Transverse momentum broadening effects of dijets in QGP

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based on:

[Blanco, Kutak, Płaczek, MR, Straka, arXiv:2009.03876] (k_T broadening/entropy in jets)

[v. Hameren, Kutak, Płaczek, MR, Tywoniuk, Phys. Rev. C 102, 044910] (dijet production)

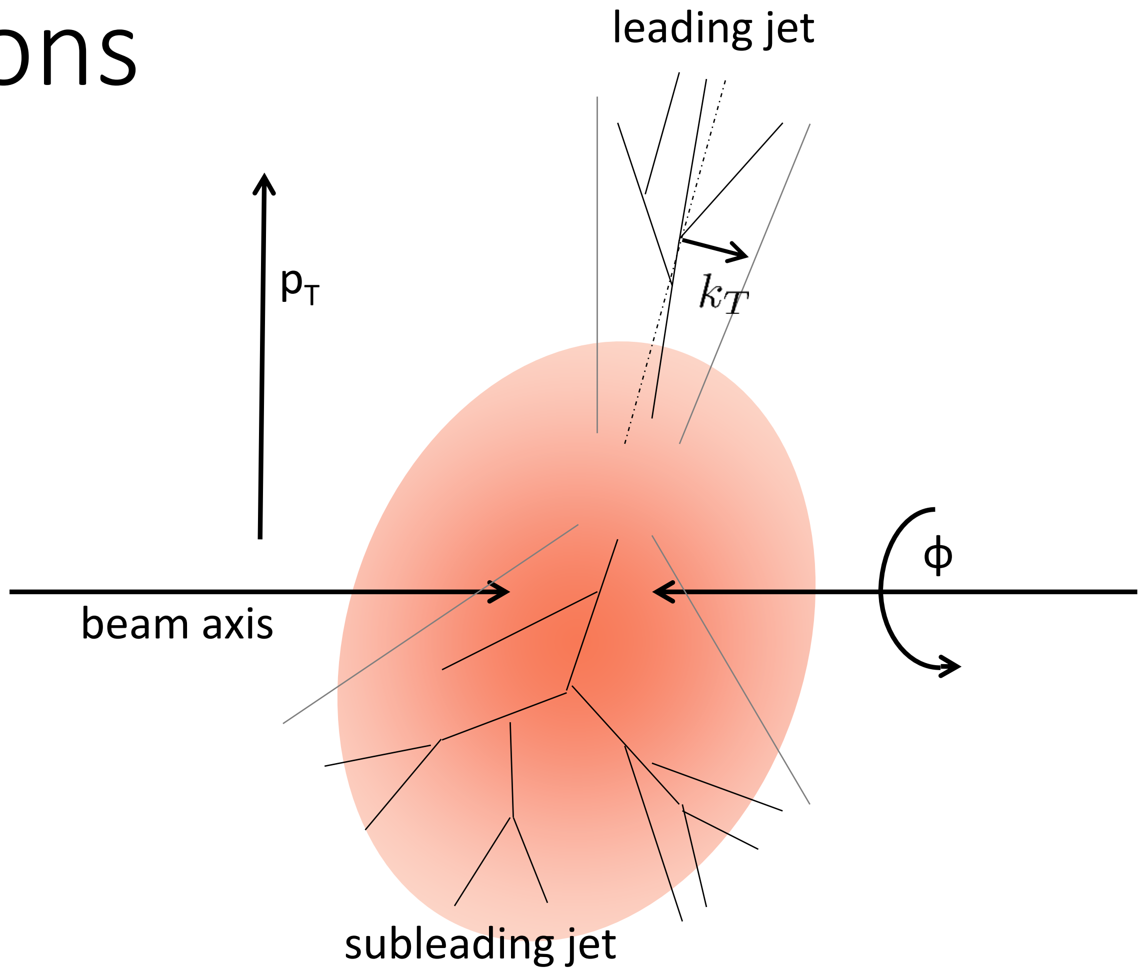
[Kutak,Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317] (Monte Carlo for gluon fragmentation functions)

Jets in Heavy Ion collisions

Jets interact with medium → Jet Quenching!

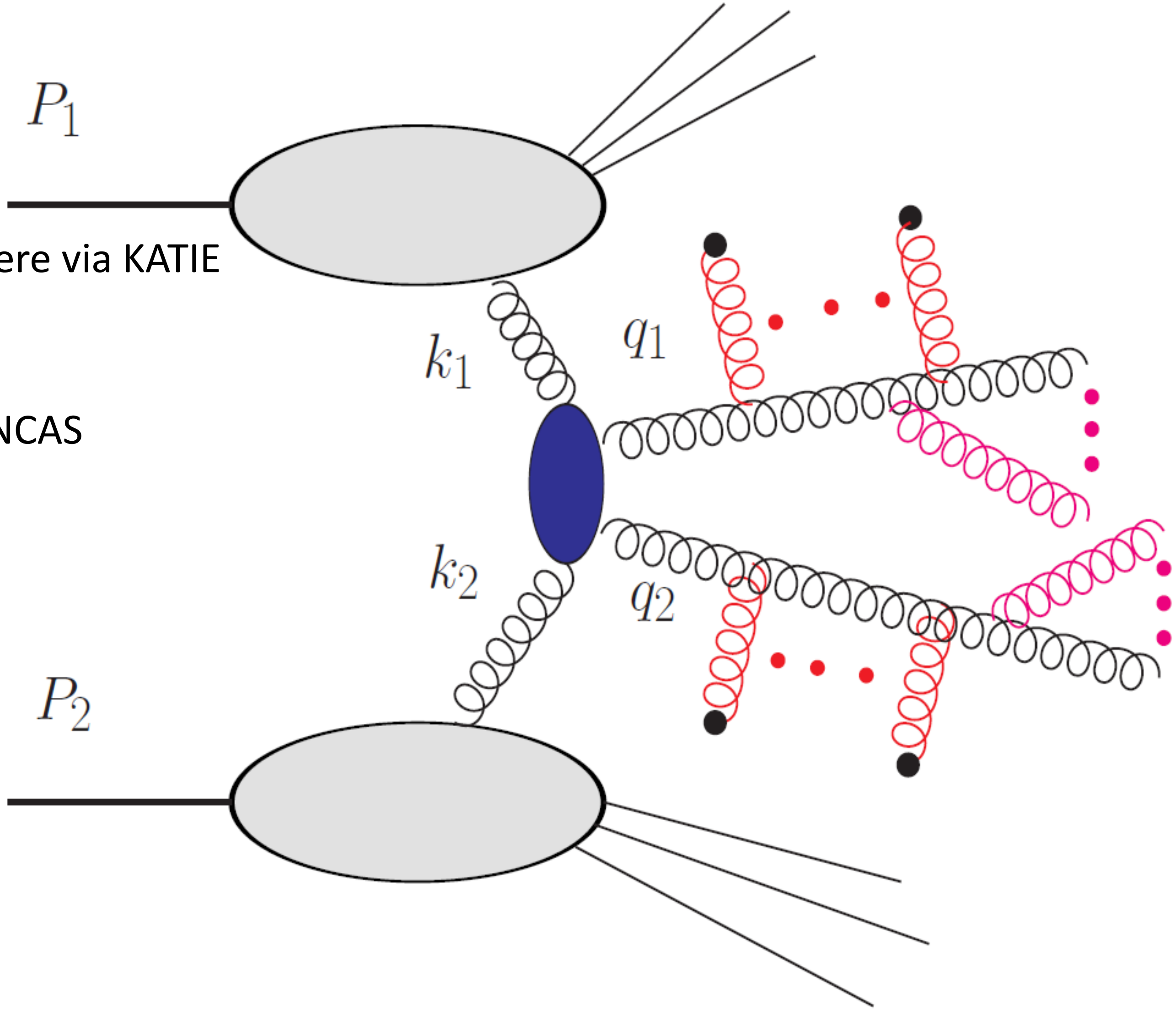
↓

probe of the medium



Jet Production(1/3)

Cross section =
(u)PDF1*(u)PDF2*hard cross section } Here via KATIE
*fragmentation of jet1
*fragmentation of jet2 } Here via MINCAS



[van Hameren: Comput.Phys.Commun. 224 (2018) 371-380] (KATIE)
[Kutak,Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317] (MINCAS)

Jet Production (2/3)

k_T factorization:

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

$\mathcal{F}_g(x,k_T^2,\mu_F^2)$ ...unintegrated parton distribution function (uPDF)

→ full phase space access at LO

Numerical simulations by **KATIE** algorithm.

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

Jet Production (3/3)

Factorization for AA collisions:

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

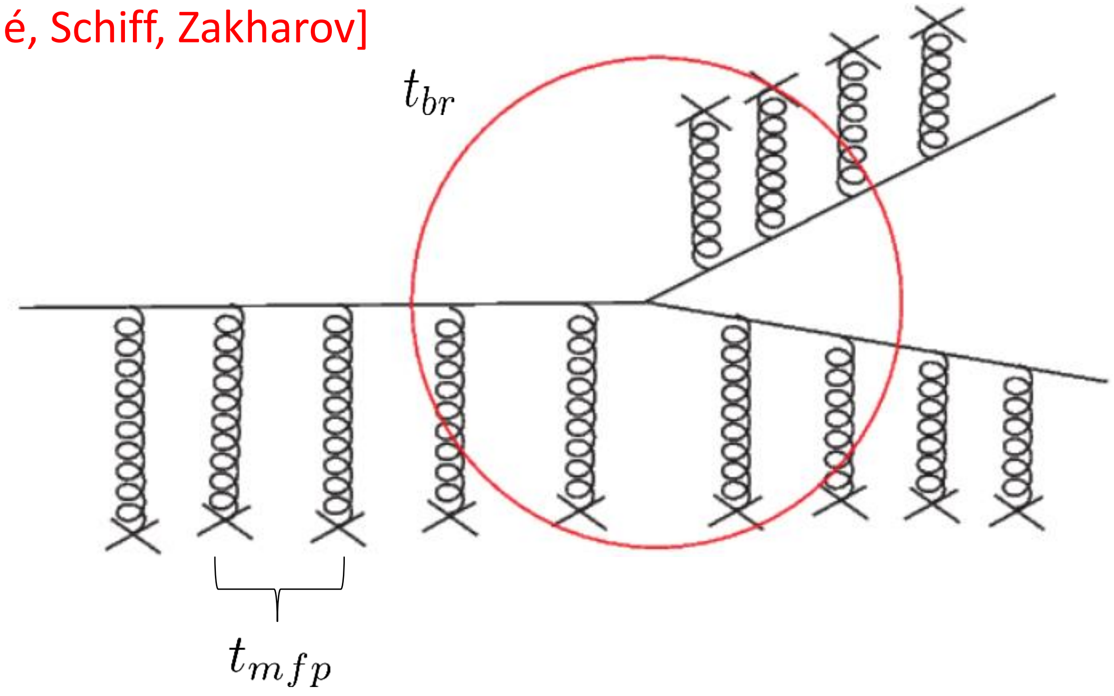
$$d\Omega_q = dq^+ d^2\boldsymbol{q} \qquad \tau(q^+) = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{q^+}}L$$

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

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

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

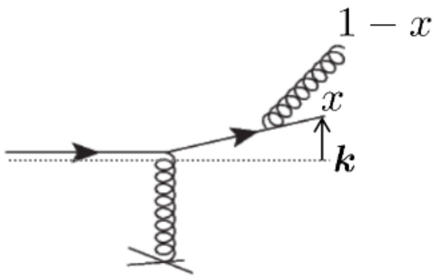
Look at range: $\omega_{BH} < \omega < \omega_c$

need effective 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]



Momentum distribution:
$p \to xp$
Momentum transfer:
$p \to p + \mathbf{k}$

→ Generalizes BDMPS-Z approach
→ Includes transverse momentum broadening

For gluon-jets:

$$\frac{\partial}{\partial t} D(x,\mathbf{k},t) = \alpha_s \int_0^1 dz \int \frac{d^2q}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q},z,\frac{x}{z}p_0^+) D\left(\frac{x}{z},\mathbf{q},t\right) - \mathcal{K}(\mathbf{q},z,xp_0^+) D(x,\mathbf{k},t) \right] + \int \frac{d^2\mathbf{l}}{(2\pi)^2} C(\mathbf{l}) D(x,\mathbf{k}-\mathbf{l},t).$$

Induced Radiation:

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

$$\omega = xp_0^+, \; k_{br}^2 = \sqrt{\omega_0 \hat{q}_0}, \; \mathbf{Q} = \mathbf{k} - z\mathbf{q}, \; \omega_0 = z(1-z)p_0^+$$

$$\hat{q}_0 = \hat{q} f(z), \; f(z) = 1 - z(1-z), \; P_{gg}(z) = N_c \frac{[1-z(1-z)]^2}{z(1-z)}$$

Scattering:

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

BDIM Equation

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

Generalizes BDMPS-Z approach ?

k_T averaged Kernel:

$$\int_0^\infty d^2\mathbf{Q}\mathcal{K}(z,\mathbf{Q},p_0^+) = 2\pi\sqrt{\frac{\hat{q}}{p_0^+}}N_c\mathcal{K}(z) \longrightarrow \mathcal{K}(z) = \frac{(1-z+z^2)^{\frac{5}{2}}}{[z(1-z)]^{\frac{3}{2}}}$$

$$\frac{1}{t^*} = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{p_0^+}} \propto \frac{1}{t_{\mathrm{br}}}$$

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

Integrate over $\mathbf{k}$

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

Departure from Gaussian broadening

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

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:

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

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

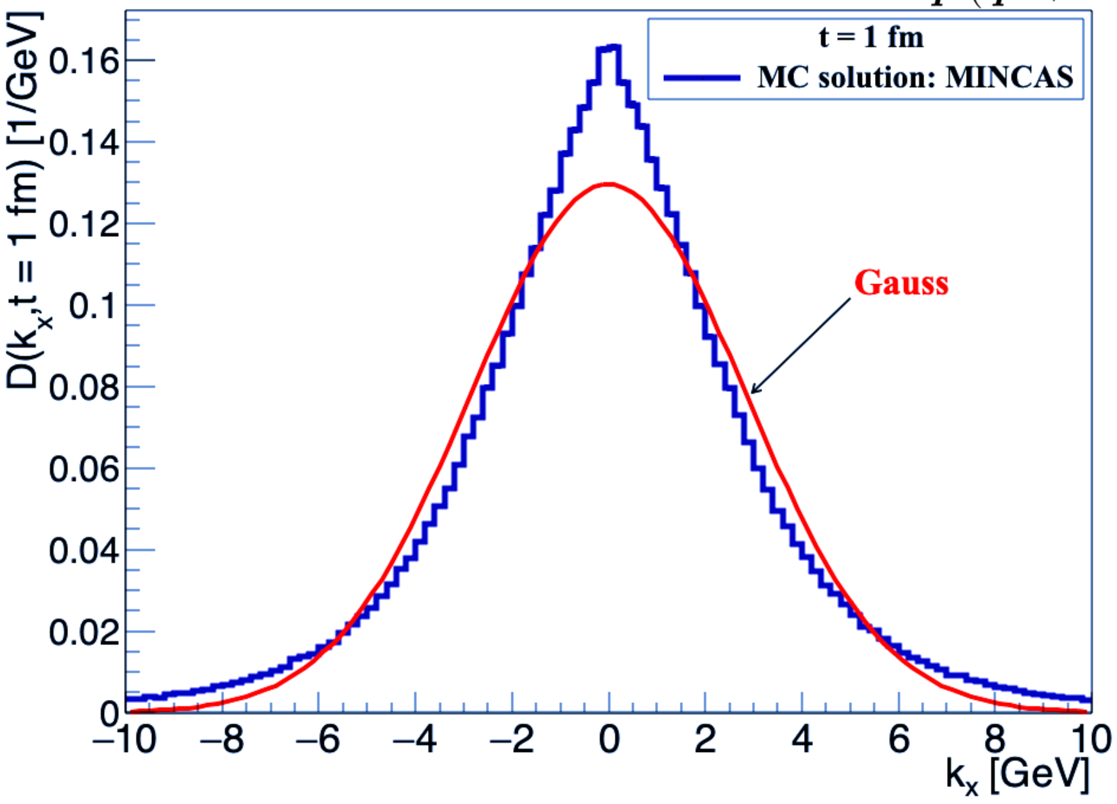


Figure: [Kutak, Płaczek, Straka: Eur.Phys.J. C79 (2019) no.4, 317]

Different models

- Broadening in branching: $$\frac{\partial}{\partial t}D(x,\mathbf{k},t)=\alpha_s\int_0^1 dz\int\frac{d^2q}{(2\pi)^2}\left[2\mathcal{K}(\mathbf{Q},z,\frac{x}{z}p_0^+)D\left(\frac{x}{z},\mathbf{q},t\right)-\mathcal{K}(\mathbf{q},z,xp_0^+)D(x,\mathbf{k},t)\right]+\int\frac{d^2\mathbf{l}}{(2\pi)^2}C(\mathbf{l})D(x,\mathbf{k}-\mathbf{l},t).$$
    - No scattering
    - Scattering: $w(\mathbf{q})=\frac{16\pi^2\alpha_s^2N_cn}{\mathbf{q}^4}$
    - Scattering: $w(\boldsymbol{q})=\frac{16\pi^2\alpha_s^2N_cn}{\boldsymbol{q}^2(\boldsymbol{q}^2+m_D^2)}$

All models yield the same k_T averaged splitting kernel $\mathcal{K}(z)$!

- No broadening in branching: $$\frac{\partial}{\partial t}D(x,\boldsymbol{k},t)=\frac{1}{t^*}\int_0^1 dz\mathcal{K}(z)\left[\frac{1}{z^2}\sqrt{\frac{z}{x}}D\left(\frac{x}{z},\frac{\boldsymbol{k}}{z},t\right)\theta(z-x)-\frac{z}{\sqrt{x}}D(x,\boldsymbol{k},t)\right]+\int\frac{d^2\boldsymbol{q}}{(2\pi)^2}C(\boldsymbol{q})D(x,\boldsymbol{k}-\boldsymbol{q},t)$$
    - Scattering: $w(\mathbf{q})=\frac{16\pi^2\alpha_s^2N_cn}{\mathbf{q}^4}$
    - Scattering: $w(\boldsymbol{q})=\frac{16\pi^2\alpha_s^2N_cn}{\boldsymbol{q}^2(\boldsymbol{q}^2+m_D^2)}$

Numerical simulations by **MINCAS** algorithm.

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

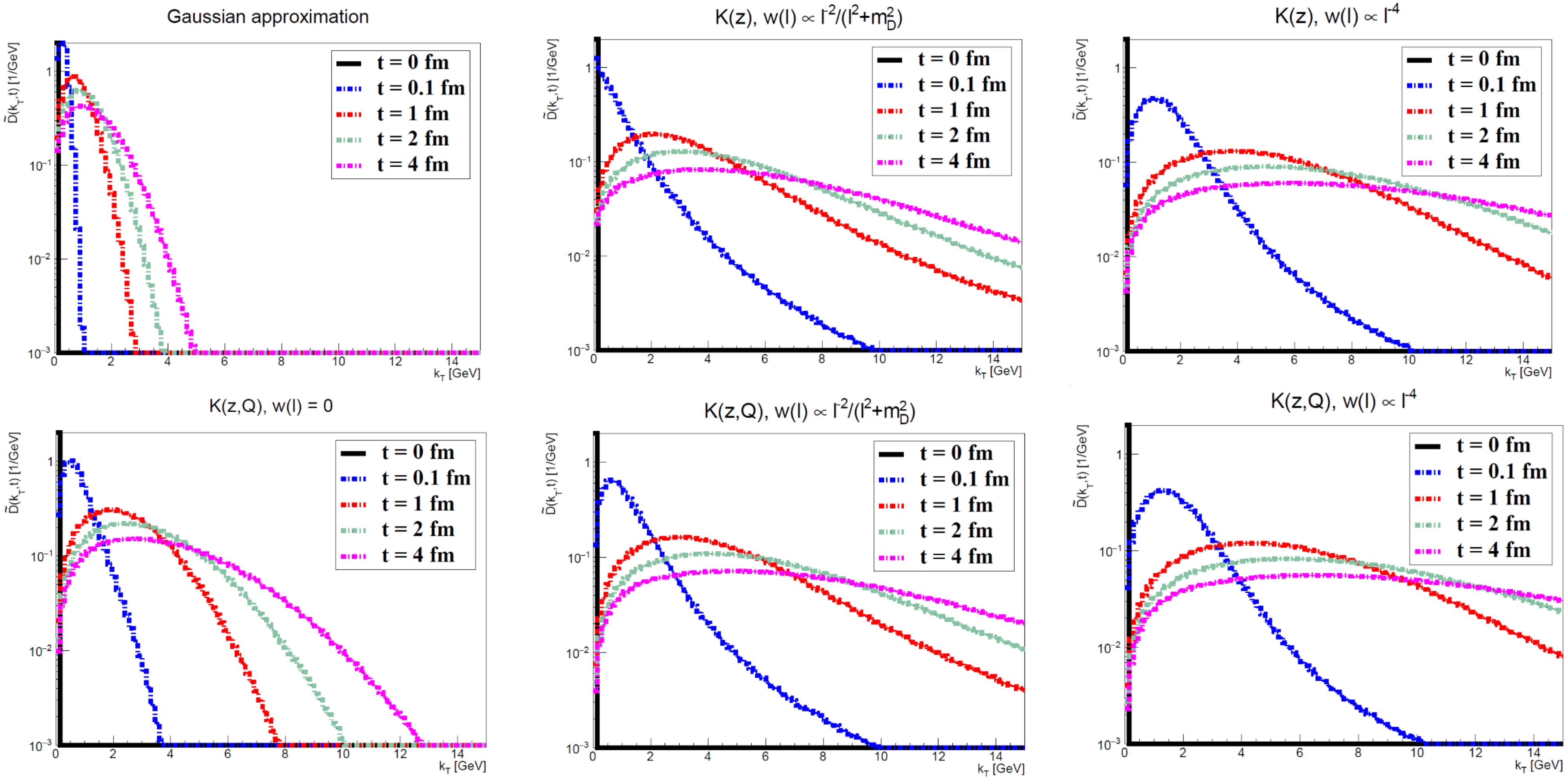
- Gaussian broadening:

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

  $\boldsymbol{k}$ given by Gaussian distribution with variance $\sigma^2\sim\hat{q}L$

k_T Broadening

$$\tilde{D}(x, k_T, t) = 2\pi k_T D(x, k_T, t)$$



[Blanco, Kutak, Płaczek, MR, Straka, arXiv:2009.03876]

k_T Broadening

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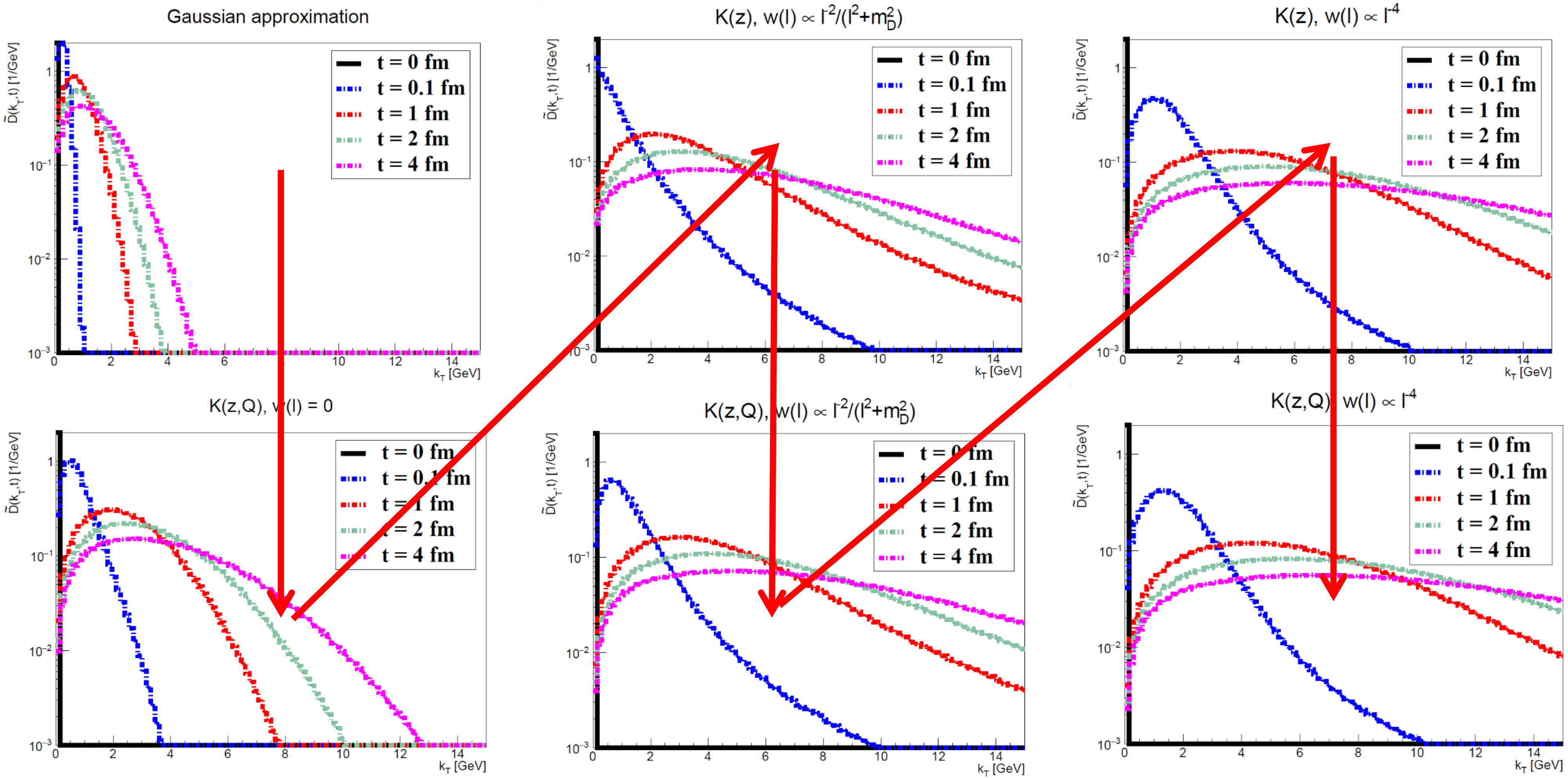


[Blanco, Kutak, Płaczek, MR, Straka, arXiv:2009.03876]

Entropy for leading particles

$$S_\Delta(t) = -\sum_{i=1}^{N} p_i(x,k_T,t)\ln p_i(x,k_T,t) + P(t)\ln[\Delta x \Delta k_T]$$

$\downarrow$ $\Delta x \to 0,\ \Delta k_T \to 0$

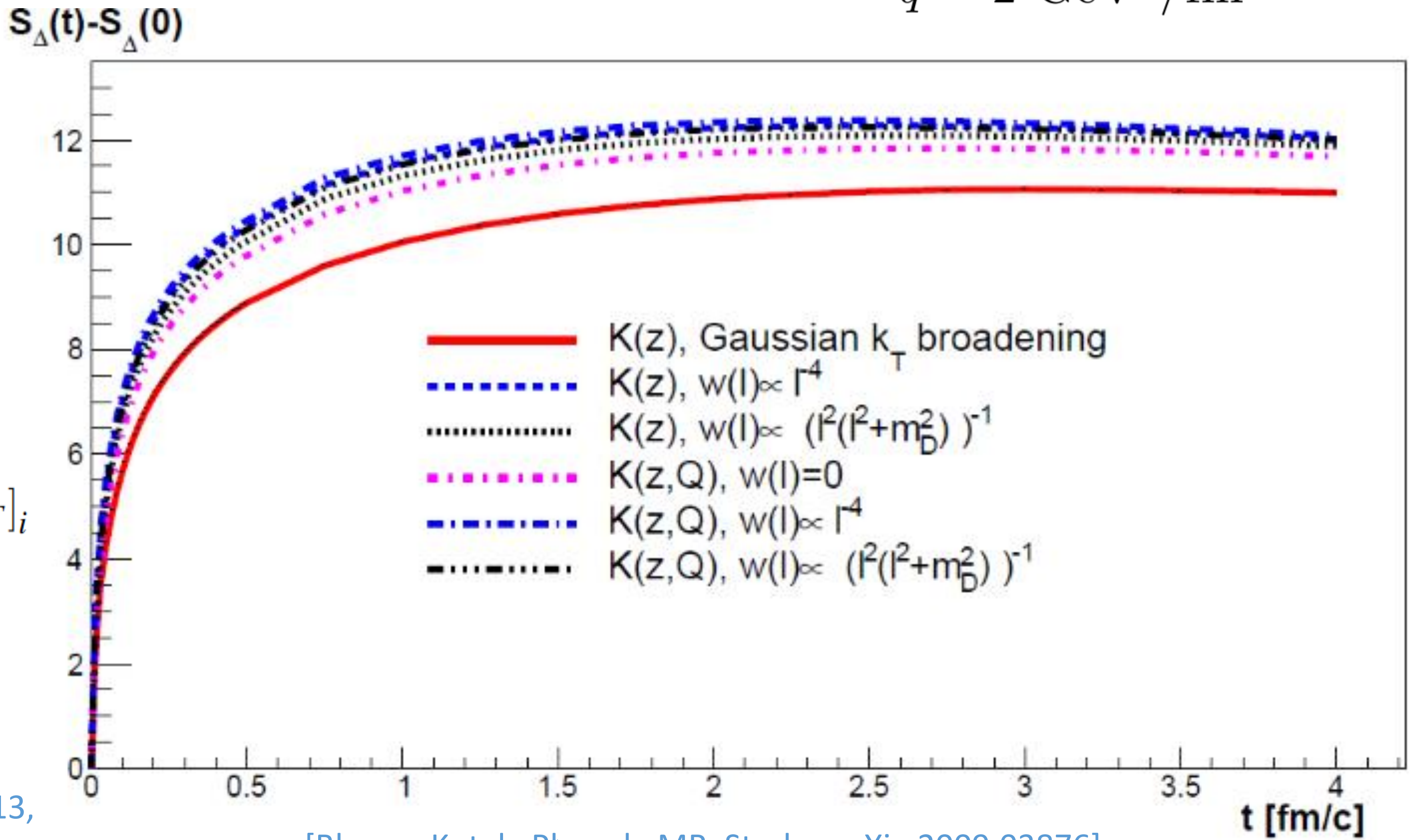
$$S_\Delta(t) \to -\int dx dk_T \tilde{D}(x,k_T,t)\ln\left(\tilde{D}(x,k_T,t)\right)$$

$$p_i(x,k_T,t) = \left[\tilde{D}(x,k_T,t)\Delta x \Delta k_T\right]_i = [2\pi k_T D(x,k_T,t)\Delta x \Delta k_T]_i$$

$$P(t) = \sum_{i=1}^{N} p_i(x,k_T,t)$$

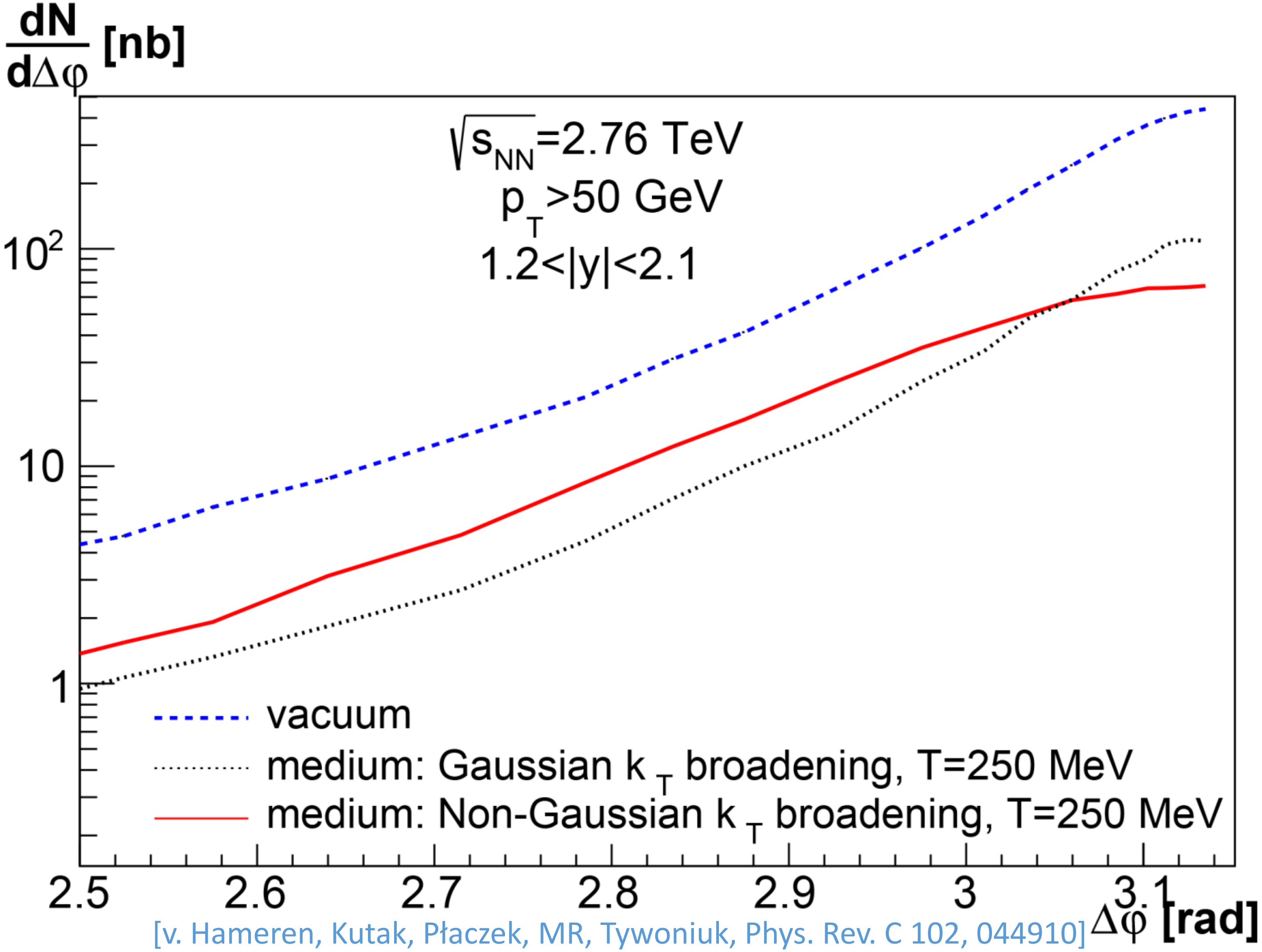
[B. Chen, Y. Zhu, J. Hu and J. C. Principe,System Parameter Identification. InformationCriteria and Algorithms. Elsevier, 2013, https://doi.org/10.1016/C2012-0-01233-1] (Delta-Entropy)

$\hat{q} = 2\ \mathrm{GeV}^2/\mathrm{fm}$



[Blanco, Kutak, Płaczek, MR, Straka, arXiv:2009.03876]

Azimuthal Decorrelations



[v. Hameren, Kutak, Płaczek, MR, Tywoniuk, Phys. Rev. C 102, 044910]

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

Summary

- **MINCAS**: jet evolution based on coherent emission and scattering
- Combination with **KATIE**: allows for calculation of jet-observables

- Transverse momentum broadening differs from Gaussian distribution
- Gaussian distribution: smallest k_T broadening
- …leads to broadening in angular dijet decorrelations

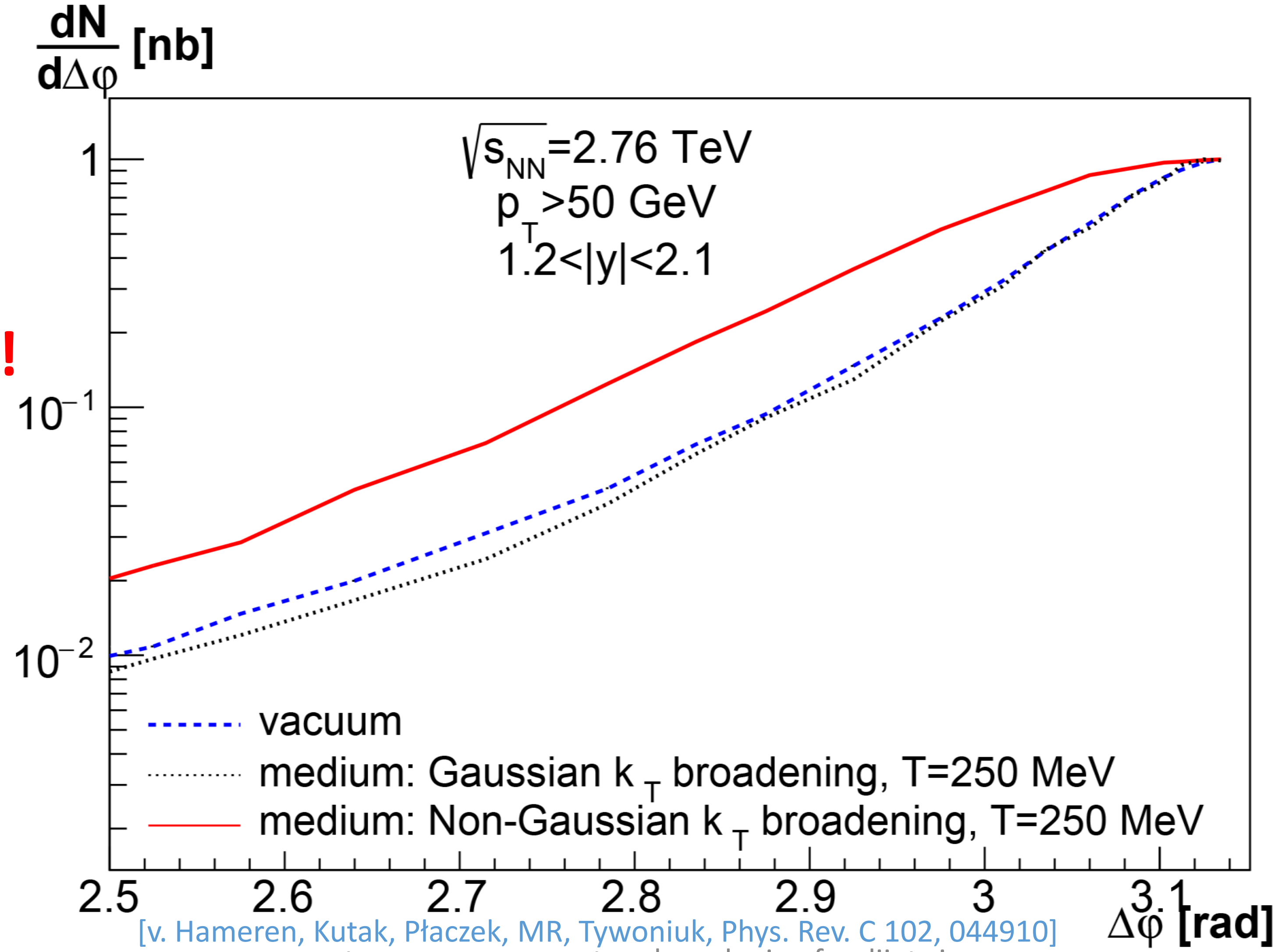
Outlook

- to account for quarks
- to study more forward processes
- and vacuum-like emissions

Thank you for your attention!

Azimuthal Decorrelations

Normalized to maximum!



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

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