



Vacuum versus medium evolution effects in photon-jet productions

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Resummation, Evolution and Factorization 2025, 15.10.2025

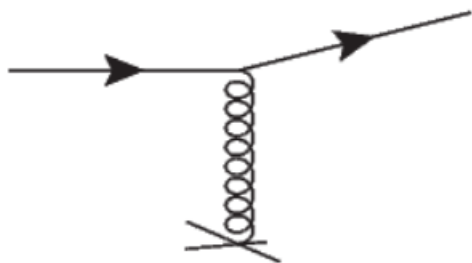
Work in collaboration with:

Souvik Adhya, Krzysztof Kutak, Wiesław Płaczek, Konrad Tywoniuk

[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

Processes in jets in the medium

Scattering:



Momentum transfer!

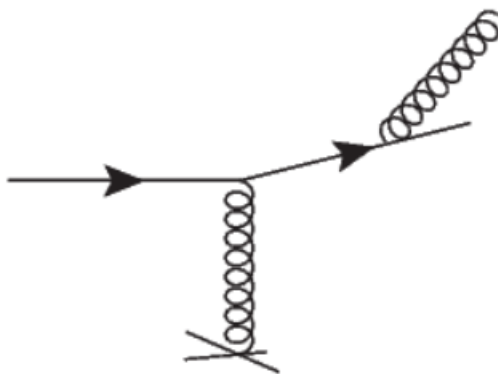
$$p \rightarrow p + Q$$

Scattering Kernel:

$$\frac{\partial^3 \mathcal{P}_{\text{scat}}}{\partial t \partial^2 \mathbf{Q}} = \frac{1}{(2\pi)^2} w(\mathbf{Q})$$

Average transfer: $\hat{q}$

Induced radiation:



Momentum distribution:

$$p \rightarrow zp$$

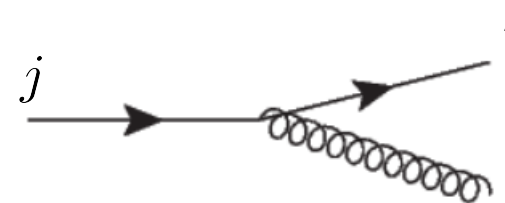
+Momentum transfer:

$$p \rightarrow zp + Q$$

Kernel:
$$\frac{\partial^4 \mathcal{P}_{\text{split}}}{\partial t \partial z \partial^2 \mathbf{Q}} = \frac{\alpha_s}{(2\pi)^2} \mathcal{K}(\mathbf{Q}, z, p_+)$$

Jet-Medium interactions

Splitting:



Bremsstrahlung as
in vacuum.

Momentum distribution:

$$p \rightarrow zp$$

DGLAP-Kernel:

$$\frac{\partial^2 \mathcal{P}_{\text{split}}}{\partial \hat{t} \partial z} \propto \frac{1}{\hat{t}} P_{ij}(z)$$

**Emissions in Vacuum,
Vacuum Like
Emissions in medium**

Coherent emission

...à la BDMPS-Z [Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov]

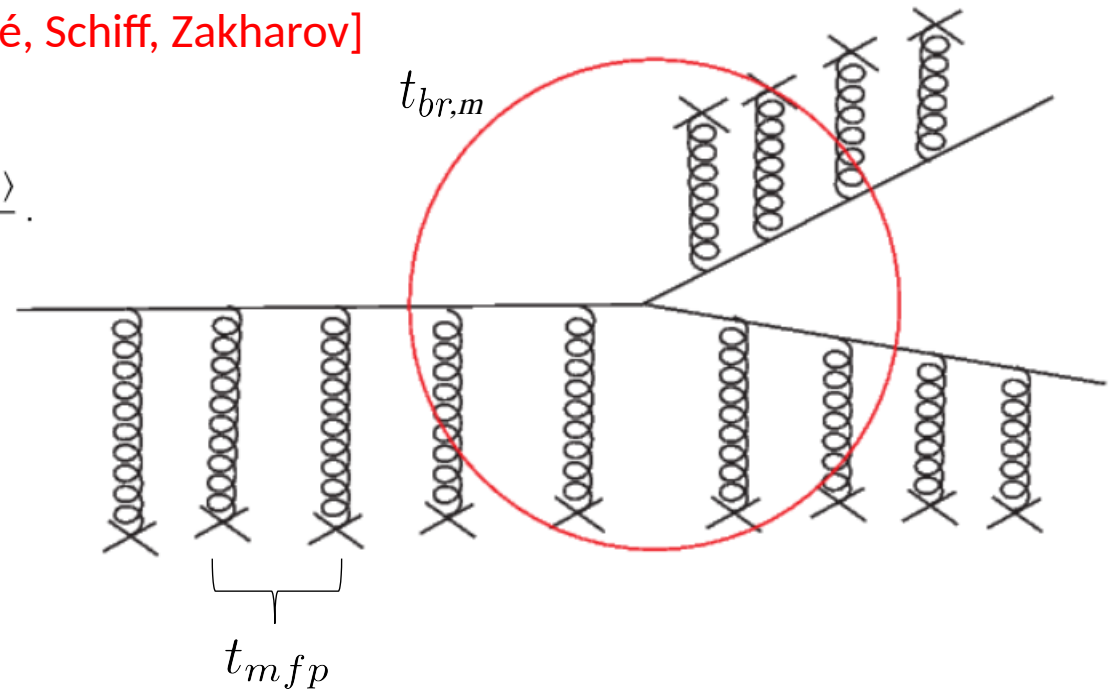
$$t_{br,m} \sim \sqrt{\frac{2\omega}{\hat{q}}}$$

$$\hat{q} = \frac{d\langle k_{\perp}^2 \rangle}{dt}$$

$t_{br,m} \sim t_{mfp}$: one scattering + radiation
...Bethe-Heitler spectrum

$t_{br,m} \gg t_{mfp}$: coherent radiation

$$\omega \frac{dI}{d\omega} \sim \alpha_s \frac{L}{t_{br,m}} = \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$



Look at range: $\omega_{BH} < \omega < \omega_c$

need effective kernel: $\mathcal{K}(z, k_T)$

cf. [Blaizot, Dominguez, Iancu, Mehtar-Tani: JHEP 1301 (2013) 143]
[Blanco, Kutak, Płaczek, MR, Tywoniuk, arxiv: 2109.05918]

Splitting Kernels for Quarks and Gluons

[Blanco, Kutak, Płaczek, MR, Tywoniuk, arxiv: 2109.05918], [Blaizot, Dominguez, Iancu, Mehtar-Tani: JHEP 1301 (2013) 143]

$$\mathcal{K}_{ij}(\mathbf{Q}, z, p_0^+) = \frac{2P_{ij}(z)}{z(1-z)p_0^+} \sin\left(\frac{Q^2}{2k_{\text{br}}^2}\right) \exp\left(-\frac{Q^2}{2k_{\text{br}}^2}\right)$$

$$k_{\text{br}}^2 = \sqrt{z(1-z)p_0^+ f_{ij}(z) \frac{\hat{q}}{N_c}}$$

$$f_{gg}(z) = (1-z)C_A + z^2C_A$$

$$f_{qg}(z) = C_F - z(1-z)C_A,$$

$$f_{gq}(z) = (1-z)C_A + z^2C_F$$

$$f_{qq}(z) = zC_A + (1-z)^2C_F$$

$$\frac{\partial^4 \mathcal{P}_{\text{split}}}{\partial t \partial z \partial^2 \mathbf{Q}} = \frac{\alpha_s}{(2\pi)^2} \mathcal{K}(\mathbf{Q}, z, p_+)$$

$$\frac{\partial^5 \mathcal{P}_{\text{split}}}{\partial t \partial x \partial z \partial^2 \mathbf{Q}} = \frac{\alpha_s}{(2\pi)^2} \mathcal{K}(\mathbf{Q}, z, \frac{x}{z} p_0^+)$$

$$\downarrow \int_0^\infty d^2 \mathbf{Q} \times$$

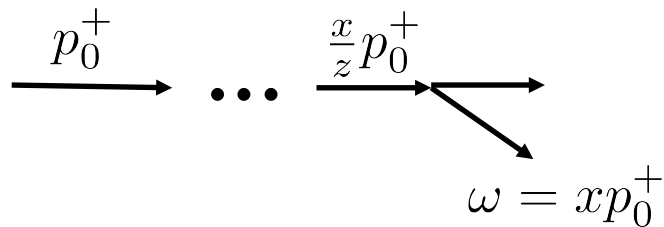
$$\frac{\partial^3 \mathcal{P}_{\text{split}}}{\partial t \partial x \partial z} = \frac{2\pi}{\sqrt{x} t^*} \sqrt{z} \mathcal{K}(z)$$

$$\frac{\partial^2 \mathcal{P}_{\text{split}}}{\partial t \partial x} = 2\pi \frac{1}{\sqrt{x} t^*} \int dz \sqrt{z} \mathcal{K}(z)$$

$$\frac{1}{t^*} = \frac{\alpha_s}{\pi} \sqrt{\frac{\hat{q}}{p_0^+}}$$

$$\sqrt{x} t^* \propto t_{\text{br},m}$$

Generalization of BDMPS-Z approach



Scattering Kernels

Used right now:

$$w_g(\mathbf{q}) = \frac{16\pi^2 \alpha_s^2 N_c n_{\text{med}}}{\mathbf{q}^4} \qquad w_g(\mathbf{q}) = \frac{g^2 m_D^2 T}{\mathbf{q}^2 (\mathbf{q}^2 + m_D^2)}, \qquad g^2 = 4\pi\alpha_s$$

n_{med} ... density of scatterers

m_D ... Debye mass

T ... medium temperature

$$w_q(\mathbf{q}) = \frac{C_F}{C_A} w_g(\mathbf{q})$$

Monte-Carlo algorithms

Probabilities of interaction:

$$\Phi_g(x) = \alpha_s \int_{\epsilon}^{1-\epsilon} dz \int_{q>0} \frac{d^2\mathbf{q}}{(2\pi)^2} \left[\mathcal{K}_{gg}(\mathbf{q}, z, xp_+) + \mathcal{K}_{qg}(\mathbf{q}, z, xp_+) \right] + \int_{q>q_{\min}} \frac{d^2\mathbf{q}}{(2\pi)^2} w_g(\mathbf{q}),$$
$$\Phi_q(x) = \alpha_s \int_{\epsilon}^{1-\epsilon} dz \int_{q>0} \frac{d^2\mathbf{q}}{(2\pi)^2} \mathcal{K}_{qq}(\mathbf{q}, z, xp_+) + \int_{q>q_{\min}} \frac{d^2\mathbf{q}}{(2\pi)^2} w_q(\mathbf{q}),$$

Probability of no interaction for particle A over time (t_2-t_1):

$$\Delta_A(x, t_2 - t_1) = \exp(-\Phi_A(x)(t_2 - t_1)) \quad \dots \text{Sudakov factor}$$

TMDICE code:

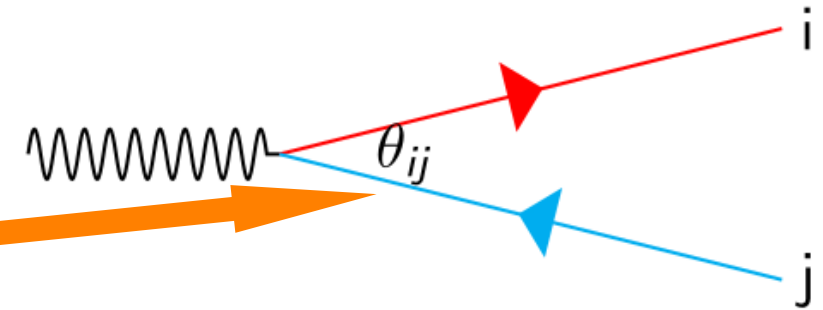
- Written in C++
- Source code available at <https://github.com/Rohrmoser/TMDICE>

Other codes implementing
BDMPS-Z spectra:

MARTINI, JEWEL, QPYTHIA, ...

Color Coherence

Individual colors of partons may not be resolvable by medium particles



Phenomenological estimation of color resolution via
Decoherence time:

$$t_{decoh} \approx \left(\frac{12}{\hat{q} \theta_{ij}^2} \right)^{1/3}$$

and Branching time:

$$t_{br} \approx \frac{2E}{Q^2}$$

$$\hat{q} = \frac{d\langle k_{\perp}^2 \rangle}{dt}.$$

**No color resolution if $t_{br} < t_{decoh}$
=> Branching as in Vacuum**

Vacuum Like Emissions (VLE)

DGLAP-Evolution as in Vacuum
Branching probability:

$$P_{qq}(z) = C_F \frac{1+z^2}{1-z},$$

$$P_{gq}(z) = P_{qg}(1-z),$$

$$P_{qg}(z) = T_R [z^2 + (1-z)^2],$$

$$P_{gg}(z) = C_A \left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z) \right].$$

$$\frac{d^2 \mathcal{P}_{ji}}{dQ^2 dz} = \frac{\alpha_s}{2\pi} \frac{1}{Q^2} P_{ji}(z),$$

Evolve as long as $t_{\text{br}} < t_{\text{decoh}}$

Then: In-Medium Evolution

Jet-photon Production:

Cross section =

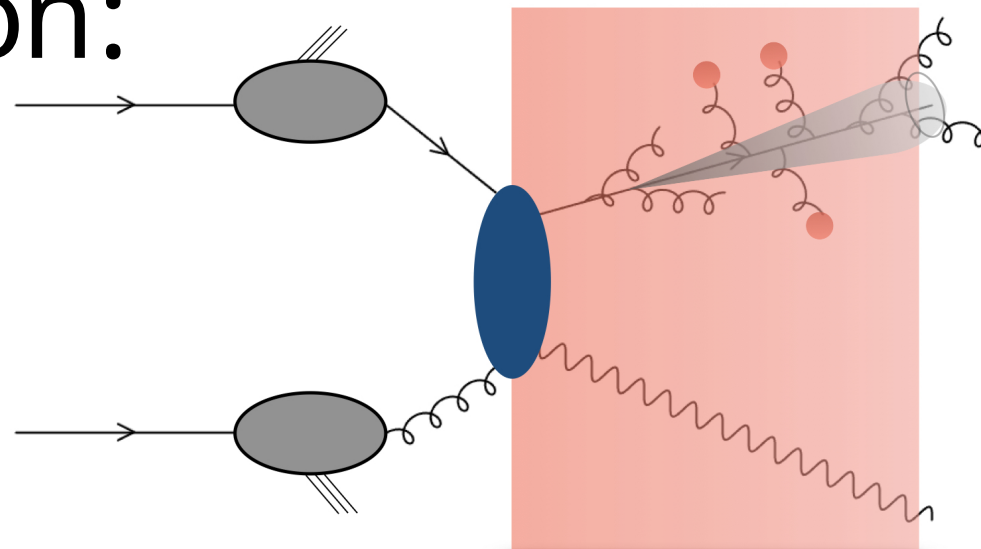
PDF*TMD

* hard cross section

* fragmentation of jet

} Here via KATIE

[van Hameren: Comput.Phys.Commun. 224 (2018) 371-380]



k_T -factorization:

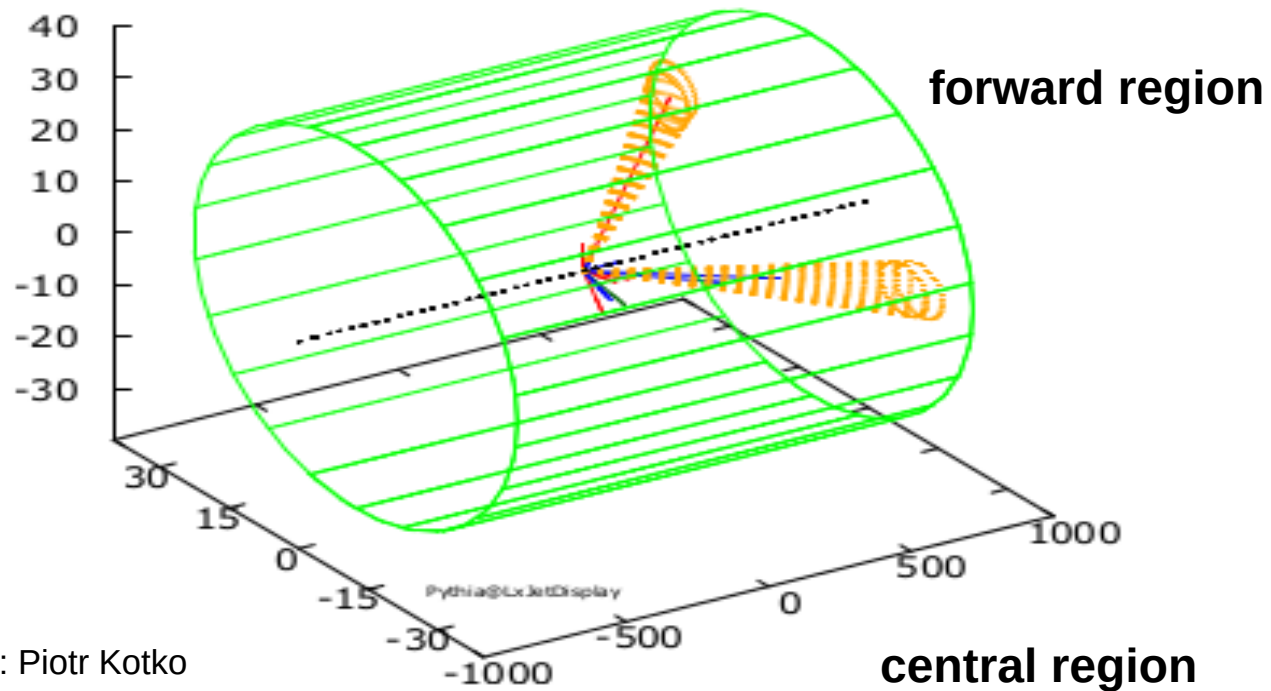
$$\frac{d\sigma^{AA \rightarrow \gamma + \text{jet} + X}}{dy_1 dy_2 dp_{1T} dp_{2T} d\Delta\phi} = \frac{p_{1T} p_{2T}}{8\pi^2 (x_1 x_2 s)^2} \sum_a x_1 f_{a/A}(x_1, \mu_F^2) |\mathcal{M}_{ag^* \rightarrow \gamma a}^{\text{off-shell}}|^2 \mathcal{F}(x_2, k_{2T}^2, \mu_F^2)$$

cf. [I. Ganguli, A. van Hameren, P. Kotko, K. Kutak, Eur.Phys.J.C 83 (2023) 9, 868]

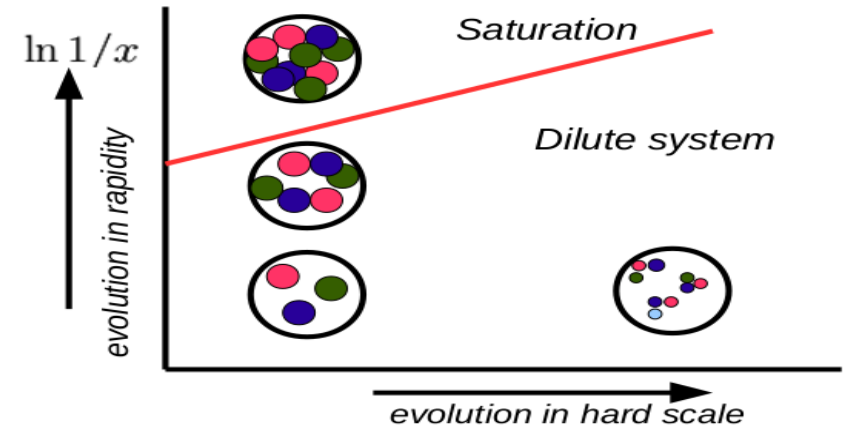
TMDs used: [K. Kutak, S. Sapeta: Phys. Rev. D 86 (2012) 094043, M. A. Al-Mashad, A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, P. van Mechelen, S. Sapeta, JHEP 12 (2022) 131]

- Ksln: solution of BFKL eq.
- Pb KS: solution of BK eq. for Pb.
- p KS: solution of BK eq.

p – A (dilute-dense) forward-forward di-jets

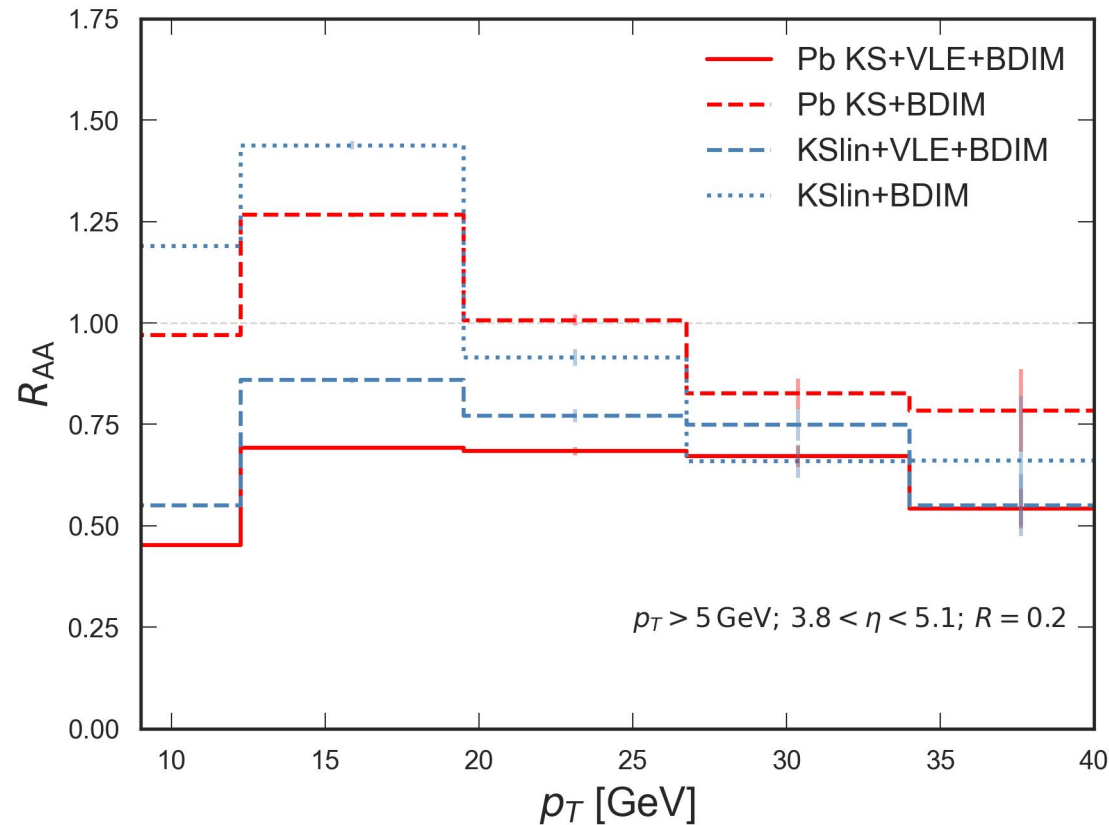


From: Piotr Kotko
LxJet



It originated from the aim to provide predictions for forward-forward jet production at the LHC

Photon-jet production

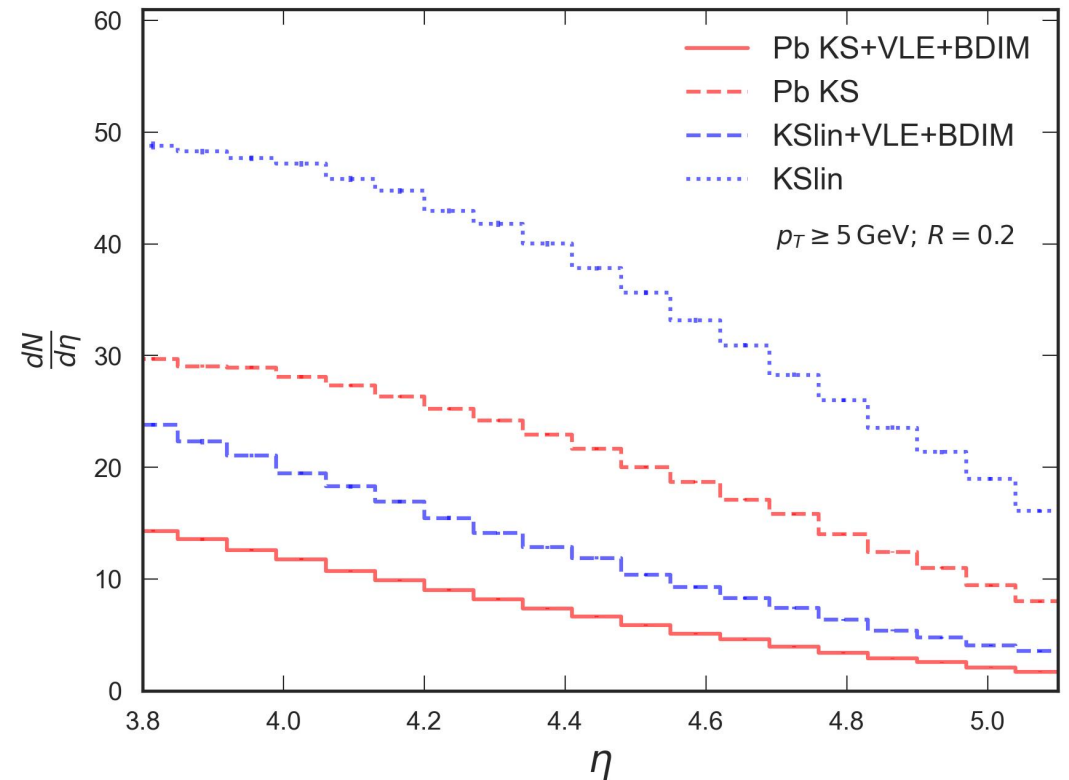
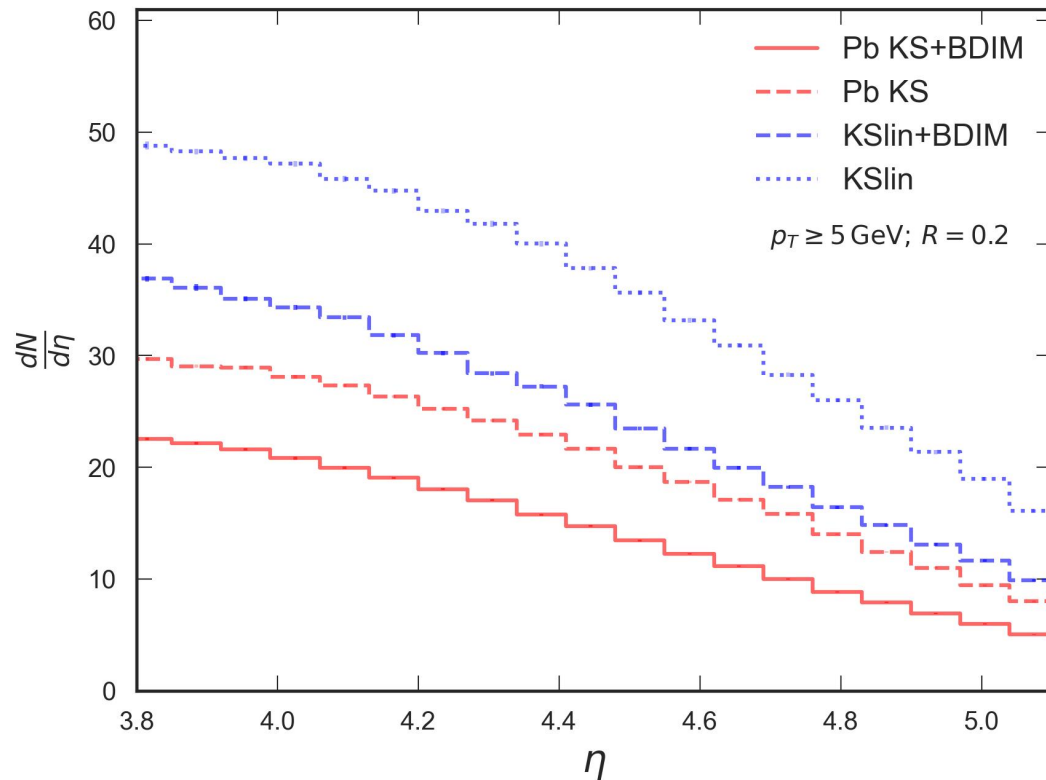


$L = 5 \text{ fm}$ $T = 250 \text{ MeV}$:

n_{med}	$\hat{q}$	m_D
0.08 GeV^3	$0.29 \text{ GeV}^2/\text{fm}$	0.61 GeV

[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

Rapidity distributions

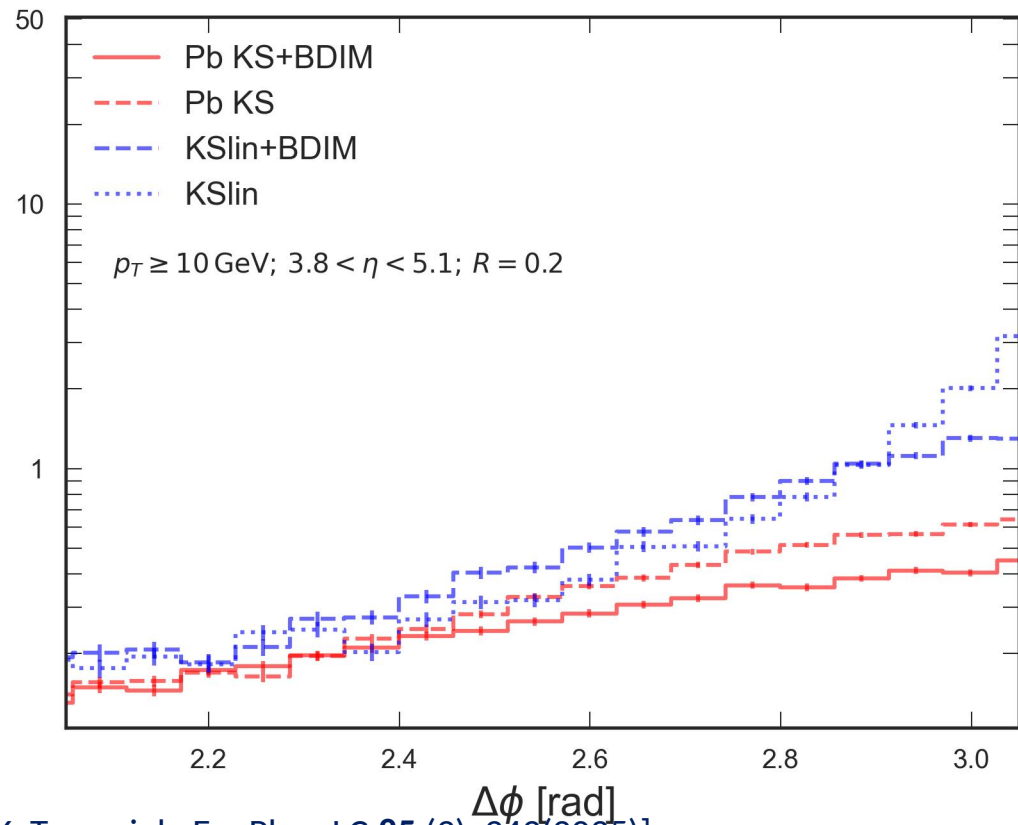
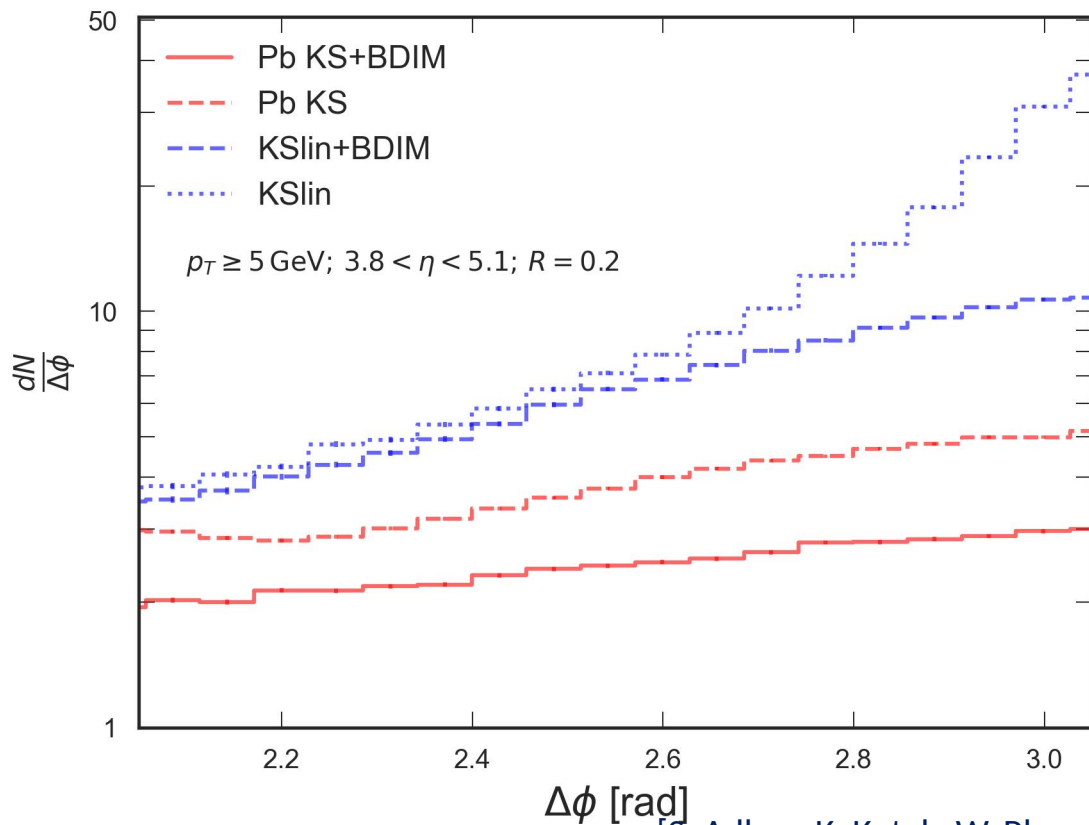


[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

L= 5fm T=250MeV :

n_{med}	$\hat{q}$	m_D
0.08 GeV ³	0.29 GeV ² /fm	0.61 GeV

Azimuthal decorrelations (1/2)

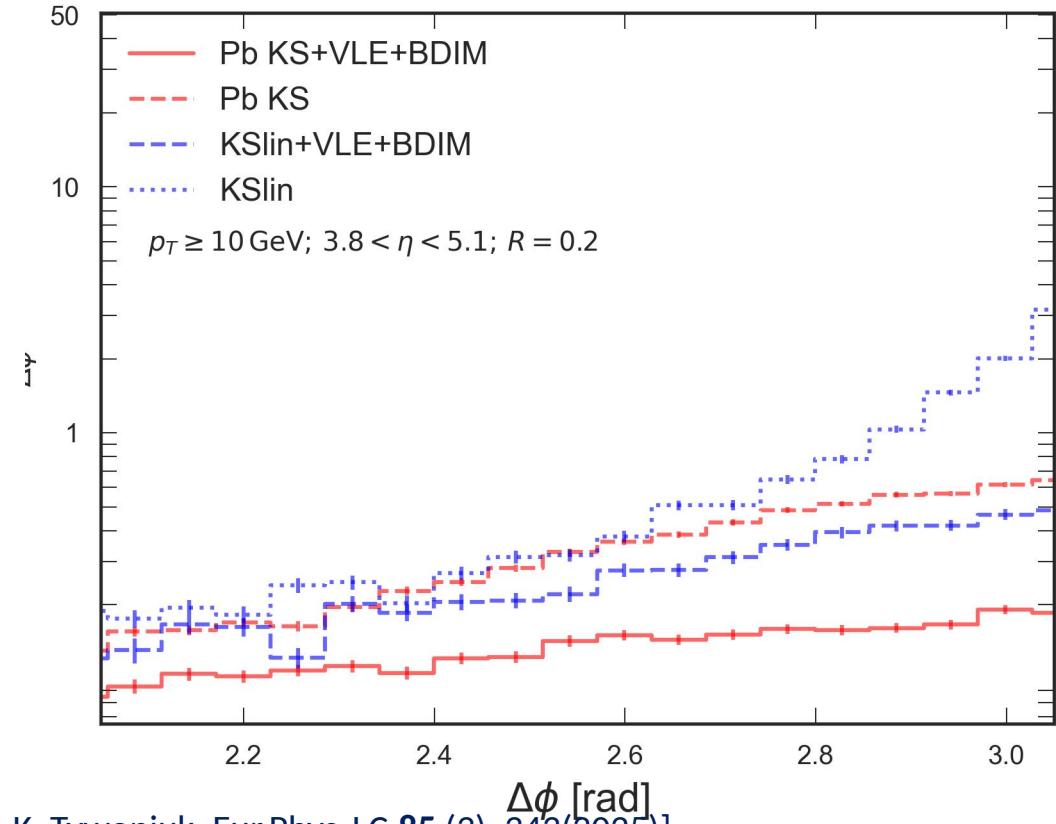
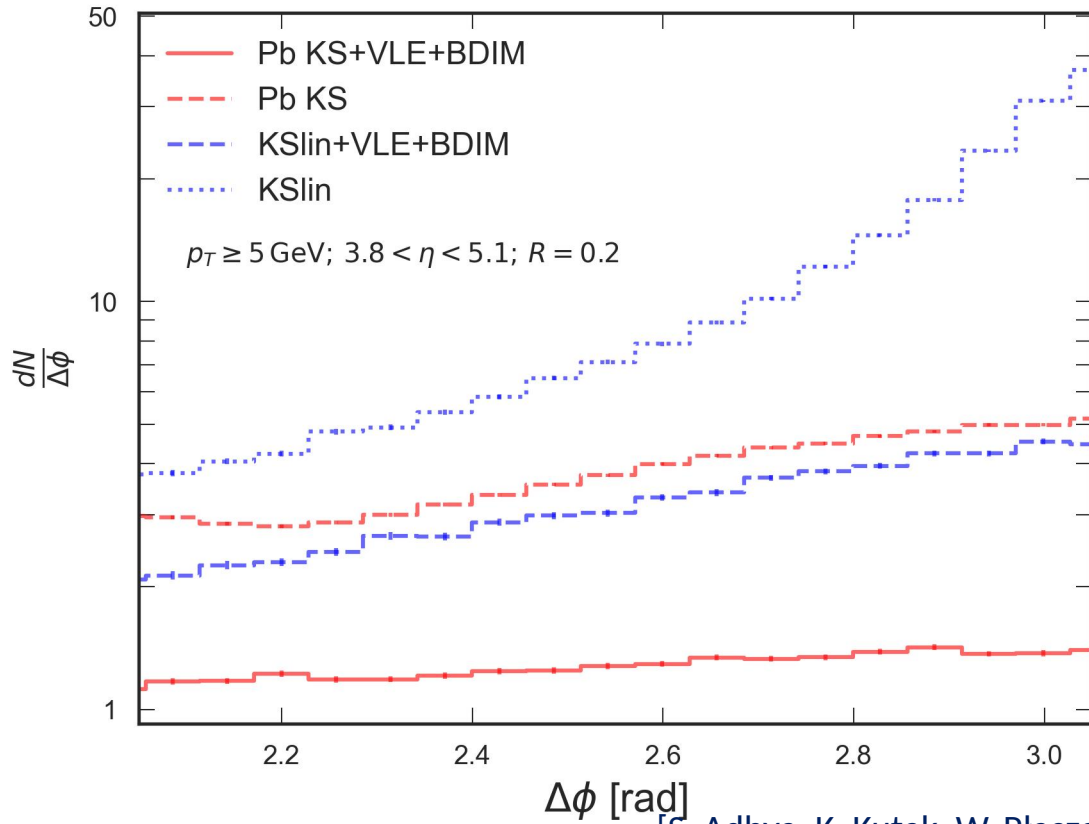


[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

L= 5fm T=250MeV :

n_{med}	$\hat{q}$	m_D
0.08 GeV^3	$0.29 \text{ GeV}^2/\text{fm}$	0.61 GeV

Azimuthal decorrelations (2/2)



[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

L= 5fm T=250MeV :

n_{med}	$\hat{q}$	m_D
0.08 GeV^3	$0.29 \text{ GeV}^2/\text{fm}$	0.61 GeV

Summary & Outlook:

- Estimation of photon-jet events in forward direction (FOCAL-range) via Monte-Carlo algorithms
- Quenching: k_T Broadening and jet suppression.
 - Emissions at low energies
- Inclusion of VLE in quenching:
 - VLE yield strong suppression broadening effects
- Gluon-saturation effects survive after jet quenching.

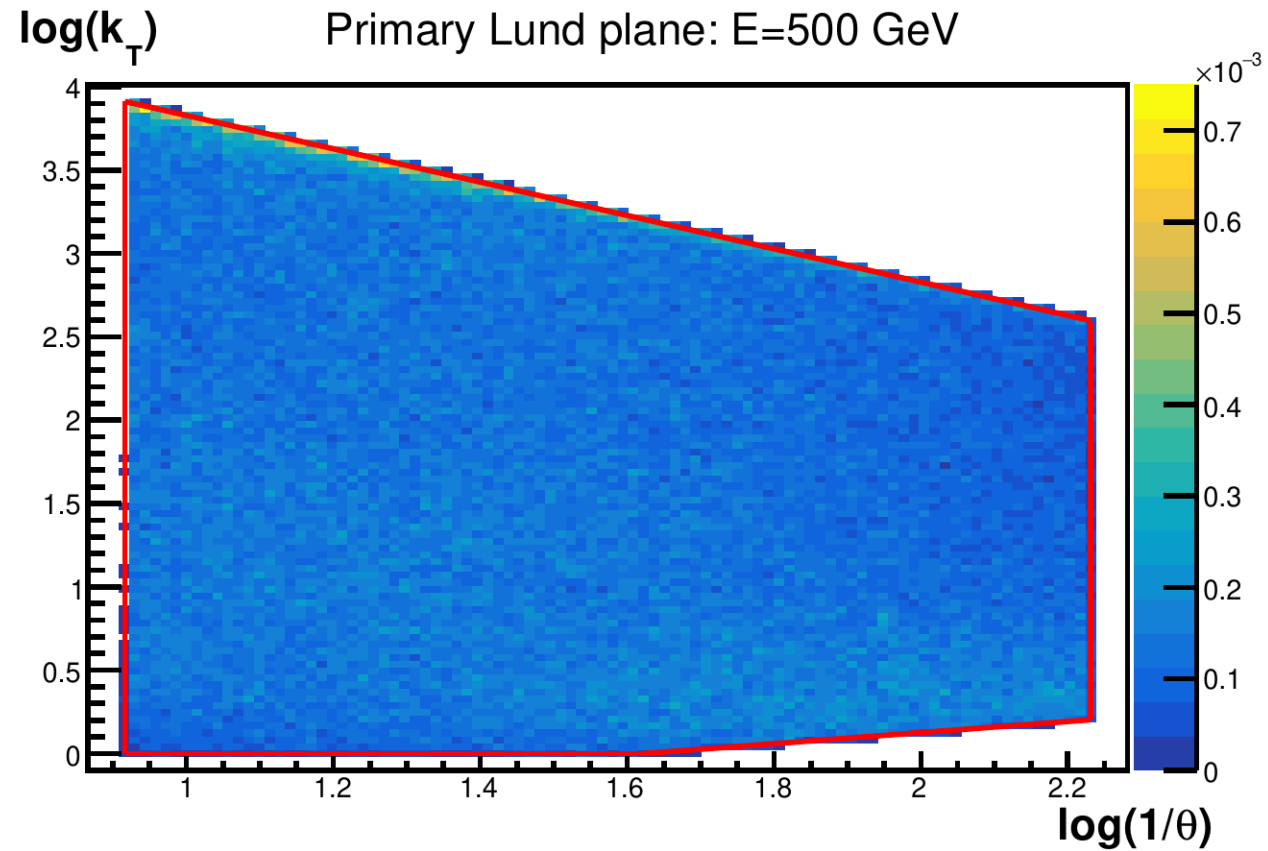
Outlook:

- More realistic Media (e.g.: expanding media; Temperature profiles)
- Study dijets.

Thank you for your attention!

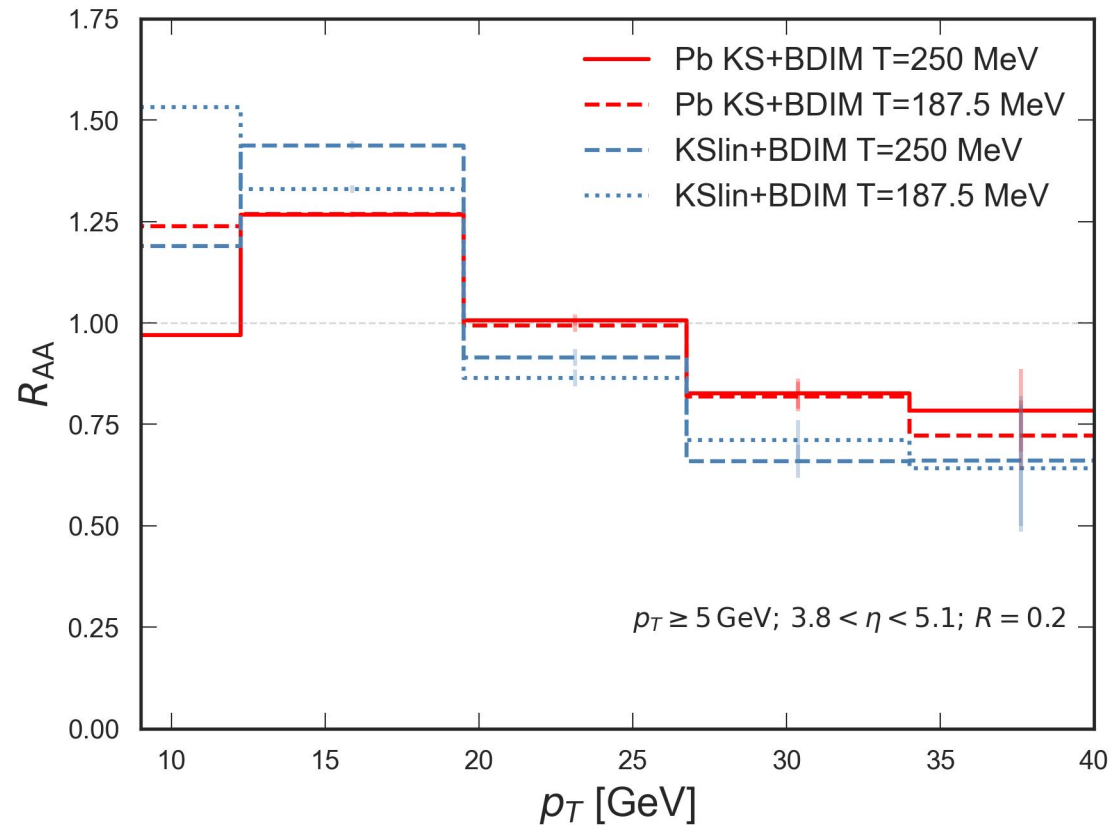
Back-up slides

VLEs for quark gun



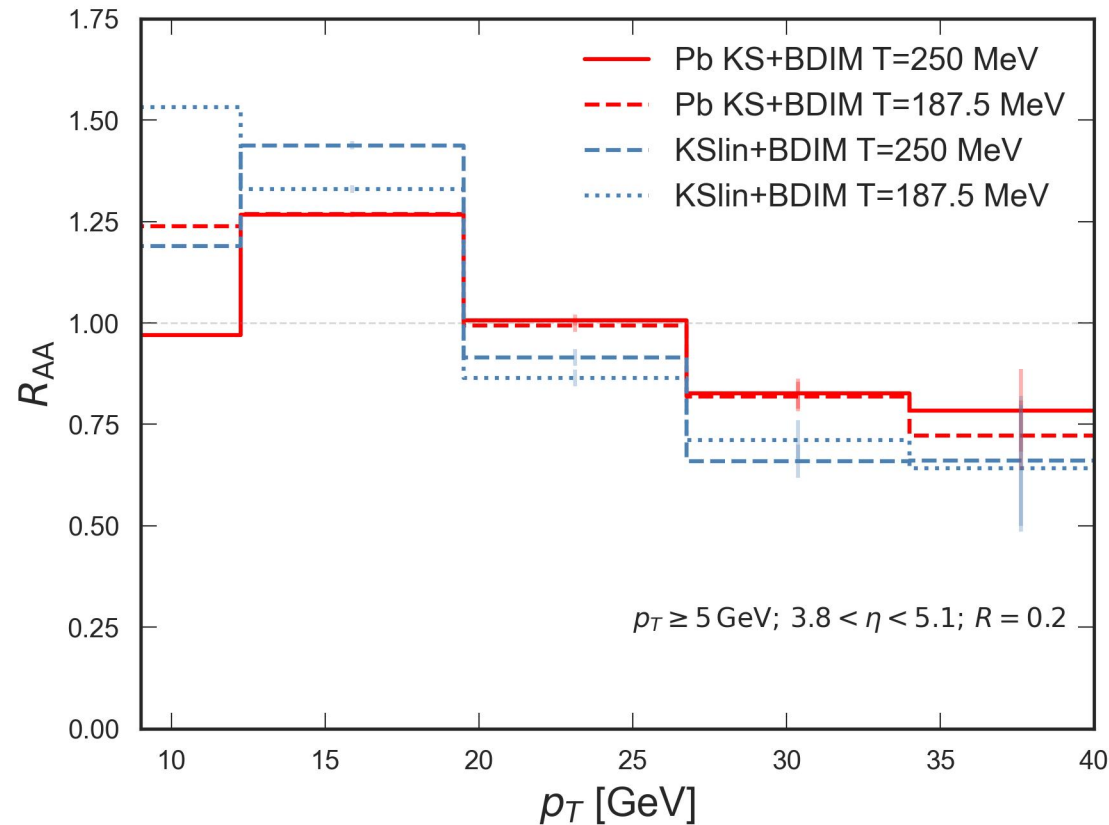
[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

Photon-jet production (T dependence)



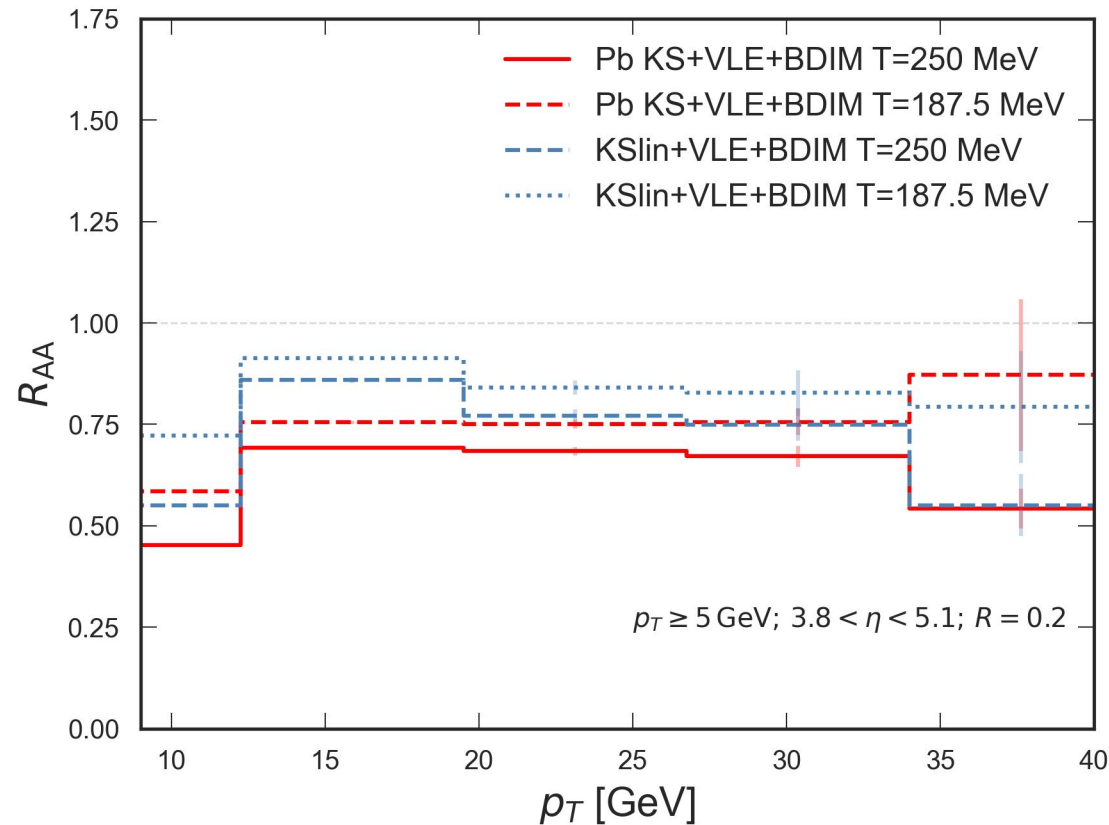
[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

Photon-jet production (T dependence)



[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

Photon-jet production (T dependence)



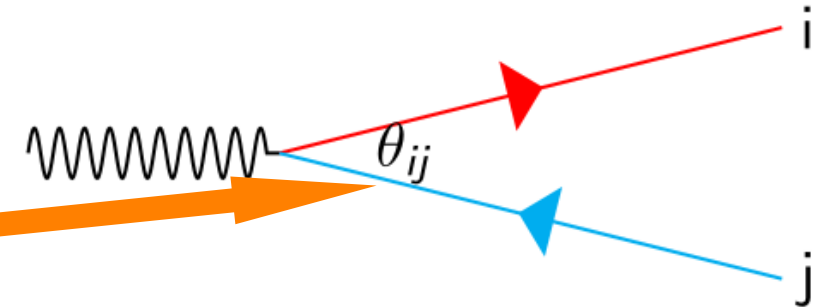
[S. Adhya, K. Kutak, W. Płaczek, MR, K. Tywoniuk, Eur.Phys.J.C **85** (3), 343(2025)]

Color Resolution

$$\hat{q} = \frac{d\langle k_{\perp}^2 \rangle}{dt}.$$

- Transverse length of dipole: $r_t \sim \theta_{ij} t$
- Momentum transfer from medium: $Q_s = \sqrt{\hat{q} t}$

Individual colors of partons may not be resolvable by medium particles



$$t_{decoh} \approx \left(\frac{12}{\hat{q} \theta_{ij}^2} \right)^{1/3}$$

Branching time

Uncertainty principle in particle rest-frame:

$$\Delta m \Delta t_{\text{rest}} \geq \frac{\hbar}{2}$$

⇒ Estimation of particle life-time in the rest frame:

$$\Delta t_{\text{rest}} \sim \frac{\hbar}{2\Delta m} \sim \frac{1}{Q}$$

Branching time, boosted to Lab-frame:

$$t_{br} \approx \frac{2E}{Q^2}$$

The saturation problem: suppressing gluons below Q_s

Originally formulated in coordinate space

Balitsky '96, Kovchegov '99

Fit AAMQS '10

NLO accuracy

Balitsky, Chirilli '07

and solved

Lappi, Mantysaari '15

Kinematic corrections

Iancu et al

Solved b dependent

Stasto, Golec-Biernat '02

with kinematic

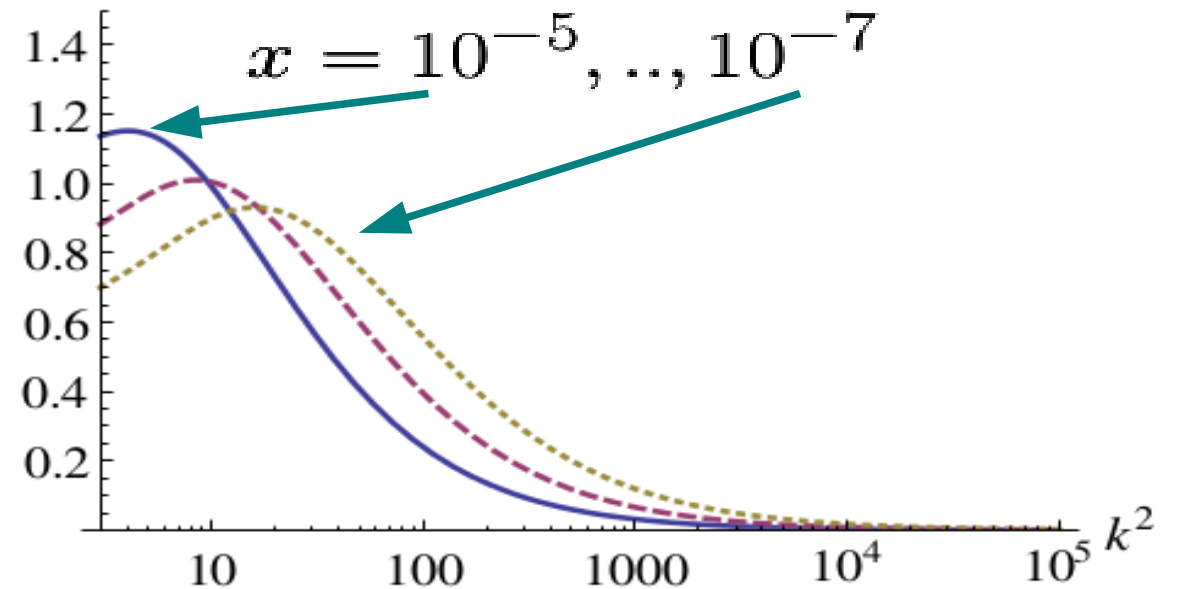
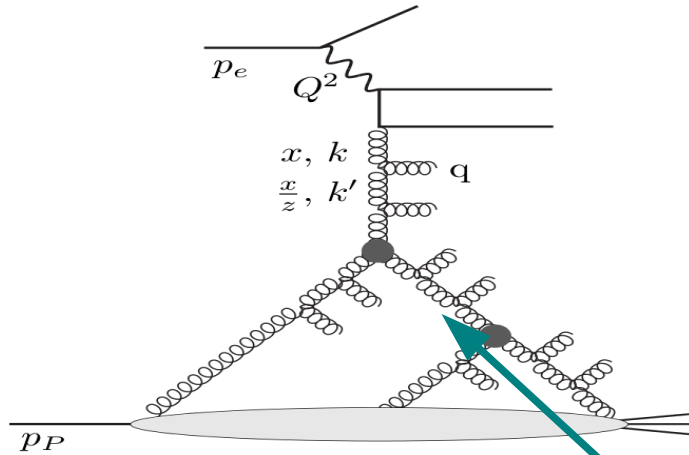
corrections and b

Cepila, Contreras, Matas '18

The momentum space 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



solution of Balitsky-Kovchegov directly for dipole gluon density

Kwiecinski, Kutak '02

Nikolaev, Schafer '06

Fit to F_2 data

KK. Sapeta '12

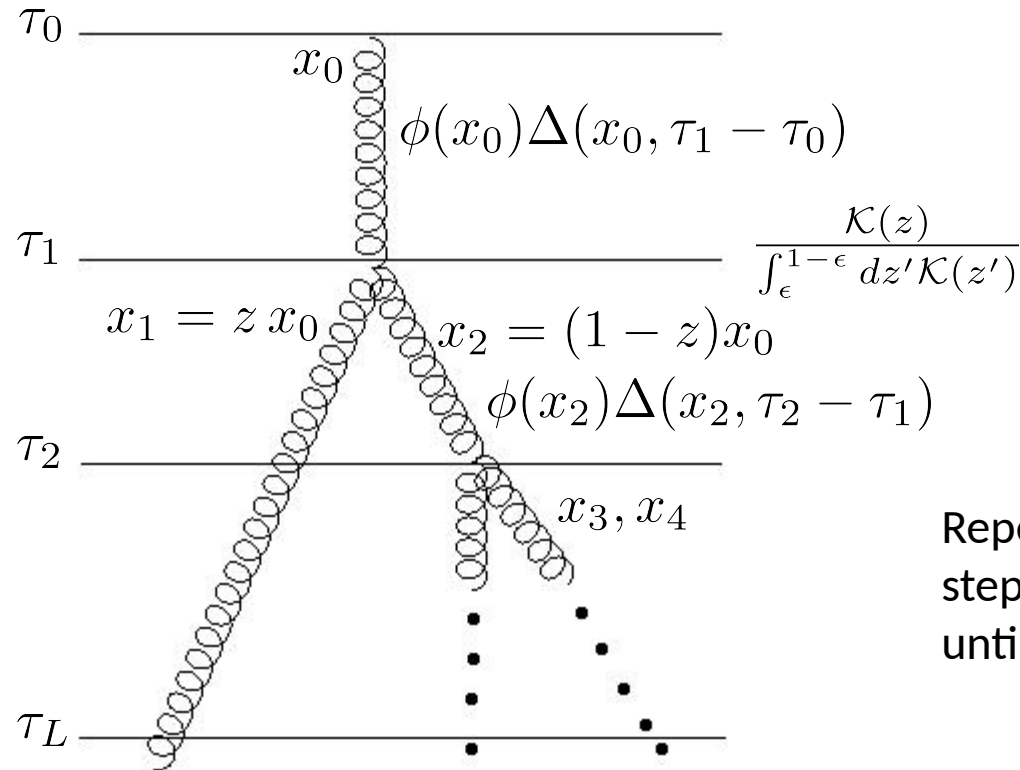
Accounts for kinematical constraint,

Nonsingular parts of splitting function, running coupling

Monte-Carlo algorithms

Other codes implementing
BDMPS-Z spectra:

MARTINI, JEWEL, QPYTHIA, ...



Analogous for the k_T
dependent equation in
 x , k_T , and, τ and
system of equations!

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

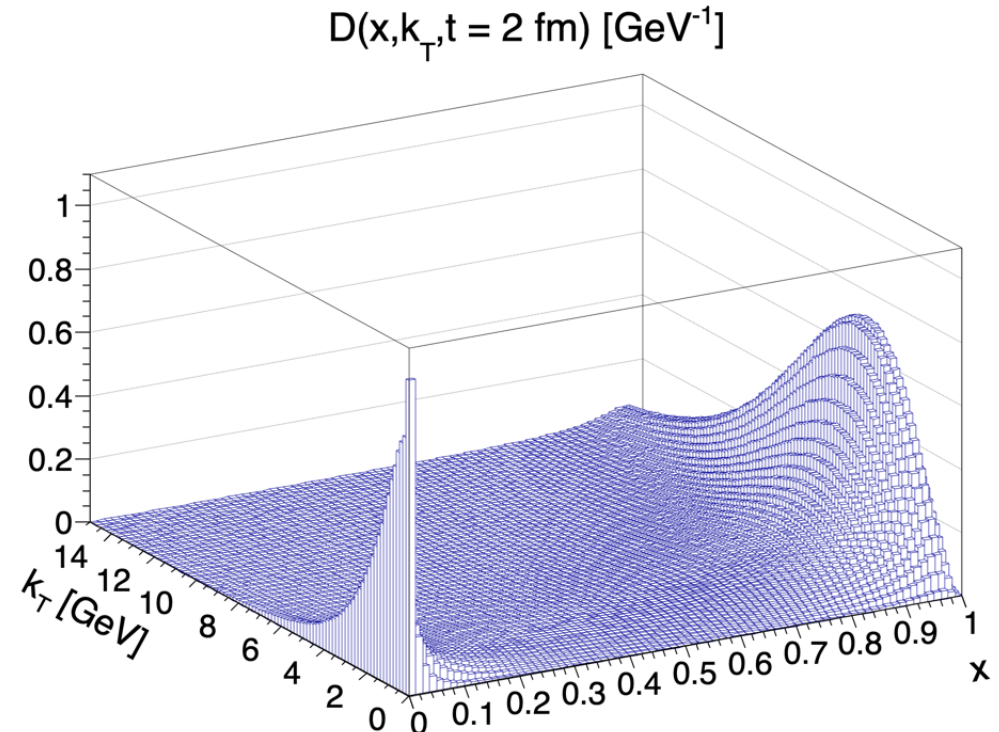
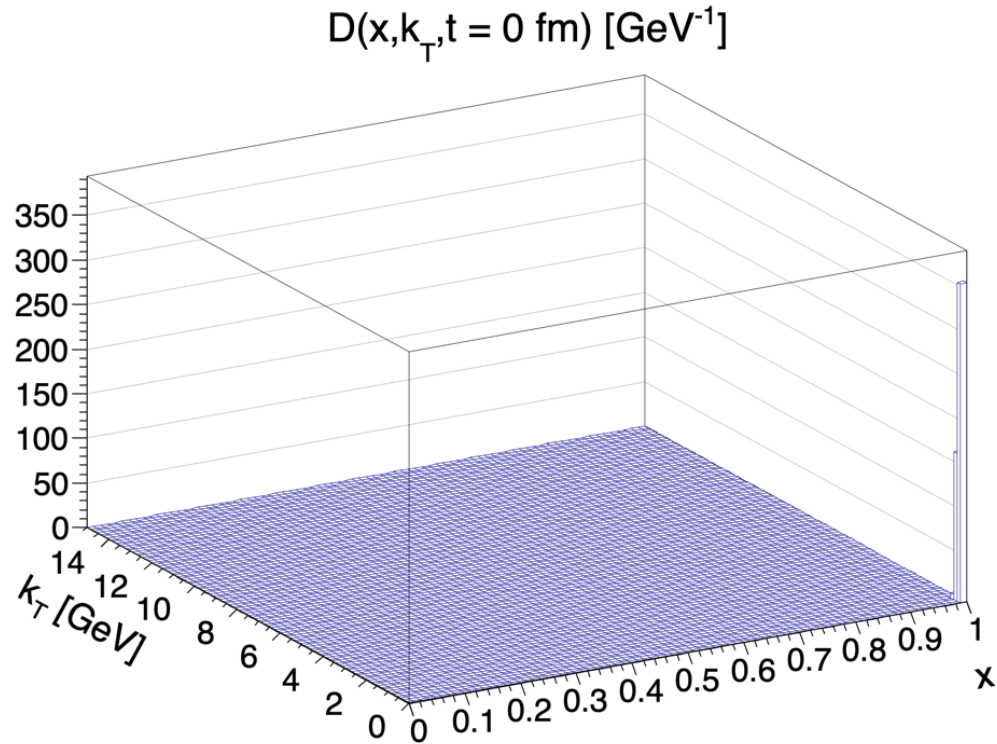
TMDICE code: [MR, Comput.Phys.Commun. 276 (2022) 108343]

- Written in C++
- Source code available at

<https://github.com/Rohrmoser/TMDICE>

Evolution of $D(x, k_T, t)$

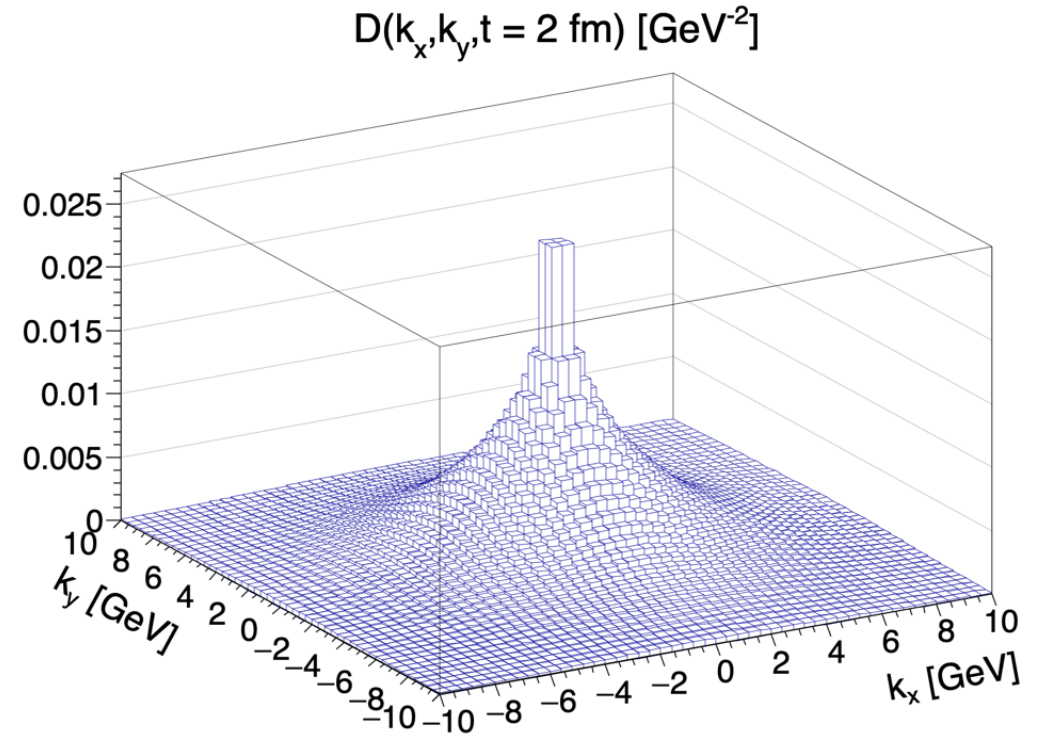
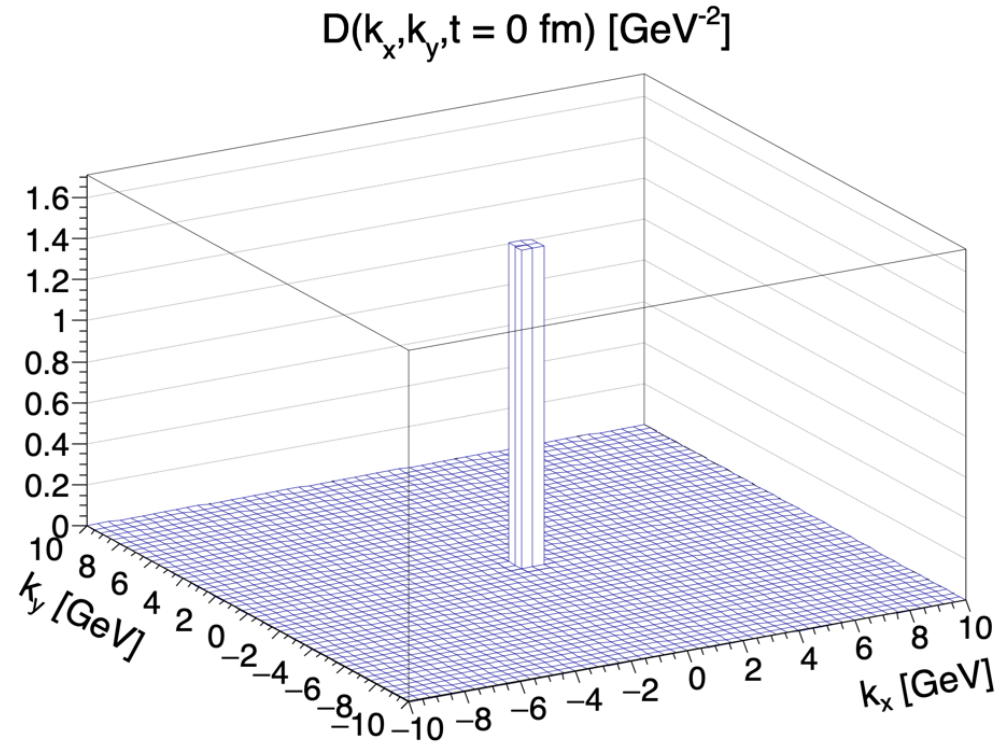
$$D(x, k_T, t) = x \frac{\partial^2 N(t)}{\partial x \partial k_T}$$



[Kutak, Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317]

Evolution of $D(x, k_T, t)$

$$\mathcal{K}(z) \quad w(\mathbf{q}) = \frac{16\pi^2 \alpha_s^2 N_c n}{\mathbf{q}^2 (\mathbf{q}^2 + m_D^2)}$$



[Kutak, Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317]

Departure from Gaussian broadening

Both:

- Parton Branching
- Scattering

Central Limit Theorem does not necessarily apply.

$$\begin{aligned} p &\rightarrow z_1 p \rightarrow z_1 p + \mathbf{q}_1 \\ &\rightarrow z_1 p + \mathbf{q}_1 + \mathbf{q}_2 \\ &\rightarrow z_2(z_1 + \mathbf{q}_1 + \mathbf{q}_2) \rightarrow \dots \end{aligned}$$

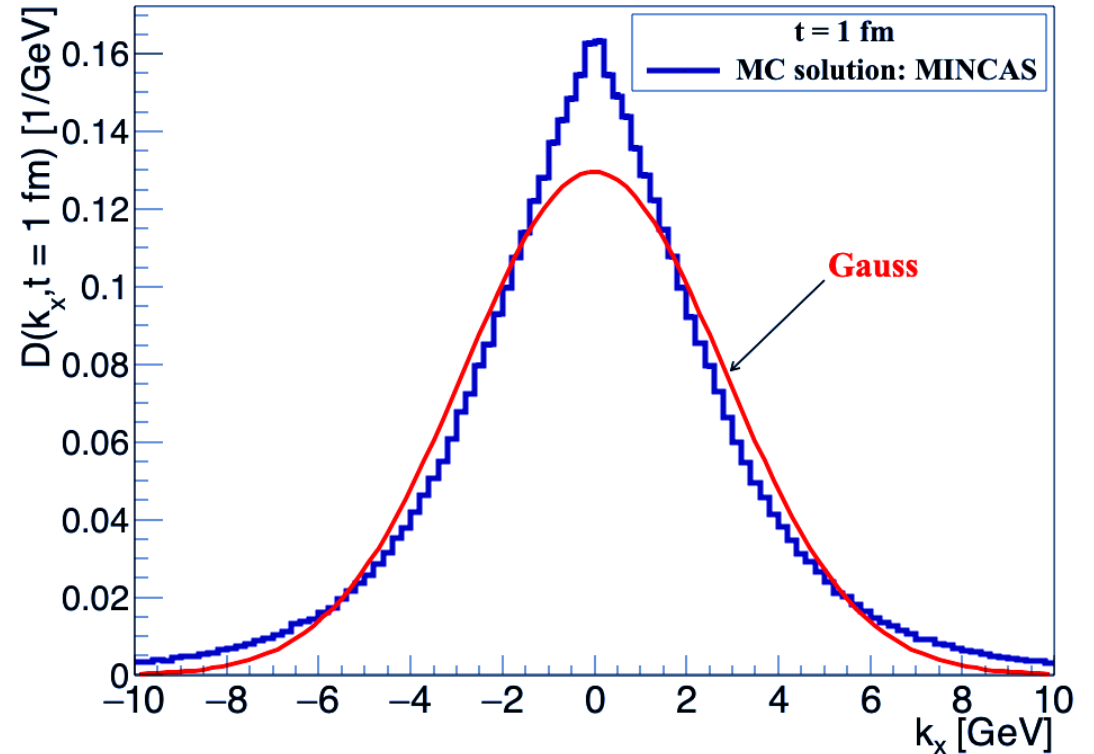


Figure: [Kutak, Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317]

Jet Production

Factorization for AA collisions:

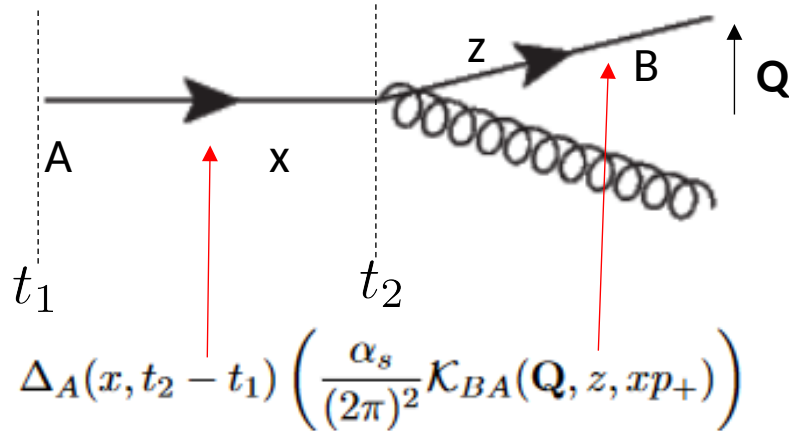
$$\frac{d\sigma_{AA}}{d\Omega_p} = \int d\Omega_q \int d^2l \int_0^1 \frac{d\tilde{x}}{\tilde{x}} \delta(p^+ - \tilde{x}q^+) \delta^{(2)}(\mathbf{p} - \mathbf{l} - \mathbf{q}) D(\tilde{x}, \mathbf{l}, \tau(q^+)) \frac{d\sigma_{pp}}{d\Omega_q}$$

$$d\Omega_q = dq^+ d^2\mathbf{q} \qquad \tau(q^+) = \frac{\alpha_s N_c}{\pi} \sqrt{\frac{\hat{q}}{q^+}} L$$



$$\begin{aligned} \frac{d^2\sigma_{AA}}{d\Omega_{p_1} d\Omega_{p_2}} &= \int d\Omega_{q_1} \int d\Omega_{q_2} \int d^2l_1 \int d^2l_2 \int_0^1 \frac{d\tilde{x}_1}{\tilde{x}_1} \delta(p_1^+ - \tilde{x}_1 q_1^+) \int_0^1 \frac{d\tilde{x}_2}{\tilde{x}_2} \delta(p_2^+ - \tilde{x}_2 q_2^+) \\ &\quad \delta^{(2)}(\mathbf{p}_1 - \mathbf{l}_1 - \mathbf{q}_1) \delta^{(2)}(\mathbf{p}_2 - \mathbf{l}_2 - \mathbf{q}_2) D(\tilde{x}_1, \mathbf{l}_1, \tau(q_1^+)) D(\tilde{x}_2, \mathbf{l}_2, \tau(q_2^+)) \frac{d^2\sigma_{pp}}{d\Omega_{q_1} d\Omega_{q_2}} \end{aligned}$$

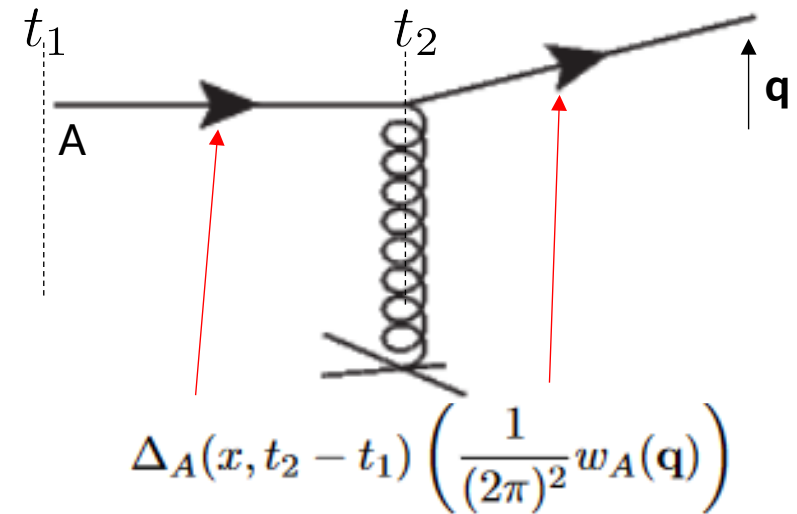
Probabilities for interactions



$$(\Delta_A(x, t_2 - t_1) \phi_A(x)) \underbrace{\left(\frac{\sum_B \rho_{BA}(x)}{\phi_A(x)} \right)}_{\text{Splitting probability}} \underbrace{\left(\frac{\rho_{BA}(x)}{\sum_B \rho_{BA}(x)} \right)}_{\text{Probability for splitting into B}} \left(\frac{1}{\rho_{BA}(x)} \frac{\alpha_s}{(2\pi)^2} \mathcal{K}_{BA}(\mathbf{Q}, z, xp_+) \right)$$

Splitting
probability

Probability for
splitting into B



$$(\Delta_A(x, t_2 - t_1) \phi_A(x)) \underbrace{\left(\frac{W_A}{\phi_A(x)} \right) \left(\frac{1}{W_A} \frac{1}{(2\pi)^2} w_A(\mathbf{q}) \right)}_{\text{Scattering probability}}$$

Scattering
probability

$$\rho_{BA}(x) = \alpha_s \int_{\epsilon}^{1-\epsilon} dz \int_{q>0} \frac{d^2 q}{(2\pi)^2} \mathcal{K}_{BA}(\mathbf{q}, z, xp_+)$$

$$W_A = \int \frac{d^2 \mathbf{q}}{(2\pi)^2} w_A(\mathbf{q})$$

BDIM Equation for Gluons

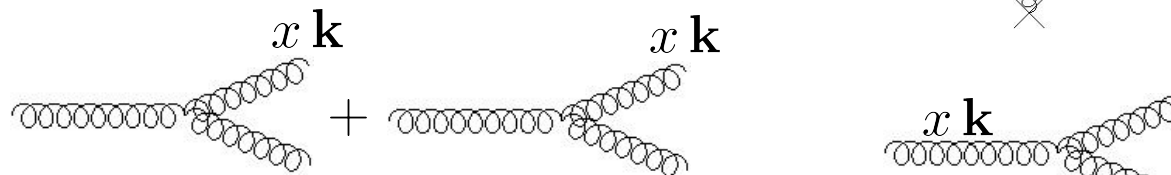
[Blaizot, Dominguez, Iancu, Mehtar-Tani: JHEP 1406 (2014) 075]

Scattering:

$$C(\mathbf{q}) = w(\mathbf{q}) - \delta(\mathbf{q}) \int d^2 \mathbf{q}' w(\mathbf{q}')$$



$$D(x, \mathbf{k}, t) = x \frac{\partial^3 N(x, \mathbf{k}, t)}{\partial x \partial^2 \mathbf{k}}$$



For gluon-jets:

$$\frac{\partial}{\partial t} D(x, \mathbf{k}, t) = \alpha_s \int_0^1 dz \int \frac{d^2 \mathbf{q}}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q}, z, \frac{x}{z} p_0^+) D\left(\frac{x}{z}, \mathbf{q}, t\right) - \mathcal{K}(\mathbf{q}, z, x p_0^+) D(x, \mathbf{k}, t) \right] + \int \frac{d^2 \mathbf{l}}{(2\pi)^2} C(\mathbf{l}) D(x, \mathbf{k} - \mathbf{l}, t).$$

Average Kernels over $\mathbf{Q}$



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

Integrate over $\mathbf{k}$



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

$$D(x, t) = \int d^2 \mathbf{k} D(x, \mathbf{k}, t)$$

System of Equations for quarks and gluons

[Blanco, Kutak, Płaczek, MR, Tywoniuk, arxiv: 2109.05918]

$$\begin{aligned}\frac{\partial}{\partial t} D_g(x, \mathbf{k}, t) &= \int_0^1 dz \int \frac{d^2 \mathbf{q}}{(2\pi)^2} \alpha_s \left\{ 2\mathcal{K}_{gg} \left(\mathbf{Q}, z, \frac{x}{z} p_0^+ \right) D_g \left(\frac{x}{z}, \mathbf{q}, t \right) + \mathcal{K}_{gq} \left(\mathbf{Q}, z, \frac{x}{z} p_0^+ \right) \sum_i D_{q_i} \left(\frac{x}{z}, \mathbf{q}, t \right) \right. \\ &\quad \left. - \left[\mathcal{K}_{gg}(\mathbf{q}, z, x p_0^+) + \mathcal{K}_{qg}(\mathbf{q}, z, x p_0^+) \right] D_g(x, \mathbf{k}, t) \right\} + \int \frac{d^2 \mathbf{l}}{(2\pi)^2} C_g(\mathbf{l}) D_g(x, \mathbf{k} - \mathbf{l}, t), \\ \frac{\partial}{\partial t} D_{q_i}(x, \mathbf{k}, t) &= \int_0^1 dz \int \frac{d^2 \mathbf{q}}{(2\pi)^2} \alpha_s \left\{ \mathcal{K}_{qq} \left(\mathbf{Q}, z, \frac{x}{z} p_0^+ \right) D_{q_i} \left(\frac{x}{z}, \mathbf{q}, t \right) + \frac{1}{N_F} \mathcal{K}_{qg} \left(\mathbf{Q}, z, \frac{x}{z} p_0^+ \right) D_g \left(\frac{x}{z}, \mathbf{q}, t \right) \right. \\ &\quad \left. - \mathcal{K}_{qq}(\mathbf{q}, z, x p_0^+) D_{q_i}(x, \mathbf{k}, t) \right\} + \int \frac{d^2 \mathbf{l}}{(2\pi)^2} C_q(\mathbf{l}) D_{q_i}(x, \mathbf{k} - \mathbf{l}, t),\end{aligned}$$

$$C_{q(g)}(\mathbf{l}) = w_{q(g)}(\mathbf{l}) - \delta(\mathbf{l}) \int d^2 \mathbf{l}' w_{q(g)}(\mathbf{l}')$$