Jet quenching and transverse momentum of jets

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

Krzysztof Kutak

NCN

HORIZON 2020

Based on

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

1911. 05463 van Hameren, Kutak, Płaczek, Rohrmoser, Tywoniuk

And soon to be released paper KK, Blanco, Placzek, Rohrmoser, Straka

Motivation

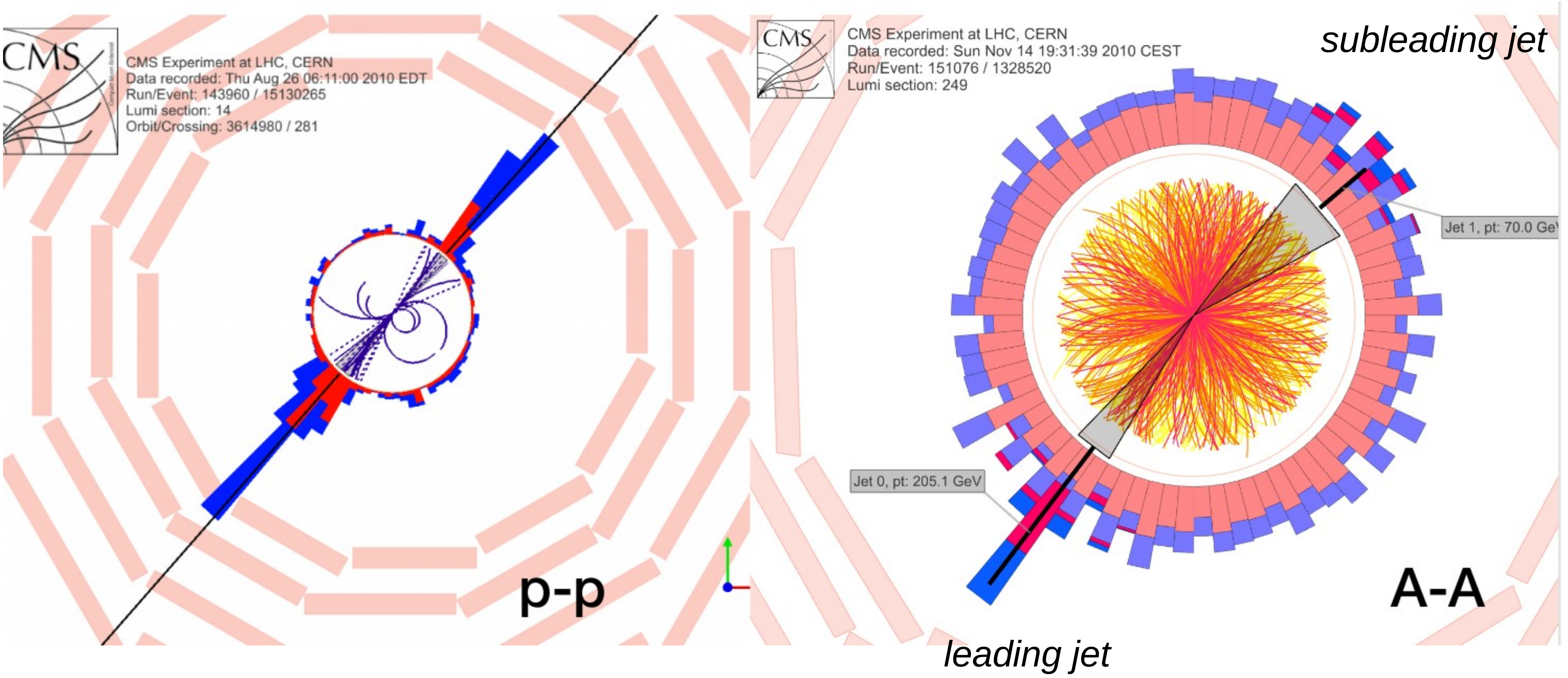
Some studies suggest that effects like gluon saturation are relevant for e-p, p-p p-A and A-A collisions.

Saturation tames the growth of gluon density end perhaps is relevant for thermalization in A-A (Venugopalan, Lappi, McLerran Schenke,Mueller Iancu, Kovchegov……)

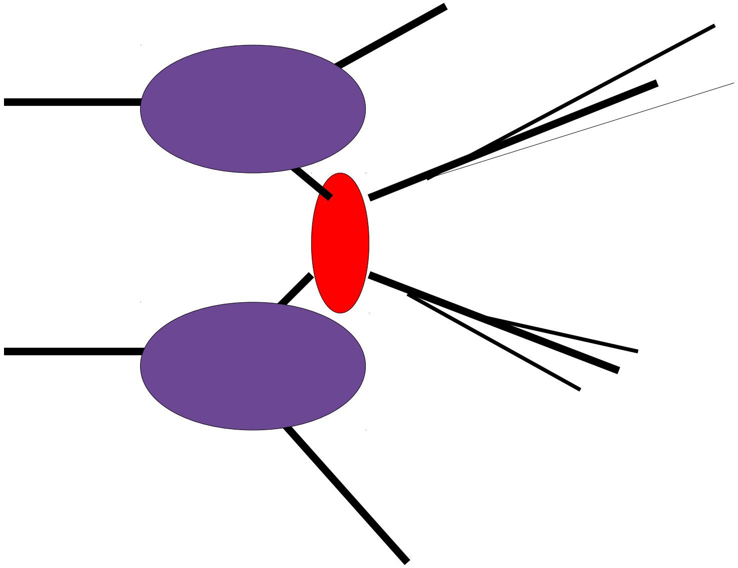
My personal motivation comes from recent studies of forward – forward dijets in p A where it seems that saturation occurs.

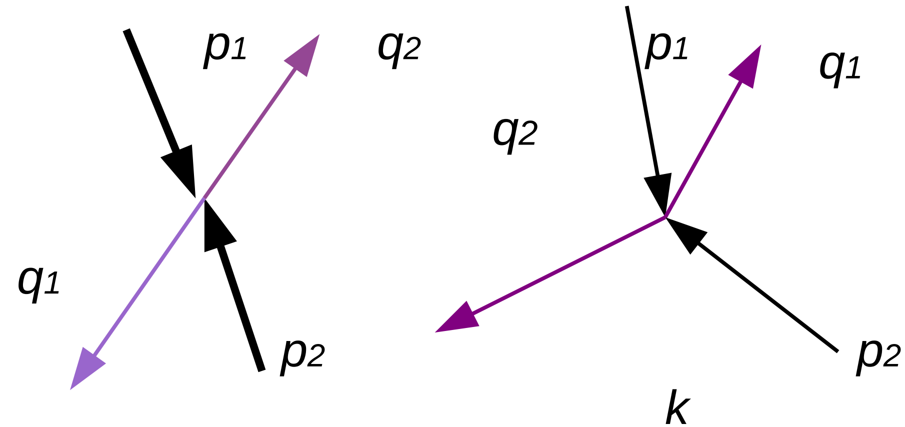
In the future I want to study combined effects of jet quenching and saturation In A-A in forward region. I want to see whether saturation is visible or washed out by jet quenching. On needs to develop formalism for merging both phenomena.

Jets in vacuum and in medium



QCD at high energies – k_t factorization





$p_1+p_2=q_1+q_2$ $\qquad$ $p_1+p_2=q_1+q_2+k$

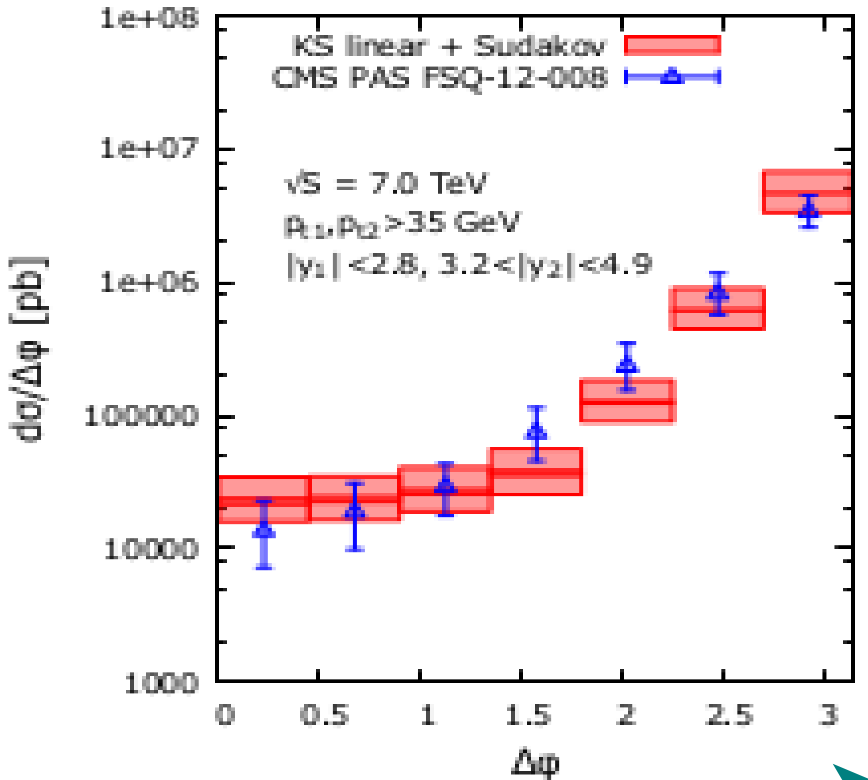
$$\frac{d\sigma}{dPS} \propto \mathcal{F}_{a^*}(x_1, k_{\perp\,1}) \otimes \hat{\sigma}_{ab\to cd}(x_1, x_2) \otimes \mathcal{F}_{b^*}(x_2, k_{\perp\,2})$$

Ciafaloni, Catani, Hautman '93
Collins, Ellis '93

New helicity based methods for ME
Van Hameren, Kotko, K.K, '12

Decorelations forward-central

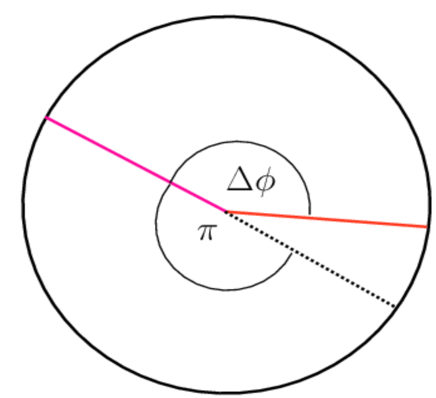
saturation
Is negligible here

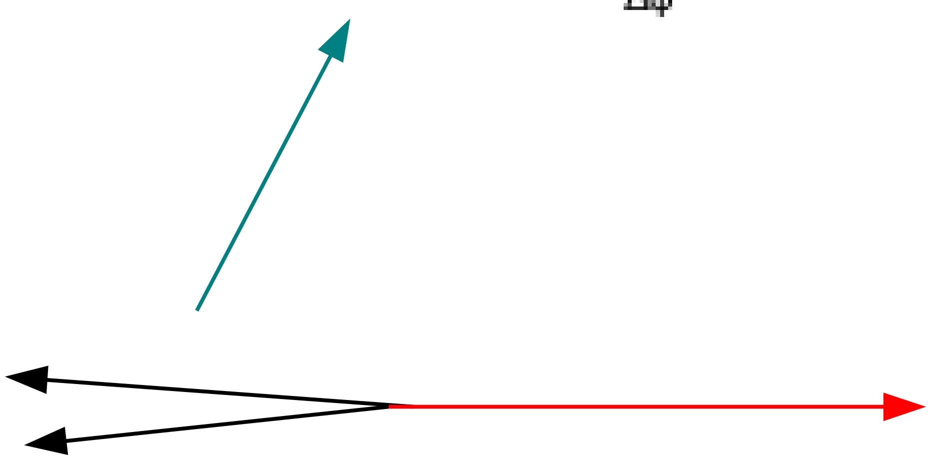


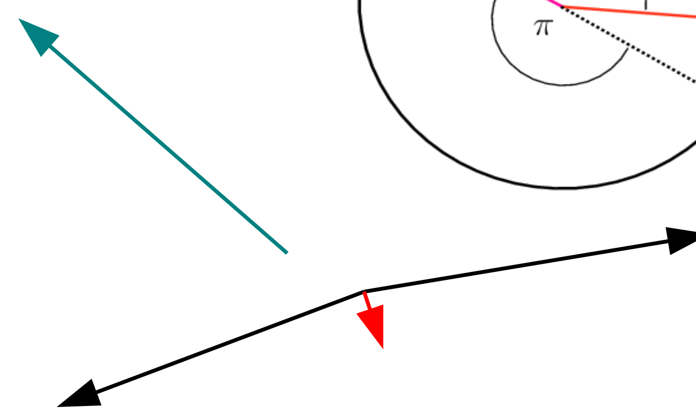
Van Hameren,, Kotko, K.K, Sapeta '14

Observable suggested to study BFKL effects
Sabio-Vera, Schwensen '06

Studied also context of RHIC
Albacete, Marquet '10

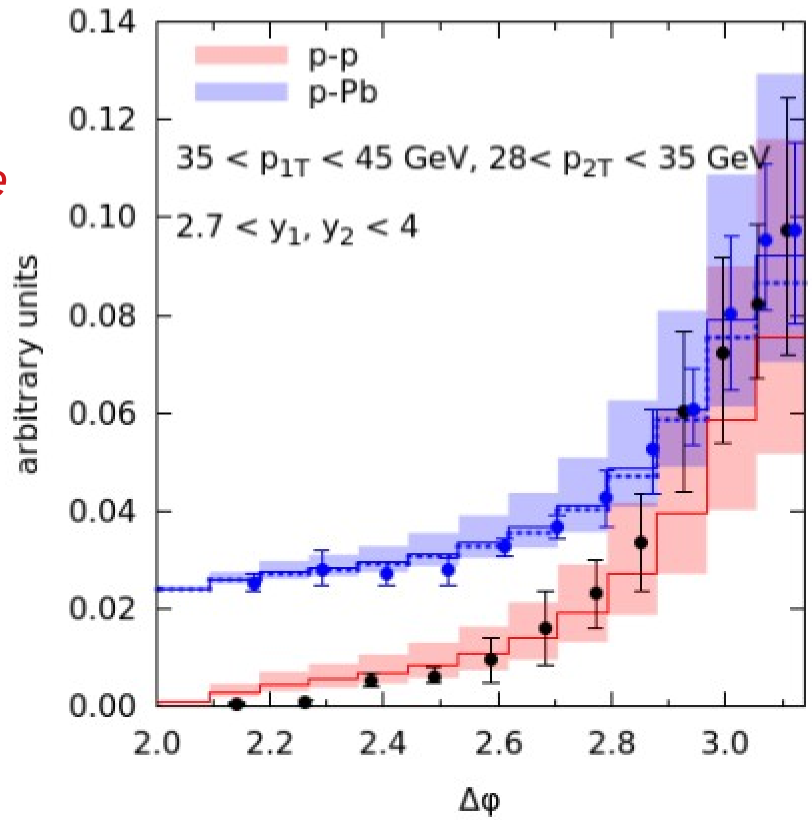






Decorelations forward-forward

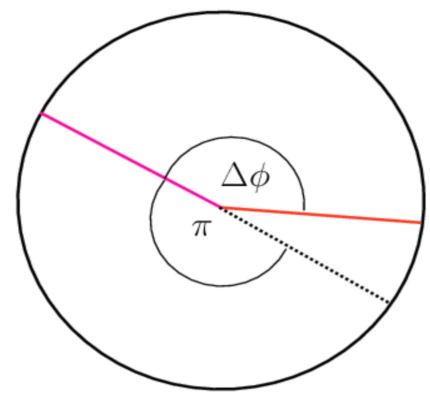
saturation
Is essential here

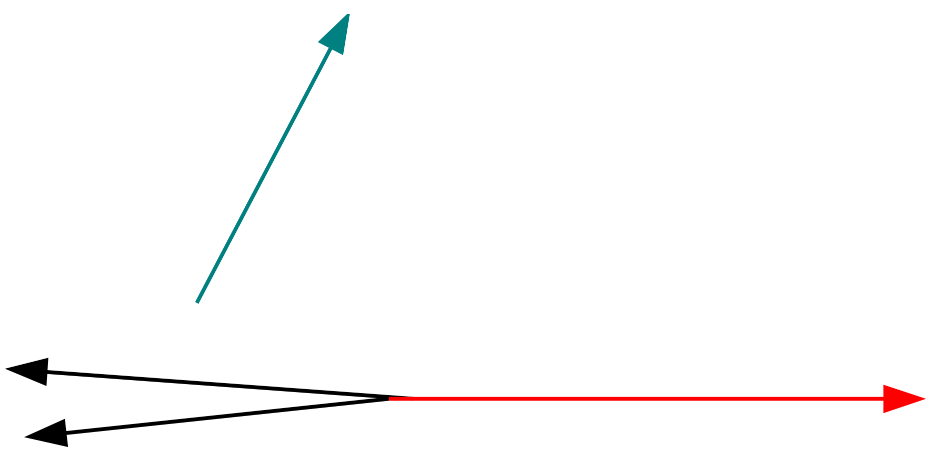


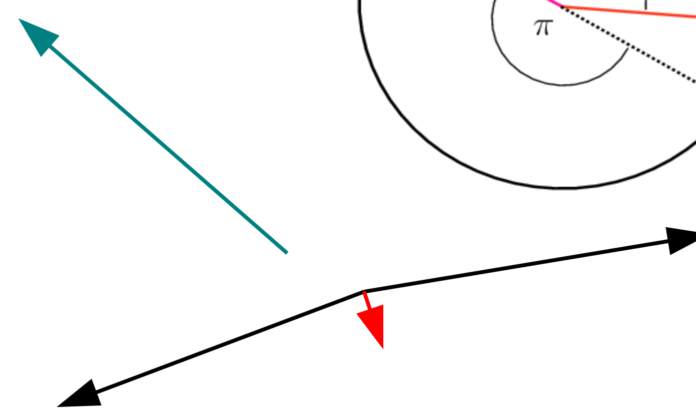
Van Hameren, Kotko, Kutak, Sapeta

Phys.Lett. B 795 (2019) 511-515

Studied also context of RHIC
Albacete, Marquet '10

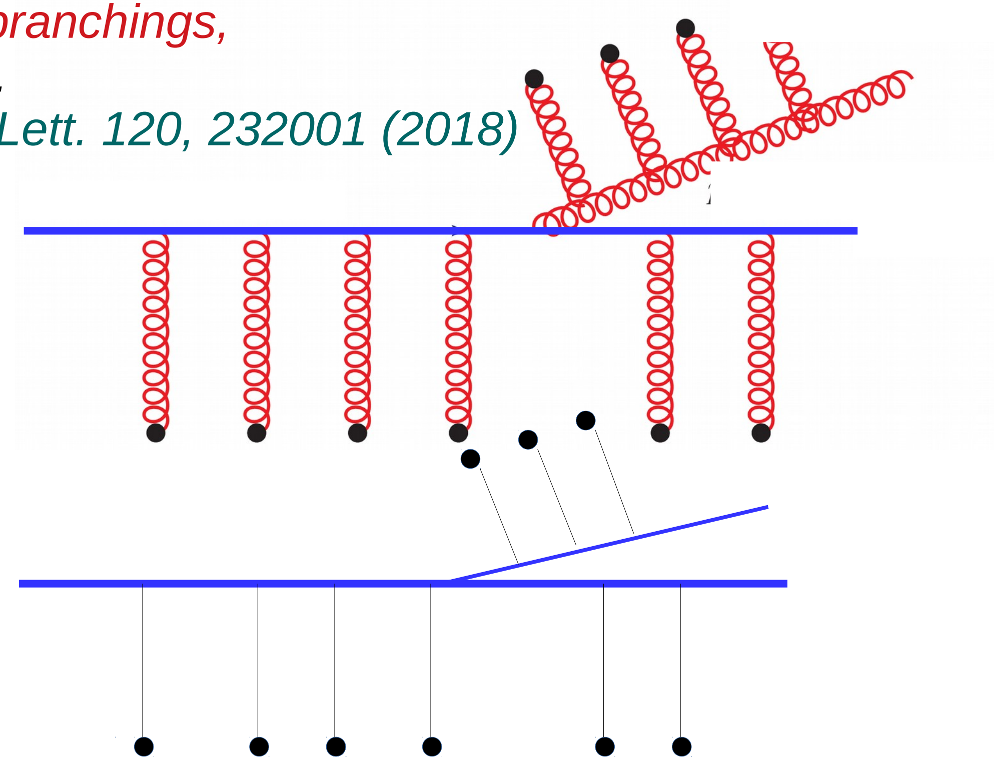






Jet quenching formalism

The process of jet medium interaction has many phases.
Vacuum like emissions, medium induced branchings, braodening. Emissions outside of medium.
Caucal, Iancu, Mueller, Soyez Phys. Rev. Lett. 120, 232001 (2018)

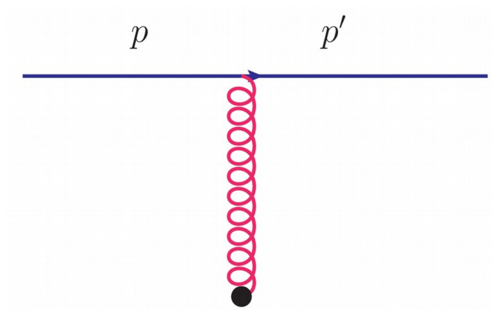


General formalism for medium induced branching established by BDMPS-Z (Baier, Dokshitzer, Mueller, Peigné, Schiff; Zakharov). Later, AMY (Arnold, Moore, Yaffe) in real time formalism.

Additionally, there exists two approximation schemes to obtain an analytical form of the spectrum:

- *Harmonic oscillator approximation (BDMPS-Z; AMY; Wiedemann, Salgado, …)*

- *N=1 approximations (Gyulassy, Levai, Vitev; Wiedemann)*
- *Only accounts for a single scattering in the medium valid for thin media).*



BDMPS-Z

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 $t_{coh} \ll t_{mfp}$.

Radiation spectrum

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

maximal energy that can be taken by single gluon (ω_c)

energy of observed gluon (ω)

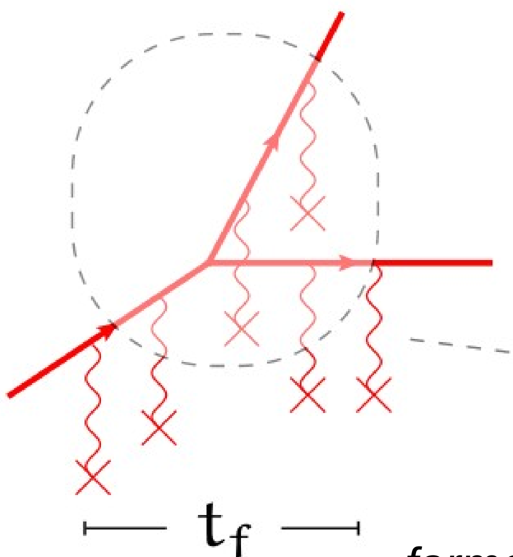
$$\omega \frac{\mathrm{d}I_{\mathrm{BH}}}{\mathrm{d}\omega} \simeq \alpha_s \frac{L}{\ell_{\mathrm{mfp}}} = \alpha_s N_{\mathrm{scatt}}$$

if $t_{coh} \sim t_{mfp}$ only one scattering is involved in radiation

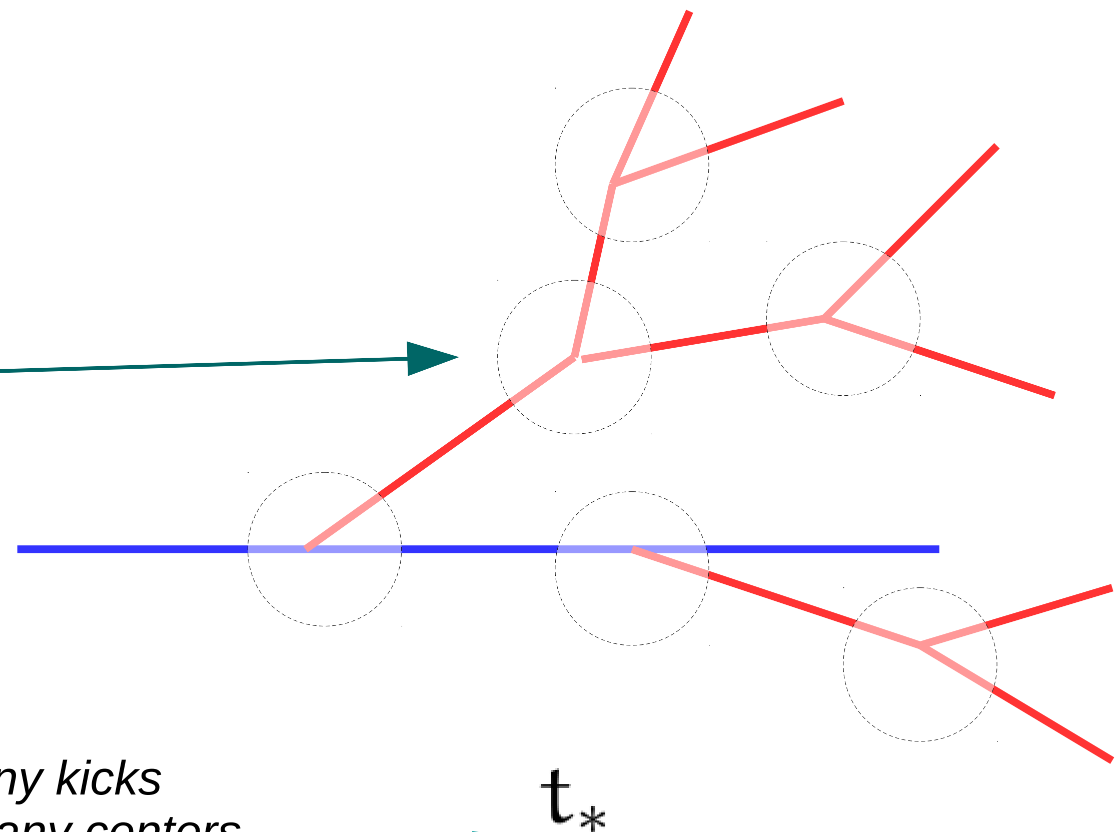
Look at range $\omega_{BH} < \omega < \omega_{C}$...

Towards more general picture - multiple branching - relevant time scales

Beyond energy lost by the leading particle…. effects of multiple branching at large angles are important….



formation time; many kicks before radiation; many centers act as a single source



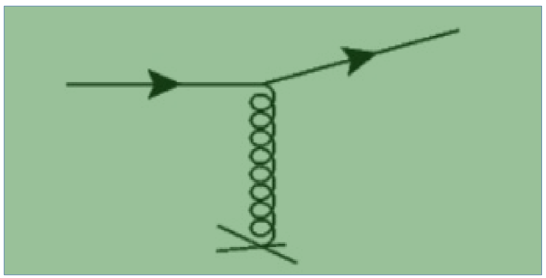
From Yacine Mehtar-Tani

stopping time → time at which energy has been emitted in form of soft gluons

Jet medium interaction

we do not account for this now

scattering...



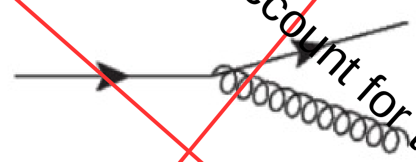
Transverse momentum transfer!

$p \to p + k_T$

Scattering Kernel: $C(k_T)$

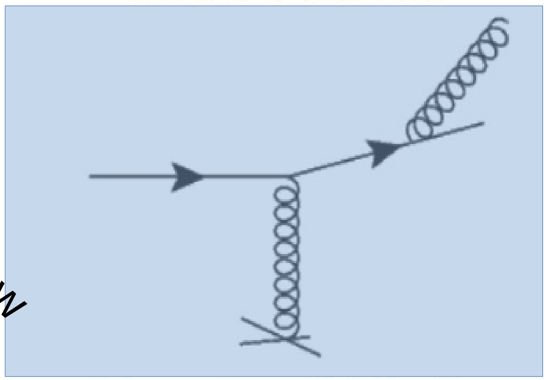
Average transfer: $\hat{q}$

...splitting...



Bremsstrahlung as in vacuum.

...induced radiation



Momentum distribution:

$p \to zp$

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

procedure almost the same as for energy distribution

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

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

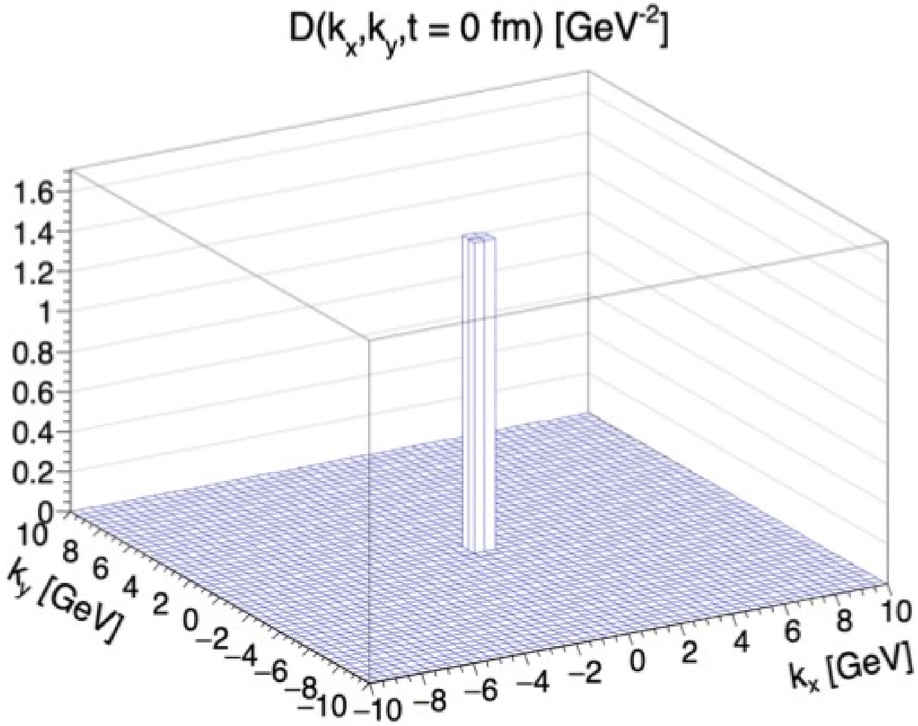
mathematics: *transformation of differential equation to integral equation*

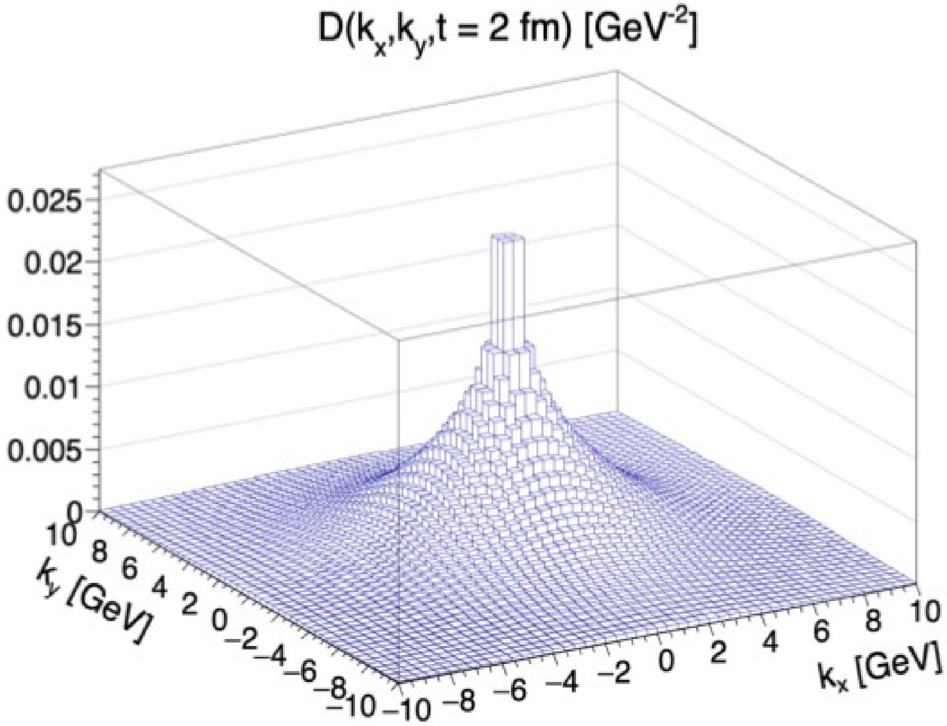
physics: *resummation of virtual and unresolved real emissions*

Sudakov form factor resumes virtual and unresolved real emissions

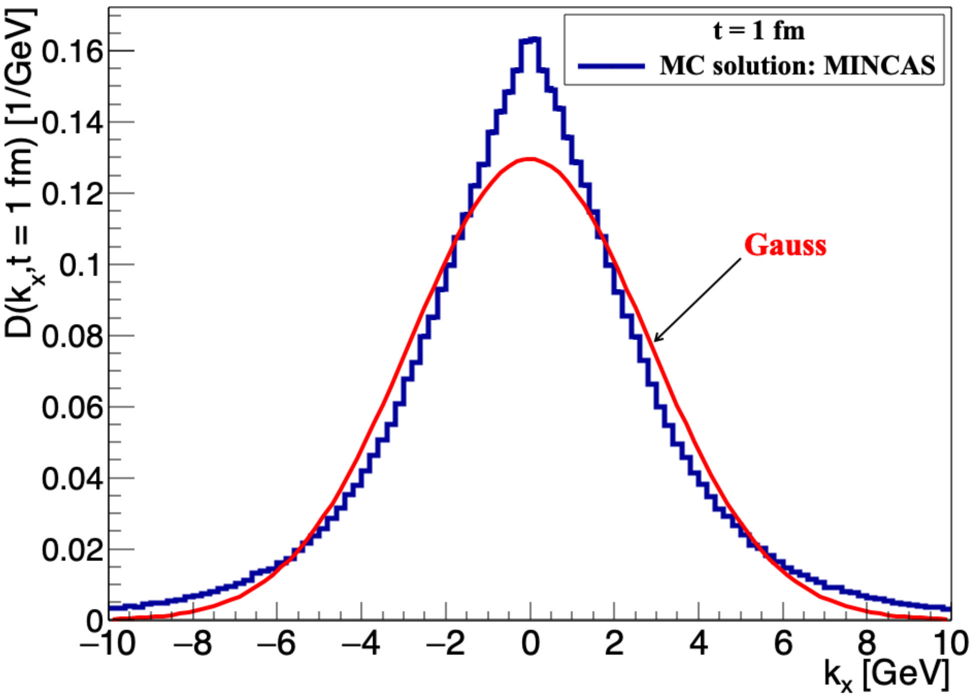
$$D(x,\mathbf{k},\tau) = e^{-\Psi(x)(\tau-\tau_0)}D(x,\mathbf{k},\tau_0) + \int_{\tau_0}^{\tau}d\tau'\int_0^1 dz\int_0^1 dy\int d^2\mathbf{k}'\int d^2\mathbf{q}\,\mathcal{G}(z,\mathbf{q}) \times\delta(x-zy)\,\delta(\mathbf{k}-\mathbf{q}-z\mathbf{k}')\,e^{-\Psi(x)(\tau-\tau')}D(y,\mathbf{k}',\tau')$$

Broadening of jet





Non Gaussianity



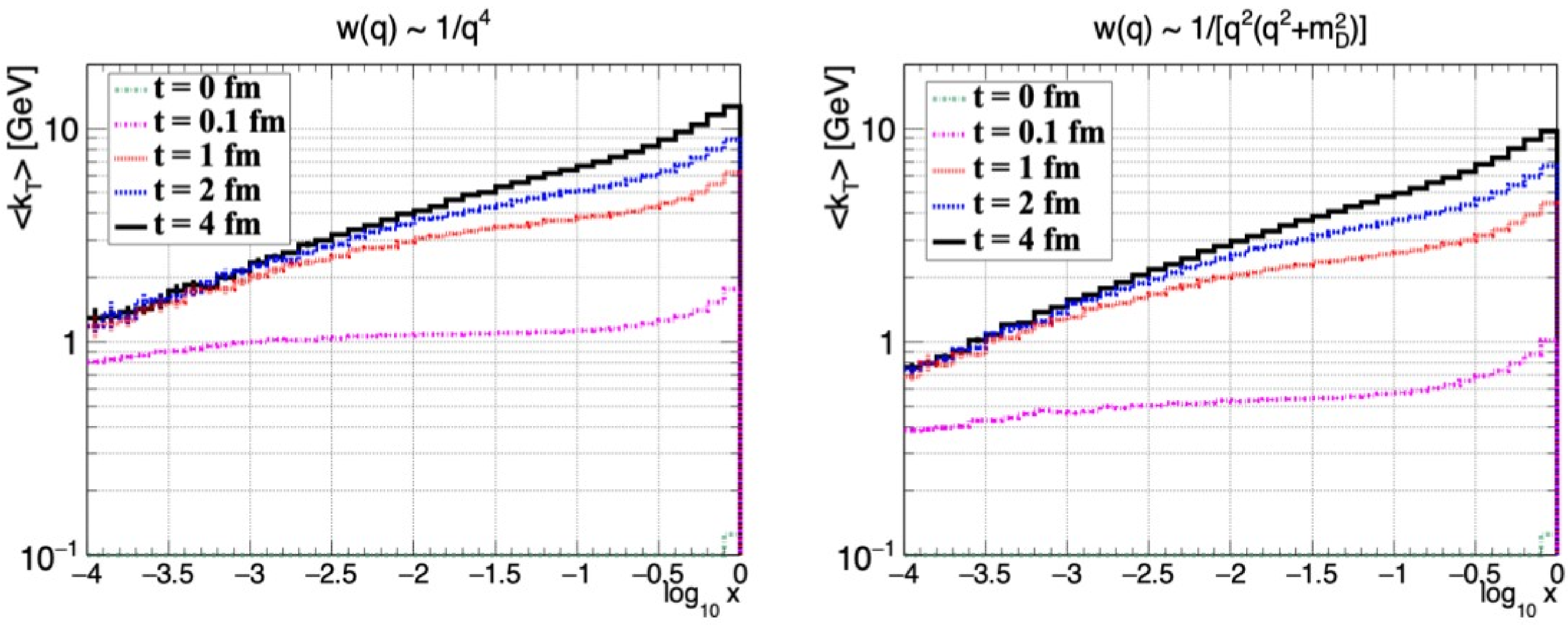
Result of:

- *sum of many Gaussians with different width*
- *the exact treatment of the gluon transverse-momentum broadening due to an arbitrary number of the collisions with the medium*
- *it is also shrinking due an arbitrary number of the emission branching*

Quenching line

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

Non-termalized medium *Termalized medium*



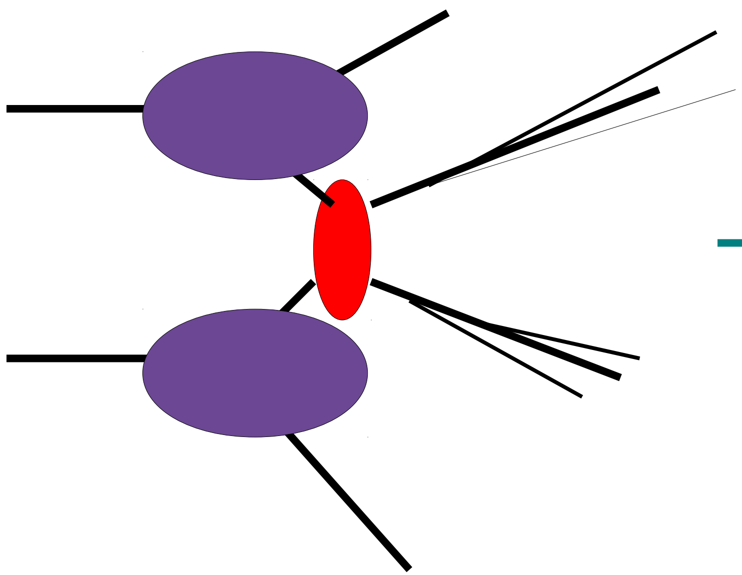
Thermalized medium suppresses jets stronger

Universal behavior at larger times

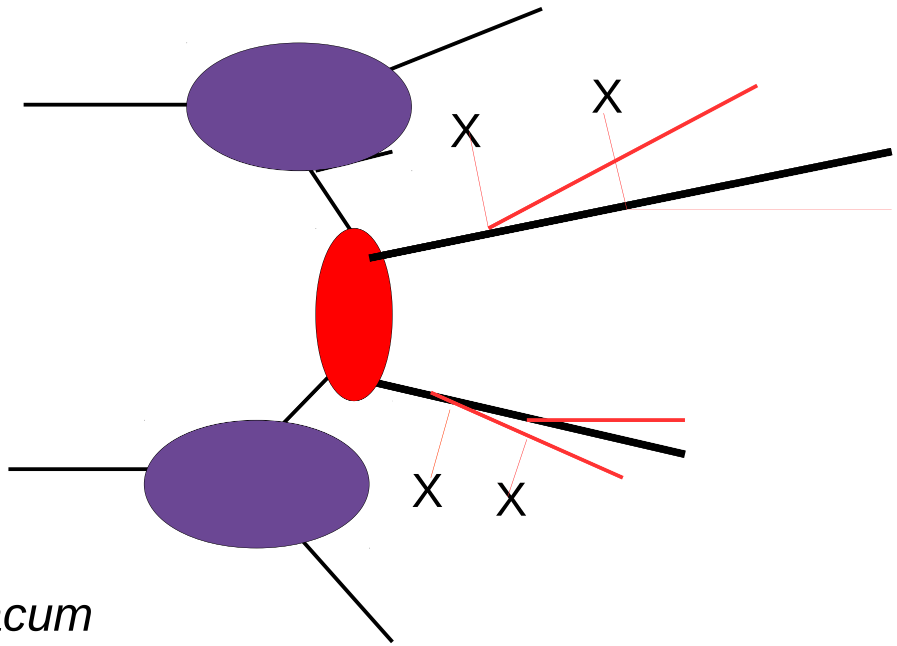
Similar line obtained in from analitical approximated solution by Blaizot, Torres, Mehtar-Tani

From vacuum to medium

vacuum



medium



*vacuum x-section = ME * pdf * fragmentaion in vacum*

*complete x-section = ME * pdf * fragmentaion in medium +*
*ME * pdf * fragmentation in vacum*

From vacuum to medium

1911.05463
Van Hameren, Kutak,Placzek, Rohrmoser, Tywoniuk

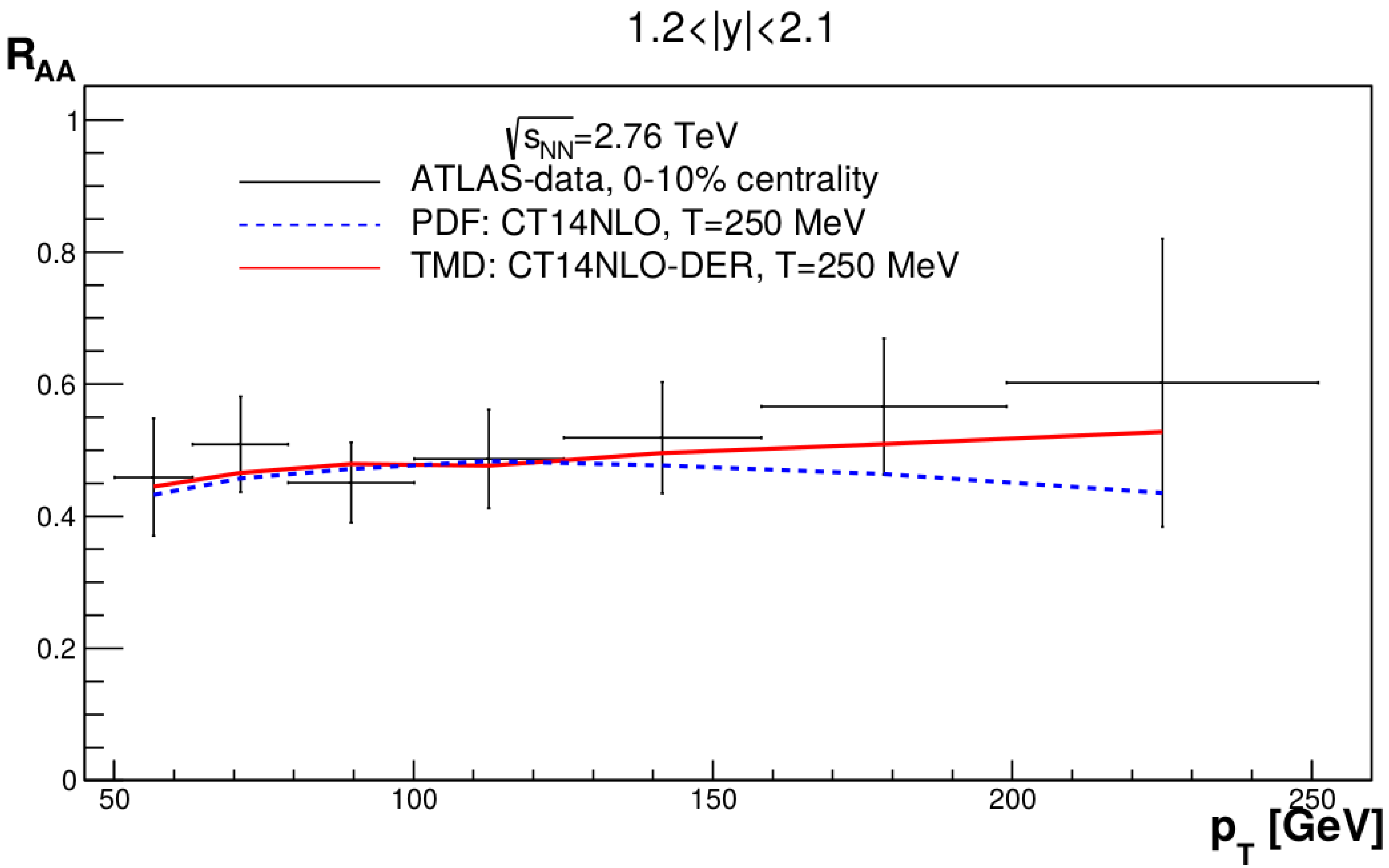
$$\frac{d\sigma_{pp}}{dy_1 dy_2 d^2q_{1T} d^2q_{2T}} = \int \frac{d^2k_{1T}}{\pi}\frac{d^2k_{2T}}{\pi}\frac{1}{16\pi^2(x_1x_2s)^2}\overline{|\mathcal{M}^{\mathrm{off-shell}}_{g^*g^*\to gg}|^2} \times \delta^2\left(\vec{k}_{1T}+\vec{k}_{2T}-\vec{q}_{1T}-\vec{q}_{2T}\right)\mathcal{F}_g(x_1,k_{1T}^2,\mu_F^2)\,\mathcal{F}_g(x_2,k_{2T}^2,\mu_F^2)$$

$$\frac{\mathrm{d}\sigma_{AA}}{\mathrm{d}\Omega_{p_1}\Omega_{p_2}} = \int \mathrm{d}^2\boldsymbol{q}_1 \int \mathrm{d}^2\boldsymbol{q}_2 \int_0^1 \frac{\mathrm{d}\tilde{x}_1}{\tilde{x}_1^2}\int_0^1 \frac{\mathrm{d}\tilde{x}_2}{\tilde{x}_2^2} D(\tilde{x}_1,\boldsymbol{p}_1-\boldsymbol{q}_1,\tau(p_1^+/\tilde{x}_1))D(\tilde{x}_2,\boldsymbol{p}_2-\boldsymbol{q}_2,\tau(p_2^+/\tilde{x}_2)) \left.\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}q_1^+\mathrm{d}q_2^+\mathrm{d}^2\boldsymbol{q}_1\mathrm{d}^2\boldsymbol{q}_2}\right|_{q_1^+=p_1^+/\tilde{x}_1,\,q_2^+=p_2^+/\tilde{x}_2}$$

Our assumptions:

- *only gluonic jets*
- *uniform plasma*
- *we neglect shower outside of plasma*
- *we neglect vacuum like emissions in plasma*
- *we assume Bjorken model to tune the temperature to describe R_{AA}*

R_{AA} nuclear modificatio ratio

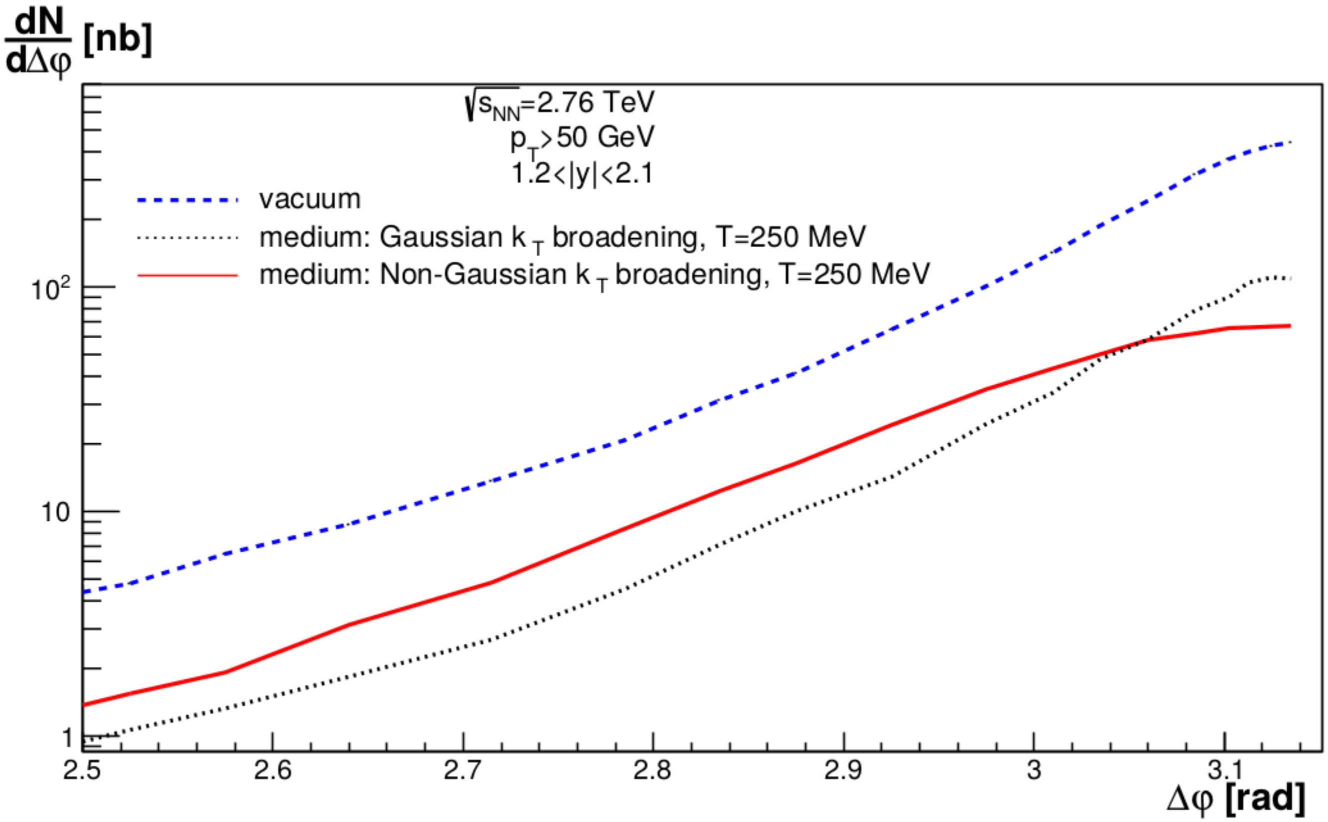


1911.05463
Van Hameren, Kutak,Placzek, Rohrmoser, Tywoniuk

Obtained using Monte Carlo
KaTie (hard cross-section) + MINCAS (jet quenching part)

Azimutal decorelations

1911.05463
Van Hameren, Kutak,Placzek, Rohrmoser, Tywoniuk

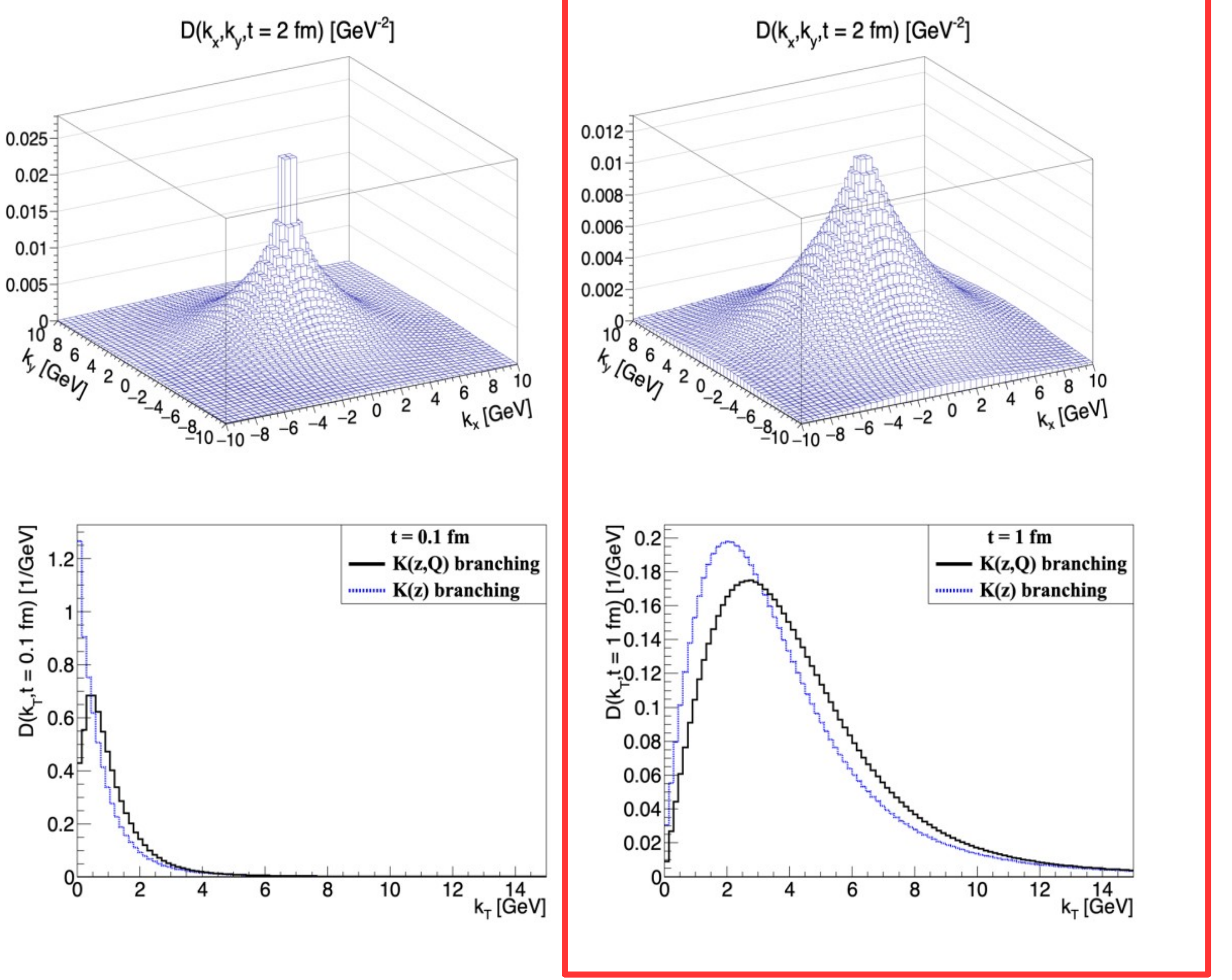


Suppression at large angles
Enhancement at moderate angles

Obtained using Monte Carlo
KaTie (hard cross-section) + MINCAS (jet quenching part)

Taking into account momentum transfer during branching

KK, Blanco, Placzek, Rohrmoser, Straka



Other effects not discussed here

- *Vacum emissions, vacuum like emissions in medium: DGLAP. Medium like emissions: generalized BDMPS*
  Caucal, Iancu, Mueller, Soyez Phys. Rev. Lett. 120, 232001 (2018)
  Caucal, Iancu, Mueller, Soyez, JHEP 10 (2019) 273

- *Interferences of emissions in medium and outside of medium and expansion of medium - negative corrections to broadening*
  Zakharov Zh.Eksp.Teor.Fiz. 156 (2019) 615-637

- *Harmonic approximation relaxed but limited to low x*
  Andres, Apolinario, Dominguez arxiv:2002.01517

- *Higher order corrections to jet quenching parameter*
  Mehtar-Tani, Tywoniuk arxiv 1910.02032

- *Rate equation for energy solved in expanding medium only energy distribution. No kt dependence*
  Adhya, Tywoniuk, Salgado, Spousta arxiv 1911.12193

Summary and outlook

- *we obtained solution of equation for gluon distribution in medium that depends on t, x,* k_T
- *combination of MINCAS with KaTiE: allows for calculation of jet-observables within* k_T *factorization approach*
- *results differ from pure Gaussian broadening. In back-to-back region cross section is suppressed. In moderate angles it is enhanced.*
- *Momentum transfer during branching is significant*

In the future we want to study more forward processes and in particular combine jet quenching and saturation