In-medium transverse momentum broadening effects on di-jet observables

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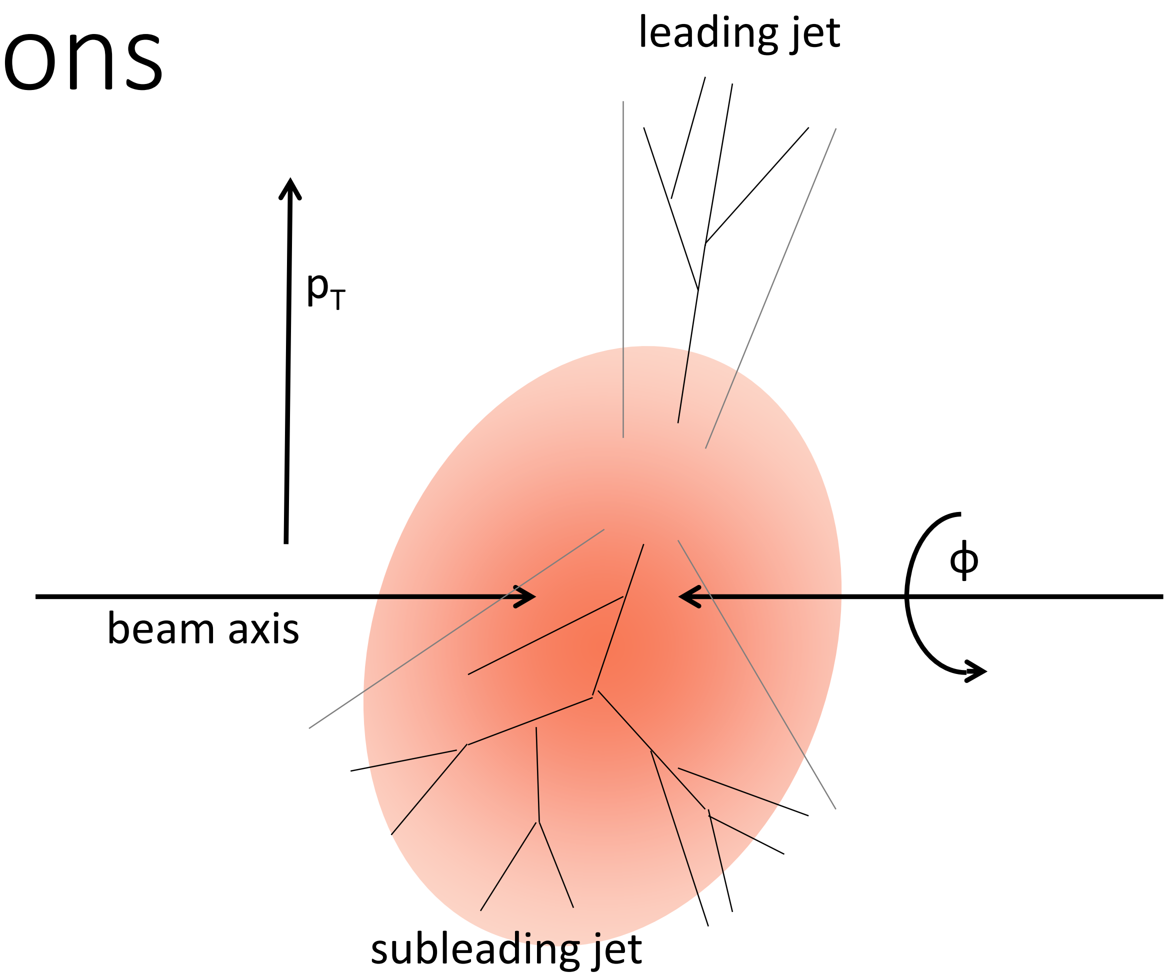
based on: [arXiv:1911.05463]

Jets in Heavy Ion collisions



Jets interact with medium → Jet Quenching!

↓

probe of the medium

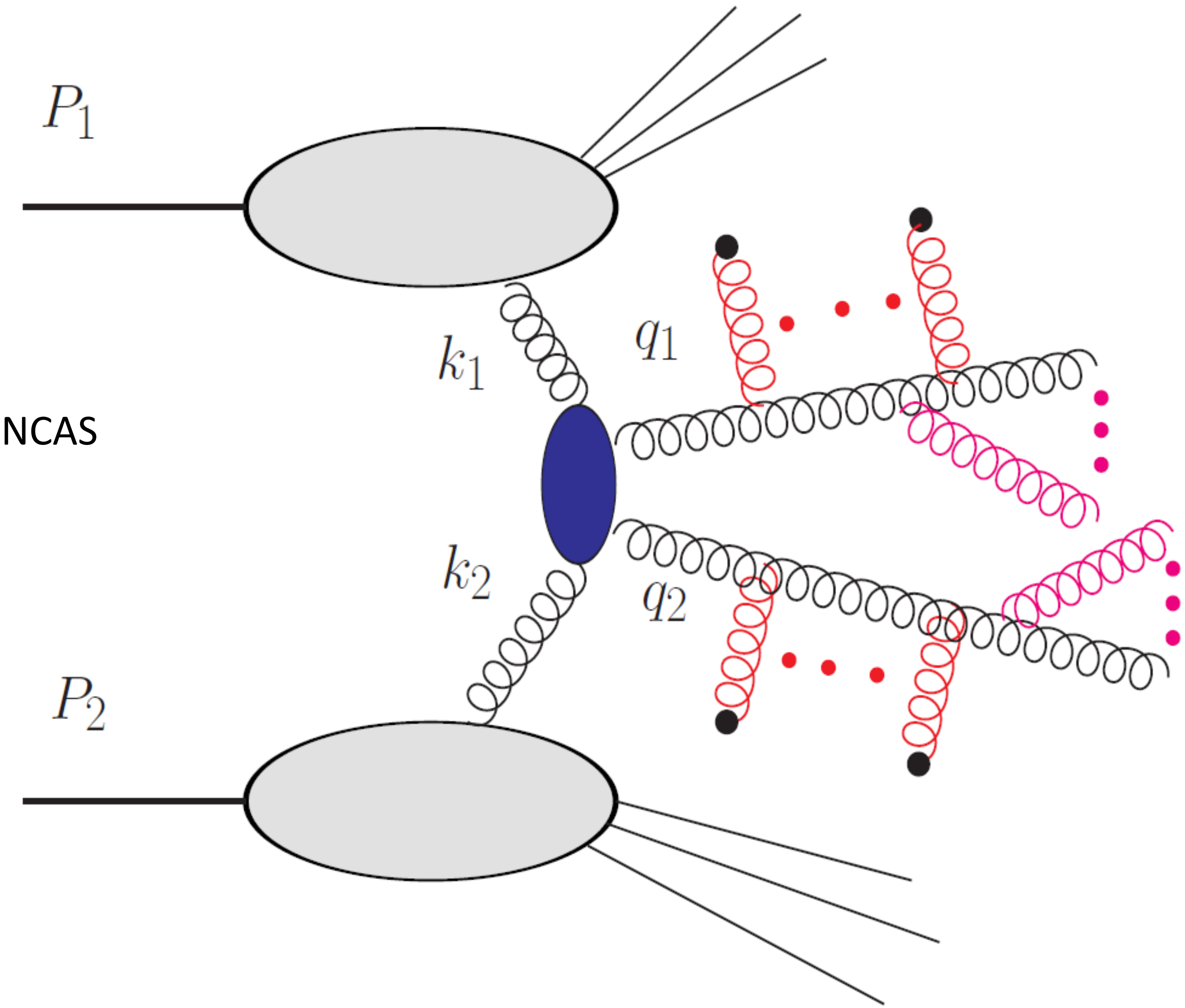
Jet Production(1/2)

Cross section =
(u)PDF1*(u)PDF2
*hard cross section

Here via KATIE

*fragmentation of jet1
*fragmentation of jet2

Here via MINCAS



Jet Production (2/2)

k_T factorization:

$$\frac{d\sigma_{pp}}{dy_1 dy_2 d^2q_{1T} d^2q_{2T}} = \int \frac{d^2k_{1T}}{\pi}\frac{d^2k_{2T}}{\pi}\frac{1}{16\pi^2(x_1x_2s)^2}\overline{|\mathcal{M}^{\text{off-shell}}_{g^*g^*\to gg}|^2}$$
$$\times\delta^{(2)}\left(\vec{k}_{1T}+\vec{k}_{2T}-\vec{q}_{1T}-\vec{q}_{2T}\right)\mathcal{F}_g(x_1,k_{1T}^2,\mu_F^2)\mathcal{F}_g(x_2,k_{2T}^2,\mu_F^2)$$

$\mathcal{F}_g(x,k_T^2,\mu_F^2)$ …unintegrated parton densities

full phase space access at LO
particularly relevant at low x

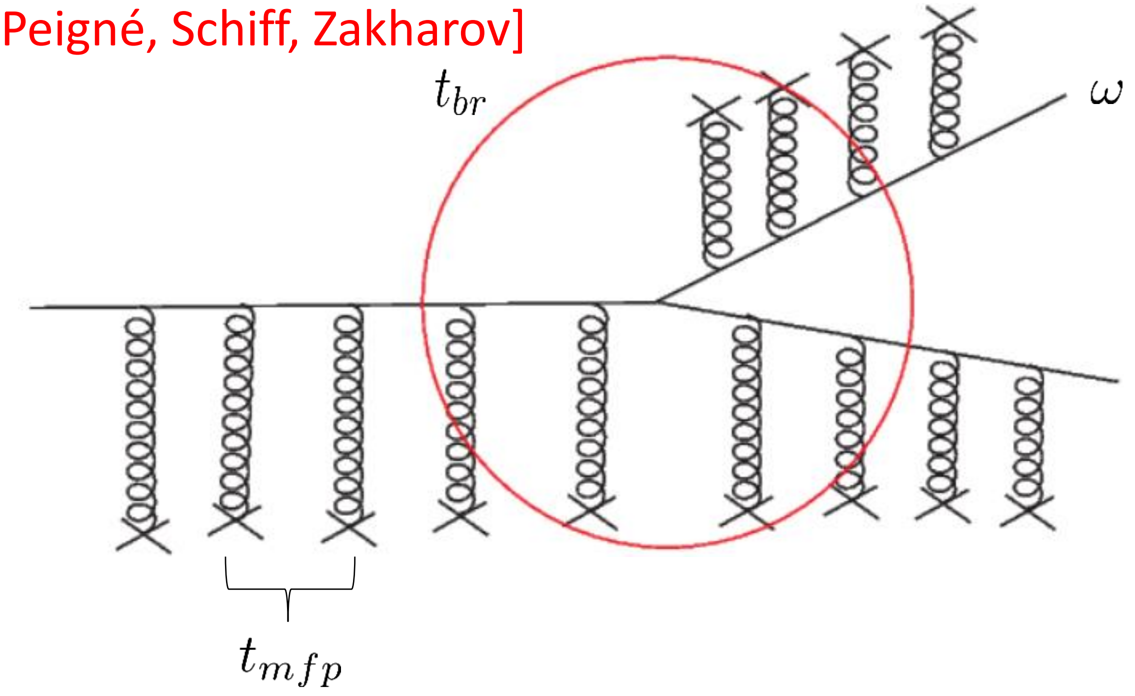
Coherent Emission

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

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

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

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



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

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

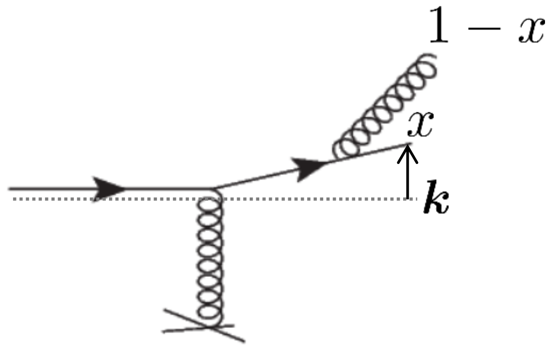
need effective splitting kernel

cf. [Blaizot, Dominguez, Iancu, Mehtar-Tani: JHEP 1301 (2013) 143]

BDIM Equation

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

- Generalizes BDMPS-Z approach
- Includes transverse momentum broadening



Momentum distribution:

$p \to xp$

Momentum transfer:

$p \to p + \mathbf{k}$

For gluon-jets:

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

Induced Radiation:

$$\mathcal{K}(z) = \frac{(1-z+z^2)^{\frac{5}{2}}}{[z(1-z)]^{\frac{3}{2}}}$$

$$\frac{1}{t^*} = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{\omega}} \propto \frac{1}{t_{br}}$$

Integration over $\boldsymbol{k}$

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

Scattering:

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

we use: $w(\boldsymbol{q}) = \dfrac{16\pi^2\alpha_s^2 N_c n}{\boldsymbol{q}^2(\boldsymbol{q}^2 + m_D^2)}$

BDIM Equation as Integral Equation

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

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

$$\tau = \frac{t}{t^*}$$

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

$$\begin{aligned}\Phi(x) &= \frac{1}{\sqrt{x}}\int_0^{1-\varepsilon} dz\, z\mathcal{K}(z),\\ W &= t^*\int_{|\mathbf{q}|>q_{\min}} d^2\mathbf{q}\,\frac{w(\mathbf{q})}{(2\pi)^2},\\ \Psi(x) &= \Phi(x) + W,\end{aligned}$$

$$\mathcal{G}(z,\mathbf{q}) = \sqrt{\frac{z}{x}}z\mathcal{K}(z)\,\theta(1-\varepsilon-z)\,\delta(\mathbf{q}) + t^*\frac{w(\mathbf{q})}{(2\pi)^2}\theta(|\mathbf{q}|-q_{\min})\delta(1-z)$$

Monte-Carlo algorithm

Set/Select x_0 and $\mathbf{k}_0$ at τ_0

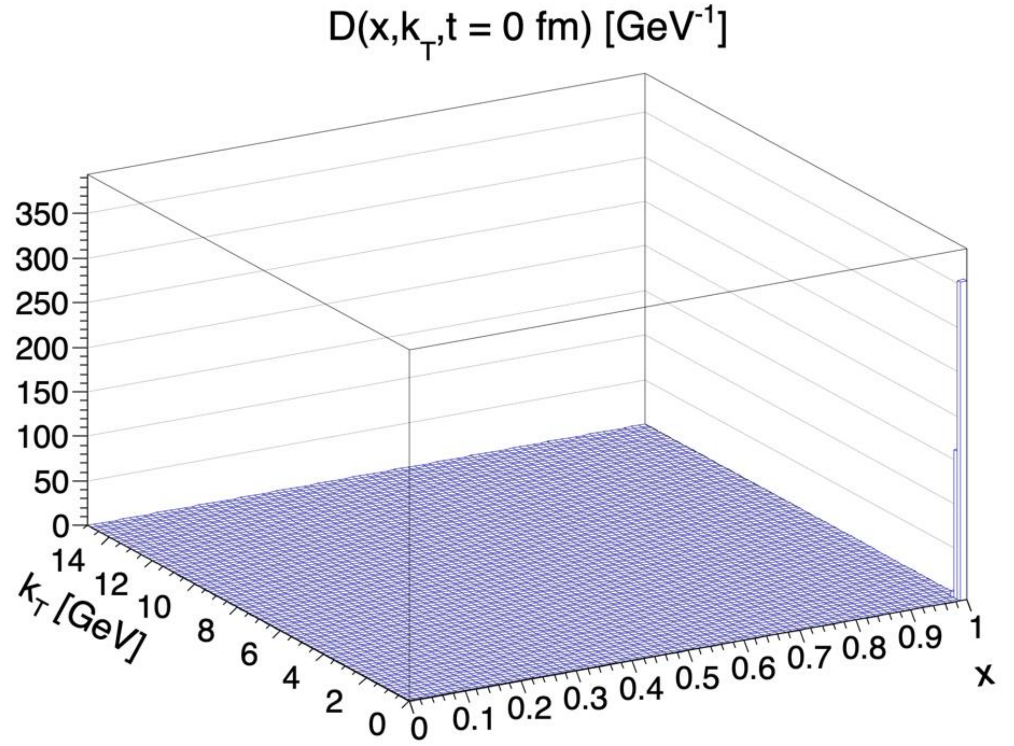
- Select τ_{i+1}:
  Probability density: $\Psi(x_i)e^{-\Psi(x_i)(\tau_{i+1}-\tau_i)}$
- Splitting with probability $p = \Phi(x_i)/\Psi(x_i)$
  otherwise: scattering.
- If splitting, select $z = \frac{x_{i+1}}{x_i}$
  probability density: $\frac{z\mathcal{K}(z)}{\int_0^{1-\epsilon} dz' z'\mathcal{K}(z')}$
- If scattering, select $\mathbf{q}_{i+1}$
  probability density $\frac{t^*}{(2\pi)^2}\frac{w(\mathbf{q}_{i+1})}{W}$

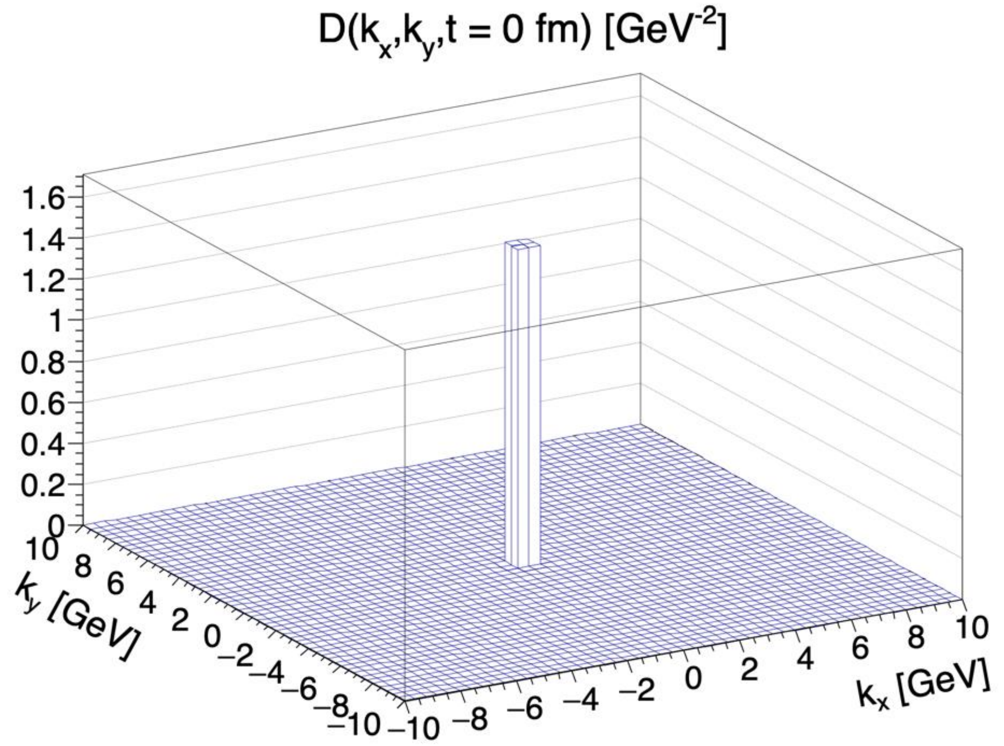
Repeat for next step in τ and x or $\boldsymbol{k}$

Stop once $\tau > \tau_L$

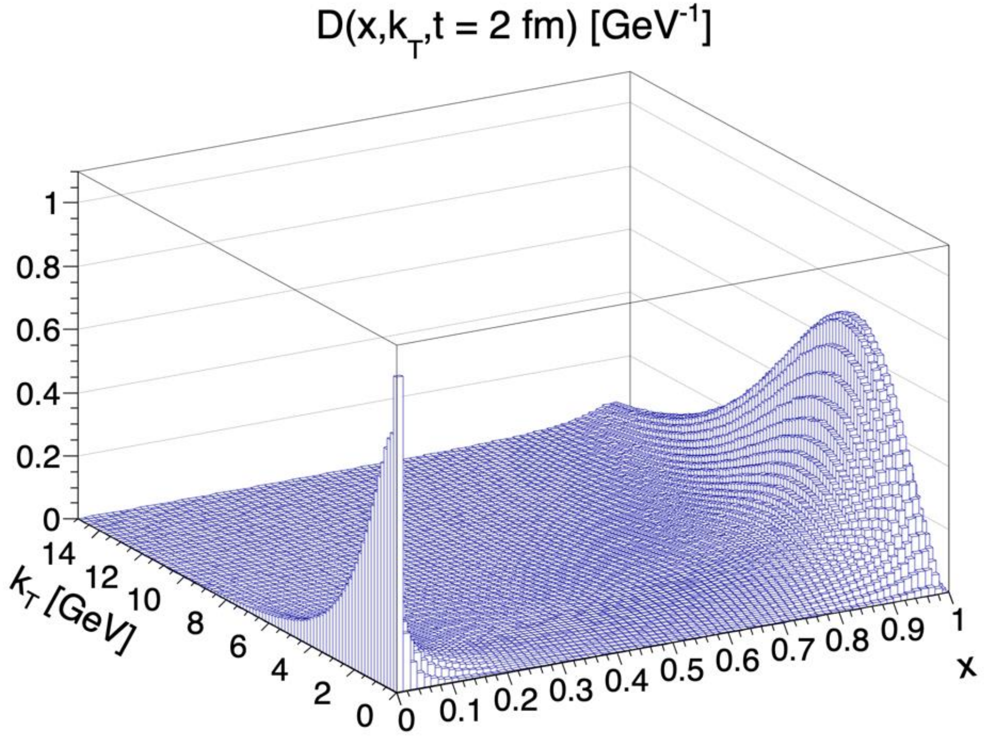
M I N C A S

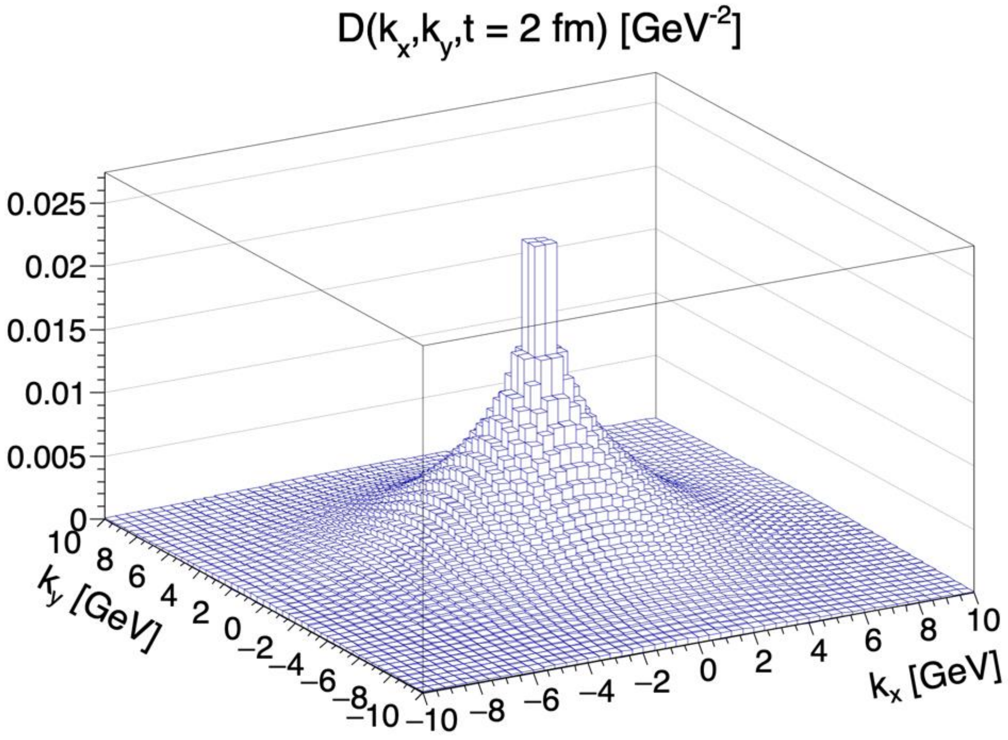
Evolution of D(x,**k**,t) (1/2)





Evolution of D(x,**k**,t) (2/2)





k Distribution

always same distribution for changes $p \to p + \boldsymbol{q}$
→central limit theorem

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

Splitting à la $p \to zp$
→ perturbations of different sizes
→non Gaussian behavior

Virtual emissions

For example:

$$p \to z_1 p \to z_1 p + \boldsymbol{q}_1$$
$$\to z_1 p + \boldsymbol{q}_1 + \boldsymbol{q}_2$$
$$\to z_2(z_1 + \boldsymbol{q}_1 + \boldsymbol{q}_2) \to \ldots$$

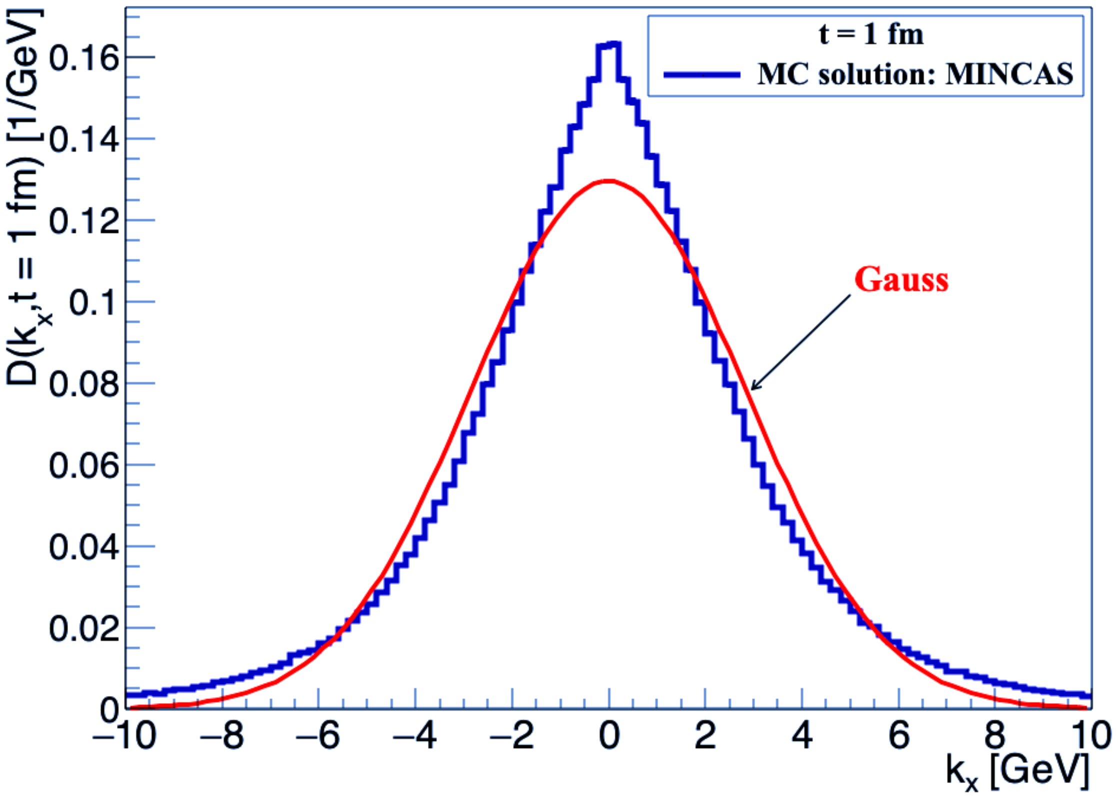


Figure: [Kutak, Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317]

Program: KATIE+MINCAS

- Use KATIE for hard initial collisions:
  - (u)PDFsfor colliding nucleons
  - Hard collision cross-section (Monte-Carlo simulation)
  - Resulting particles→initial particles of jets

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

- Jets: by MINCAS
  - Monte-Carlo simulation of BDIM equation
  - Time-evolution of jets in medium

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

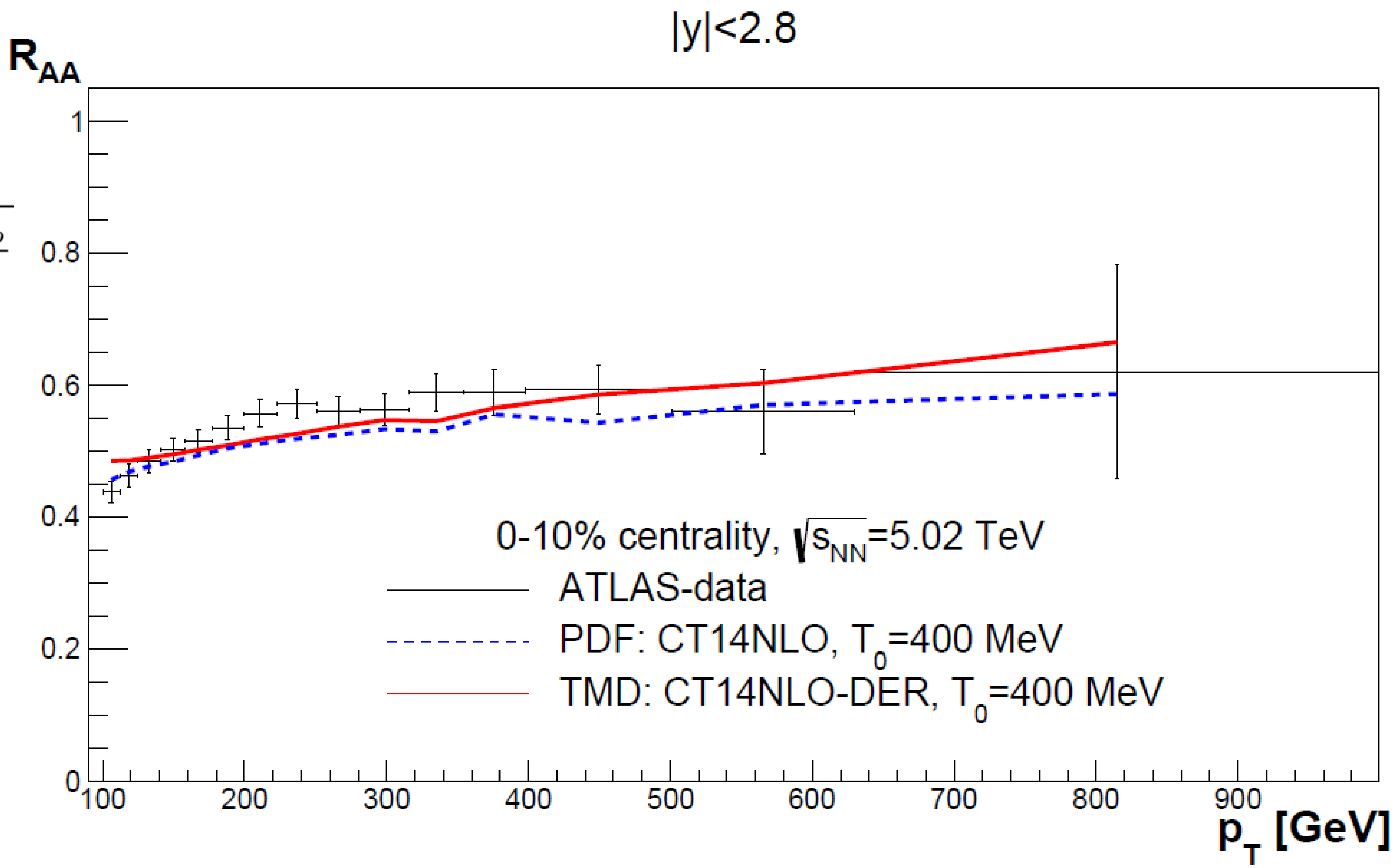
Other codes implementing BDMPS-Z:

MARTINI, JEWEL, QPYTHIA, …

R_{AA}

$$R_{AA}(p_T) = \frac{\frac{dN_{AA}}{dp_T}}{\langle T_{AA}\rangle \frac{d\sigma_{pp}}{dp_T}}$$

$$\approx \frac{\frac{d\sigma_{AA}}{dp_T}}{\frac{d\sigma_{pp}}{dp_T}}$$



Gaussian k_T broadening

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

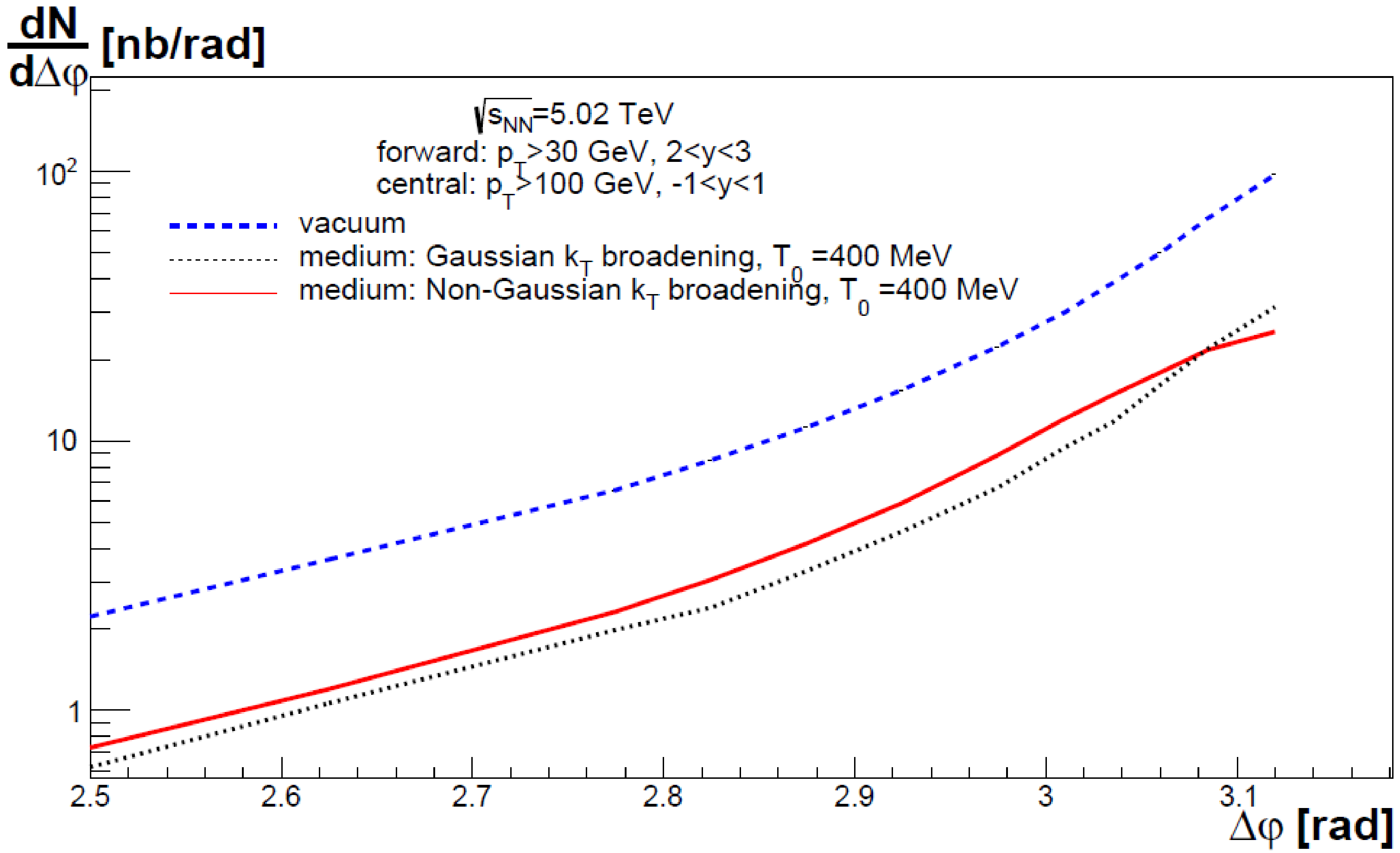
↓ Integrate over $d^2\boldsymbol{k}$

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

↓

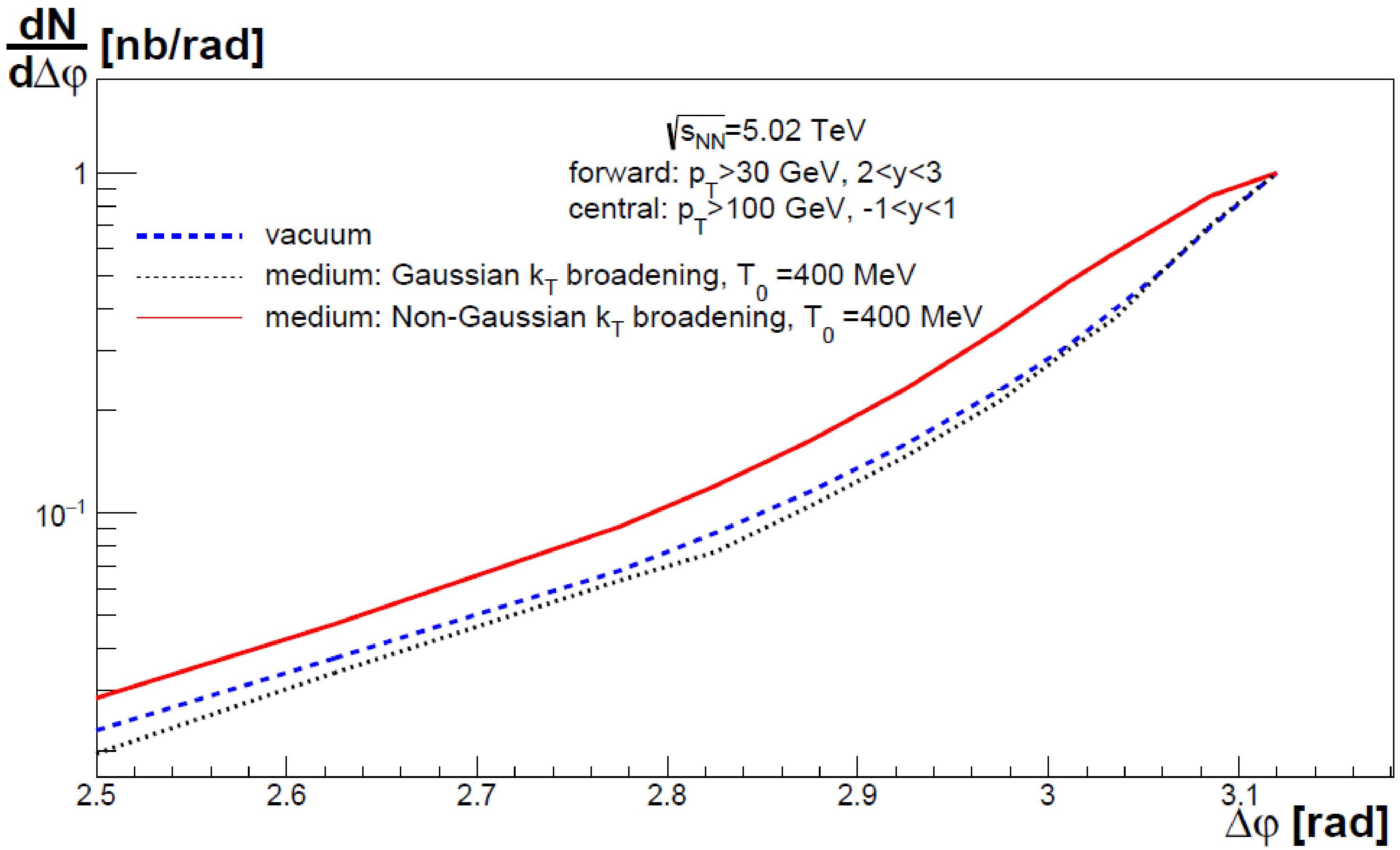
For comparison with full equation: add k_T selected from Gaussian! width: $\sigma^2 \sim \hat{q}L$

Azimuthal Decorrelations



Azimuthal Decorrelations

Normalized to maximum!



Summary

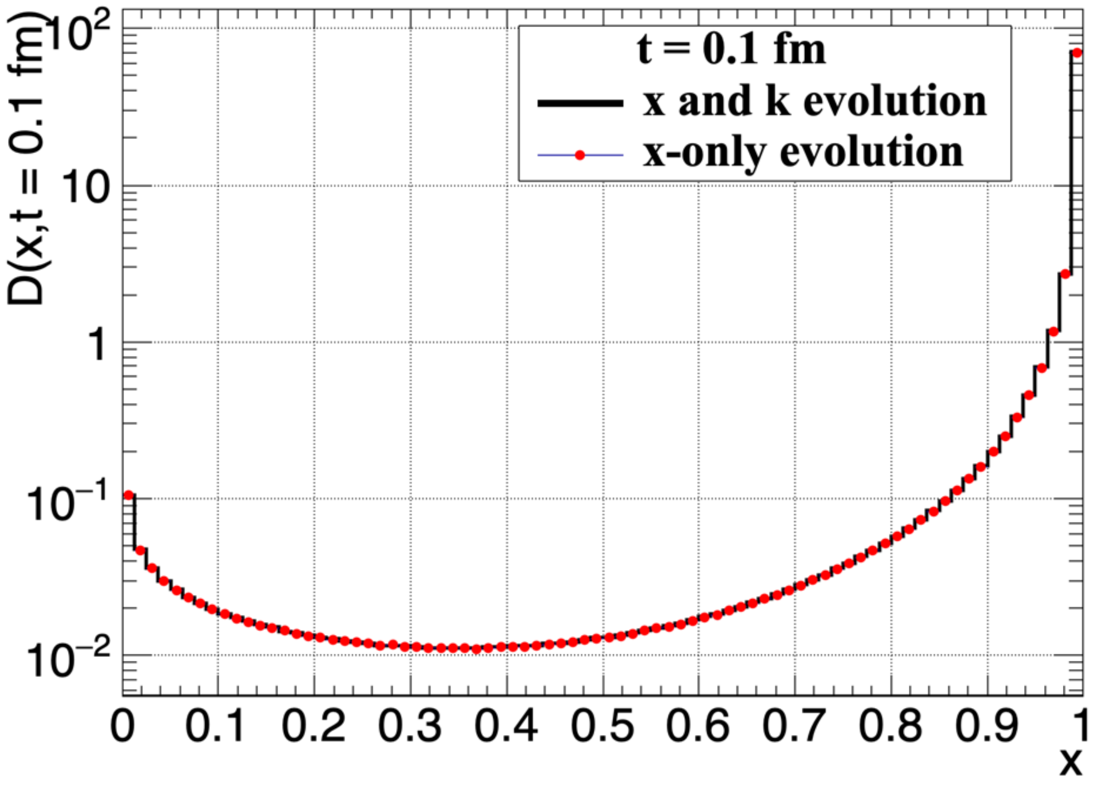
- MINCAS: jet evolution based on coherent emission and scattering
- Combination with KATIE: allows for calculation of jet-observables
- Results differ from pure Gaussian broadening…
- …e.g.: in angular correlations of di-jets,
- But p_T distributions seem to be invariant (so far)

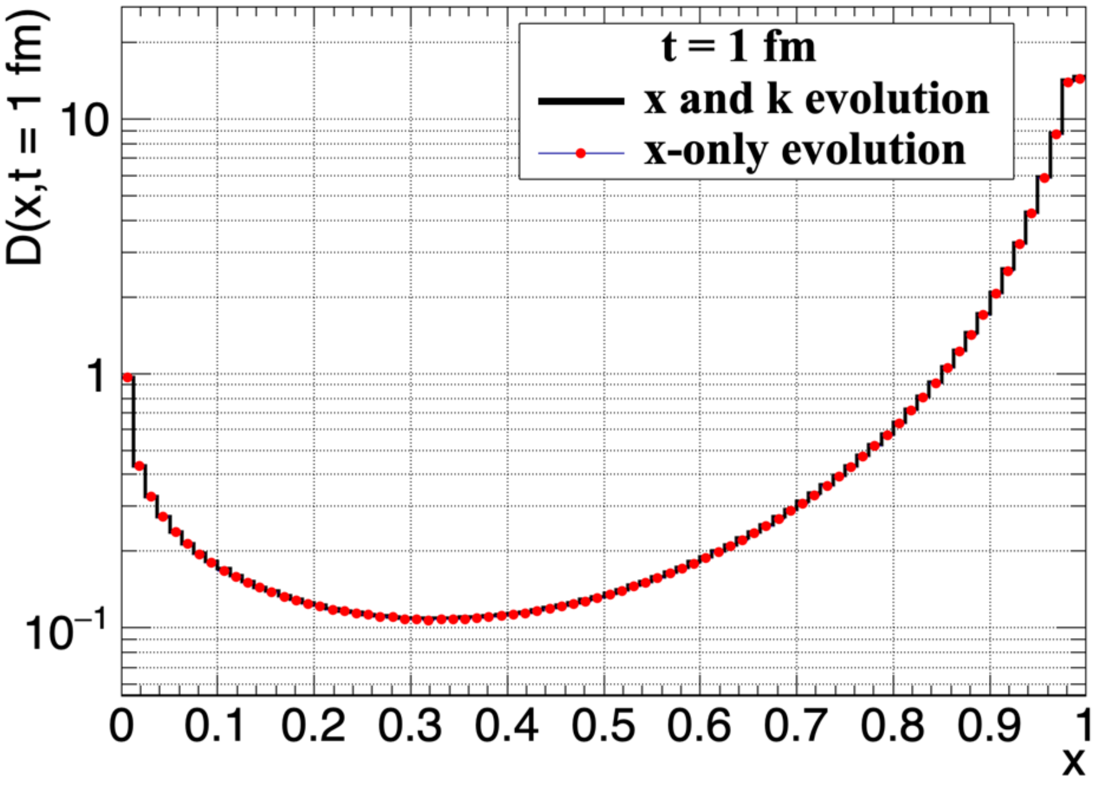
Outlook

- to account for quarks
- to study more forward processes

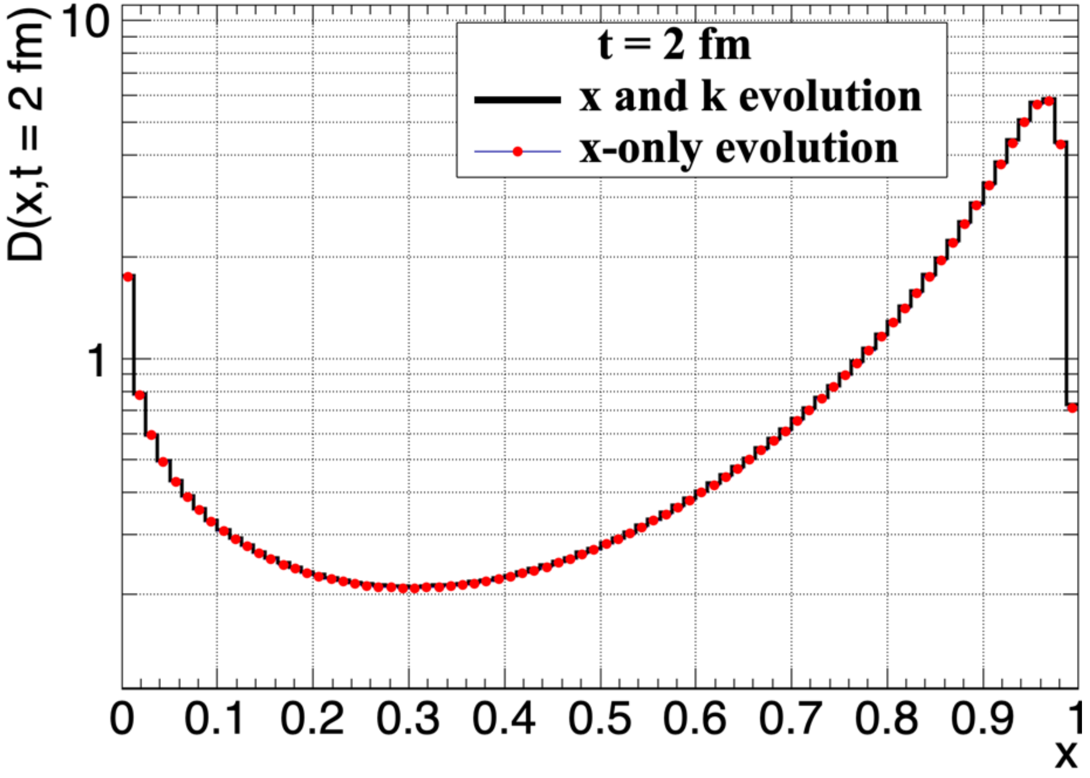
Back-up slides

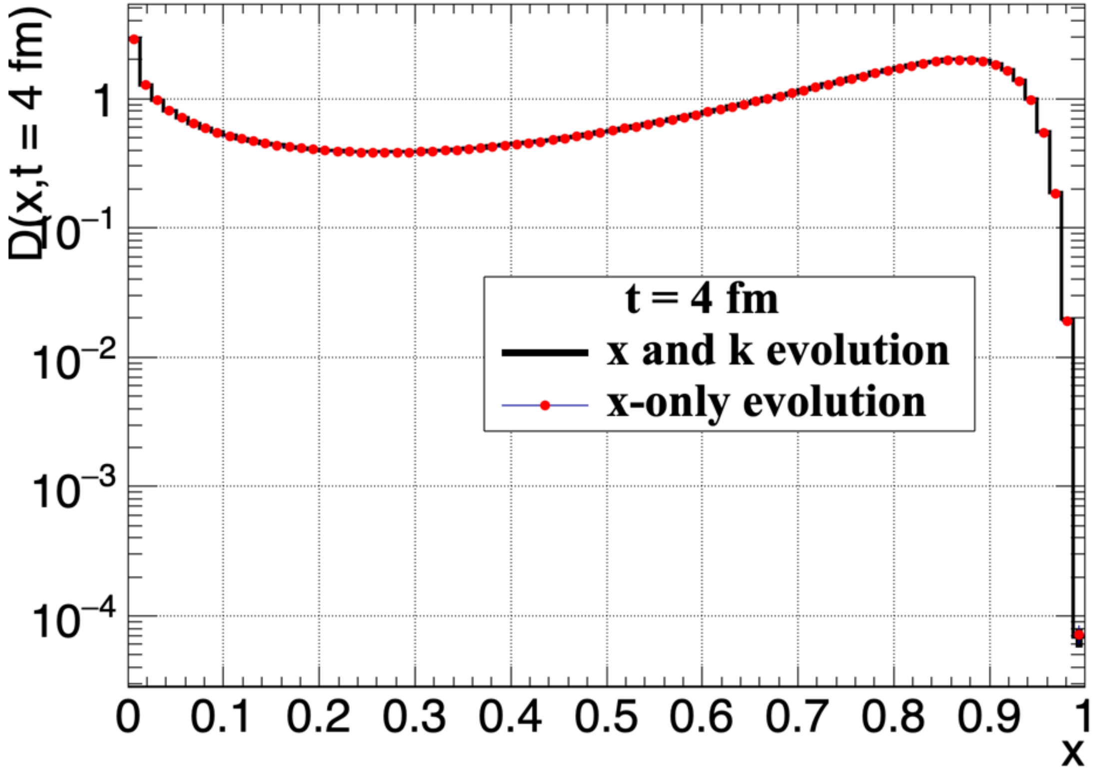
Turbulent behavior (1/2)





Turbulent behavior (2/2)





Jet Production

Factorization for AA collisions:

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

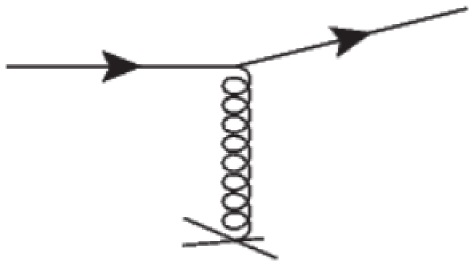
$$d\Omega_q = dq^+ d^2\boldsymbol{q} \qquad \tau(q^+) = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{q^+}}L$$

$$\Big\downarrow$$

$$\frac{d^2\sigma_{AA}}{d\Omega_{p_1} d\Omega_{p_2}} = \int d\Omega_{q_1} \int d\Omega_{q_2} \int d^2\boldsymbol{l}_1 \int d^2\boldsymbol{l}_2 \int_0^1 \frac{d\tilde{x}_1}{\tilde{x}_1} \delta(p_1^+ - \tilde{x}_1 q_1^+) \int_0^1 \frac{d\tilde{x}_2}{\tilde{x}_2} \delta(p_2^+ - \tilde{x}_2 q_2^+)$$
$$\delta^{(2)}(\boldsymbol{p}_1 - \boldsymbol{l}_1 - \boldsymbol{q}_1)\delta^{(2)}(\boldsymbol{p}_2 - \boldsymbol{l}_2 - \boldsymbol{q}_2) D(\tilde{x}_1, \boldsymbol{l}_1, \tau(q_1^+)) D(\tilde{x}_2, \boldsymbol{l}_2, \tau(q_2^+)) \frac{d^2\sigma_{pp}}{d\Omega_{q_1} d\Omega_{q_2}}$$

Processes in Jets

scattering…



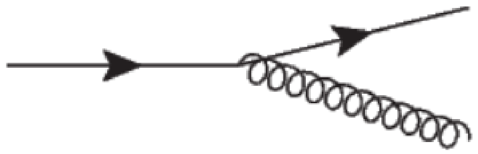
Transverse momentum transfer!

$$p \to p + k_T$$

Scattering Kernel: $C(k_T)$

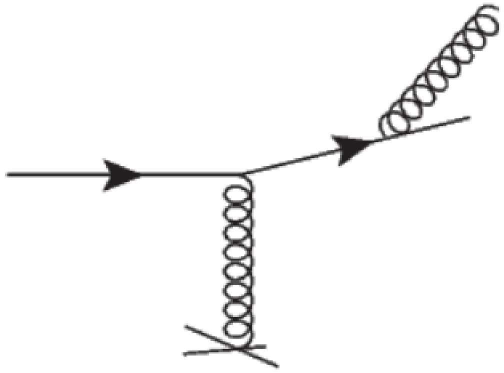
Average transfer: $\hat{q}$

…splitting…



Bremsstrahlung as in vacuum.

…induced radiation



Momentum distribution:

$$p \to zp$$

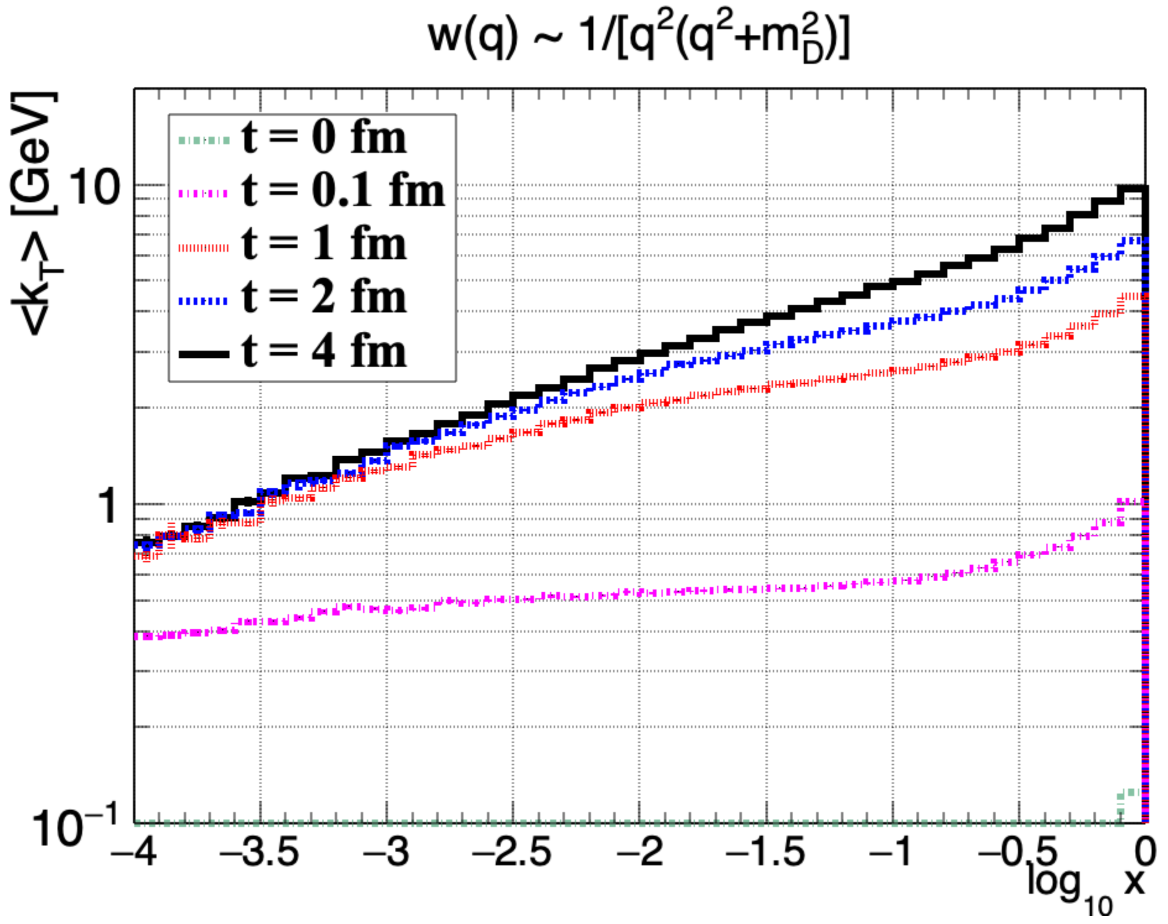
+Momentum transfer:

$$p \to zp + k_T$$

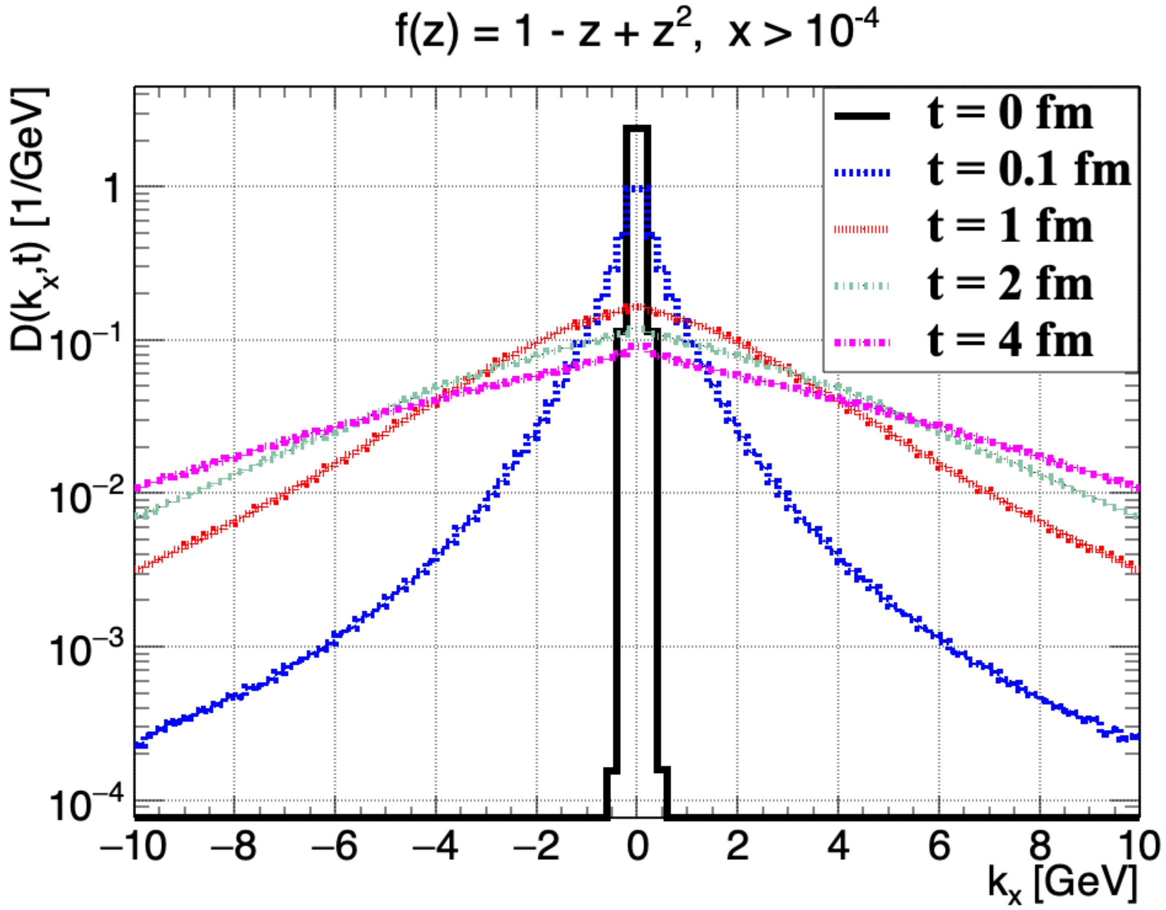
Kernel: $\mathcal{K}(z, k_T)$

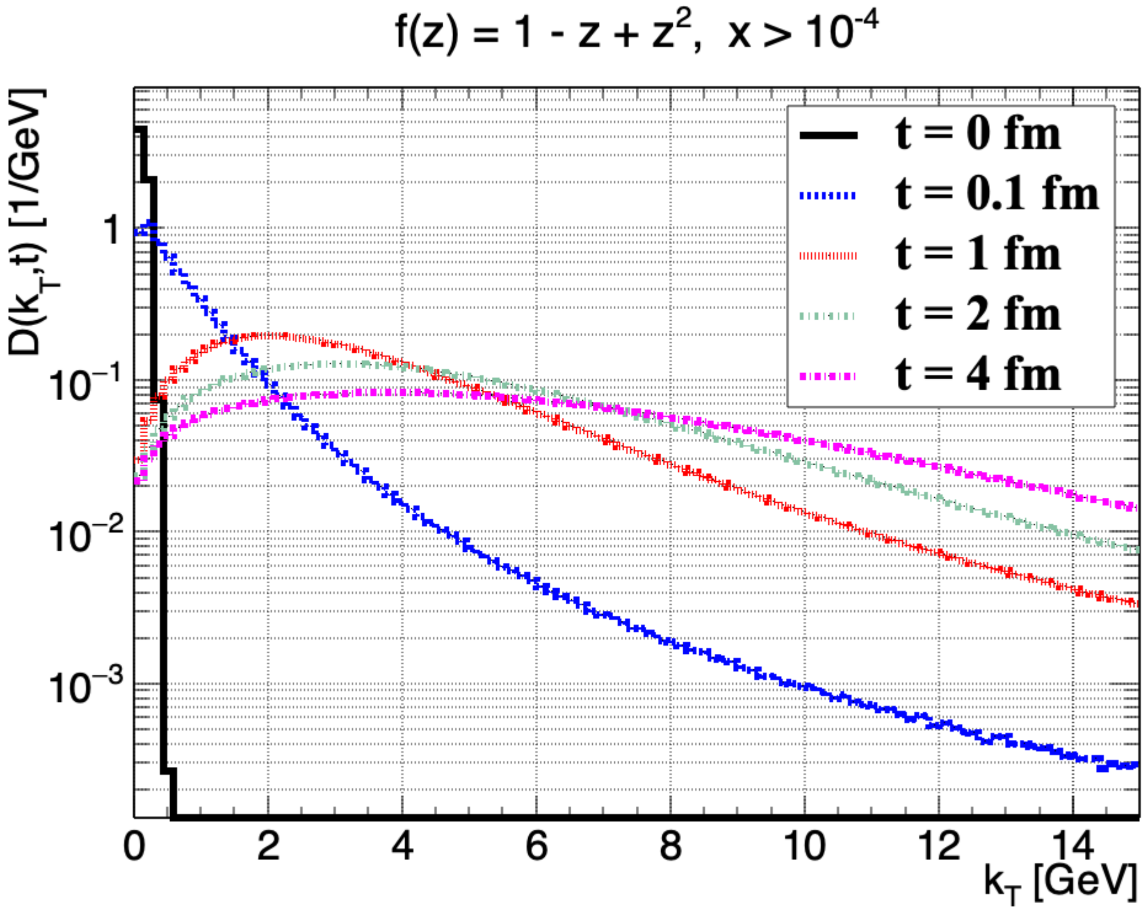
Our results: combination of scattering and induced radiation processes!

k_T Distribution



k_T Distribution





R_{AA}

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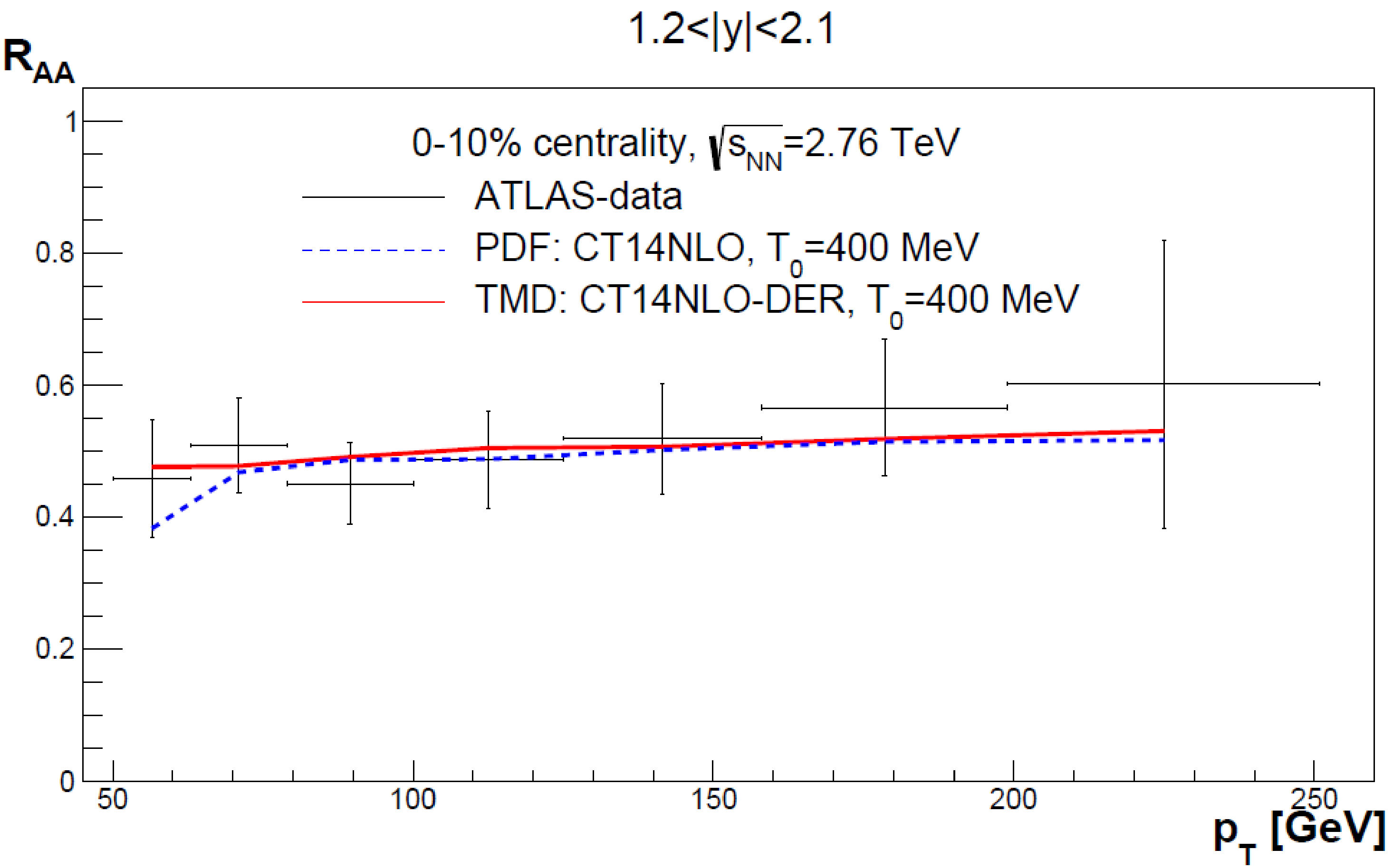

Asymmetry A_j

$$A_j = \frac{p_{Tc} - p_{Tf}}{p_{Tc} + p_{Tf}}$$