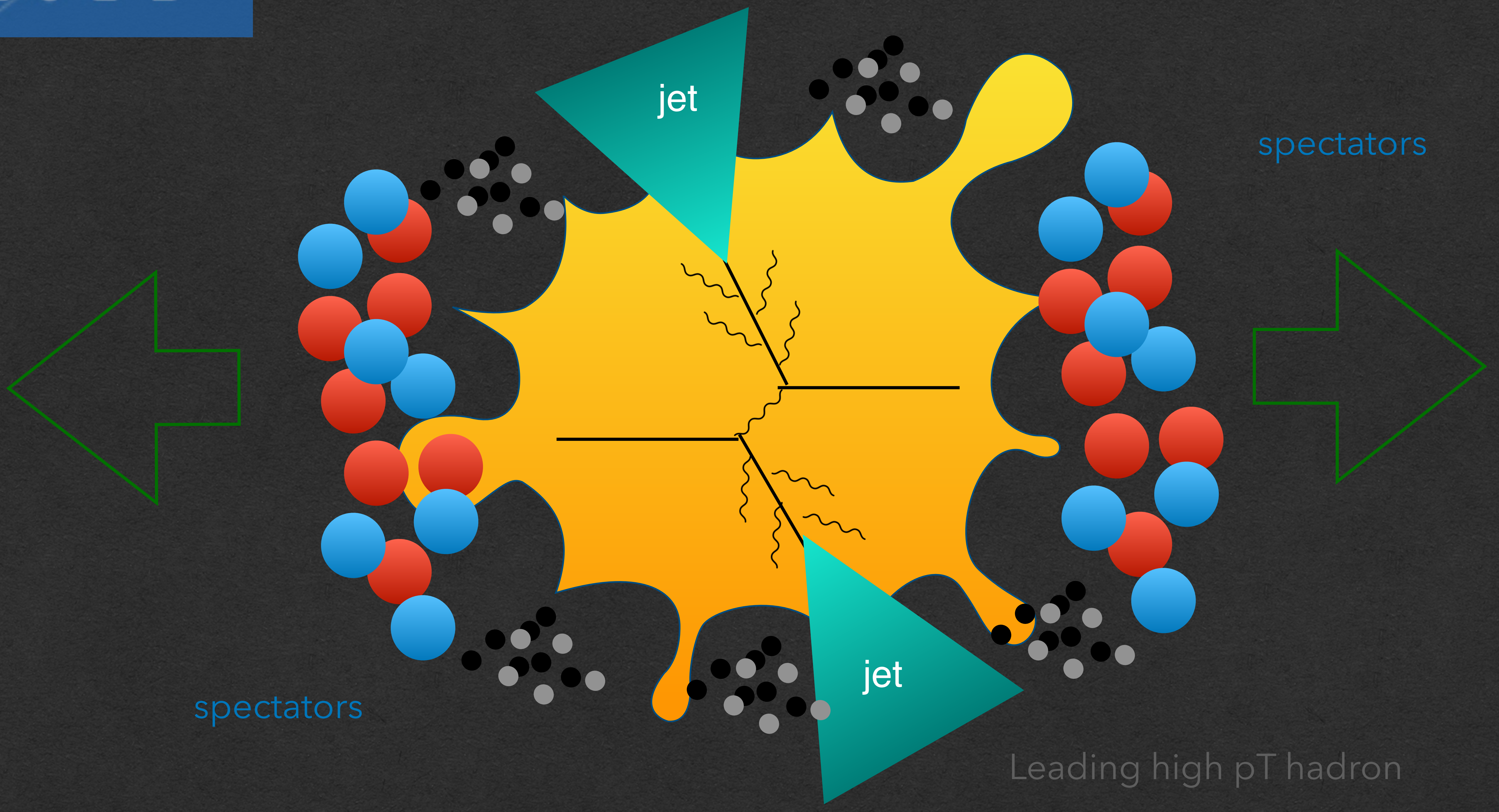


# Exploring quenching features of multi-partonic cascades in expanding medium


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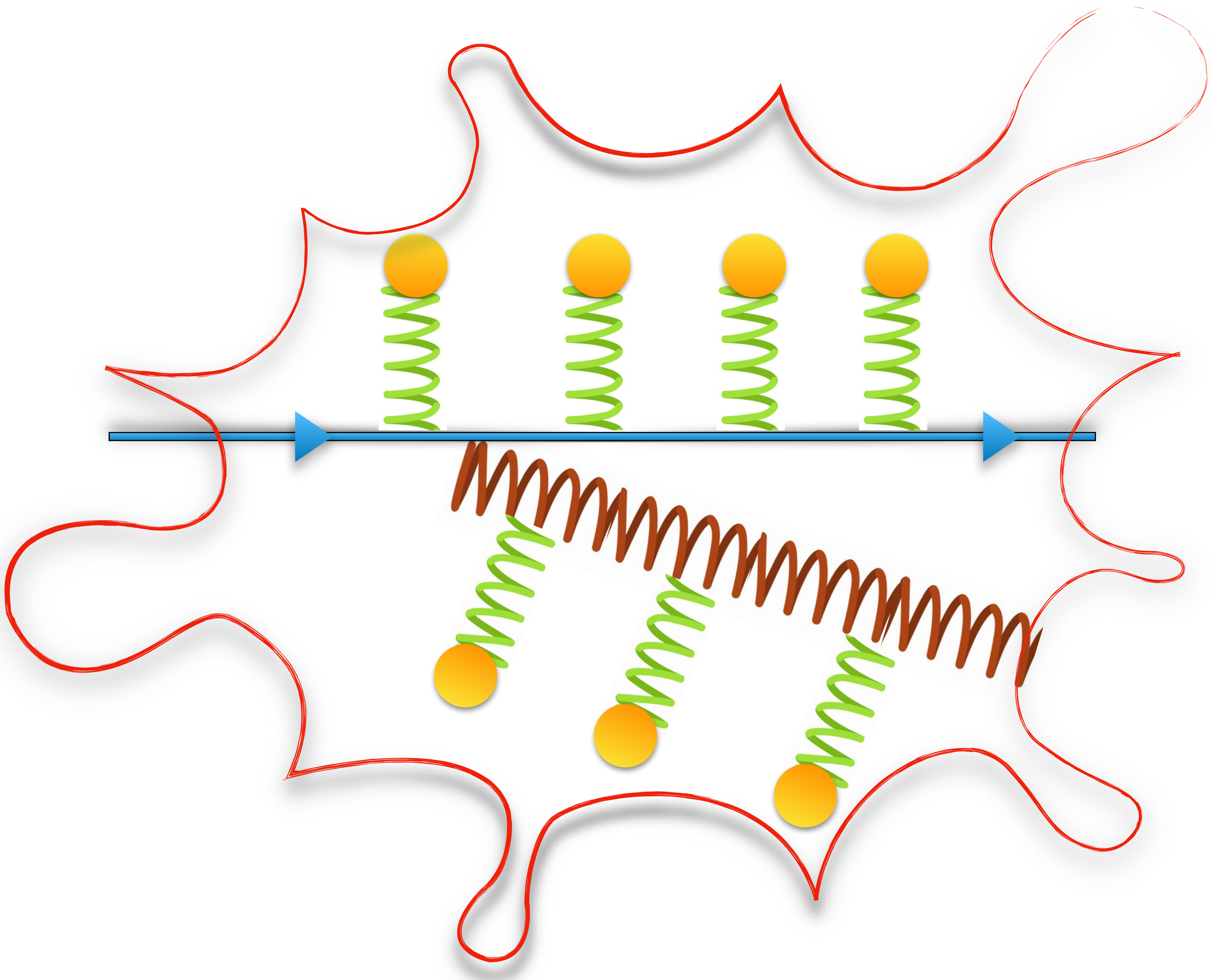
# Jet formation : few words

- High energy partons, resulting from an initial hard scattering, will create a high energy collimated spray of particles → JETS

- Partons traveling through a dense color medium are expected to lose energy via **medium induced gluon radiation** contributing to "jet quenching".

- We have adopted the *BDMPS-Z* (Baier, Dokshitzer, Mueller, Peigné, Schiff; Zakharov) formalism (*multiple soft scattering approximation*).



Medium induced emissions : Johanne's talk, today, 4 pm

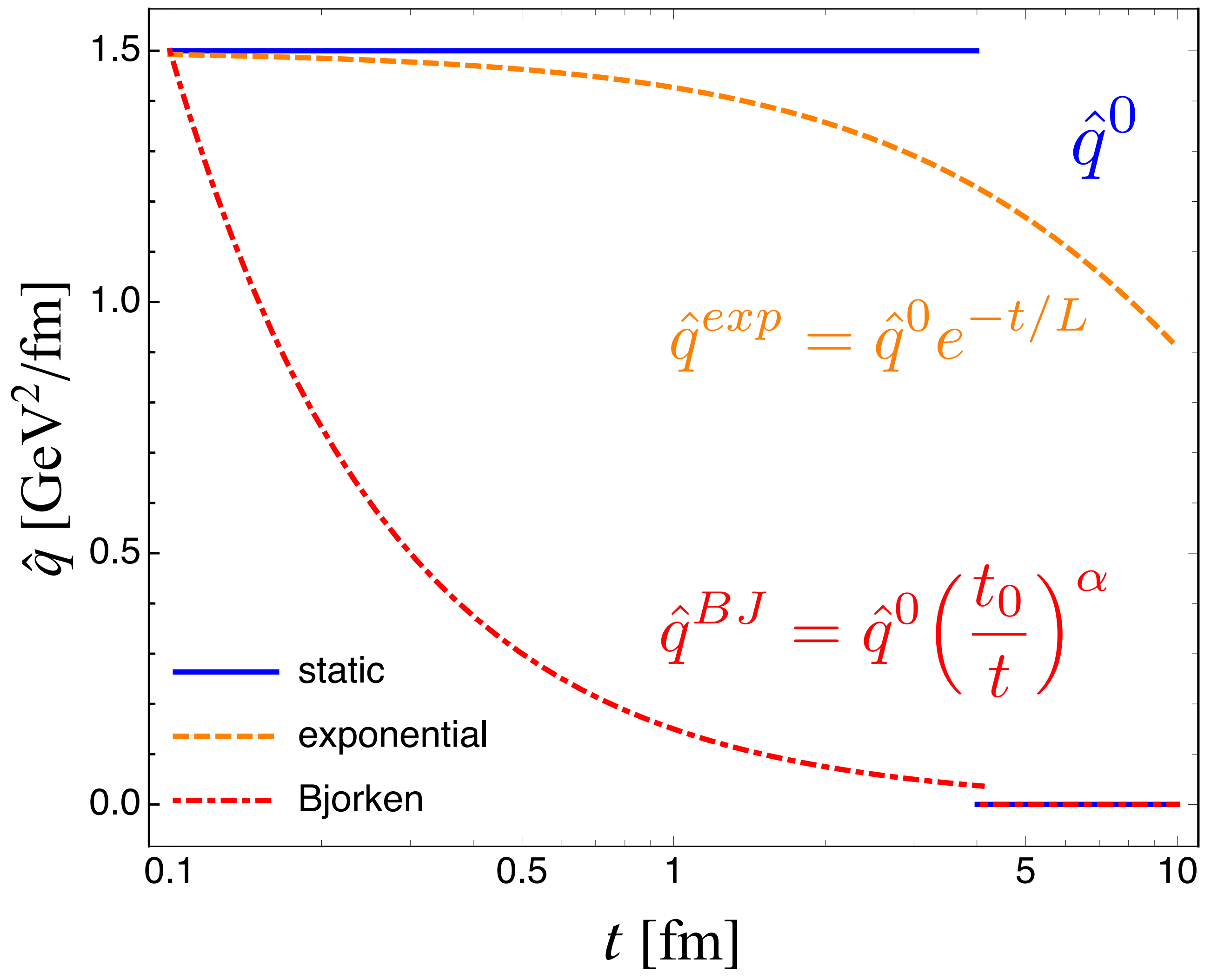
# Collecting the pieces



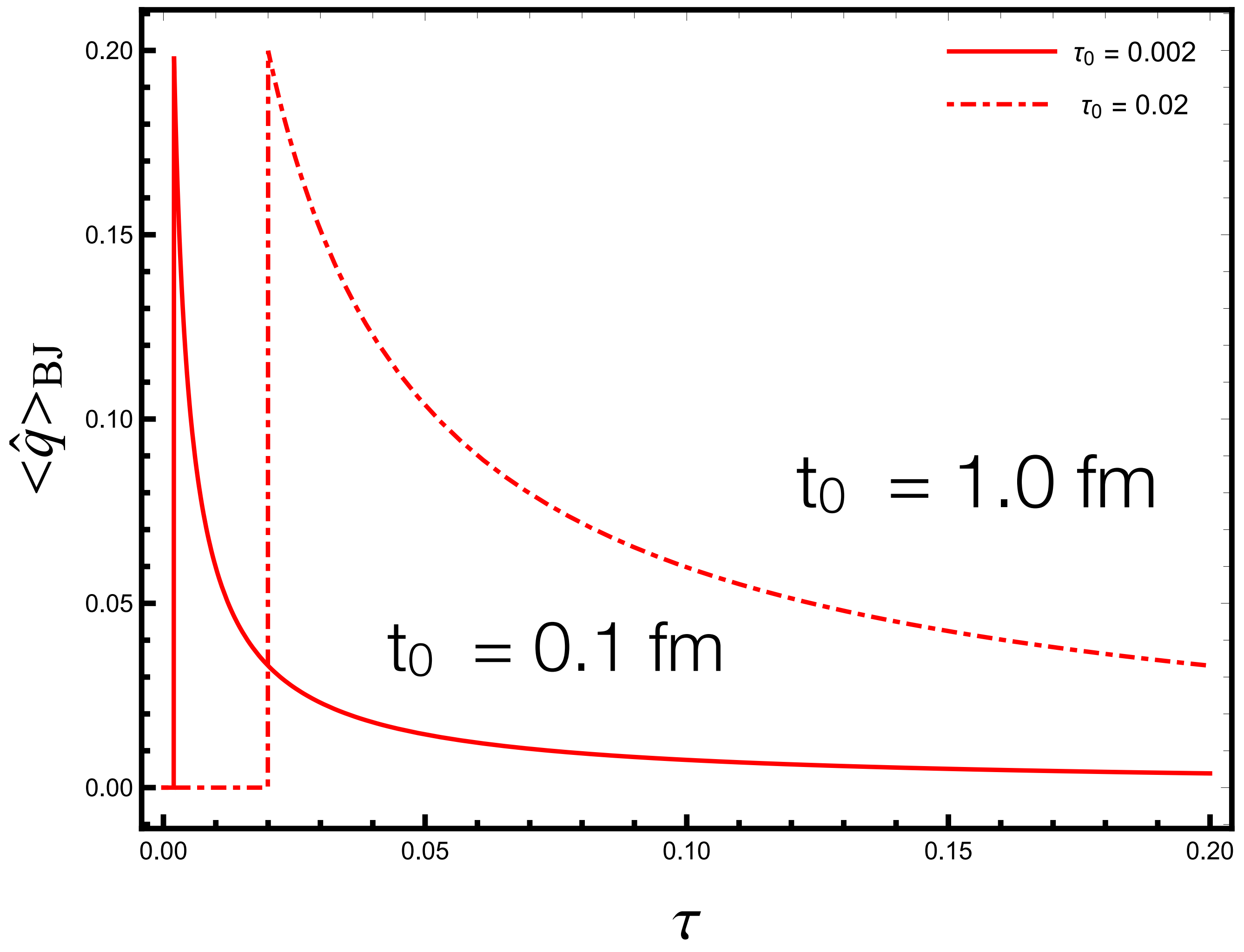
- Gluonic cascades in expanding medium.
- Multi- partonic cascades with expanding medium.
- Transverse momentum broadening in cascades in expanding medium.

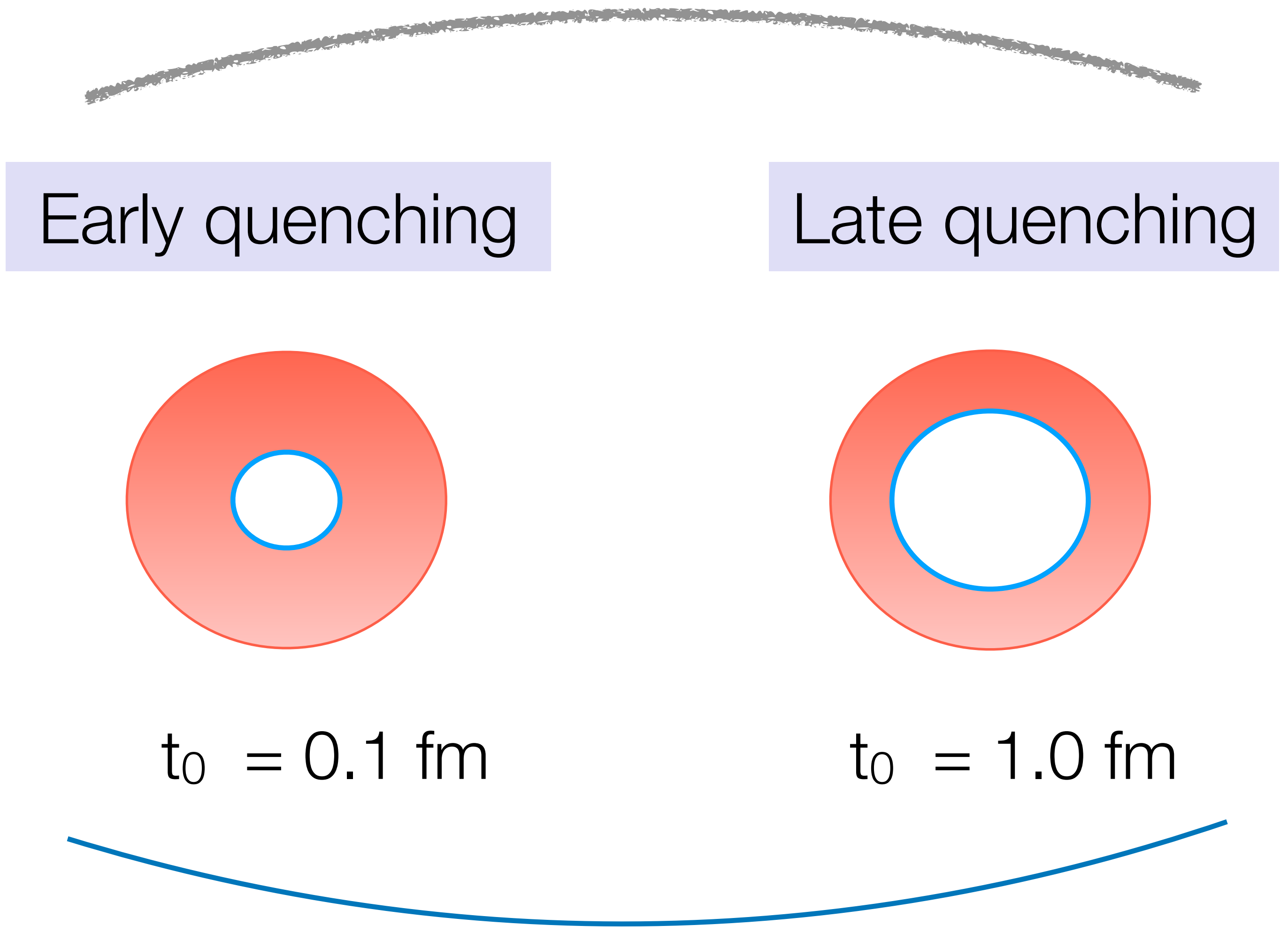
*Complexity/ Completeness towards understanding* →

# Medium profiles and calculation workflow :




Quenching parameter




Bjorken initial conditions

Evolution equations =>

$$\frac{\partial}{\partial\tau} D_g(x,\tau) = \int dz\, \mathcal{K}(z,\tau|p)\left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z},\tau\right) - \frac{z}{\sqrt{x}} D(x,\tau)\right] - \int_0^1 z K_{qg}(z) \frac{z}{\sqrt{x}} D_g(x) + \int_0^1 z K_{gq}(z) \sqrt{\frac{z}{x}} D_S\left(\frac{x}{z}\right)$$

$$\frac{\partial}{\partial\tau} D_S(x,\tau) = \int_0^1 dz\, K_{qq}(z)\left[\sqrt{\frac{z}{x}} D_S\left(\frac{x}{z}\right) - \frac{1}{\sqrt{x}} D_S(x)\right] + \int_0^1 dz\, K_{qg}(z)\sqrt{\frac{z}{x}} D_g\left(\frac{x}{z}\right)$$

$D_S$ = q singlet spectra
Dg = gluon spectra
K = splitting rate
τ = evolution variable


S. S and Y. M-T ; JHEP 09 (2018) 144.

J-P. B., F. D., E. I, Y. M-T ; JHEP 06 (2014) 075.


Single parton emission spectra (D) in BDMPS-Z formalism for static, exponential and Bjorken expanding media → Splitting rates in static, exponential and Bjorken expanding media → Kinematic rate equation taking into account all the possible splittings for quark & gluon initiated jets → Optimisation in the Quenching factor for jets with combined q and g fractions through modified power law, nPDF and VLE → Study of rapidity dependence and estimation of elliptic flow

# Scaling behaviour of the spectrum

S. P. Adhya, C. Salgado, M. Spousta, K. Tywoniuk; JHEP 07 (2020) 150.

The single gluon emission spectra are given as :

$$\frac{dI}{dz}^{static,soft} \simeq \frac{\alpha_s P(z)}{\pi}\sqrt{\frac{\omega_c}{2\omega}}$$

$$\frac{dI}{dz}^{static} = \frac{\alpha_s}{\pi} P(z)\, \mathrm{Re}\ln[\cos(\Omega_0 L)]$$

$$\frac{dI}{dz}^{expo} = \frac{\alpha_s}{\pi} P(z)\, \mathrm{Re}\ln J_0(2\Omega_0 L)$$

$$\frac{dI}{dz}^{BJ} = \frac{\alpha_s}{\pi} P(z)\, \mathrm{Re}\ln\left[\left(\frac{t_0}{L+t_0}\right)^{1/2} \frac{J_1(z_0)Y_0(z_L) - Y_1(z_0)J_0(z_L)}{J_1(z_L)Y_0(z_L) - Y_1(z_L)J_0(z_L)}\right]$$

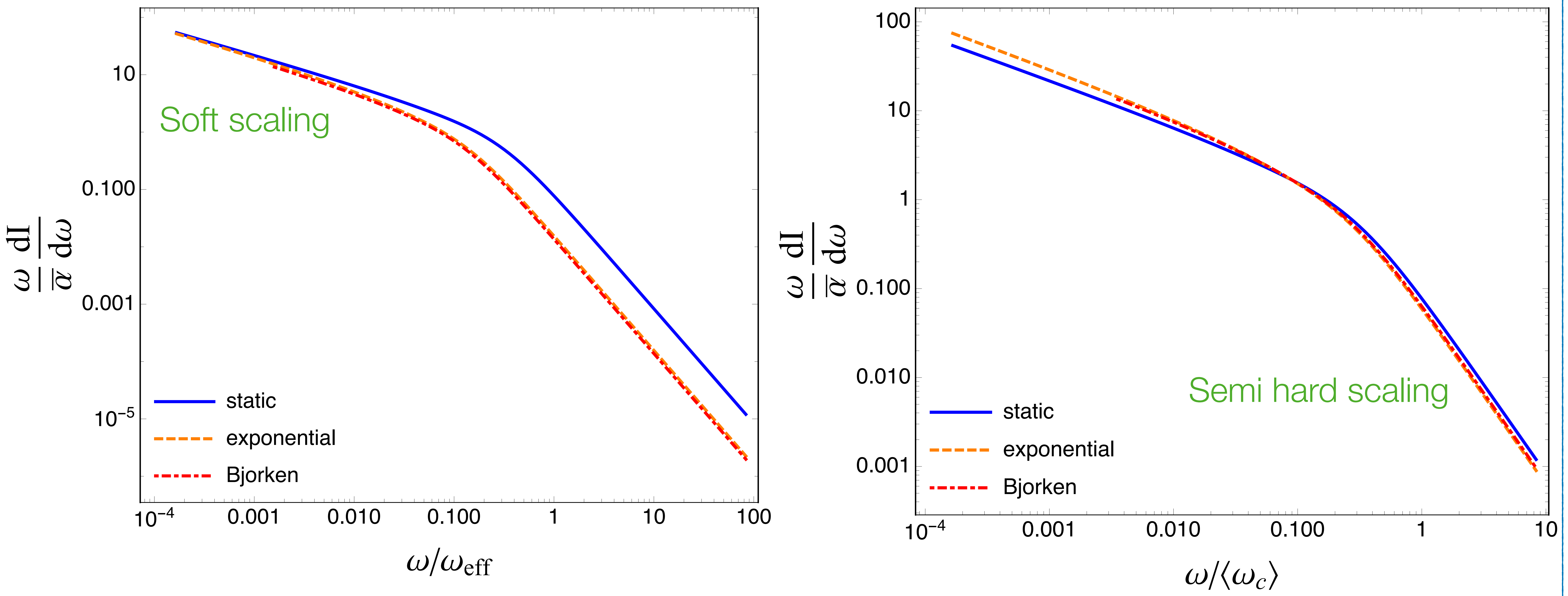
P. B. Arnold., PRD 79 (2009) 065025

$$\Omega_0 L = \sqrt{\frac{-i}{2}\frac{\hat{q}_0}{p}\kappa(z)}L \qquad \tau \equiv \sqrt{\frac{\hat{q}_0}{p}}L$$

$$z_0 \equiv (1-i)\kappa(z)\tau_0$$

$$z_L \equiv (1-i)\kappa(z)\sqrt{\tau_0(\tau+\tau_0)}\,,$$

Can we interpret the scalings in different kinematical limits ?




Effective parameter

$$\frac{dI}{dz}^{static,sing} \simeq \frac{dI}{dz}^{expo,sing} \simeq \frac{dI}{dz}^{BJ,sing}$$

The singular spectra can be re-scaled

$$\omega_{\rm eff} = \begin{cases} \frac{1}{2}\hat{q}_0 L^2 & \text{static medium} \\ 2\hat{q}_0 L^2 & \text{exponentially expansion} \\ 2\hat{q}_0 t_0 L & \text{Bjorken expansion} \end{cases}.$$

$$\hat{q}_{eff}^{expo} = 4\hat{q}_0$$

$$\hat{q}_{eff}^{BJ} = 4\hat{q}_0 t_0/L$$

# Medium evolved gluon spectra



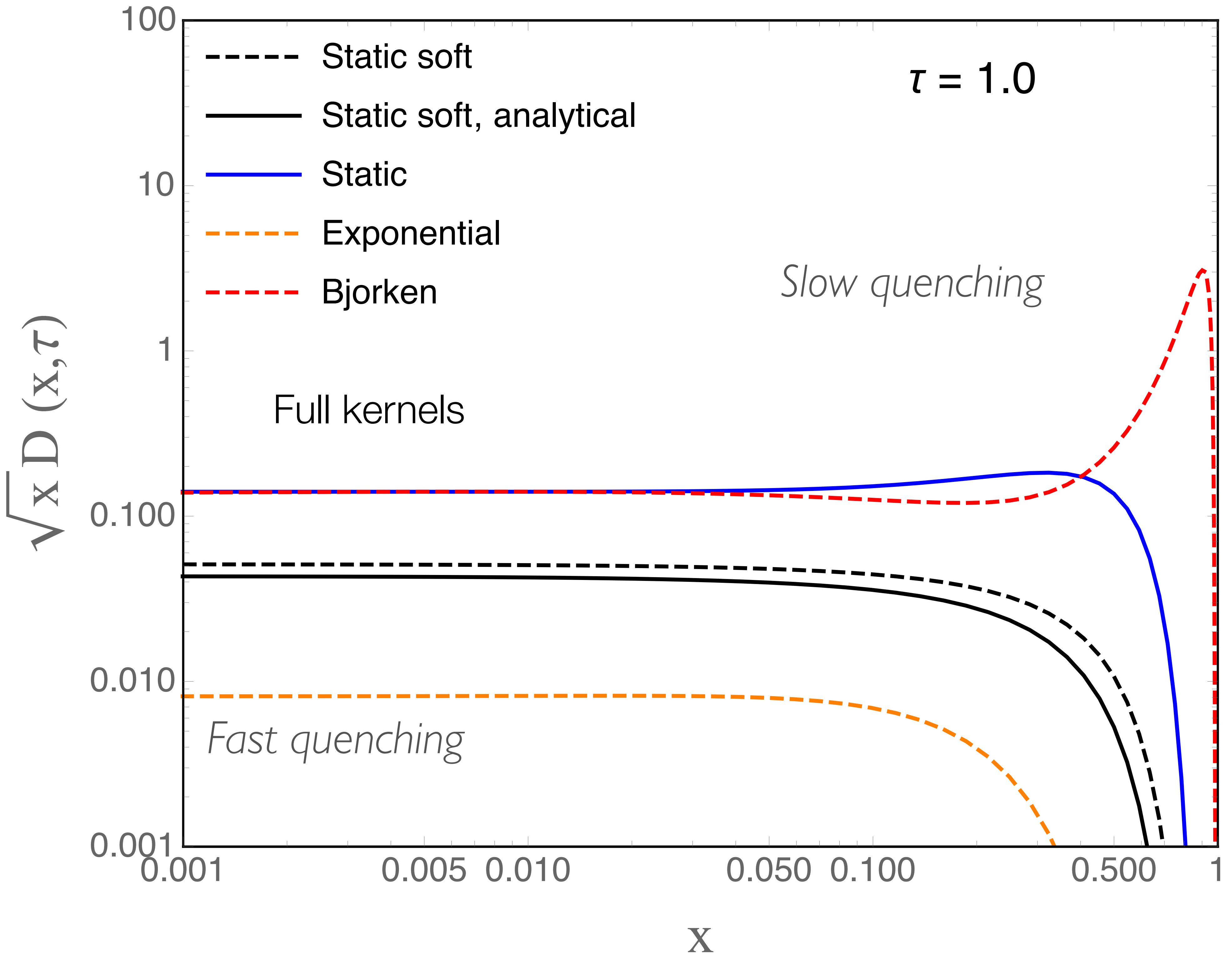
- The kinematic evolution equation (GAIN + LOSS terms) in terms of gluon spectra :

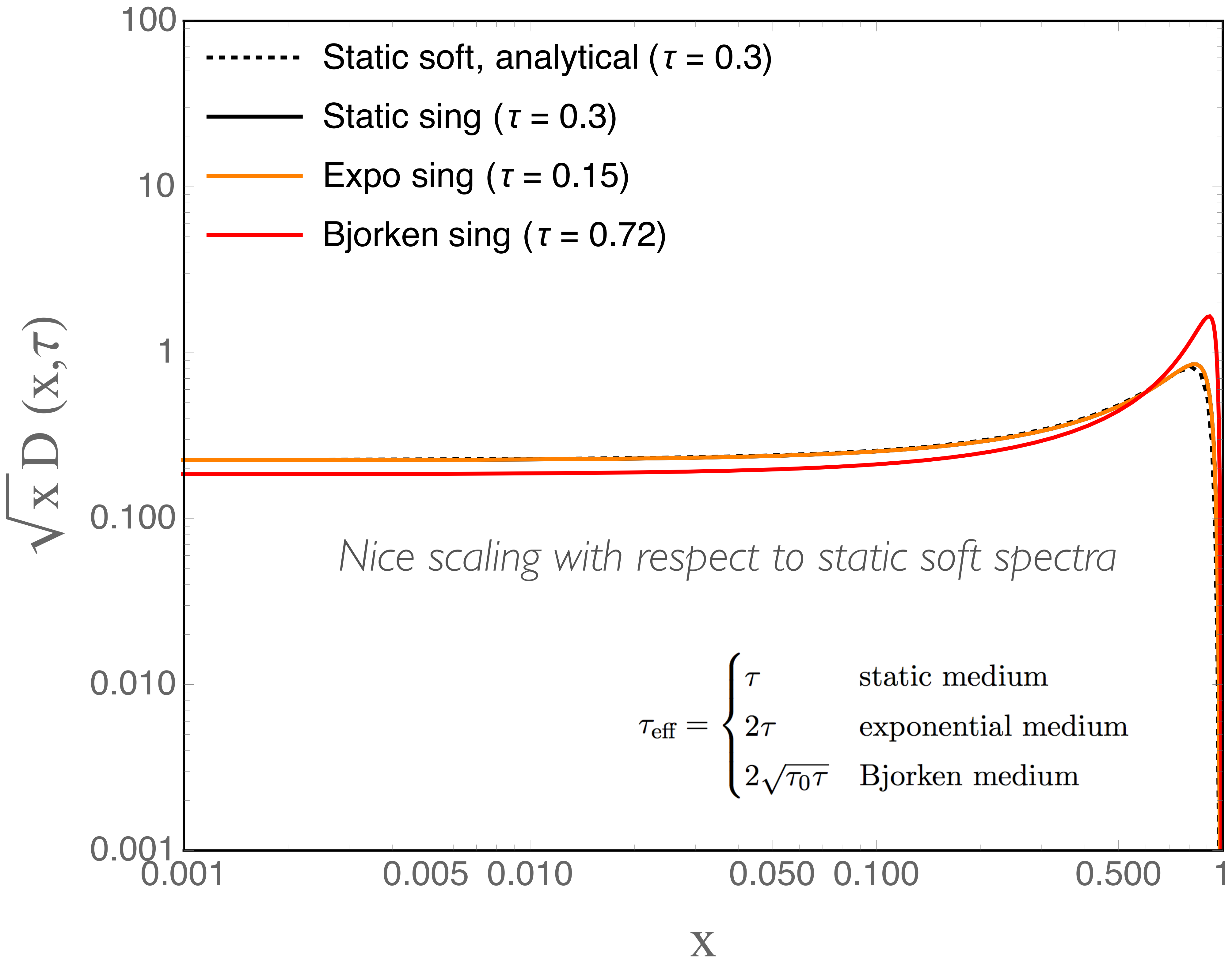
$$\frac{\partial D(x,t)}{\partial \tau} = \int dz \mathcal{K}(z,\tau|p) \left[ \sqrt{\frac{z}{x}} D\left(\frac{x}{z},\tau\right) - \frac{z}{\sqrt{x}} D(x,\tau) \right]$$

Static, soft gluon spectra (analytical)

$$D(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} e^{-\pi \frac{\tau^2}{1-x}}$$

J. P. B, E. I., Y. M-T, PRL. 111 (2013) 052001.




A. Singular spectra ==> Nice scaling in $\tau_{\rm eff}$ .

B. Full spectra ==> No scaling in $\tau_{\rm eff}$.

$$\mathcal{K}(z,\tau) \equiv \frac{dI}{dz d\tau}$$

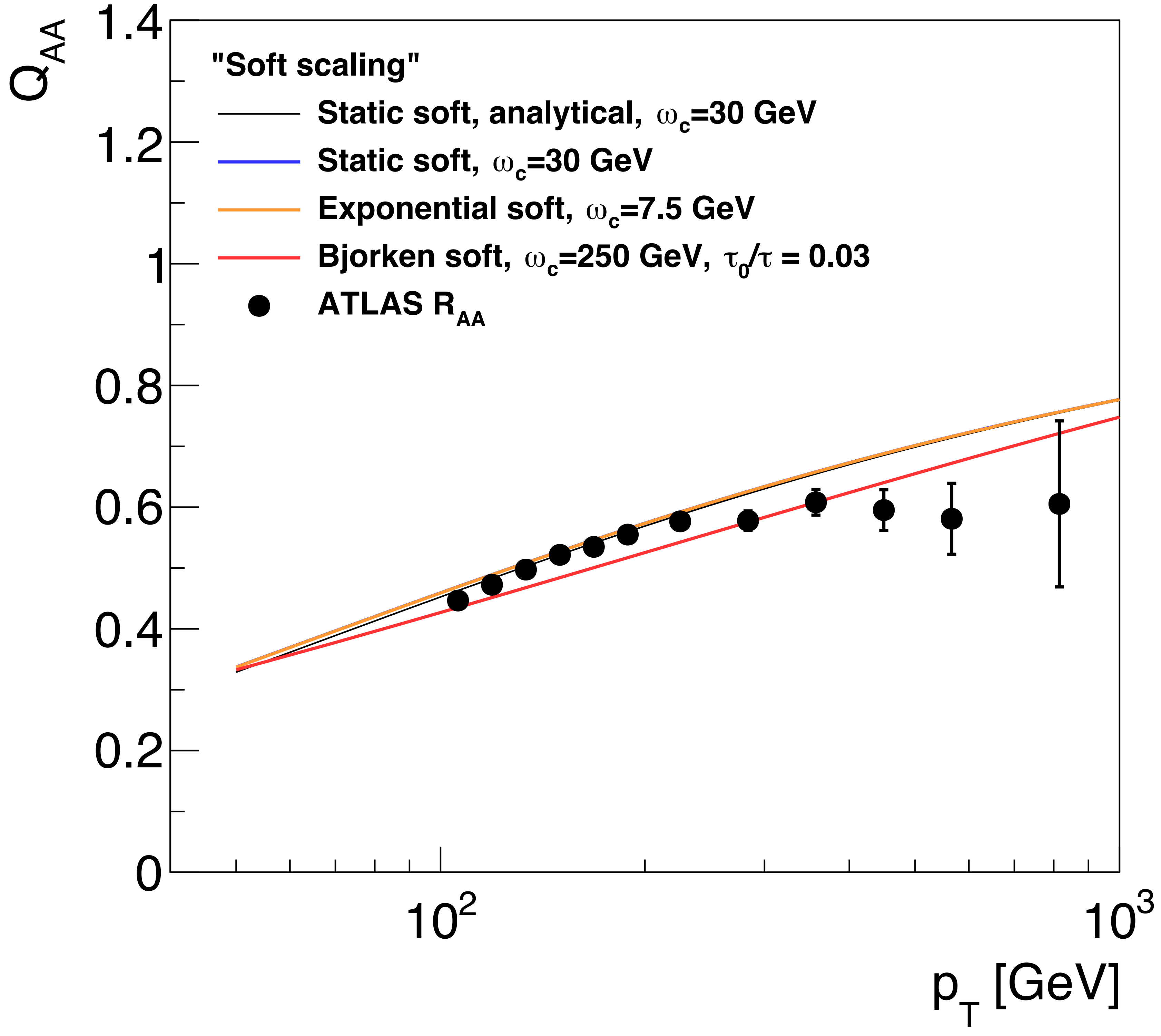
- At low x, we see a 1/(√x) behaviour of all the profiles >> *recovered from the similar gluon splitting at low x.*

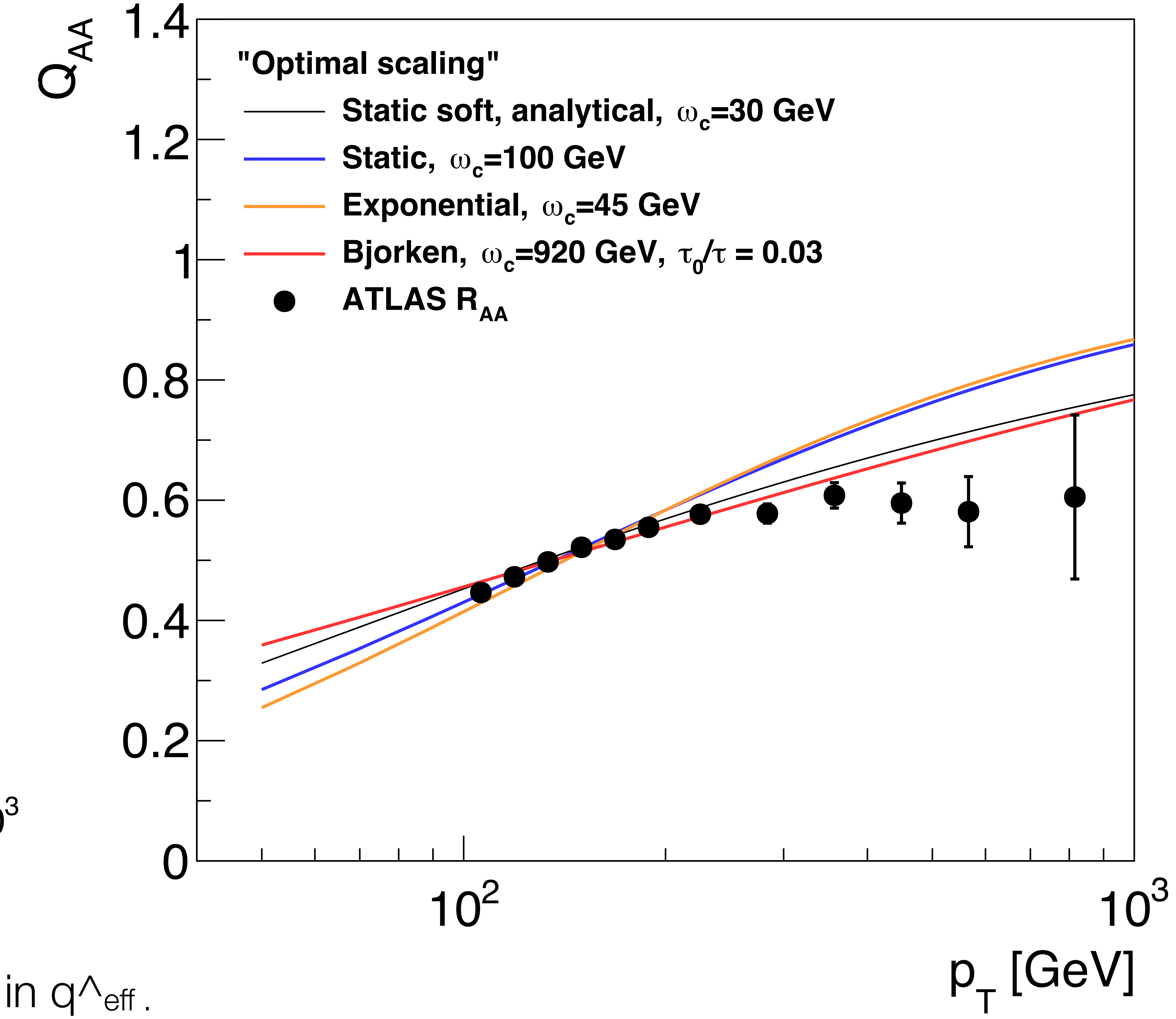
S. P. Adhya, C. Salgado, M. Spousta, K. Tywoniuk; JHEP 07 (2020) 150.

# Is it possible to re-scale $Q_{AA}$ for different media ?



$$Q_{AA}(p_T) = \int_0^1 \mathrm{d}x\, x^{n-1} D(x, \sqrt{x}\tau)$$




No

| $\hat{q}_0$ [GeV$^3$] | static | exponential | Bjorken |
|---|---|---|---|
| no scaling | 0.2 | 0.2 | 0.2 |
| soft scaling | 0.2 | 0.05 | 1.66 |
| optimal scaling | 0.2 | 0.09 | 1.84 |
| scaling by $\langle\omega_c\rangle$ | 0.2 | 0.1 | 3.33 |

- Significant differences in values of q^ for different types of medium and kinematical ranges point to the importance of precise modelling of jet quenching phenomenon.

- Soft scaling => Scaling for singular spectra in $q\hat{}_{eff}$ .
- The Bjorken profile depends on additional choice of $(\tau_0/\tau)$ : No universal scaling.
- Good, but not perfect scaling is achieved by optimisation.
- Scaling for exponential medium ~ average scaling.

S. P. Adhya, C. Salgado, M. Spousta, K. Tywoniuk; JHEP 07 (2020) 150.

Recent expt. results on $R_{AA}$: Reynier's talk, today, 12:25 pm

# Collecting the pieces



- Gluonic cascades with expanding medium.
- **Multi- partonic cascades in expanding medium.**
- Transverse momentum broadening in cascades in expanding medium.

*Complexity/ Completeness towards understanding* →

# Does the media behave differently for rapidity ?

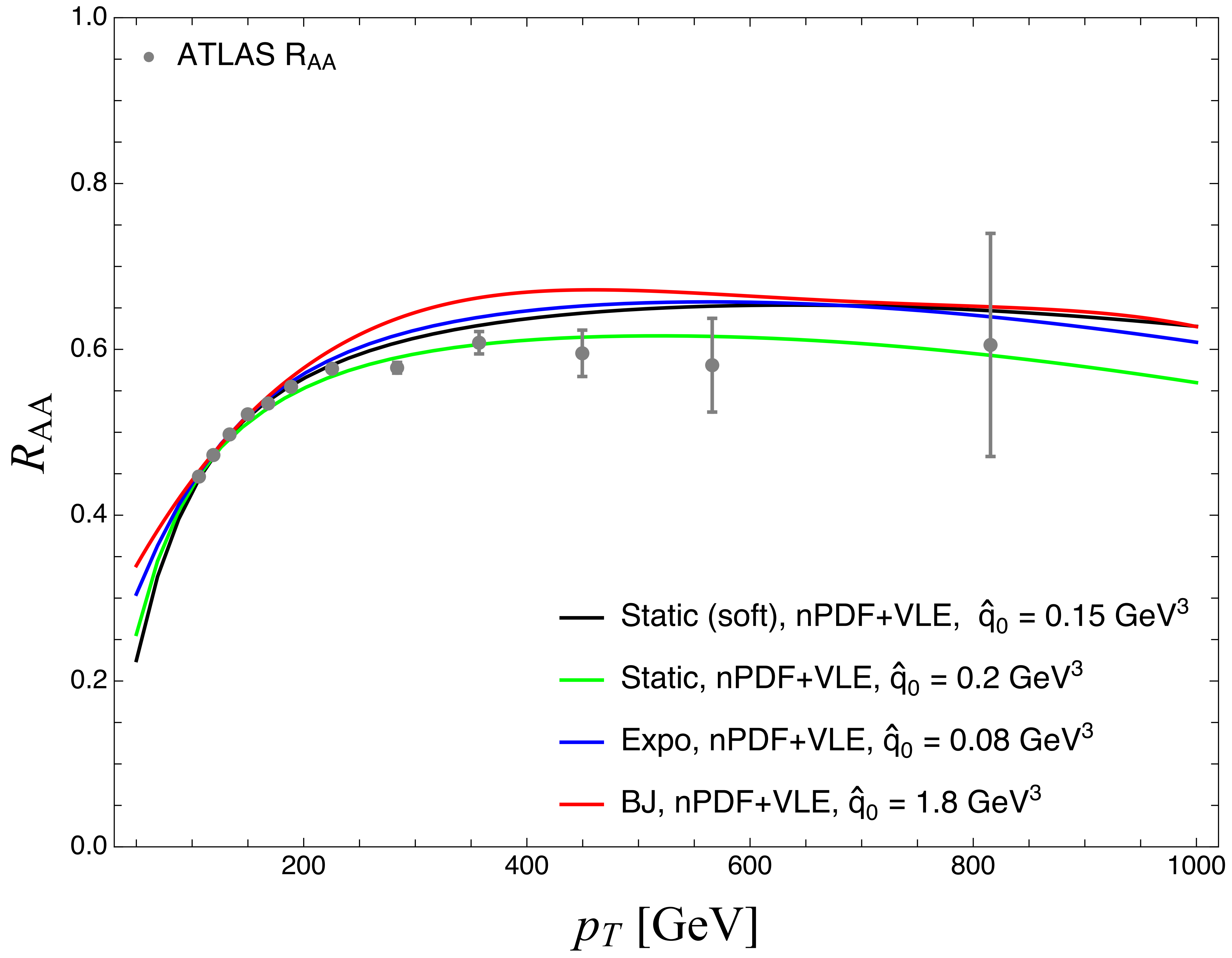
S. P. Adhya, C. Salgado, M. Spousta, K. Tywoniuk, EPJC 82 (2022) 1.



(on VLE) : YM-T, KK, PRD 98, 051501(R).

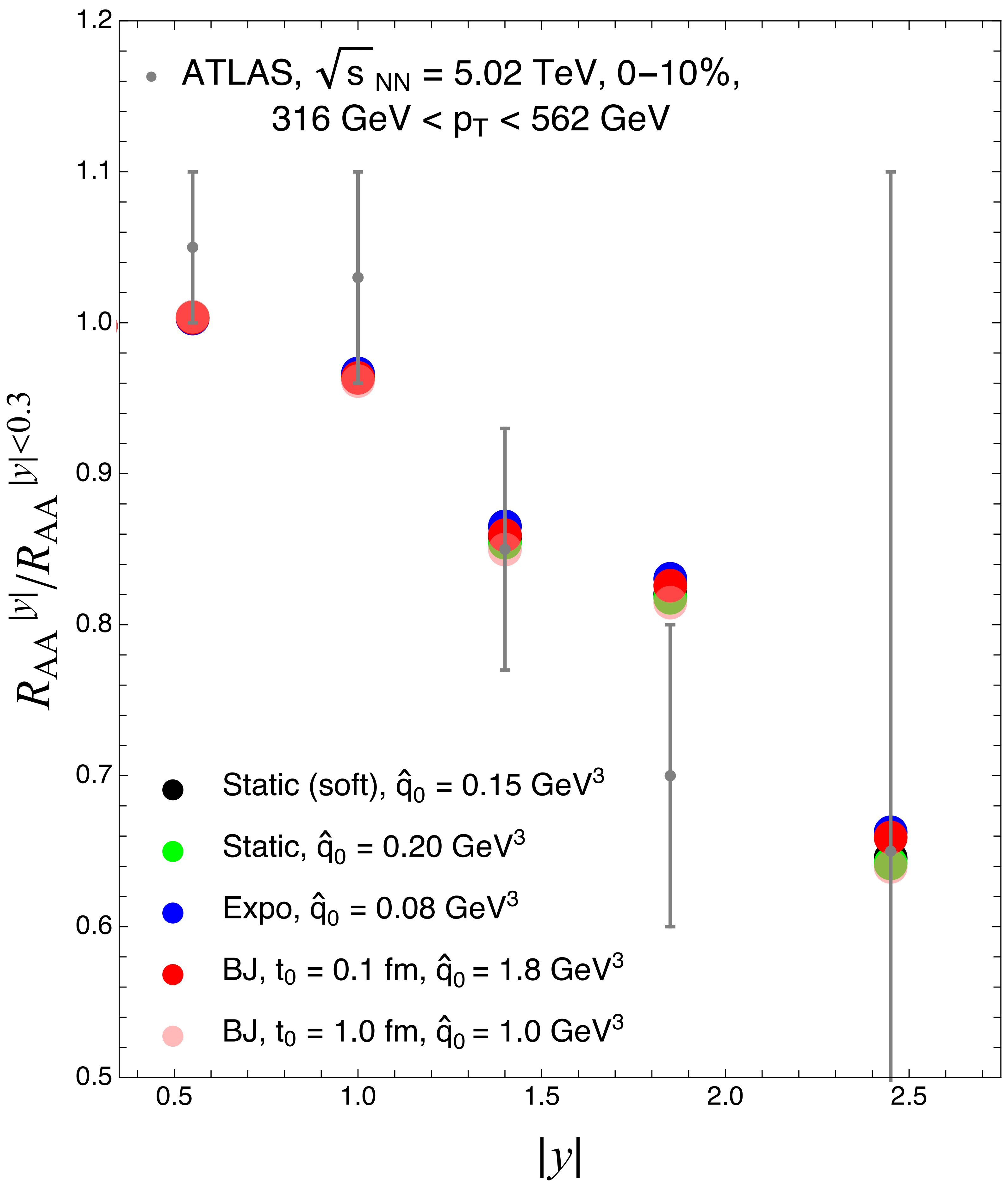
Multi- partonic cascades

Yes




Jet $R_{AA}$ for different medium profiles

No

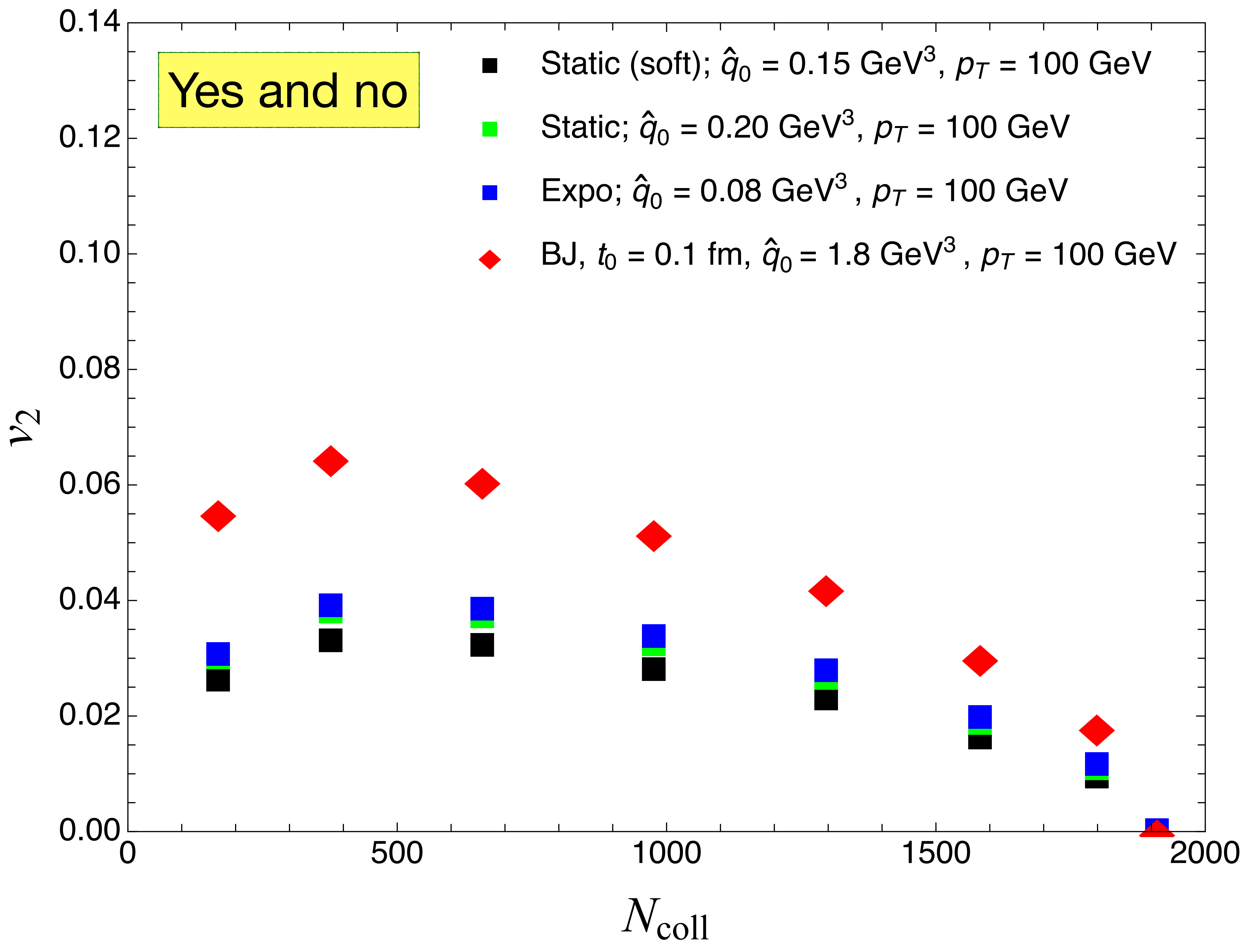


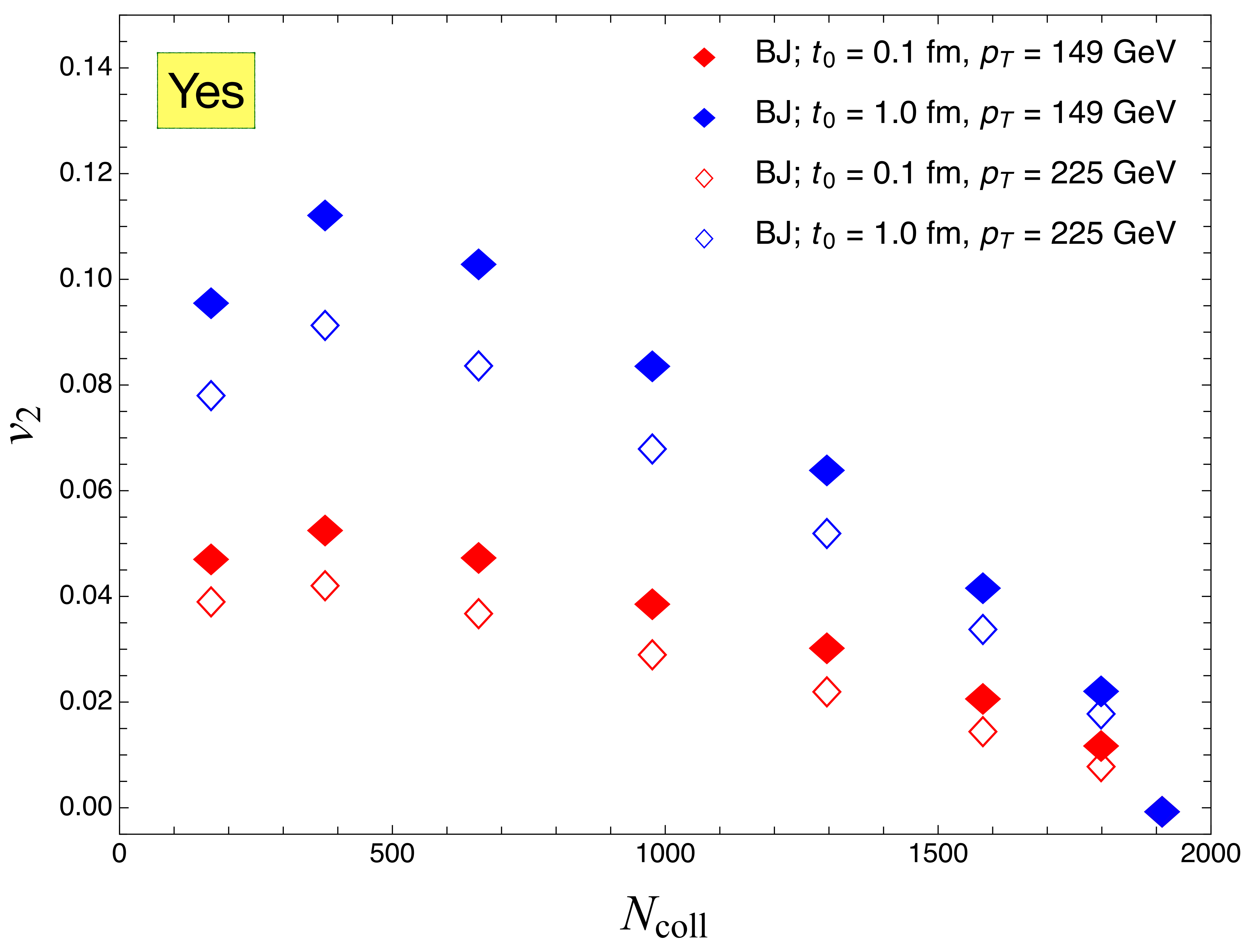

Rapidity ratio with respect to |y| for different medium profiles

# Does the media behave differently for $v_2$?

S. P. Adhya, C. Salgado, M. Spousta, K. Tywoniuk,
EPJC 82 (2022) 1.






- The impact of the medium expansion can be largely scaled out by a suitable choice of q̂ [*confirming Adhya et. al., 2020*].

- The jet $v_2$ remains sensitive to choice of starting time of Bjorken quenching $t_0$.

$$v_2 = \frac{1}{2}\frac{R_{AA}(L^{in}) - R_{AA}(L^{out})}{R_{AA}(L^{in}) + R_{AA}(L^{out})}$$

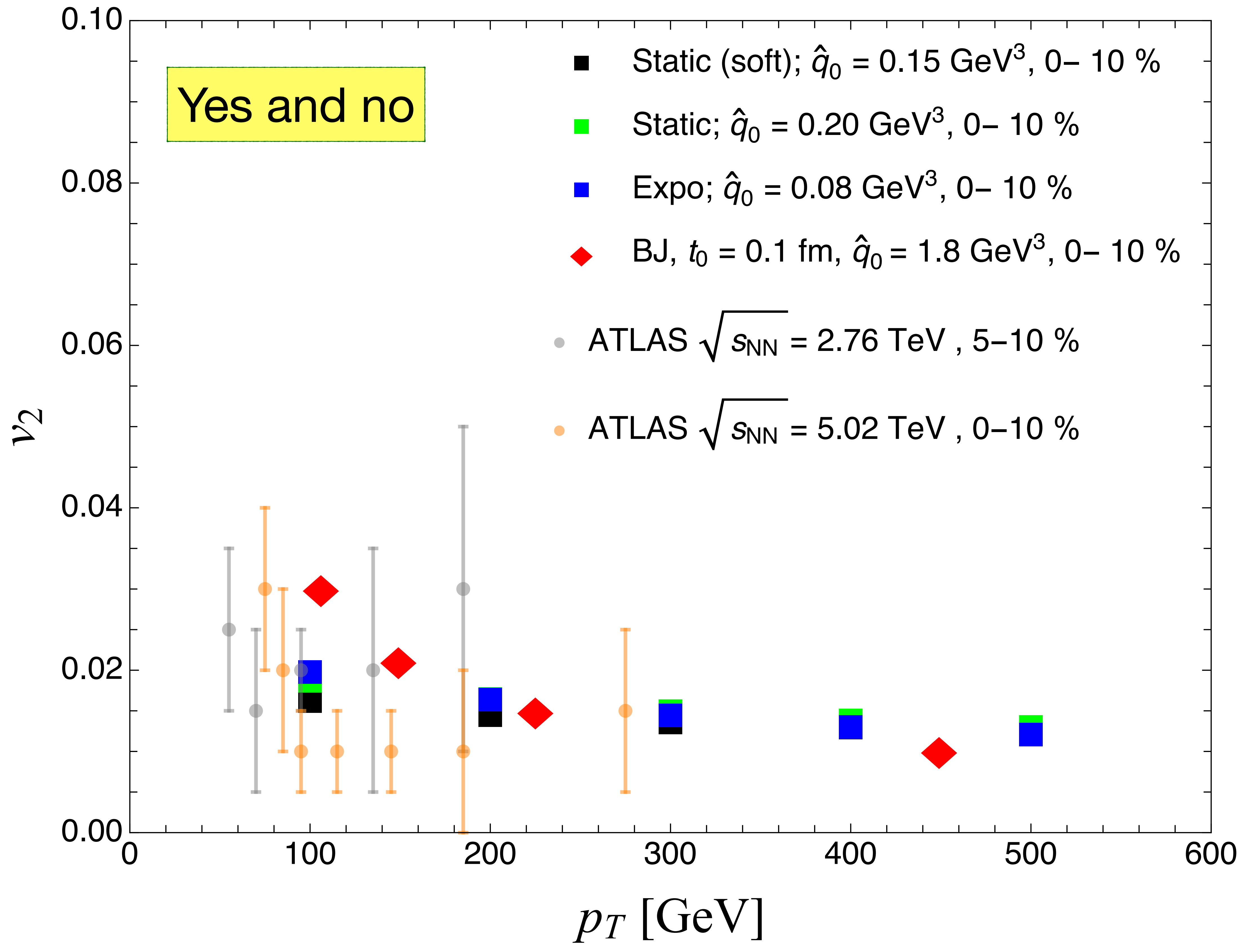
Zijic et. al.; J. P. G 46 (2019) 085101.

# Does the media behave differently for $v_2$?

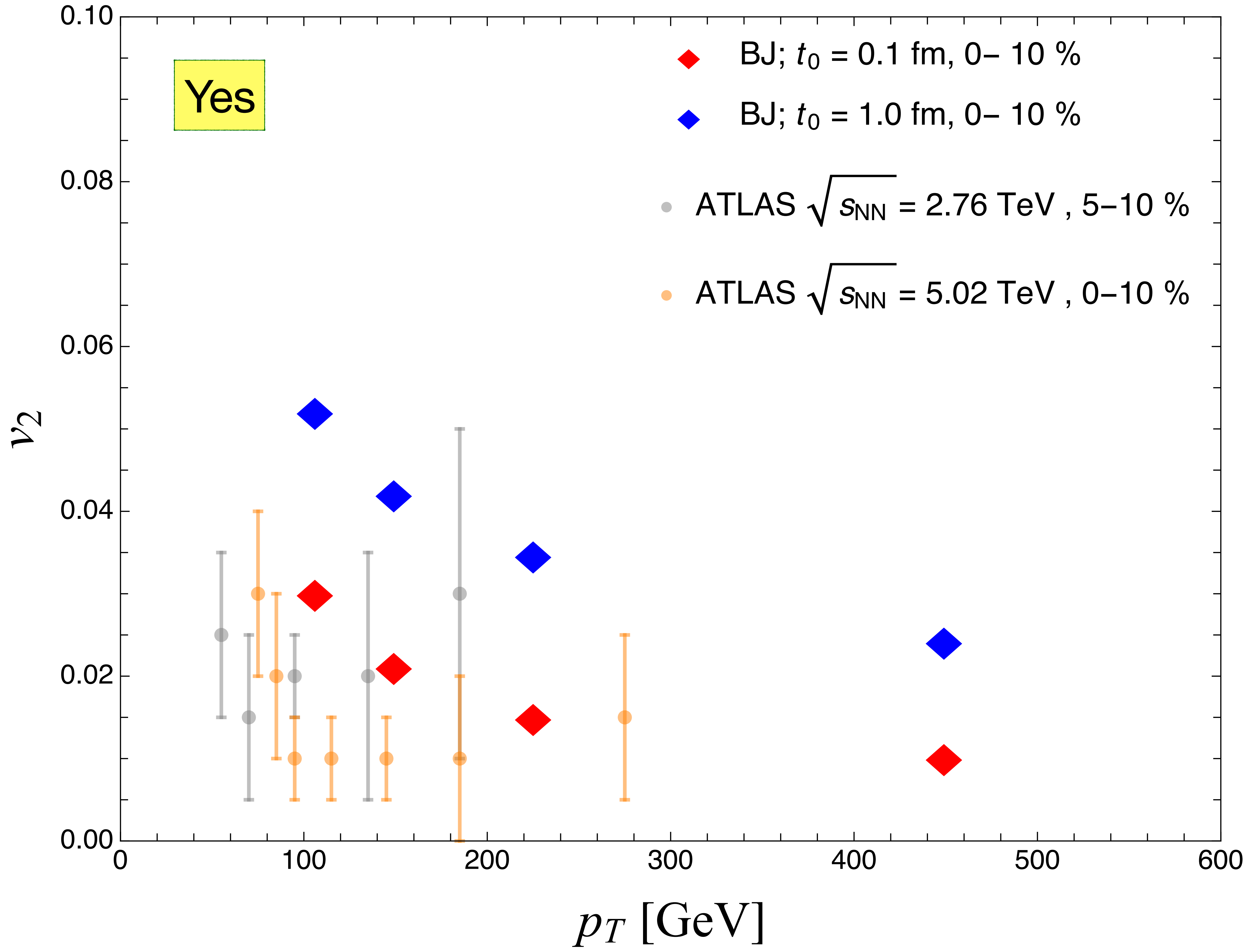
S. P. Adhya, C. Salgado, M. Spousta, K. Tywoniuk, EPJC 82 (2022) 1.



Elliptic flow $v_2$ as a function of $p_T$ for different media




Elliptic flow $v_2$ as a function of $p_T$ for Bjorken initial conditions




- Agreement with findings of the sensitivity of $v_2$ on $t_0$ [*Carlota et. al., PLB, 2020*] which was done in more complex modelling of the collision geometry, but less complex modelling of the medium induced showering.

# Collecting the pieces

- Gluonic cascades with expanding medium.
- Multi- partonic cascades with expanding medium.
- Transverse momentum broadening in cascades in expanding medium.

*Complexity/ Completeness towards understanding*

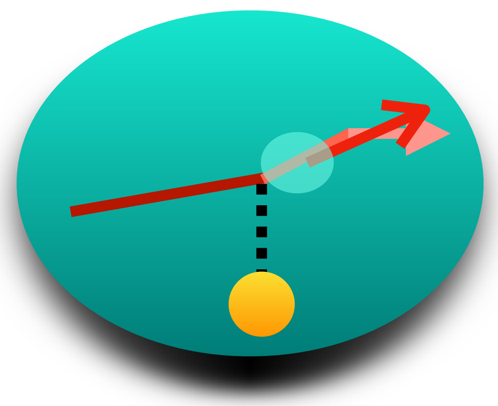
# Comparison of momentum broadening probabilities

S. P. A. , K. Kutak, W. Placek, M. Rohrmorser, K. Tywoniuk (in preparation)

'x' integrated D (x, k, t) integrated spectra = $\mathcal{P}$ (k) —> Broadening of jet

**Single hard (SH) scattering**

$$\mathcal{P}^{\rm SH}(\boldsymbol{k},L)\Big|^{eff} = 4\pi\frac{Q^2_{s0,eff}}{\boldsymbol{k}^4}$$

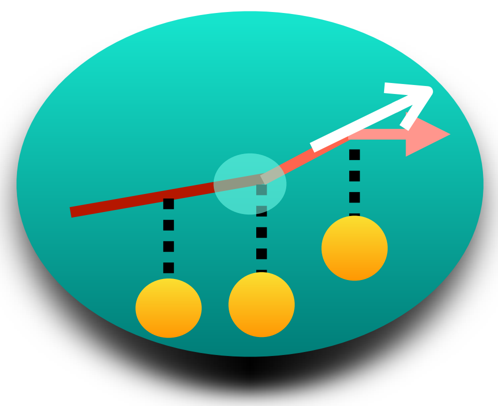


+

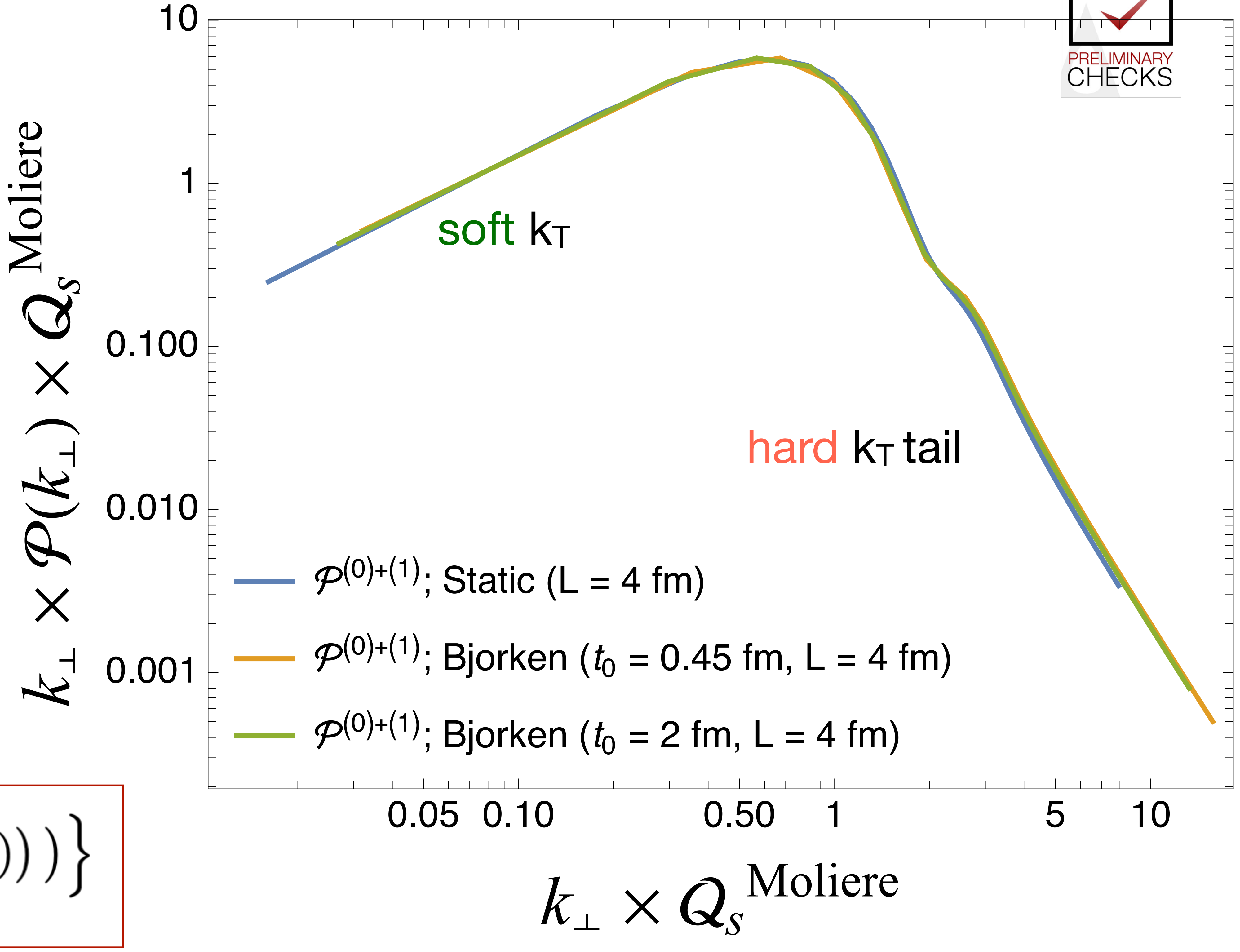
$\simeq$

**Multiple soft (MS) scattering**

$$\mathcal{P}^{\rm MS}(\boldsymbol{k},L)\Big|^{eff} = \frac{4\pi}{Q^2_{s,eff}}\,{\rm e}^{-\frac{\boldsymbol{k}^2}{Q^2_{s,eff}}}$$



Nice scaling of the Bjorken with static !




**Moli`ere's theory of multiple scattering**

$$\mathcal{P}^{(0)+(1)}(\boldsymbol{k},L)\Big|^{eff} = \frac{4\pi}{Q_s^2}{\rm e}^{-x}\Big\{1-\lambda\left({\rm e}^x-2+(1-x)\,\left({\rm Ei}\,(x)-\log(4x\,a)\right)\right)\Big\}$$

$$x \equiv \frac{\boldsymbol{k}^2}{Q^2_{s,eff}}$$

Static media $Q_s^2$ ⟶ $Q_s^2\left(\frac{t_0}{L}\right)\log\left(\frac{L}{t_0}\right)$ Bjorken expanding media

$$Q_s^2 = \hat{q}_0 L \log\frac{aQ_s^2}{\mu_*^2}$$

$$Q_{s0}^2 \equiv \hat{q}_0 L$$

- Single particle momentum broadening distribution ( $\mathcal{P}$ ) reproduce the Gaussian behavior at small-k⊥ together with the power-law tail ==> *simple analytic expression* in Moli`ere prescription (effective).

(Static media) JB, YMT, ASO, KT PRD 104, 054047 (2021).

# How does the $k_T$ dependent spectra look like ?

S. P. A. , K. Kutak, W. Placek, M. Rohrmorser, K. Tywoniuk (in preparation)



Ansatz | Numerical solution

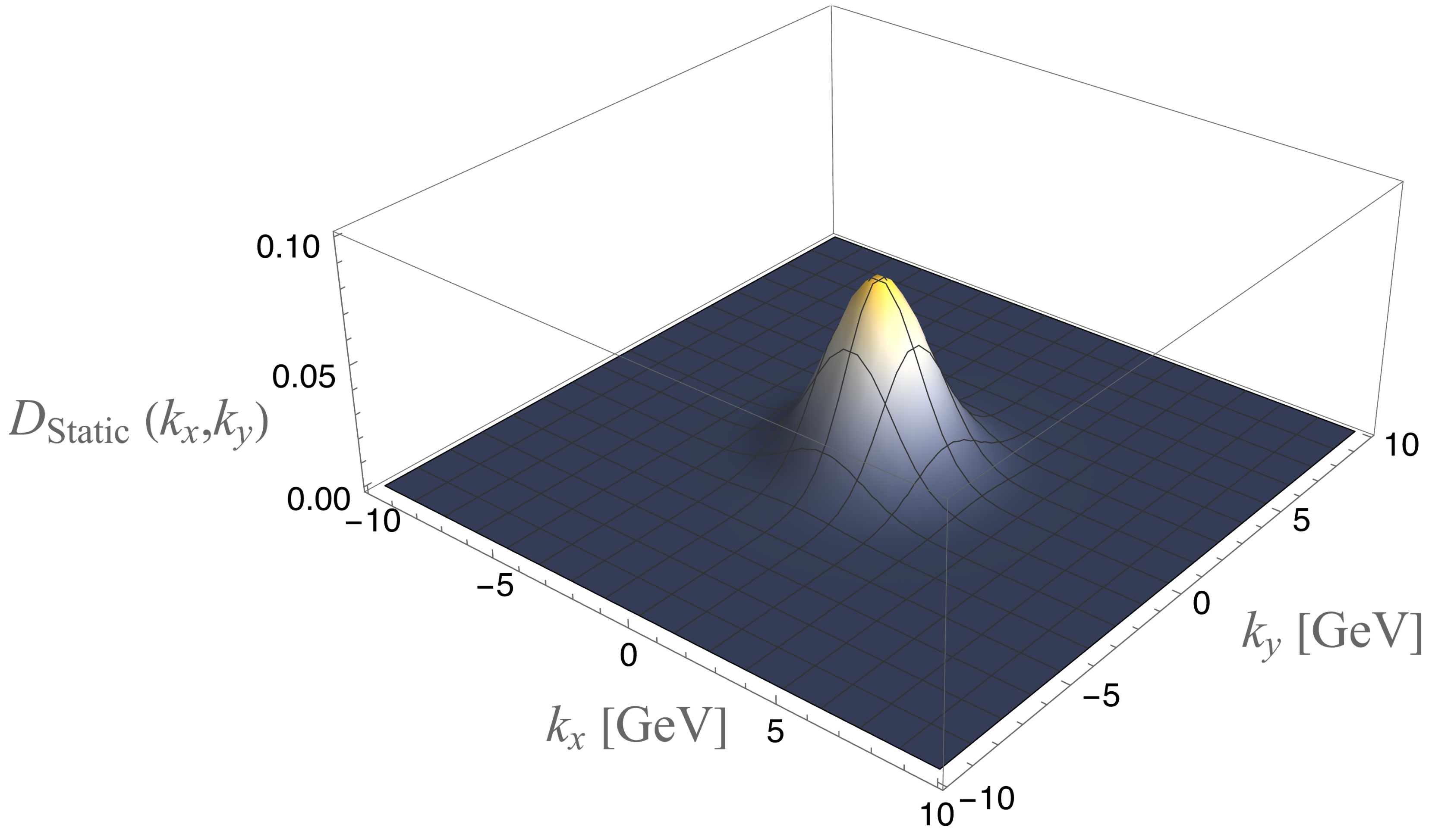
- We consider different schemes for the transverse momentum broadening.

| Schemes | Gaussian broadening only | General broadening | |
|---|---|---|---|
| Medium evolved spectra w/o broadening | $D(x,\tau)$ | $D(x,\tau)$ | – |
| Momentum broadening term | $\mathcal{P}^{GB}(\boldsymbol{k},\tau)$ | $\mathcal{P}^{(0)+(1)}(\boldsymbol{k},\tau)$ | – |
| Medium evolved spectra with broadening | $D^{GB}(x,\mathbf{k}_T,\tau)$ $= \mathrm{D}(x,\tau) \times \mathcal{P}^{GB}(\boldsymbol{k},\tau)$ | $D^{eGB}(x,\mathbf{k}_T,\tau)$ $= \mathrm{D}(x,\tau) \times \mathcal{P}^{(0)+(1)}(\boldsymbol{k},\tau)$ | $D^{nGB}(x,\mathbf{k}_T,\tau)$ |

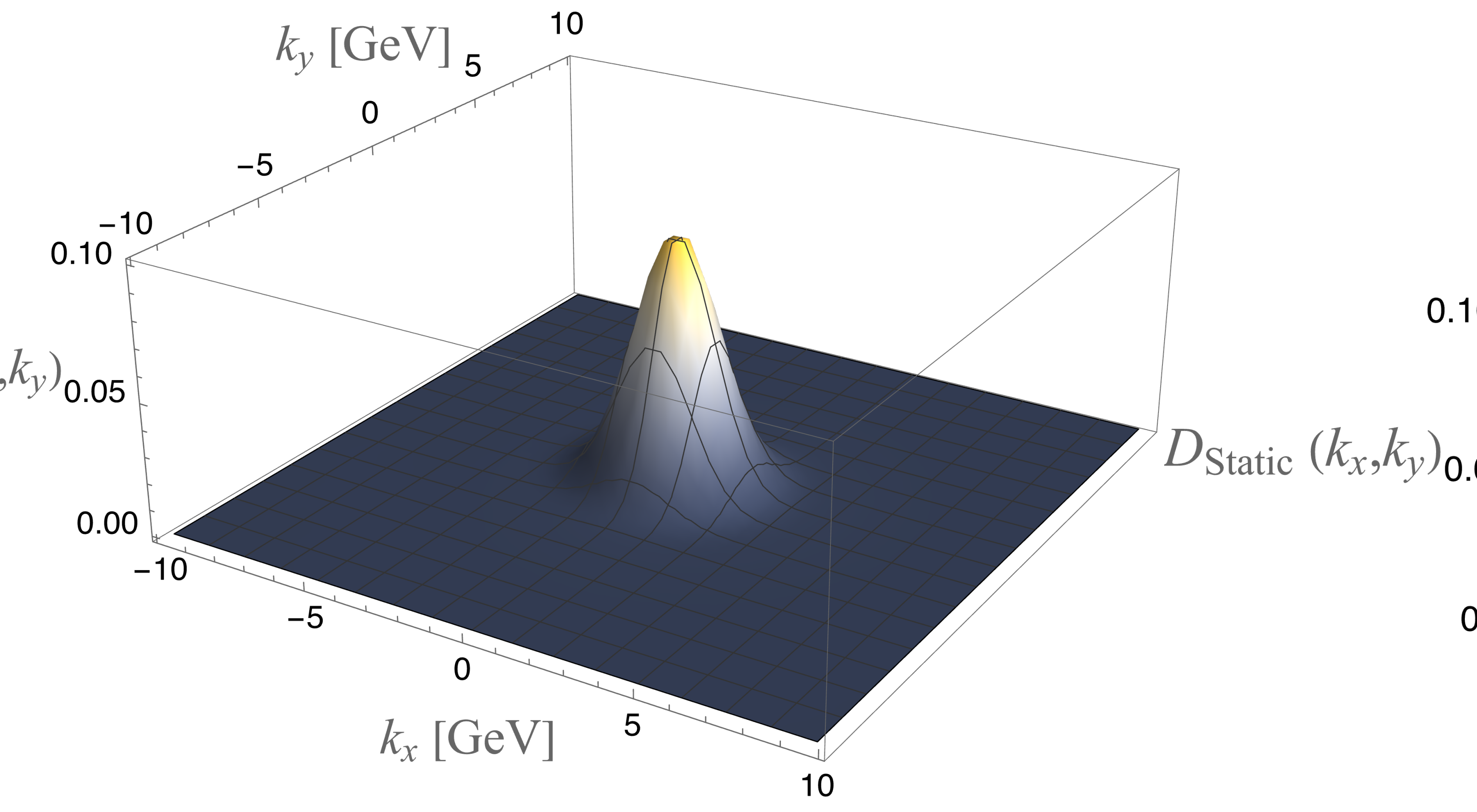
- *$k_T$ independent kernel. This is an approximation. The whole broadening comes from rescattering.*
- *Non- Gaussianity : Sum of many Gaussians of different widths; arbitrary number of the collisions with the medium.*

(Static media) A. v-H , K. K, W. P. , M. R., K.T., PRC 102 (2020) 044910.

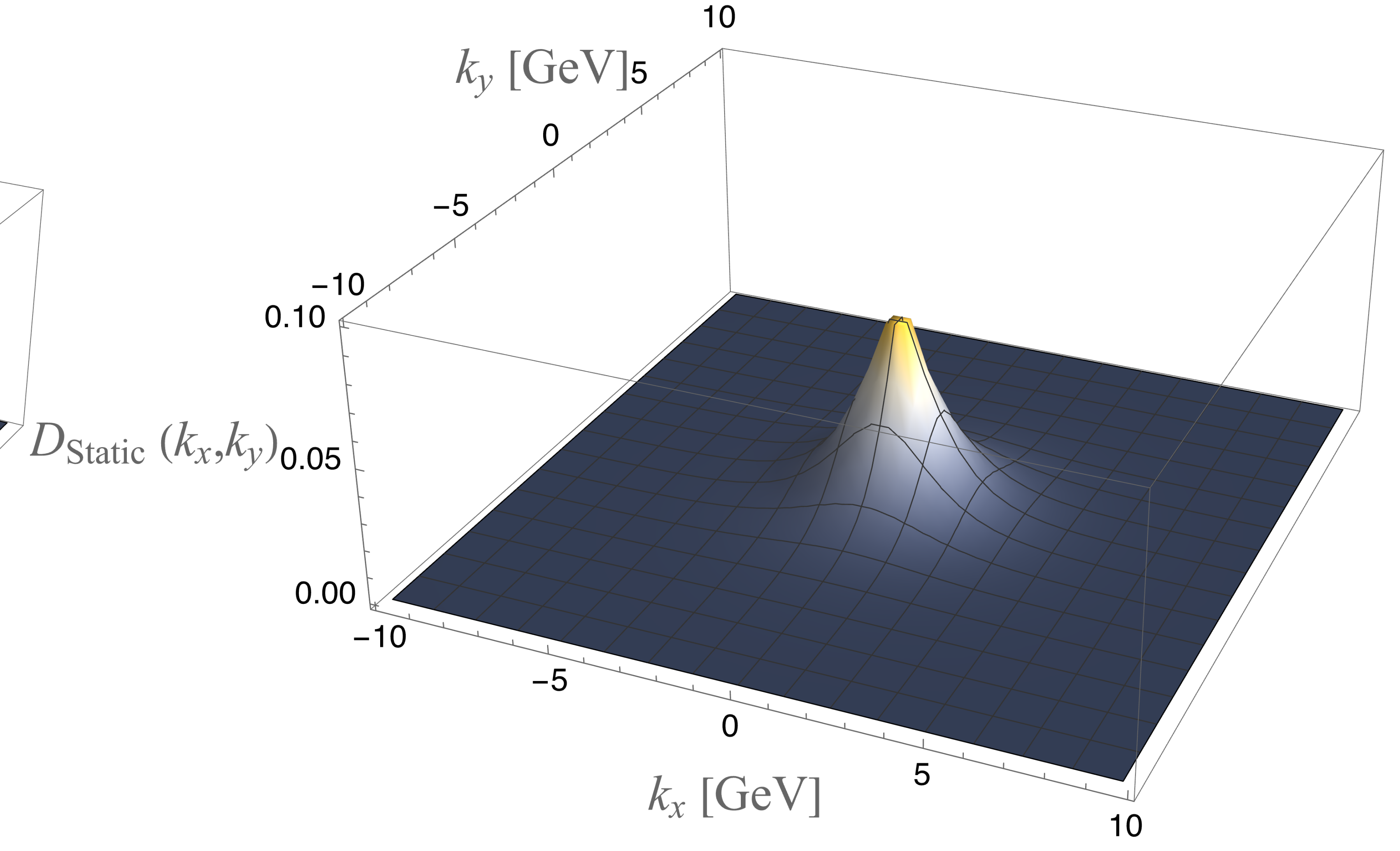
$D^{GB}$ (Gaussian broadening)




$D^{eGB}$ (effective broadening)




$D^{nGB}$ (non- Gaussian broadening)




STATIC medium

# How does the $k_T$ dependent spectra look like ?

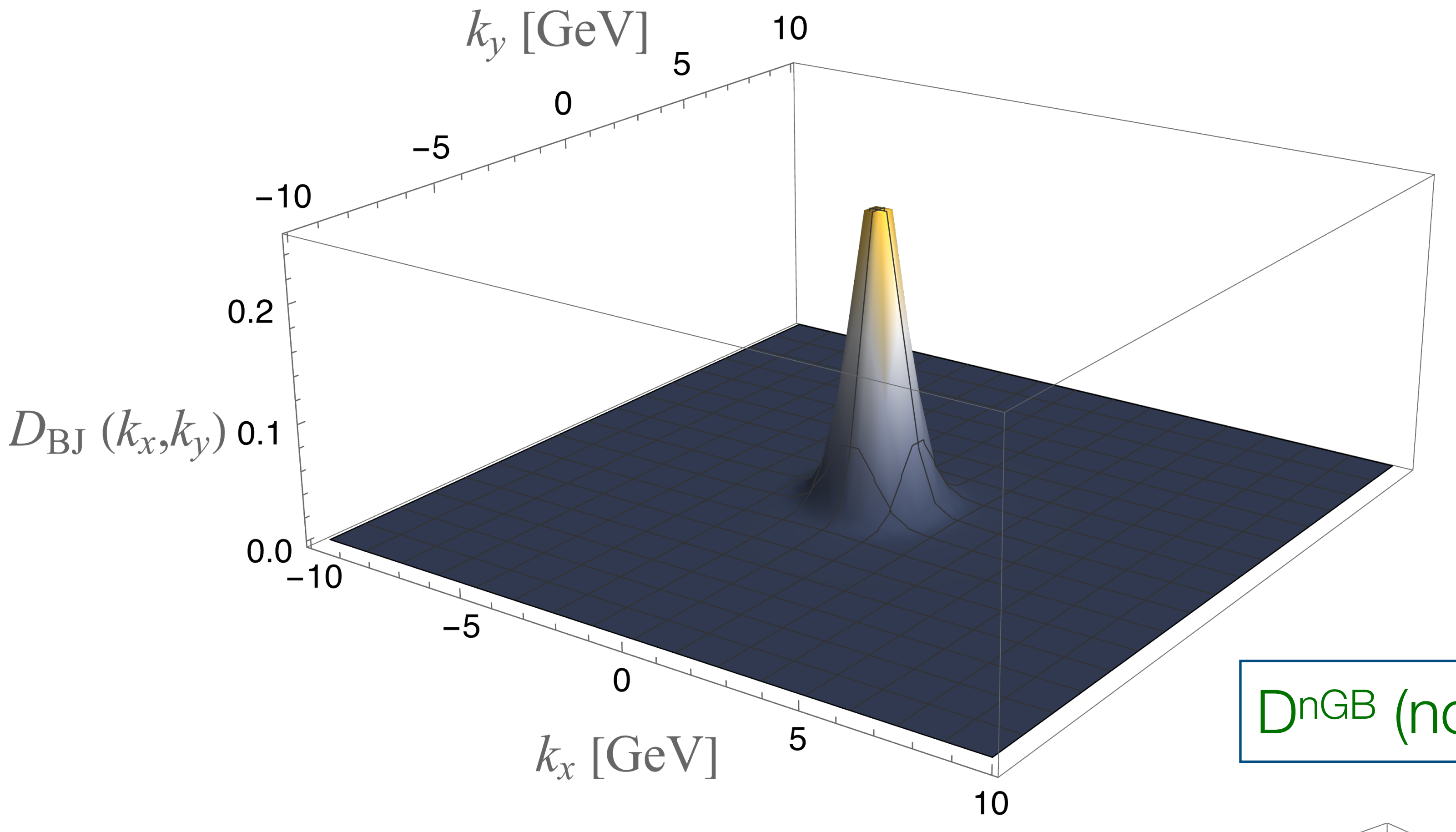
S. P. A. , K. Kutak, W. Placek, M. Rohrmorser, K. Tywoniuk (in preparation)



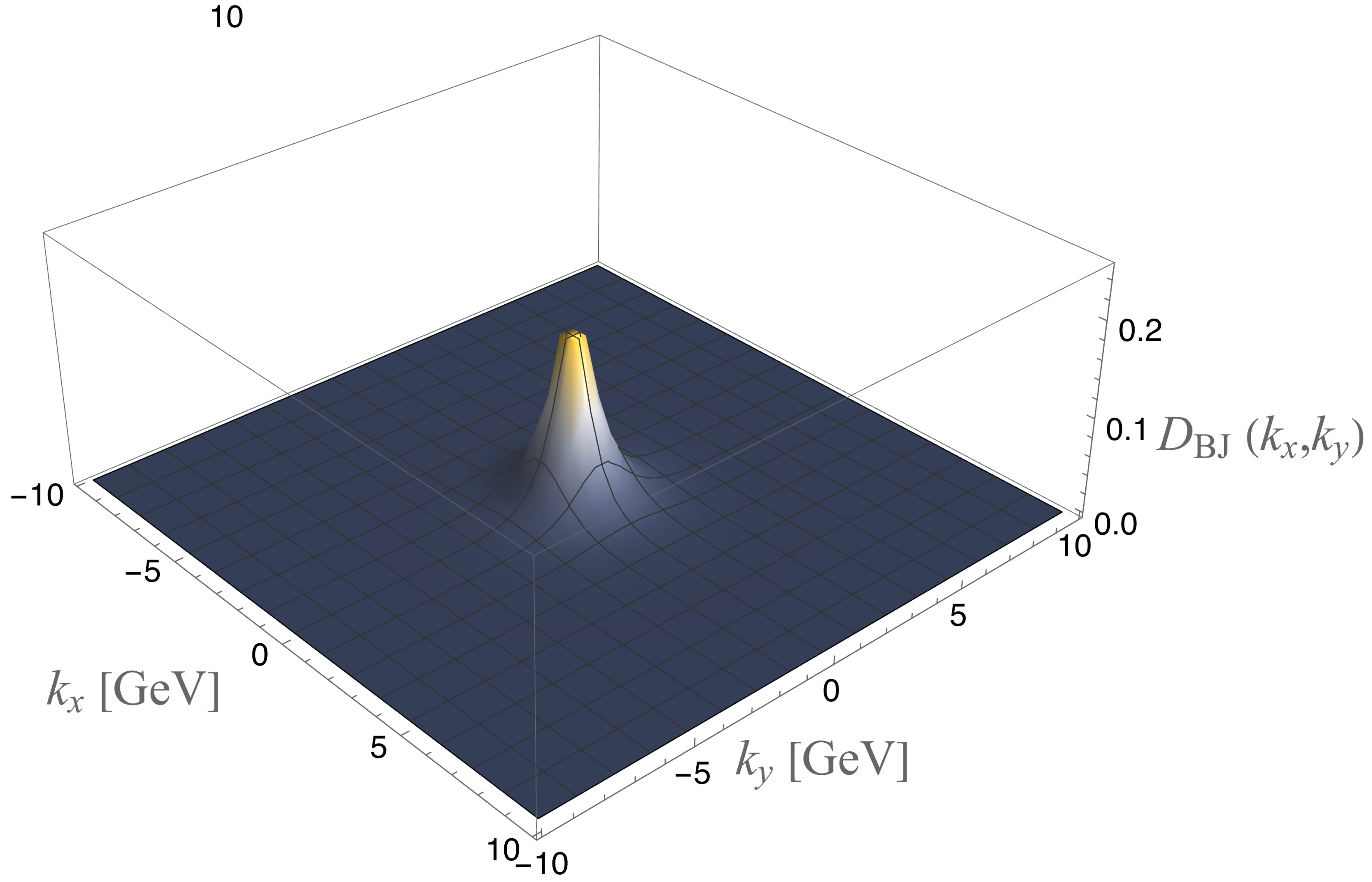
Total evolution = 4 fm, $t_0$ (early) = 0.45 fm, $t_0$ (late) = 2 fm

**Bjorken medium (*early* quenching)**

$D^{eGB}$ (effective broadening)

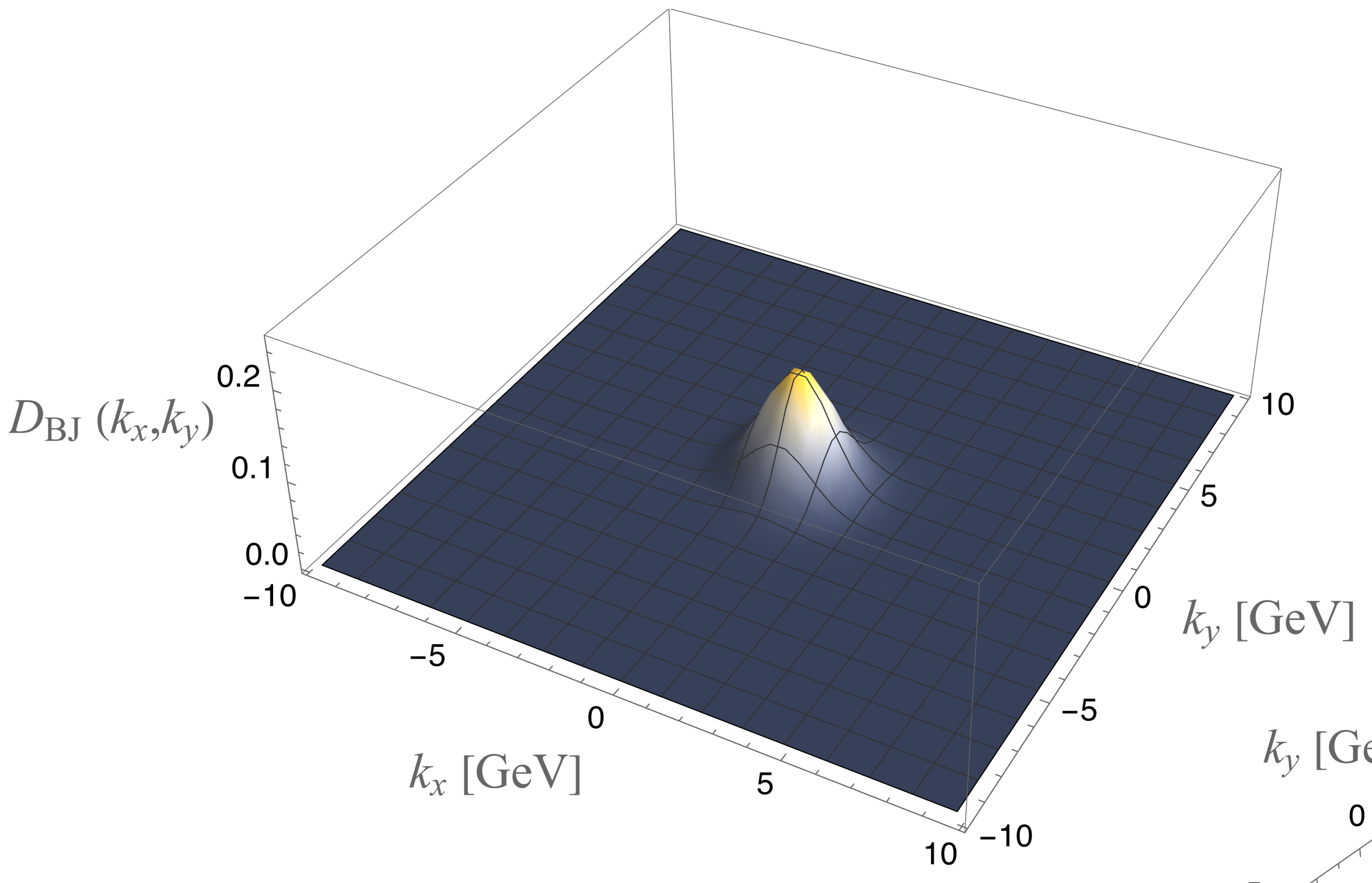


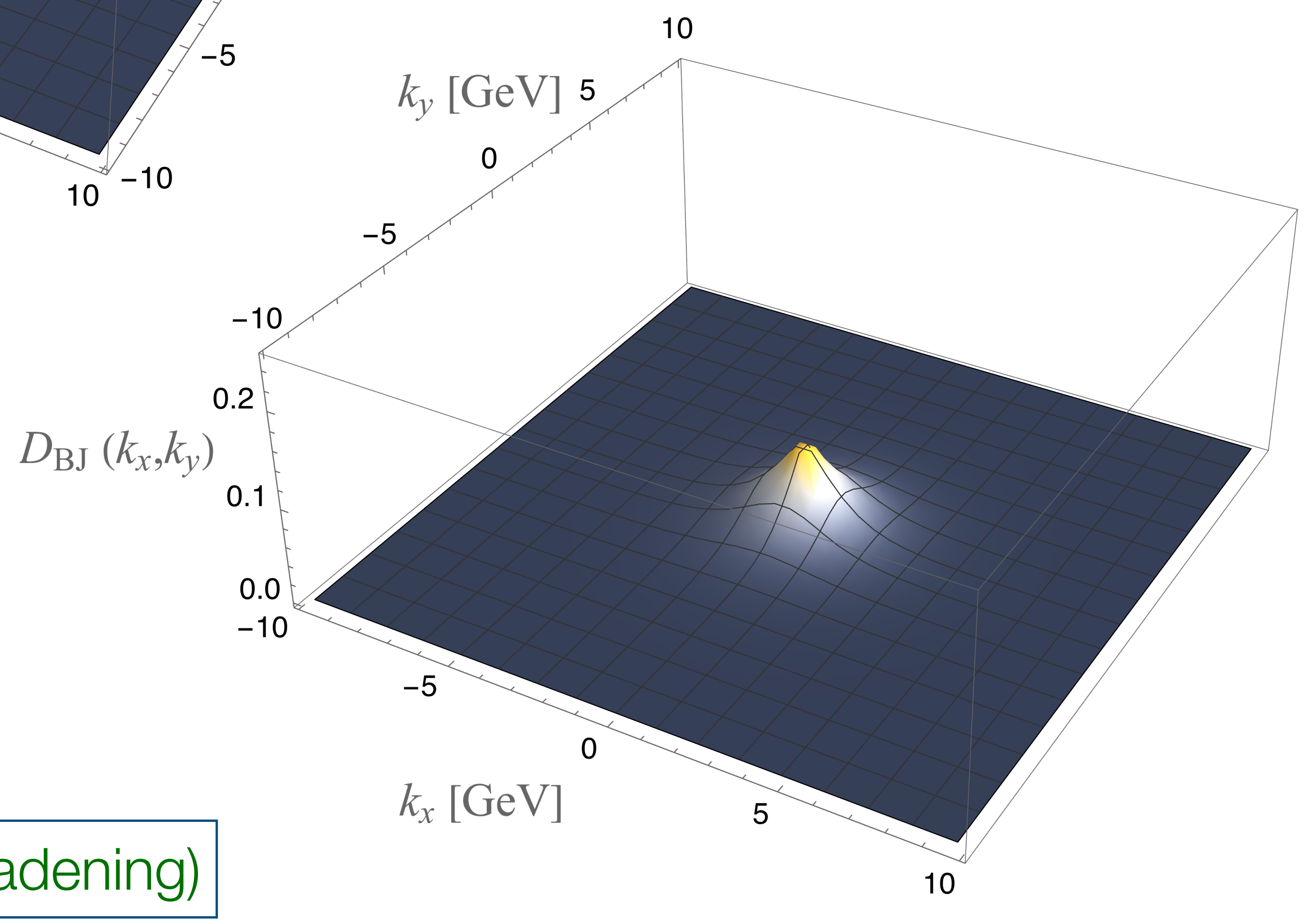

$D^{nGB}$ (non- Gaussian broadening)




**Bjorken medium (*late* quenching)**

$D^{eGB}$ (effective broadening)



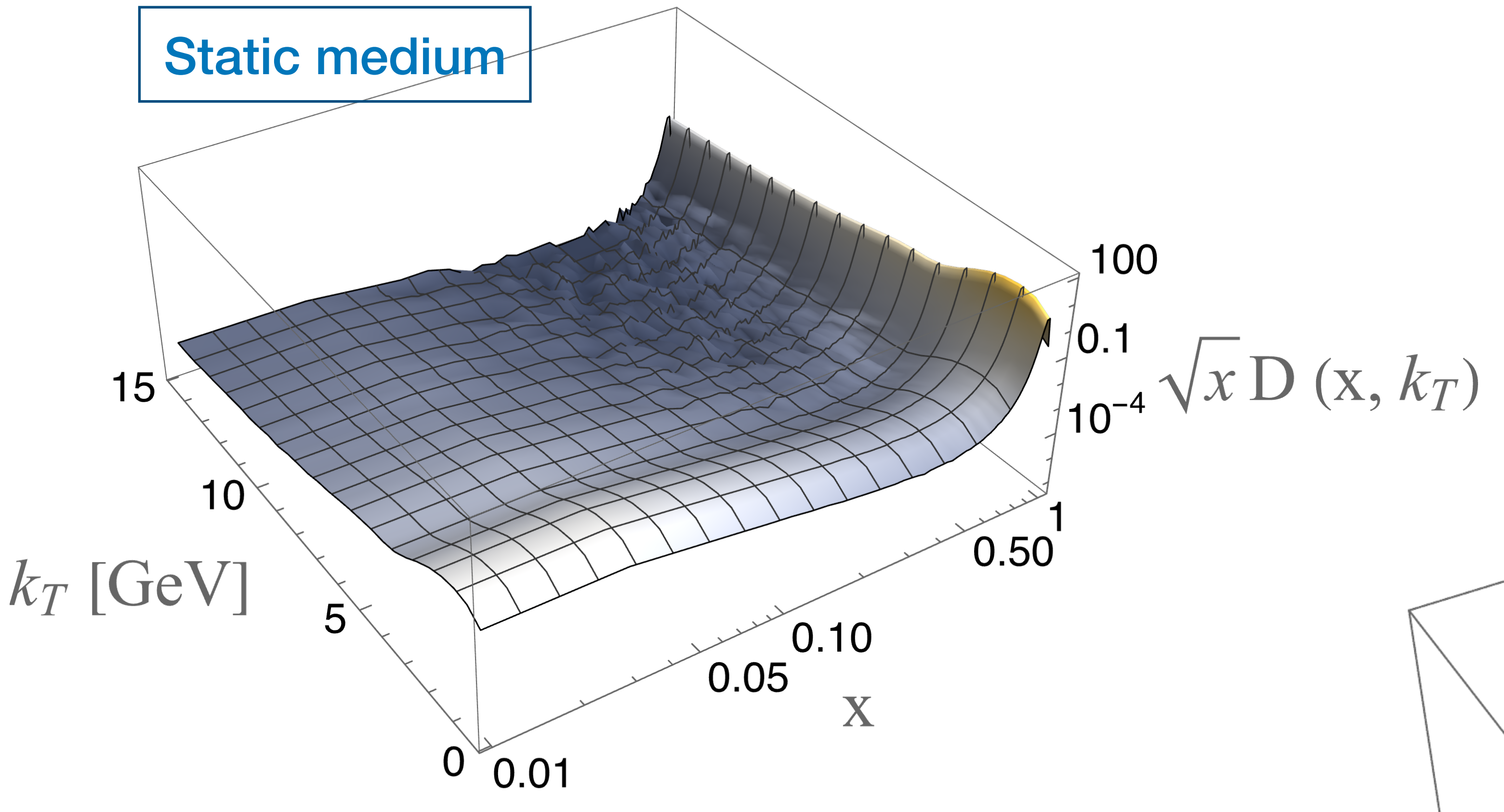

$D^{nGB}$ (non- Gaussian broadening)

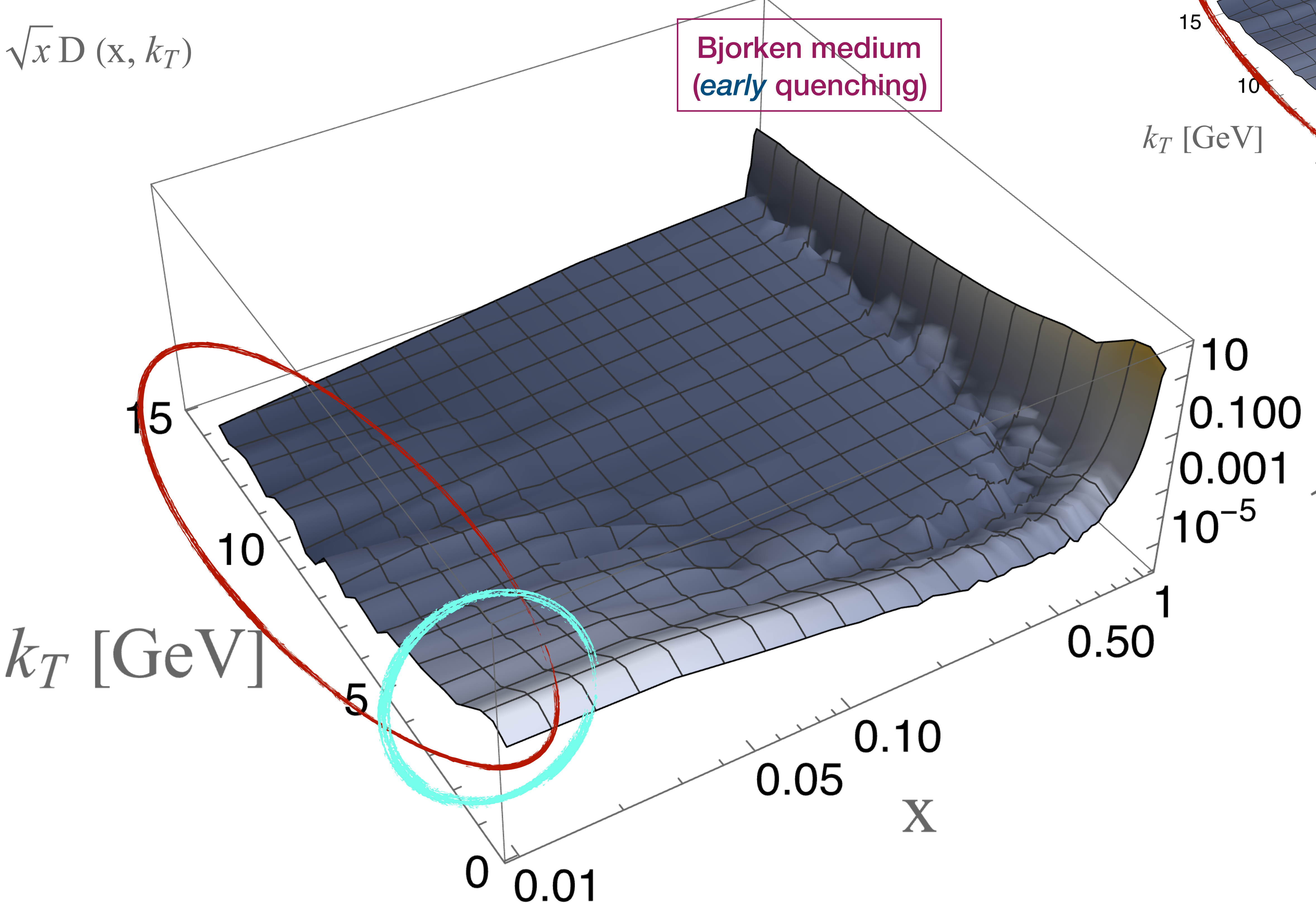
# How does the $k_T$ dependent spectra look like ?

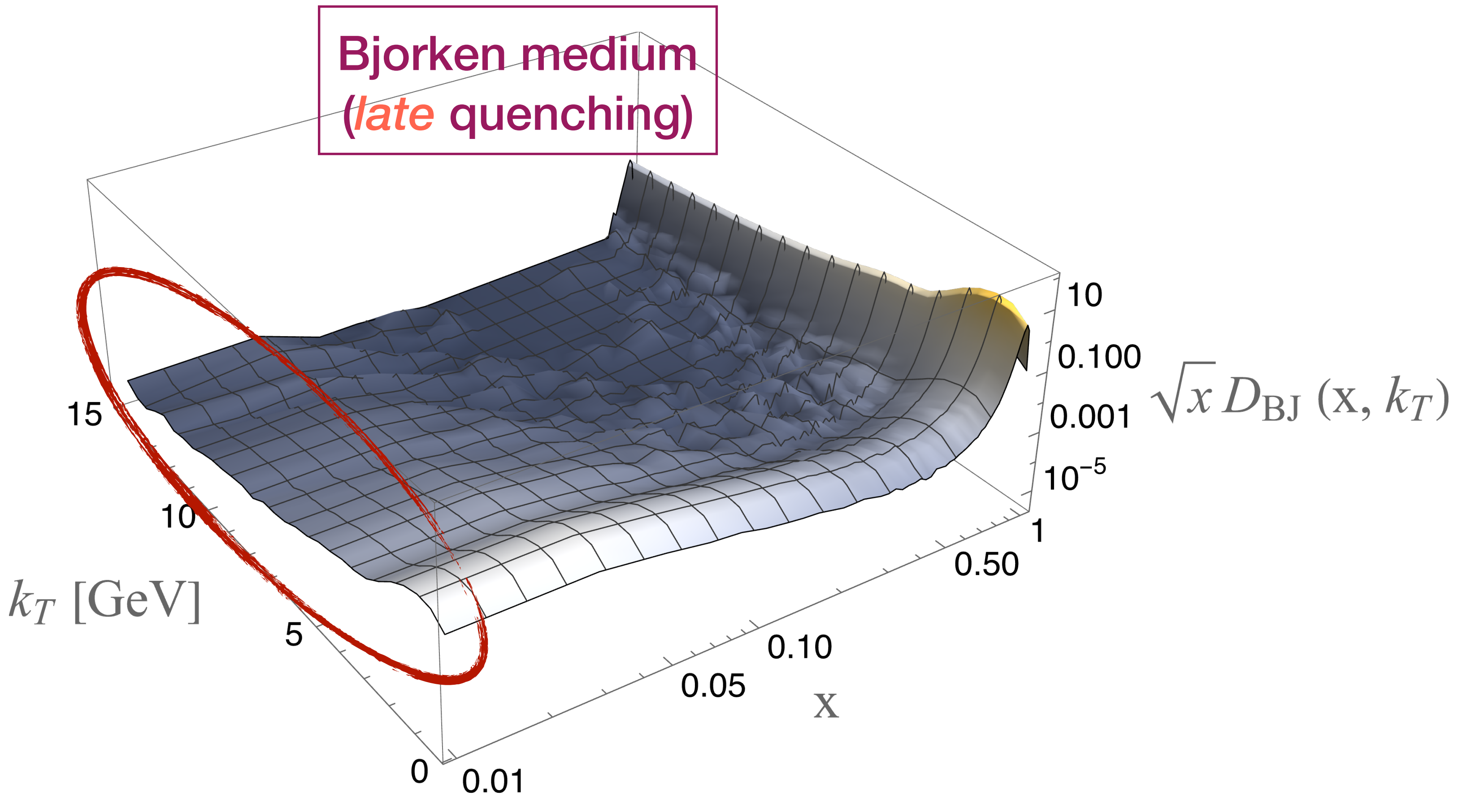
S. P. A. , K. Kutak, W. Placek, M. Rohrmorser, K. Tywoniuk (in preparation)



- Let's compare with the static spectra in x and $k_T$ with the Bjorken media




We can see the behavior at large angle once we rescale $k_T$ —-> xEΘ !

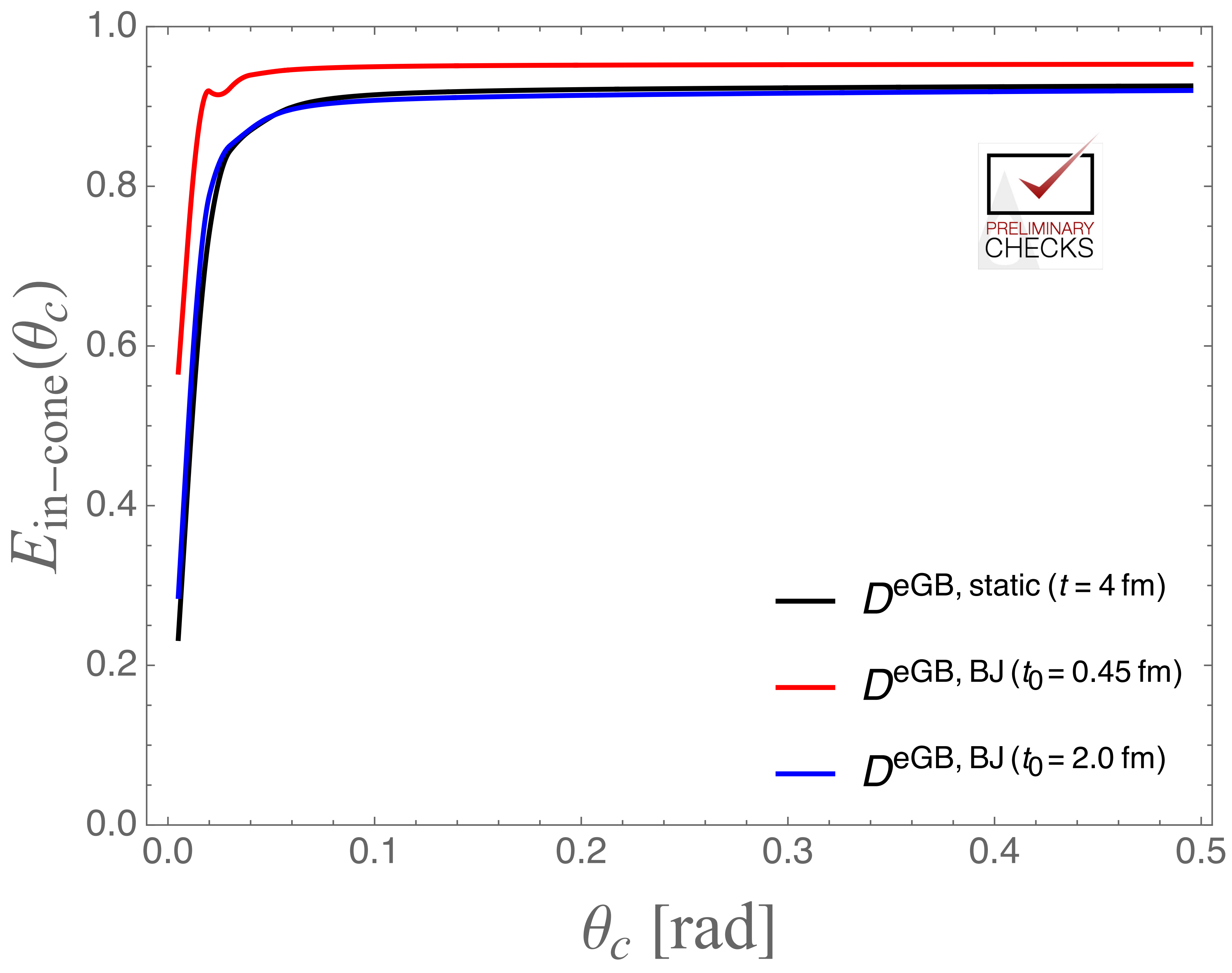
We expect different (and more) soft gluons at large angles among the medium profiles.

# Angular distributions for different medium profiles

S. P. A. , K. Kutak, W. Placek, M. Rohrmorser, K. Tywoniuk (in preparation)



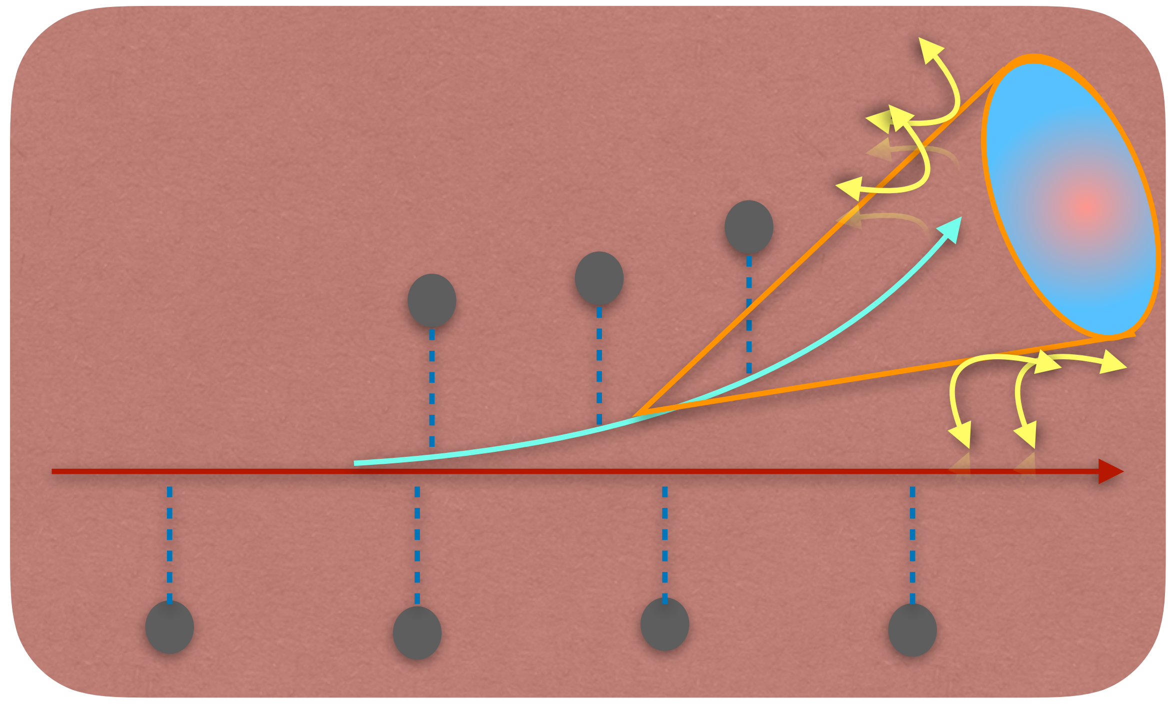
One can estimate the fraction of the parent gluon (jet) energy that is contained within a cone of size Θ.




- Most of the energy is contained in a small cone.
- More in cone energy, more is the parton collimated.

$$E_{\text{in-cone}}(\Theta) = \int_0^1 dx D(x, L) \left[1 - \exp\left(-\frac{\Theta^2}{\langle\theta^2\rangle}\right)\right]$$

$$\langle\theta^2\rangle = \langle k_\perp^2\rangle/(xE)^2$$

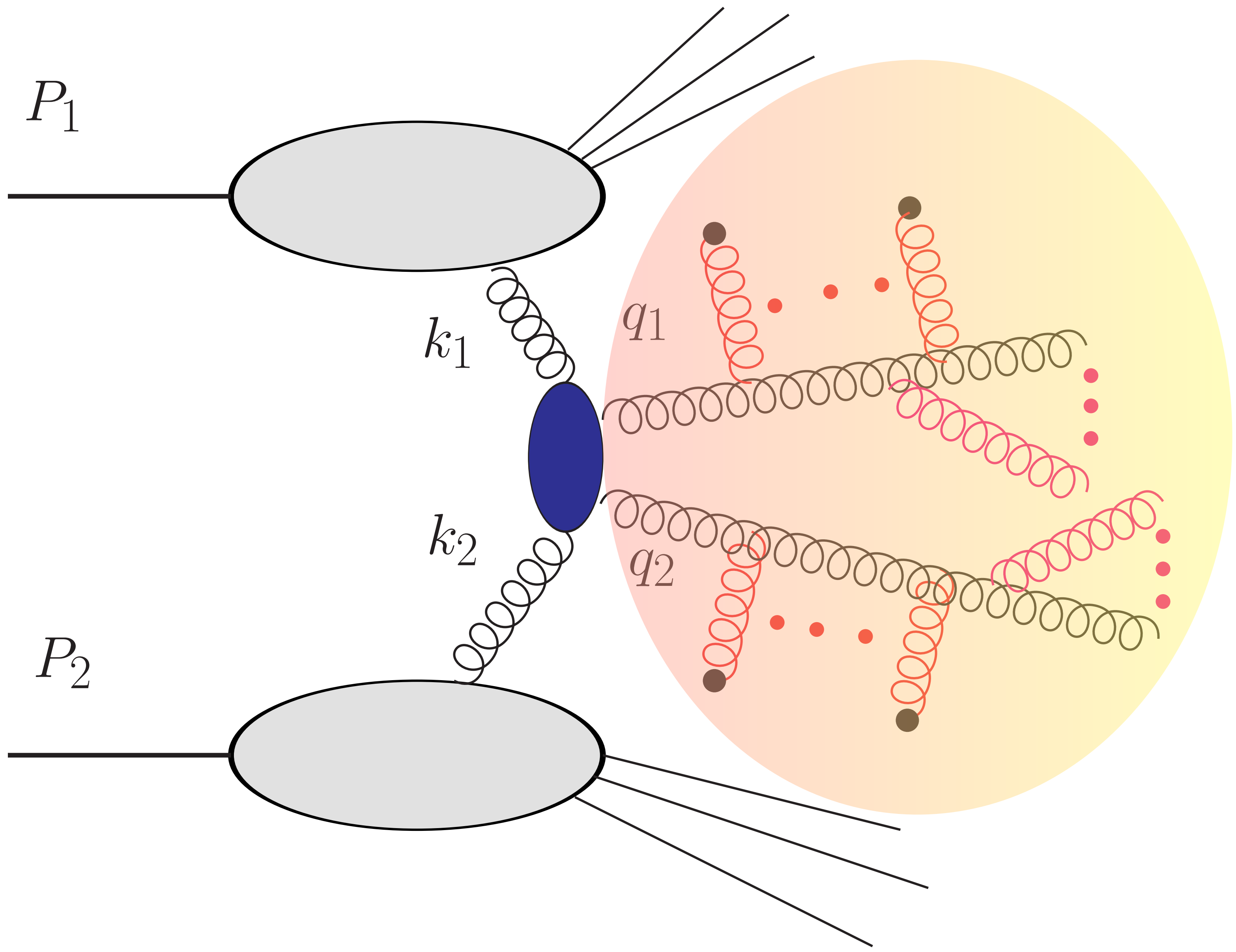


(Static media) A. v-H , K. K, W. P. , M. R., K.T., PRC 102 (2020) 044910.

# Take home messages and Scopes ?

S. P. A. , K. Kutak, W. Placek, M. Rohrmorser, K. Tywoniuk (in preparation)

Pic courtesy : K. Kutak




- For the Bjorken expansion, the medium evolved spectra as well as quenching factors are still sensitive to the onset of quenching through the ratio ($t_0$/L), which spoils the universal scaling features.
- Rapidity dependence of the inclusive jet suppression is not very sensitive to the way how the medium expands.
- Jet $v_2$ is sensitive to the medium expansion with difference in initial starting time of expansion.
- Exploring the $k_T$ *dependent cascades* and its role on observables for an *expanding medium*.

Dynamically groomed jets:
Adam's talk, today, 12:00 pm

Heavy flavor jets:
Kara's talk, today, 12:50 pm

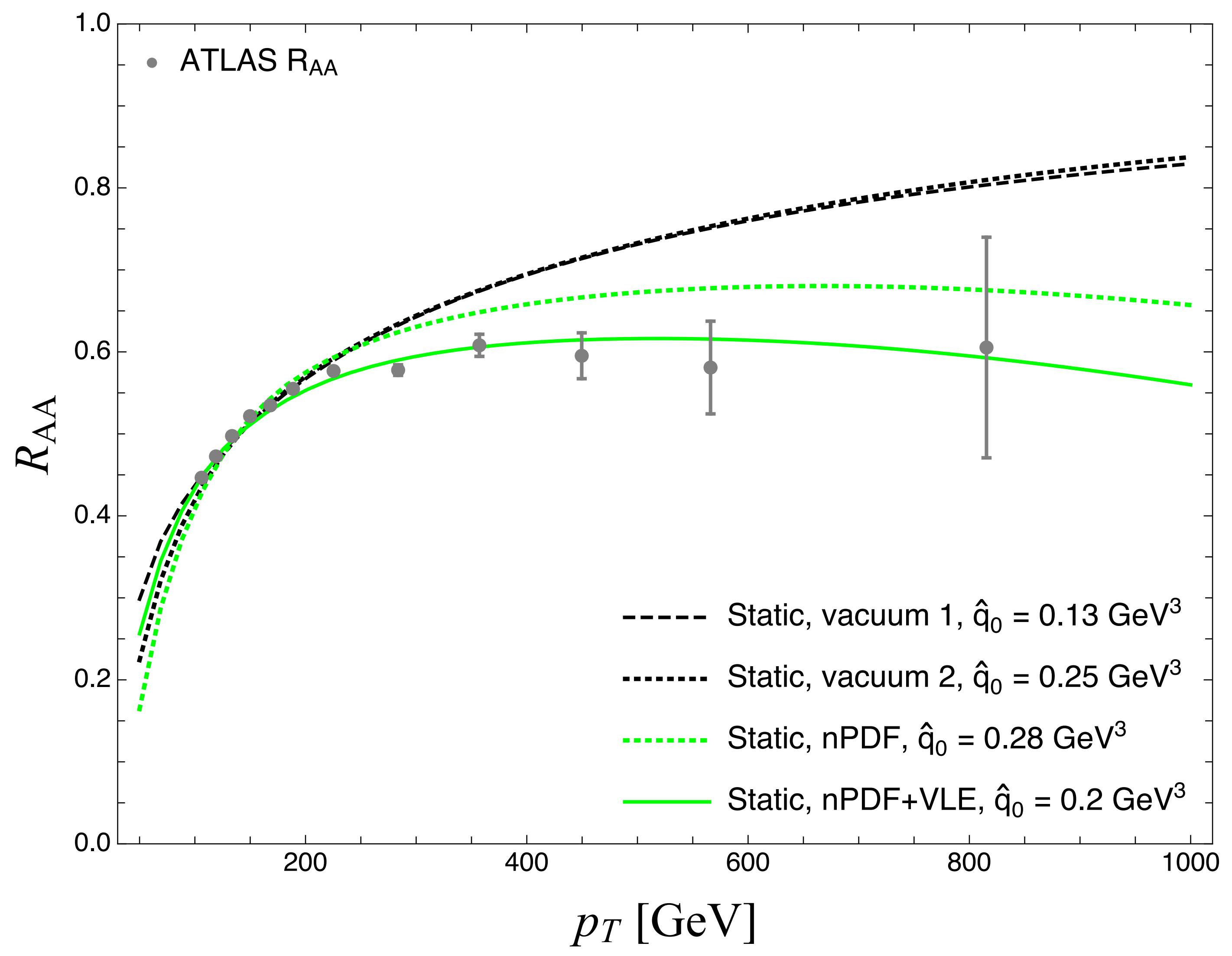
*Thanks !*

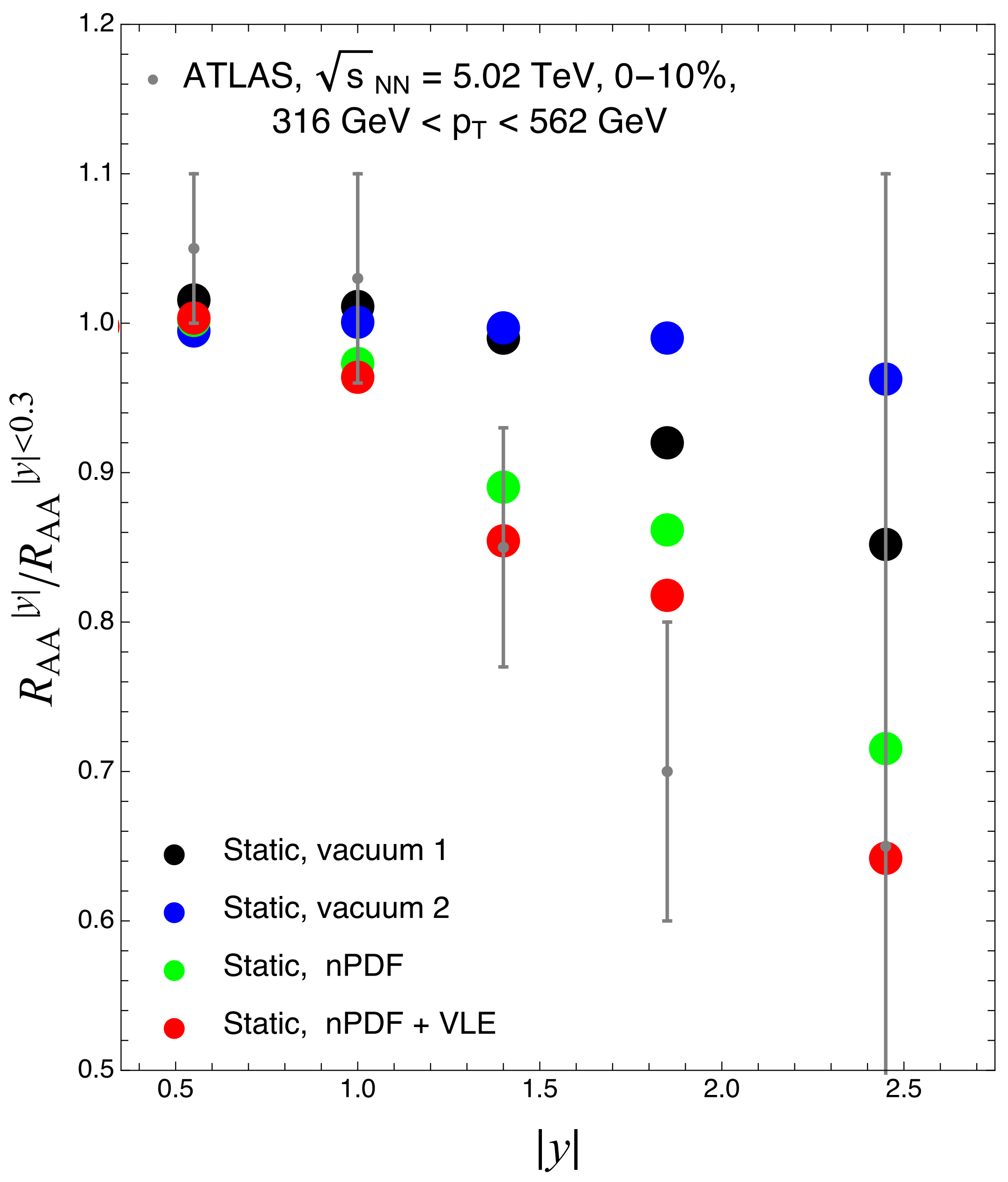
*Complexity/ Completeness towards understanding* →

BACKUP

# Effects of nPDF and VLE

S. P. Adhya, C. Salgado, M. Spousta, K. Tywoniuk, EPJC 82 (2022) 1.




- Vacuum like emissions (VLE) :

Phase space for VLE : $$\Pi_{\text{in}} = 2\frac{\alpha_s C_i}{\pi}\int_{R_{\text{min}}}^{R}\frac{d\theta}{\theta}\int_{k_{\perp,\text{min}}}^{p_T\theta}\frac{dk_\perp}{k_\perp} = \frac{\alpha_s C_i}{\pi}\ln\left(\frac{R}{R_{\text{min}}}\right)\ln\left(\frac{p_T^2 R\, R_{\text{min}}}{k_{\perp,\text{min}}^2}\right)$$

$$R_{\text{min}} = \max[\theta_c, \theta_d] \text{ and } k_{\perp,\text{min}} = \max[Q_s(L), Q_0]$$

Collimator function : $$\mathcal{Q}_i(p_T, R) = \mathcal{Q}_i^{(0)}(p_T)\exp\left[\Pi_{\text{in}}\left(\mathcal{Q}_g^{(0)}(p_T) - 1\right)\right]$$

- Effect of VLE : Increase of the quenching.

- Effect of nPDF : Flattening at high $p_T$.

| Quenching parameter ($\hat{q}$) | Static (soft) | Static | Expo | Bjorken $t_0 = 0.1$ fm |
|---|---|---|---|---|
| $\hat{q}_0$ (nPDF+VLE) [GeV$^3$] | 0.15 | 0.2 | 0.08 | 1.8 |
| $\hat{q}_0$ (gluon-only) [GeV$^3$] | 0.20 | 0.2 | 0.09 | 2.6 |

Configurations:

Vacuum 1 = Input parton spectra, PYTHIA8.185+AU2+CT10 PDF.
Vacuum 2 = PYTHIA 8.306 (default).
nPDF = PYTHIA 8.306 (default), EPS09LO nPDF.
nPDF + VLE = PYTHIA 8.306 (default), VLE.

Comparison of "nPDF" and "nPDF+VLE" configuration implies that adding VLE to the calculation has an important impact on both the shape of $R_{AA}$ and its overall normalization which has an impact on the extracted values of $\hat{q}$.

# ATLAS measurements