

Process where one can study:

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

Estimate of multiplicity in DLL

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

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

At central rapidities

$$E = p_T$$

At forward rapidities

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

medium energy scale from multiple scattering

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BDMPS-Z spectrum

Multiple soft scattering resummed to all orders. It is expected to be important for short mean free-path

Because medium-induced radiation can occur anywhere along the medium with equal probability, the radiation spectrum is expected to scale linearly with L.

Many scattering centers act coherently

during the radiation over time $t_{coh} << t_{mfp}$.

Radiation spectrum

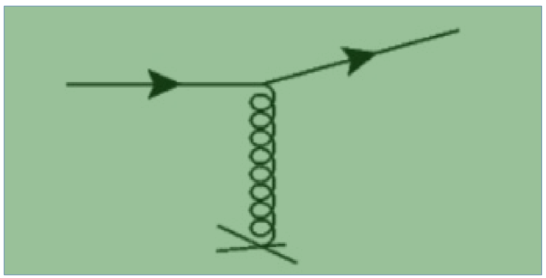
maximal energy that can be taken by single gluon

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \simeq \alpha_s \frac{L}{t_{\mathrm{coh}}} = \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

energy of observed gluon

Jet medium interaction

scattering...

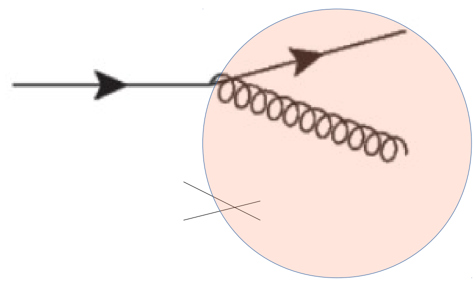


Transverse momentum transfer!

$p \rightarrow p + k_T$

Scattering Kernel: $C(k_T)$

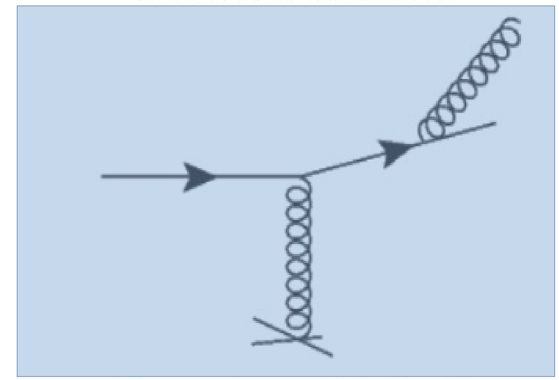
...splitting...



Bremsstrahlung as in vacuum.

Individual colors of partons may not be resolvable by medium particles

...induced radiation



Momentum distribution:

$p \rightarrow zp$

Average transfer: $\hat{q}$

Blaizot, Dominguez, Iancu, Mehtar-Tani '12

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

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

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

Rearrangement of the equation for gluon density

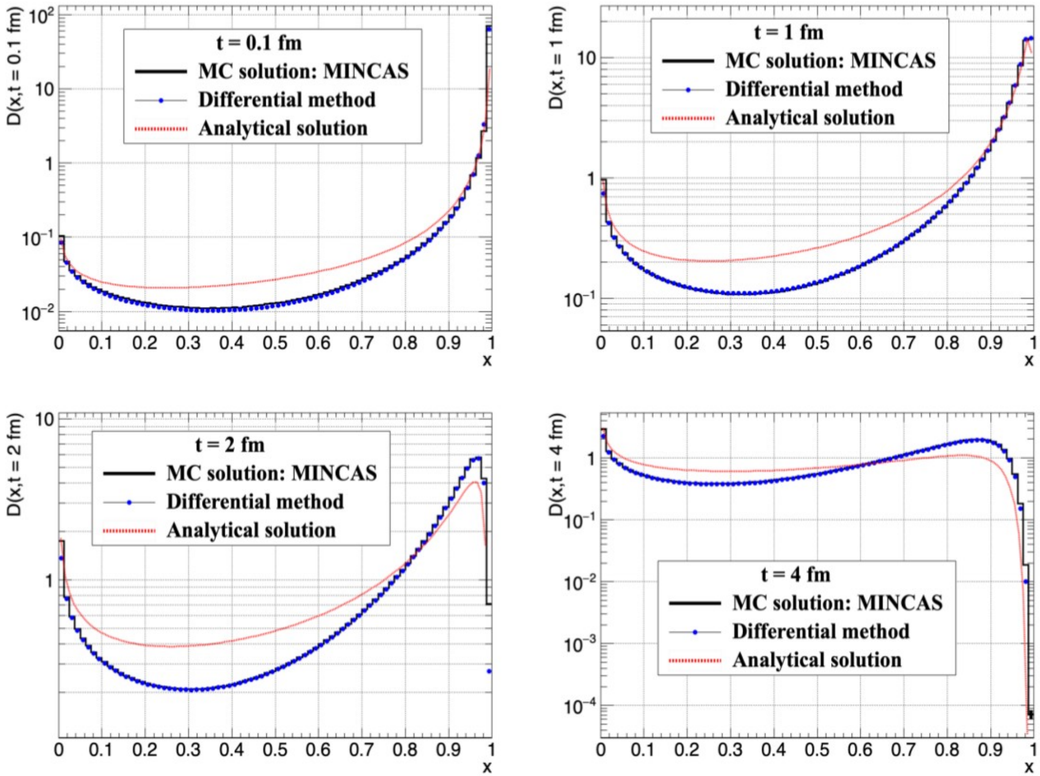
$$\frac{\partial}{\partial t}D(x,\mathbf{k},t) = \frac{1}{t^*}\int_0^1 dz\,\mathcal{K}(z)\left[\frac{1}{z^2}\sqrt{\frac{z}{x}}D\left(\frac{x}{z},\frac{\mathbf{k}}{z},t\right)\theta(z-x) - \frac{z}{\sqrt{x}}D(x,\mathbf{k},t)\right] + \int\frac{d^2\mathbf{q}}{(2\pi)^2}C(\mathbf{q})\,D(x,\mathbf{k}-\mathbf{q},t)$$

$$\Big\downarrow$$

Kutak, Płaczek, Straka Eur.Phys.J.C 79 (2019) 4, 317

$$D(x,\mathbf{k},\tau) = e^{-\Psi(x)(\tau-\tau_0)}D(x,\mathbf{k},\tau_0) + \int_{\tau_0}^{\tau}d\tau'\int_0^1 dz\int_0^1 dy\int d^2\mathbf{k}'\int d^2\mathbf{q}\;\mathcal{G}(z,\mathbf{q}) \times\delta(x-zy)\,\delta(\mathbf{k}-\mathbf{q}-z\mathbf{k}')\,e^{-\Psi(x)(\tau-\tau')}D(y,\mathbf{k}',\tau')$$

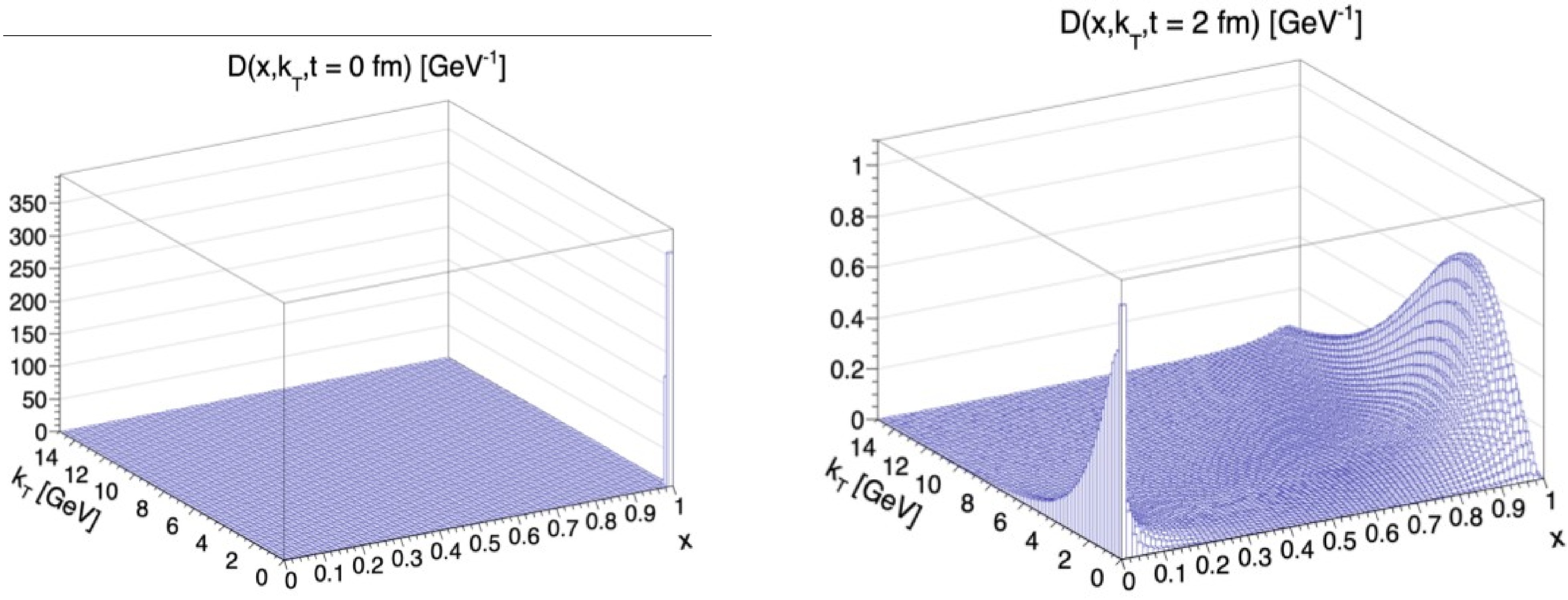
Jet fragmentation and turbulence



J. Blaizot, E. Iancu, Y. Mehtar-Tani '13

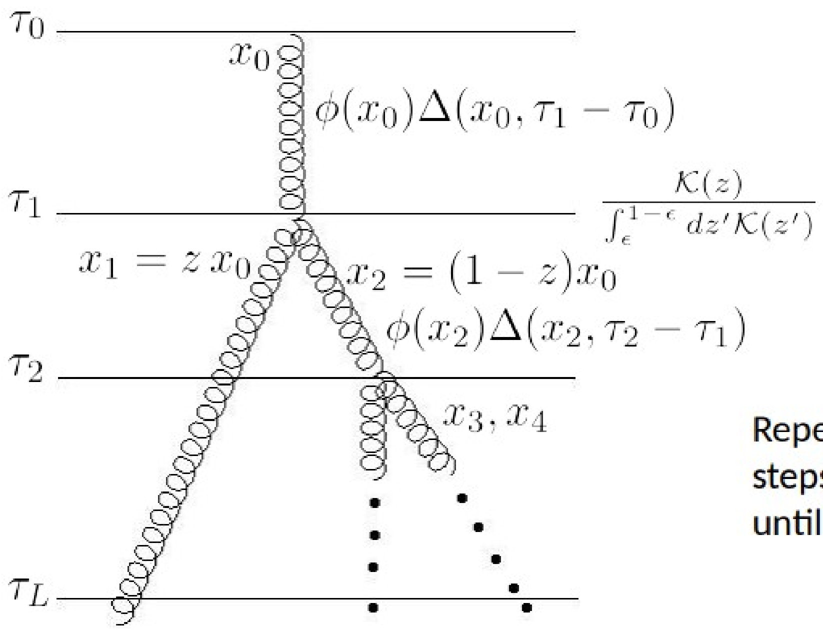
The fact that the spectrum keeps the same x-dependence when t keeps increasing reflects the fact that the energy flows to x = 0 without accumulating at any finite value of x
→ wave turbulence

Jet fragmentation x, t, k_t



Kutak, Placzek, Straka '18

Monte Carlo - TMDICE

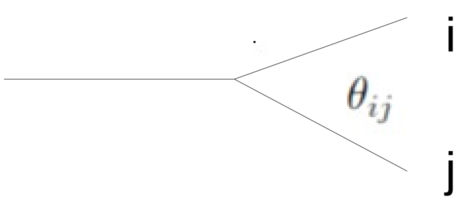


Repeat for all steps in τ and x until $\tau > \tau_L$

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

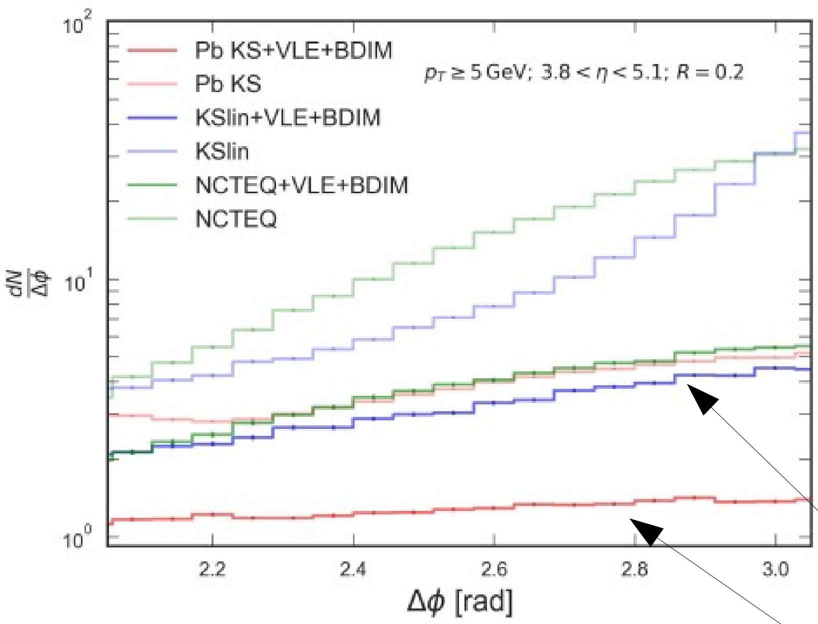
$$t_{br} < t_{decoh}$$

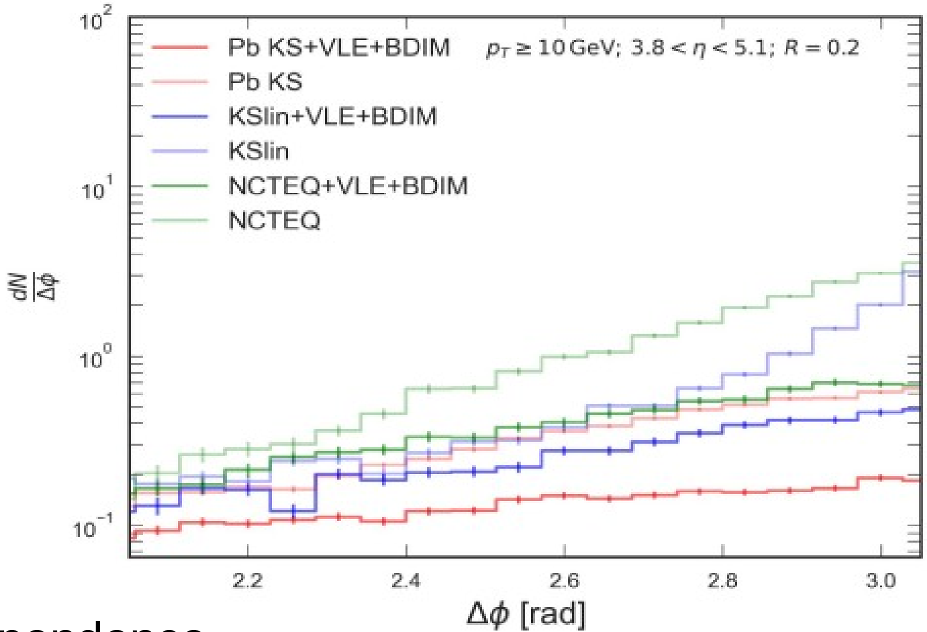
time of formation of radiation

Branching as in vacuum

See
Caucal, Iancu, Soyez, Mueller ‘18

Azimuthal angle decorelations





p_T dependence

clearly visible supression due to saturation (and Sudakov)

MC used:

KaTie and TMDICE

temperature and saturation dependence

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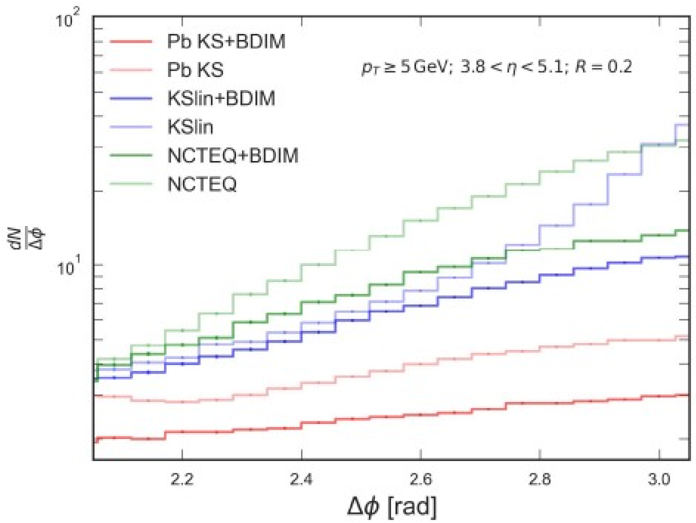
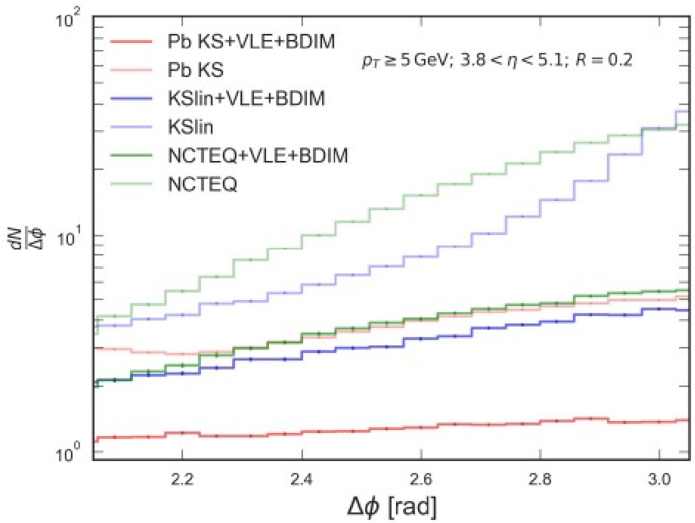
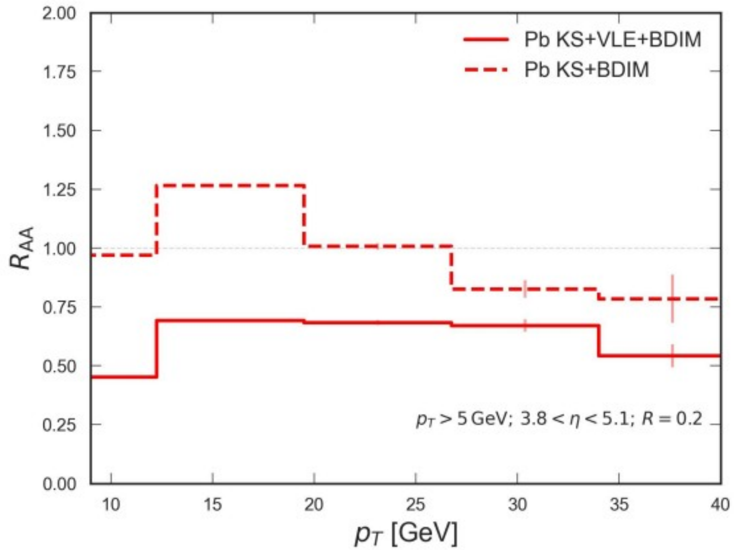
Effect of VLE

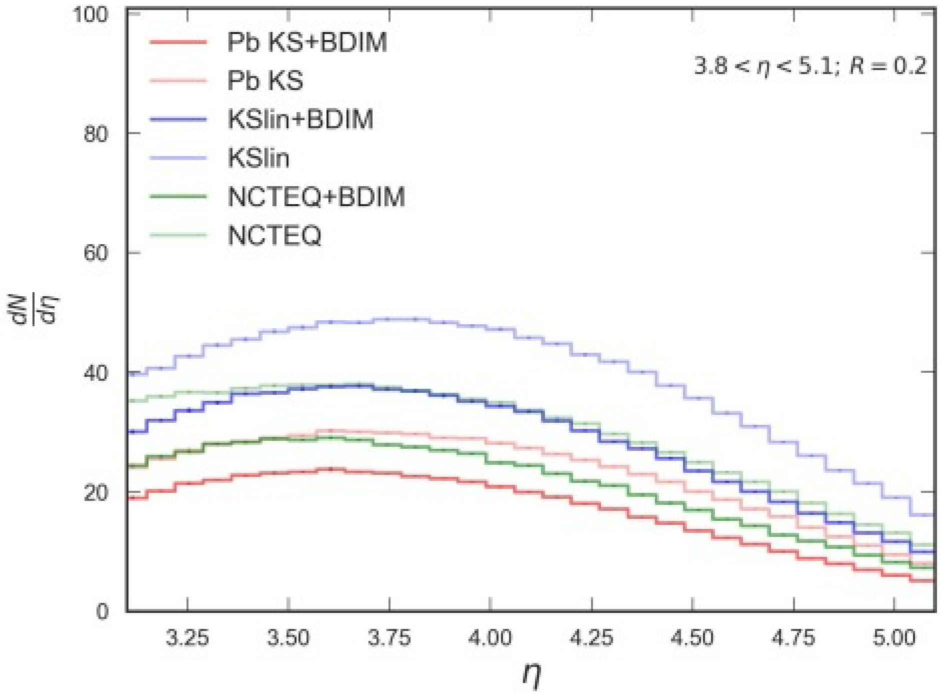


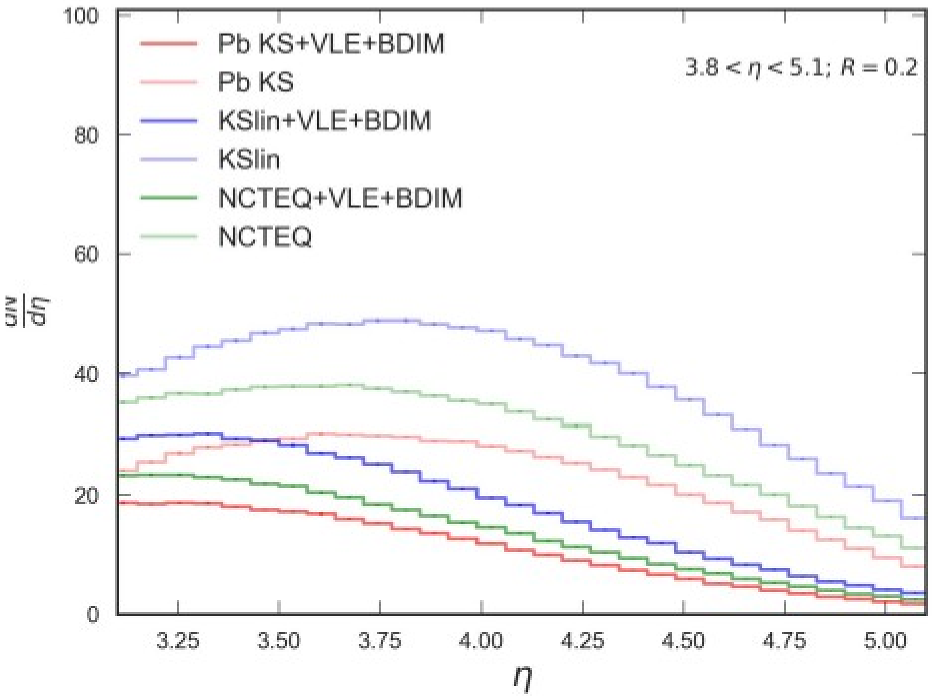




Large suppression due to VLE

Rapidity spectra





VLE emissions accounted for

Large supression due to VLE

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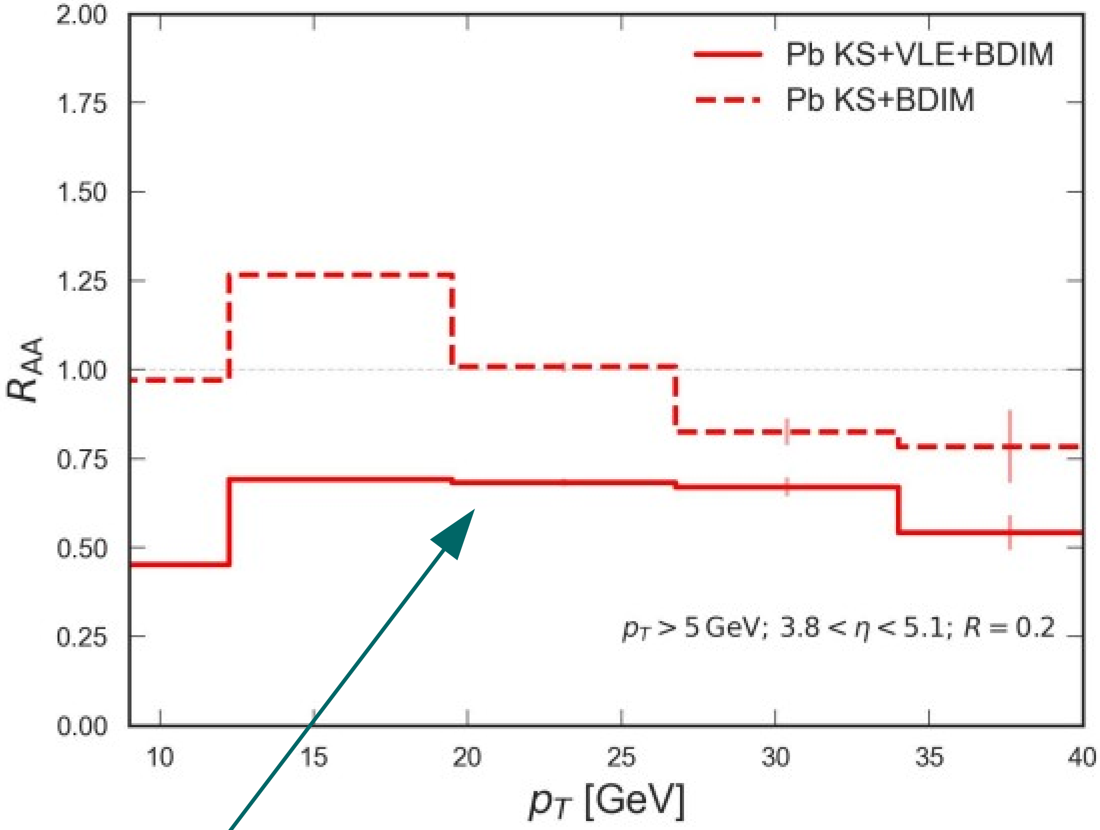
Nuclear modification ratio – relevance of VLE



suppression due to quenching and saturation

Conclusions and future plans

- We provided first predictions for forward jet production in Pb-Pb accounting for saturation, quenching and VLE
- Forward jets in Pb-Pb offer interesting possibility to look for saturation. Preliminary results show that saturation is visible even after accounting for jet quenching
- The plans include accounting for higher order corrections, new fits of TMD, accounting for expansion of medium and rapidity dependent medium