Jets in heavy-ion collisions

24th Zimányi Winter Workshop, 3rd of December 2024

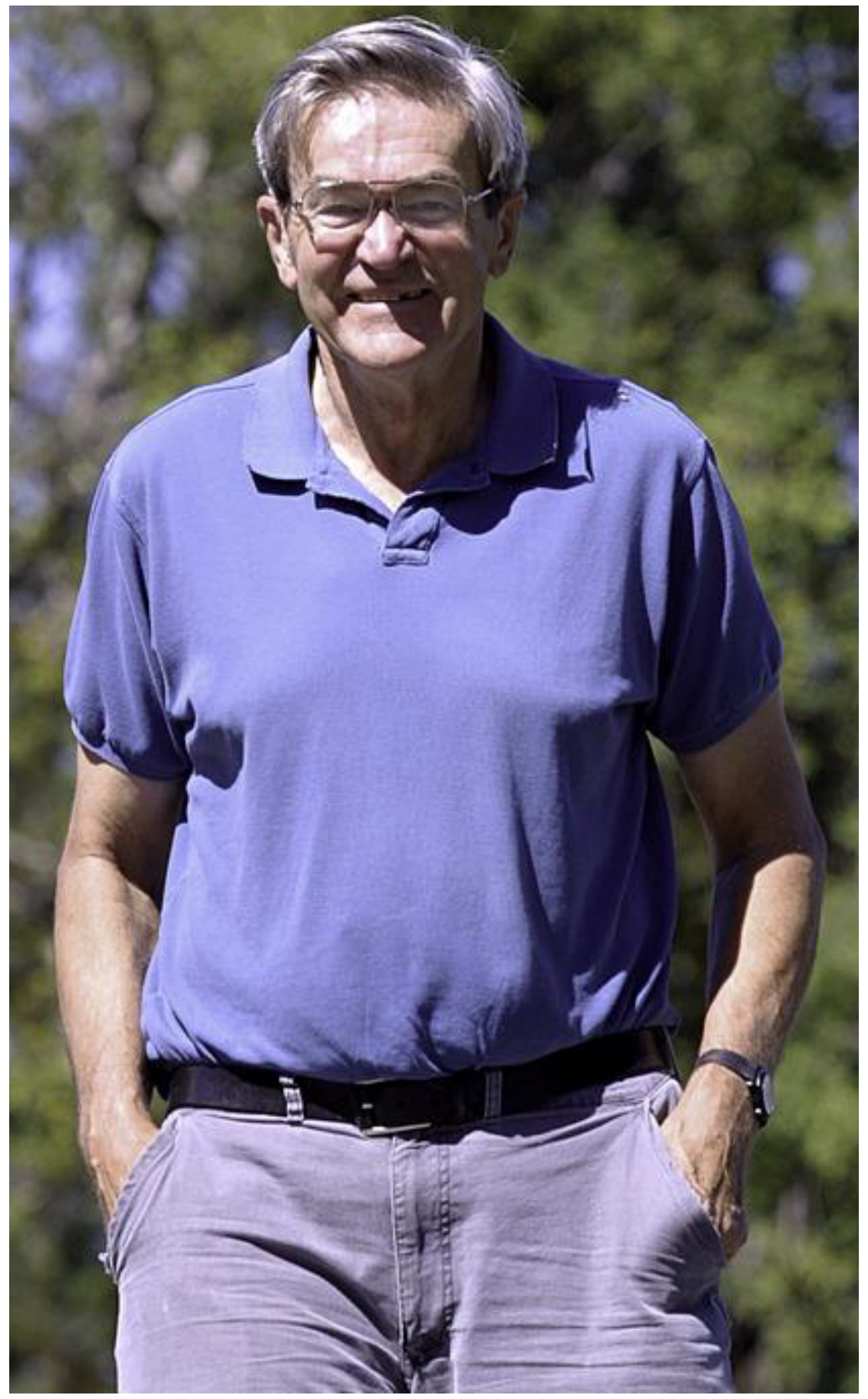
João Barata, CERN-TH

The origins: J. D. Bjorken

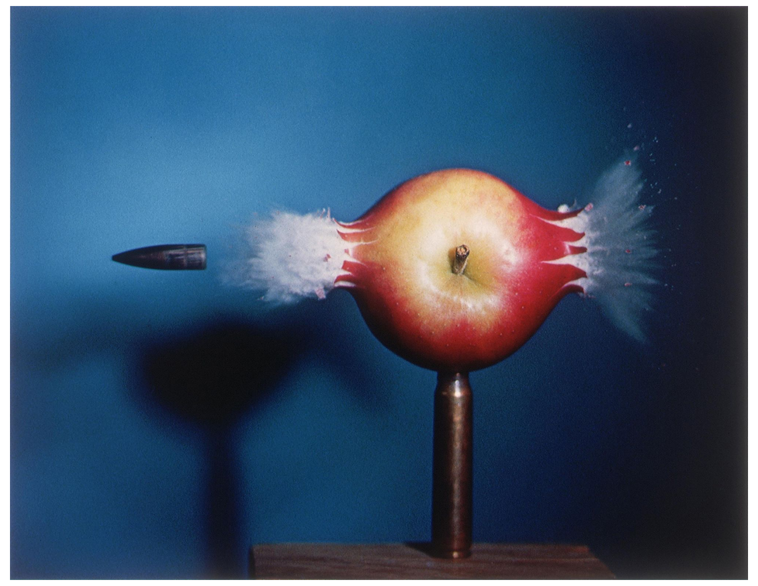
1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

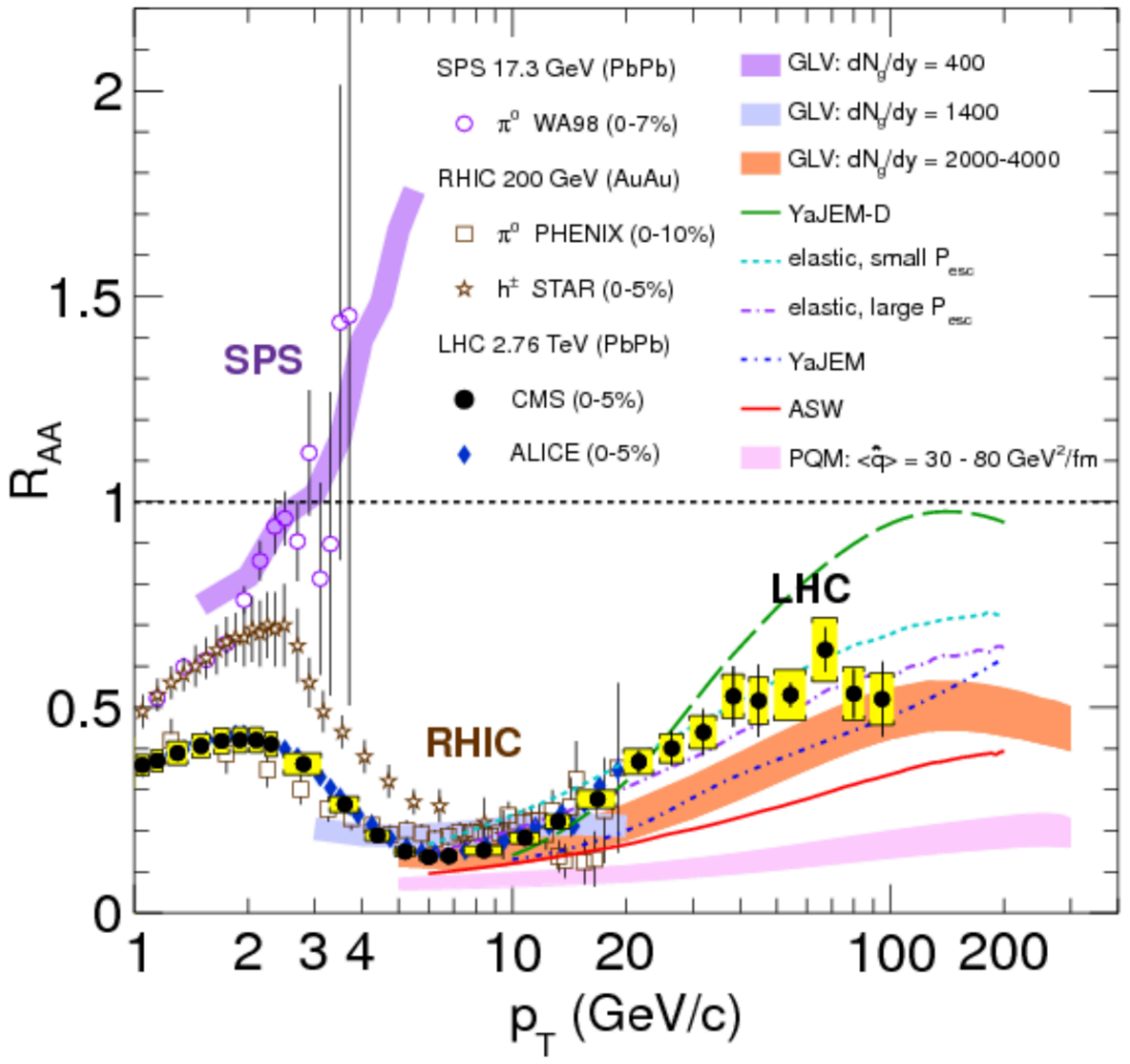


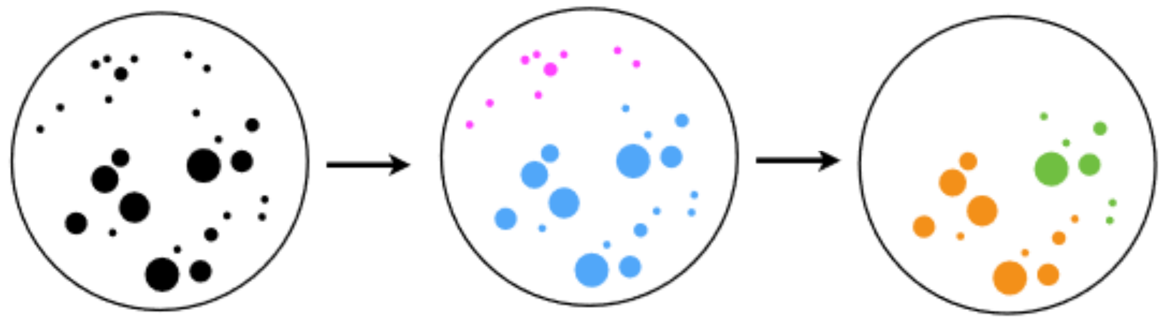
1934-2024

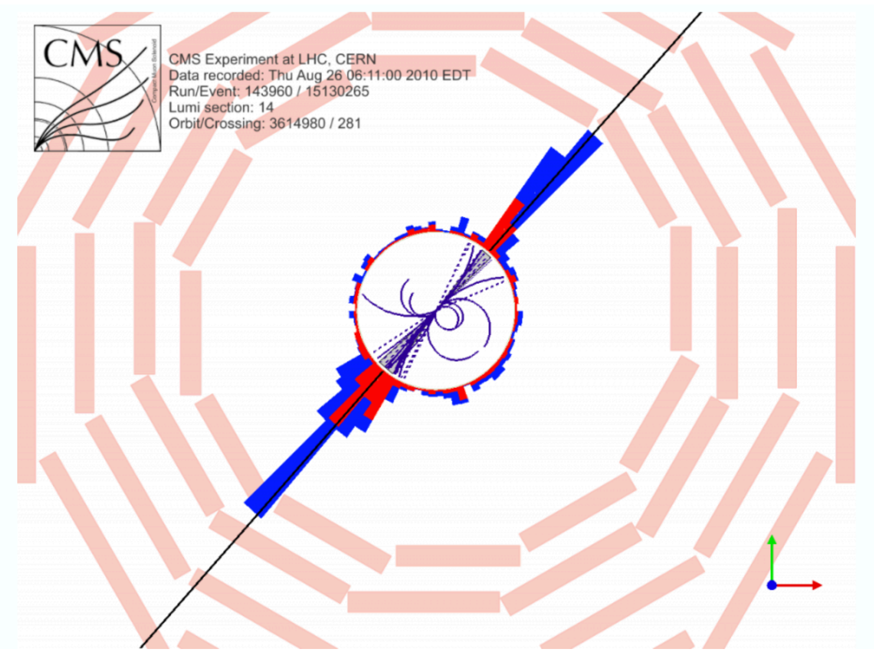


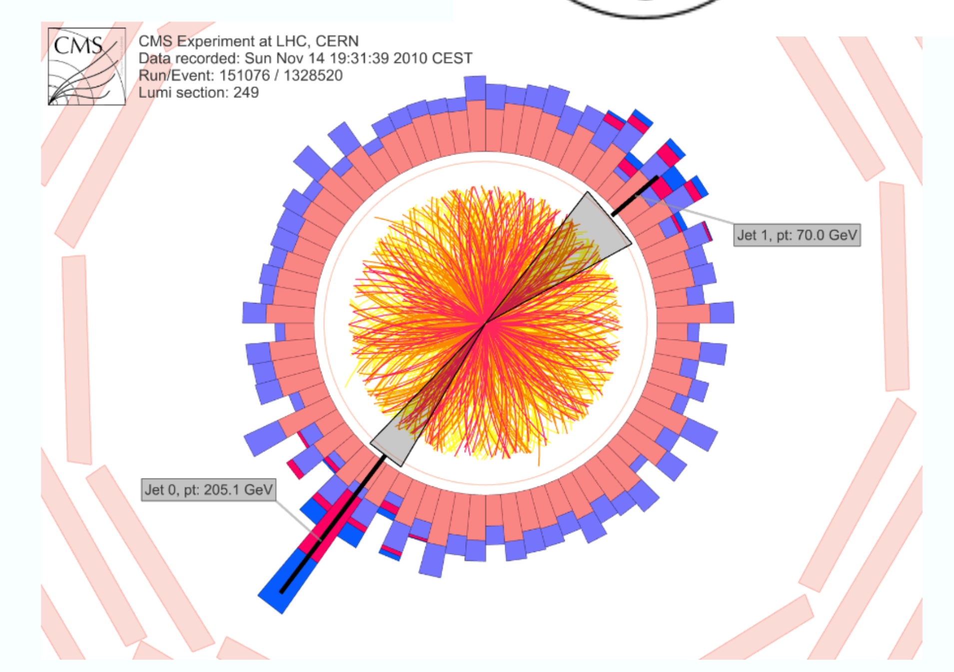
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter.

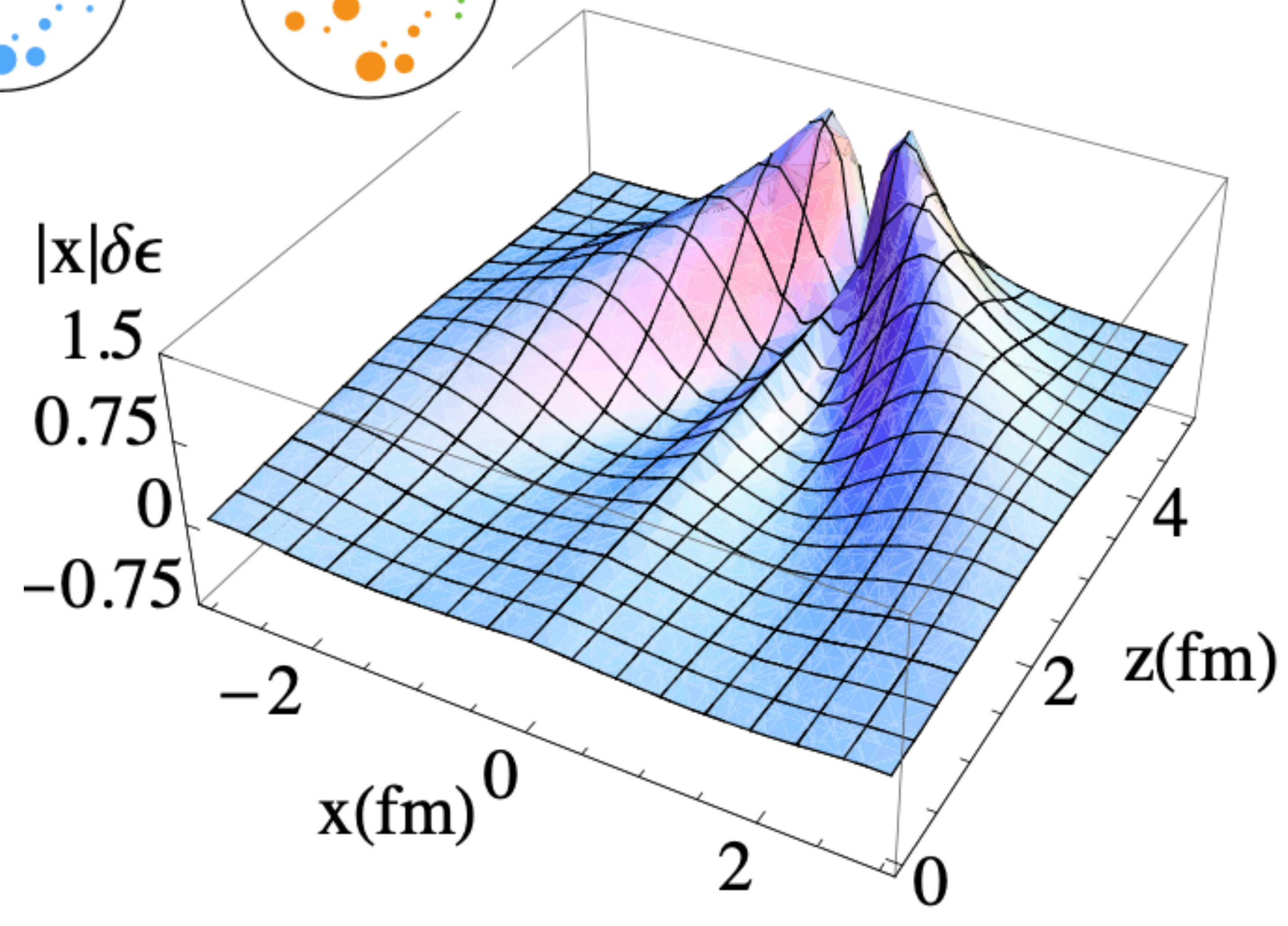
Today: Much more than quarks and gluons

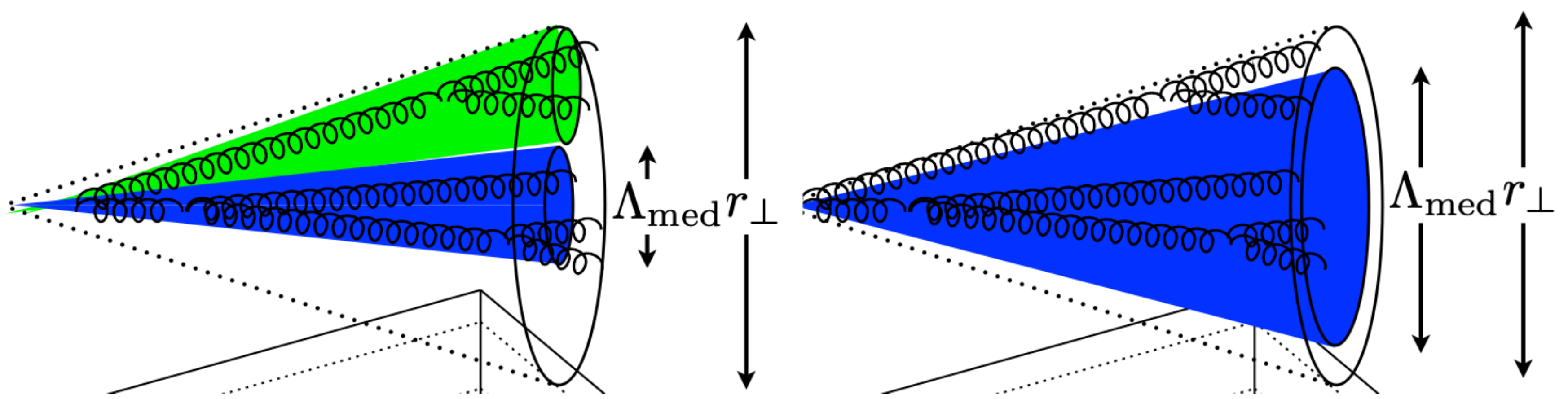


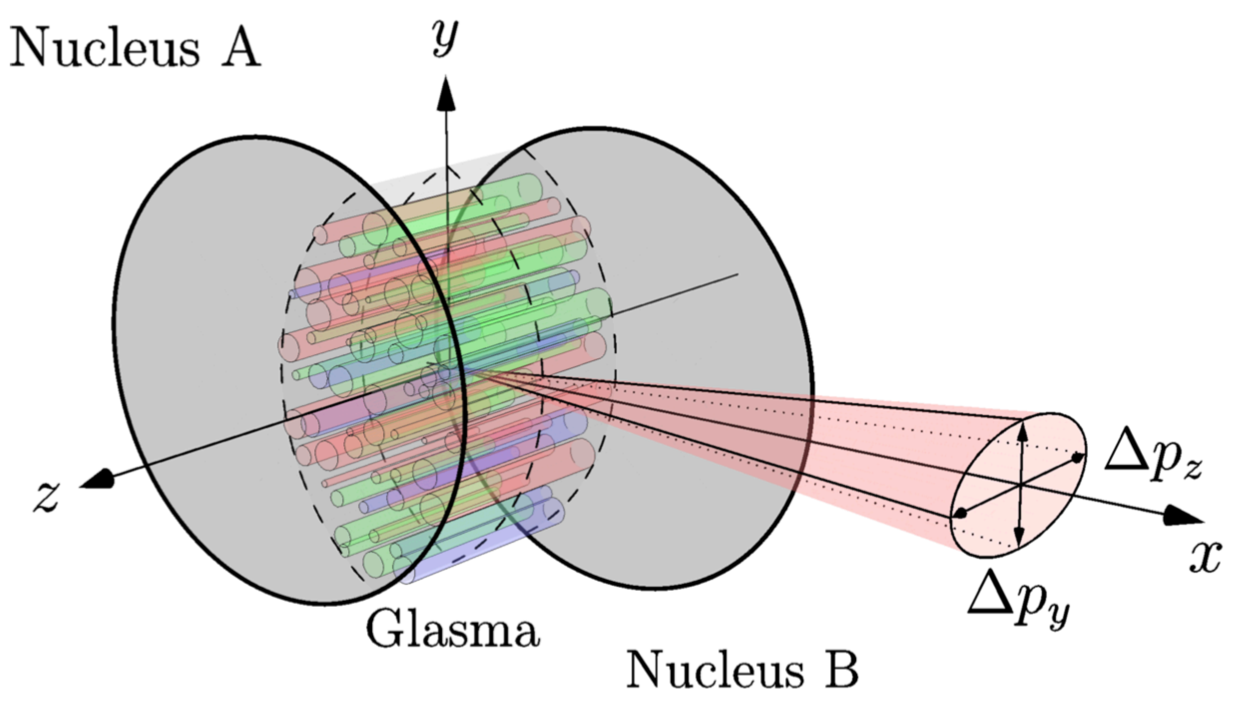






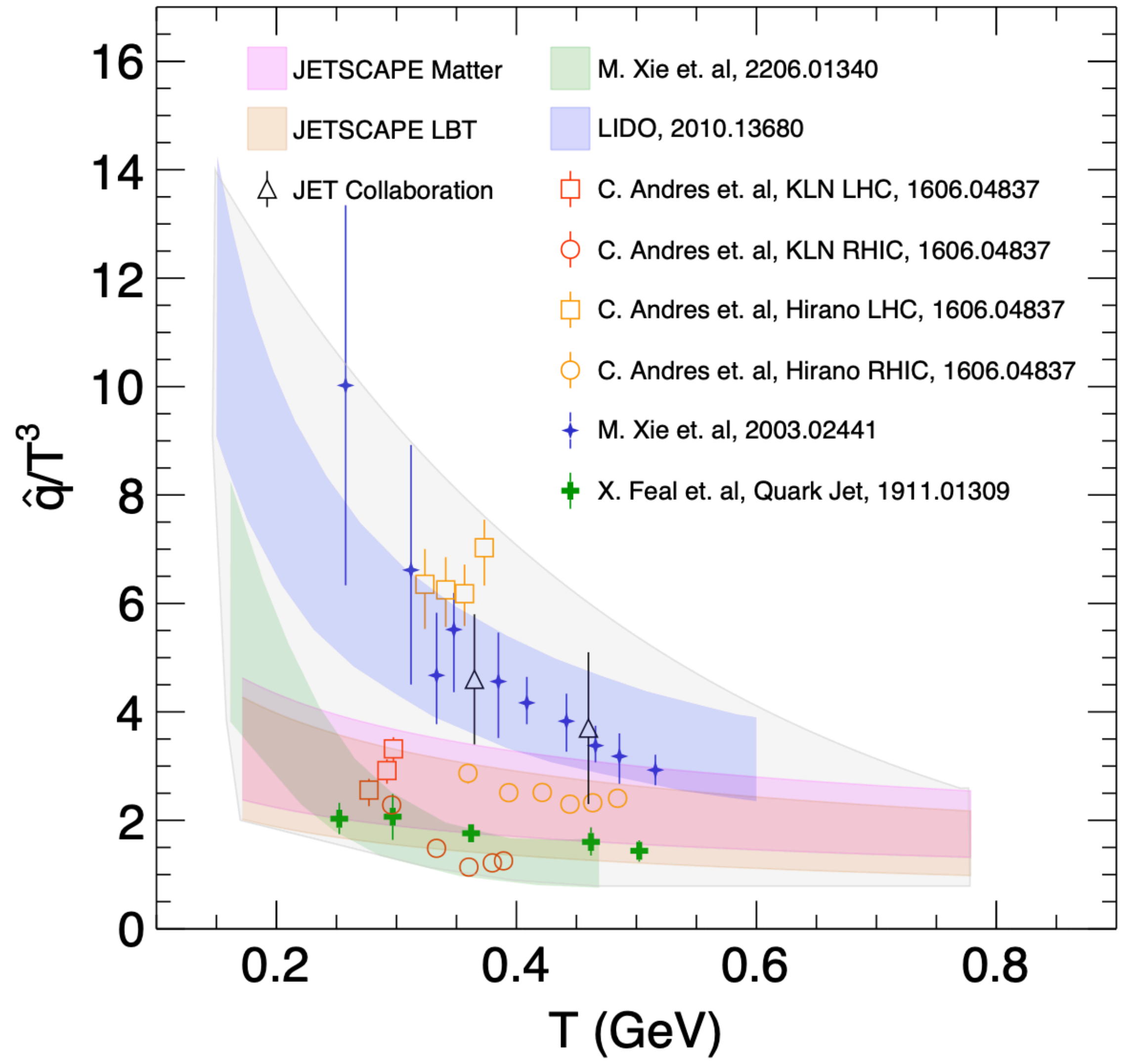






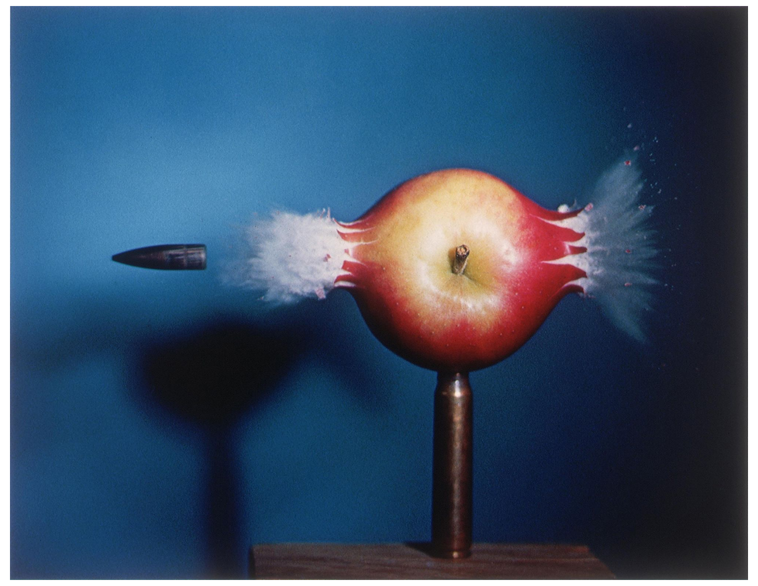
Many theoretical and experimental results !

Very active field in heavy ions collisions (HICs).

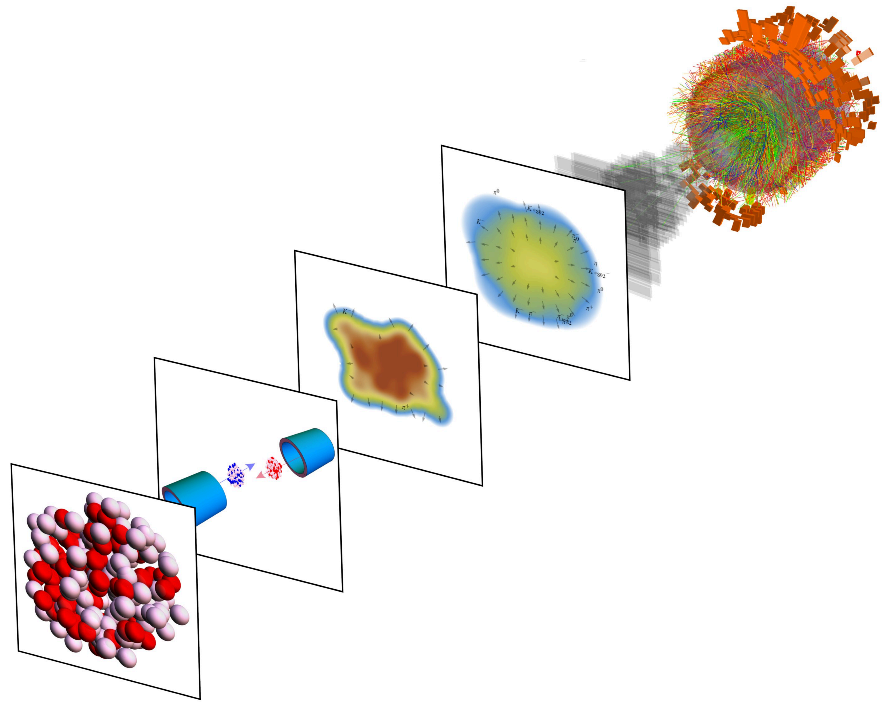


Quark and Gluon jets are the prime spacetime probes of HICs.

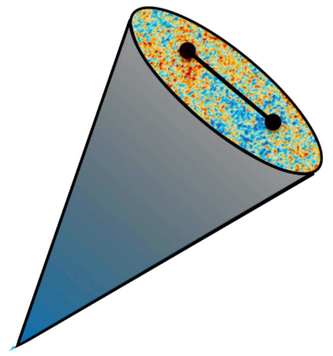
Outline



The general picture of jets in HICs

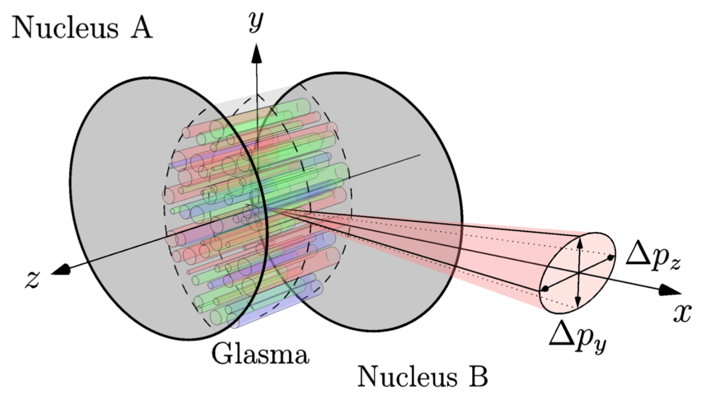


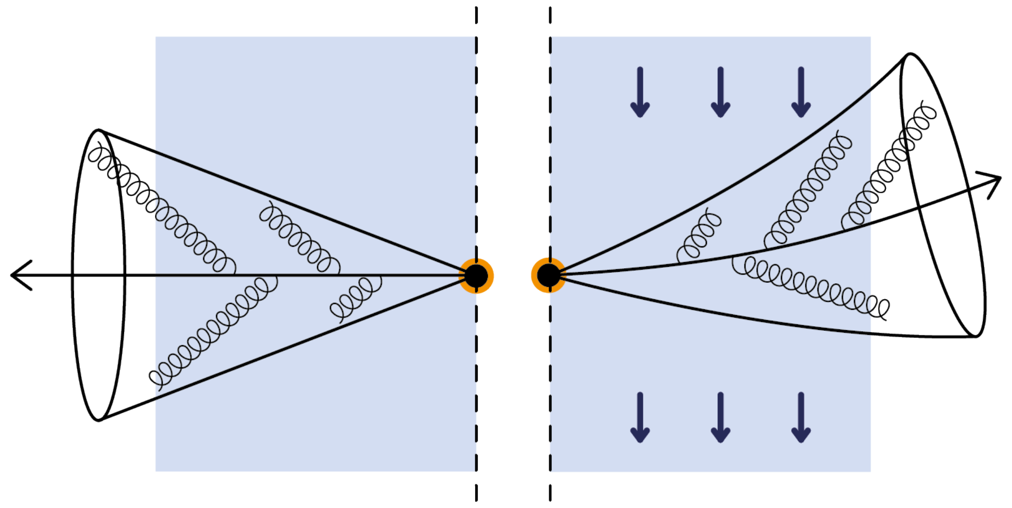
Recent theory developments



Jet substructure observables

Jets in the early stages of HICs

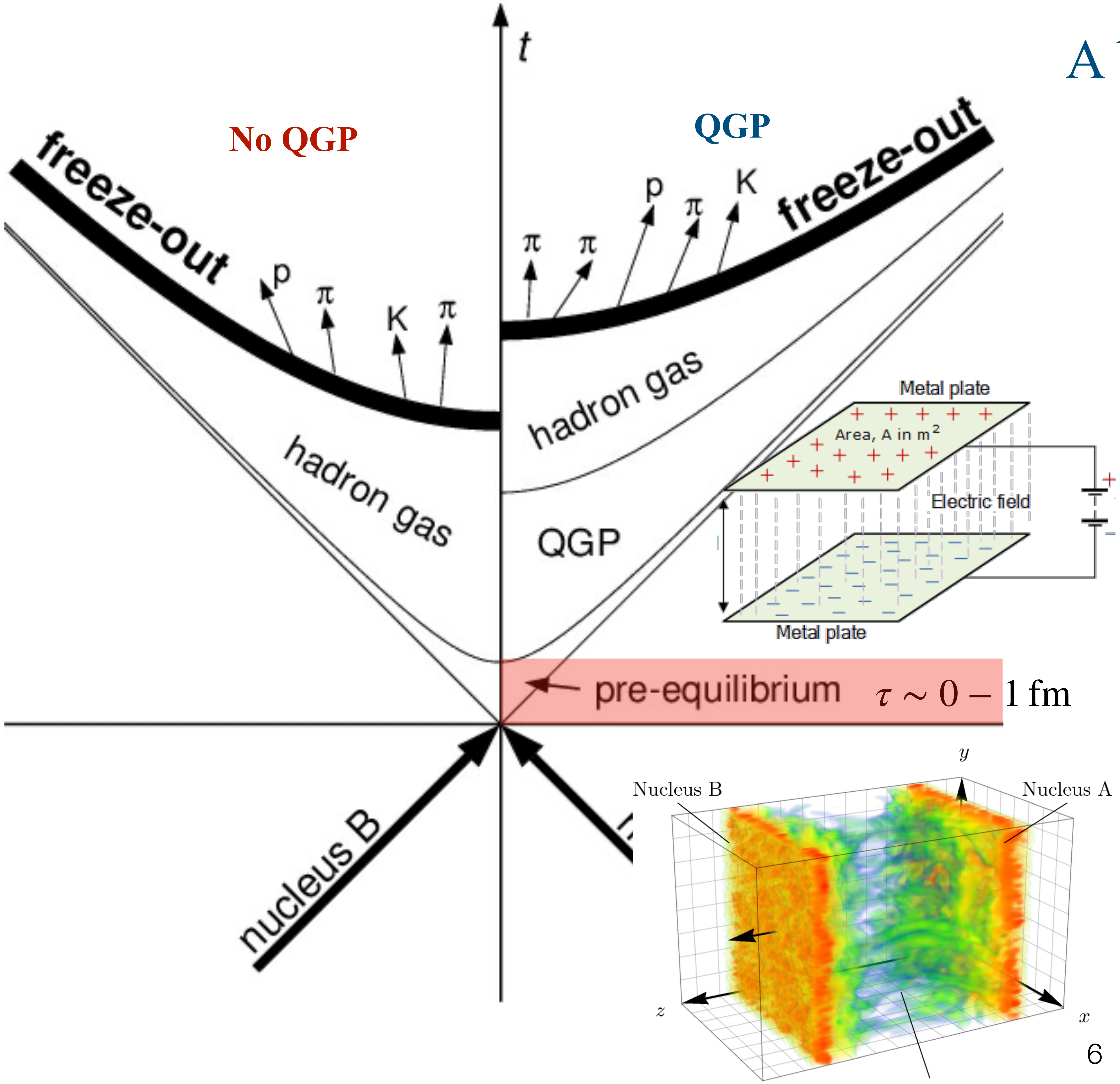




Jets in anisotropic and flowing matter

The general picture of jets in HICs

The spacetime picture of HICs

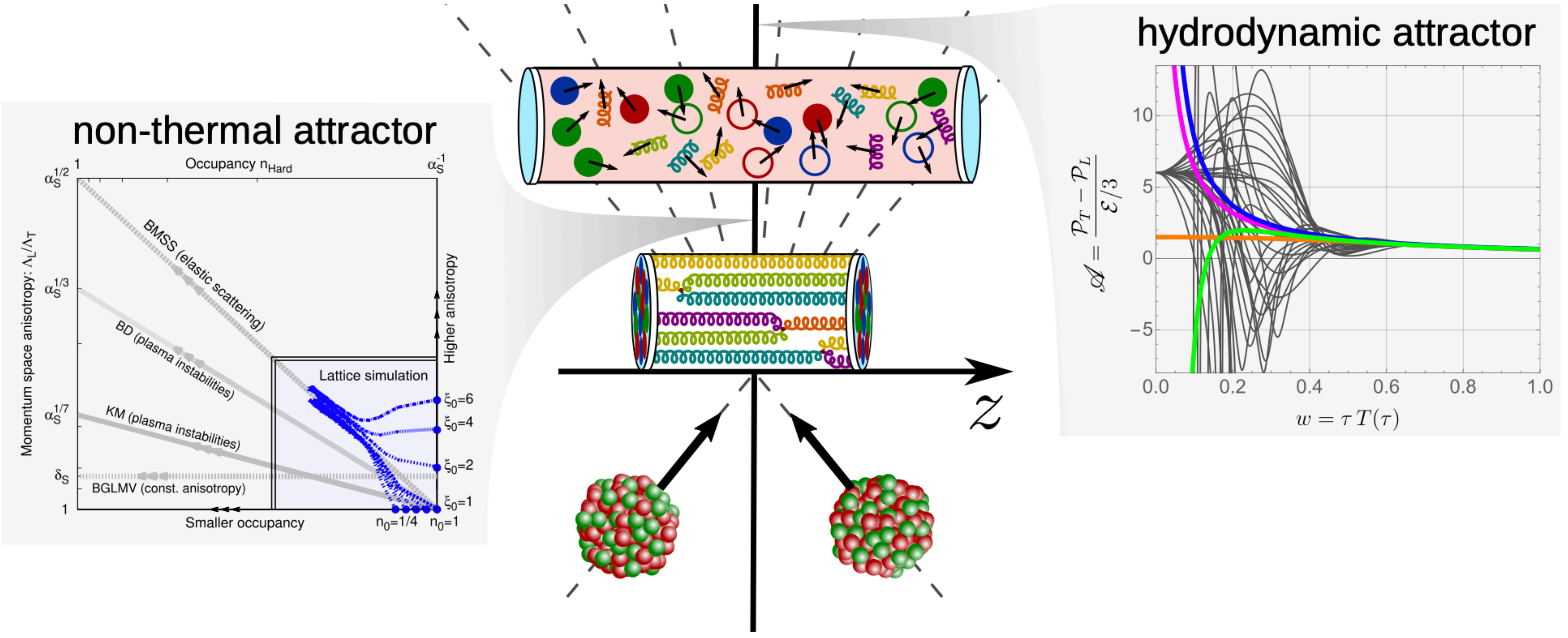


$$1\,\text{fm} \sim 10^{-24}\,\text{s}$$

A brief summary of the different epochs in HICs

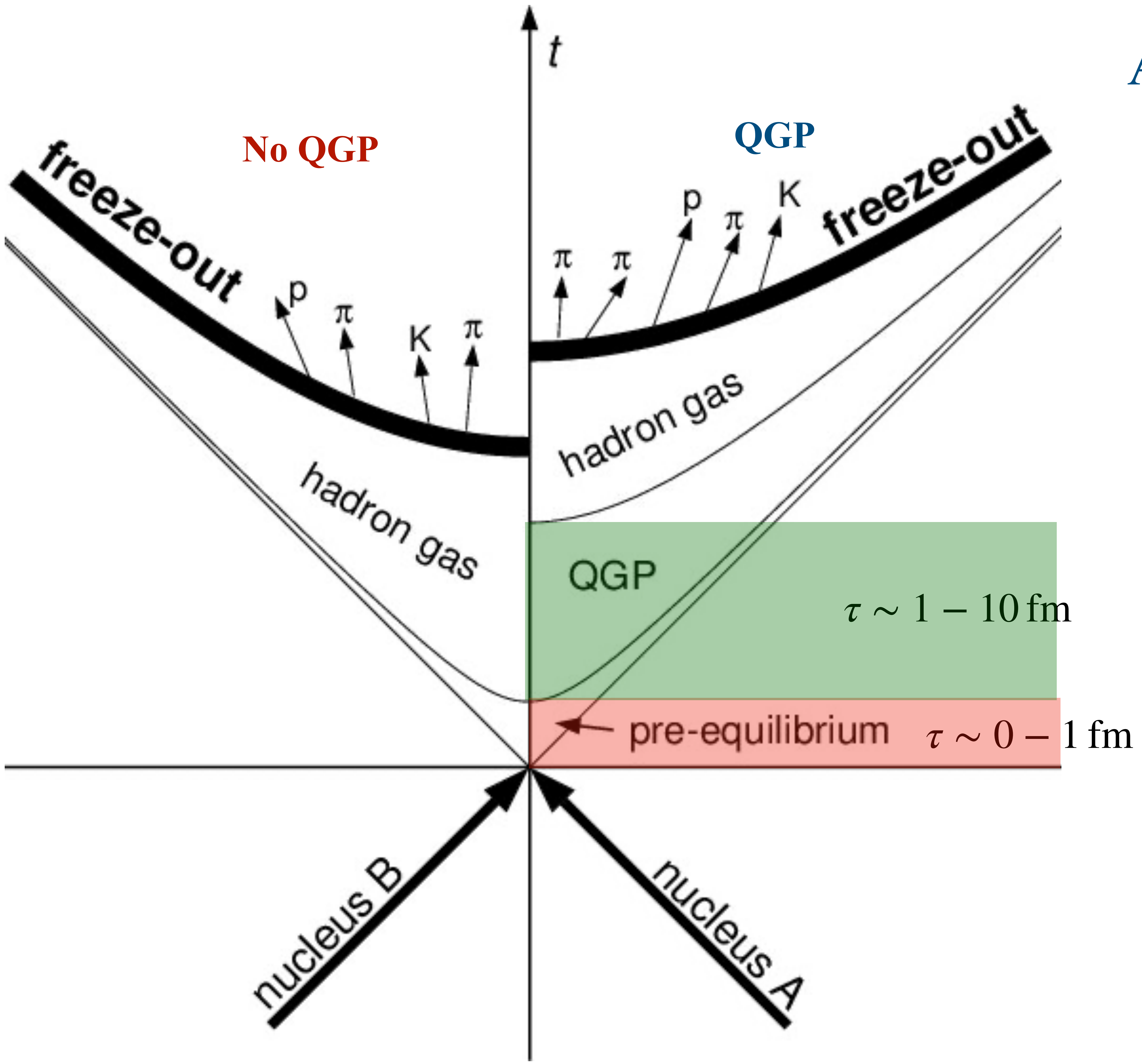
Early times: Out of equilibrium matter (Glasma)

Short lived and dominated by classical configurations



[Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299]

The spacetime picture of HICs



$1\,\mathrm{fm} \sim 10^{-24}\,\mathrm{s}$

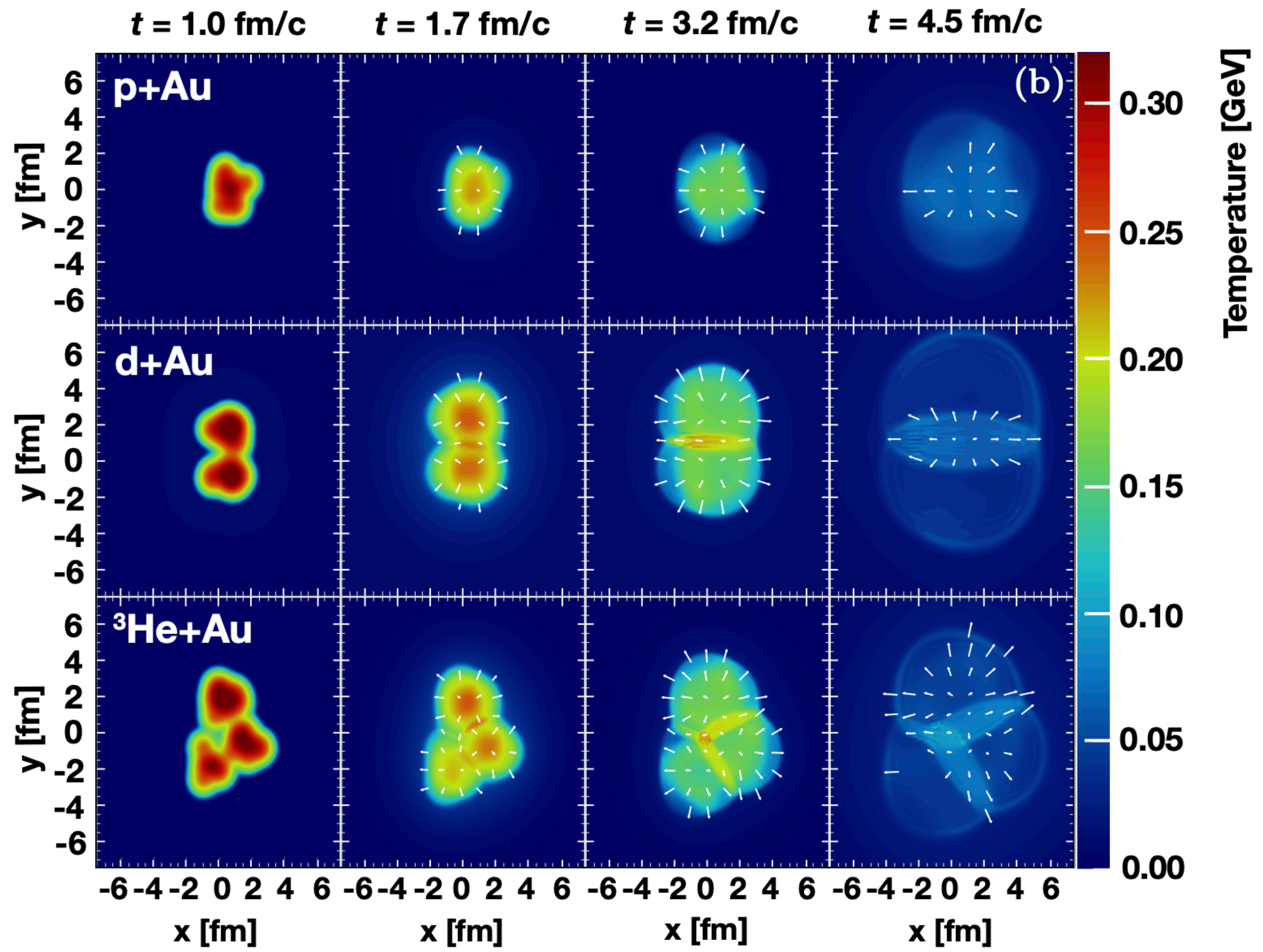
A brief summary of the different epochs in HICs

Early times: Out of equilibrium matter (Glasma)

Short lived and dominated by classical configurations

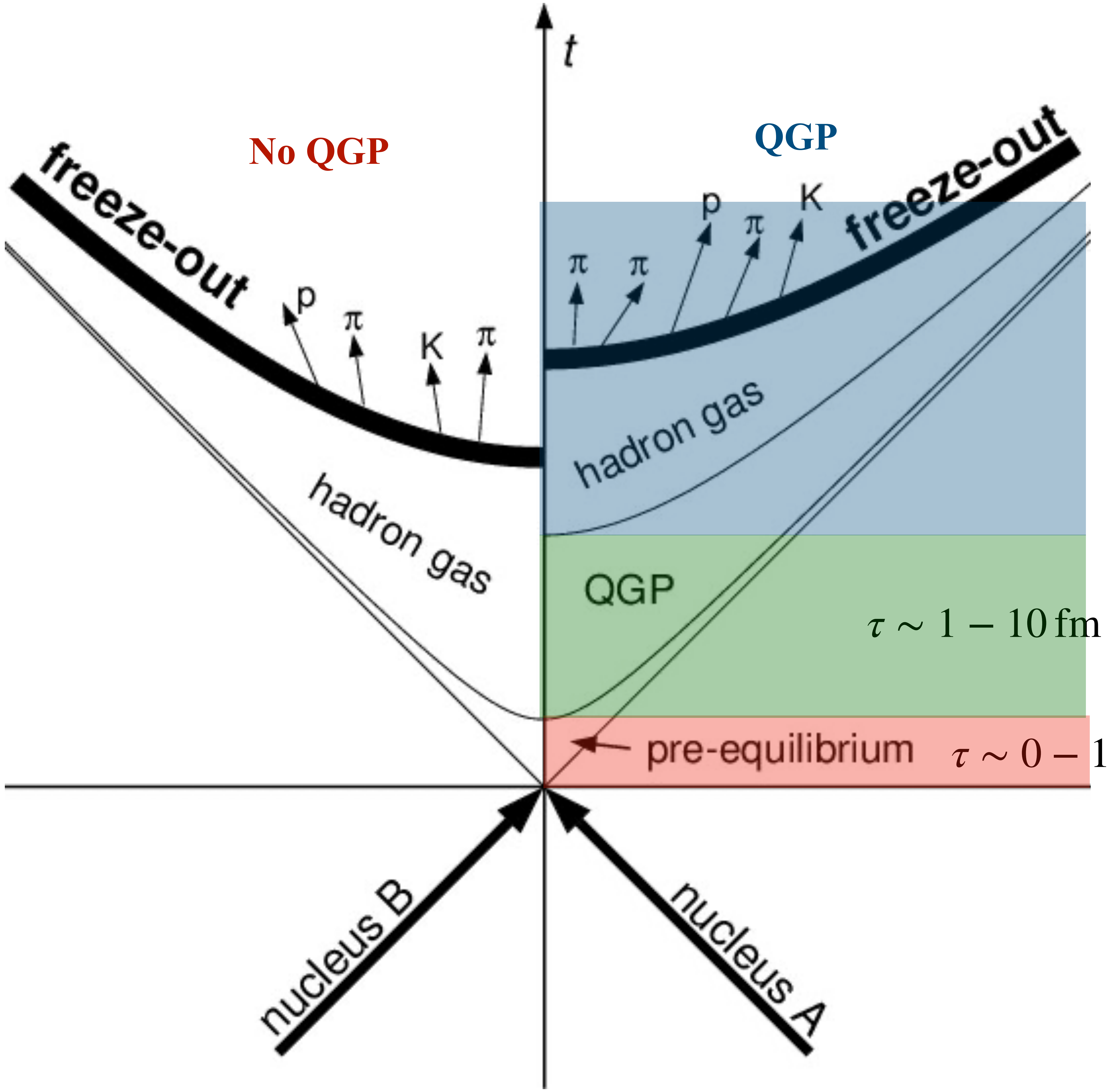
Intermediate times: Quark Gluon Plasma phase

Long lived, expanding hydro system where quarks and gluons are not confined inside hadrons



[PHENIX collaboration, 2018]

The spacetime picture of HICs



$\tau \sim 1 - 10\,\text{fm}$

$\tau \sim 0 - 1\,\text{fm}$

$1\,\text{fm} \sim 10^{-24}\,\text{s}$

A brief summary of the different epochs in HICs

Early times: Out of equilibrium matter (Glasma)

Short lived and dominated by classical configurations

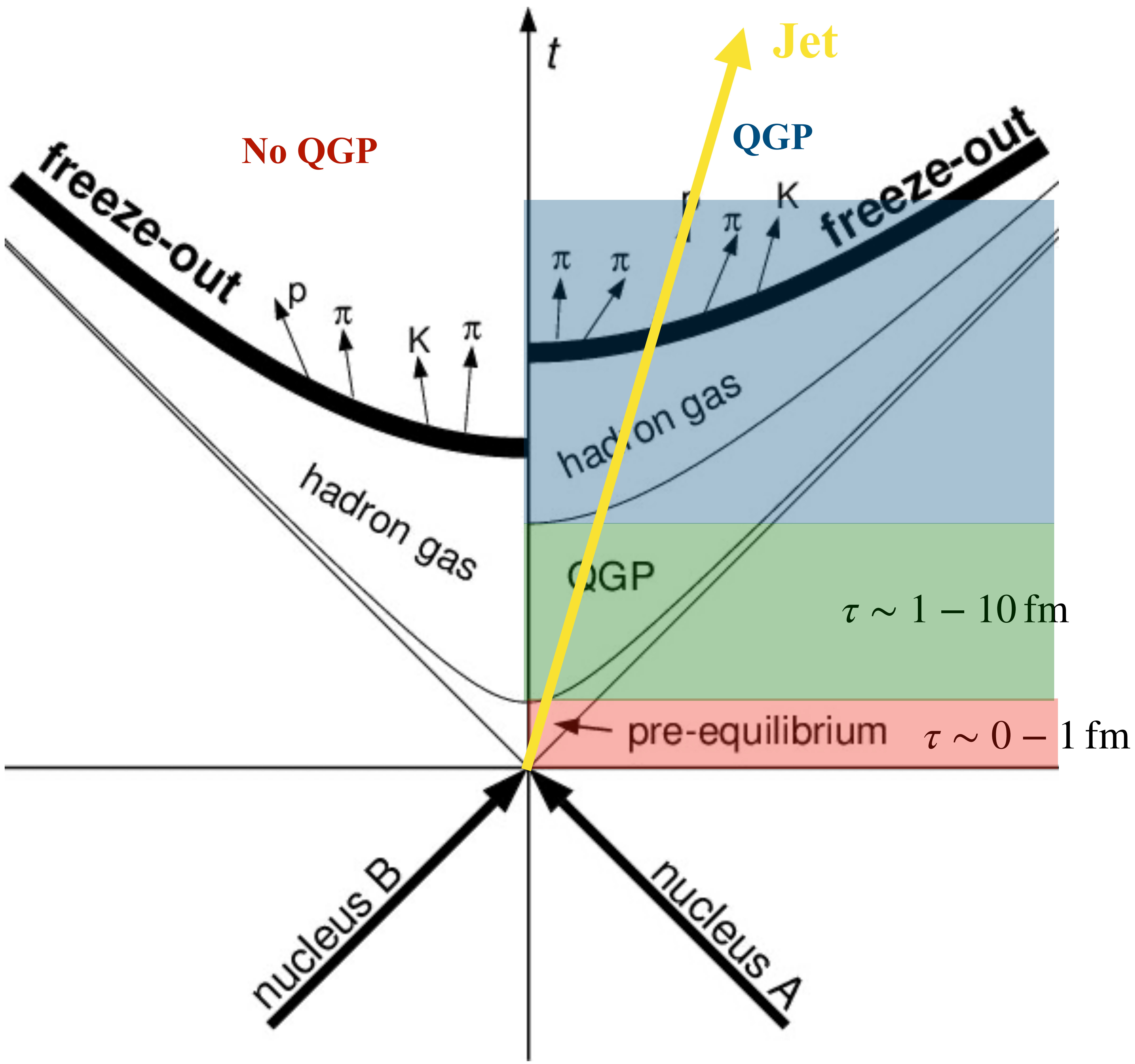
Intermediate times: Quark Gluon Plasma phase

Long lived, expanding hydro system where quarks and gluons are not confined inside hadrons

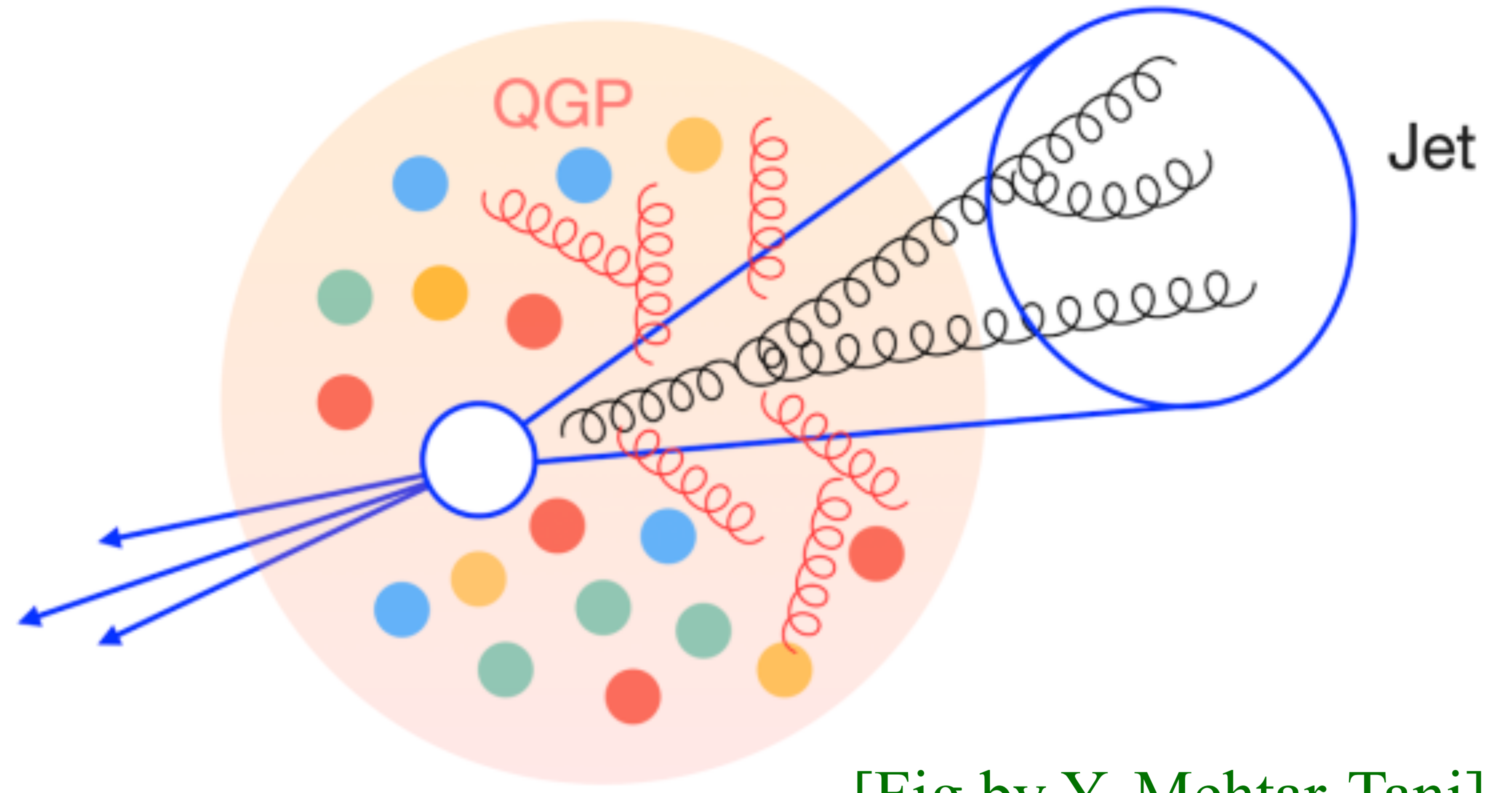
Hadronic phase: Temperature below critical value

Gas of hadrons, which eventually free streams to the detectors

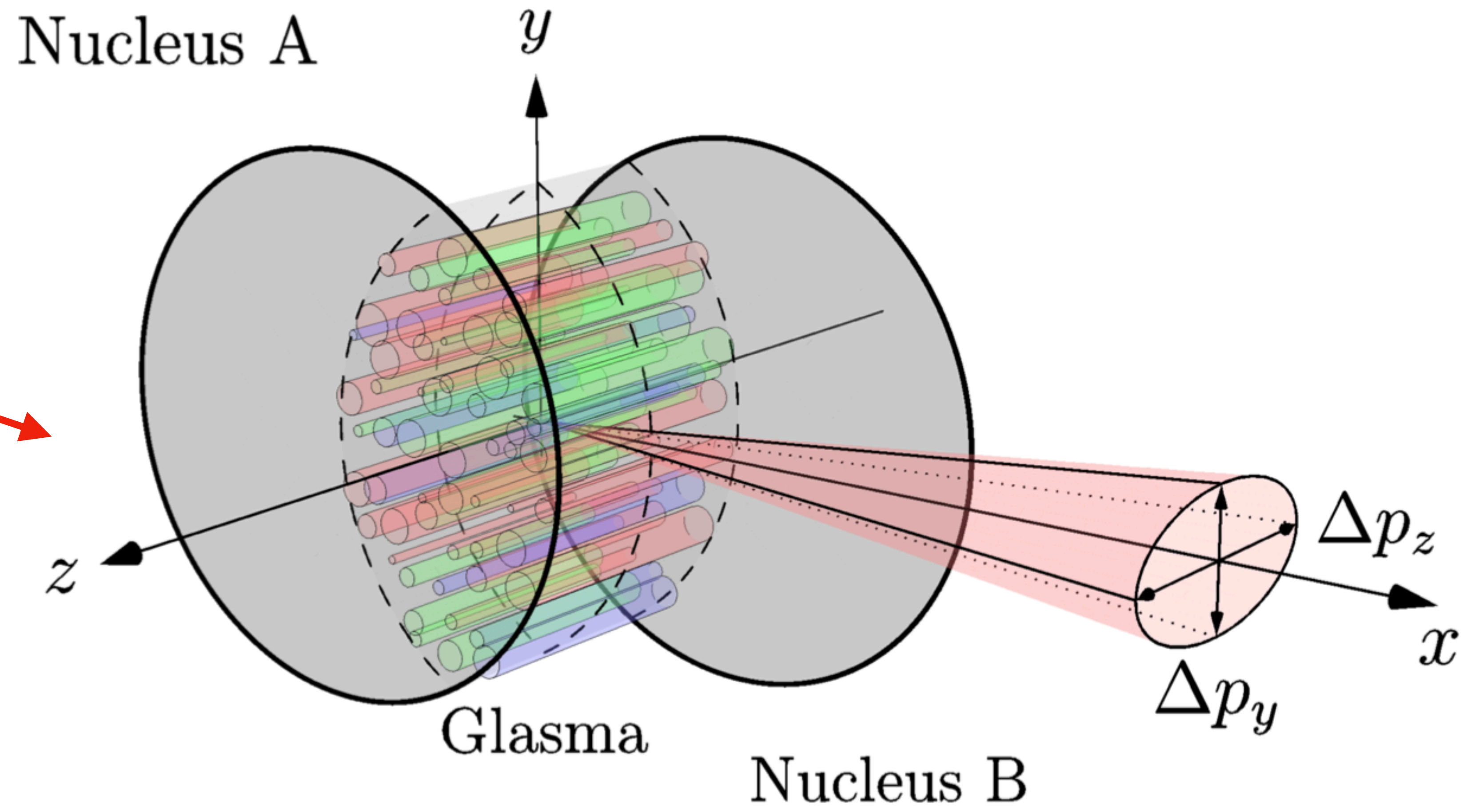
The spacetime picture of HICs



An ideal probe: QCD jets



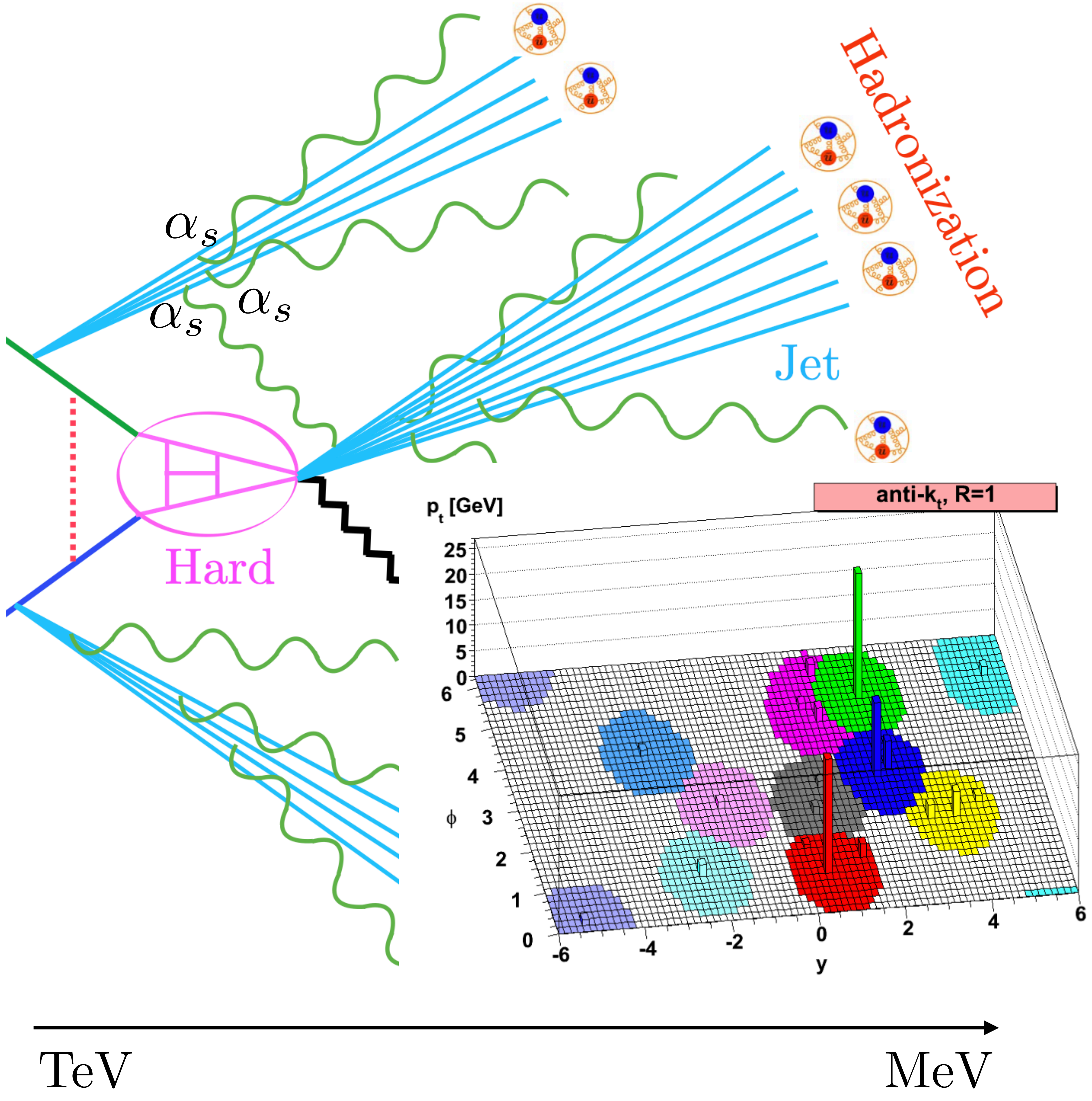
[Fig by Y. Mehtar-Tani]



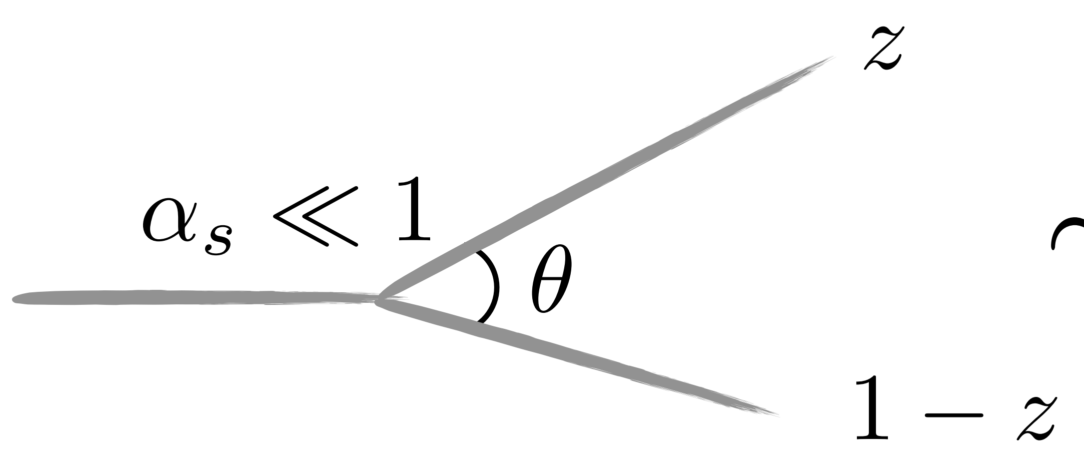
[A. App, D. I. Muller, D. Schuh, 2009.14206]

Jets in pp

In general, an event is decomposed as



The probability to branch takes the form

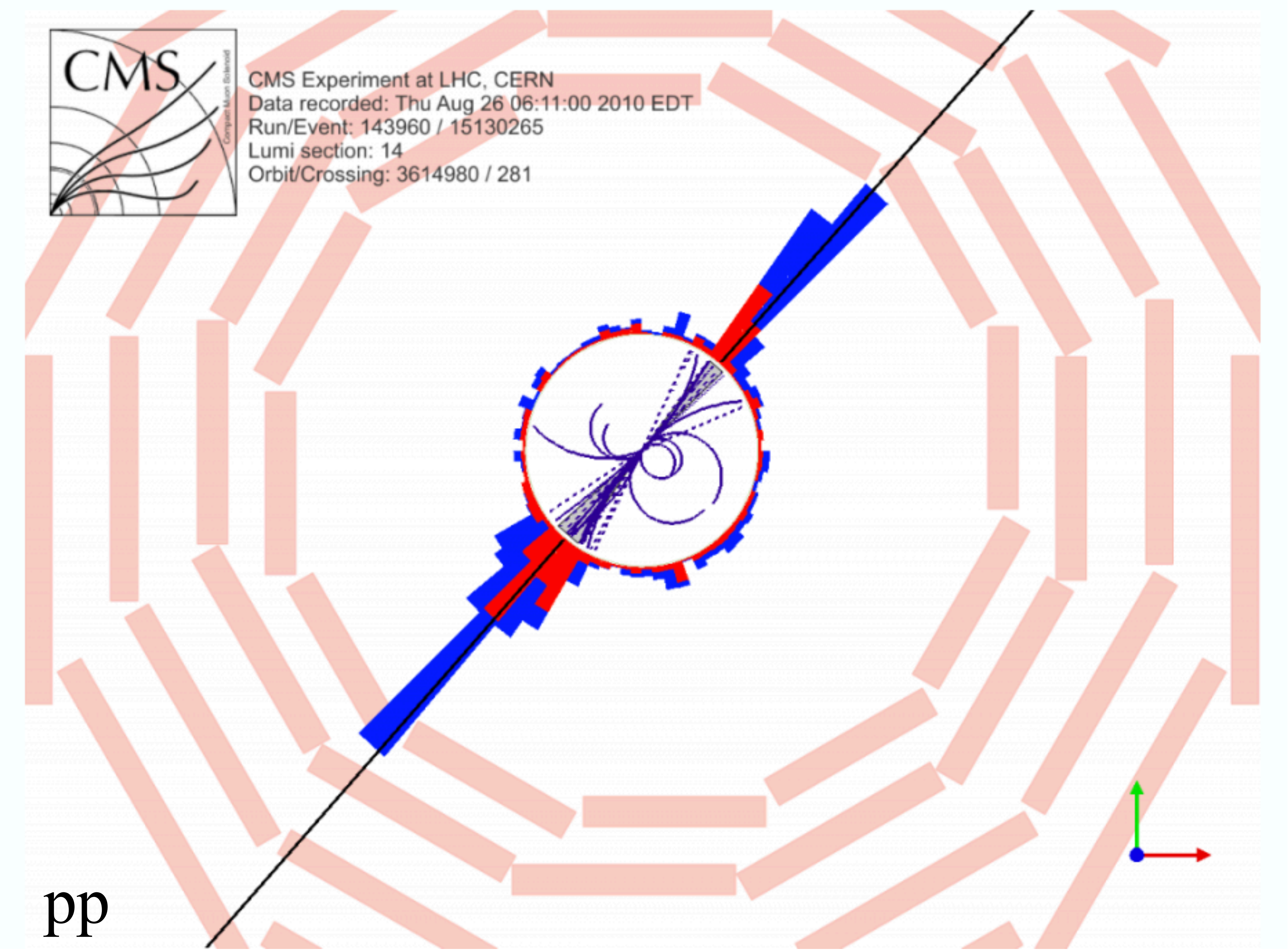


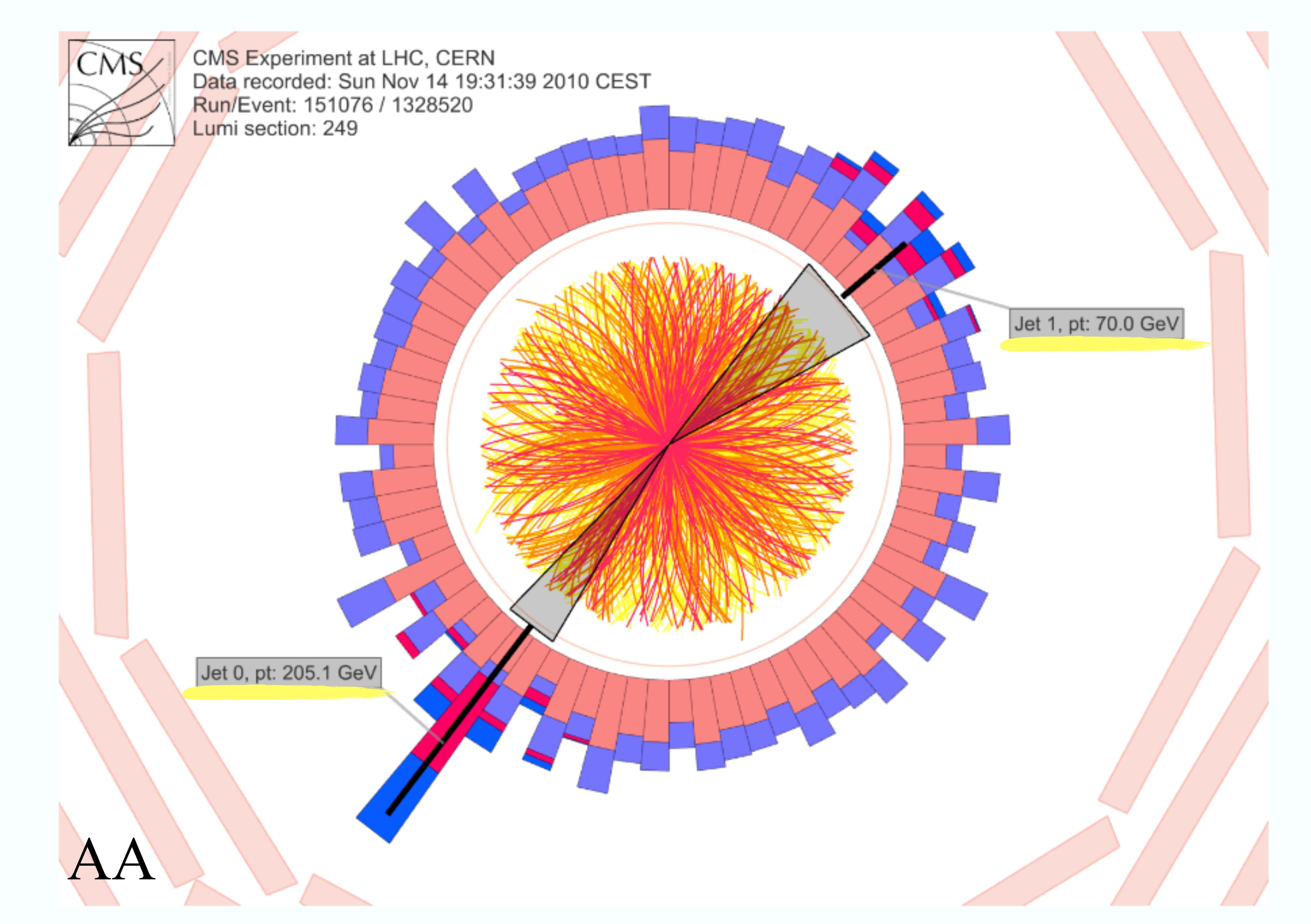
$$\sim \alpha_s \, \mathrm{d}\log\theta \, \mathrm{d}\log z$$

LO	1		
NLO	$\alpha\, L$	α	
NNLO	$\alpha^2\, L^2$	$\alpha^2\, L$	α^2
$\ldots$	$\ldots$	$\ldots$	$\ldots$
N^{k}LO	$\alpha^k\, L^k$	$\alpha^k\, L^{k-1}$	$\alpha^k\, L^{k-2}$

L is some large logarithm of scales' ratios

What happens to jets in HICs ?



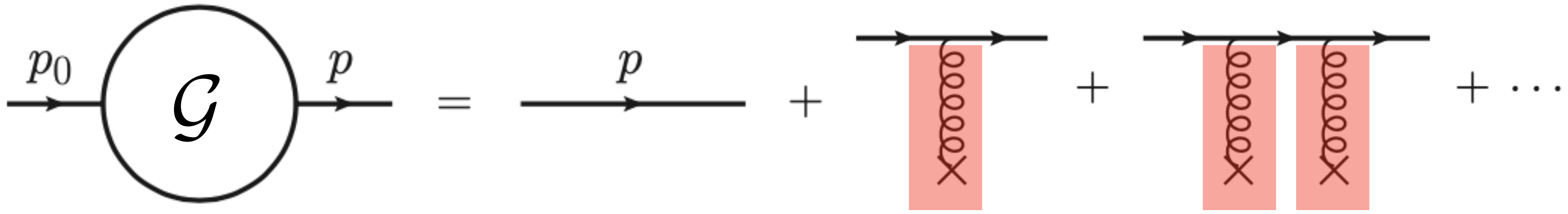


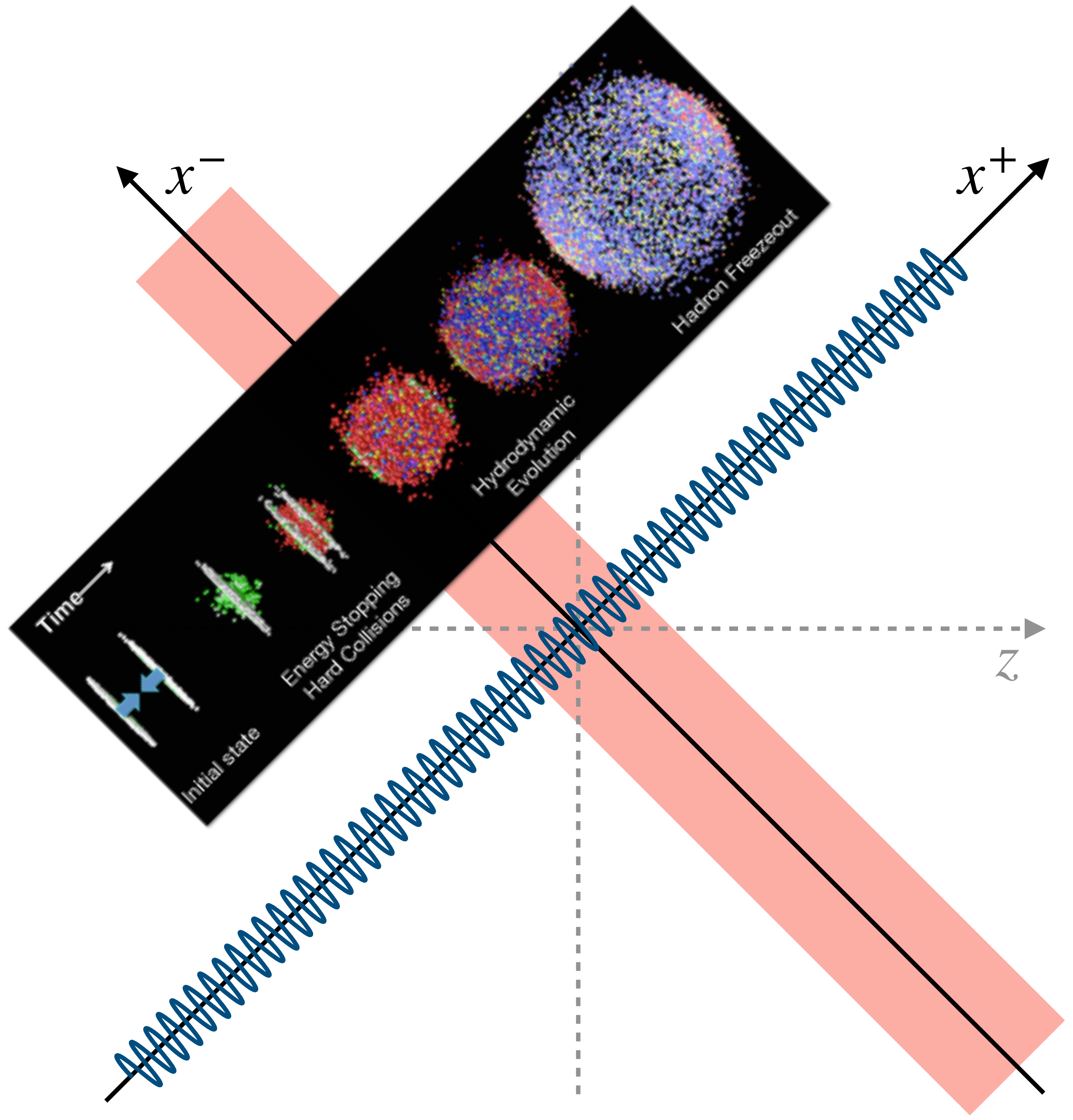
The modification of jets due to the propagation in the QGP is generally referred to as **jet quenching**

How does one compute these modifications ?

Jets in AA

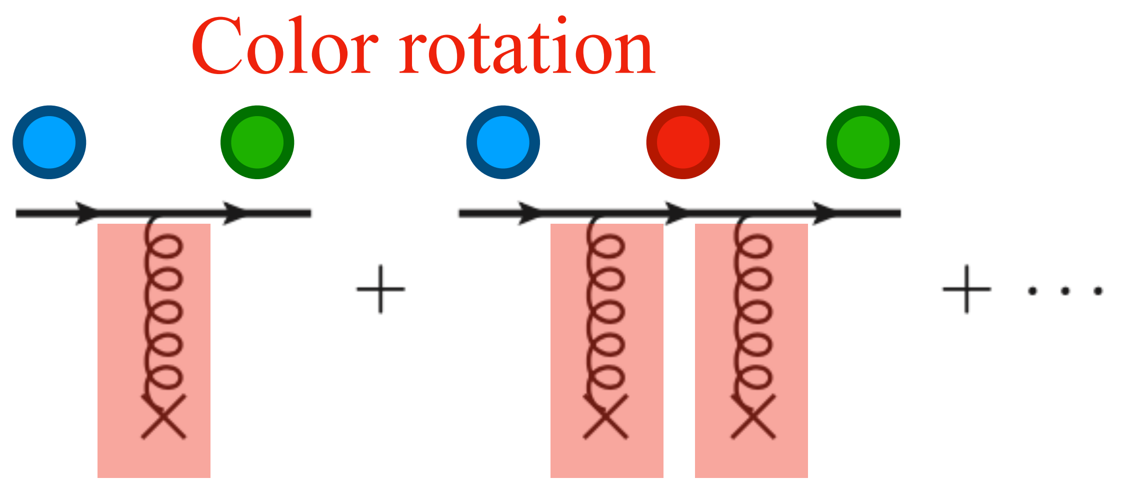
In the medium, one needs to account for interactions with the QGP:





For very energetic particles there is a simple solution:

$$\mathcal{G}(\boldsymbol{x}_2, t_2; \boldsymbol{x}_1, t_1) =$$ Positional kicks from medium particles



[Higher-Twist, early 2000s]

[BDMPS-Z, early 2000s]

[GLV, early 2000s]

[AMY, early 2000s]

Any process reduces to computing correlators of these objects

QCD vertices

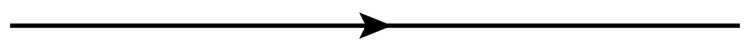
$$d\sigma \sim \langle \mathcal{T} \prod \{\mathcal{G}, \Gamma\} \rangle_{\text{matter}}$$

Simplest example, consider just 1 particle

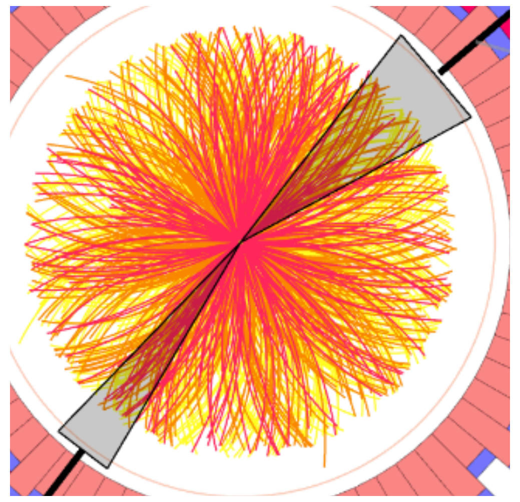
$$d\sigma^{(1)} \sim \langle \mathcal{G}\mathcal{G}^{\dagger} \rangle_{\text{matter}}$$

Jets in AA

$$\alpha_s^0$$

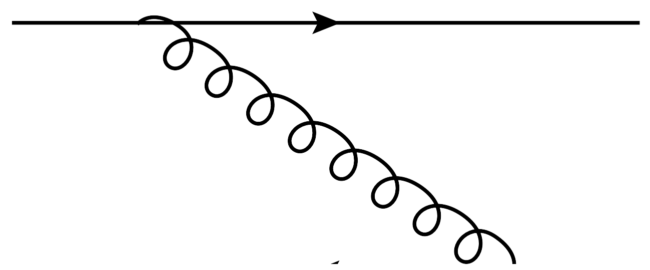


Momentum broadening

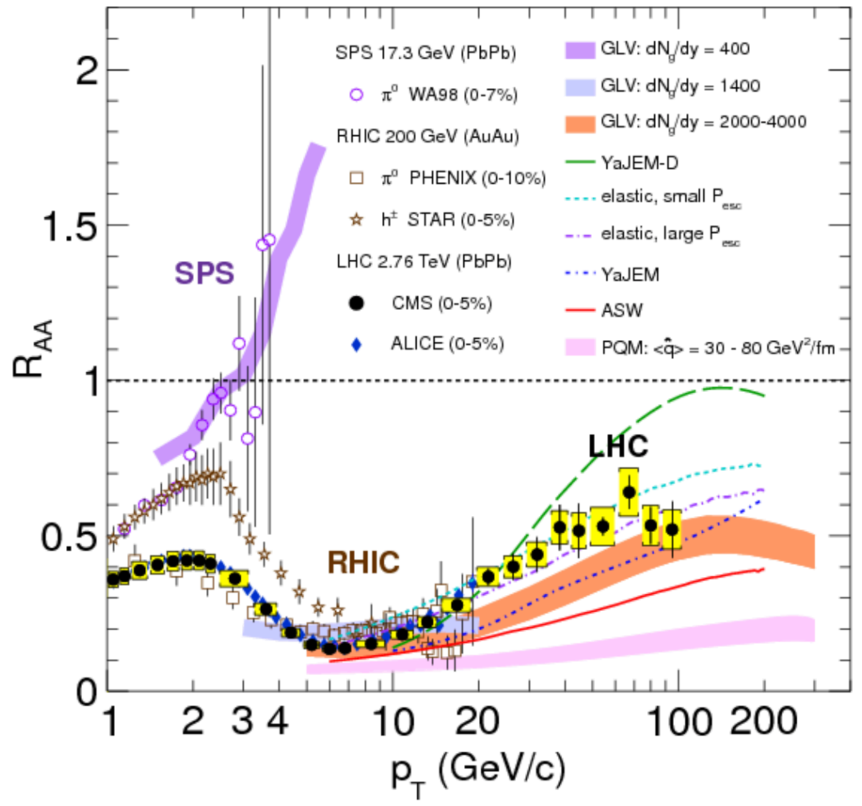


Known from pre-QCD era

$$\alpha_s$$



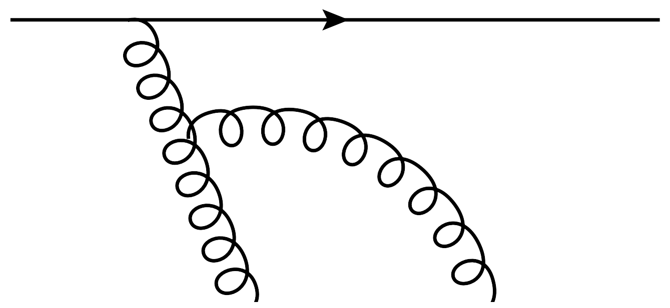
Energy loss



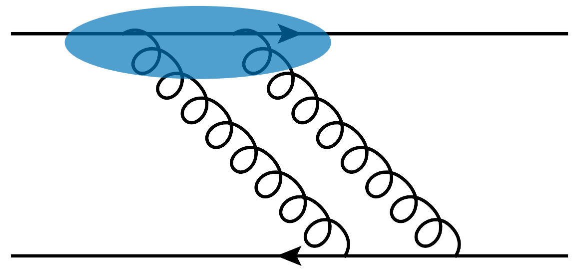
First studies, early 2000's

Full kinematics, 2000-ongoing

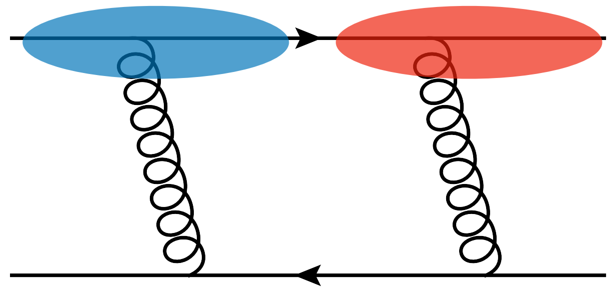
$$\alpha_s^{n \gg 1}$$



Medium modified partonic cascades



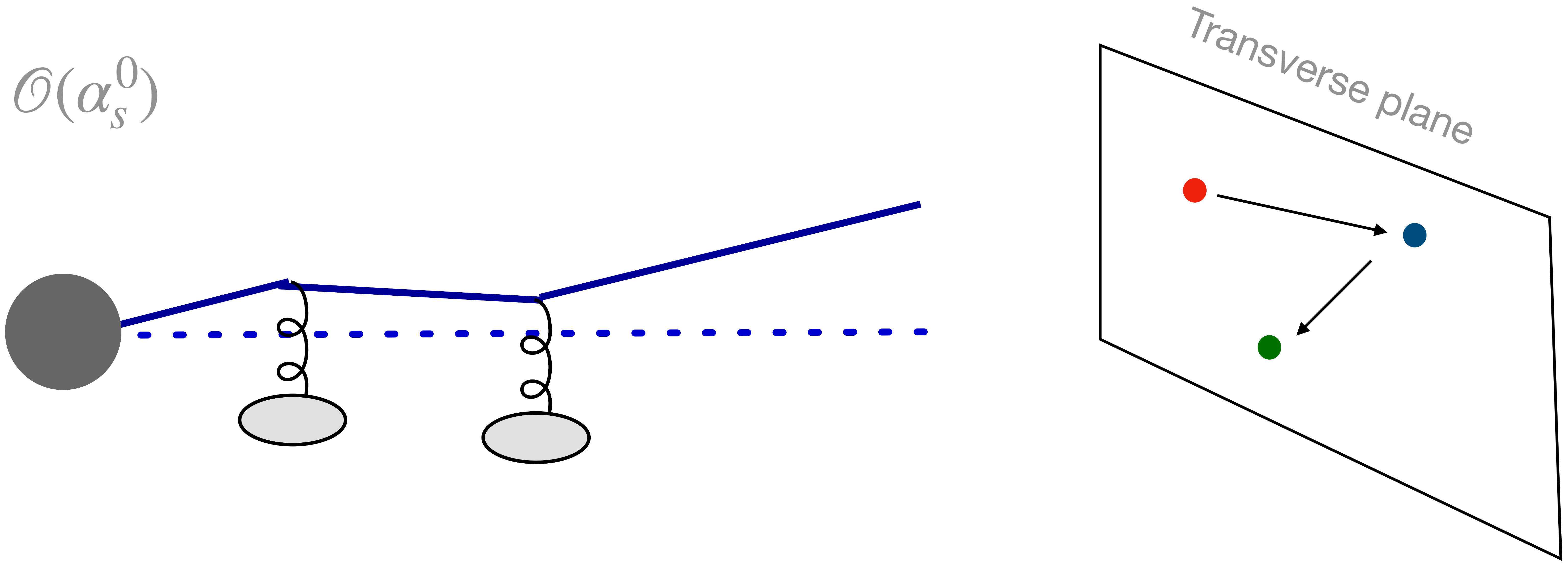
vs



Simple set ups, 2010-ongoing

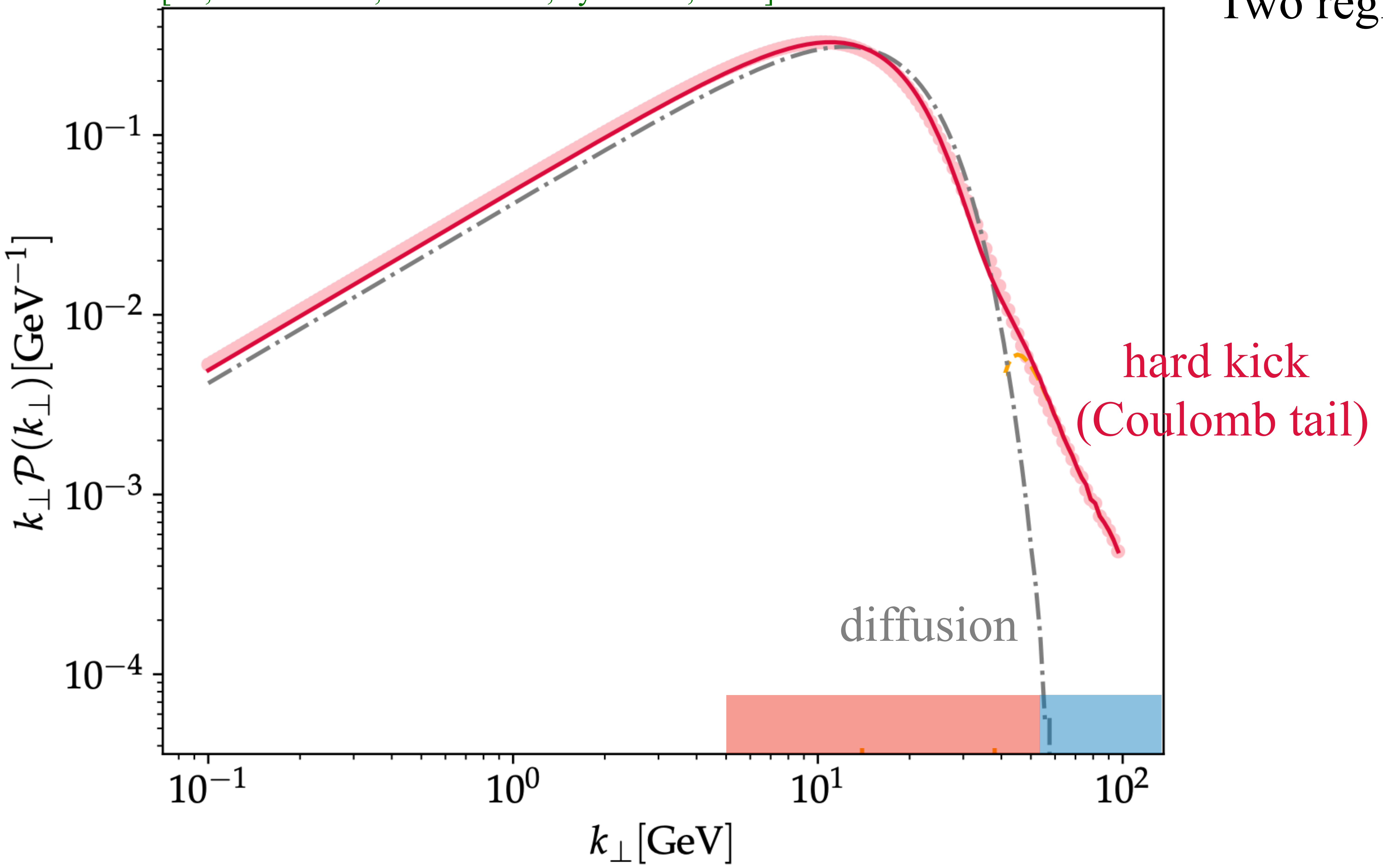
Momentum broadening

$\mathcal{O}(\alpha_s^0)$



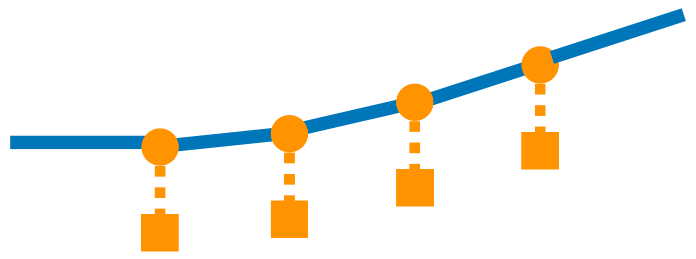
How is momentum transferred to the parton ?

[JB, Mehtar-Tani, Soto-Ontoso, Tywoniuk, 2022]



Two regimes :

Diffusive broadening

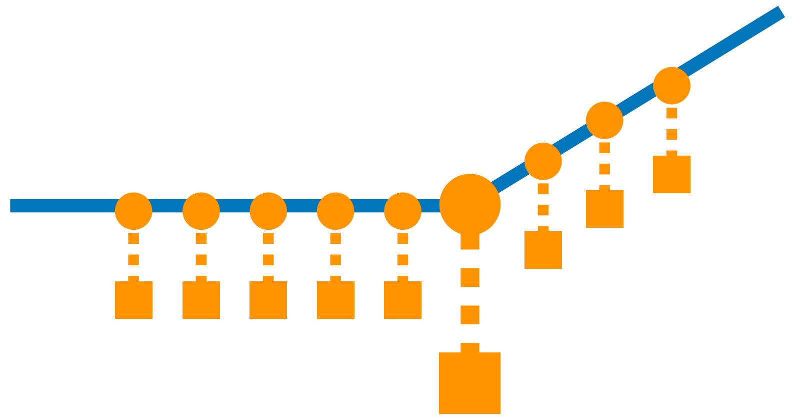


= many soft kicks

jet quenching parameter

$$\partial_t \mathcal{P}(\boldsymbol{k}) = -\frac{\hat{q}}{4}\partial^2_{\boldsymbol{k}}\mathcal{P}(\boldsymbol{k})$$

Single hard interaction

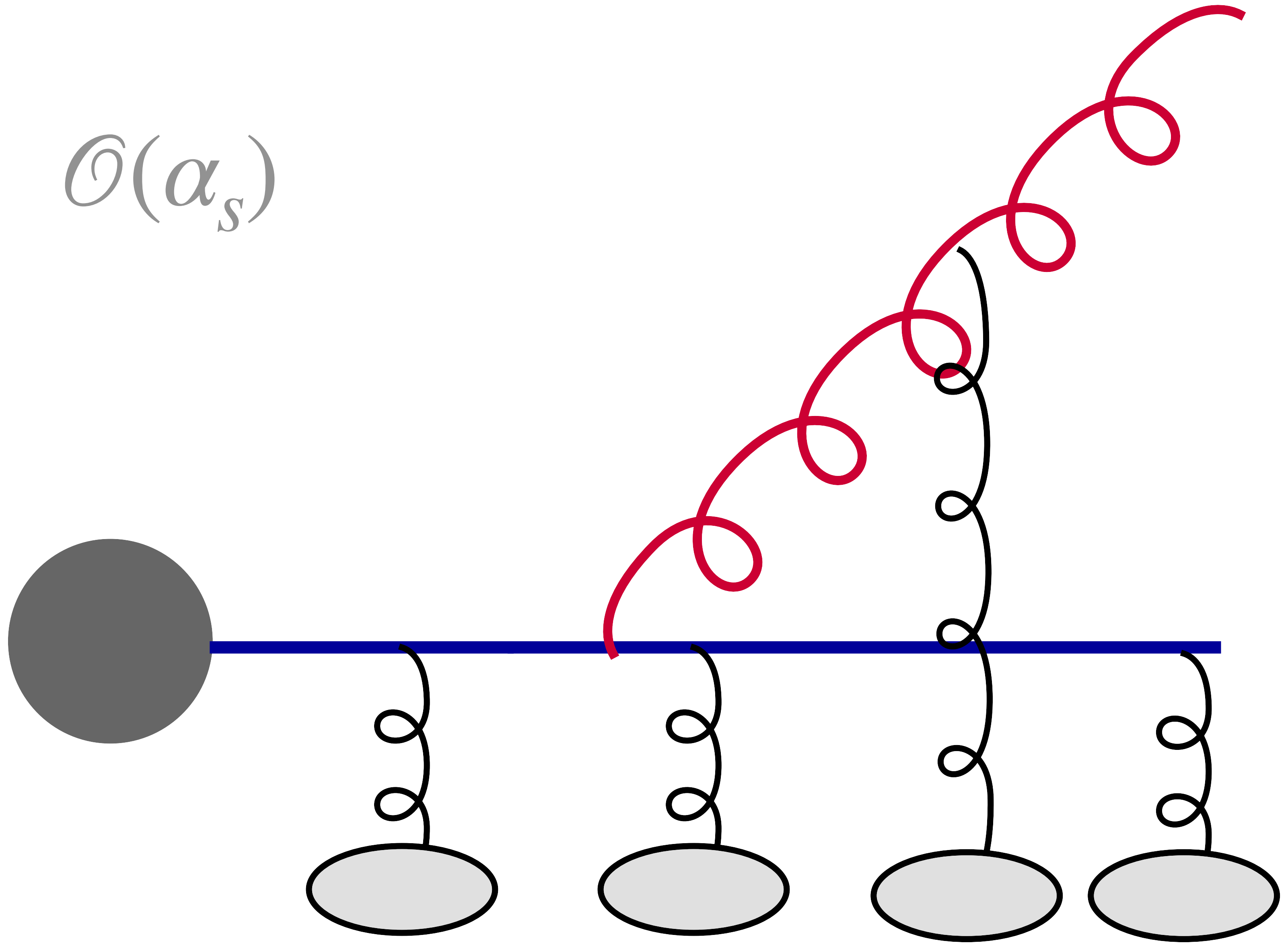


= one hard kick

$$\mathcal{P}(\boldsymbol{k}) \propto \frac{1}{\boldsymbol{k}^4}$$

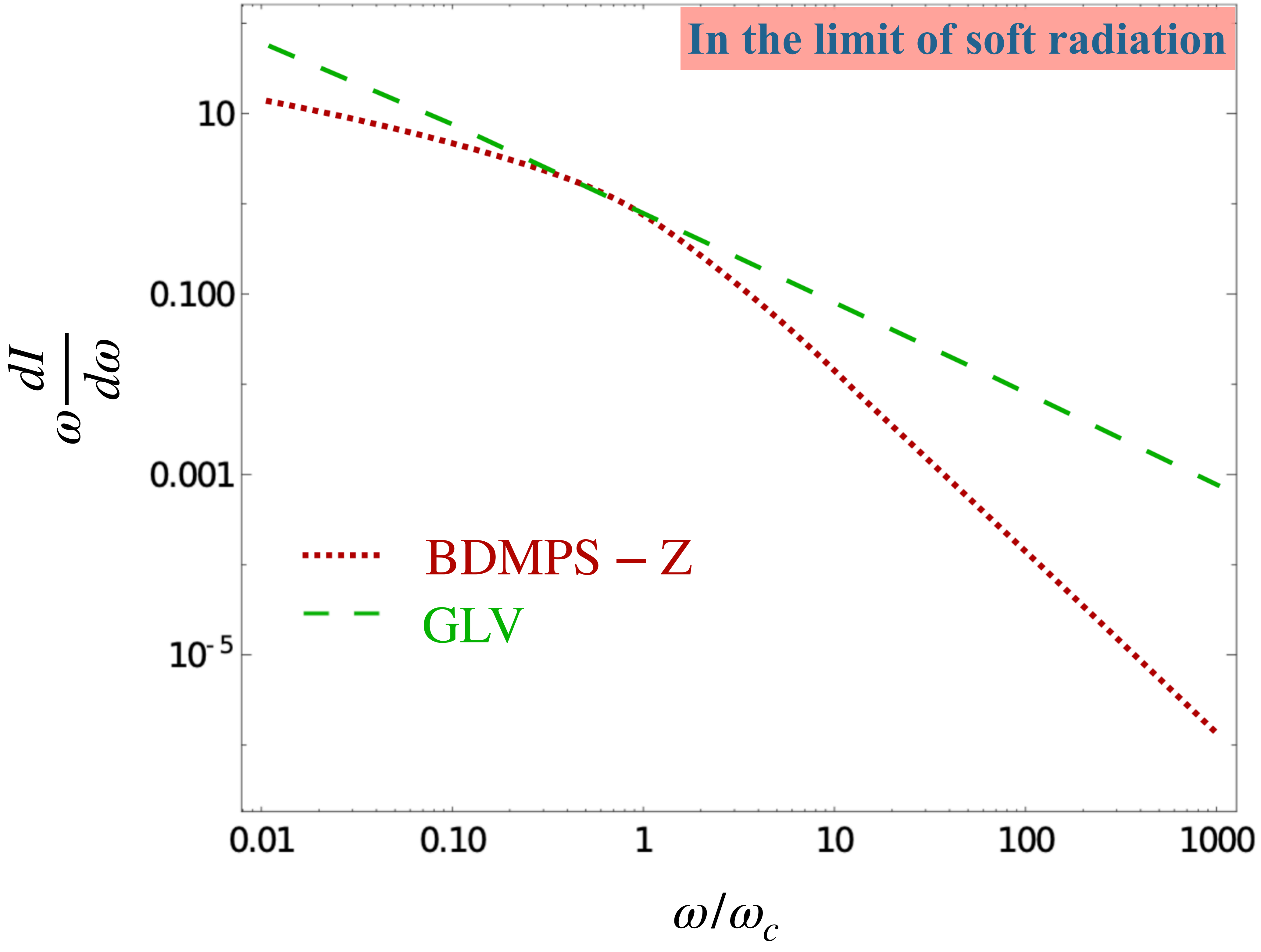
Medium induced radiation

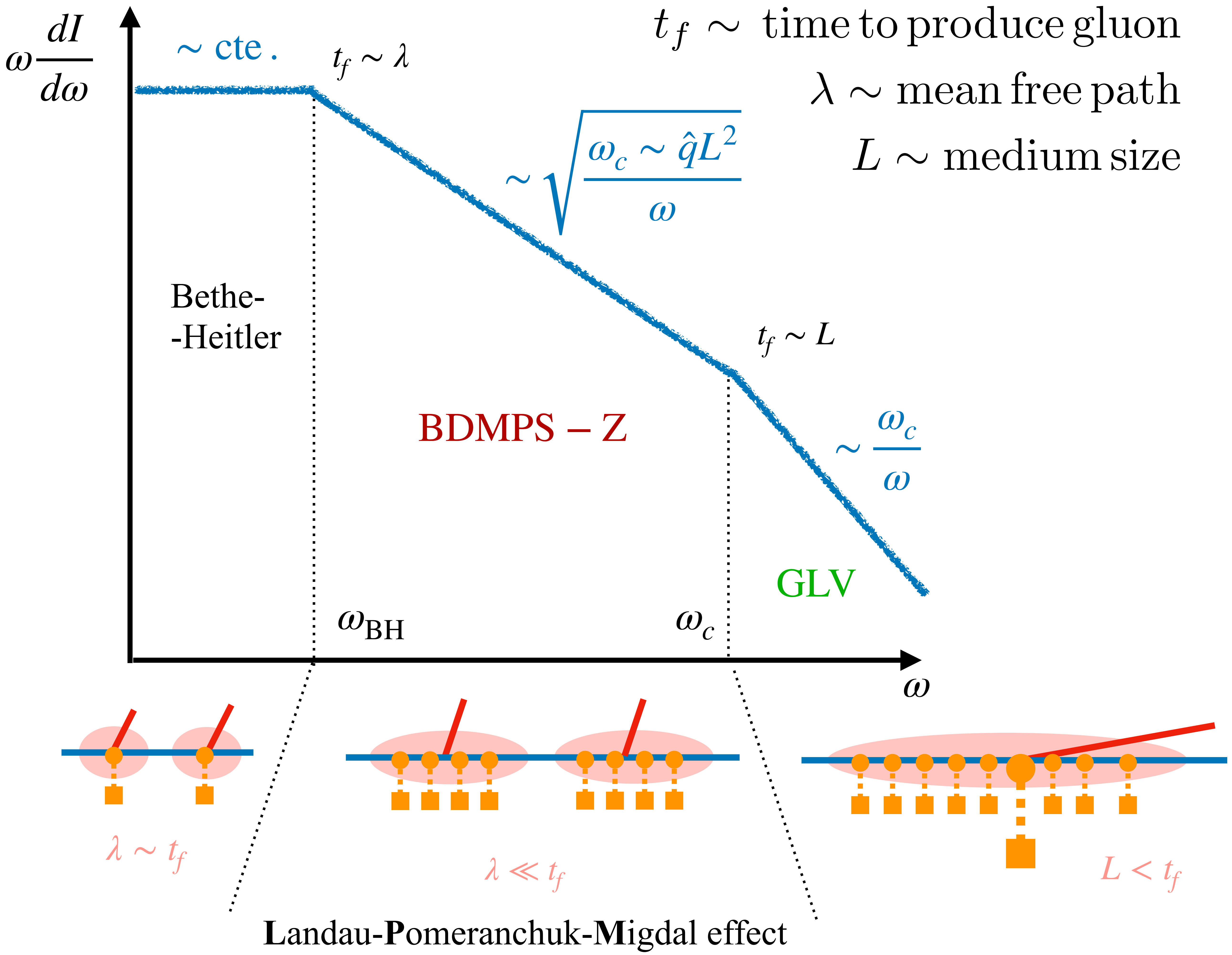
$\mathcal{O}(\alpha_s)$



How do particles radiate in-medium ?

[JB, Mehtar-Tani, 2021]





$$t_f \sim \frac{2\omega}{k_\perp^2} \sim \frac{2\omega}{\hat{q}t_f} \longrightarrow \omega\frac{dI}{d\omega} \sim \alpha_s\frac{L}{t_f} \sim \alpha_s\sqrt{\frac{\hat{q}L^2}{\omega}}$$

$\langle k_\perp^2\rangle \sim \hat{q}t$

LPM effect

Jets in AA

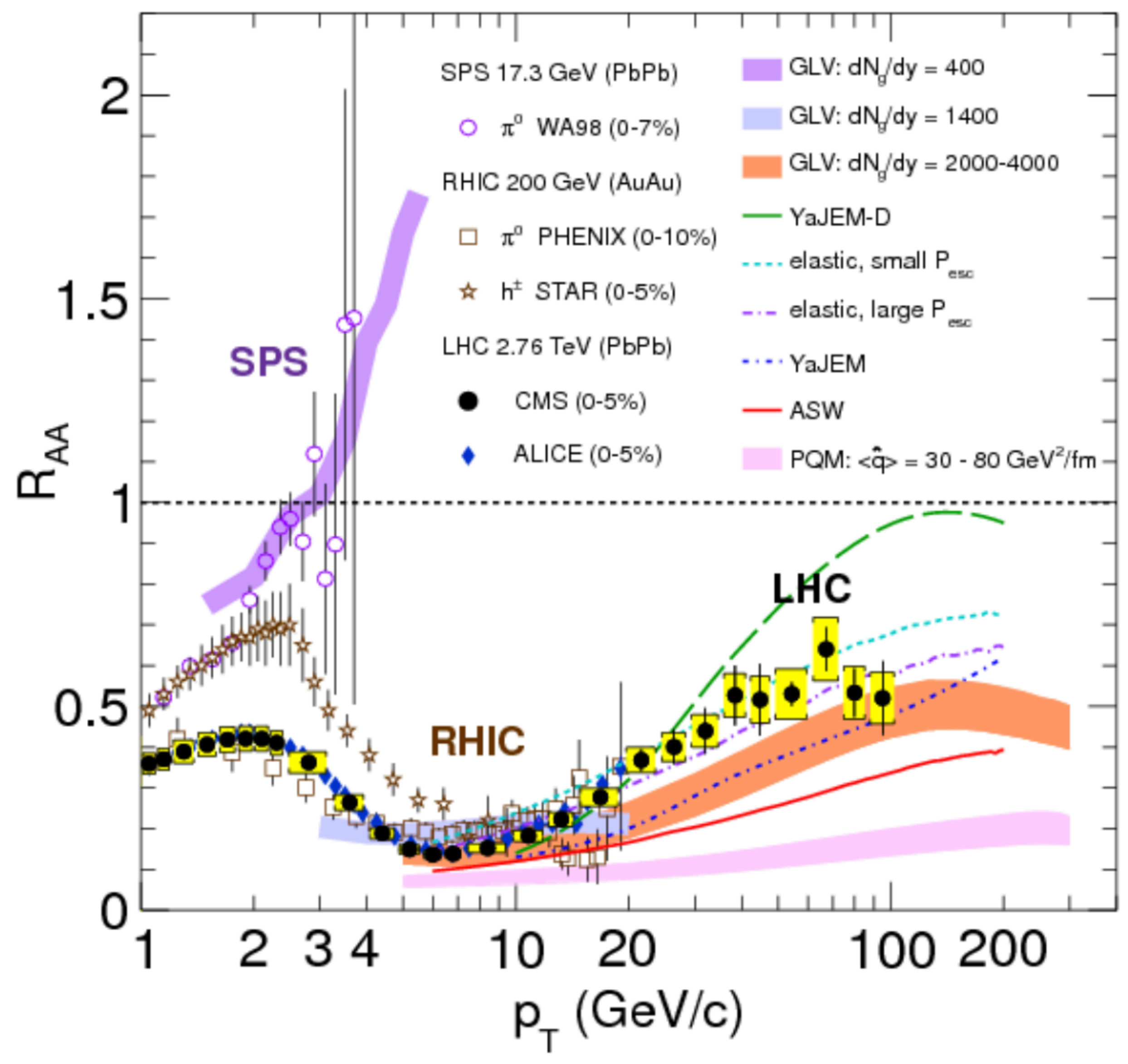
Energy loss in the quenching weight approximation

$$\frac{d\sigma_q^{\rm med}}{dp_t d\theta} = \int_0^\infty d\varepsilon\, D_q(\varepsilon) \frac{d\sigma_q^{\rm vac}}{dp_t' d\theta}\Big|_{p_t'=p_t+\varepsilon}$$

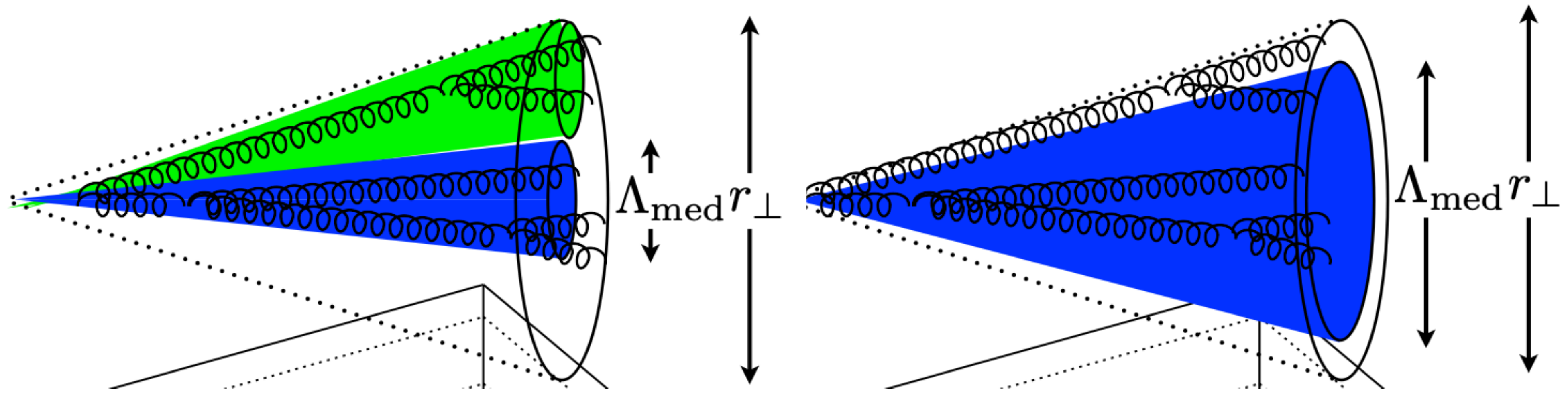
$$\frac{d\sigma_q^{\rm med}}{dp_t d\theta} \approx \frac{d\sigma_q^{\rm vac}}{dp_t d\theta} \int_0^\infty d\varepsilon\, D_q(\varepsilon) e^{-\frac{n\varepsilon}{p_t}} \equiv Q_q(p_t) \frac{d\sigma_q^{\rm vac}}{dp_t d\theta}$$

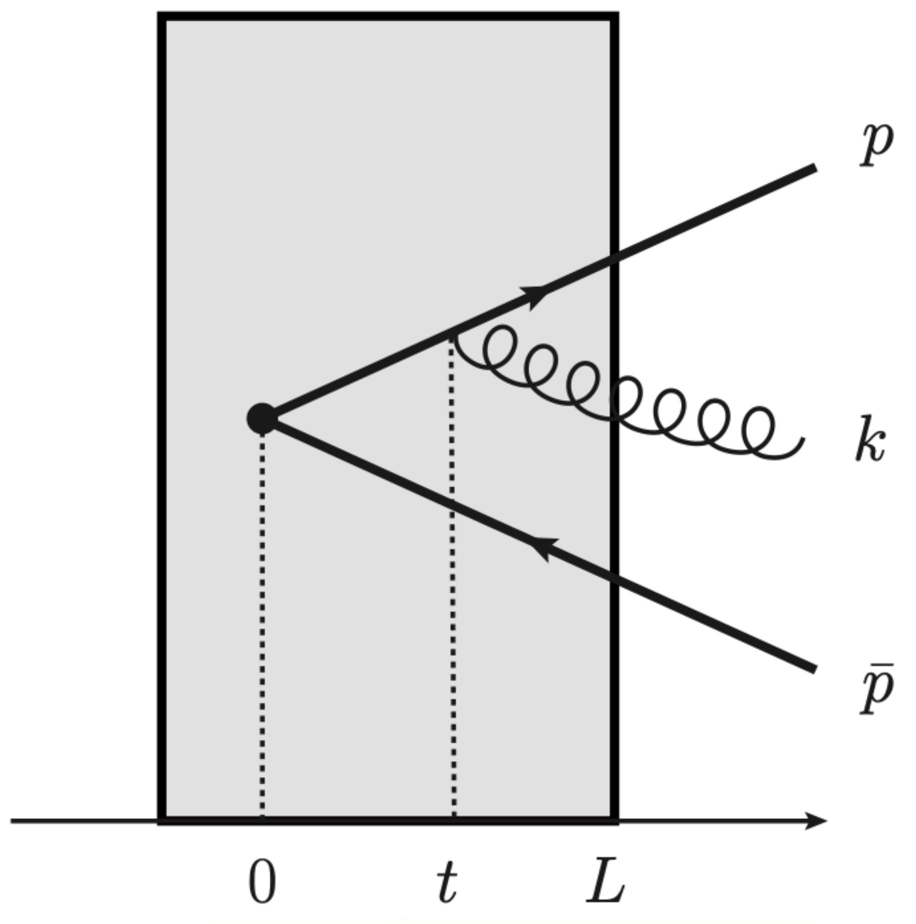
[R. Baier, Y. Dokshitzer, A. H. Mueller, hep-ph/0106347]

$0 < Q_q < 1$



Color coherence and anti-angular ordering





vacuum → angular ordering

medium → anti-angular ordering

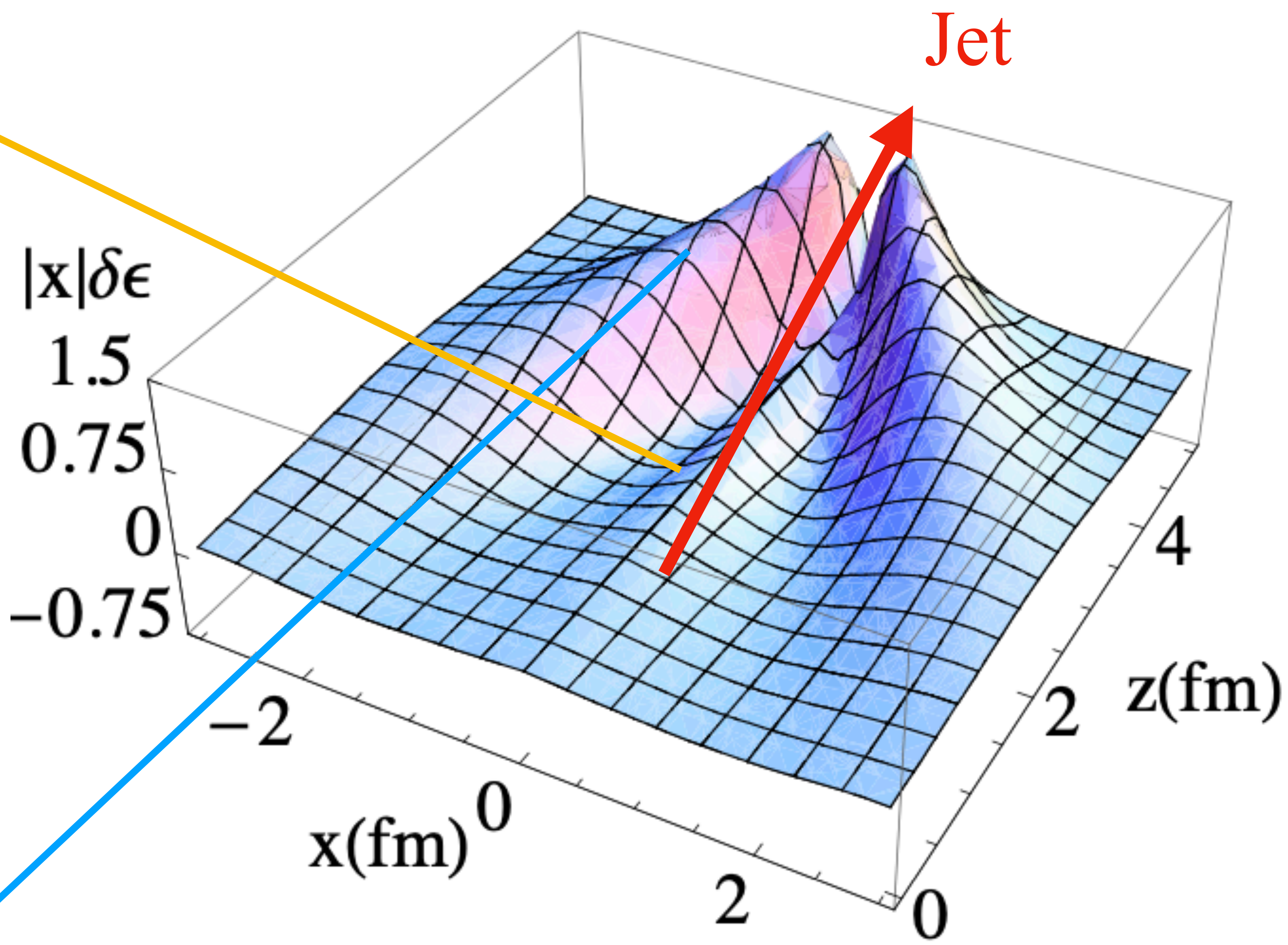
[Salgado, Tywoniuk, Mehtar-Tani; Iancu, Casalderrey-Solana, early 2010s]

Jets in AA

Back-reaction: Jet induced wake on the plasma

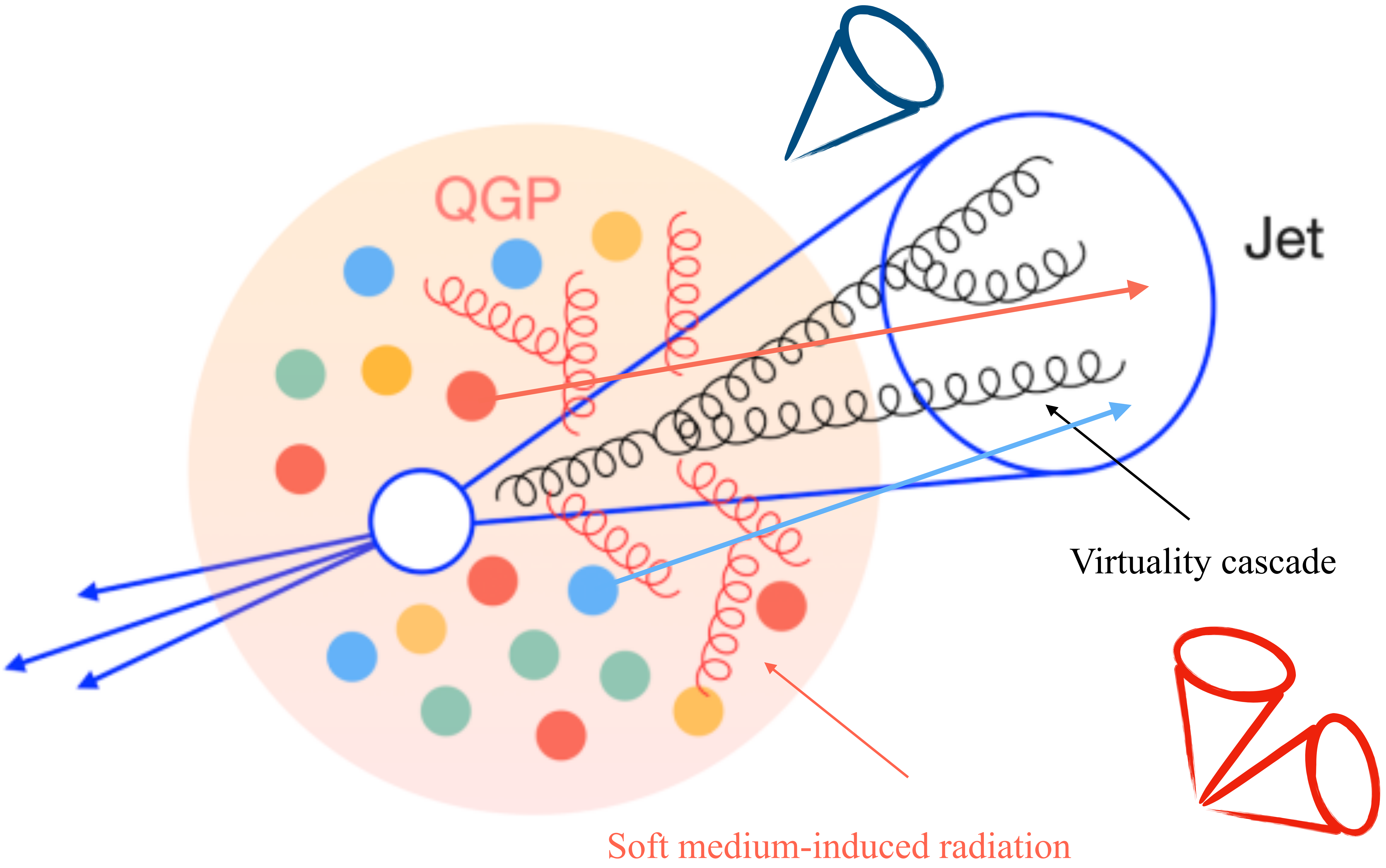
Depletion of energy

[G.-Y. Qin, A. Majumder, H. Song, U. Heinz, 0903.22255]



Excess of soft particles

These results form the basis for jet quenching phenomenology



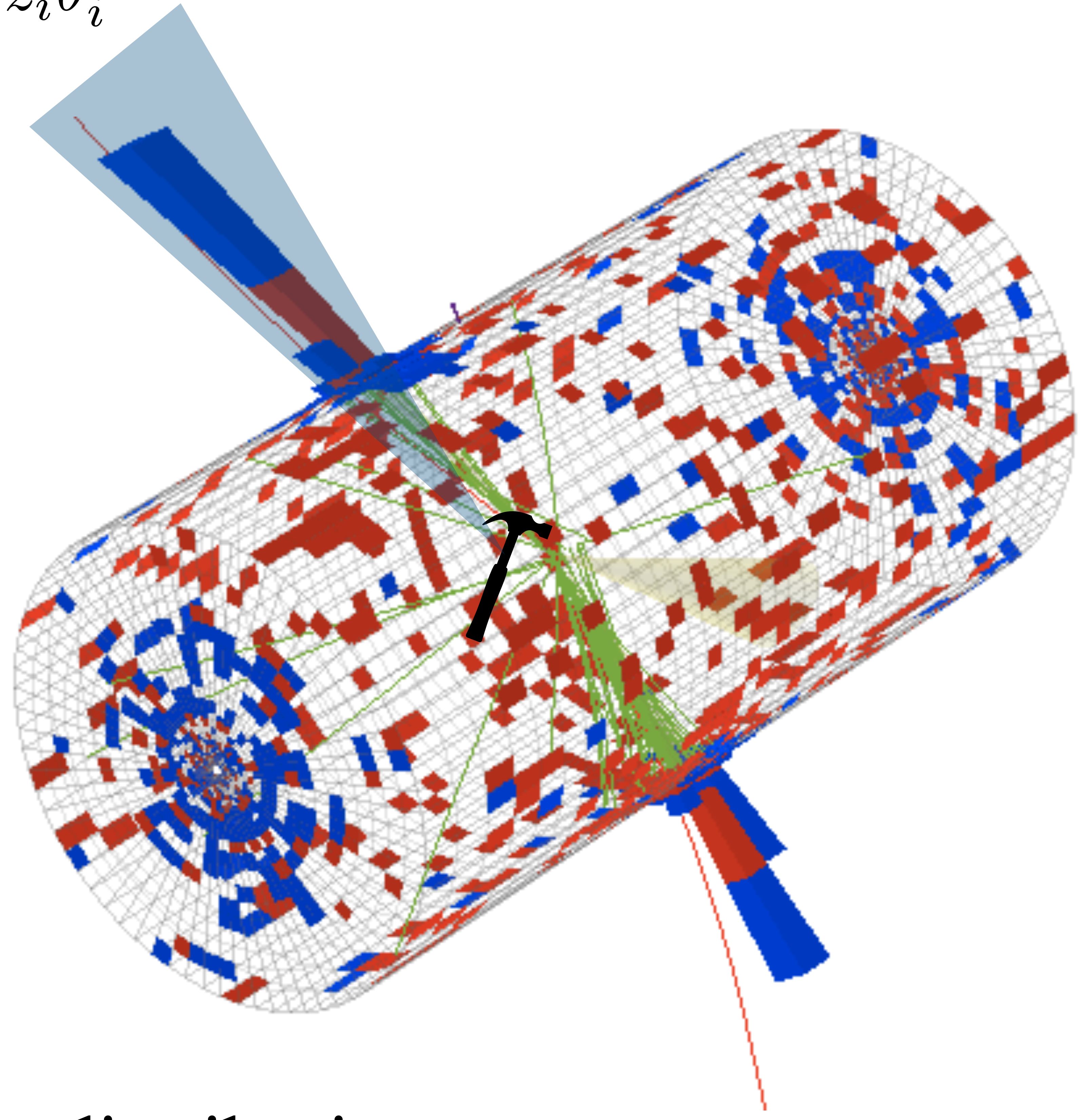
Jet substructure observables

How to understand the structure of jets

[Caron-Huot, et al, 2209.00008]

$\approx$

$$o_{m^2} = \sum_i z_i \theta_i^2$$



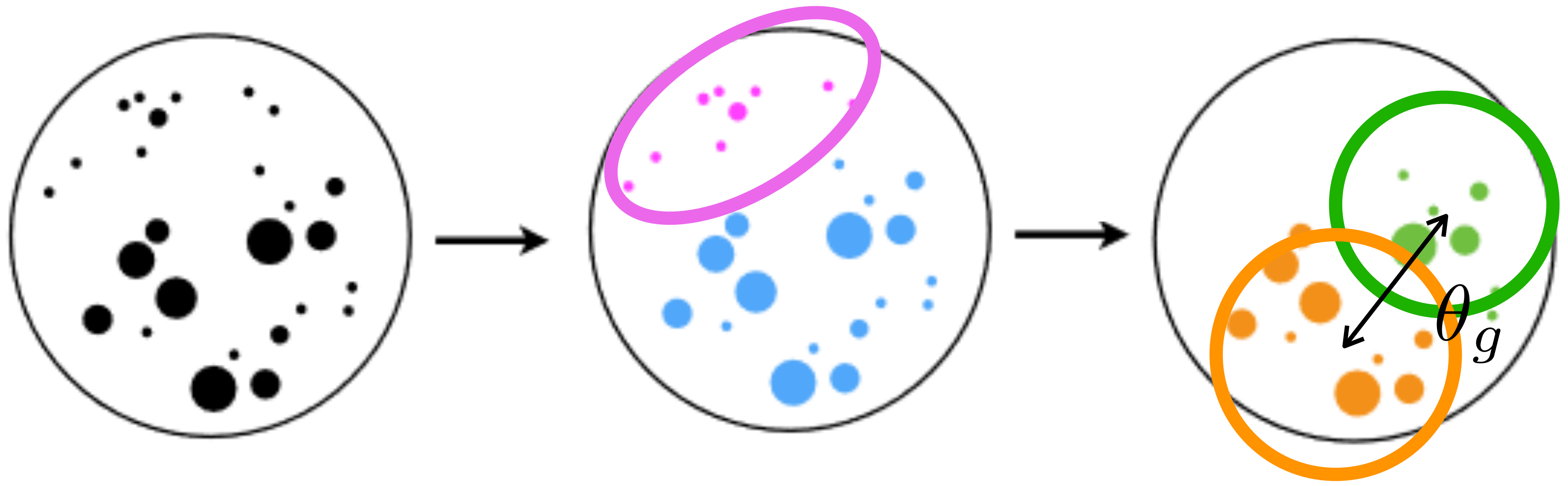
Schematically, one can compute “shapes” of the underlying distribution

$$\frac{d\sigma}{do} = \int d^4x \, e^{iq^\mu x_\mu} \langle \Omega | \hat{O}(x) \mathcal{M}[\hat{o}] O^\dagger(0) | \Omega \rangle \,, \qquad \text{e.g.} \qquad \mathcal{M}[\hat{o}] = \delta(\hat{o} - o)$$

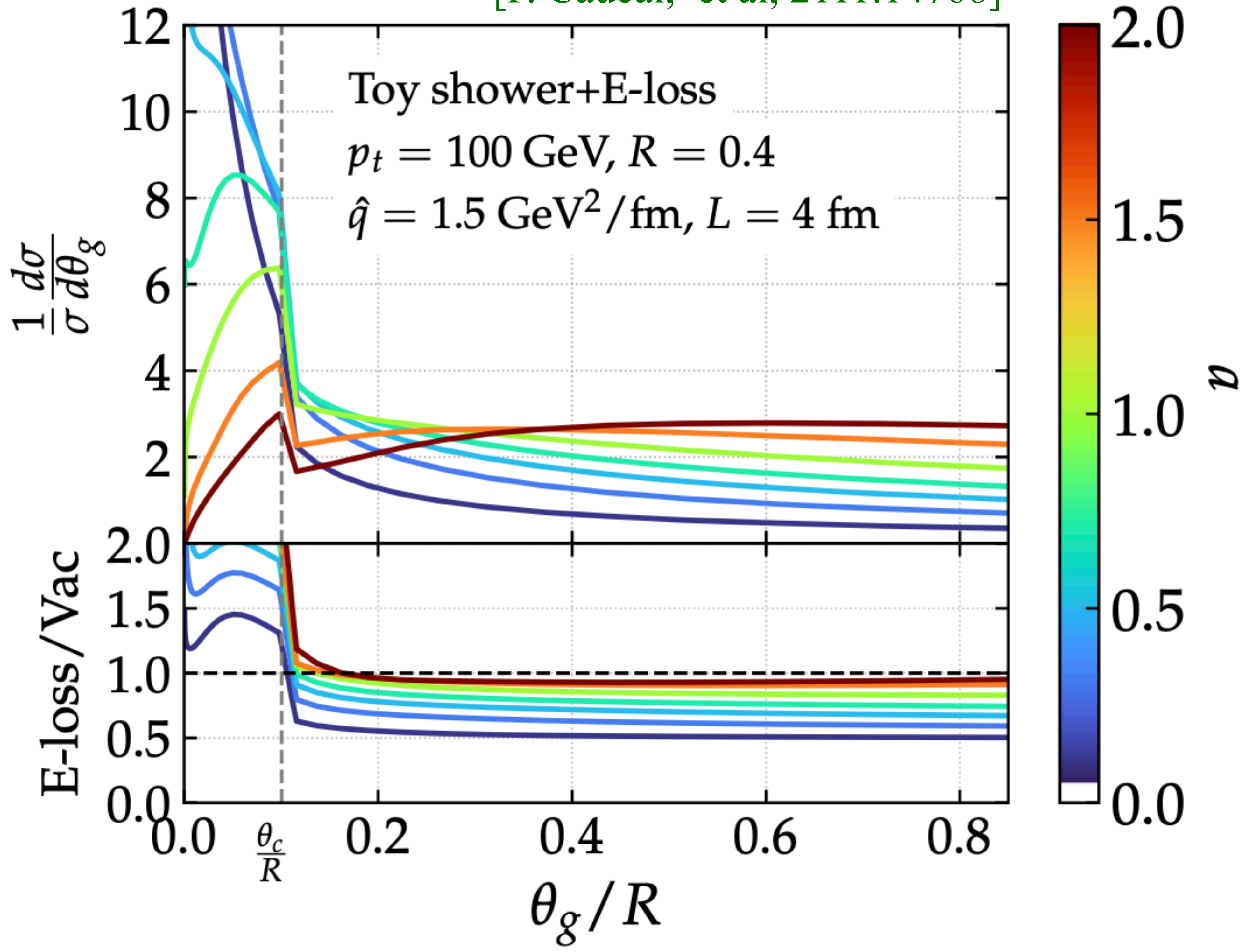
How to understand the structure of jets: jet shapes

The common strategy boils down to reclustering the jet and then selecting only a subset of constituents

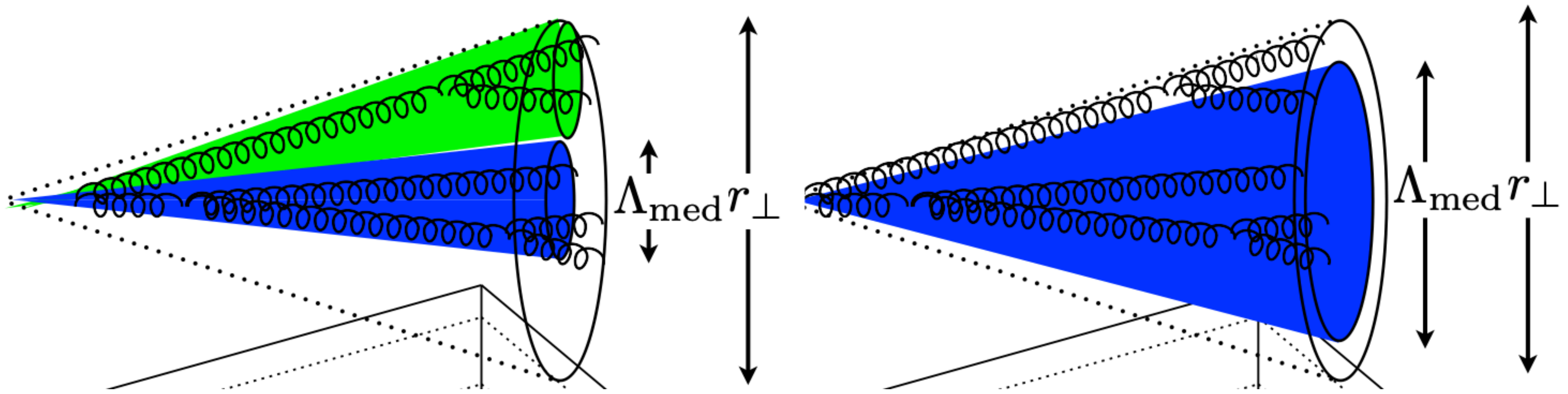
remove these particles



[P. Caucal, et al, 2111.14768]



Allows to explore the details of the jet cascade. However, formally the treatment is not trivial even in vacuum.

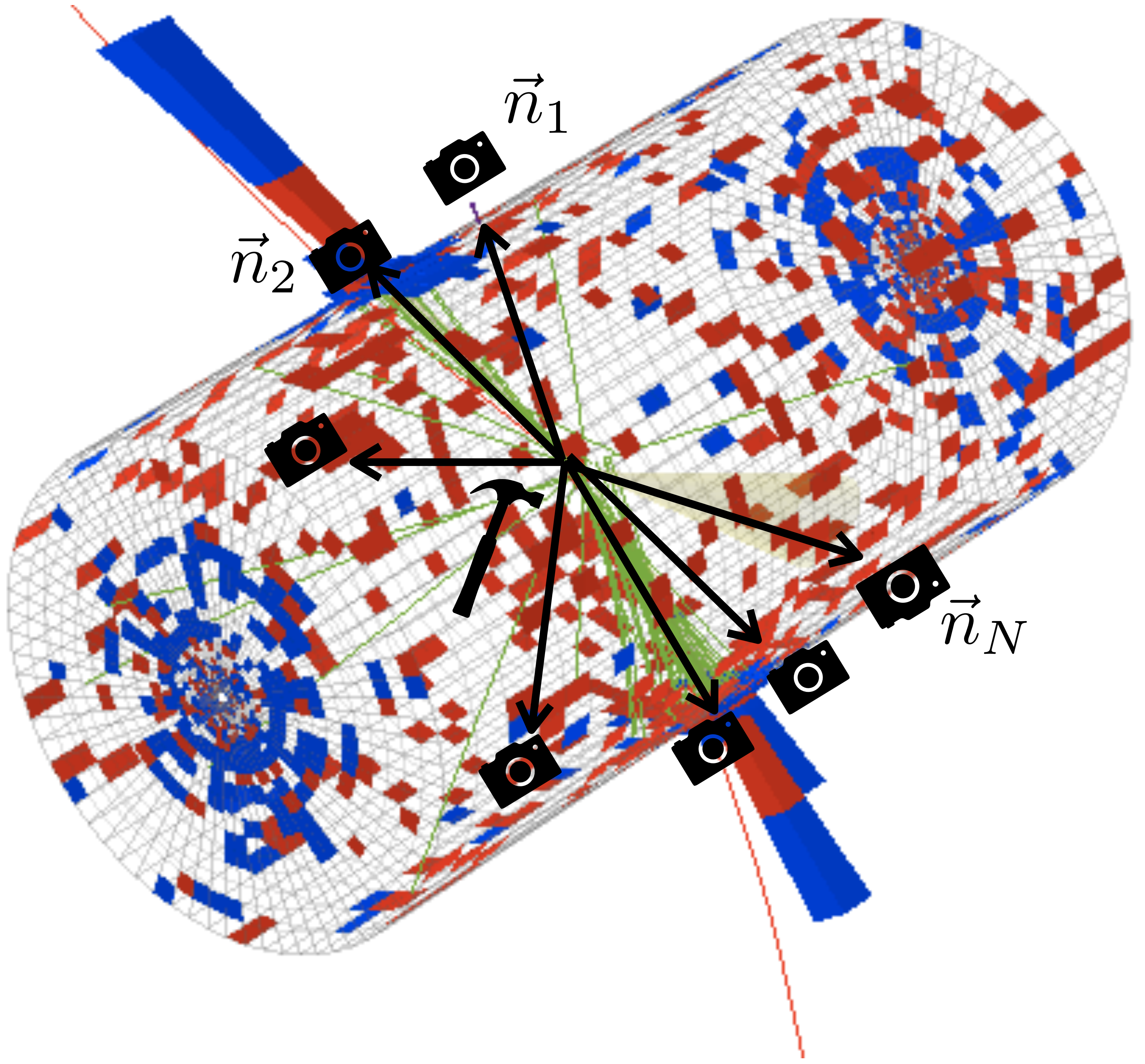


[See Takao and Monika's talk in this session for more substructure studies]

How to understand the structure of jets

[Caron-Huot, et al, 2209.00008]

$\approx$

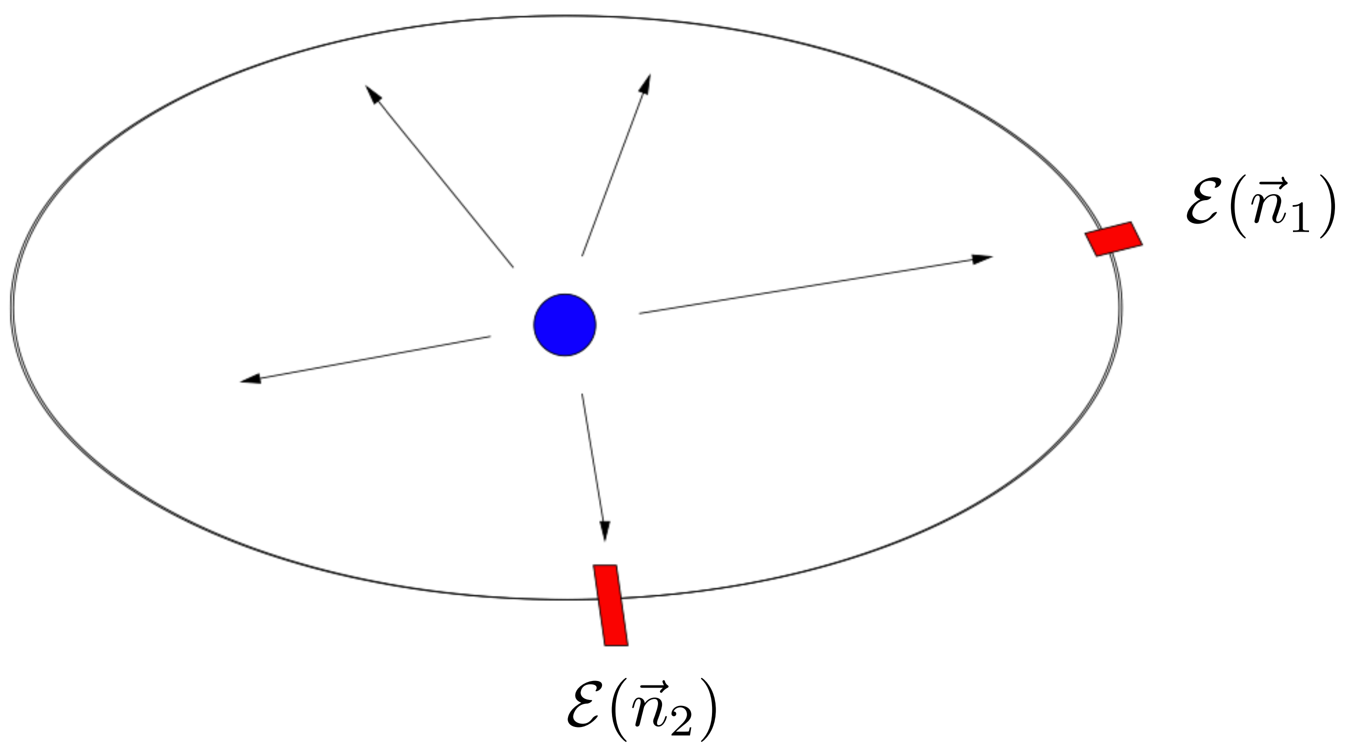


Another option is to weight the final state by the energy of particles

$$\sigma = \int d^4x\, e^{iq^\mu x_\mu} \langle \Omega | \hat{O}(x) \mathcal{E}(\vec{n}_1) \cdots \mathcal{E}(\vec{n}_N) \hat{O}(0) | \Omega \rangle \,, \quad \text{where} \quad \mathcal{E}(\vec{n})|P\rangle = \sum_i E_i \delta(\Omega_{\vec{n}} - \Omega_{\vec{k}_i})|P\rangle$$

How to understand the structure of jets: Energy Correlators

Energy correlators were first proposed in QCD in the late 1970s



Energy Correlations in Electron-Positron Annihilation: Testing Quantum Chromodynamics

C. Louis Basham, Lowell S. Brown, Stephen D. Ellis, and Sherwin T. Love

Department of Physics, University of Washington, Seattle, Washington 98195

(Received 21 August 1978)

1-point correlator

$$\frac{d\Sigma}{d\Omega} = \sum_{N=2}^{\infty} \int \sum_{a=1} E_a^{-1} d^3p_a \frac{d^N\sigma}{E_1^{-1}d^3p_1 \cdots E_N^{-1}d^3p_N} S_N \left[\sum_{b=1}^{N} \frac{E_b}{W}\delta(\Omega_b - \Omega)\right]$$

2-point correlator

$$\frac{d^2\Sigma}{d\Omega\, d\Omega'} = \sum_{N=2}^{\infty} \int \prod_{a=1}^{N} E_a^{-1} d^3p_a \frac{d^N\sigma}{E_1^{-1}d^3p_1 \cdots E_N^{-1}d^3p_N} S_N \left[\sum_{b,c=1}^{N} \frac{E_b E_c}{W^2}\delta(\Omega_b - \Omega)\delta(\Omega_c - \Omega')\right]$$

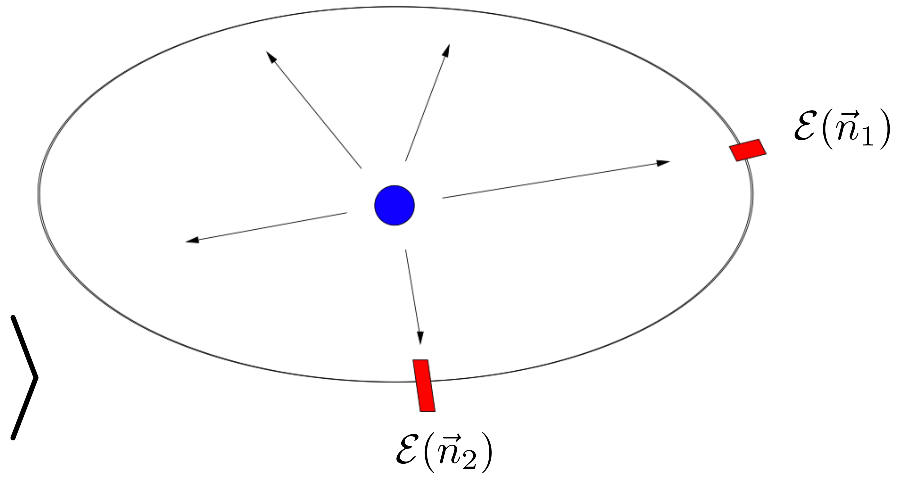
- N-particle cross-section
- Energy weighting
- Restricted angular region
- Form pairs out of N partons

It should be emphasized that the measurement of the energy cross section, Eq. (1), *does not require any detailed event-by-event analysis* as is the case for tests which specify a quantity involving the definition of a jet axis in each event.[5]

How to understand the structure of jets: Energy Correlators

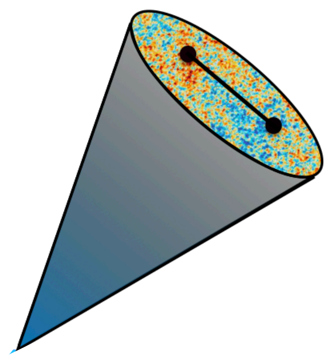
ENCs boil down to measuring correlation functions of the **energy flow operator** $\mathcal{E}(\vec{n})$

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} \int dt\, r^2 n^i T^{0i}(t, r\,\vec{n}) \longrightarrow \langle 0|\bar{\psi}(x)\mathcal{E}(\vec{n_1})\mathcal{E}(\vec{n_2})\psi(0)|0\rangle$$



In the simplest case, we can consider the one dimensional projection

$$\frac{d\Sigma}{d\theta} = \int_{\vec{n}_1,\vec{n}_2} \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle}{p_t^2}\delta(\vec{n}_1\cdot\vec{n}_2 - \cos\theta) \longrightarrow \frac{d\Sigma}{d\theta} = \int_z \frac{d\sigma}{\sigma d\theta dz} z(1-z)$$



IR safe

$$\sim \frac{1}{\theta^\alpha}$$

In summary: *The small angle behavior of the energy correlation functions is determined by the spin $j = 3$ non-local operators that appear in the OPE*

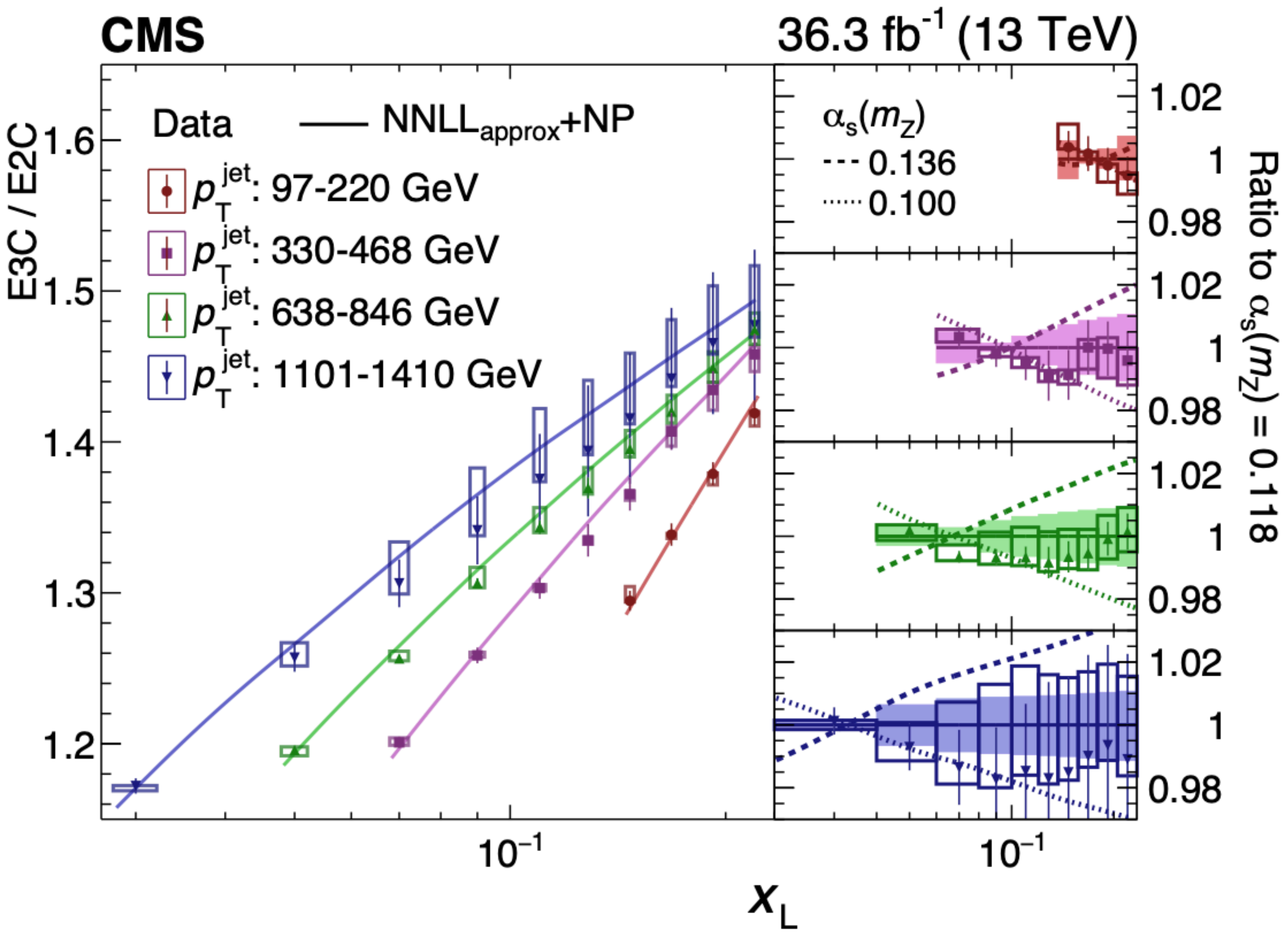
$$\langle \mathcal{E}(\theta_1)\mathcal{E}(\theta_2)\cdots\rangle \sim \sum |\theta_{12}|^{\tau_n - 4}\langle \mathcal{U}_{3-1,n}(\theta_2)\cdots\rangle \qquad (2.19)$$

[Hofman, Maldacena, 2008]

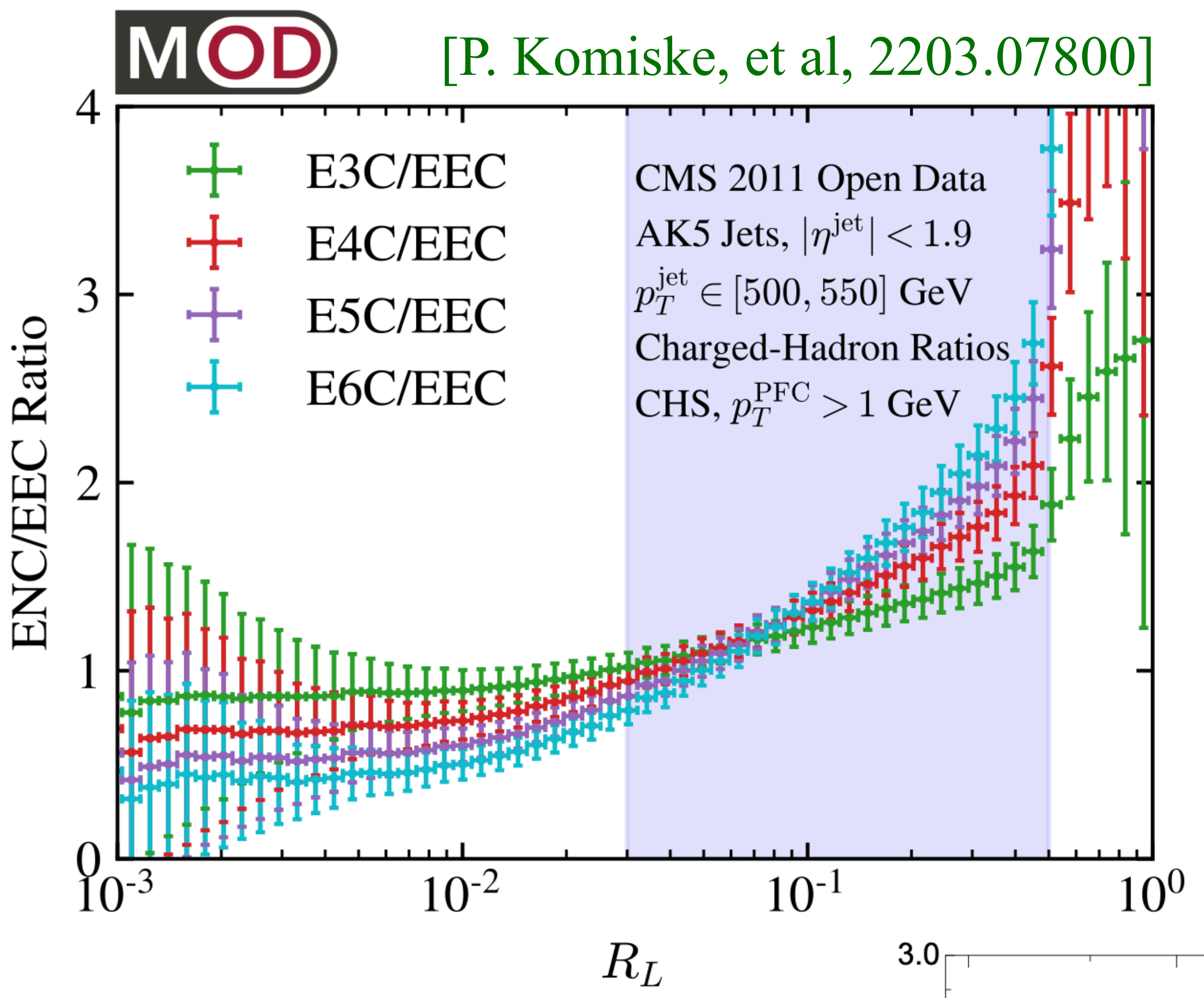
at LO : $\alpha = 1$, deviations controlled by quantum theory

How to understand the structure of jets: Energy Correlators

ENCs have been measured in QCD and they provide a wealth of interesting information about the theory

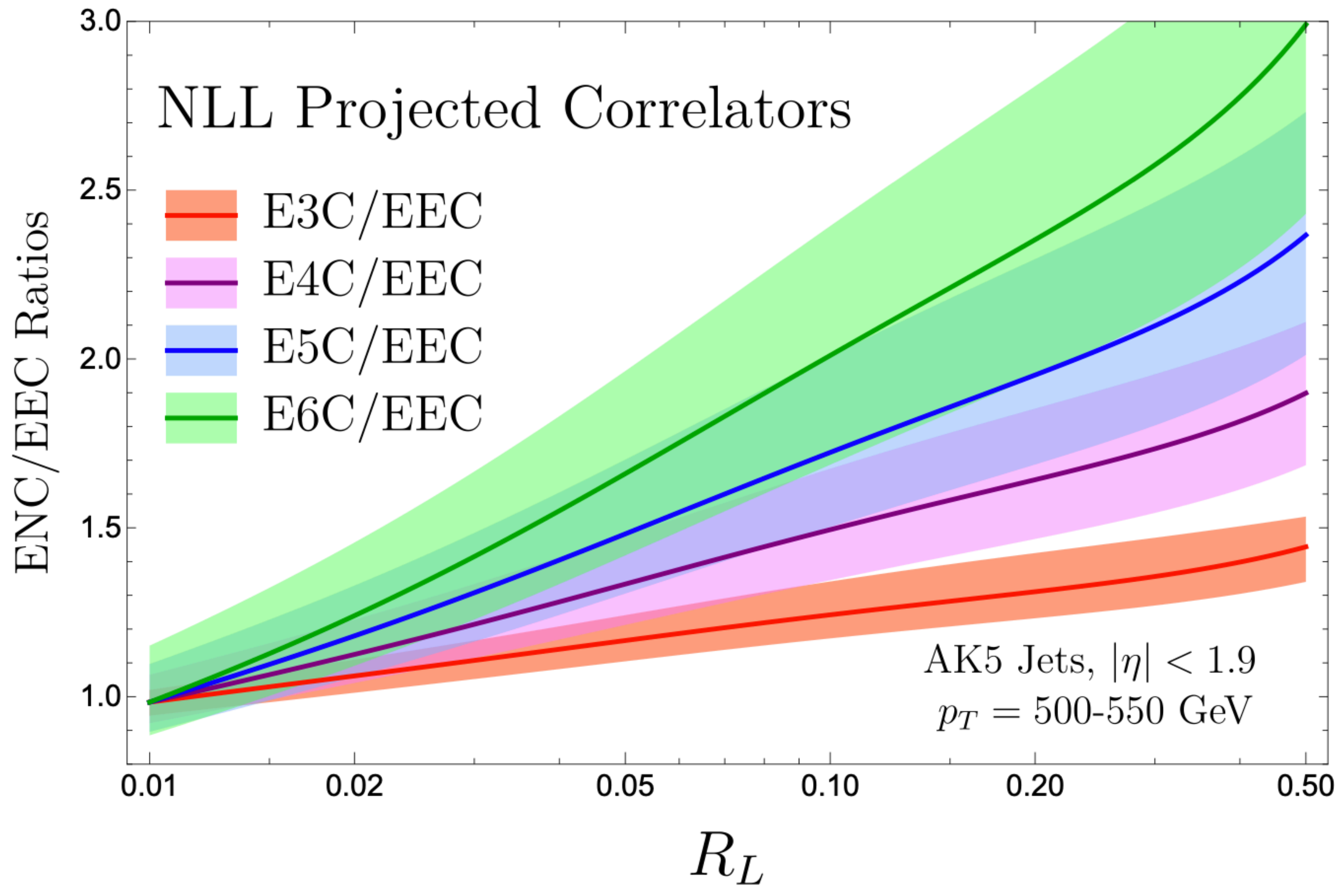


[P. Komiske, et al, 2203.07800]



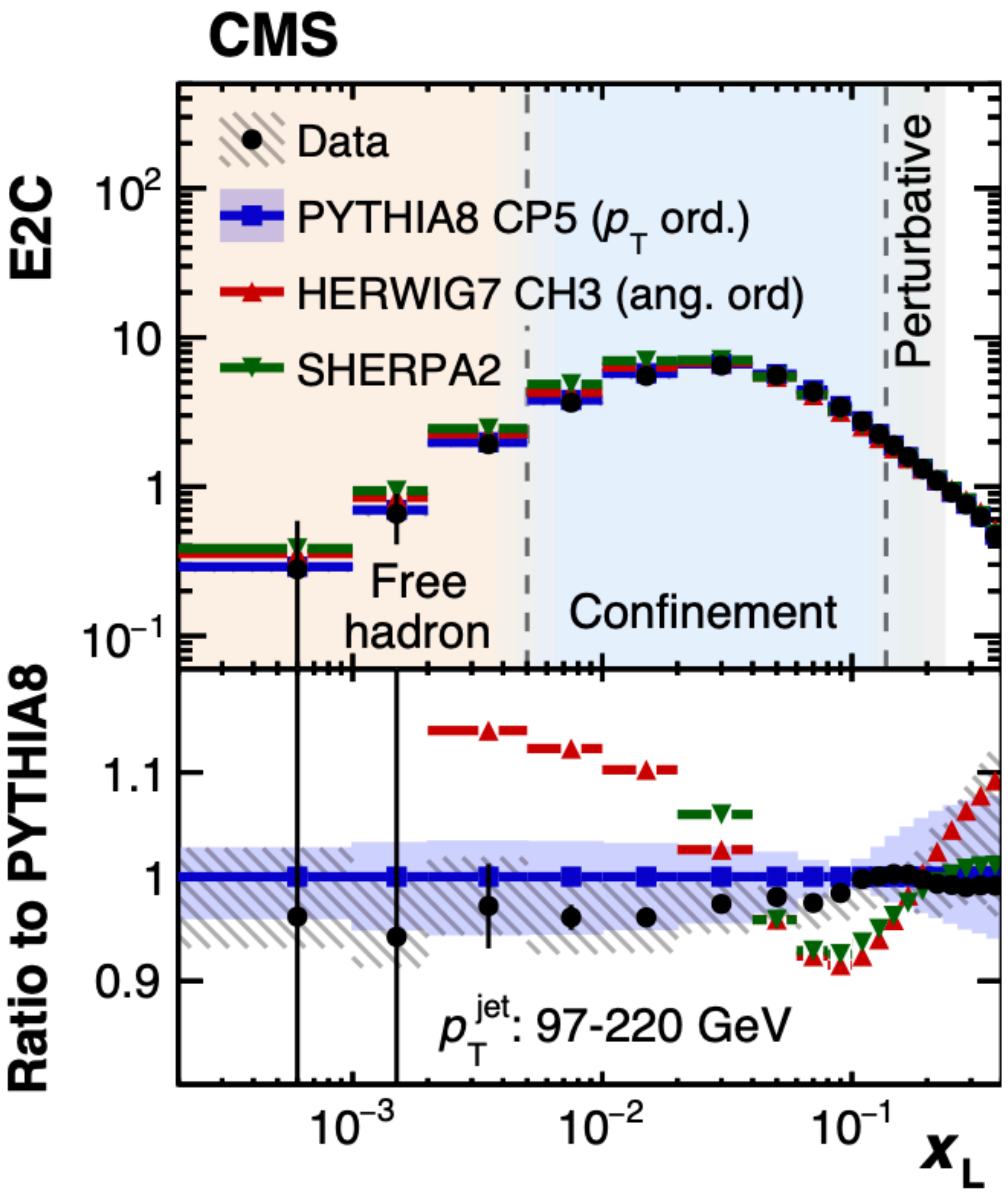
$$\frac{\text{ENC}}{\text{EEC}} \propto R_L^{\gamma(N+1)-\gamma(3)}$$

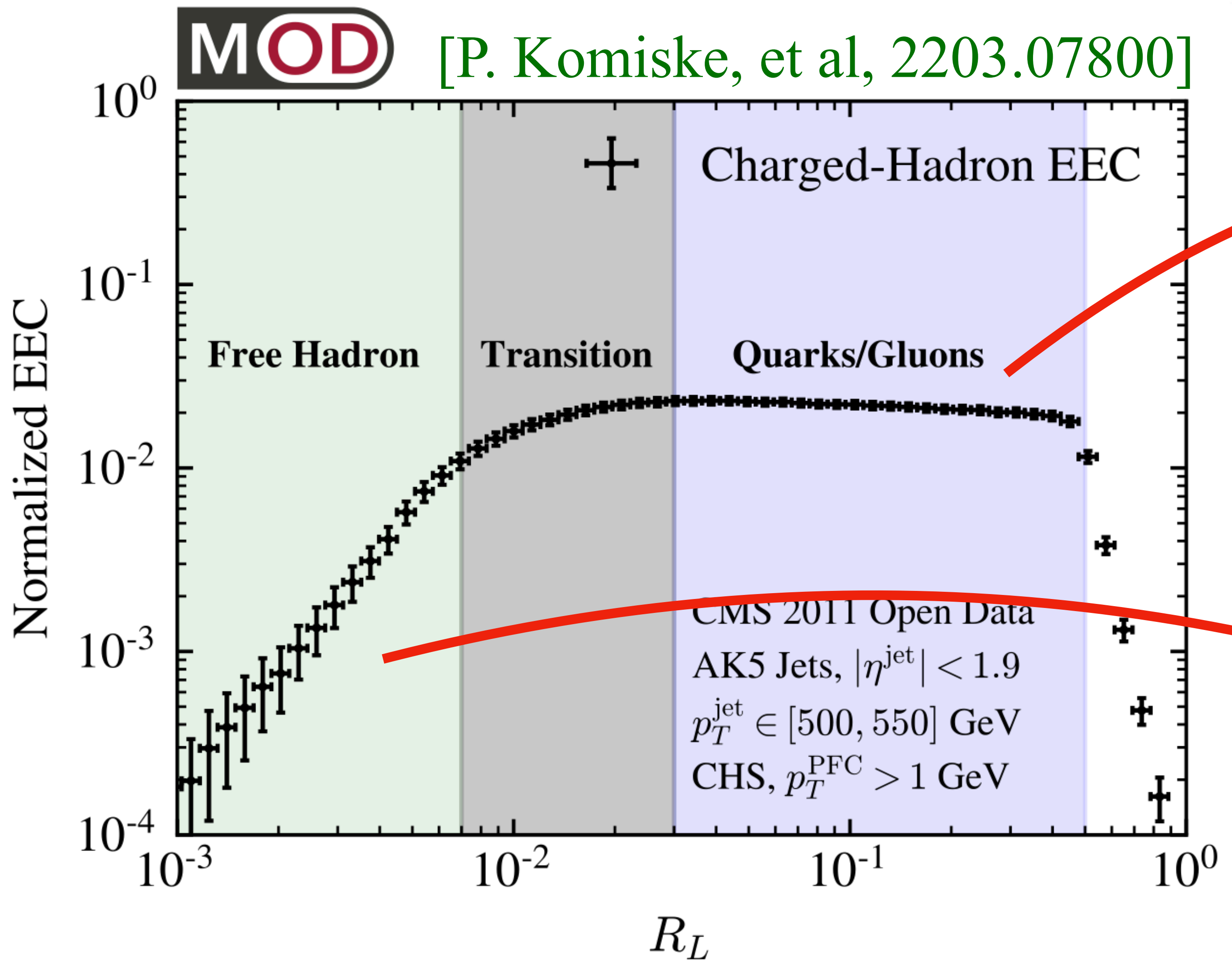
[K. Lee, et al, 2205.03414]

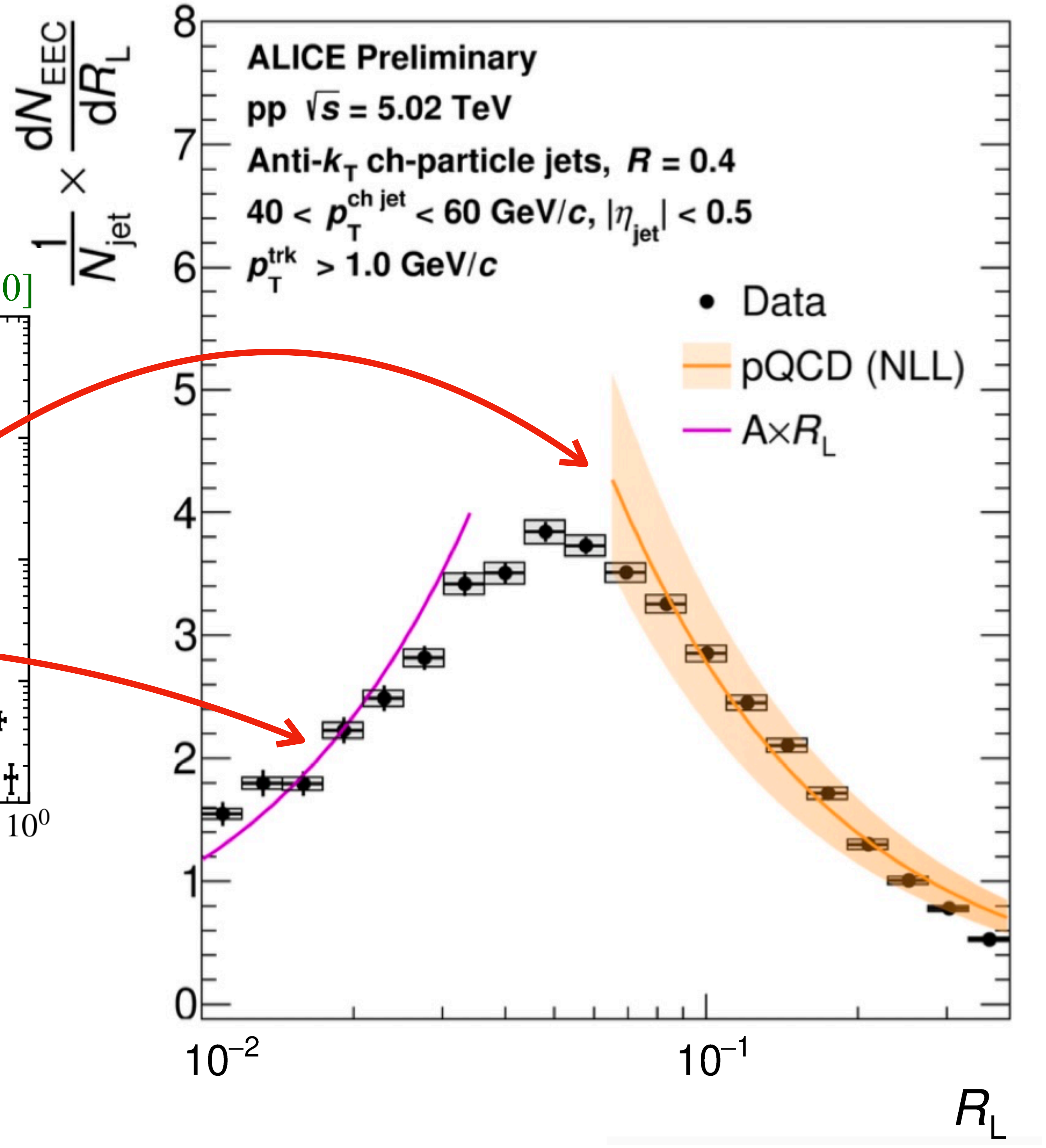


How to understand the structure of jets: Energy Correlators

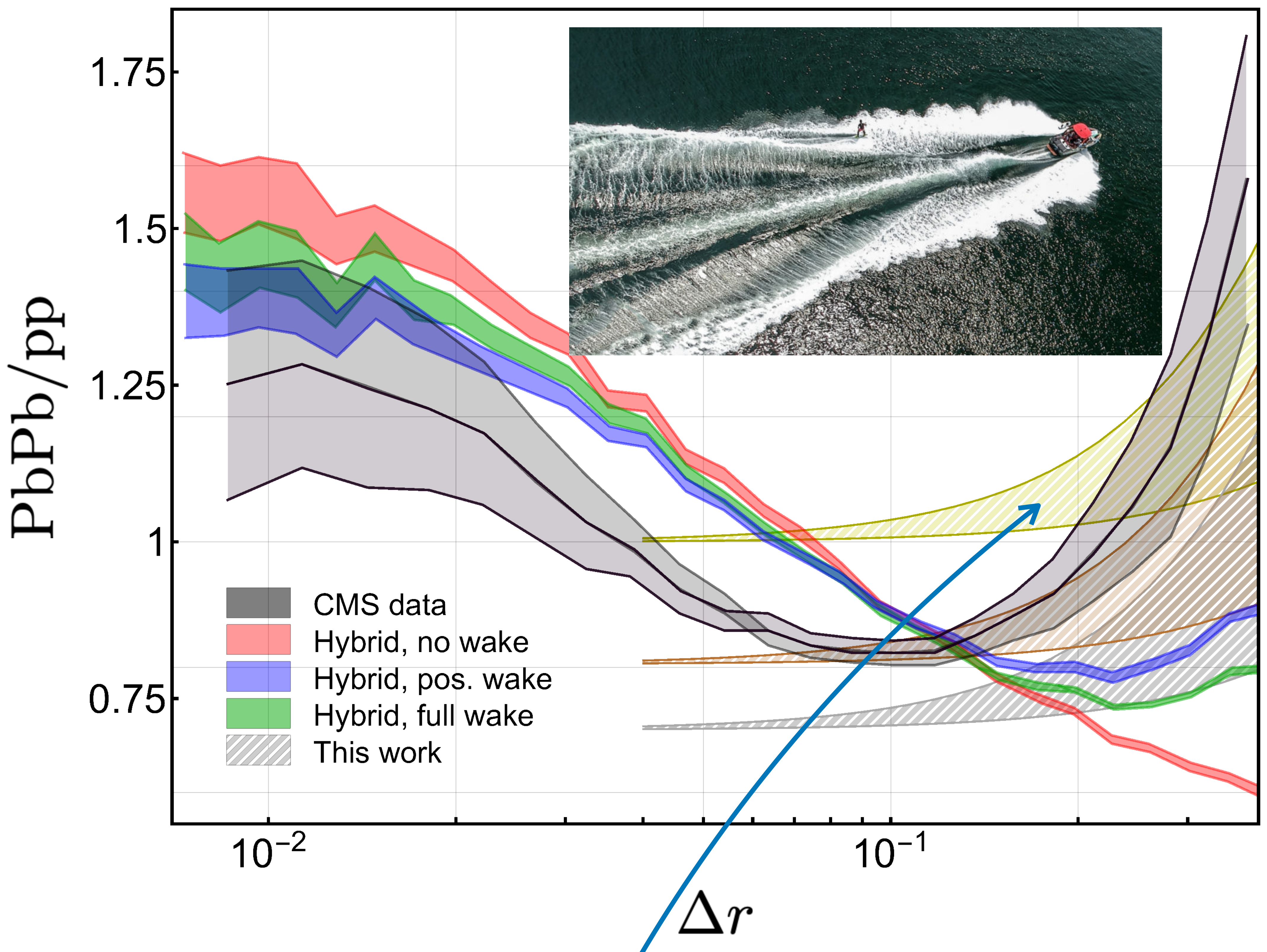
ENCs have been measured in QCD and they provide a wealth of interesting information about the theory

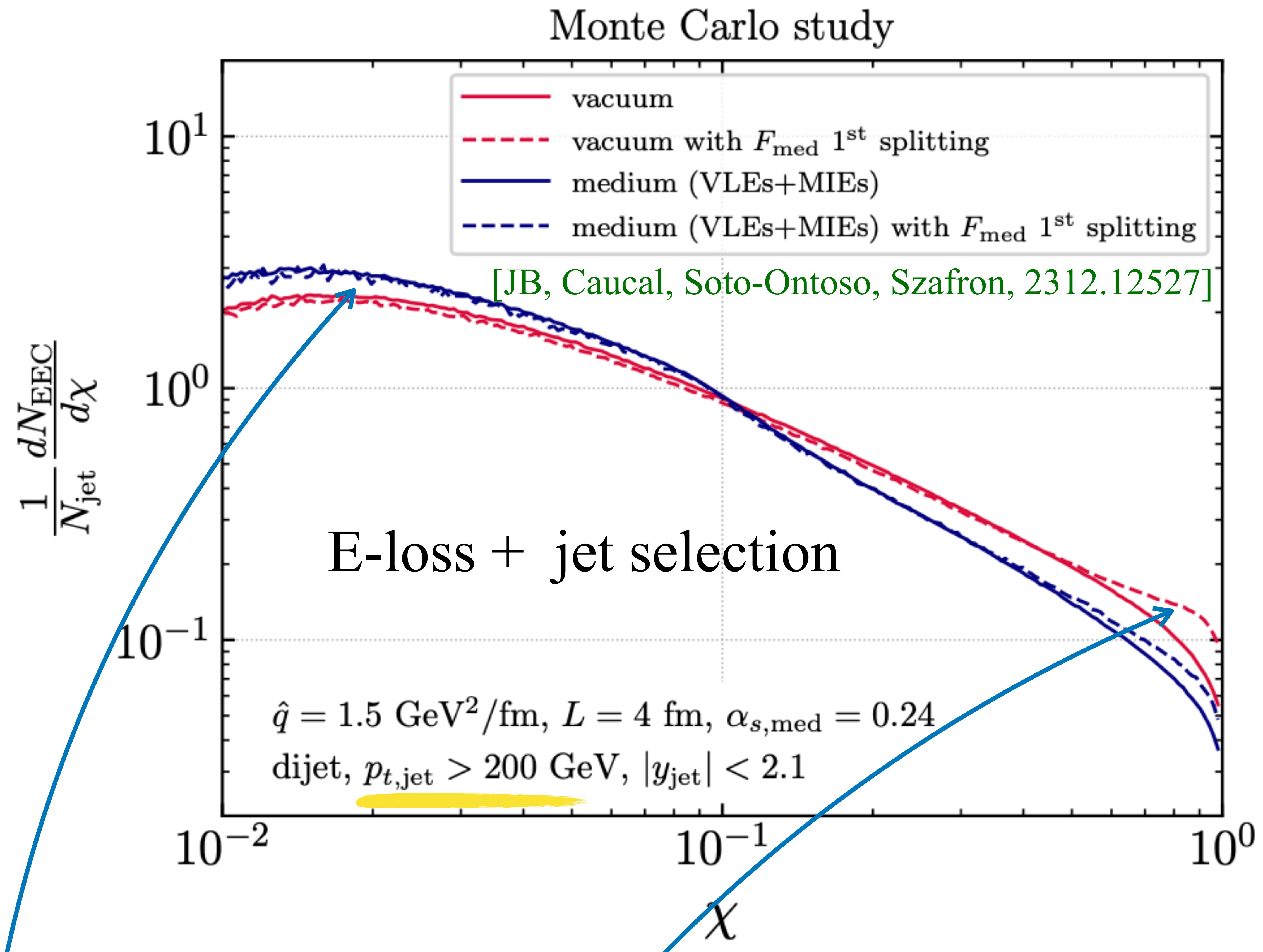






How to understand the structure of jets: Energy Correlators





→ Energy loss leads to suppression at large angles and enhancement at small ones (solid lines)

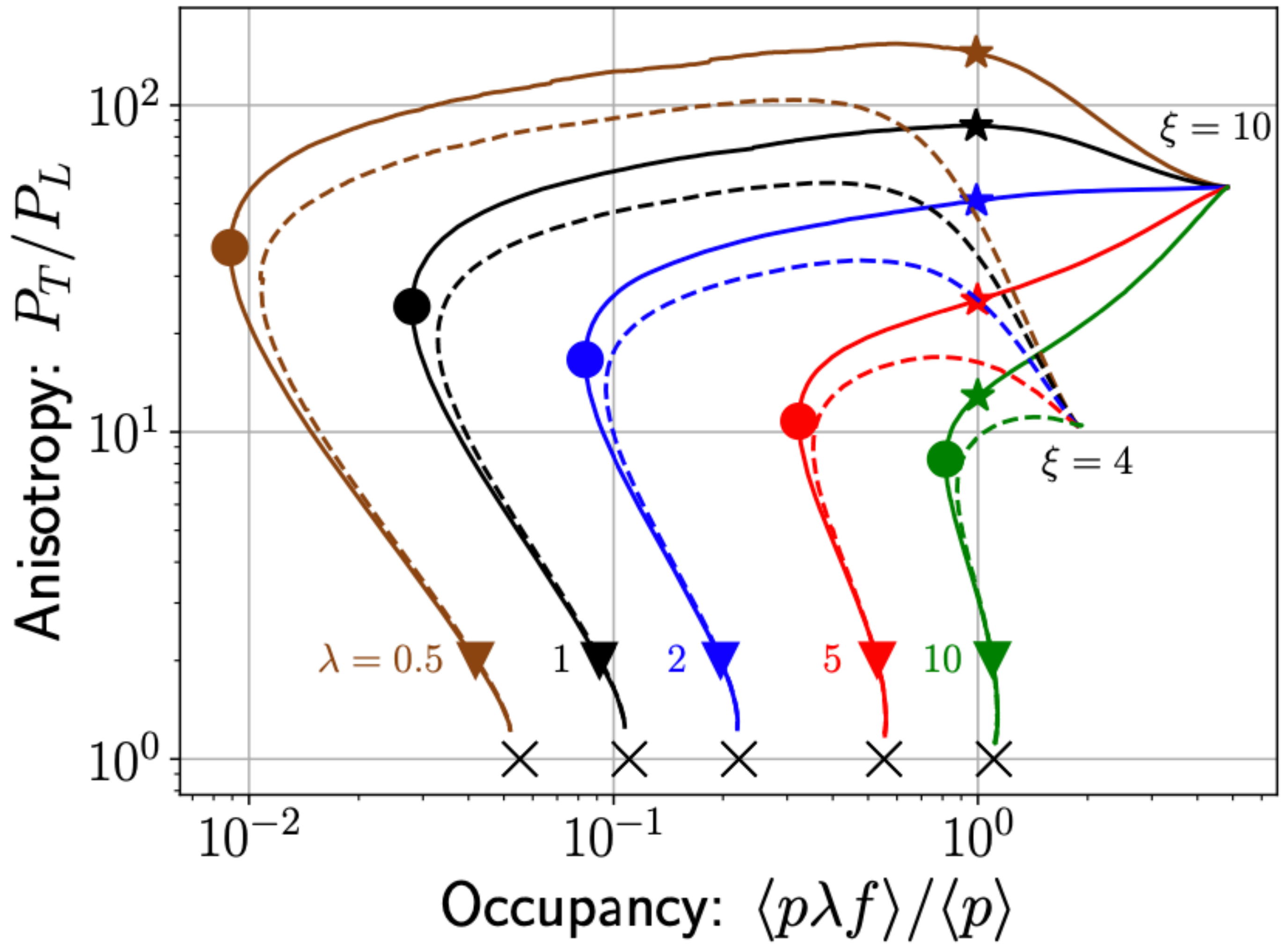
→ Medium introduces slight enhancement at large angles, which competes with E-loss. The soft contribution can overwhelm this signal.

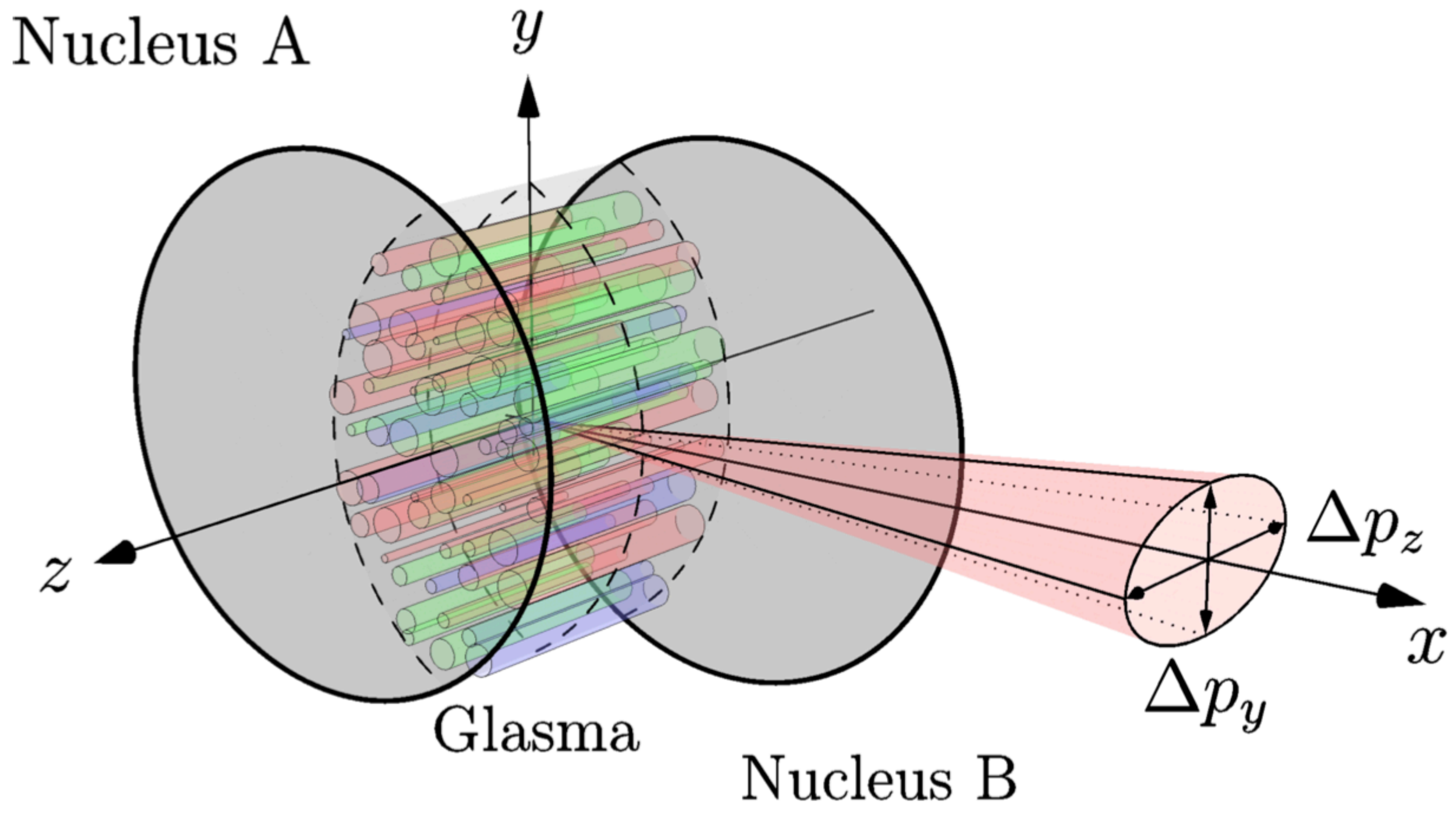
Jets in the early stages of HICs

Why are the early stages “different”

[See talk by Kirill later this week]

[F. Lindebauer, et al, 2023]





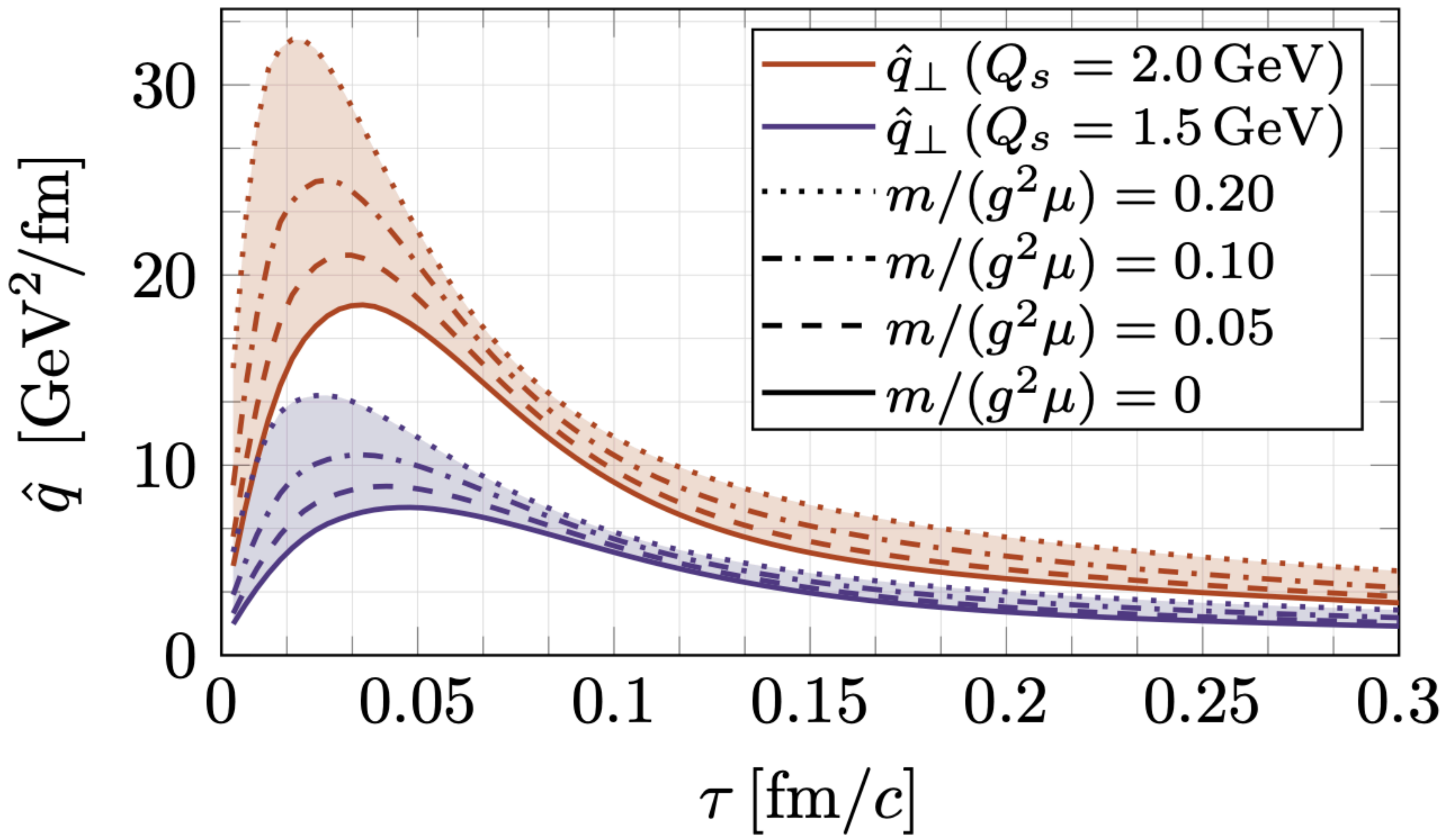
- At early times there is a big pressure anisotropy
- This reflects in an anisotropic transport coefficient
  [Can be washed out by hydro expansion]

$$\hat{q}_x \gg \hat{q}_y$$

- Furthermore, the observed jet quenching coefficient seems to be much larger than the hydro one
  [Observables integrate over jet path]

$$\hat{q}_{\text{early}} \gg \hat{q}_{\text{hydro}} \,, \tau_{\text{hydro}} \gg \tau_{\text{early}}$$

[A. Ipp, D. I. Muller, D. Schuh, 2009.14206]



Why are the early stages "different"

[See talk by Kirill later this week]

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coefficient

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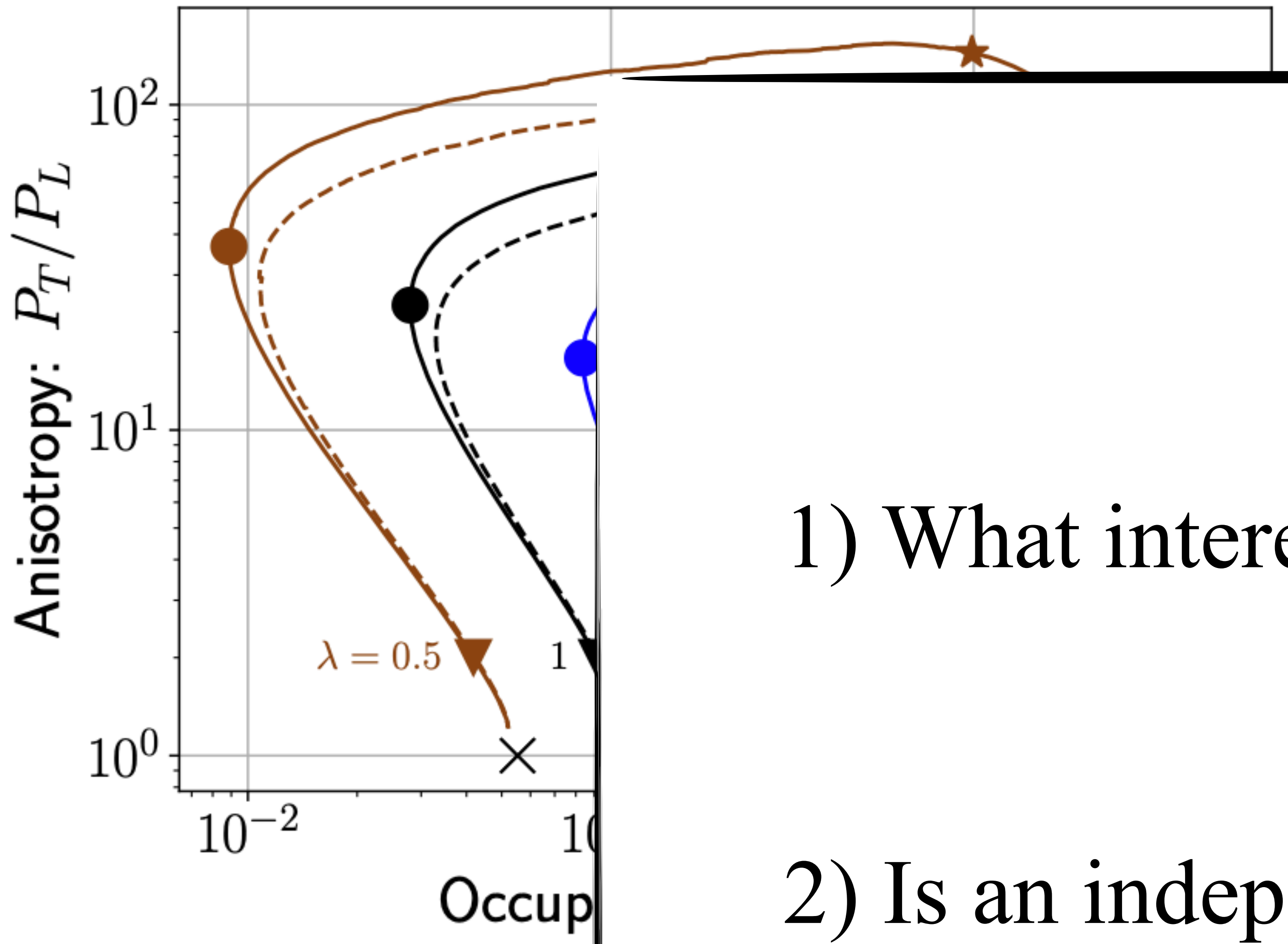
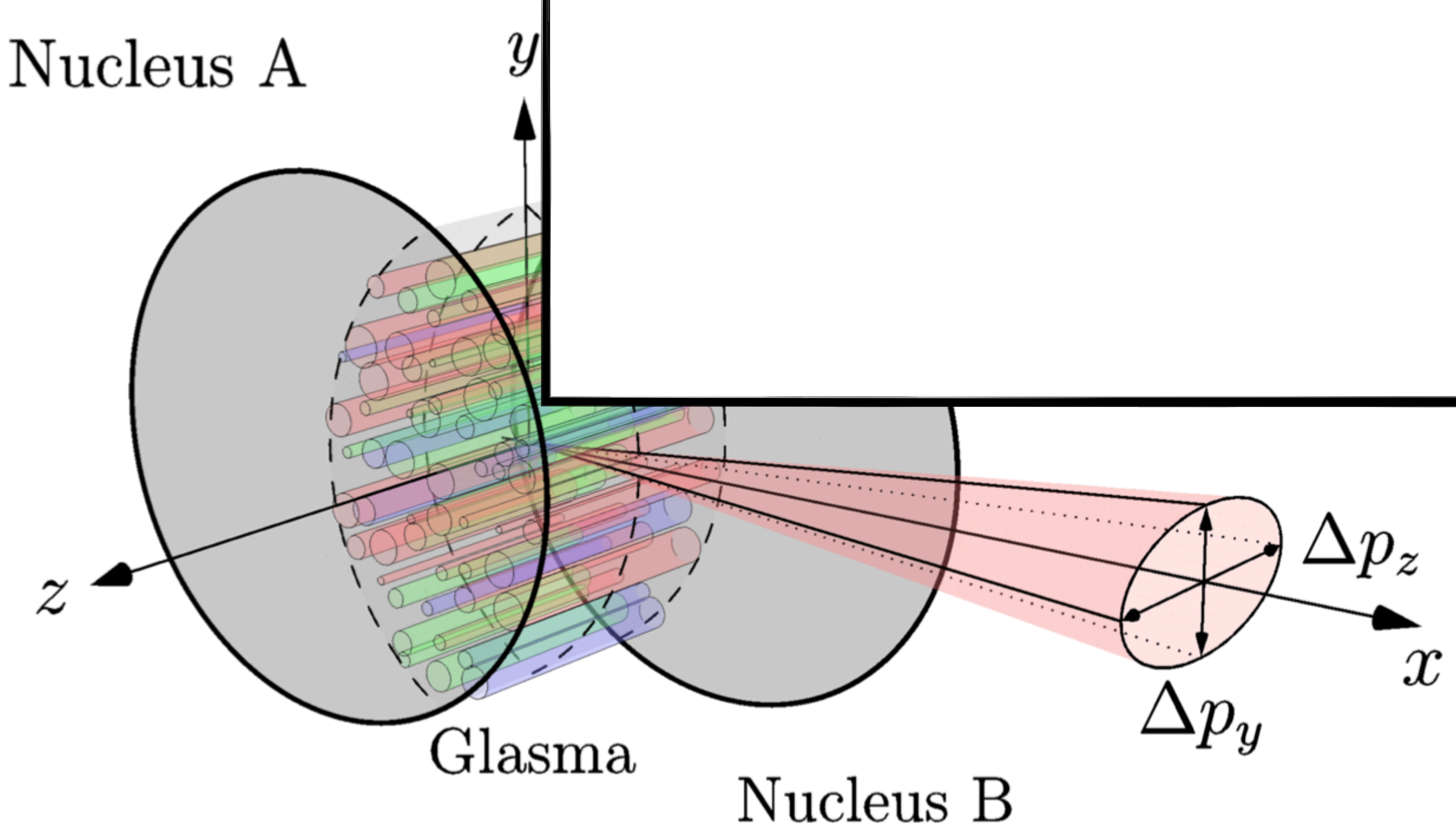
early

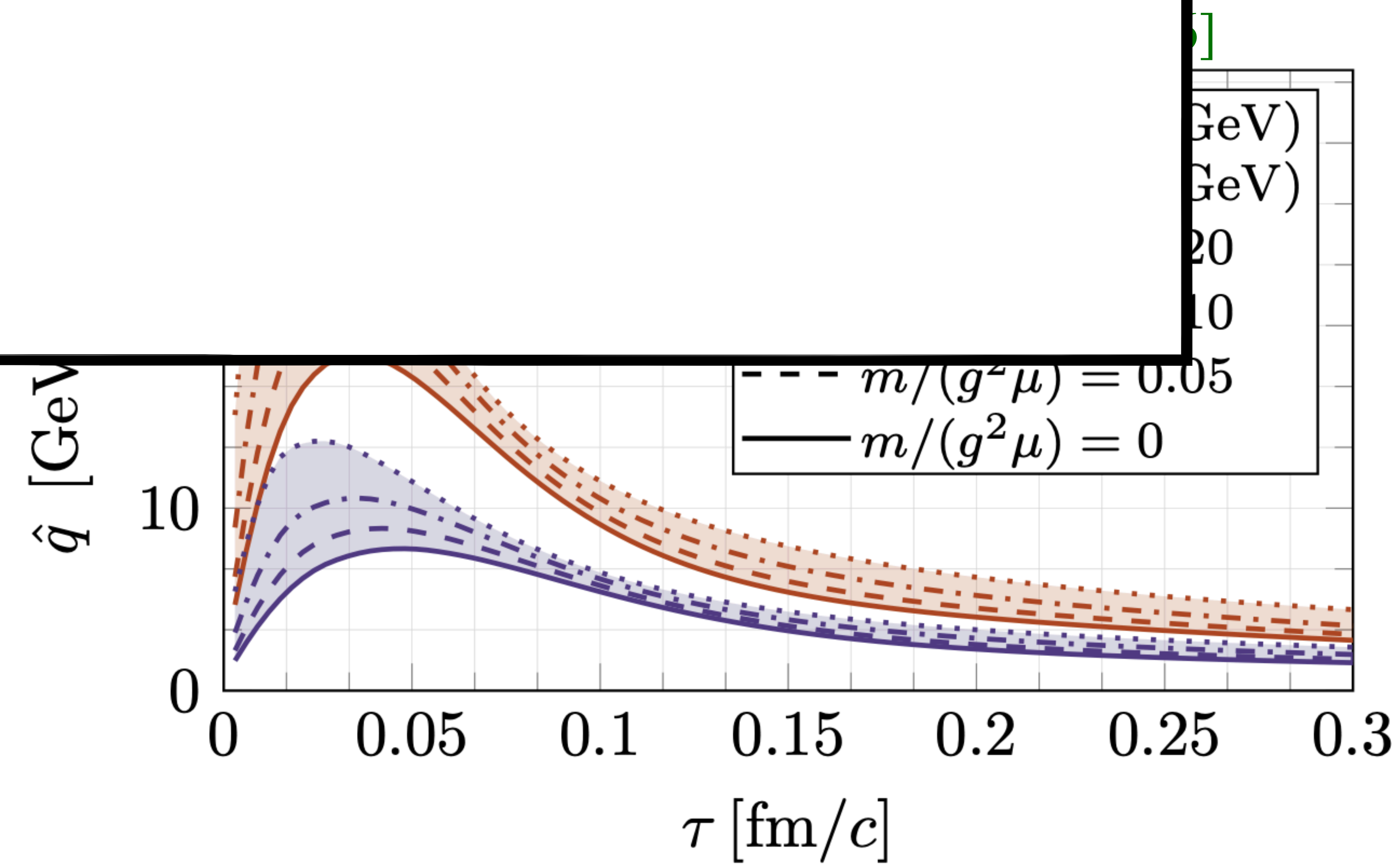
[F. Lindebauer, et al, 2023]



1) What interesting features can we see from early time anisotropies?

2) Is an independent multiple scattering picture still meaningful ?

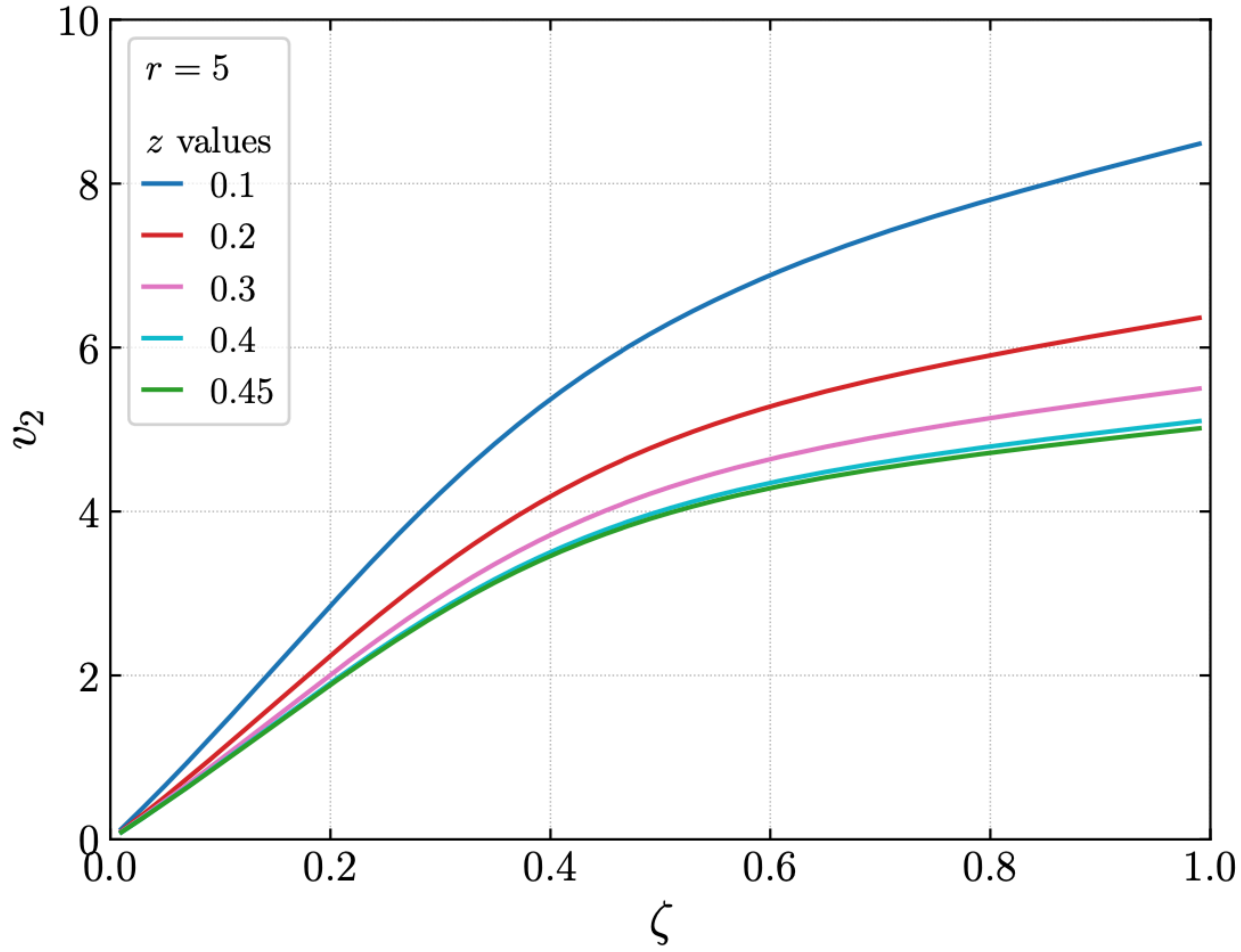


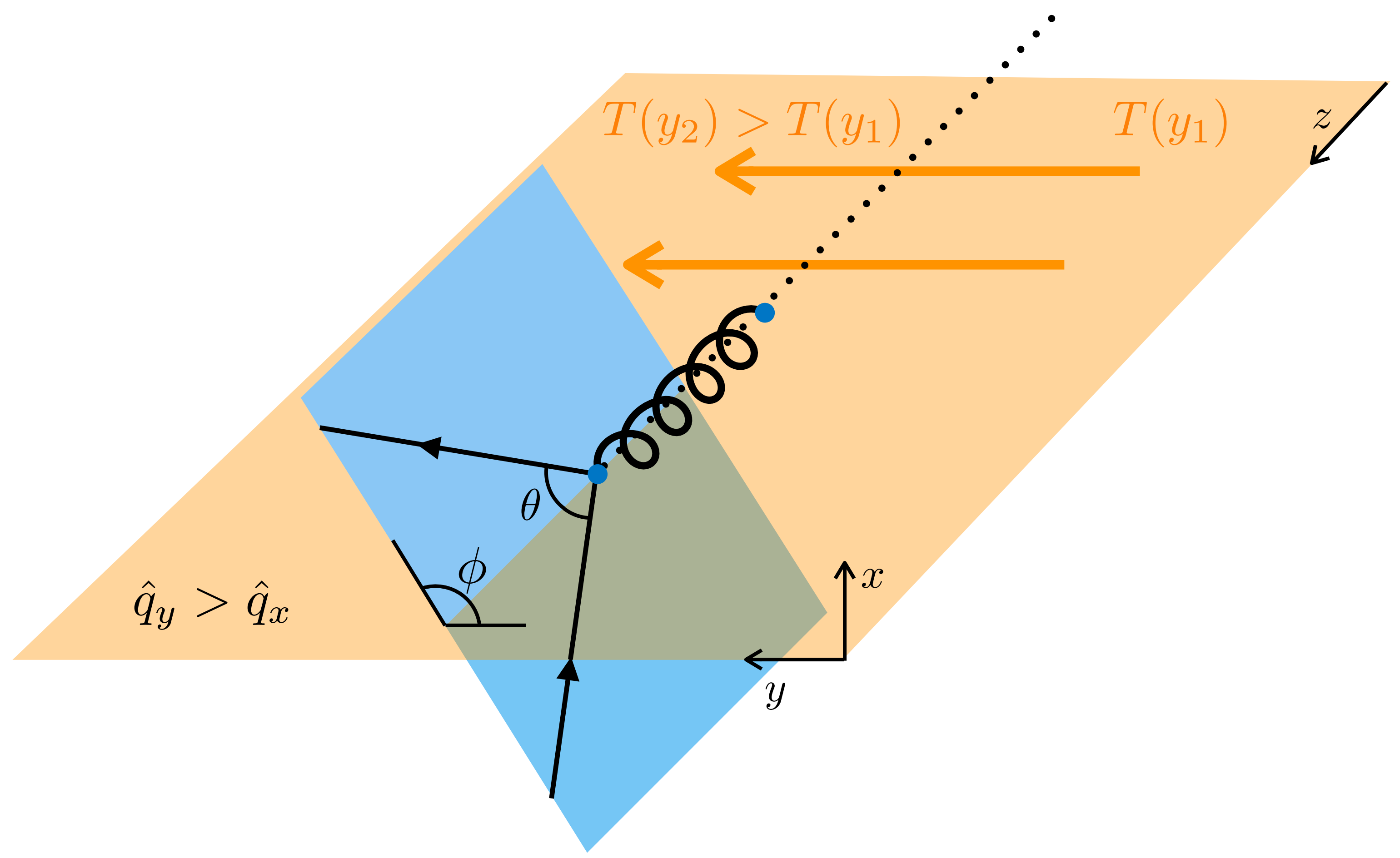


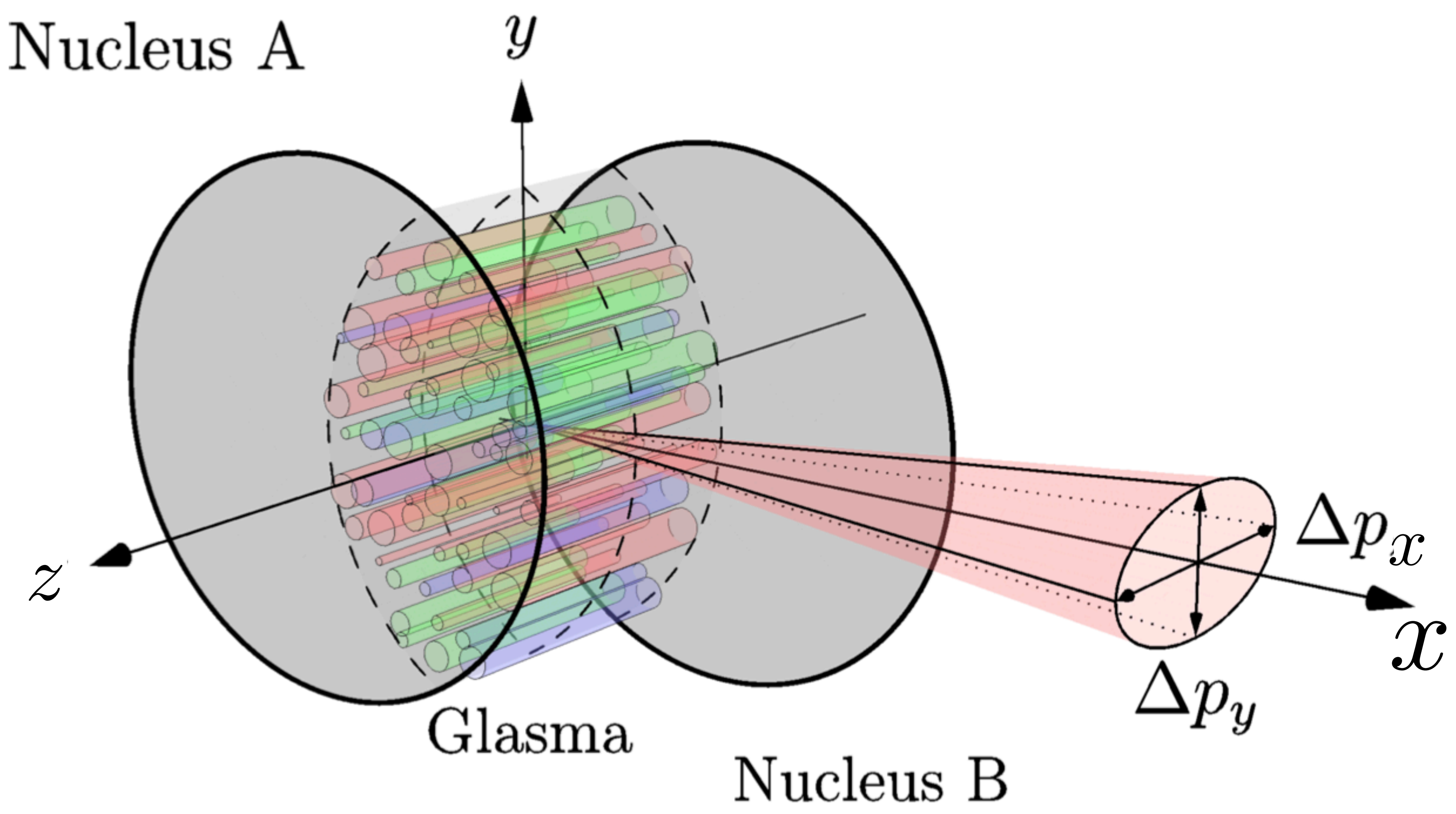
Gluon radiation in anisotropic matter

[S. Hauksson, E. Iancu, 2303.03914]
[JB, C. Salgado, J. Silva, 2407.04774]

$$\zeta = \frac{\sqrt{\hat{q}_y} - \sqrt{\hat{q}_x}}{\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}}, \quad r = L^+ \frac{\left(\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}\right)}{2\sqrt{q_0^+}}$$



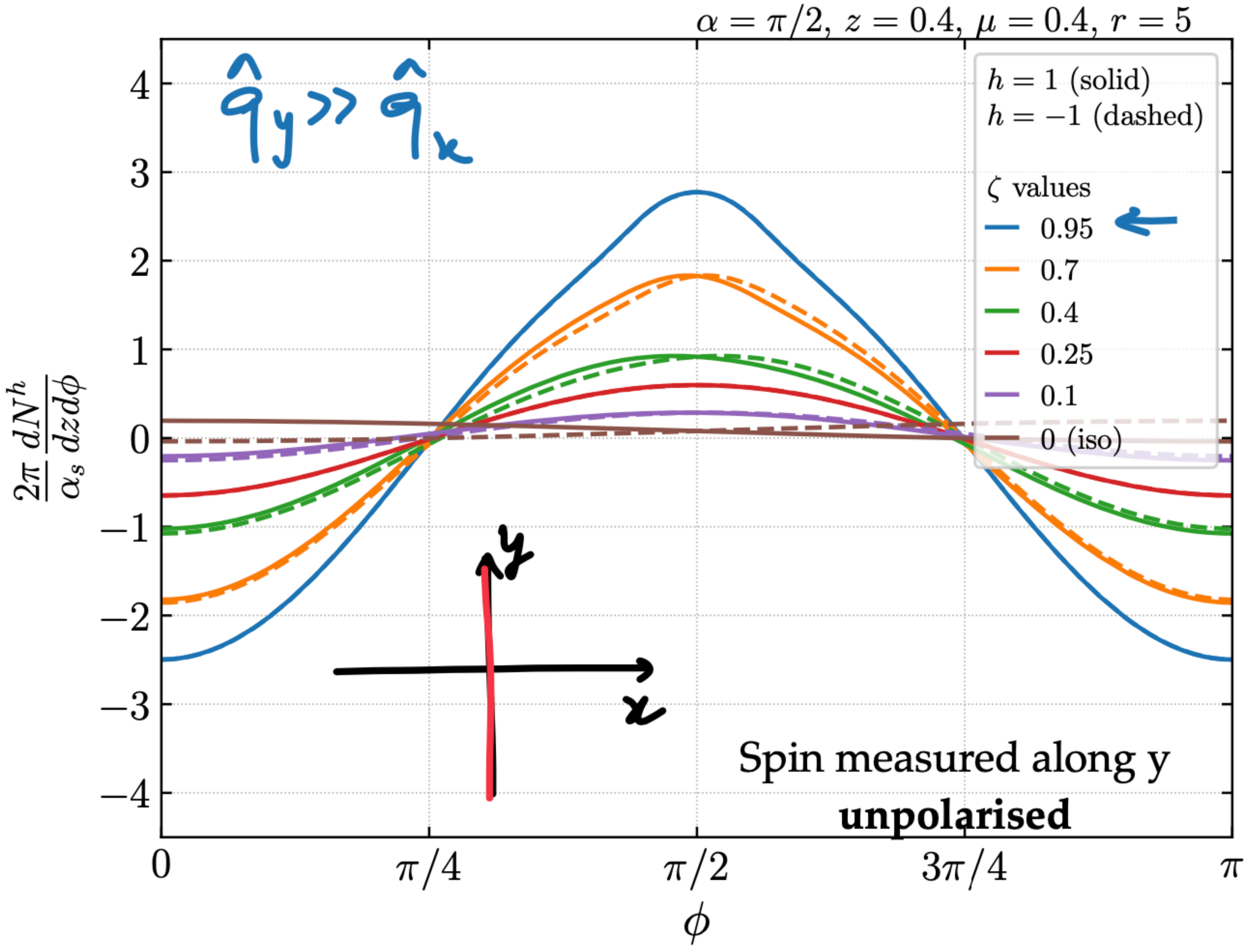


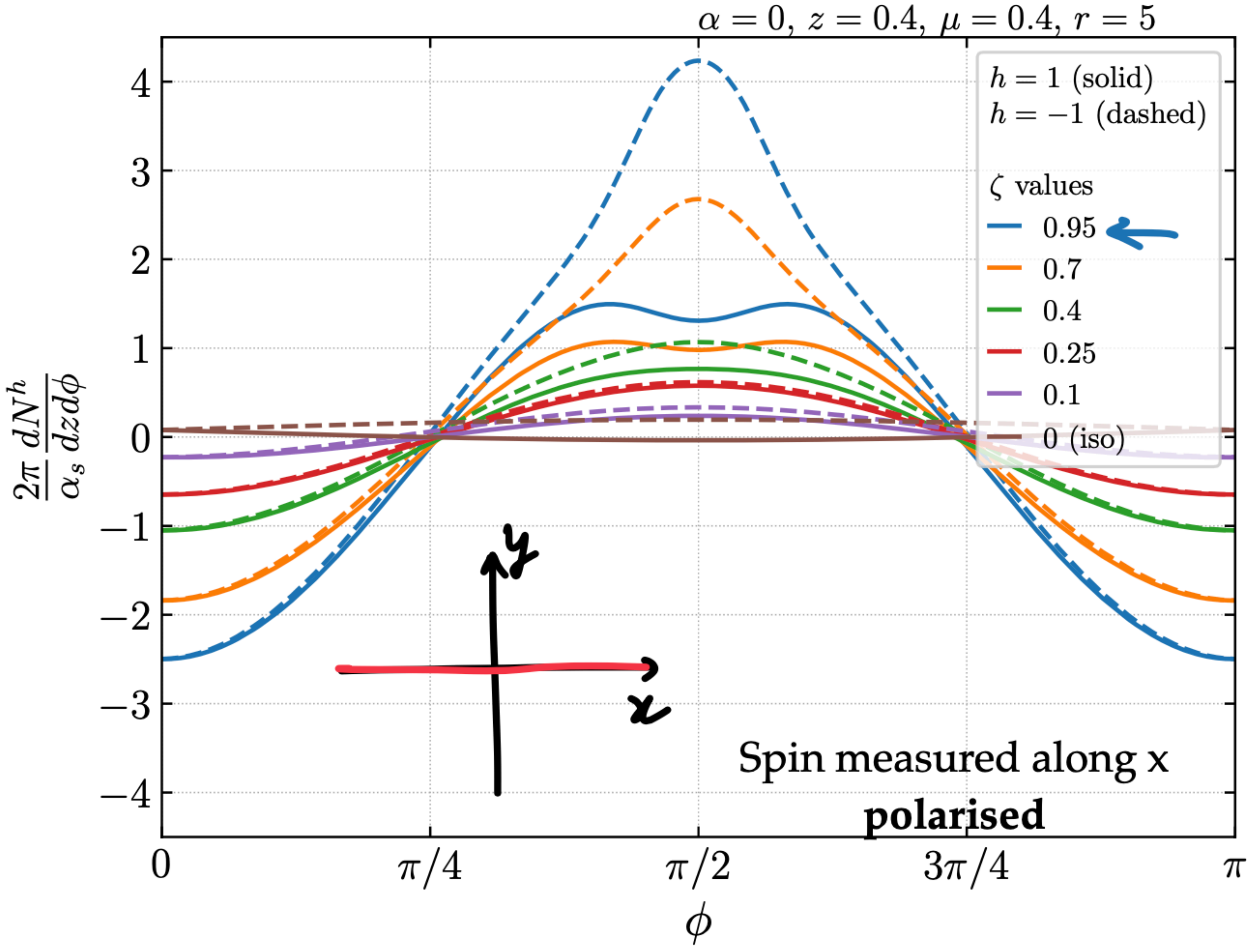


Gluon radiation in anisotropic matter

[S. Hauksson, E. Iancu, 2303.03914]
[JB, C. Salgado, J. Silva, 2407.04774]

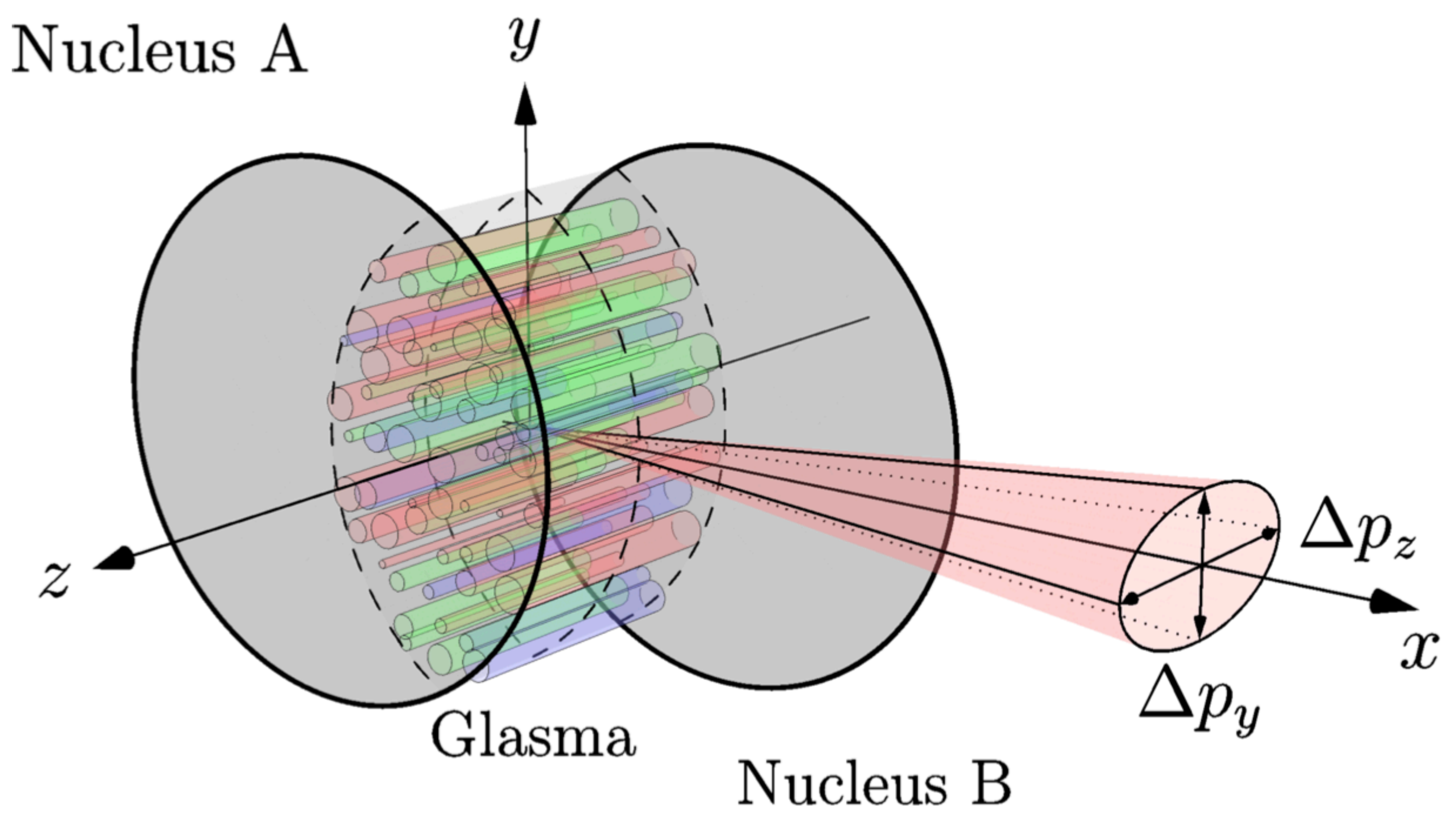
$$\zeta = \frac{\sqrt{\hat{q}_y} - \sqrt{\hat{q}_x}}{\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}}\,, \qquad r = L^+ \frac{\left(\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}\right)}{2\sqrt{q_0^+}}\,, \qquad \mu = \frac{\sqrt{2}m^2}{\left(\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}\right)\sqrt{q_0^+}}$$



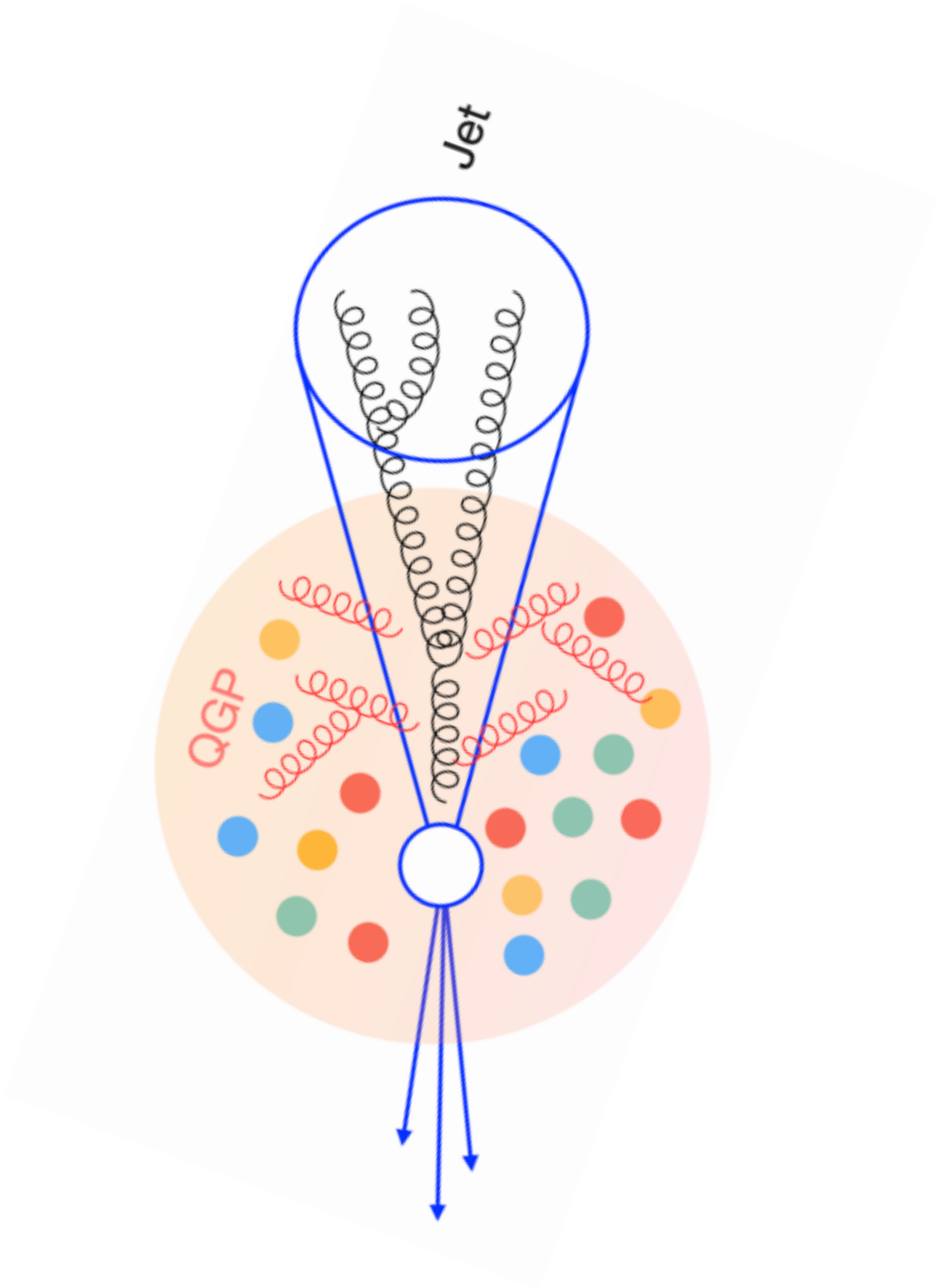


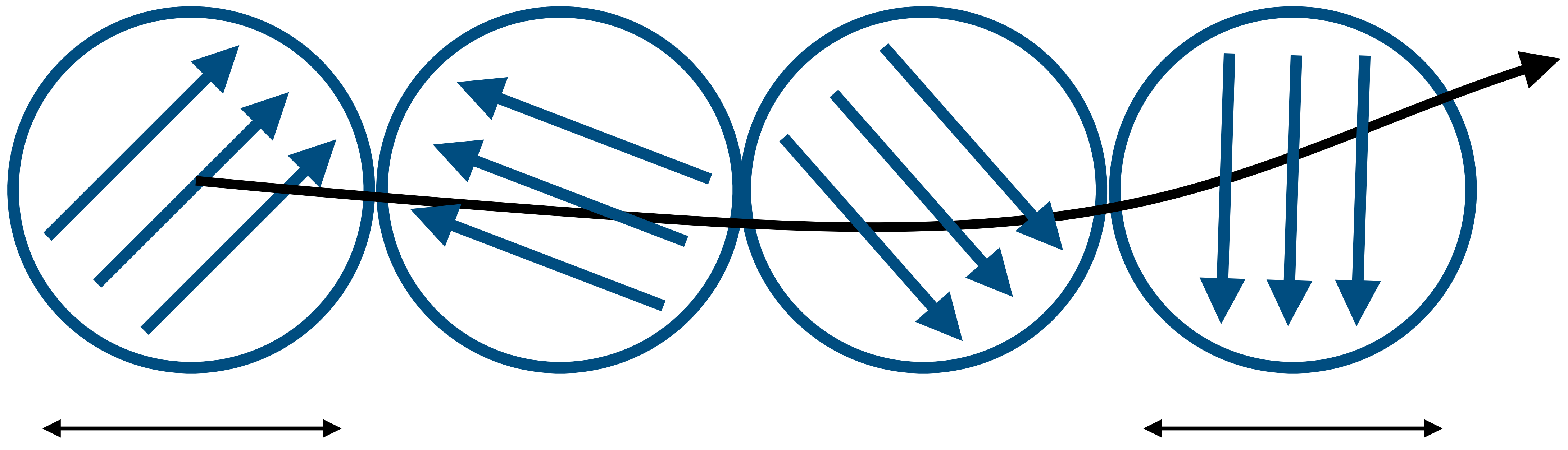
Jet evolution in the Glasma

[JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]



$$\stackrel{??}{=}$$





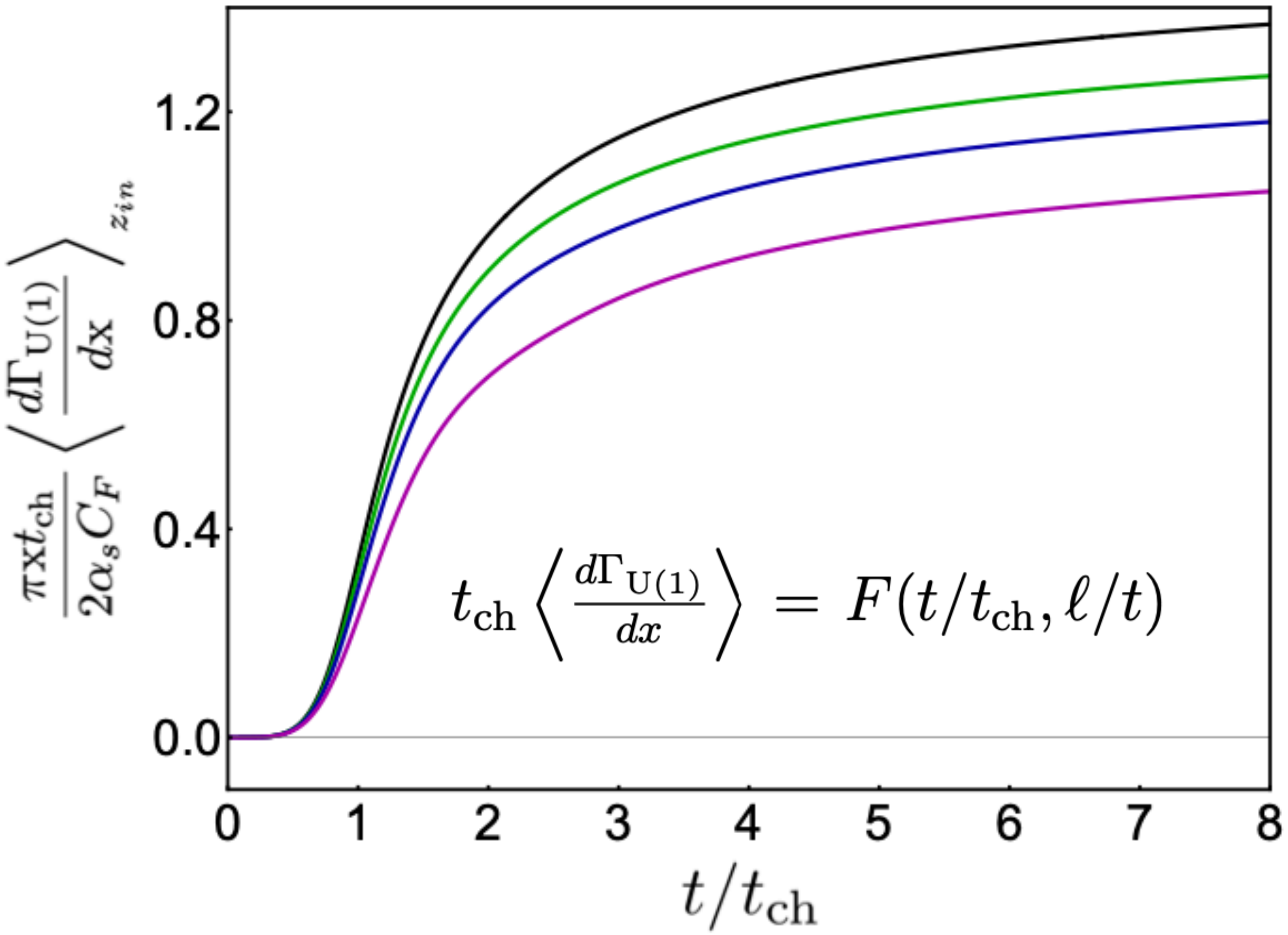
Synchrotron like scenario

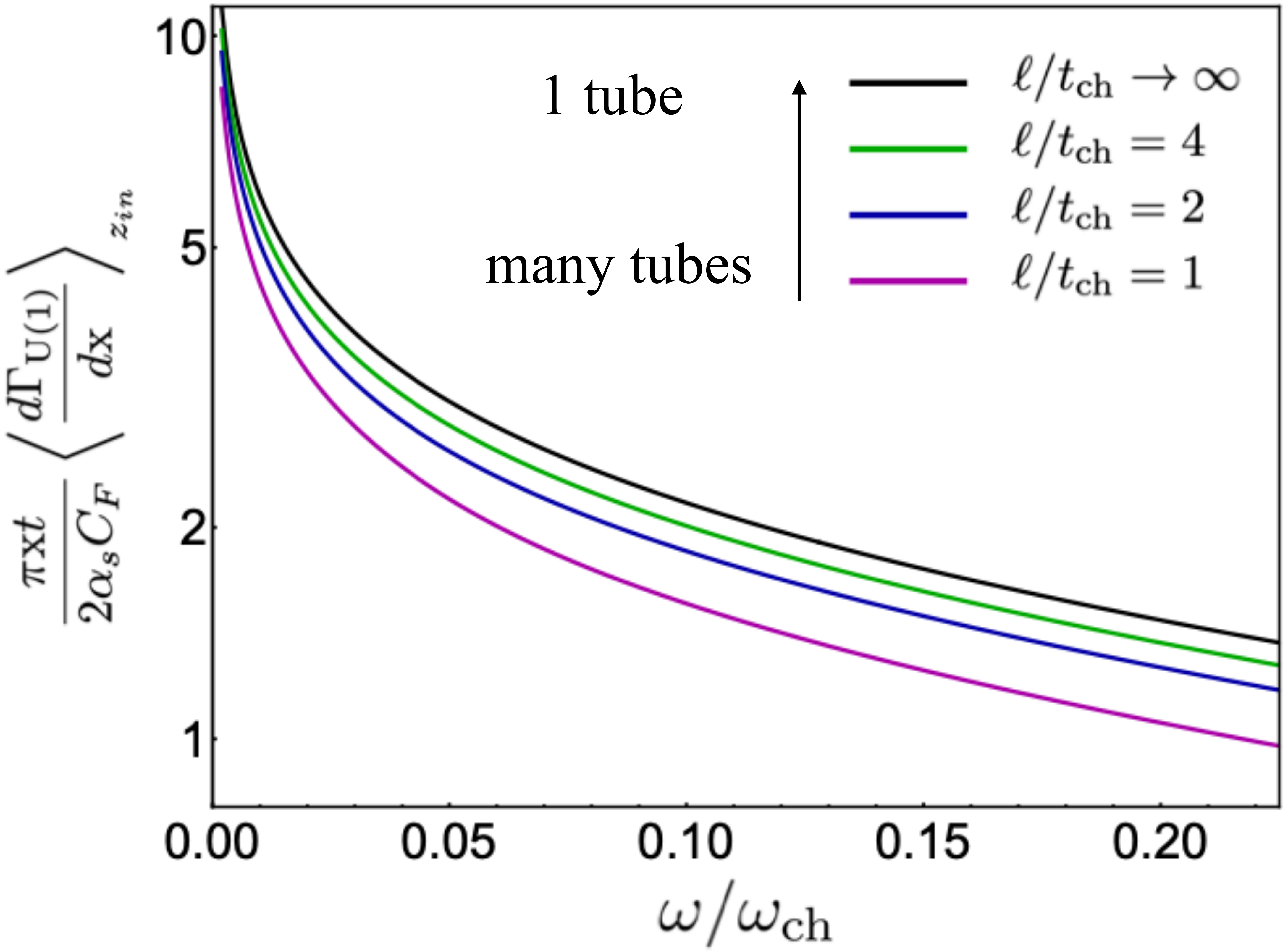
$l \sim 1/Q_s$

Jet evolution in the Glasma

[JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]

More flux tubes = longer formation time = lower rate





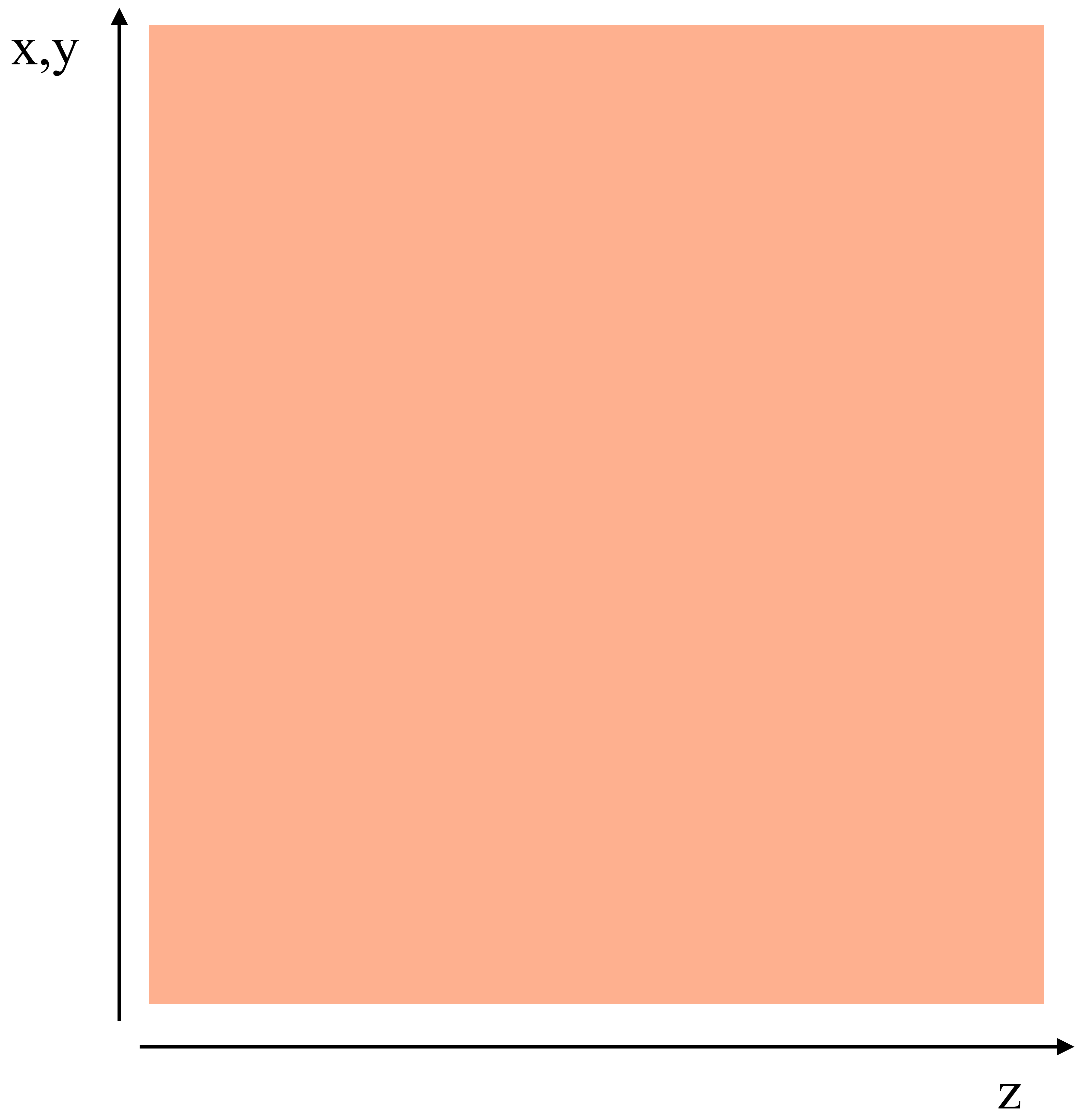
It is very important to go beyond QGP-like picture for these stages !

Jets in anisotropic and flowing matter

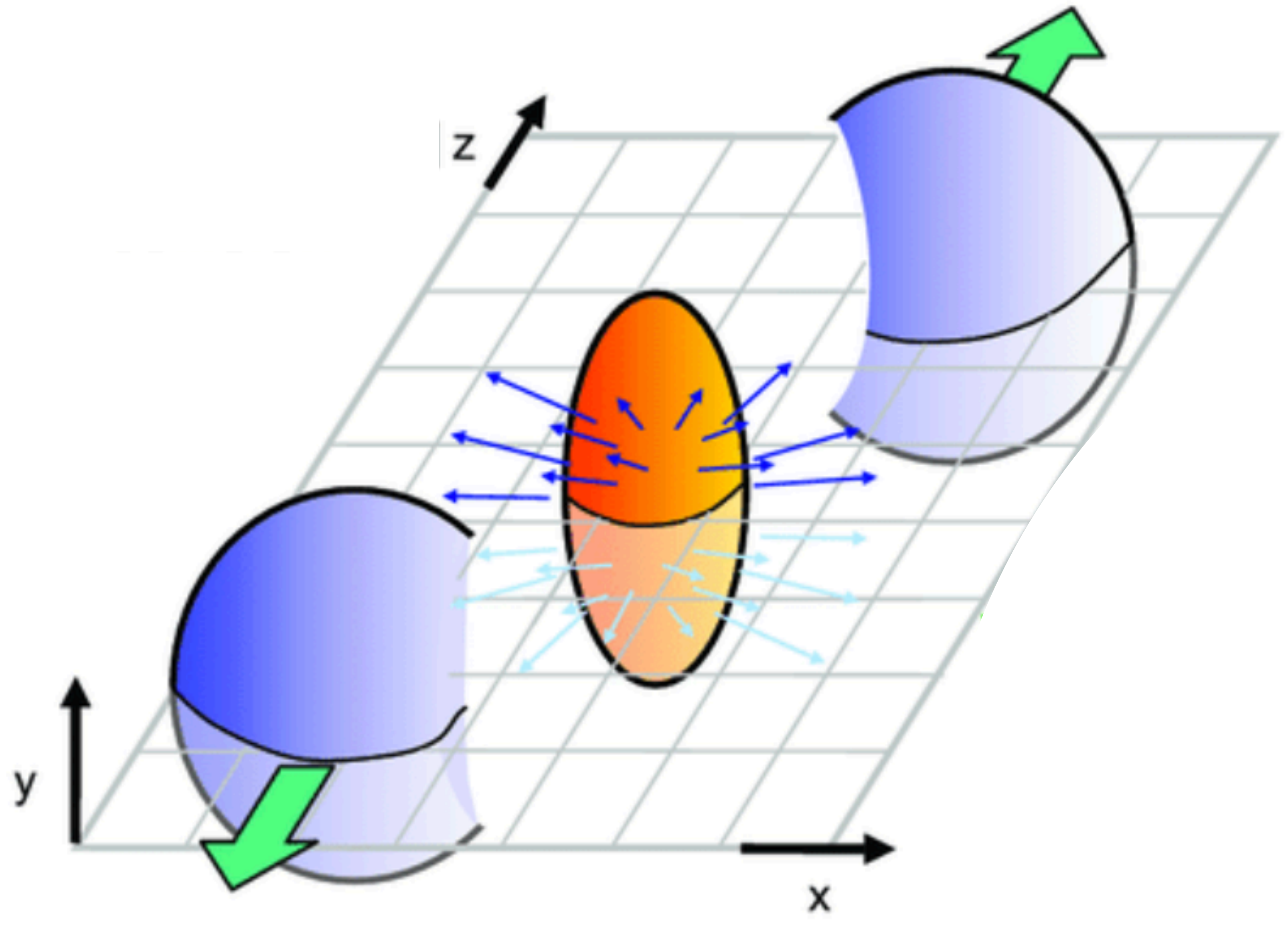
Jet evolution in structured matter

Why?

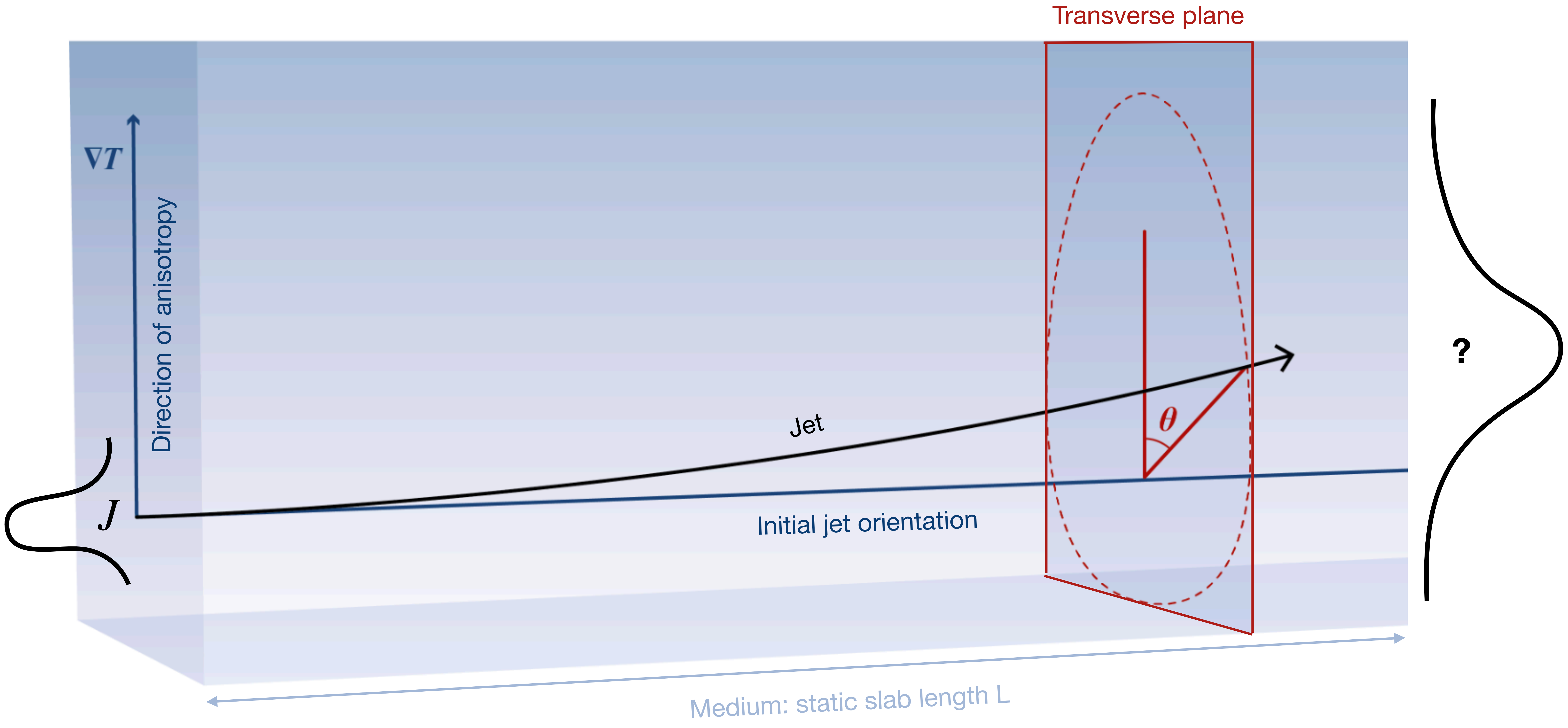
An infinitely long static medium as used in model calculations…



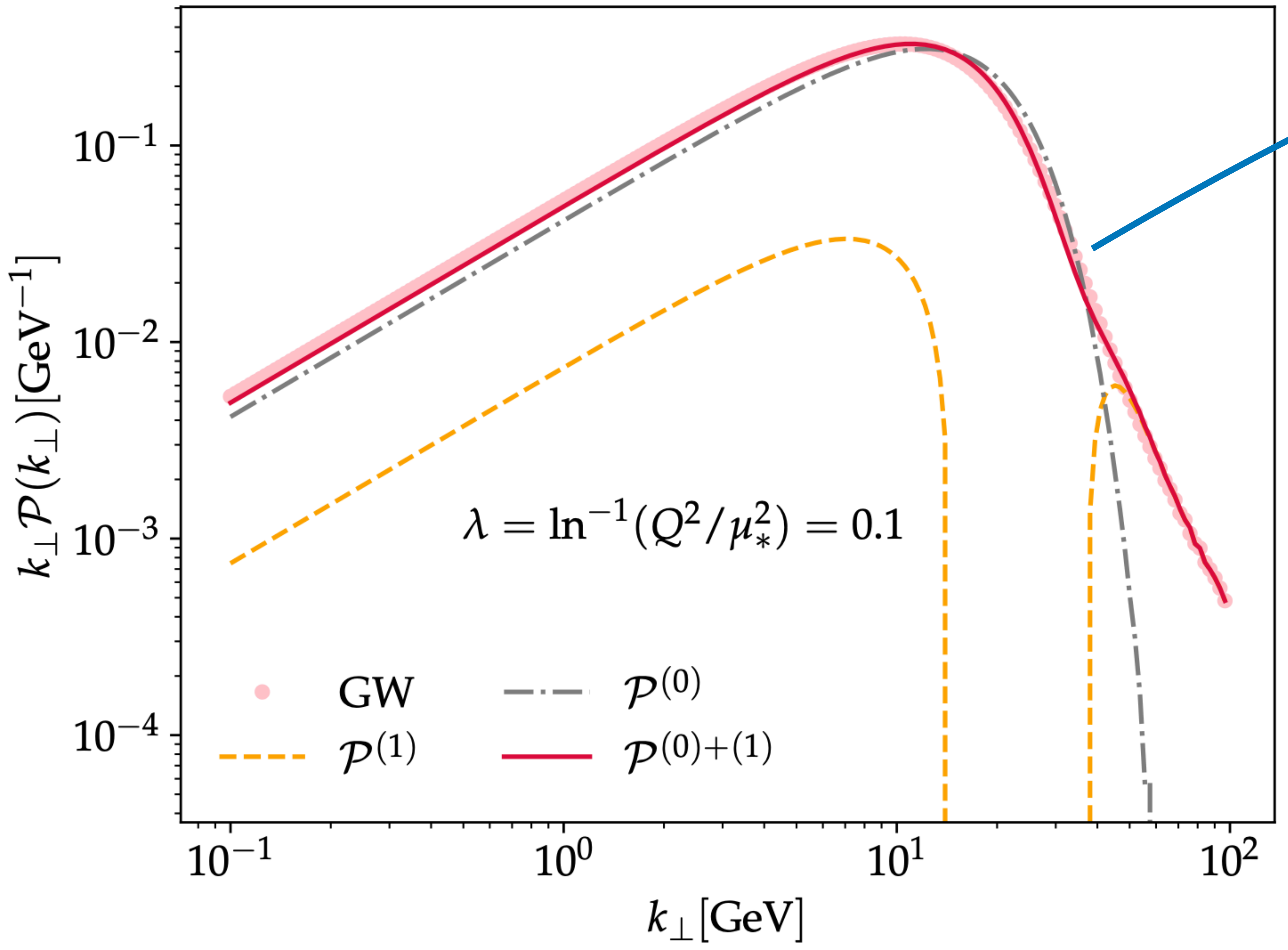
… might not be a good approximation to a real droplet

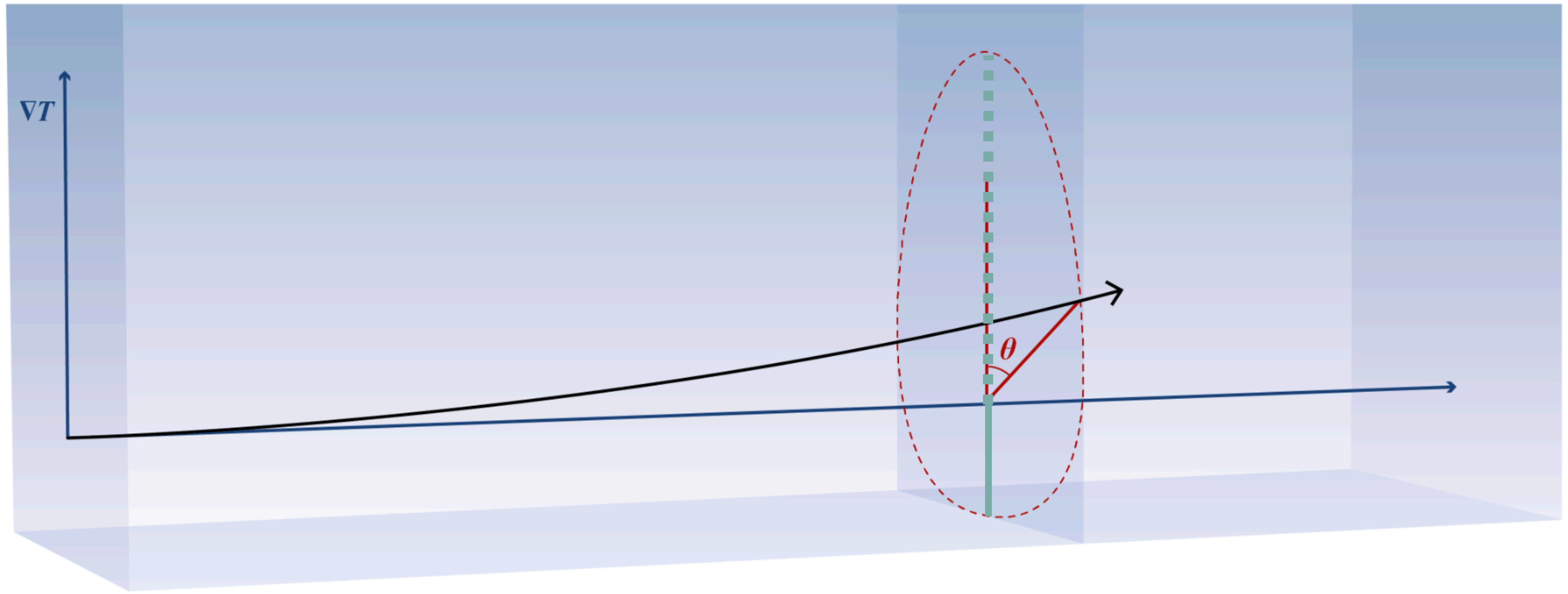


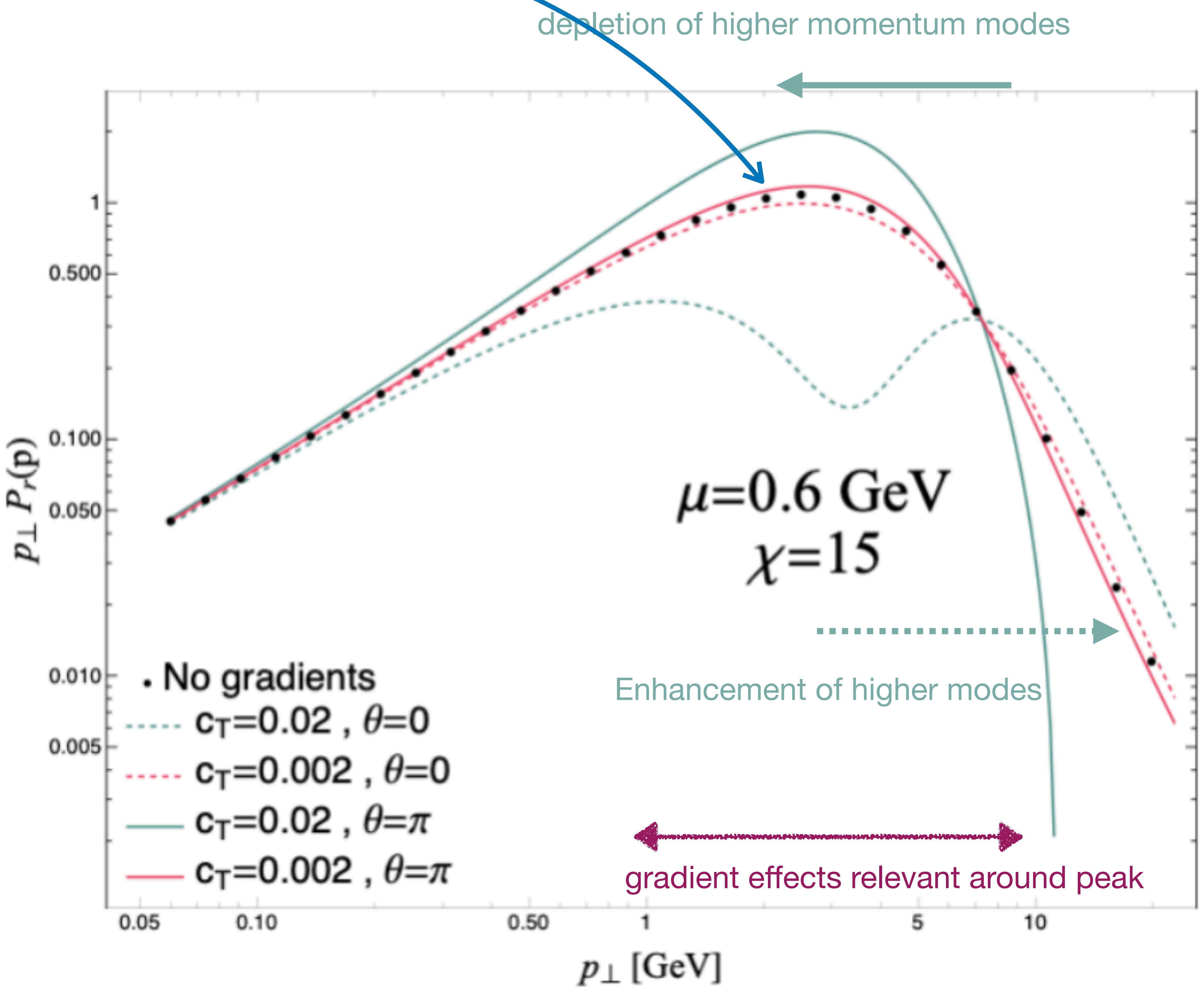
Jet evolution in structured matter: momentum broadening



Jet evolution in structured matter: momentum broadening

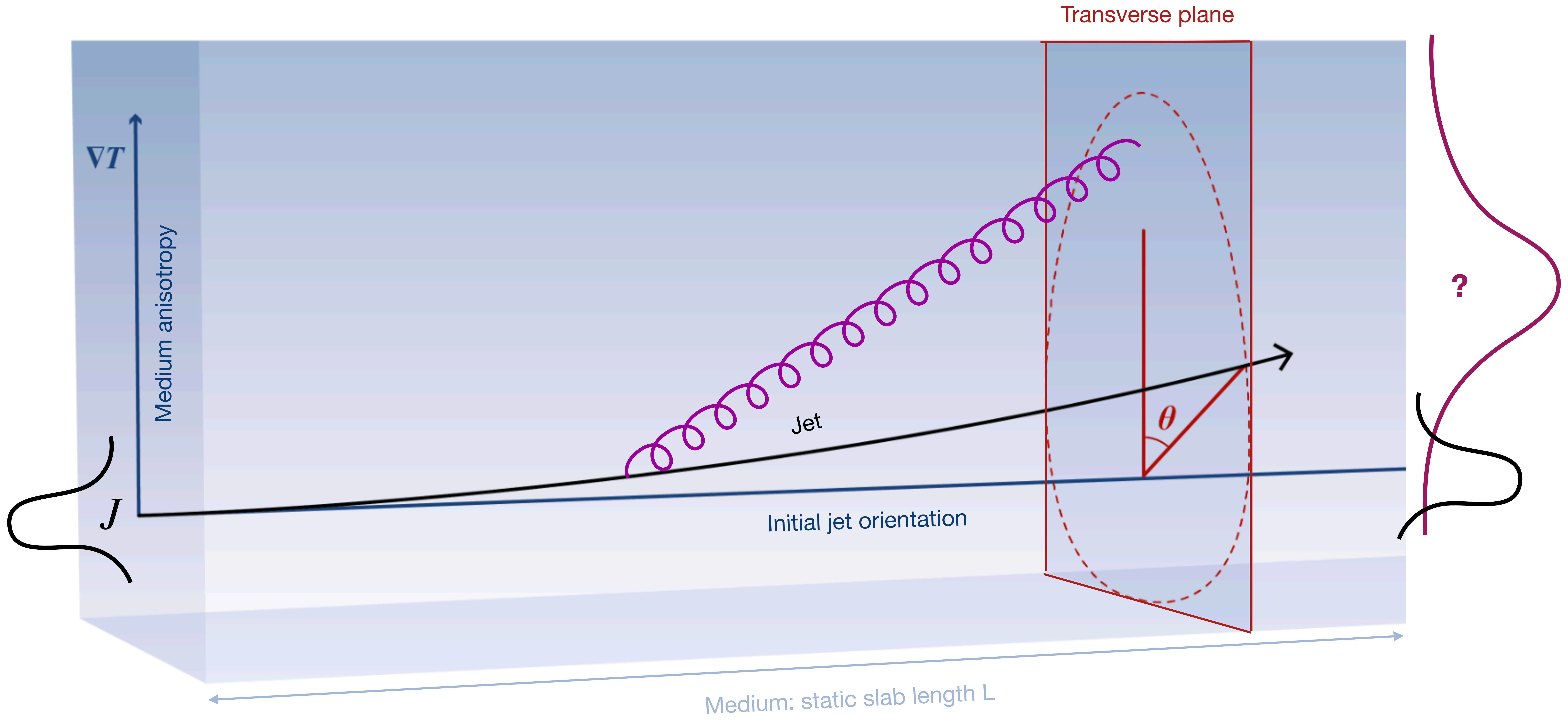






The full distribution is written in terms of the angle θ and parameter $c_T \equiv \left|\frac{\nabla T}{ET}\right|$.

Jet evolution in structured matter: gluon radiation



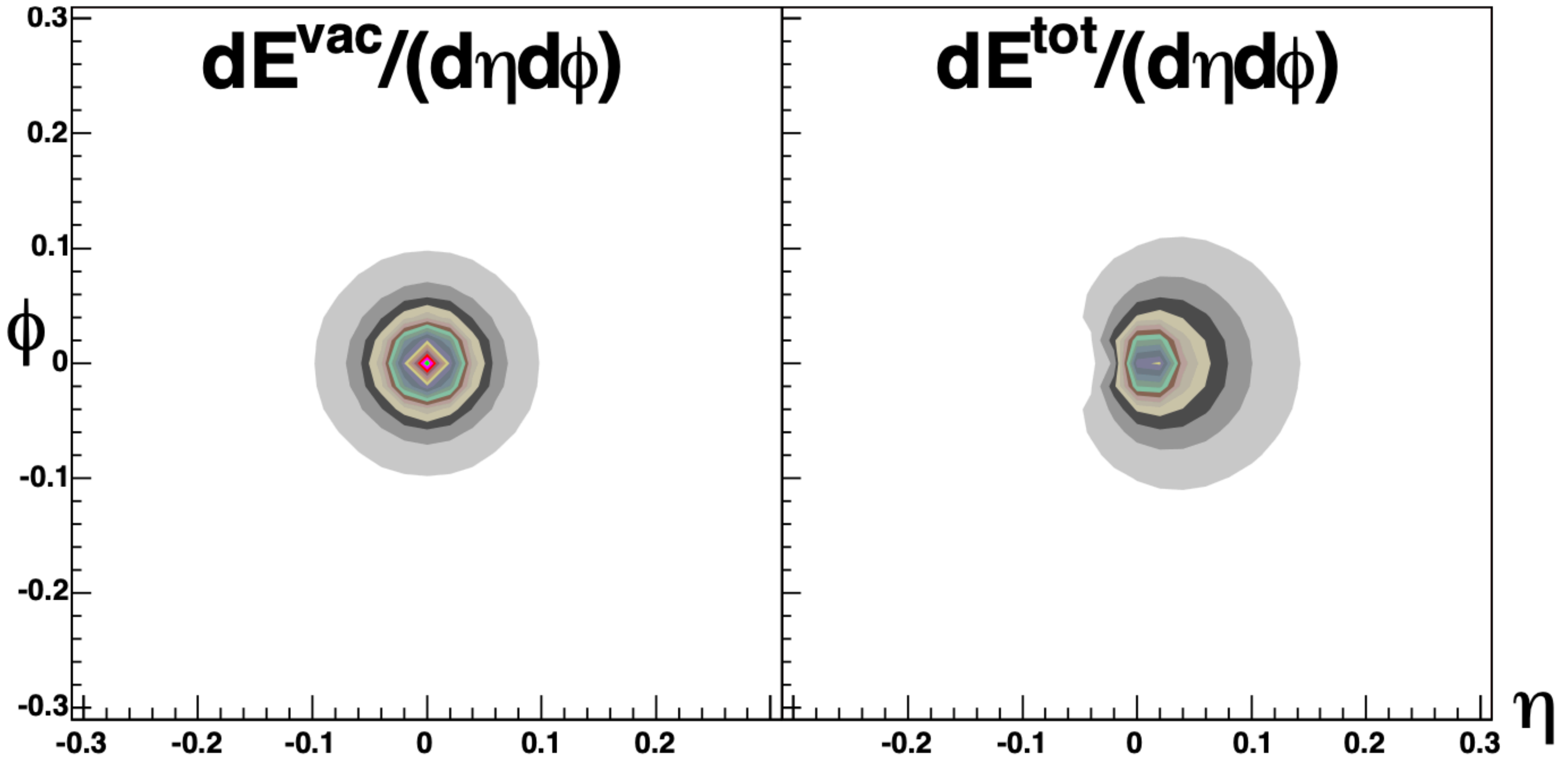
Jet evolution in structured matter: momentum broadening

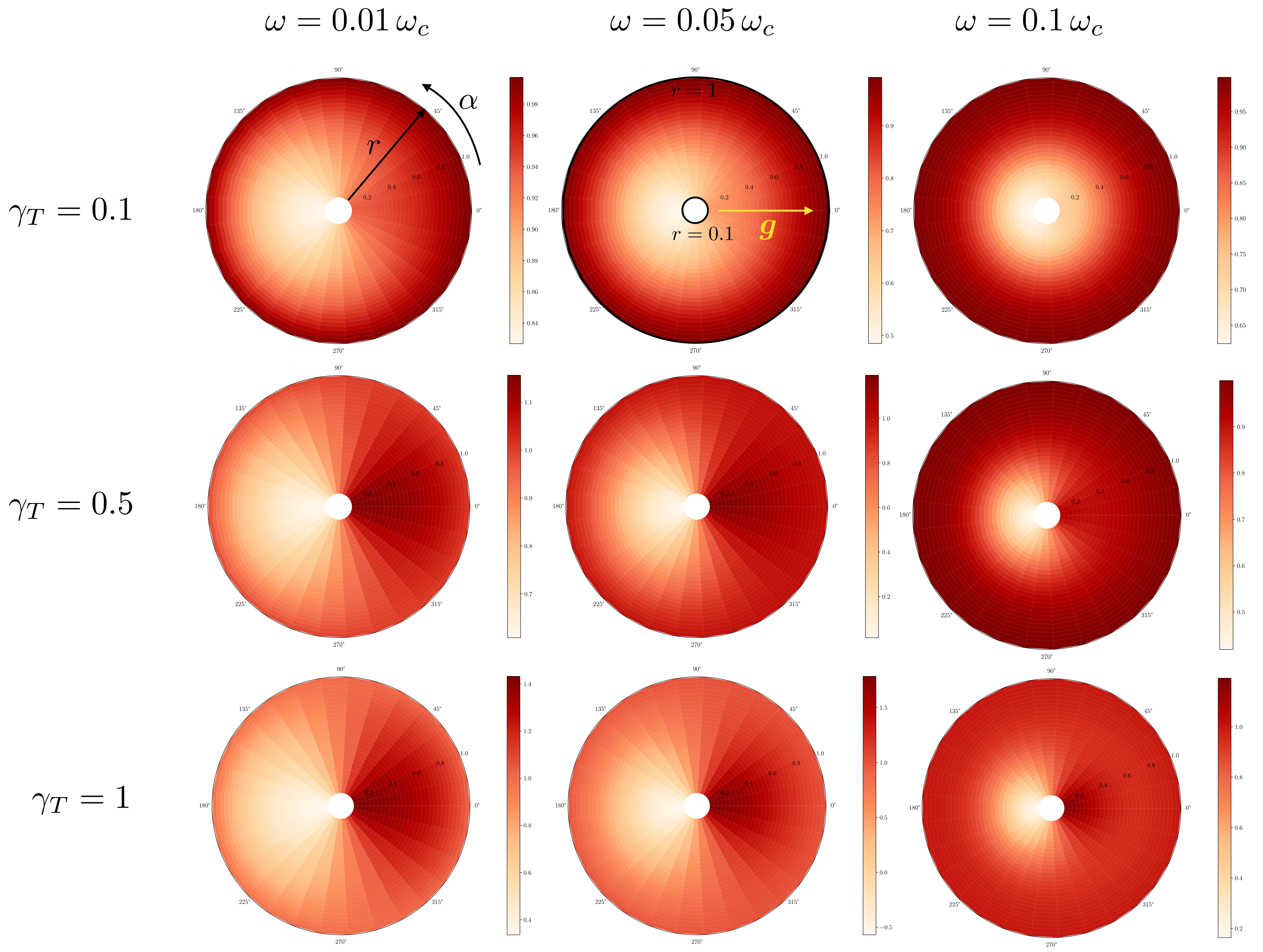
The presence of anisotropies leads to a non-trivial azimuthal structure for radiation flow. The same occurs with flowing matter.

Observable: jet shape density

$$(2\pi)p_t^{\text{jet}}\frac{d\rho(r)}{d\omega d\alpha} = 1 - 2\pi\int_{\omega r}^{\omega} dk\,k\,\omega\frac{dI}{d\omega d^2\boldsymbol{k}}$$

[Armesto, Salgado, Wiedemann, 2004]





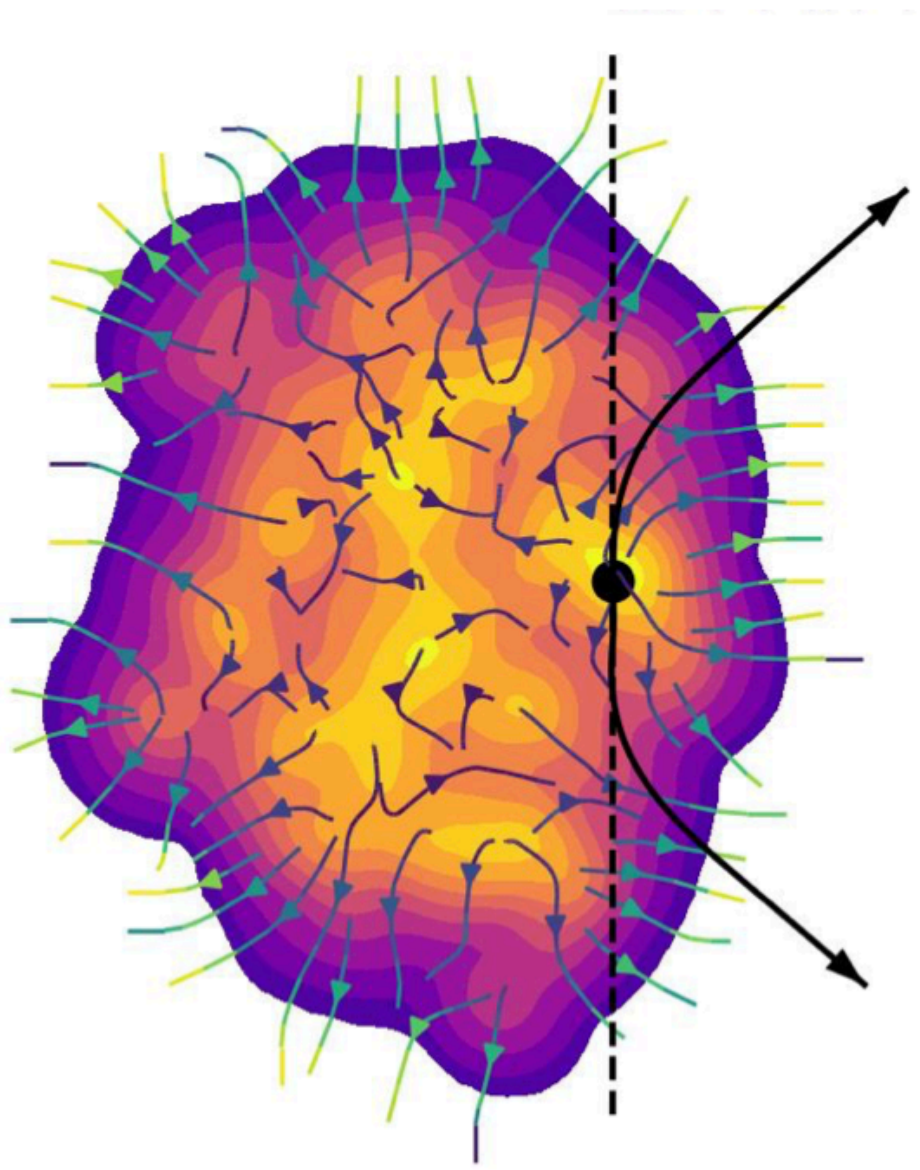
The Landscape

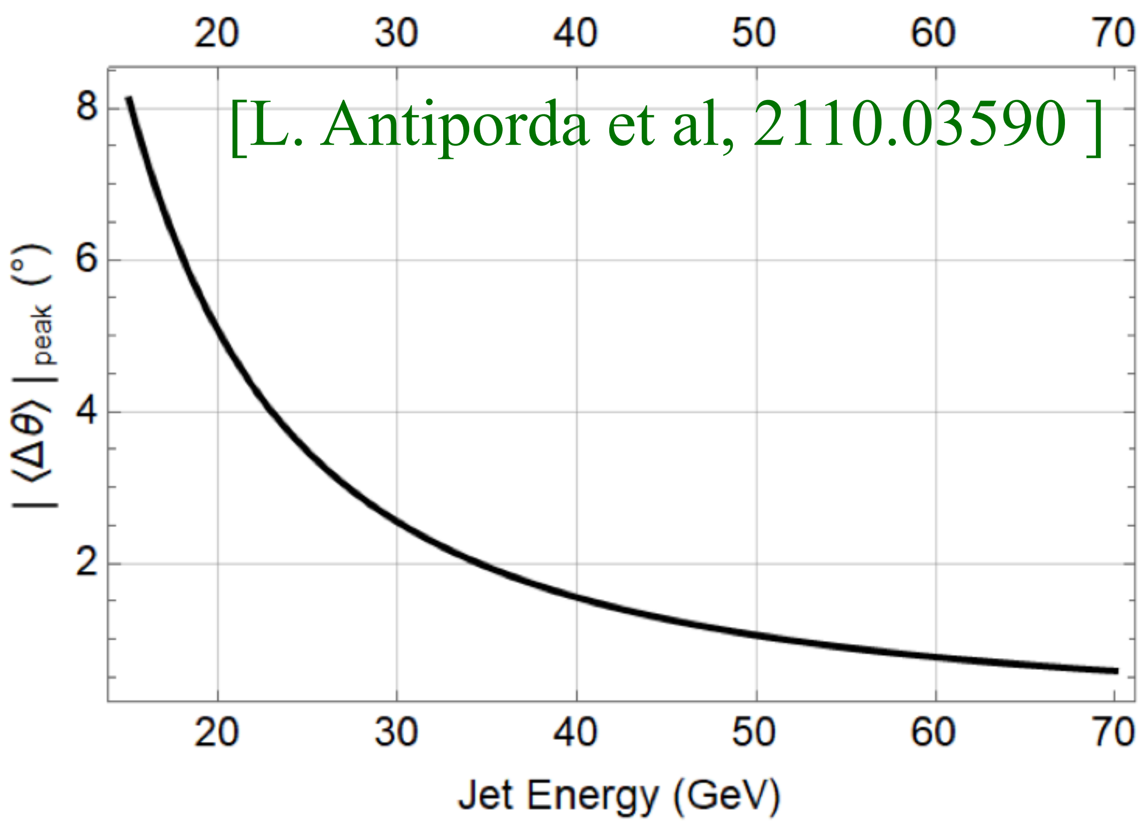
Jet evolution in hydrodynamical phase

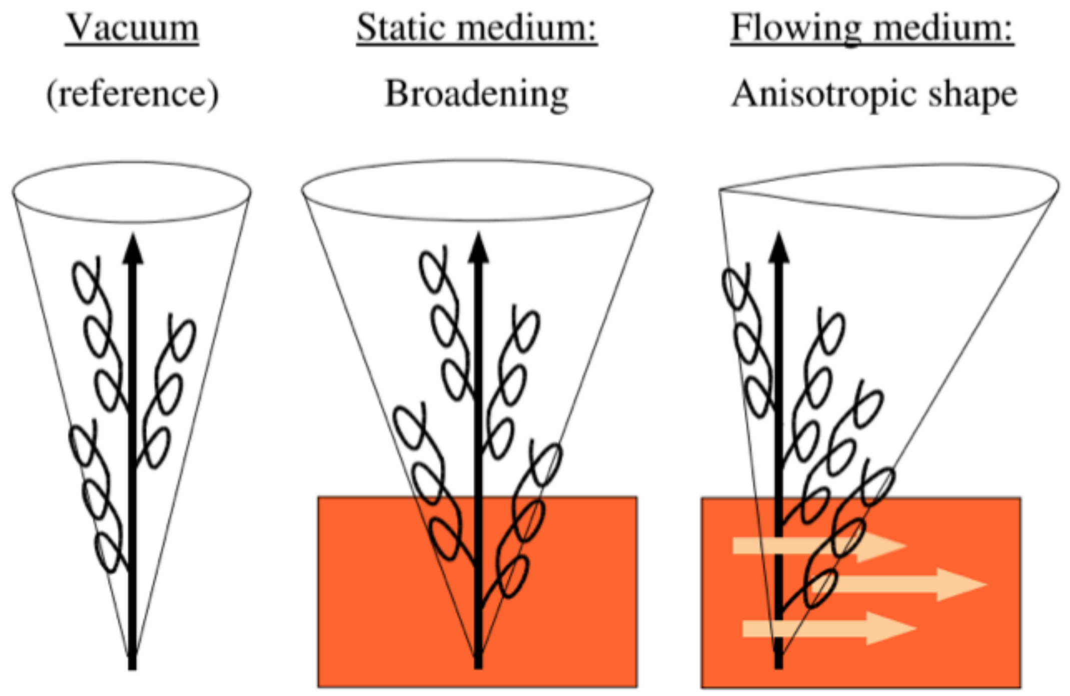
Flowing matter: 2104.09513 [N=1], 2207.07141 [Resummation], 2406.14628 [Gluon radiation], 2309.00683 [Flowing anisotropic matter], …

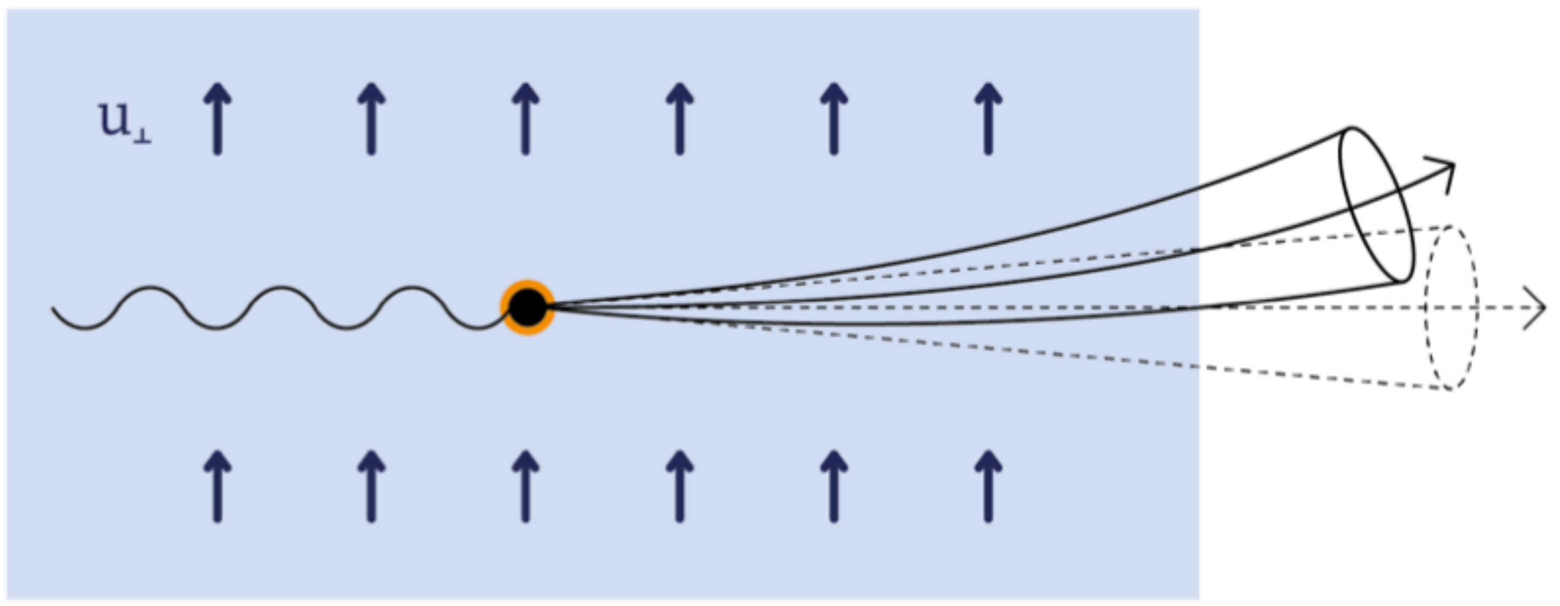
Matter gradients: 2104.09513 [N=1], 2202.08847 [Resummation], 2210.06519 [Kinetic Th.], 2304.03712 [Gluon Radiation], 2204.05323 [Broadening]

Jet observables/Pheno: 2110.03590 [Jet drift], 2308.01294 [Jet substructure], DREENA, …



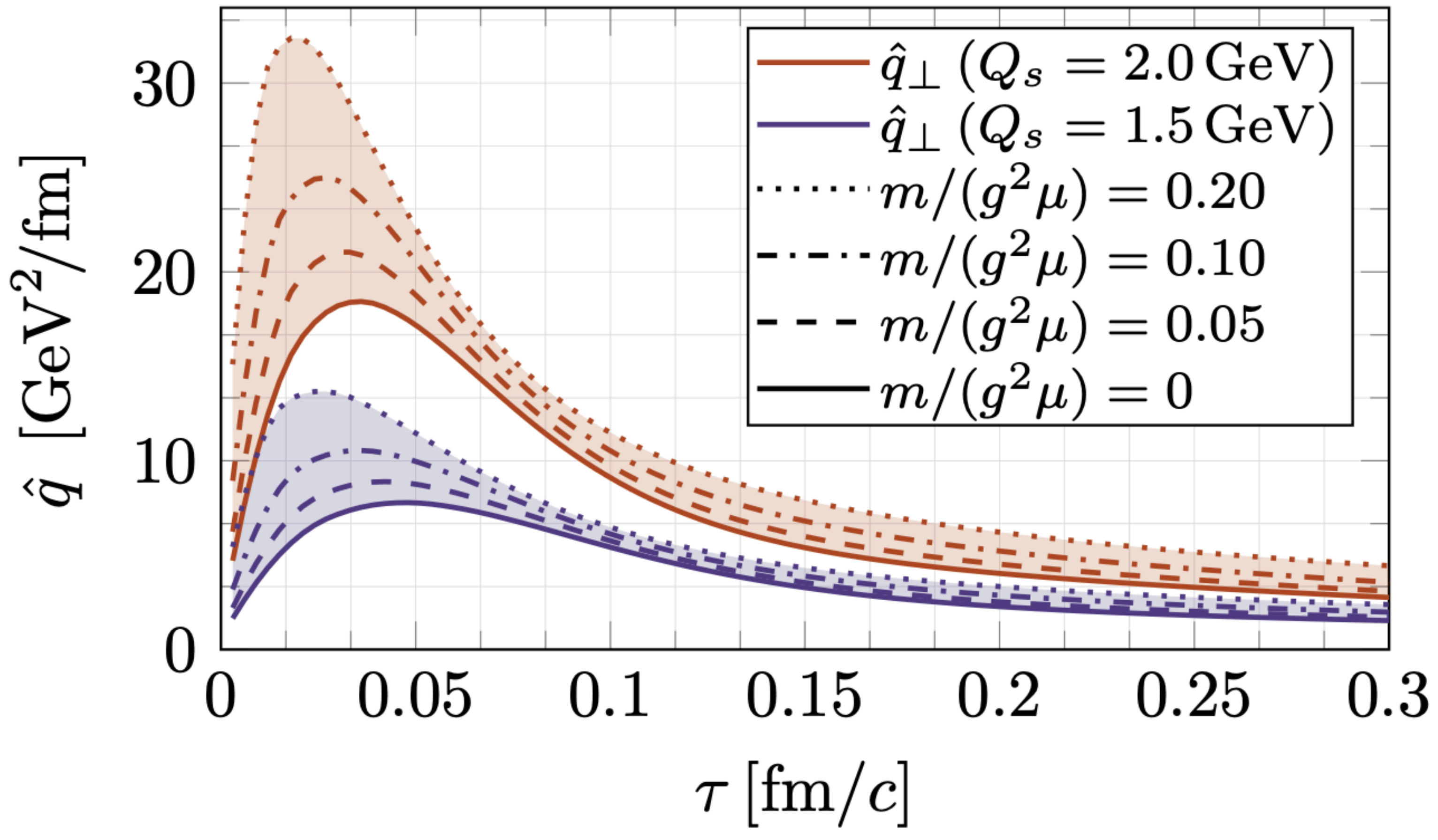


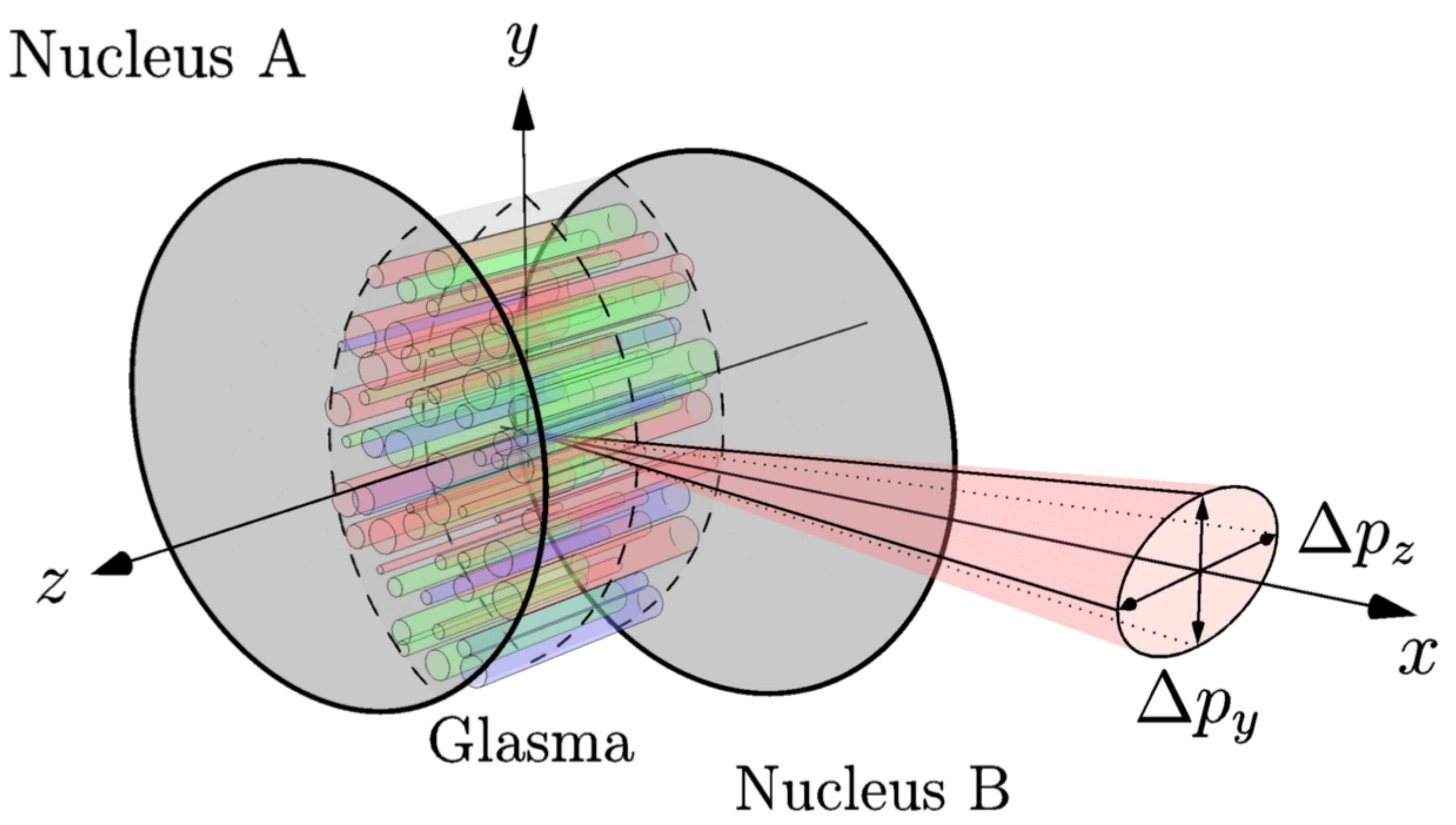




The Landscape

[A. Ipp, D. I. Muller, D. Schuh, 2009.14206]





Jet evolution in the early stages

Momentum broadening in early stages: Works by Avramescu et al; Lindebauer et al; Muller et al, …

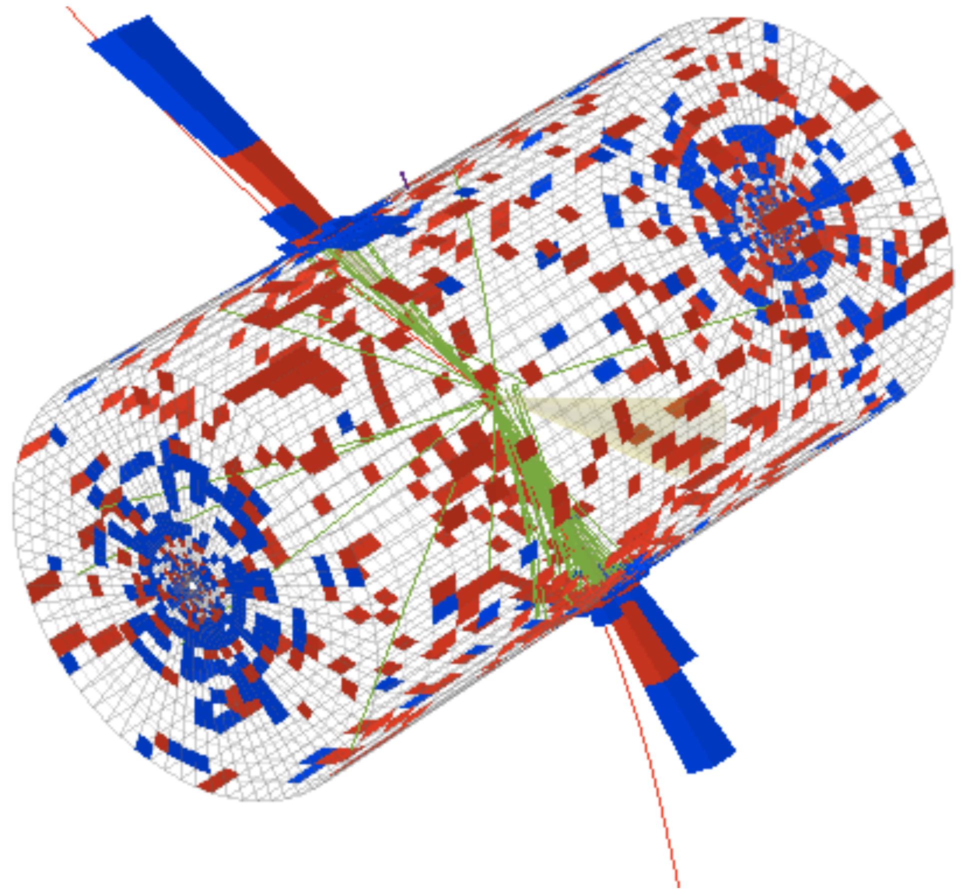
Radiative spectrum in “glasma”: 2306.20307 [Photons], 2303.03914 [Gluon branching], 2407.04774 [Quark antenna], 2406.07615 [Spatial correlations]

[See other talks by Kirill, Dusan and Bithika this week]

Summary

- The jet quenching program was initiated several decades ago; today it is one of the most active fields in the high-pt sector of HICs.
- Jets are ideal probes to resolve the spacetime structure of the plasma, and admit a perturbative treatment.
- In the future, we will need a more differential look into jets, keeping track of not only energy and momentum, but also other quantum numbers such as the spin distribution inside them.
- Many of these aspects have been studied by other communities (spin-hydro, soft sector, …) and there is a large overlap that can be exploited!

$\approx$



Thank you !