Effects of in-medium k_T broadening on di-jet observables

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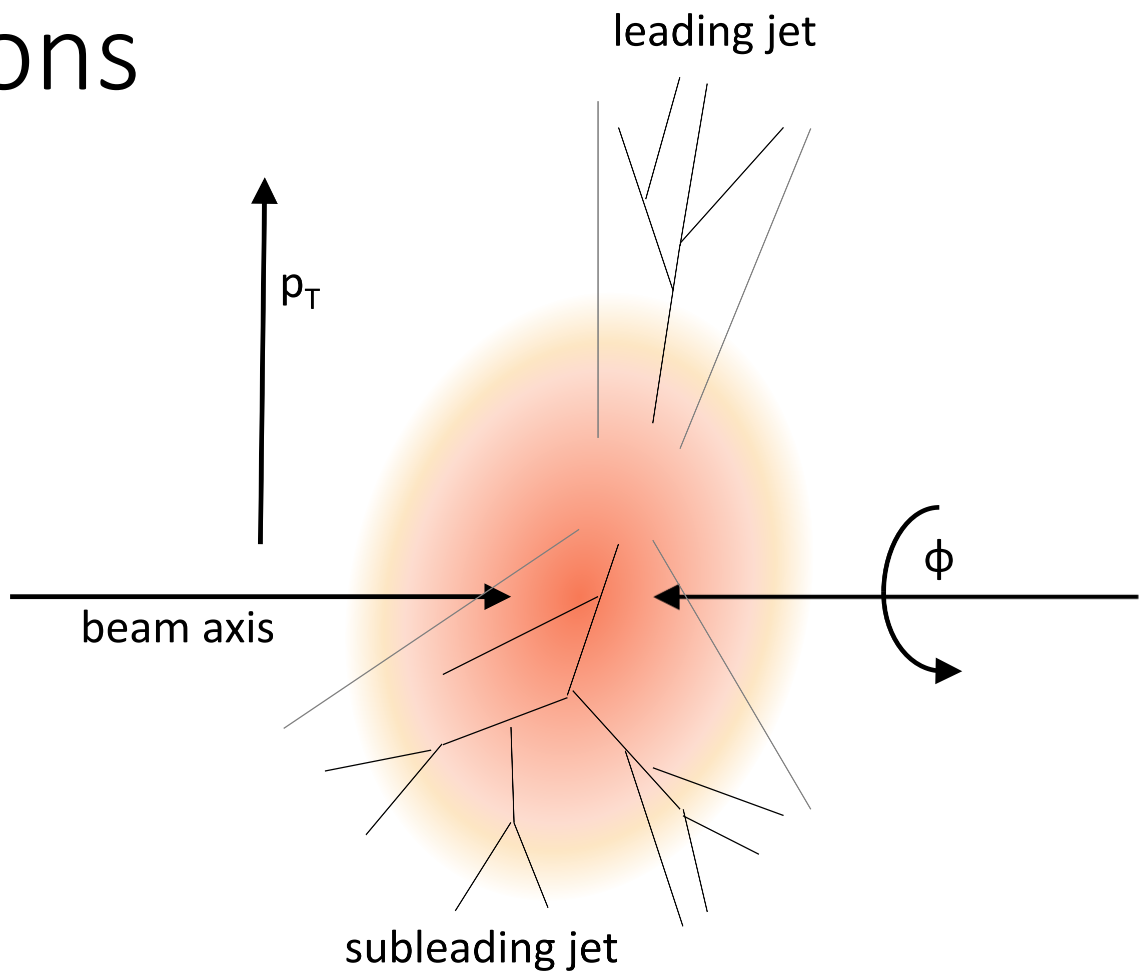
based on: [arXiv:1911.05463]

Jets in Heavy Ion collisions



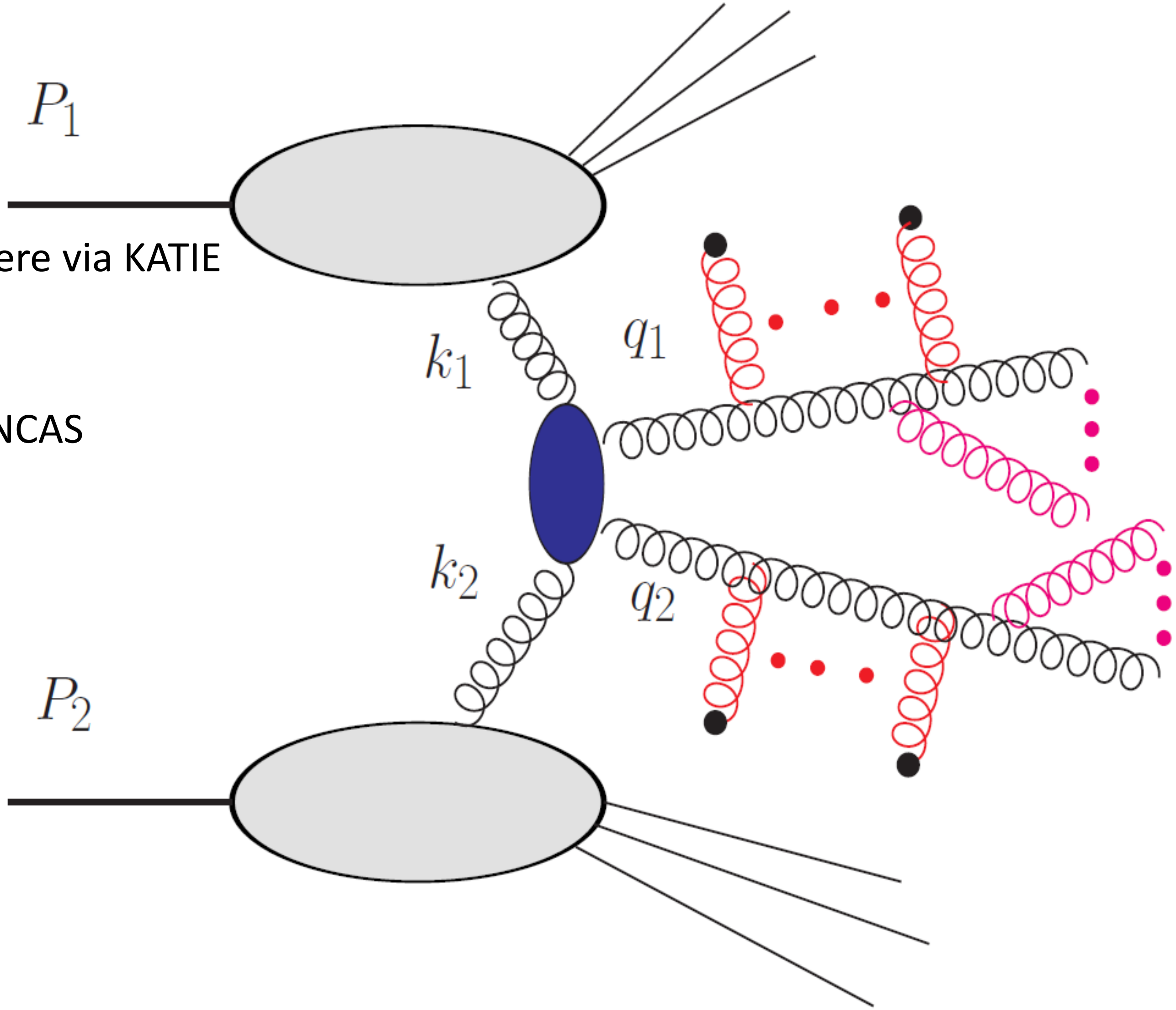
Jets interact with medium → Jet Quenching!

↓

probe of the medium

Jet Production(1/3)

Cross section =
PDF1(or TMD1)*PDF2(TMD2) *hard cross section — Here via KATIE
*fragmentation of jet1 *fragmentation of jet2 — Here via MINCAS



Jet Production (2/3)

k_T factorization:

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

$\mathcal{F}_g(x,k_T^2,\mu_F^2)$ …transverse momentum distribution (TMD)

→ full phase space access at LO
particularly relevant at low x

Jet Production (3/3)

Factorization for AA collisions:

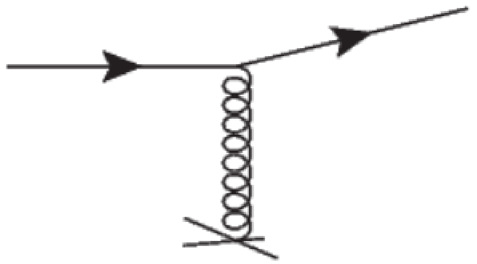
$$\frac{d\sigma_{AA}}{d\Omega_p} = \int d\Omega_q \int d^2\boldsymbol{l} \int_0^1 \frac{d\tilde{x}}{\tilde{x}} \delta(p^+ - \tilde{x}q^+)\delta^{(2)}(\boldsymbol{p} - \boldsymbol{l} - \boldsymbol{q}) D(\tilde{x}, \boldsymbol{l}, \tau(q^+)) \frac{d\sigma_{pp}}{d\Omega_q}$$

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

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

Processes in Jets

scattering…



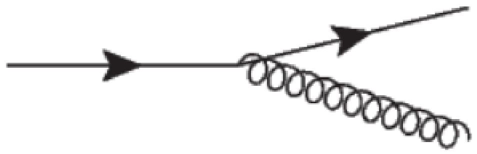
Transverse momentum transfer!

$$p \rightarrow p + k_T$$

Scattering Kernel: $C(k_T)$

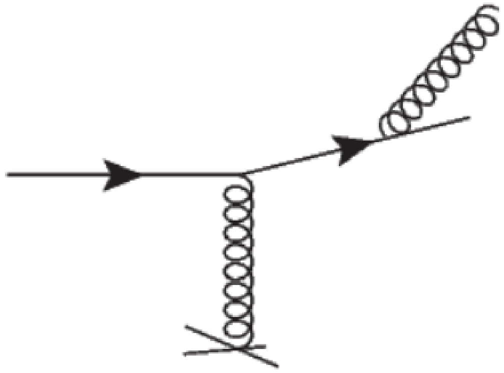
Average transfer: $\hat{q}$

…splitting…



Bremsstrahlung as in vacuum.

…induced radiation



Momentum distribution:

$$p \rightarrow zp$$

+Momentum transfer:

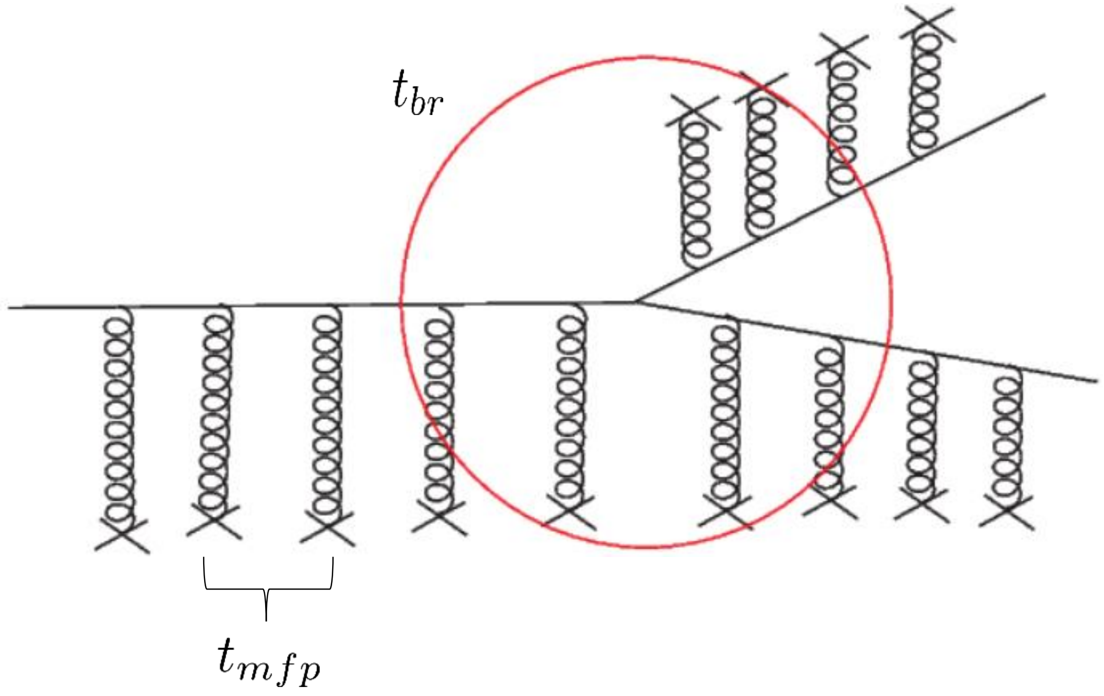
$$p \rightarrow zp + k_T$$

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

Our results: combination of scattering and induced radiation processes!

BDMPS-Z

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



$t_{br} \sim t_{mfp}$: 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 kernel: $\mathcal{K}(z, k_T)$

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

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:

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

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

Scattering:

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

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

Program: KATIE+MINCAS

- Use KATIE for hard initial collisions:
  - PDFs/TMDs for 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, …

Medium Model

Bjorken Model:

$$T(t) = T_0 \left(\frac{t_0}{t}\right)^{\frac{1}{3}}$$

T...temperature at time t

T_0...temperature at time t_0

fixed		free		resulting	
c_q	3.7	t_0	0.6 fm/c	$\langle \hat{q} \rangle$	0.54 GeV^2/fm
c_n	5.228	t_L	5 fm/c	$\langle n \rangle$	0.154 GeV^3
		T_0	0.4 GeV	$\langle m_D \rangle$	0.684 GeV

From Phenomenology (the JET-Collaboration):

$$\hat{q}(T) = c_q T^3$$

[JET Collaboration, Burke et al.: Phys. Rev.C90(2014) 014909]

From HTL:

$$m_D^2 = \left(\frac{N_C}{3} + \frac{N_F}{6}\right) g^2 T^2$$

cf. [Laine, Vuorinen: Lect. Notes Phys.925(2016)pp.1–281, 1701.01554]

Bose-Einstein/Fermi-Dirac Distribution

↓

Taylor expansion, lowest order:

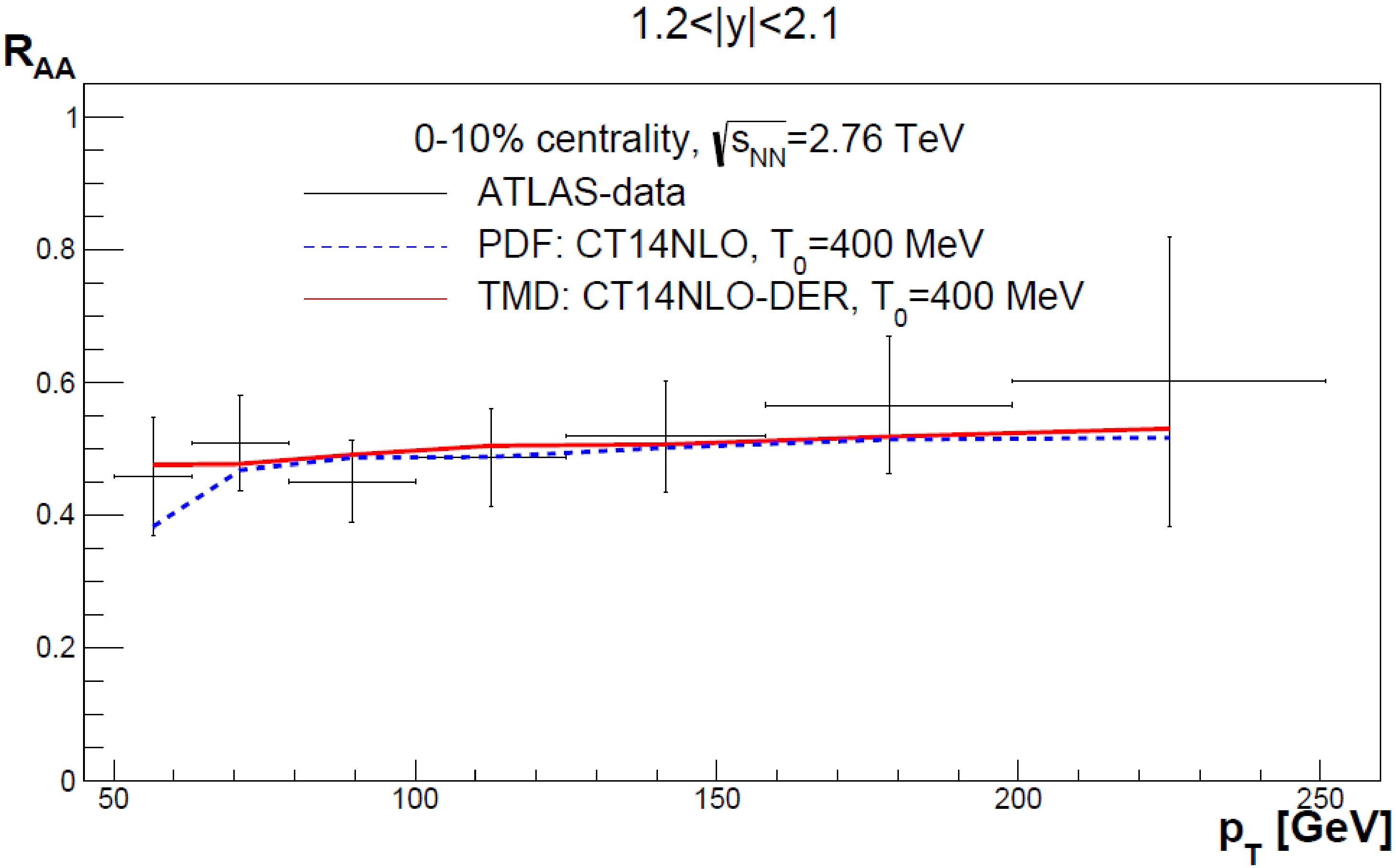
$$n(T) = n_q + n_{\bar{q}} + n_g = c_n T^3$$

cf.:[K.C.Zapp, PhD-Thesis, Heidelberg U., 2008]

R_{AA}

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

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



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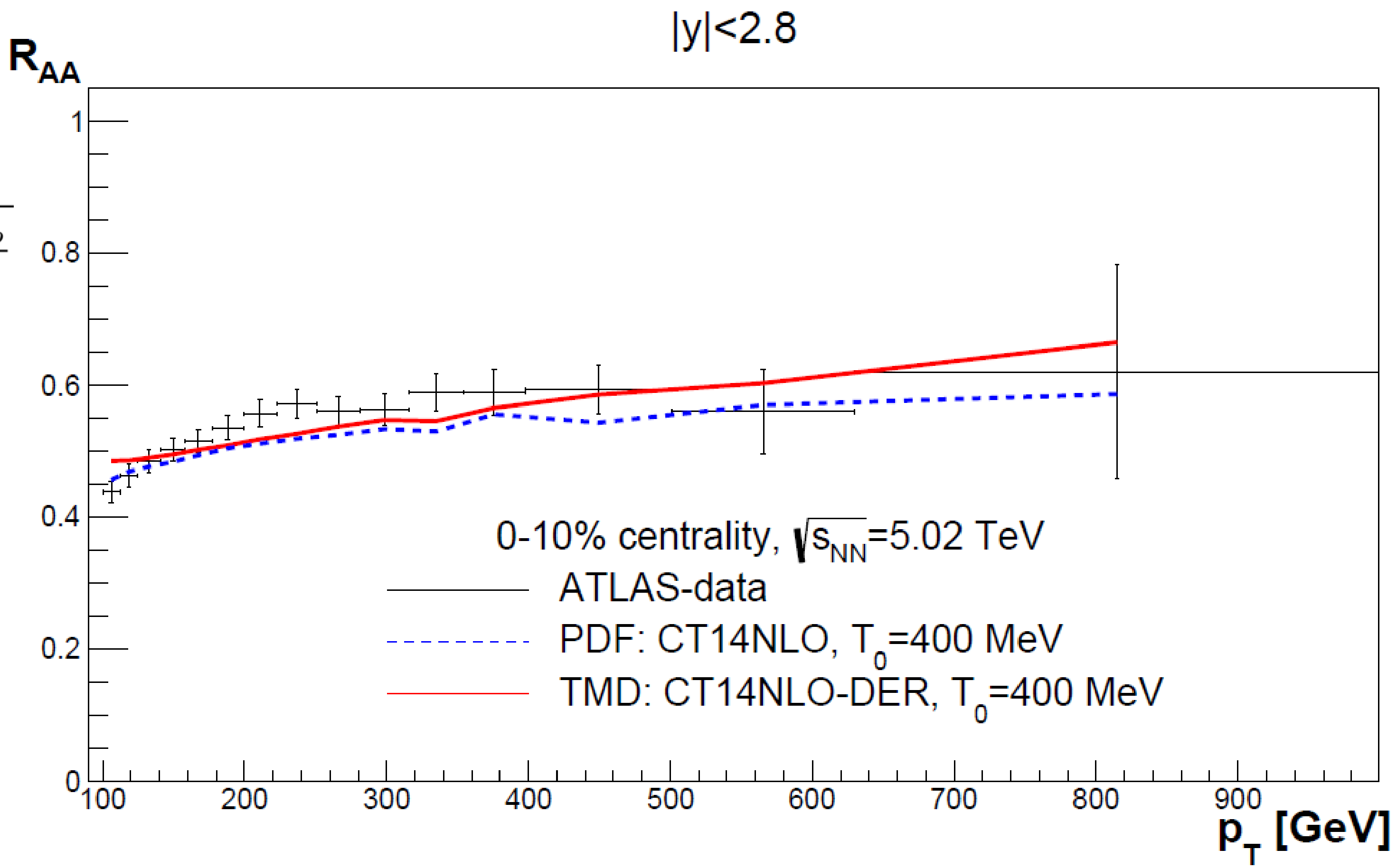


k_T Distribution

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

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

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

Virtual emissions

For example:

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

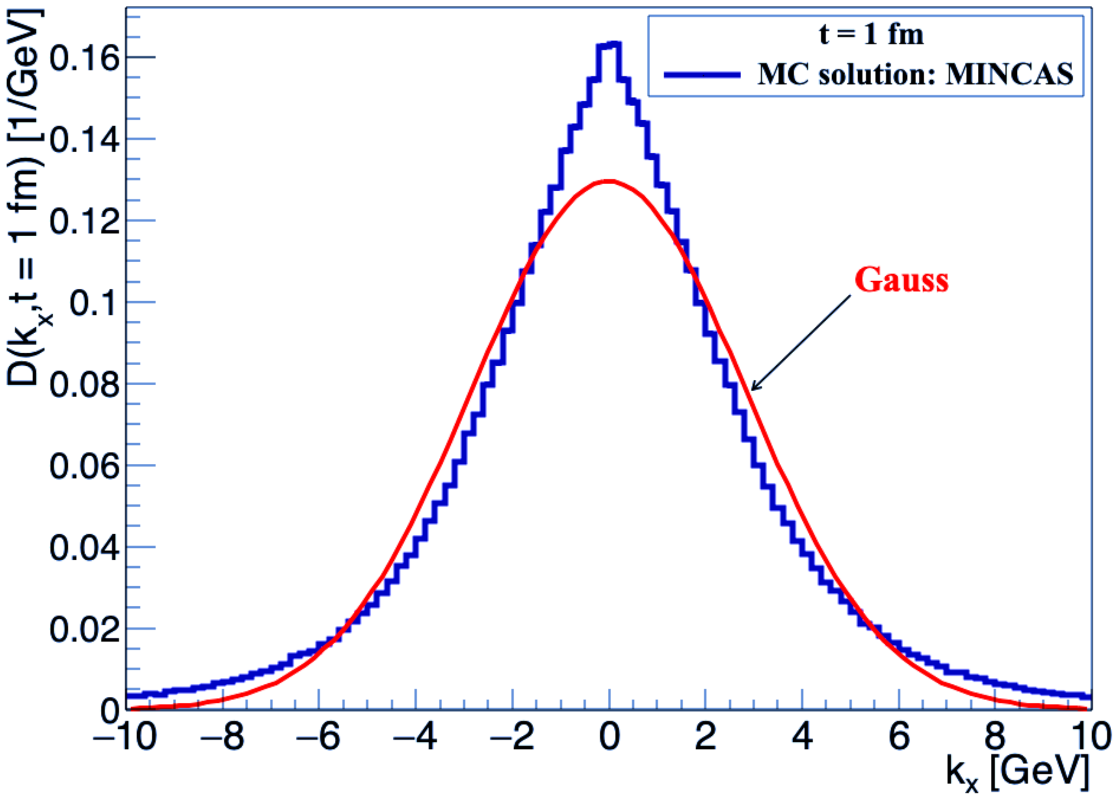


Figure: [Kutak, Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317]

Gaussian k_T broadening

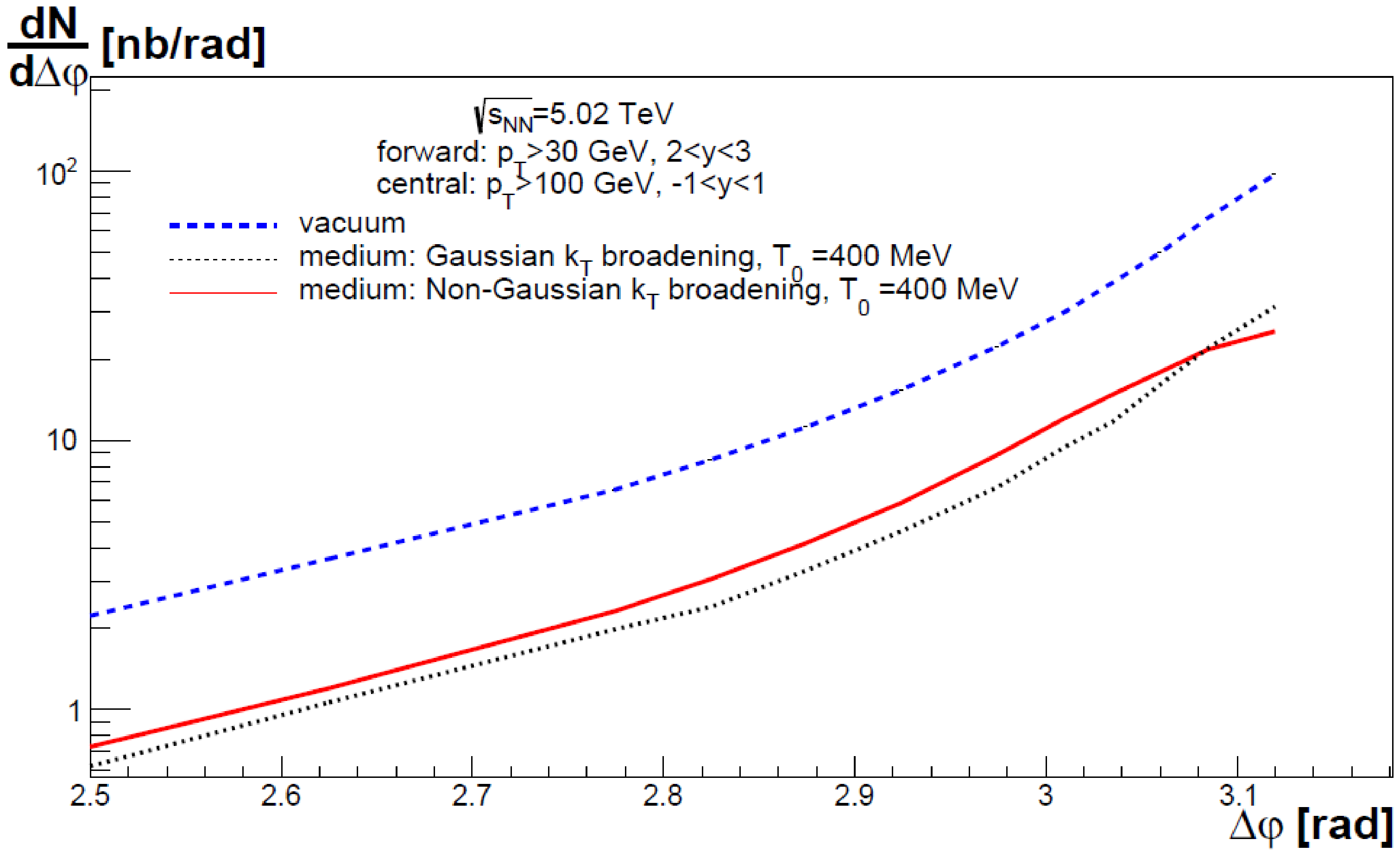
$$\frac{\partial}{\partial t}D(x,\boldsymbol{k},t) = \frac{1}{t^*}\int_0^1 dz\mathcal{K}(z)\left[\frac{1}{z^2}\sqrt{\frac{z}{x}}D\left(\frac{x}{z},\frac{\boldsymbol{k}}{z},t\right)\theta(z-x) - \frac{z}{\sqrt{x}}D(x,\boldsymbol{k},t)\right] + \int\frac{d^2\boldsymbol{q}}{(2\pi)^2}C(\boldsymbol{q})D(x,\boldsymbol{k}-\boldsymbol{q},t)$$

Integrate over $d^2\boldsymbol{k}$

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

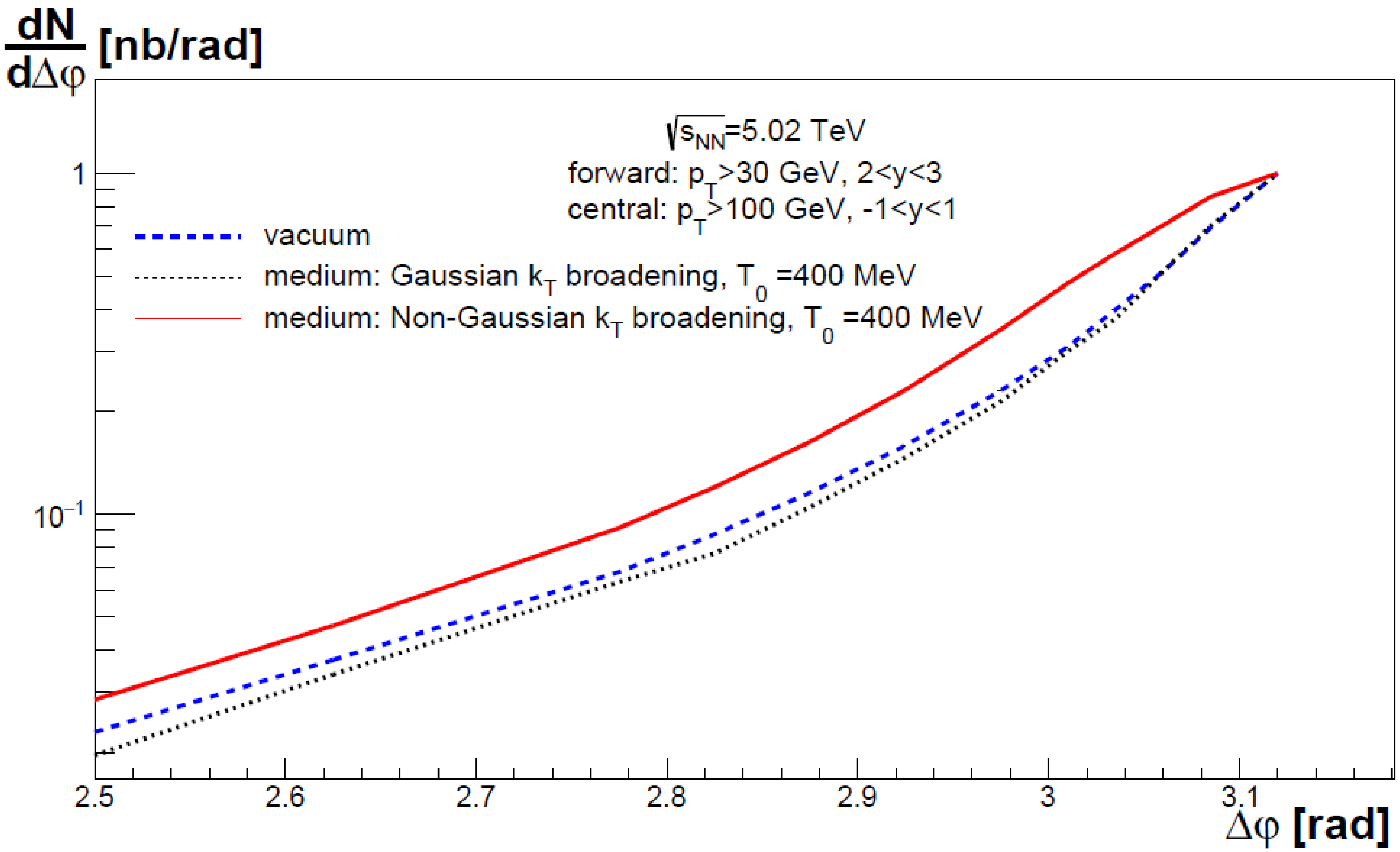
For comparison with full equation: add $\boldsymbol{k}$ selected from Gaussian! width: $\sigma^2 \sim \hat{q}L$

Azimuthal Decorrelations



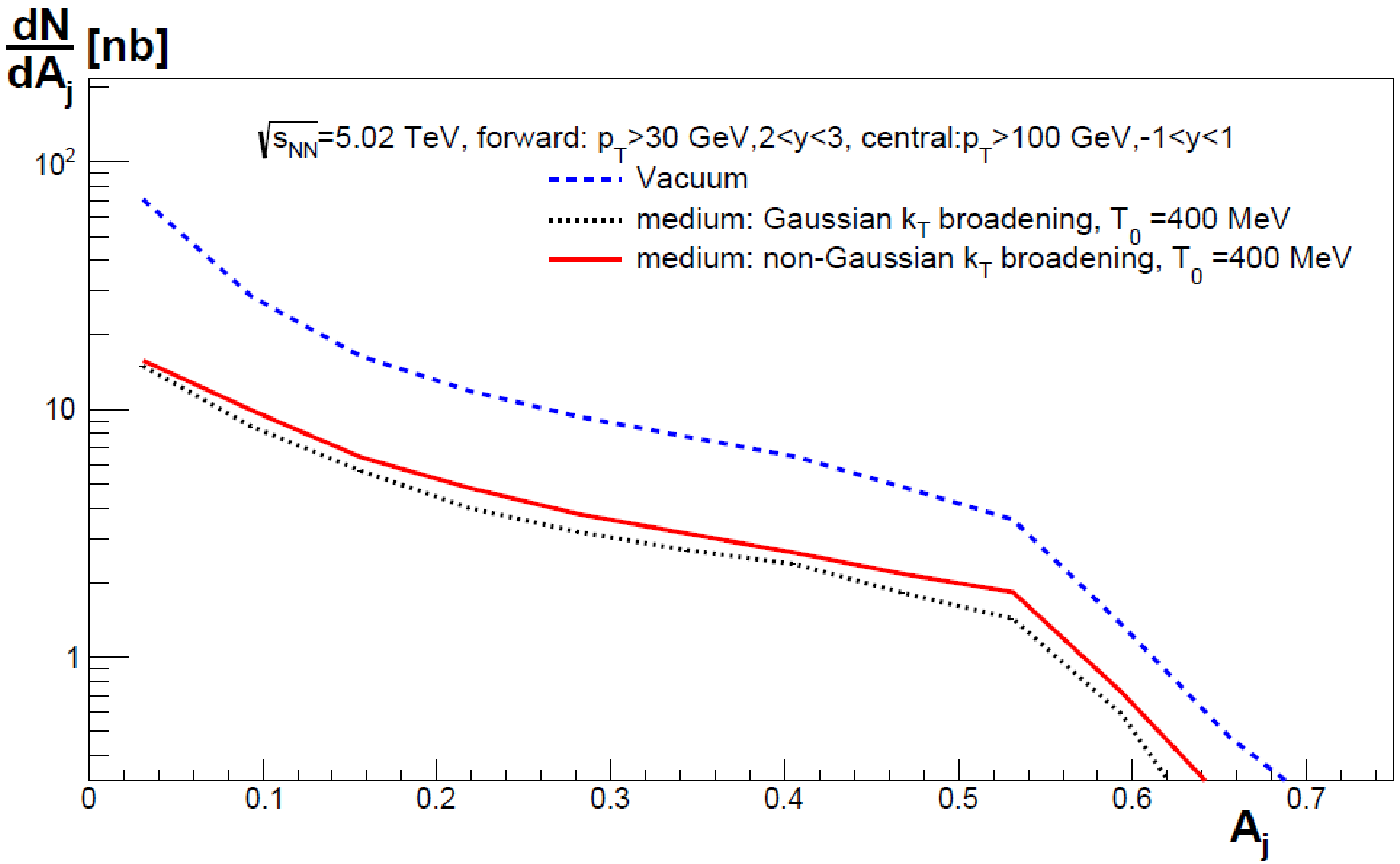
Azimuthal Decorrelations

Normalized to maximum!



Asymmetry A_j

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



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

Azimuthal Decorrelations (ratio)