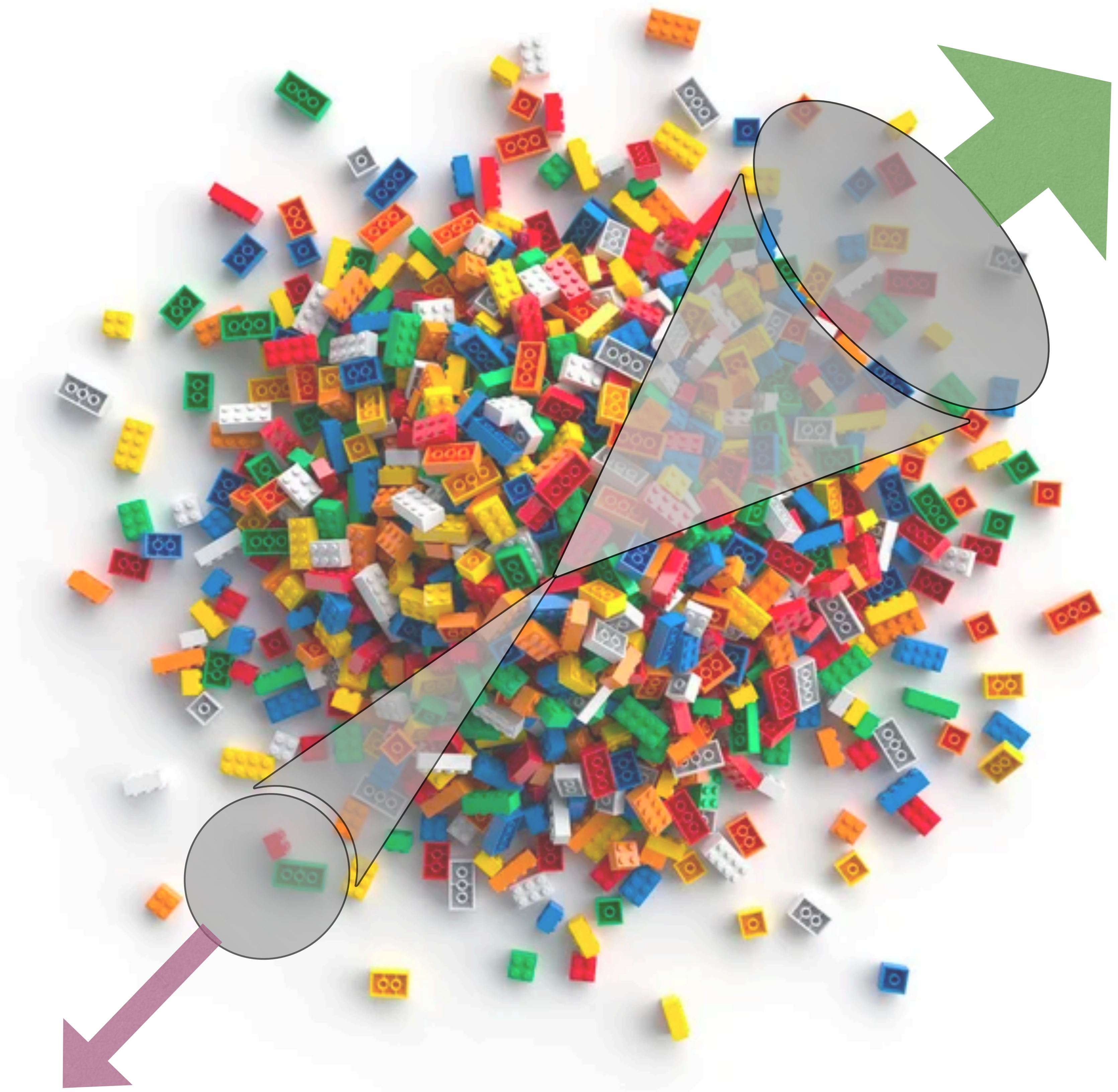

Transverse momentum broadening in expanding medium induced cascades

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ATHIC2023
Hiroshima, Japan

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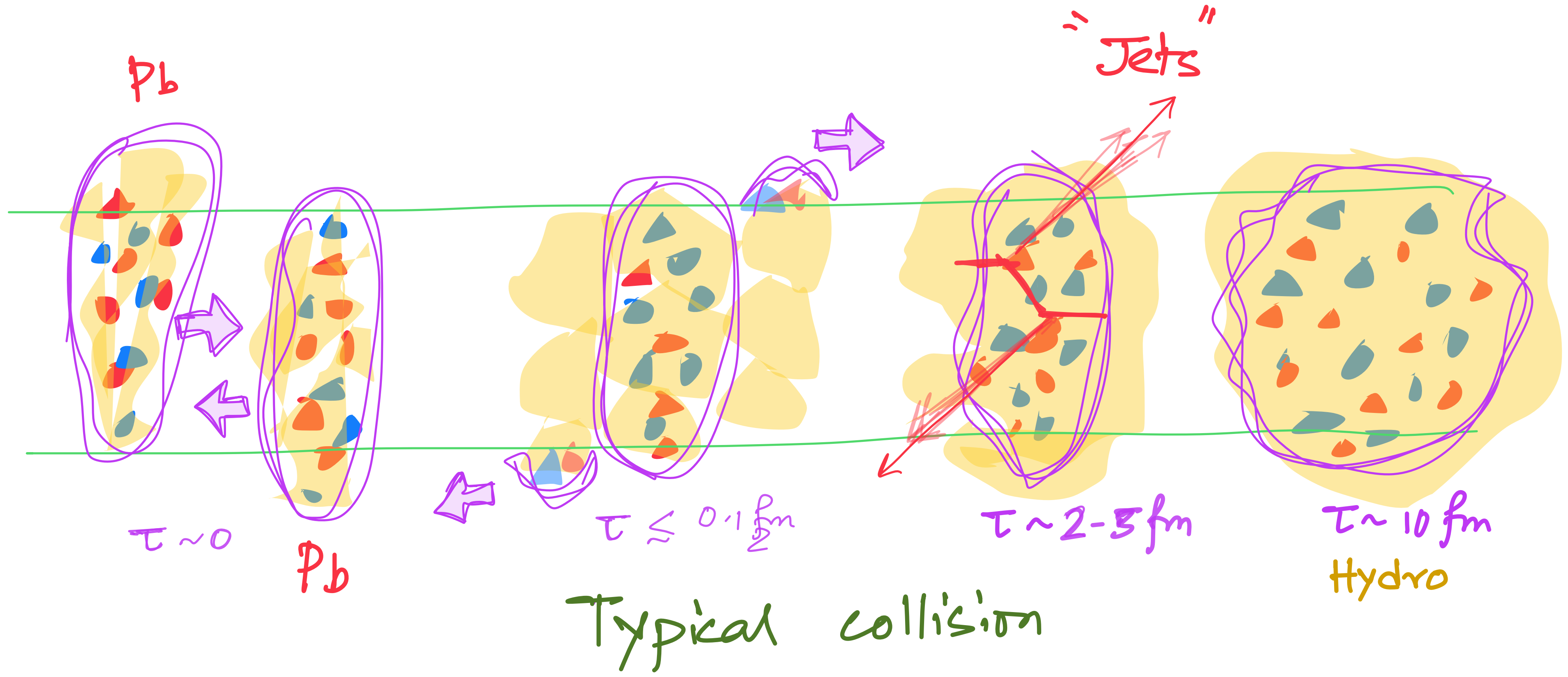
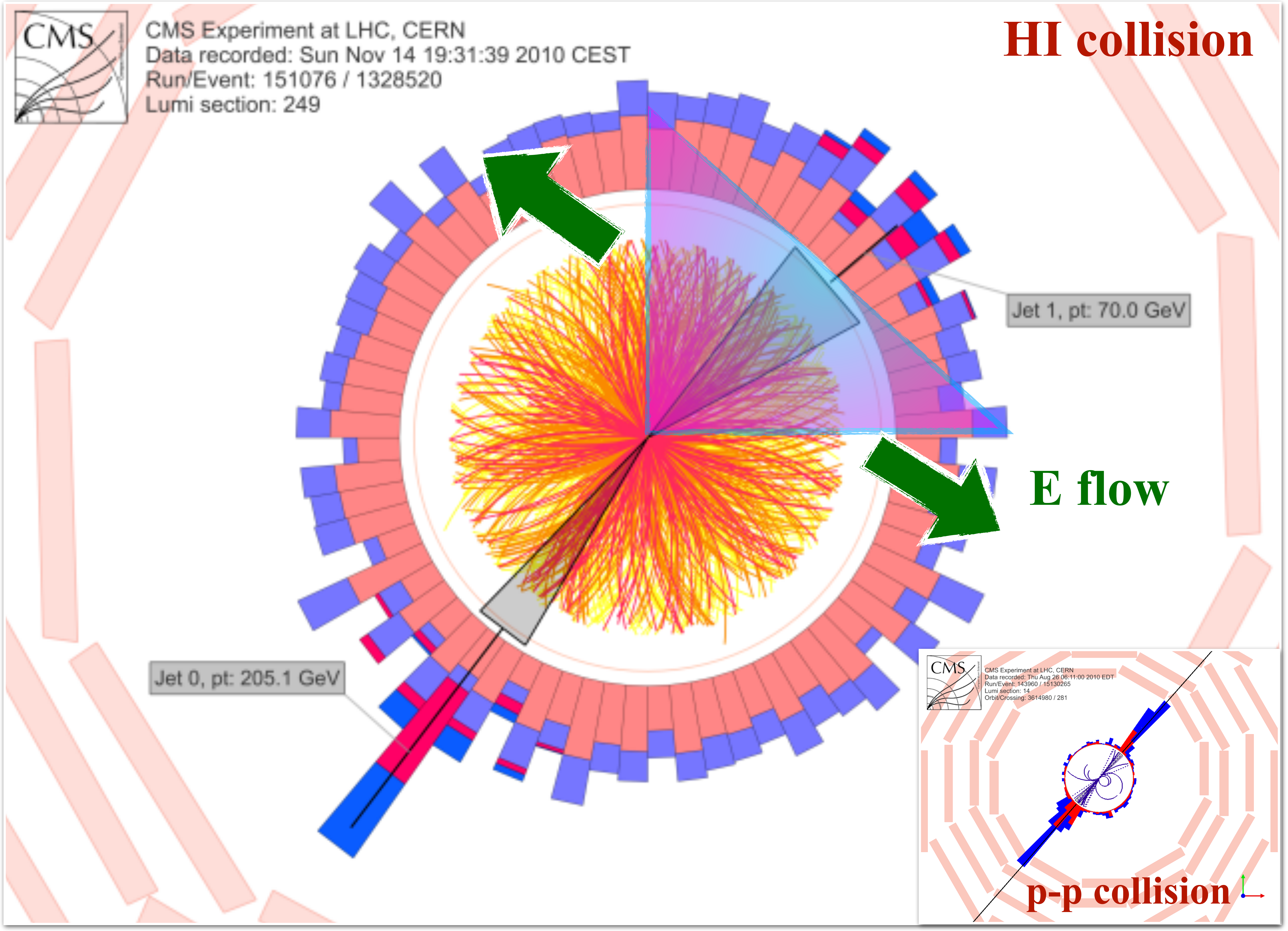
Introduction to jet quenching

- A Jet is an energetic and collimated bunch of particles produced in a high-energy collision.
- Jets are extended objects, ideal to study *space time evolution*.
- *energy is lost* in soft particles at large angles.





Vacuum vs medium induced jets

- Vacuum picture :

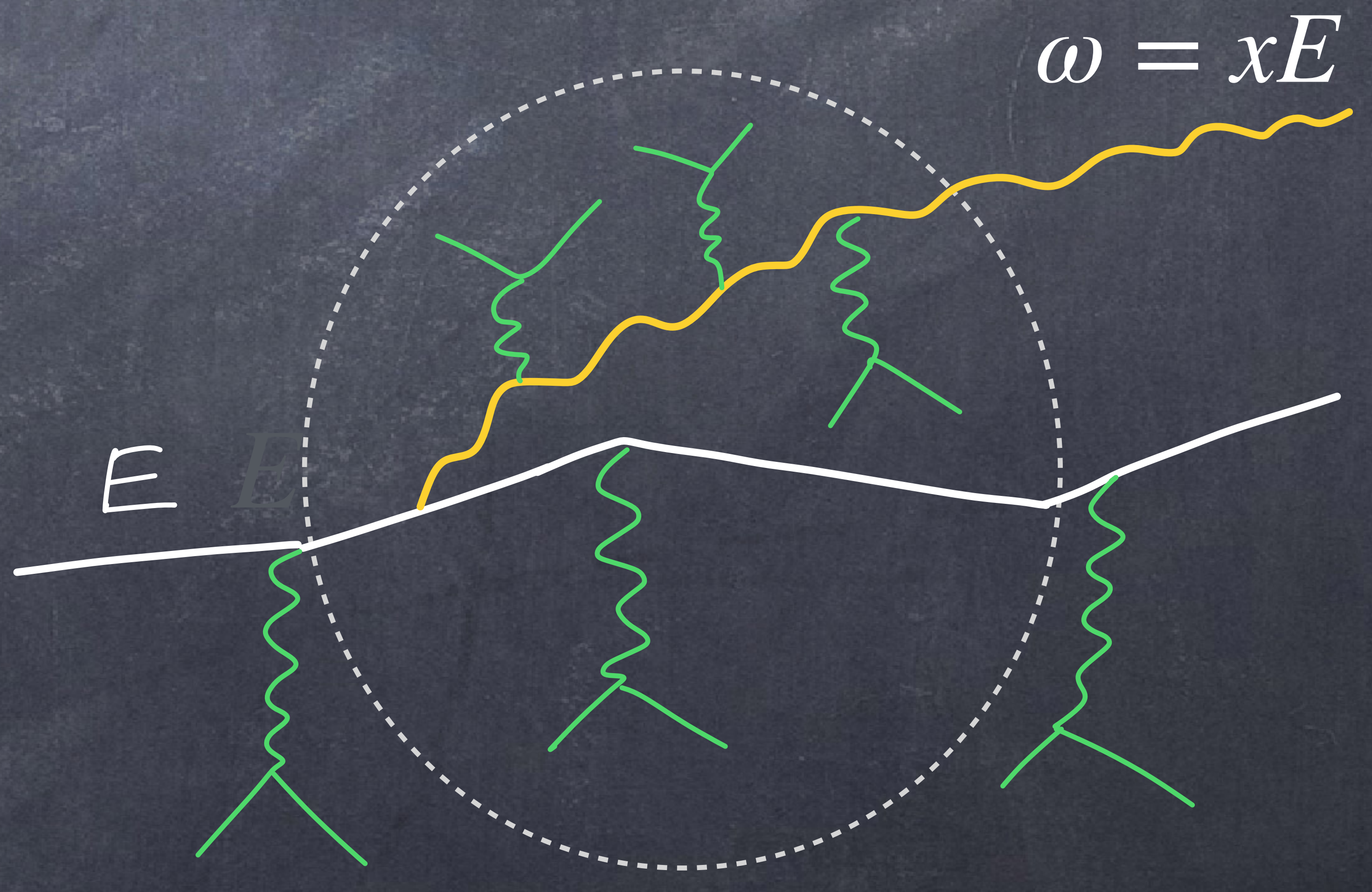
1. Jets originate from energetic partons that successively branch (similarly to an accelerated electron that radiates photons).
3. Diverges for ***soft*** and ***collinear*** radiation.
4. Successive branchings are ordered from larger to smaller angles.

$$dP = \alpha_s C_R \frac{d\omega}{\omega}\frac{d\theta}{\theta}$$

Jets in the QGP: Multi-scale problem !

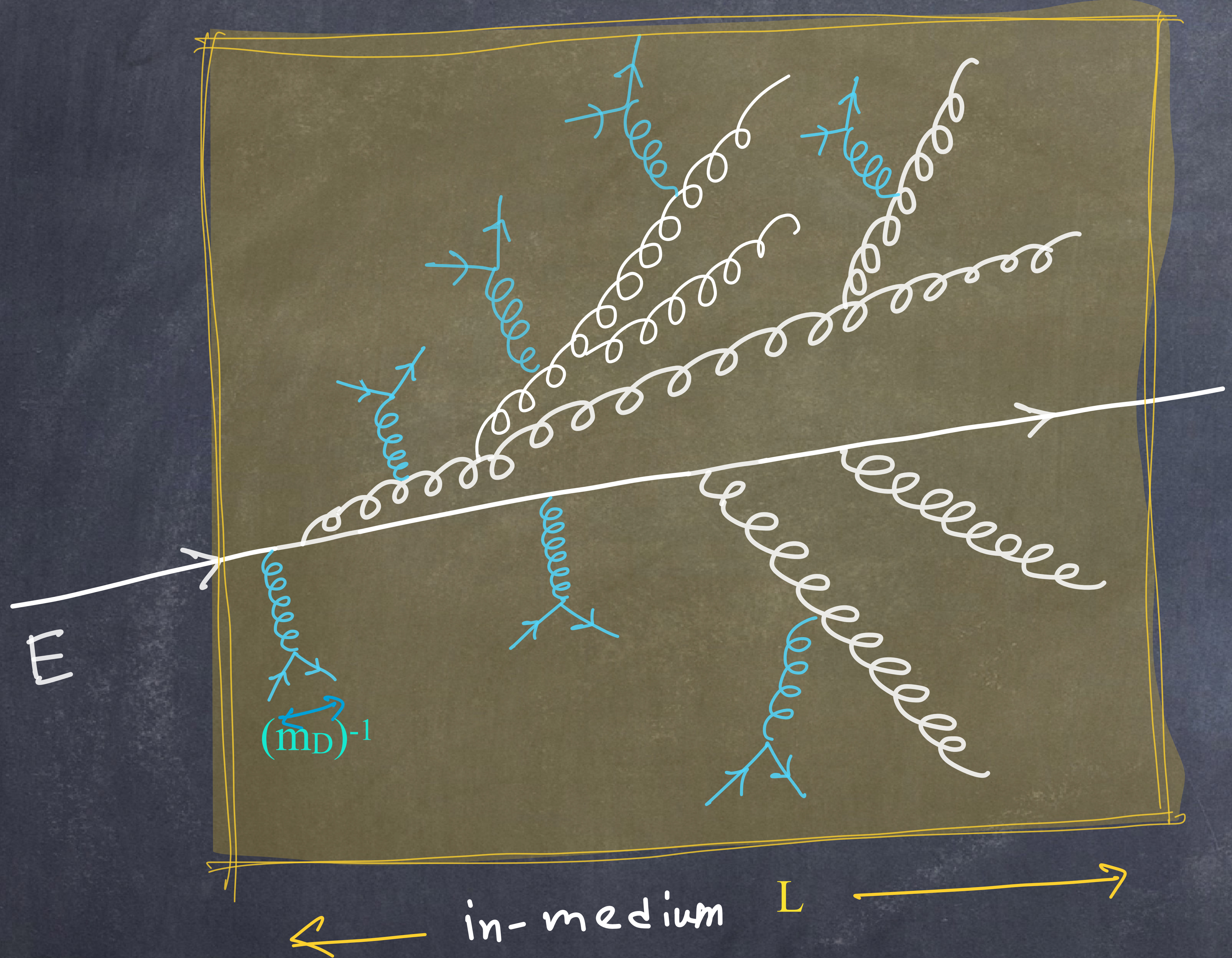
- Medium picture :

- Many interactions occur during the formation of a soft gluon.
  - LPM suppression of small angle radiation.
- No collinear divergence!
- In QCD: formation time of gluons decrease with energy decrease!



$$\longleftarrow \quad t_f = \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}} \quad \longrightarrow$$

Setting up the picture



Propagation of a fast parton
in dense medium

Branching Scattering

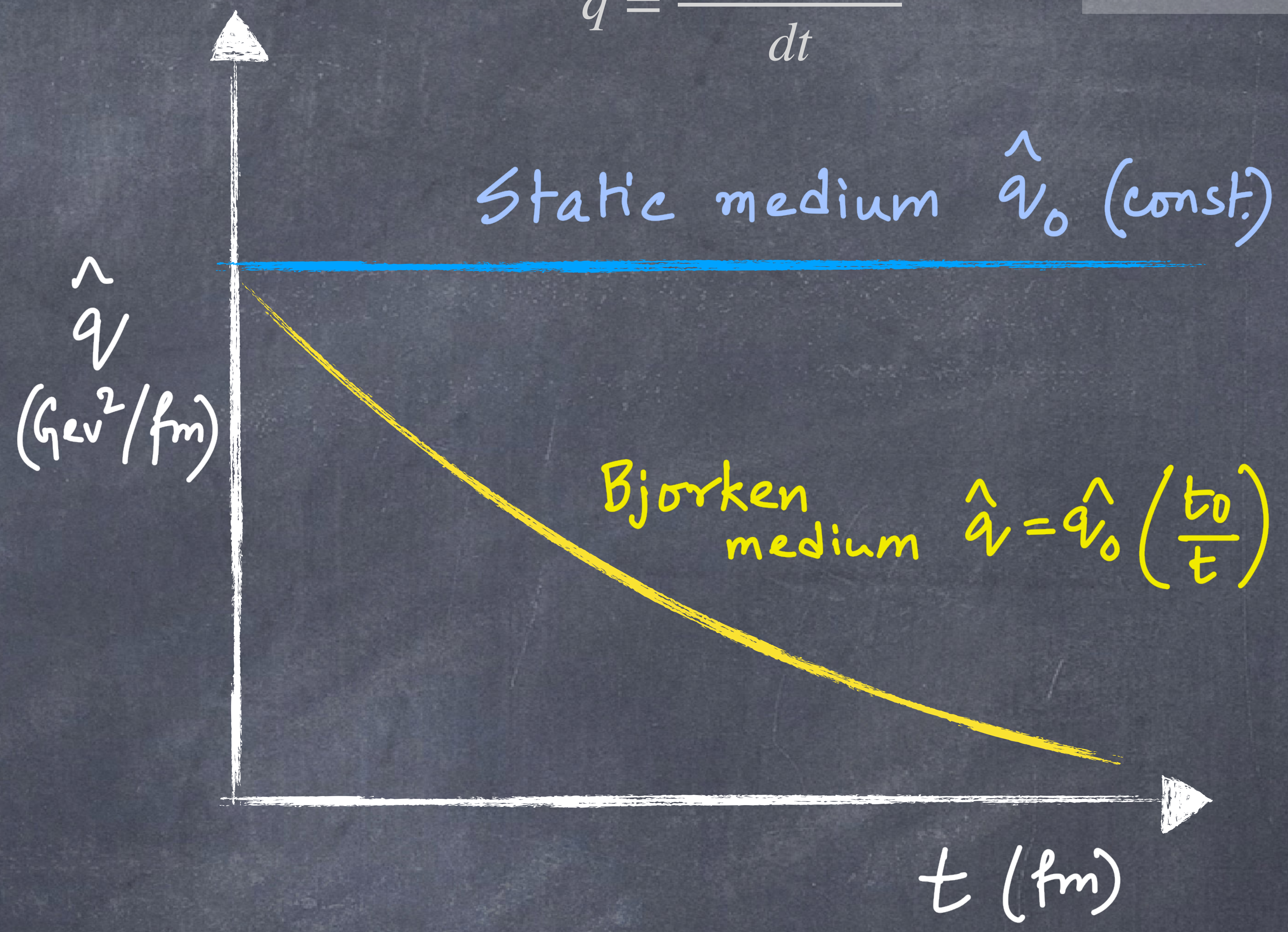
Dynamical picture

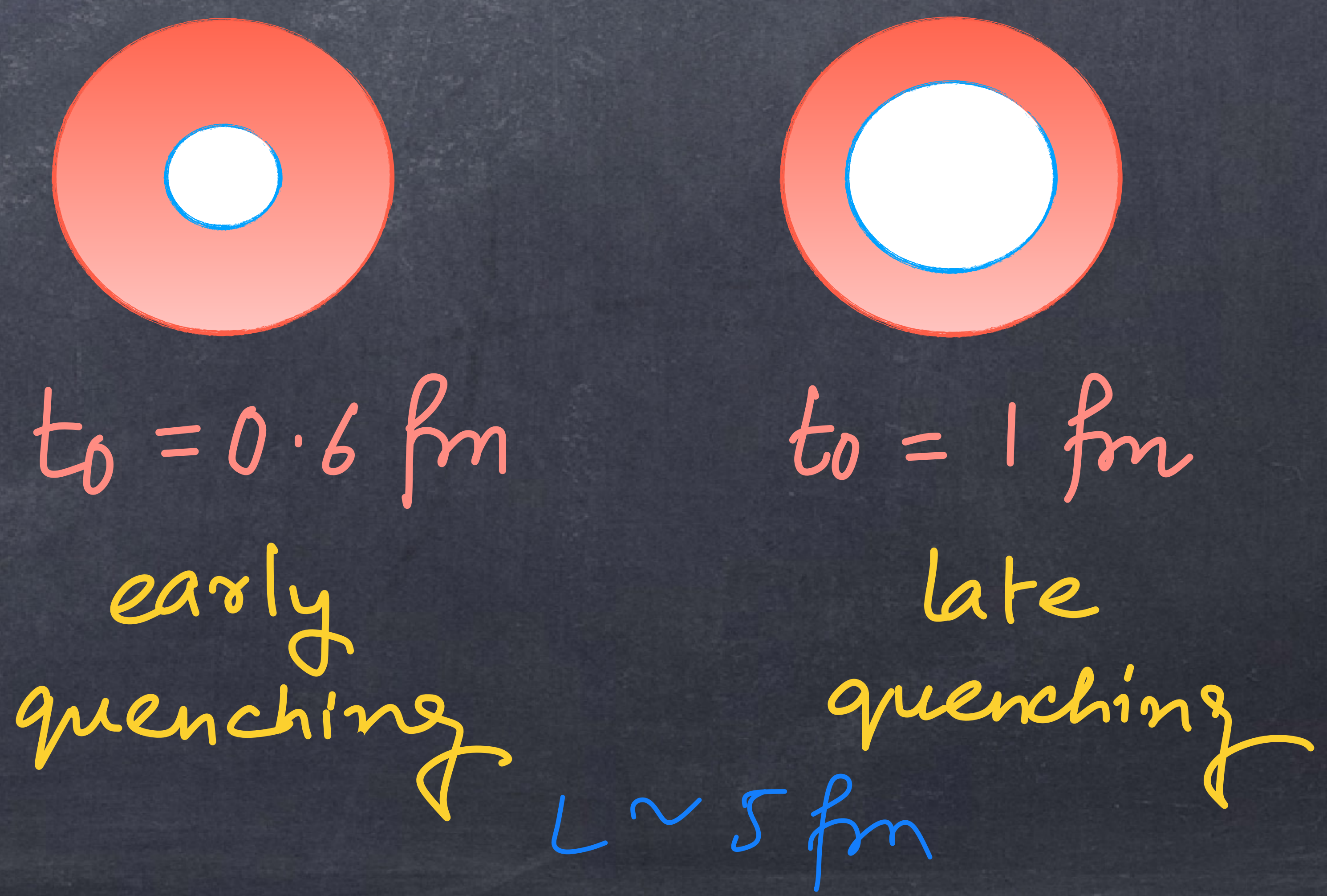
Information on "soft" and "hard"
gluons in angular space?

What's new here ?

- Inclusion of finite medium size effects.
- Expanding medium with varying time for the onset of the quenching.
- Scaling relations in effective lengths between expanding and static medium profiles, successful in describing R_{AA} *and* v_2 *of jets* with *sensitivity* to medium expansions recently.
- Exploratory study of hard and soft jets in angular regions.

$$\hat{q} = \frac{d < k_T^2 >}{dt}$$





Adhya, Kutak, Placzek, Rohrmoser, Tywoniuk, 2022
Adhya, Salgado, Spousta, Tywoniuk 2022.
Adhya, Salgado, Spousta, Tywoniuk 2020.

Single gluon emission spectra

- The *single* gluon emission spectra in BDMPS-Z* formalism are given as :

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

$$\frac{dI^{static}}{d\omega} \propto \frac{\alpha_s}{\pi}P(z)Re\log(\cos(\Omega_0 L))$$

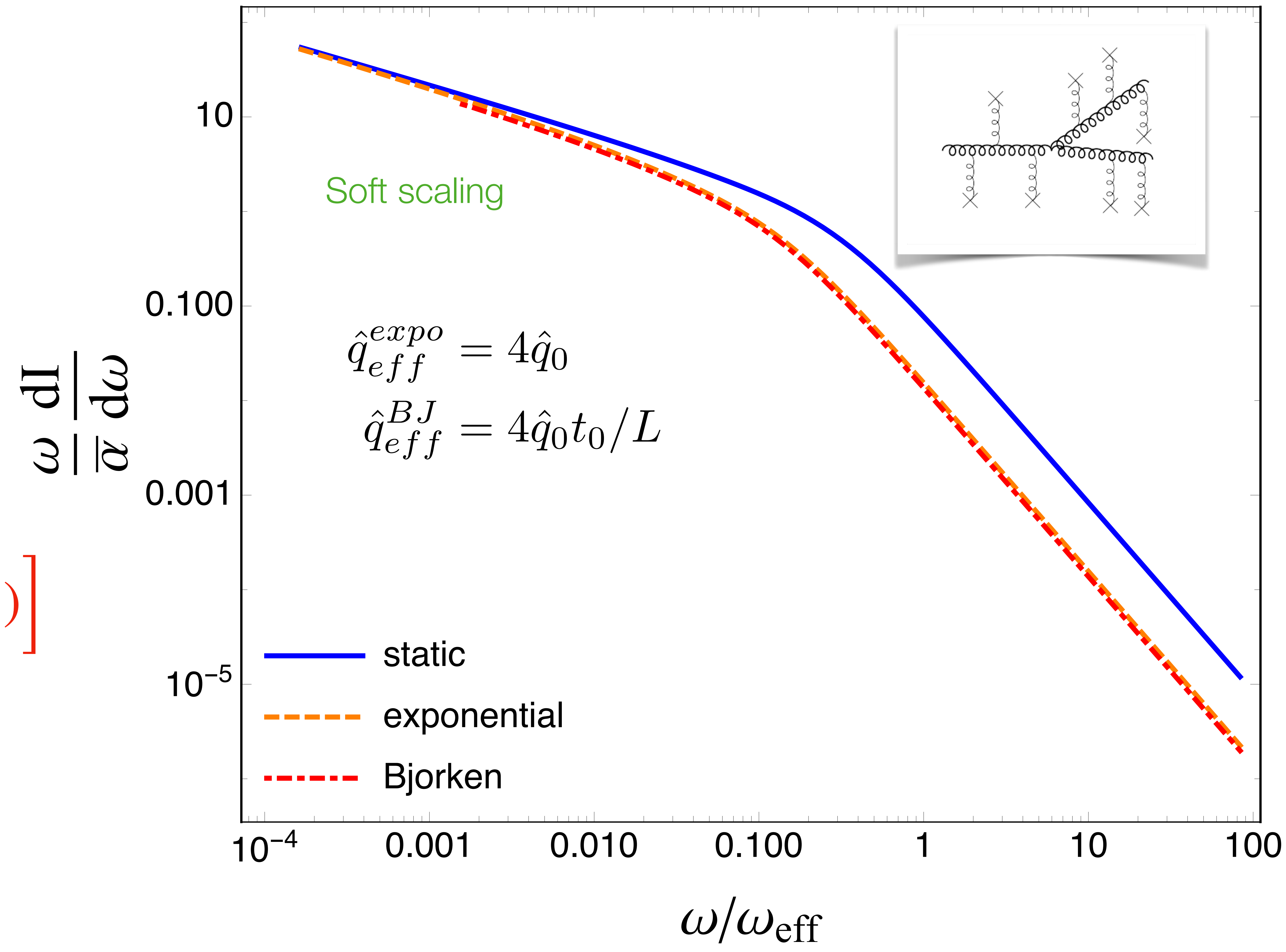
$$\frac{dI^{BJ}}{d\omega} \propto \frac{\alpha_s}{\pi}P(z)Re\log\left[\left(\frac{t_0}{L+t_0}\right)^{1/2}(Bessel's \quad fnc.)\right]$$

- *The expanding spectra has finite size dependence.*

$$\kappa(z) = \sqrt{[1-z(1-z)]/[z(1-z)]} \qquad \Omega_0 L = \frac{(1-i)}{2}\kappa(z)\tau$$

Single emission Gluon spectra

$$\tau = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{E}}t \quad \omega_c = \frac{1}{2}\hat{q}L^2 \quad \bar{\alpha} = \frac{\alpha_s N_c}{\pi}$$



Single gluon emission spectrum: Arnold, 2009.

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* Multiple soft scattering approximation

P(z) = Alteralli Parisi splitting functions

In- medium splitting rates

$$\mathcal{K}^{static}(z) \to \mathcal{K}^{expanding}(z,\tau)$$

$$\mathcal{K}(z)^{static,soft} \propto \alpha_s P(z)\kappa(z)$$

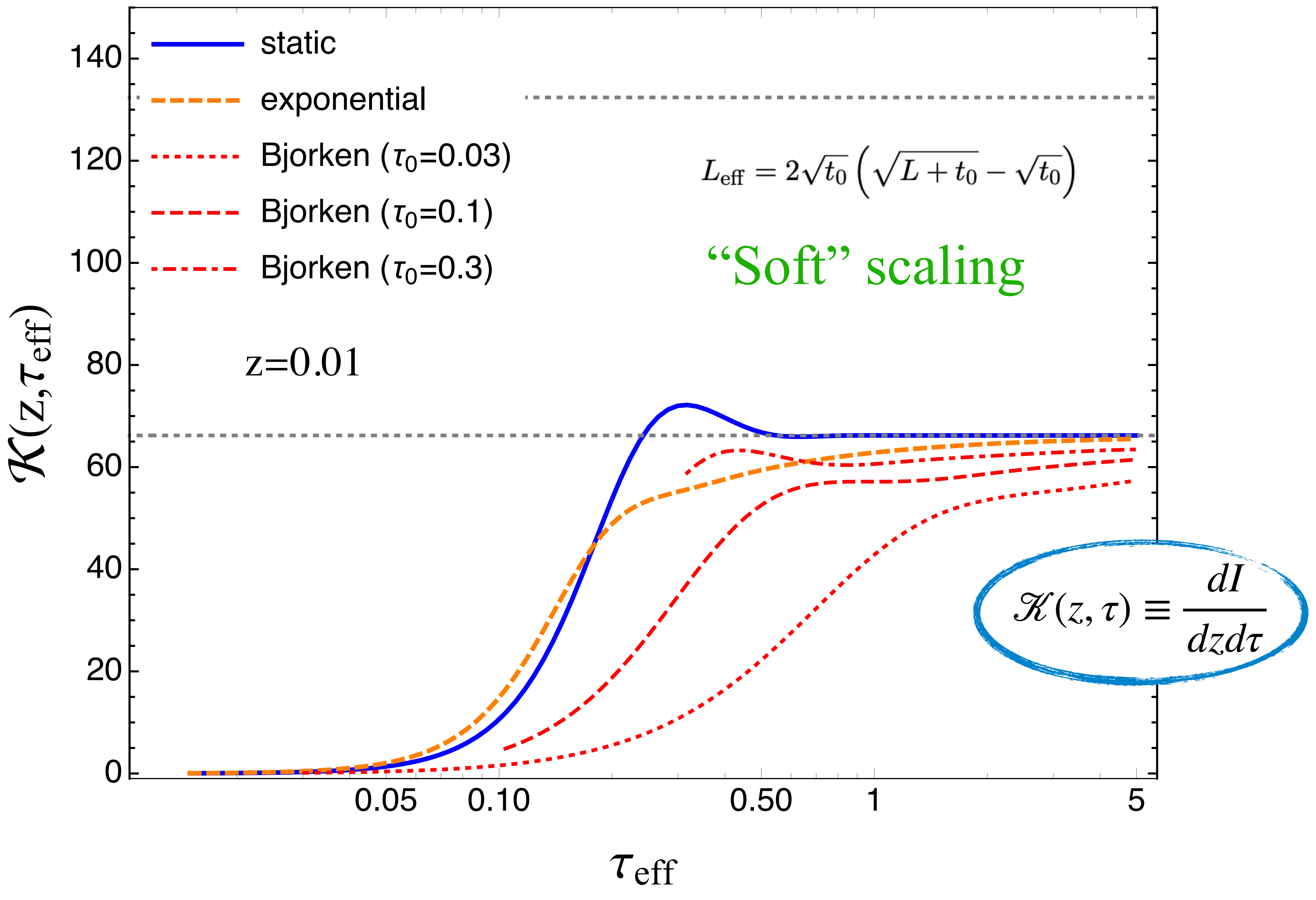
$$\mathcal{K}(z)^{static} \propto \alpha_s P(z)\kappa(z) Re\left[(i-1)\tan\left(\frac{1-i}{2}\kappa(z)\tau\right)\right]$$

$$\mathcal{K}(z,\tau)^{BJ} \propto \frac{\alpha_s}{\pi} P(z)\kappa(z) Re\left[\left(\frac{\tau_0}{\tau+\tau_0}\right)^{1/2}(Bessel's \quad func)\right]$$

- The rates for all the profiles are similar at very low evolution time or length of medium.

- In the Bjorken, the presence of the factor

Sqrt[$\tau_0/(\tau_0 + \tau)$] leads to the dumping of the splitting rate for $\tau > \tau_0$.



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

Effective scaling parameter

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

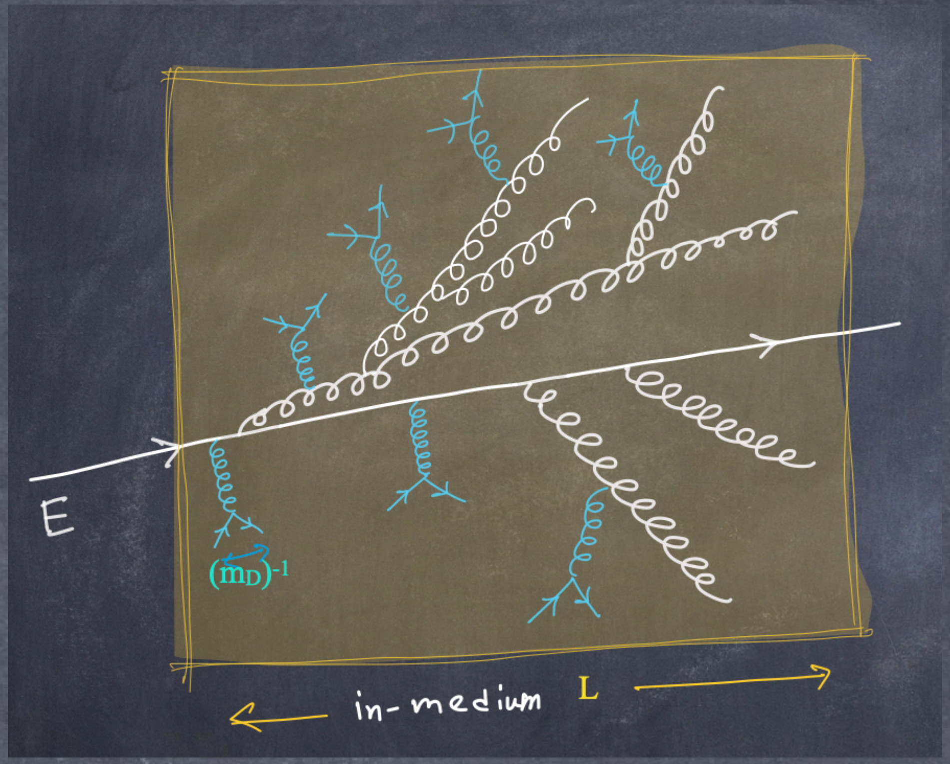
$$\hat{q}_{eff}^{BJ} = 4\hat{q}_0 t_0/L$$

Adhya, Salgado, Spousta, Tywoniuk 2020
Scaling applications also by Caucal, Iancu, Soyez 2021

$$\kappa(z) = \sqrt{[1-z(1-z)]/[z(1-z)]}$$

$$\tau = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{E}}t$$

In- medium gluon evolution eqn.



The gluon evolution inside a medium is described by the BDIM equation :

$$\frac{\partial}{\partial t}D(x,\mathsf{k},t) = \frac{1}{t^*}\int_0^1 dz\, \underbrace{\tilde{\mathcal{K}}(z,t)}_{\text{Splitting Kernel.}}\Bigg[\underbrace{\frac{1}{z^2}\sqrt{\frac{z}{x}}D\left(\frac{x}{z},\frac{\mathsf{k}}{z},t\right)\theta(z-x)}_{\text{gain term}} - \underbrace{\frac{z}{\sqrt{x}}D(x,\mathsf{k},t)}_{\text{loss term}}\Bigg] + \underbrace{\int\frac{d^2l}{(2\pi)^2}C(\mathsf{l},t)D(x,\mathsf{k}-\mathsf{l},t)}_{\text{elastic collision term}}$$

Medium evolved gluon spectra

$$D \equiv \omega\frac{dN}{d\omega}$$

$$C(l,t) = \frac{4\pi\hat{q}}{l^2(l^2+m_D^2)}$$

$m_D \sim gT$ (Debye mass)

$$\frac{1}{t^*} = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{E}} \longrightarrow \text{"Quenching parameter".}$$

Integration over all 'k' drops off the collision term.

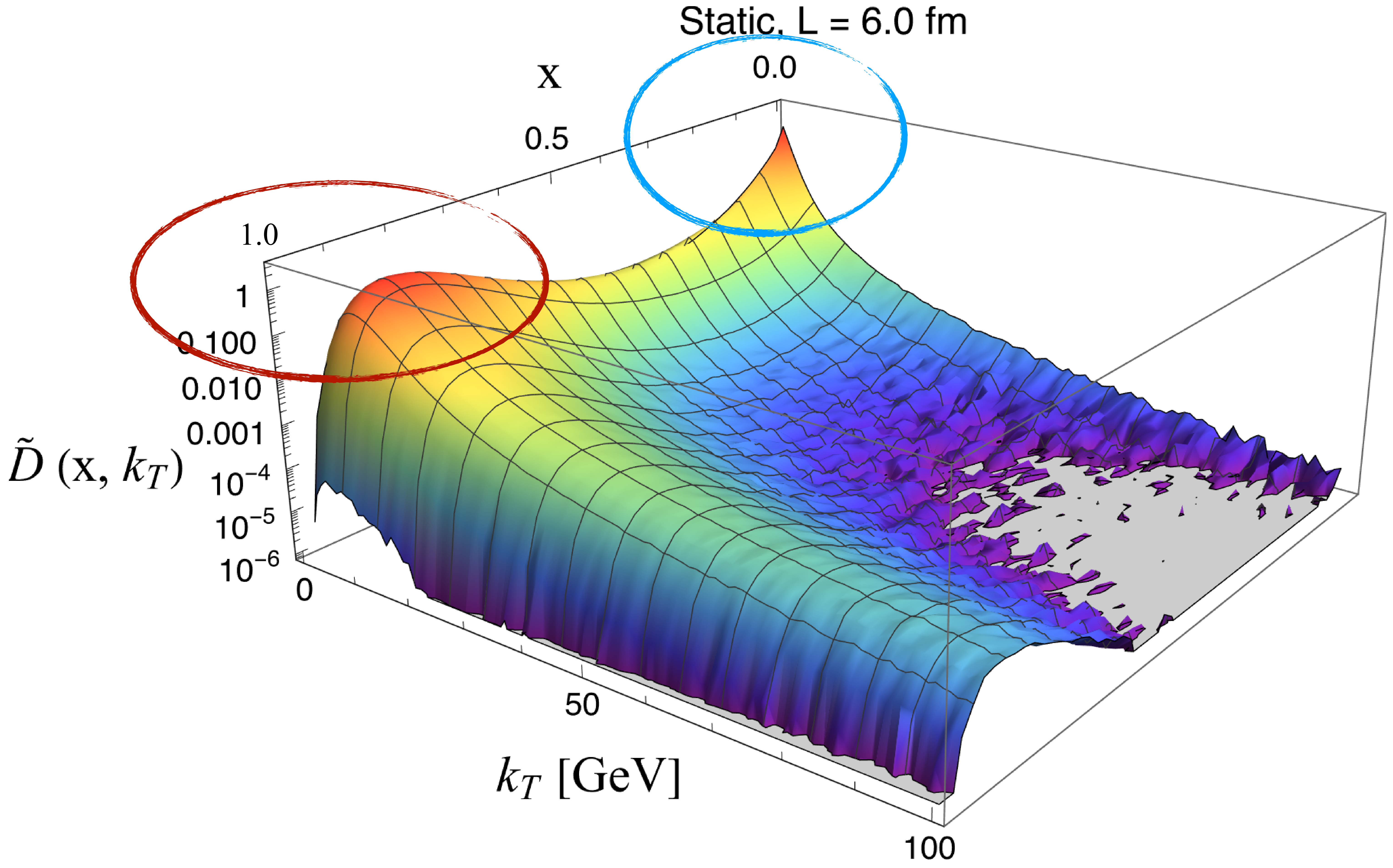
t = evolution length.

k = transverse momentum

x = energy fraction; $0 \leq x \leq 1$

Blaizot, Dominguez, Iancu, Mehtar-Tani, 2014.

2-D differential distributions



- **Hard-x (x ~1) regime**

dominated by leading fragment in cascade

  - Small k_T : Gaussian profile due to multiple soft-gluon scatterings.
  - Large k_T : Power law suppression due to rare hard medium interactions.

- **Soft-x (x << 1) regime**

accumulation of soft gluons towards the medium scale

  - Small k_T : Distribution is narrower and approx. Gaussian.
  - Large k_T : No distinct transition to a power-law behavior.

We use $k_T \sim (x\, E\, \theta)$ to analyse the behavior in angular space

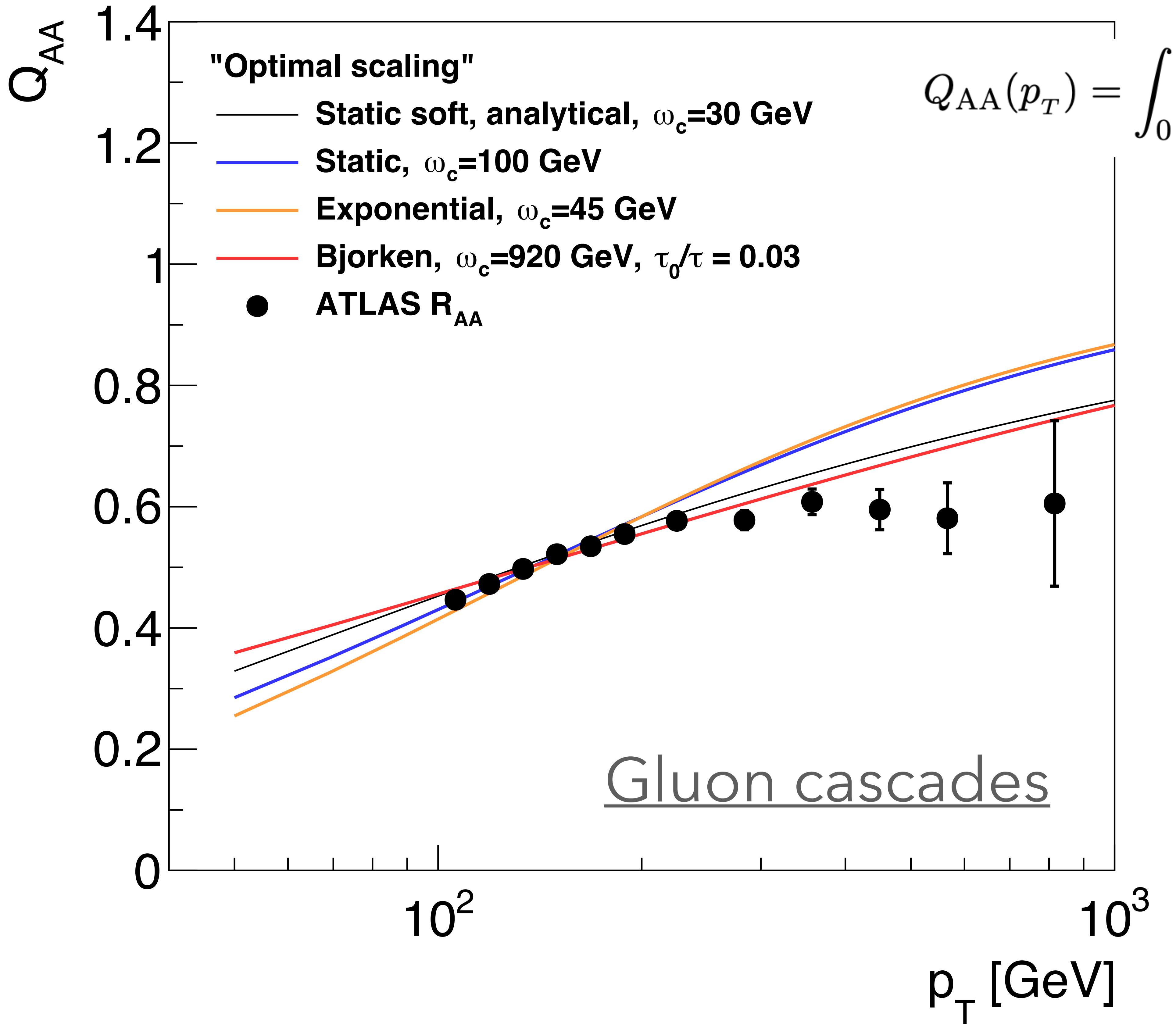
Medium INduced CAScades (MINCAS) MC :

Kutak, Placzek, Straka (2018).

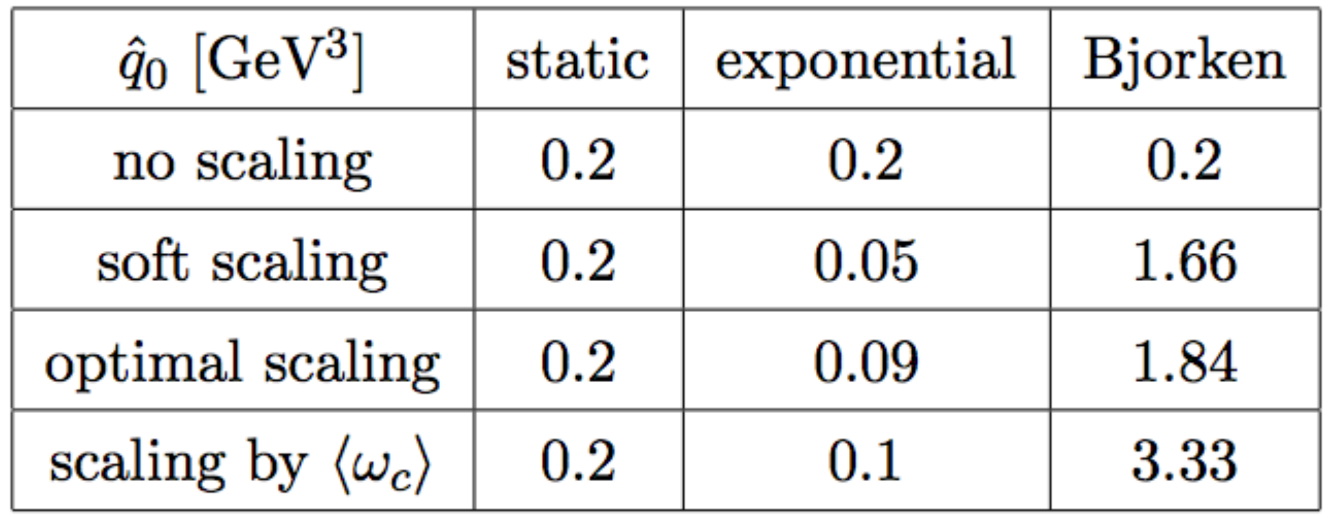
Let us explore the scaling between different medium profiles

The idea is to find the values of these parameters that
best approximate the dynamic spectrum along the path

Recent scaling applications



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



$\hat{q}_0$ [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

- The Bjorken profile depends on additional choice of (τ_0/τ) : No universal scaling.
- Good, but not perfect scaling is achieved by optimisation.

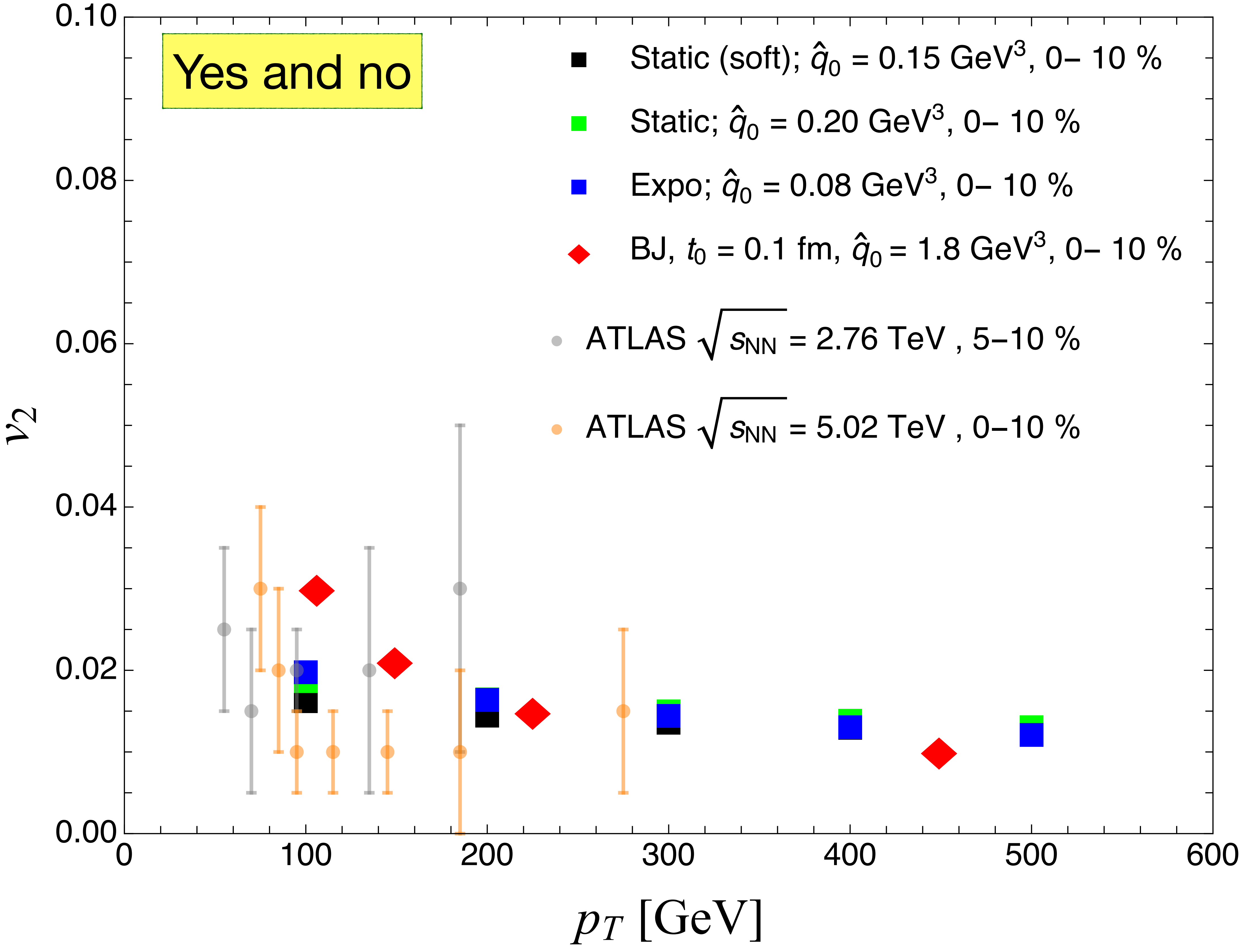
- Significant differences in q^ for different types of medium point to the importance of precise modelling of jet quenching phenomenon.

Adhya, Salgado, Spousta, Tywoniuk, 2020.

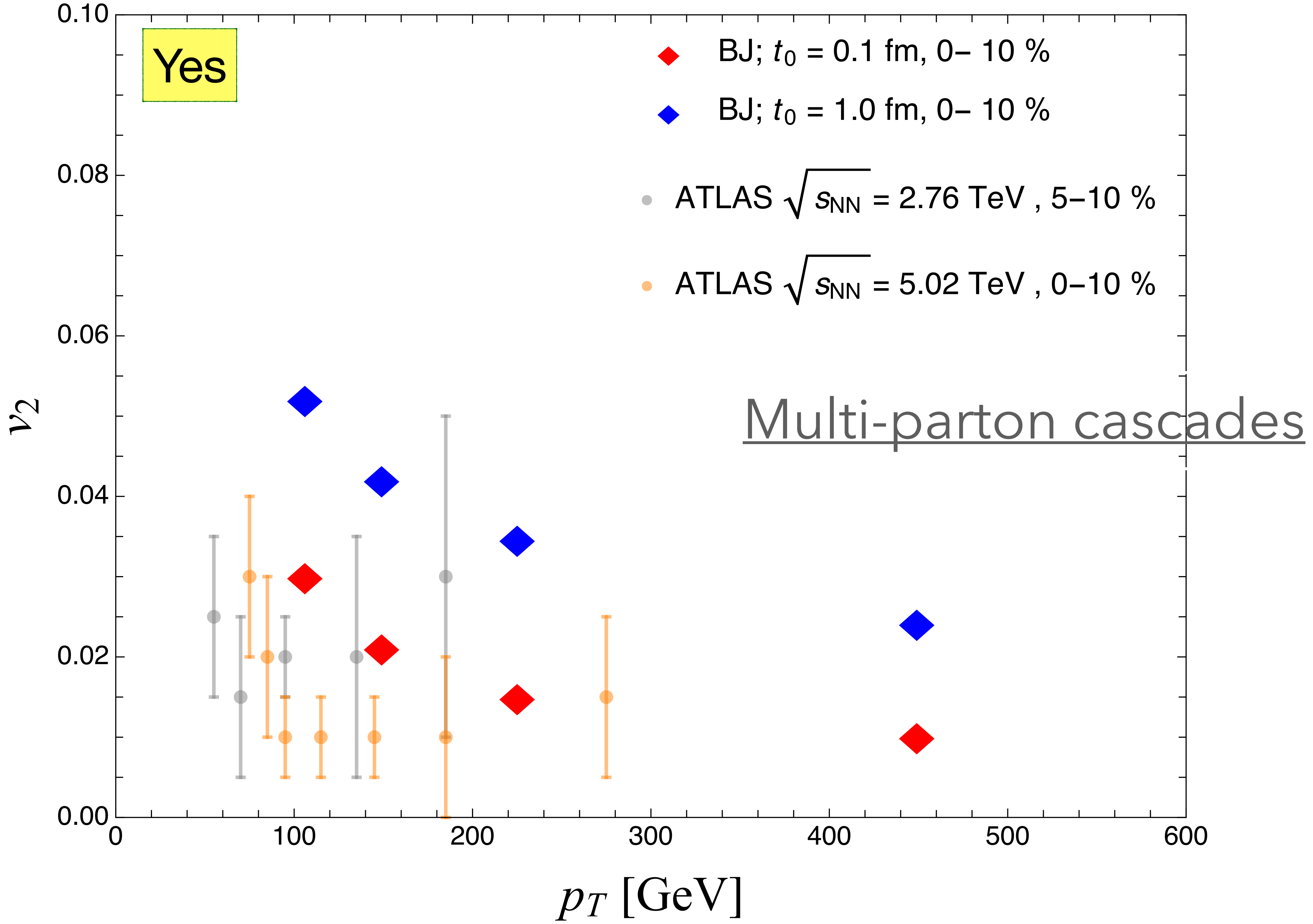
Medium behaves *different* for v_2?

Adhya, Salgado, Spousta, Tywoniuk, 2022.

Elliptic flow as a function of p_T for different media



Elliptic flow as function of p_T for BJ initial conditions

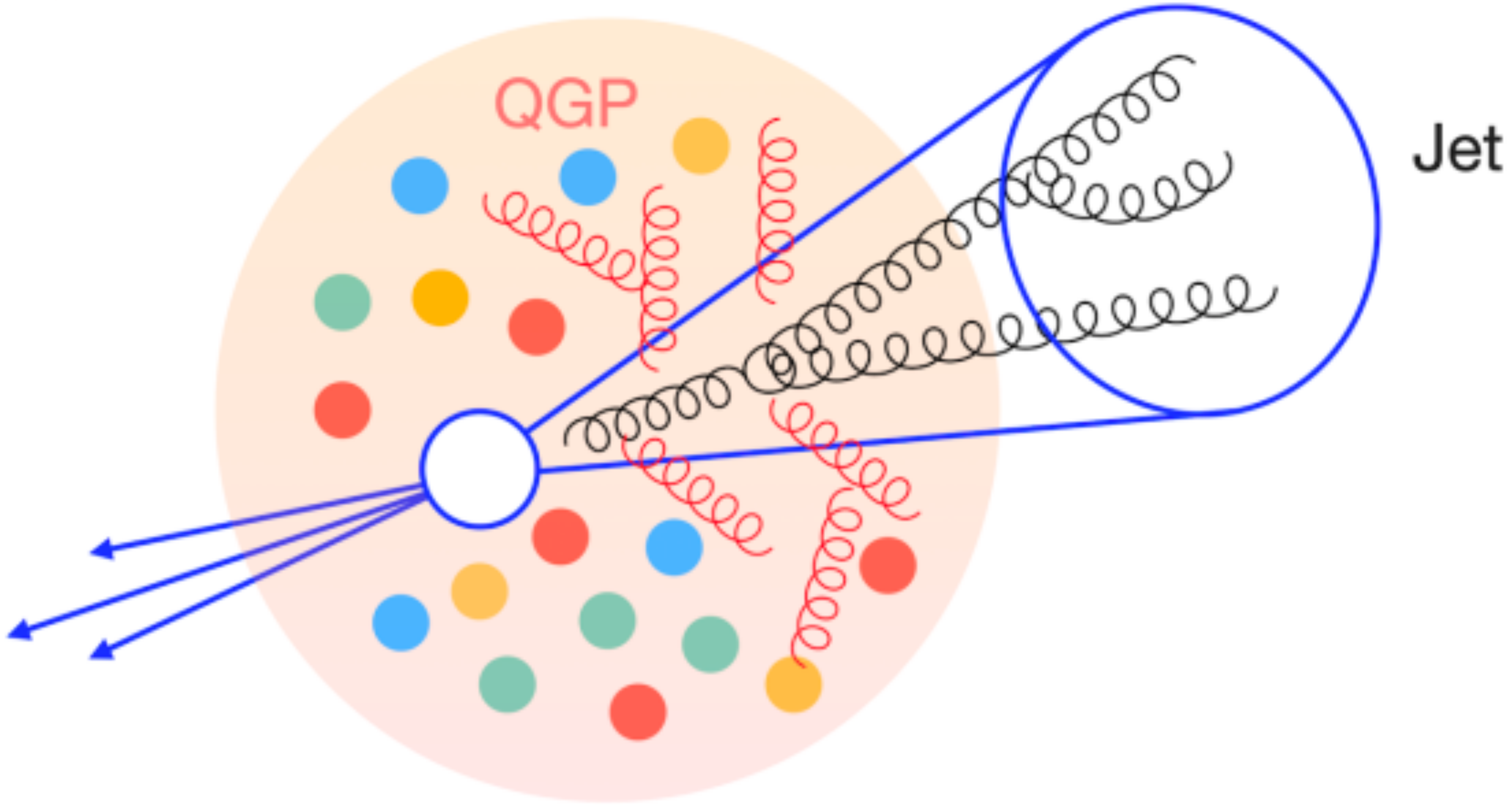


Multi-parton cascades

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

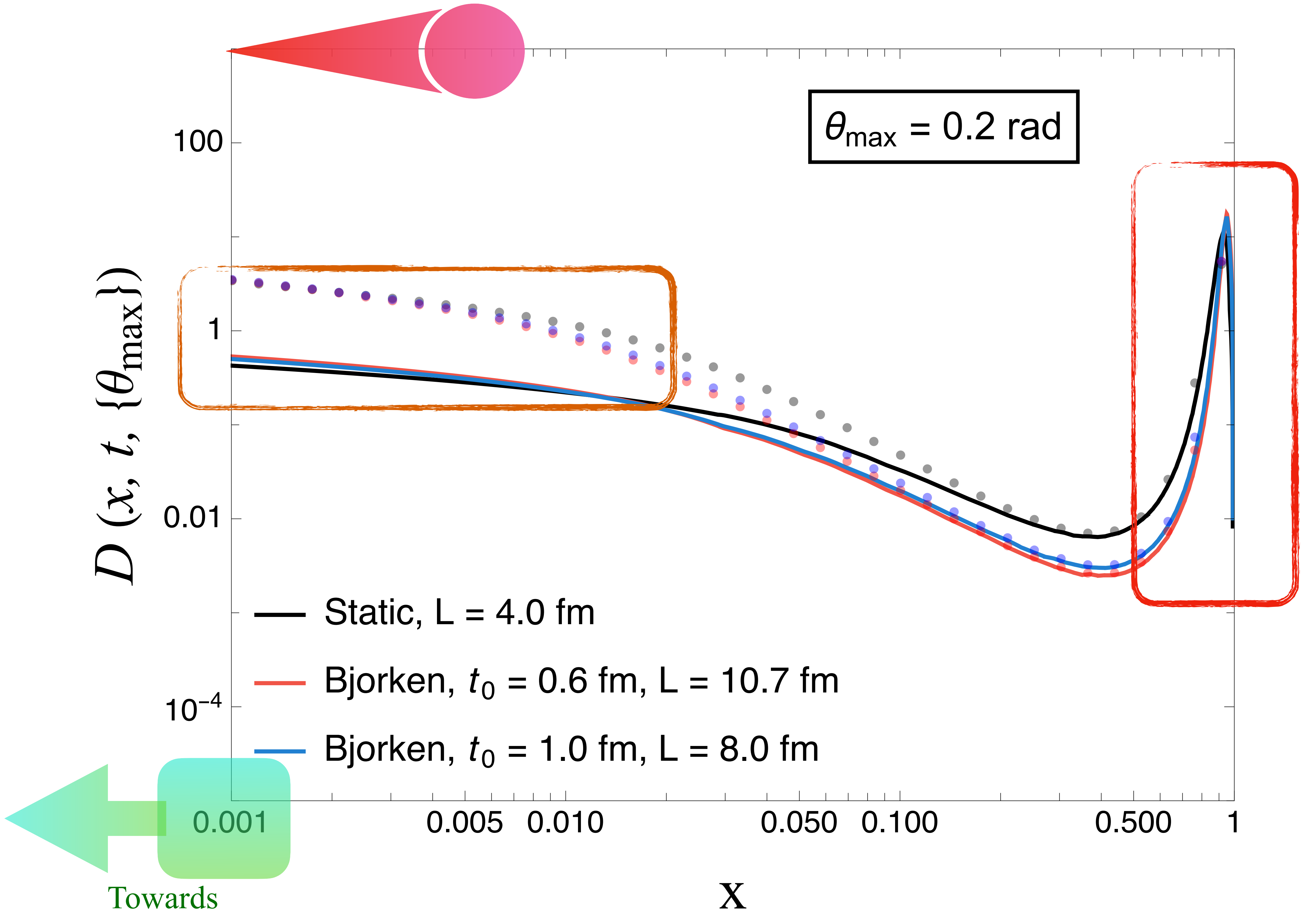
How much energy flows out of the jet cone ?

R = Radius of
the jet cone

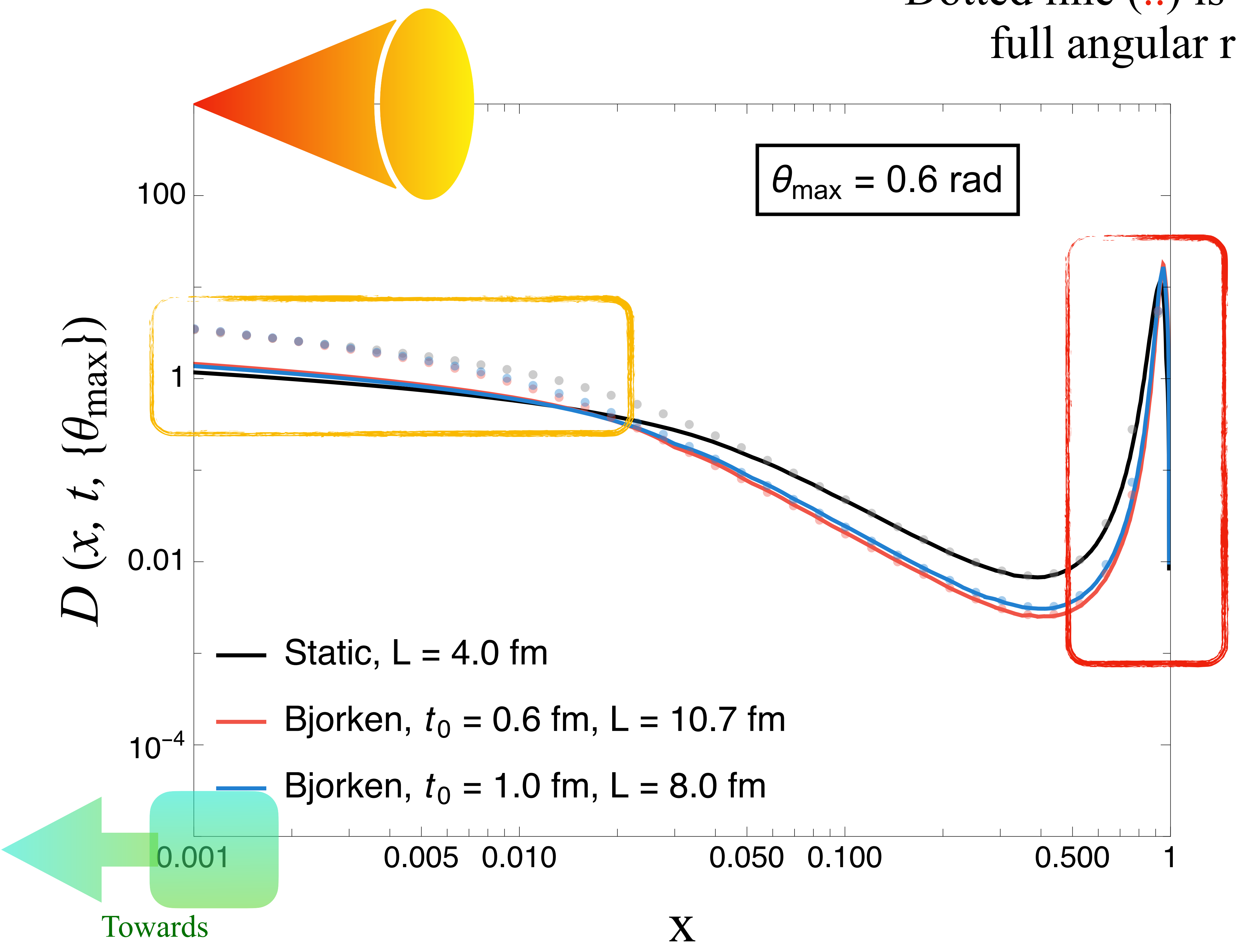


Scaling in the energy spectrum

Dotted line (..) is spectra for full angular region.



Towards thermalisation



Towards thermalisation

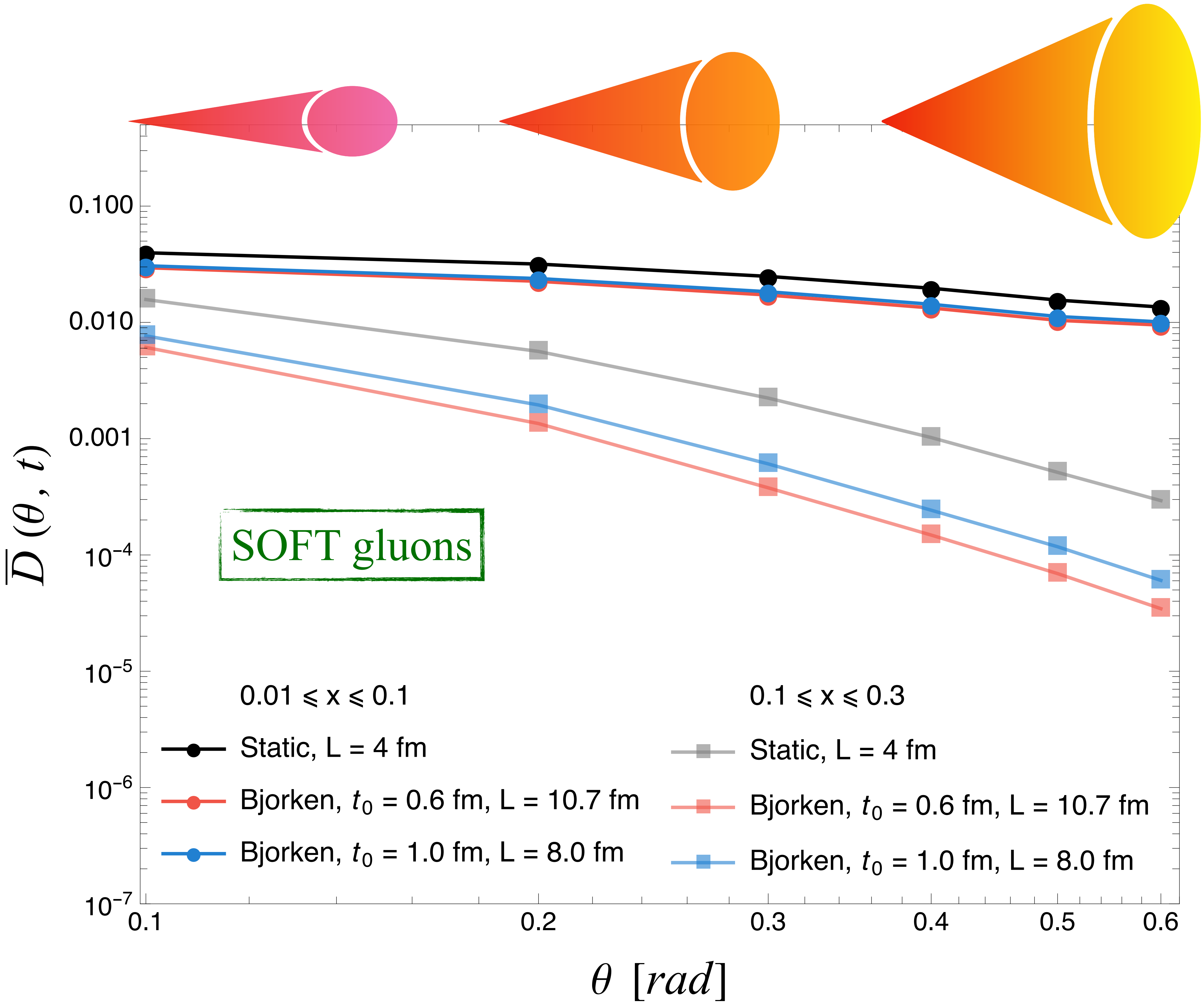
$$D(x,t;\{\theta_{\max}\}) = \int_0^{\theta_{\max}} \mathrm{d}\theta\, \bar{D}(x,\theta,t)$$

- As one opens up the angle, recovery of more softer gluons.
- No change of harder gluons as they primarily remain collimated.
- Hard jet fragments are *sensitive* to medium expansion, softer ones are not.

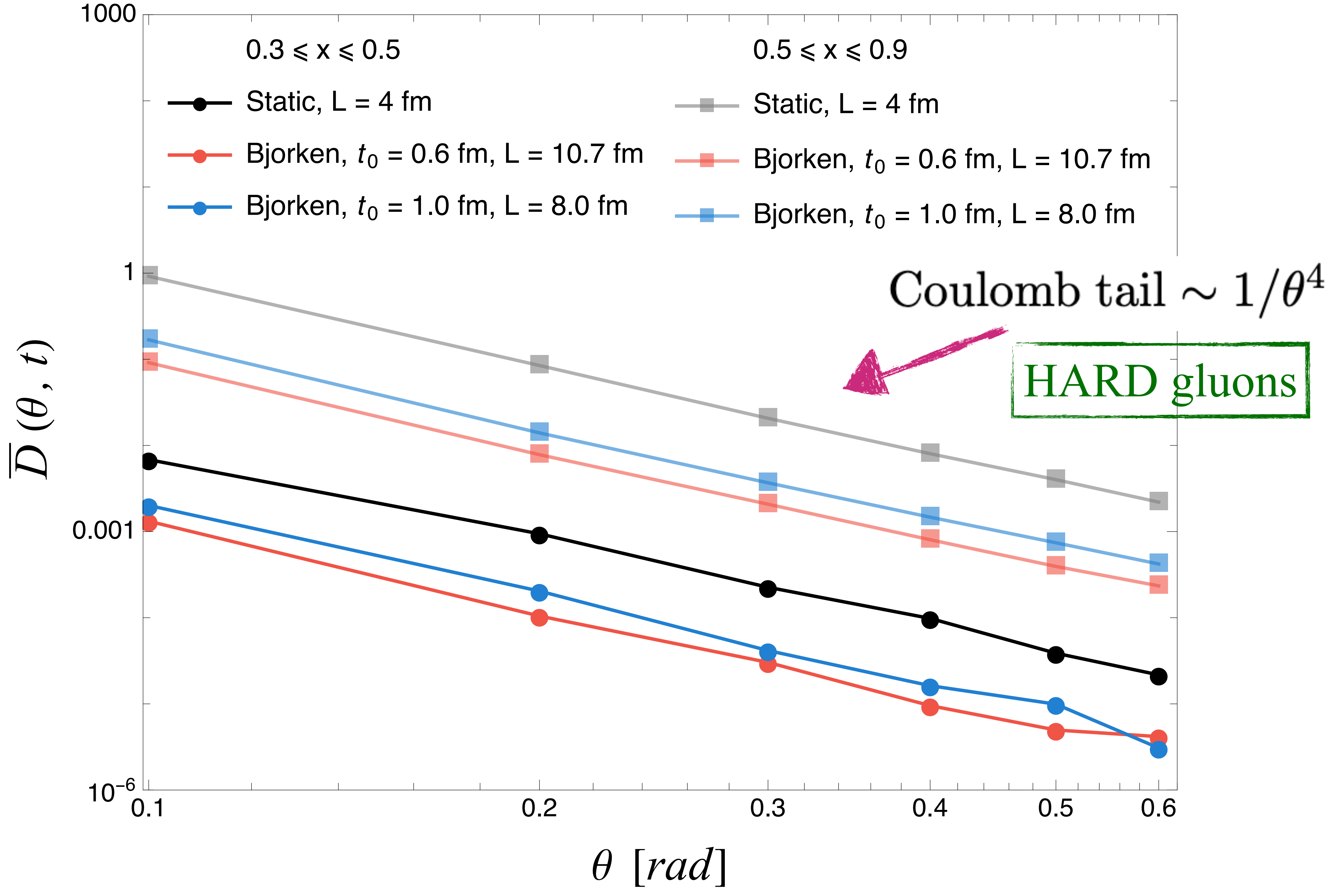
Thermalisation effects
Mehtar- Tani, Schlichting, Soudi, 2022

Adhya, Kutak, Placzek, Rohrmoser, Tywoniuk, 2022

Fully differential spectra



$$\bar{D}(\theta, t; \{x_{\min}, x_{\max}\}) = \int_{x_{\min}}^{x_{\max}} \mathrm{d}x\, \bar{D}(x, \theta, t)$$

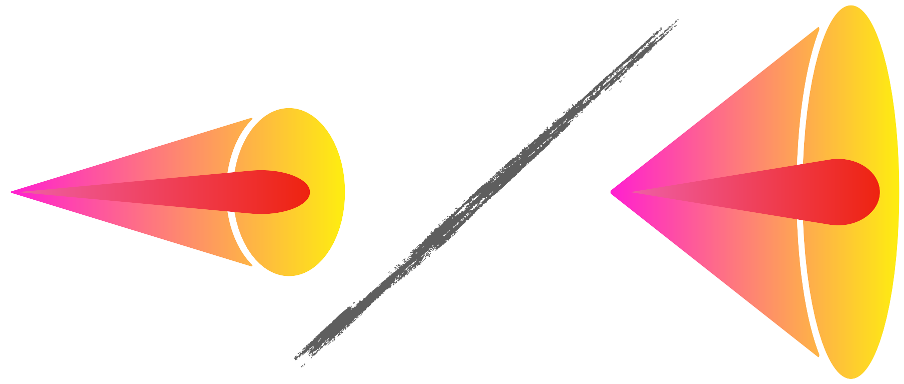


- Energy is re-distributed to larger angles for softer gluons.
- Collinear radiation with insignificant transverse mom. broadening for hard gluons.

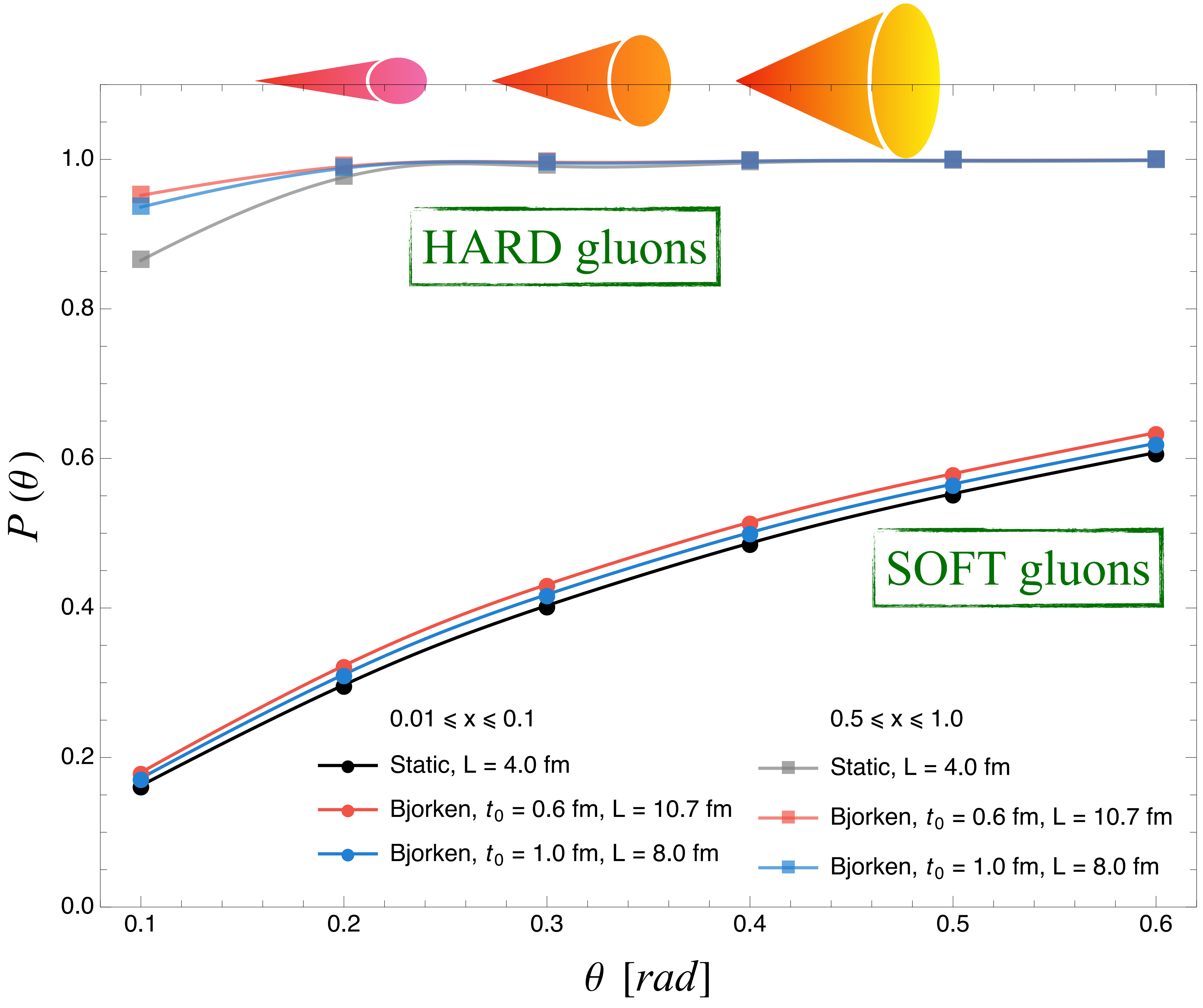
Adhya, Kutak, Placzek, Rohrmoser, Tywoniuk, 2022

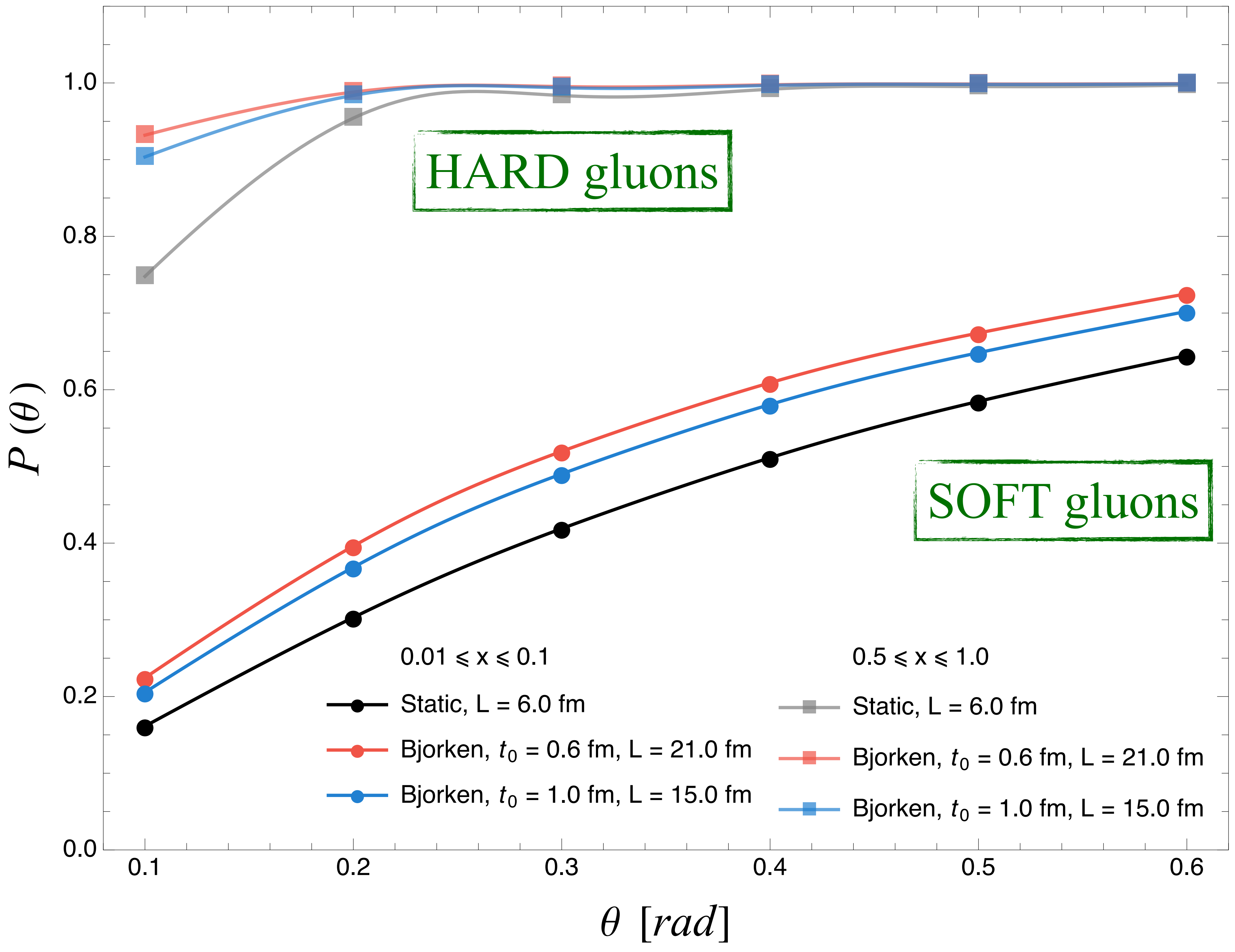
Which gluons we capture (in- cone) ?

$$P(\theta, t; \{x_{\min}, x_{\max}\}) = \frac{\int_{x_{min}}^{x_{max}} \mathrm{d}x \int_0^{\theta} \mathrm{d}\theta' \, \bar{D}(x, \theta', t)}{\int_{x_{min}}^{x_{max}} \mathrm{d}x \int_0^{\pi} \mathrm{d}\theta' \, \bar{D}(x, \theta', t)} =$$



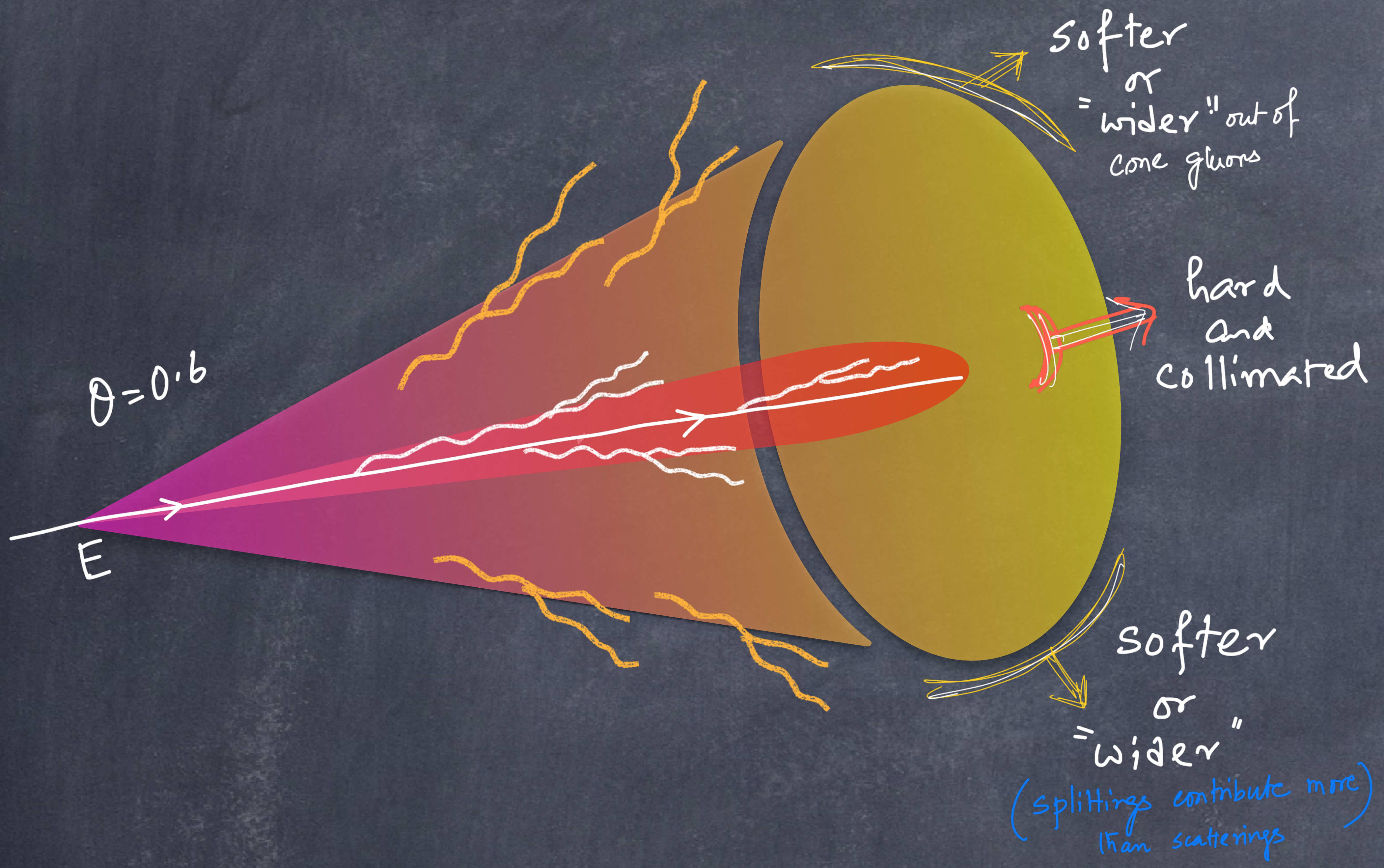
Adhya, Kutak, Placzek,
Rohrmoser, Tywoniuk, 2022





- Hard sector: Medium recovers most of the energy already at θ = 0.2; insensitive to medium expansion.
- Soft sector: Gluon cascade is narrower in the expanding medium than static medium.

Take home messages



- Hard partons remain *collinear,* momentum broadening pre-dominantly caused by *splittings* rather than medium collisions and transverse momentum exchanges.
- Subsequent decrease of momentum of hard partons into soft sector causes momentum broadening by transverse-momentum exchanges with medium through elastic scattering as well as subsequent splittings into softer fragments.
- However, in soft sector, broadening by subsequent gluon *splittings* contributes to out of cone energy loss at large angles.
- Harder and softer jet fragments within a cone are *sensitive* to details of medium expansion.
- Cascades in expanding media *more collimated* than static media.

Looking forward to more pheno applications!!

M. Spousta, C. Salgado, K. Tywoniuk, K. Kutak, M. Rohrmoser, W. Placzek

- Also working on :
- *Improved Opacity expansion* for expanding media [Adhya, Tywoniuk (in preparation)]

ありがとう