Jet quenching in evolving matter

for SoftJet 2024

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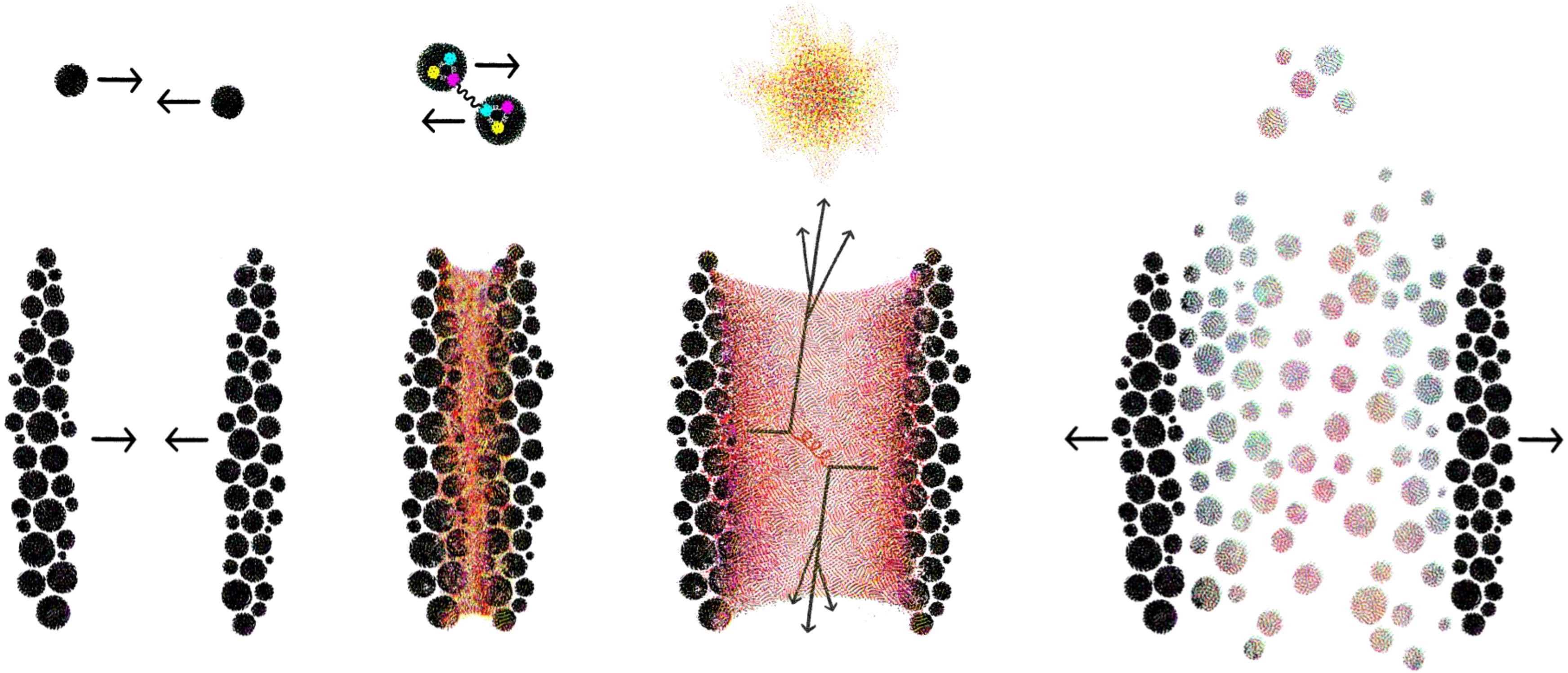
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Heavy-ion collisions

elementary
constituents

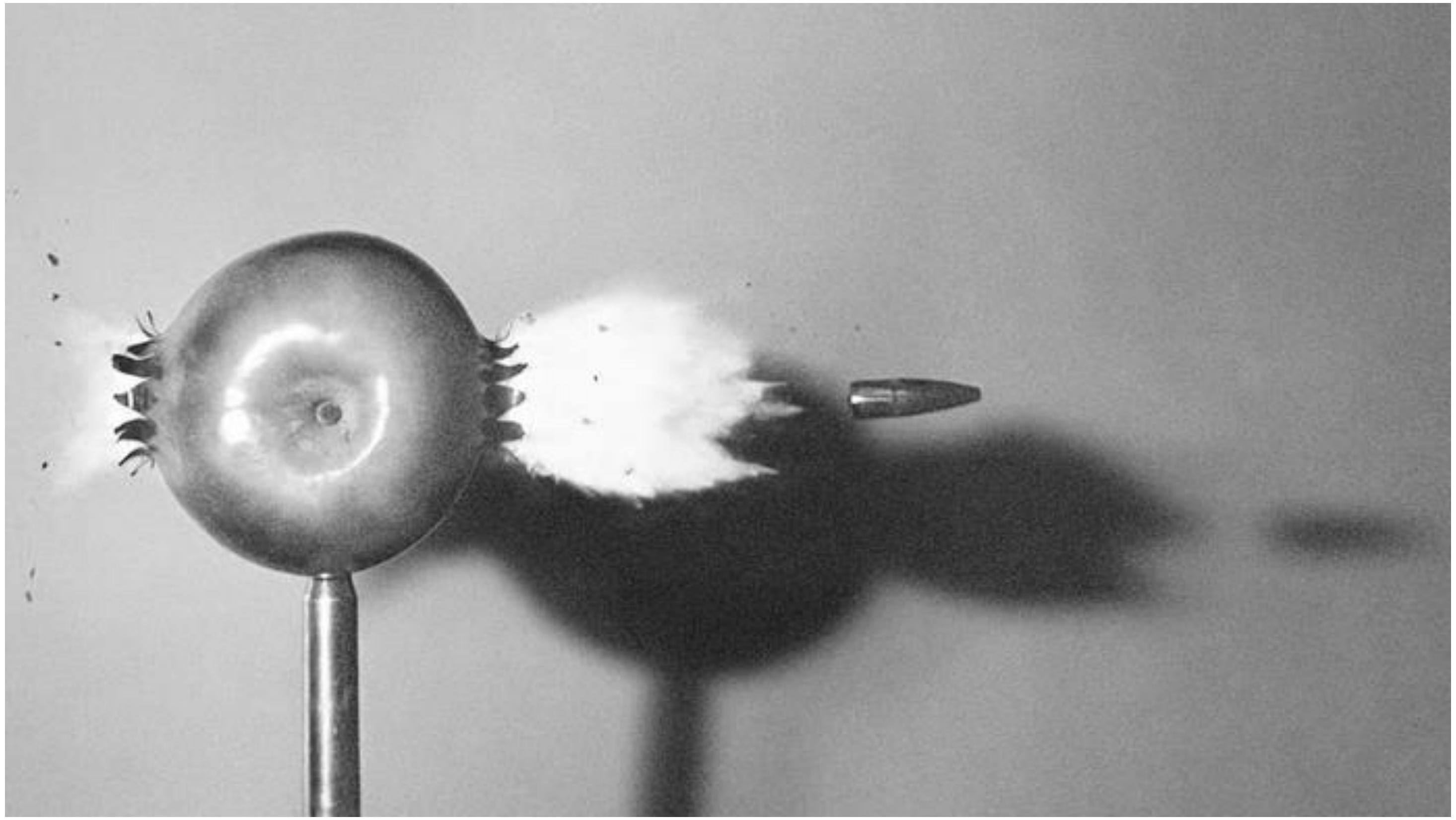
complex
nuclear matter

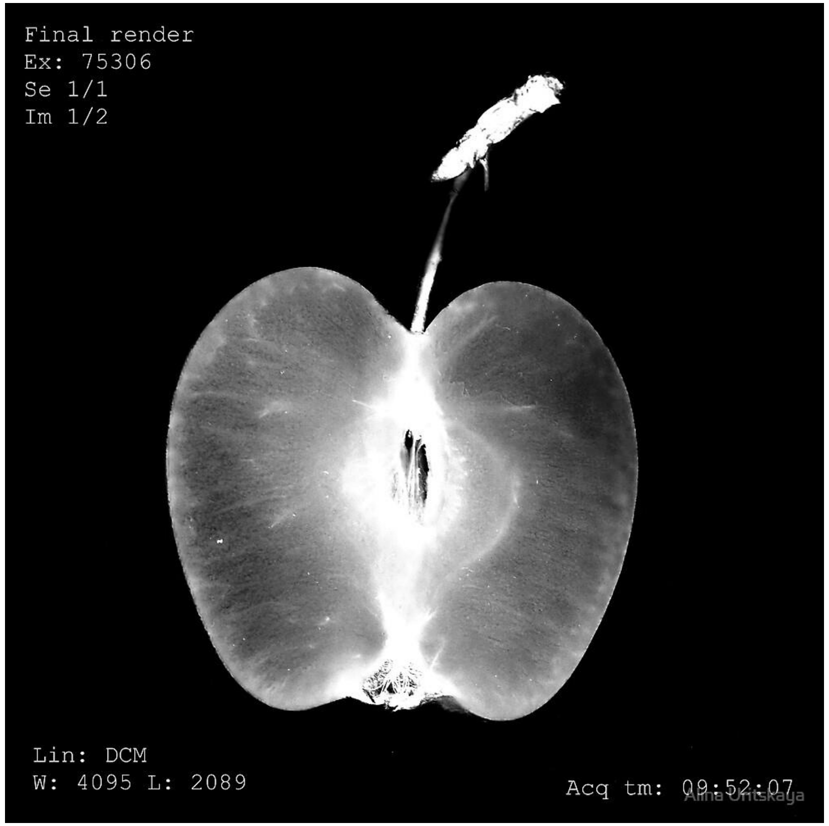


small
system

large
system

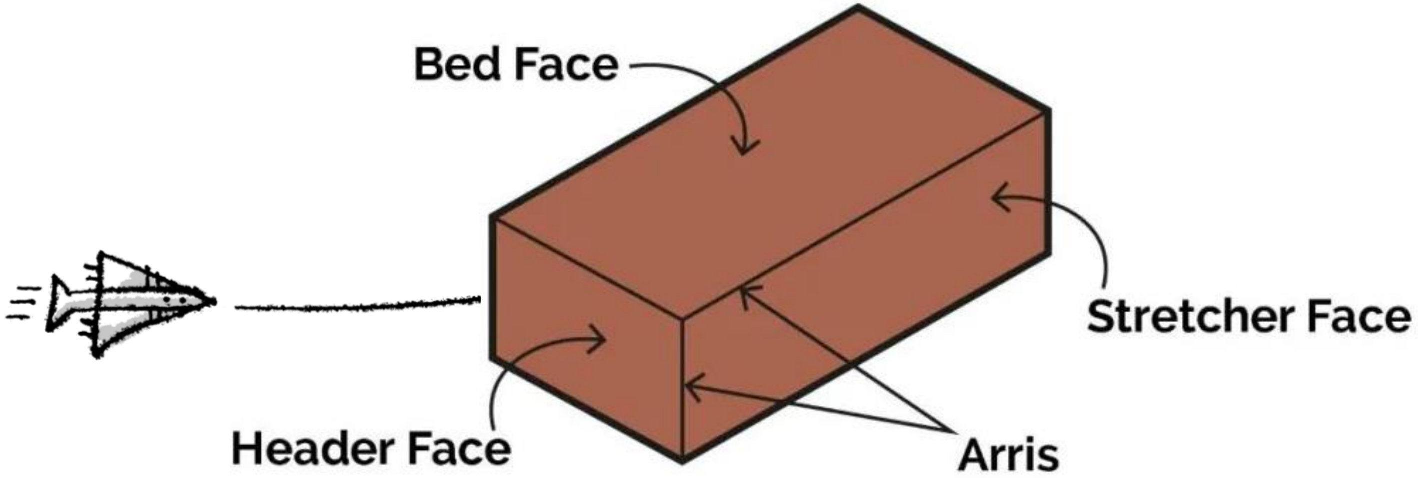
Jet tomography





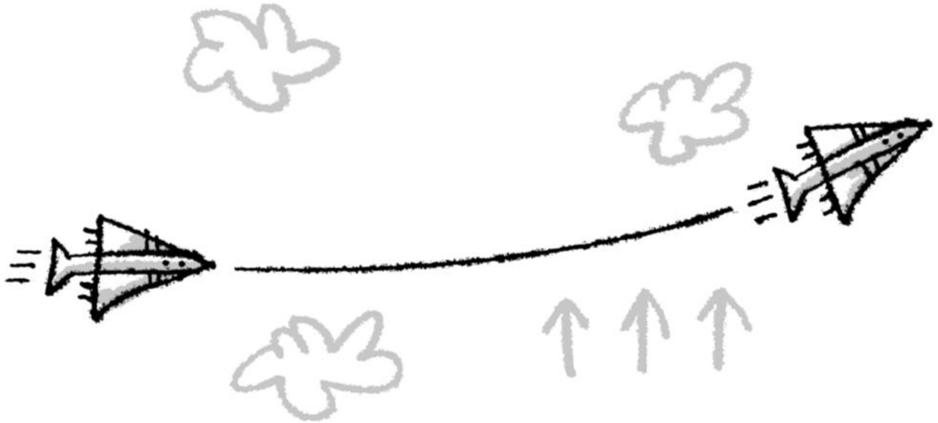
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Static brick

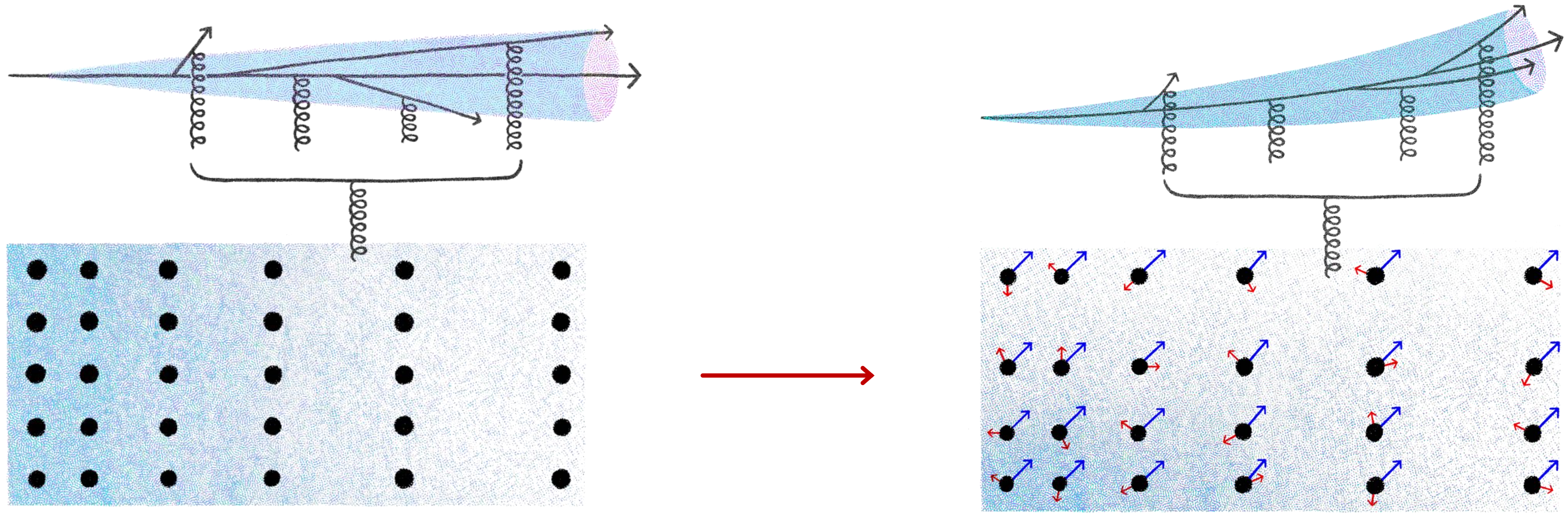


Evolving matter

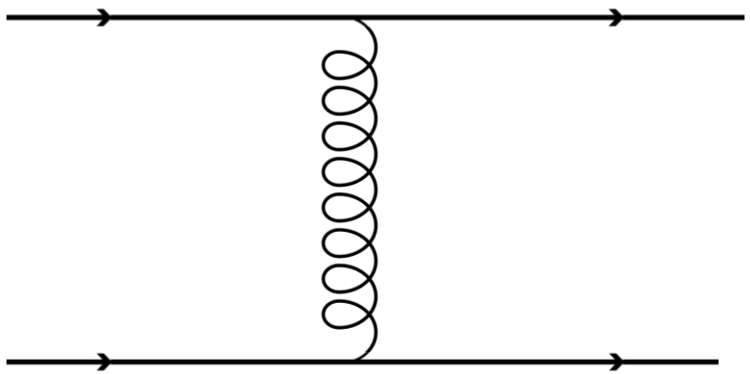
Does a jet feel the flow?



Jets in evolving matter

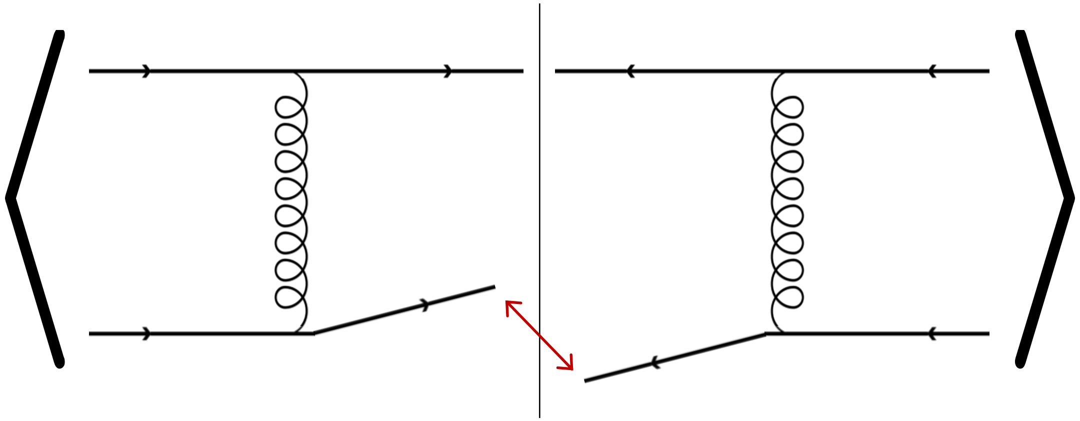


Color potential



$$\mathbf{p}' \to \gamma(\mathbf{p} - \mathbf{u}E)$$

$$\mathcal{O}\big((p_\perp/E)^n\big) \to \mathcal{O}\big((\gamma u_\perp)^n\big)$$



$$\int_{\mathbf{x}} \rho(\mathbf{x}) e^{-i(\mathbf{q}\pm\bar{\mathbf{q}})\cdot\mathbf{x}} \neq (2\pi)^2 \delta^{(2)}(\mathbf{q} \pm \bar{\mathbf{q}})$$

AS, M. Sievert, I. Vitev, PRD, 2021
J. Barata, AS, C. Salgado, PRD, 2022
C. Andres, F. Dominguez, AS, CS, PRD, 2022
L. Antiporda, J. Bahder, H. Rahman, M. Sievert, PRD, 2022
J. Barata, AS, X.-N. Wang, PRD, 2023
J. Barata, X. Mayo Lopez, AS, CS, PRD, 2023
M. Kuzmin, X. Mayo Lopez, J. Reiten , AS, PRD, 2024
J. Barata, G. Milhano, AS, EPJC, 2024
M. Kuzmin, X. Mayo Lopez, arxiv, 2024

Jets in evolving matter

What did we have?

- Jets see the matter in HIC (and DIS) at multiple scales, and essentially X-ray it;
- Theory is based on multiple simplifying assumptions: static matter, no fluctuations, etc;

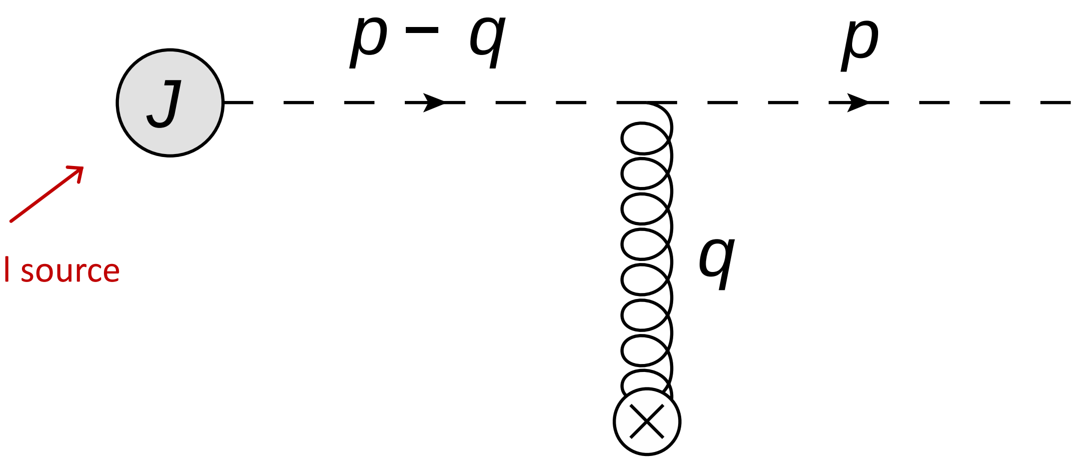
What do we have?

- The coupling of jets to the flow, structure (matter anisotropy), fluctuations, etc.
- An updated parton transport equation needed for most modern simulations of jets in QCD matter;

What is still missing?

- New jet observables sensitive to the medium evolution;
- Coupled simulations of matter and jets for quantitative phenomenology;

Color potential



the initial distribution

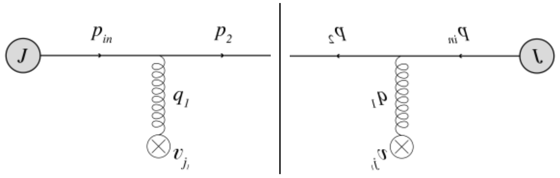
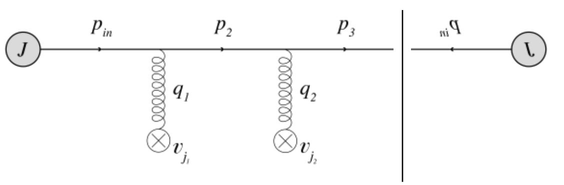
$$iM_1(p) = \int \frac{d^4q}{(2\pi)^4} \left[ig\, t^a_{\text{proj}} A^{\mu a}_{\text{ext}}(q)\, (2p-q)_\mu \right] \left[\frac{i}{(p-q)^2 + i\epsilon} \right] J(p-q)$$

$$gA^{\mu a}_{ext}(q) = \sum_i e^{iq\cdot x_i}\, t^a_i\, u^\mu_i\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \vec{u}_i \cdot \vec{q}\right)$$

inhomogeneity

the fluid velocity

Broadening (no flow, no anisotropy)

$$E\frac{d\mathcal{N}}{d^3p} \simeq f(E)\delta^{(2)}(\mathbf{p}) + \Big\langle$$  $$\Big\rangle + \Big\langle$$  $$\Big\rangle$$

$$E\frac{d\mathcal{N}^{(1)}}{d^3p} = \int_0^L dz \int_q \mathcal{V}(\mathbf{q})\, f(E)\delta^{(2)}(\mathbf{p}-\mathbf{q})$$

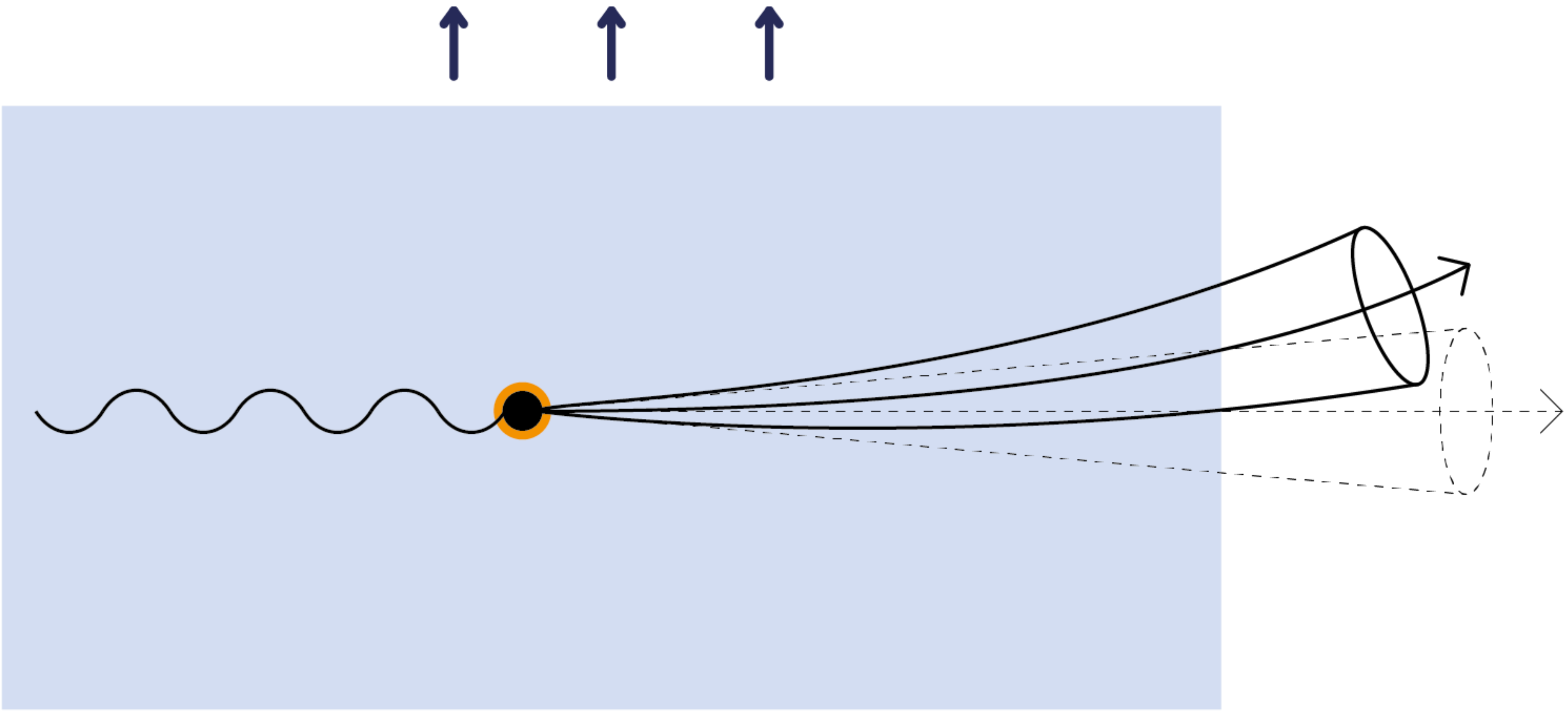
$$\mathcal{V}(\mathbf{q}) = -\mathcal{C}\rho\left(|v(\mathbf{q})|^2 - \delta^{(2)}(\mathbf{q})\int_l |v(\mathbf{l})|^2\right)$$

controls most of
the pheno simulations ⟶

$$\hat{q} = \frac{\partial}{\partial L}\langle p_\perp^2\rangle = \frac{\mathcal{C}g^4\rho}{4\pi\mu^2}L\,\frac{\mu^2}{L}\log\frac{E}{\mu}$$

opacity χ

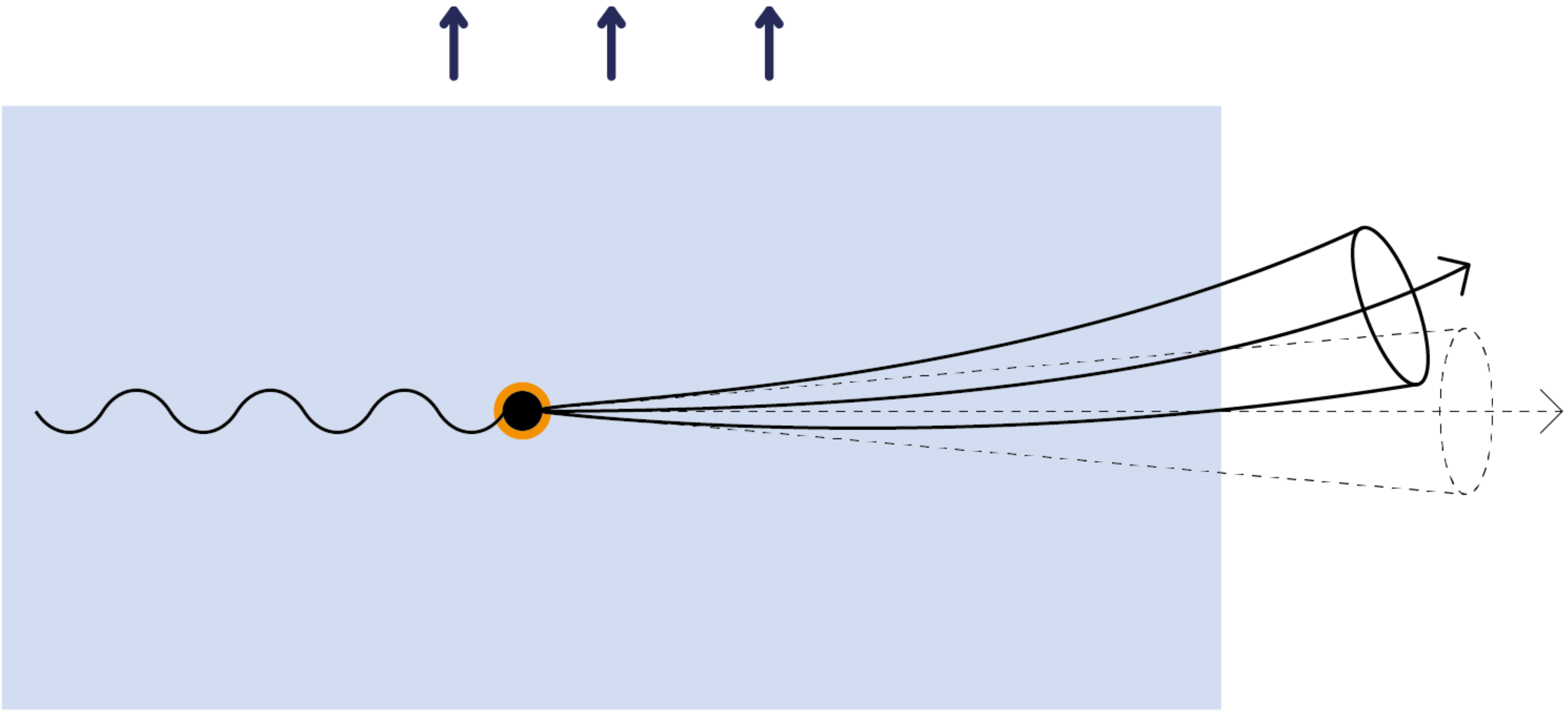
Flow



$$\langle \mathbf{p} \rangle \simeq 3\,\chi\,\mathbf{u}\,\frac{\mu^2}{E}\log\frac{E}{\mu}$$

AS, M. Sievert, I. Vitev, PRD, 2021
J. Barata, AS, C. Salgado, PRD, 2022
J. Barata, AS, X.-N. Wang, PRD, 2023

Anisotropy

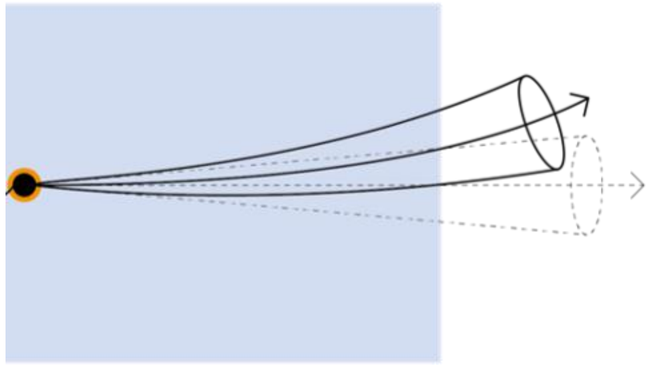


$$\langle \mathbf{p}\, p_\perp^2 \rangle \simeq \chi^2 \, \frac{L \nabla T}{2T} \, \frac{\mu^4}{E} \left(\log \frac{E}{\mu} \right)^2$$

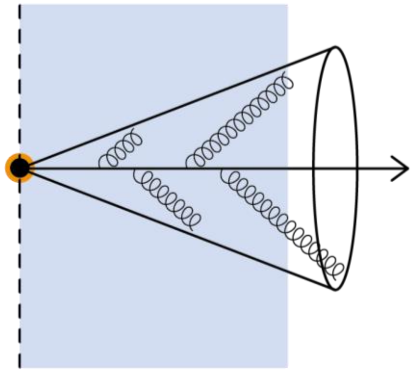
Jets in evolving matter

- Opacity $\chi \approx 4$
- $u \approx 0.7$ (about $\pi/4$ to z-axis)
- $\mu = gT$ with $g \approx 2$ and $T \approx 500\ MeV$

$$\left\langle \frac{p_\perp}{E} \right\rangle \simeq 3\,\chi\,\frac{u_\perp}{1-u_z}\,\frac{\mu^2}{E^2}\log\frac{E}{\mu}$$

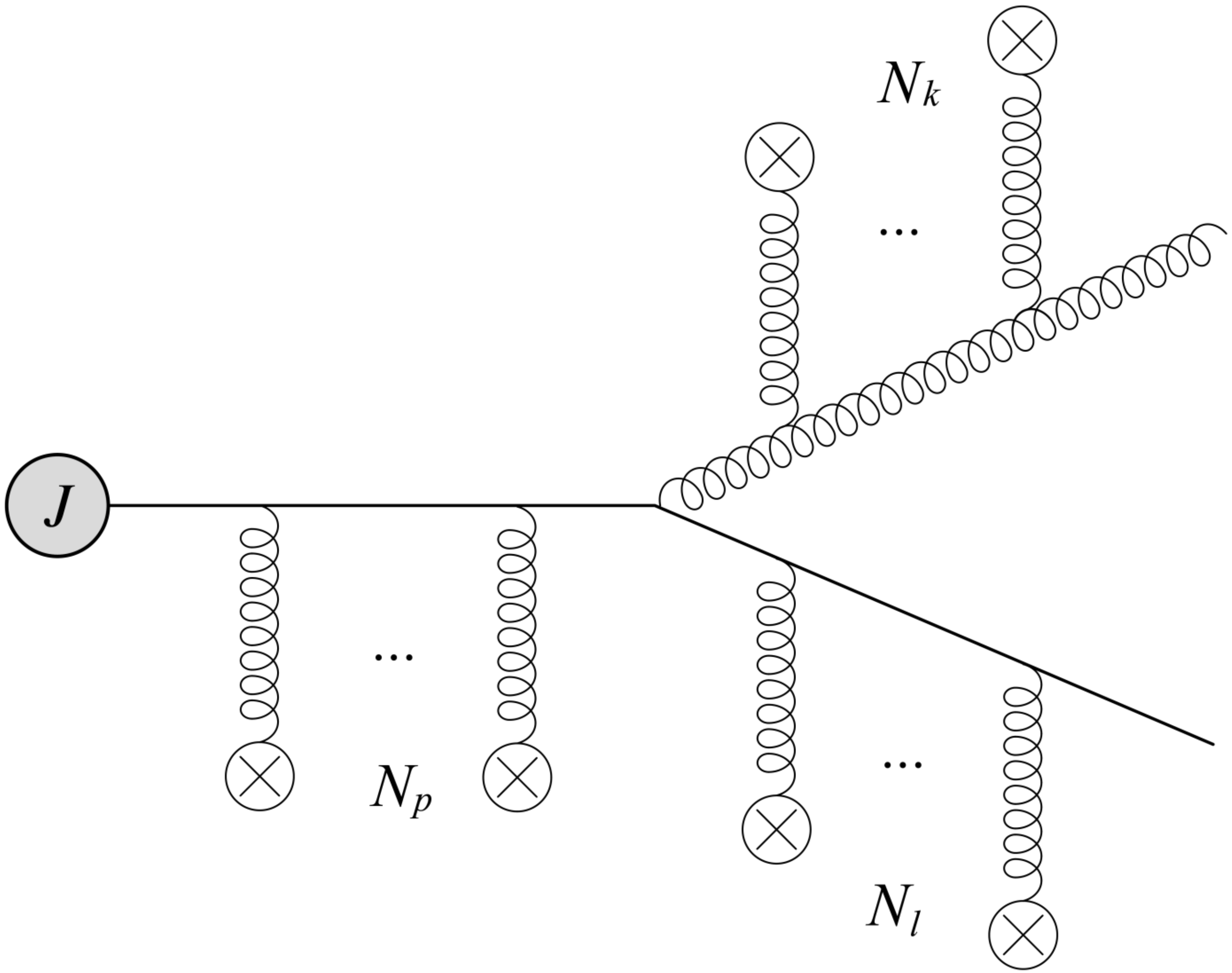


$E \sim 50$ GeV and $\langle\theta\rangle \sim 1^o$

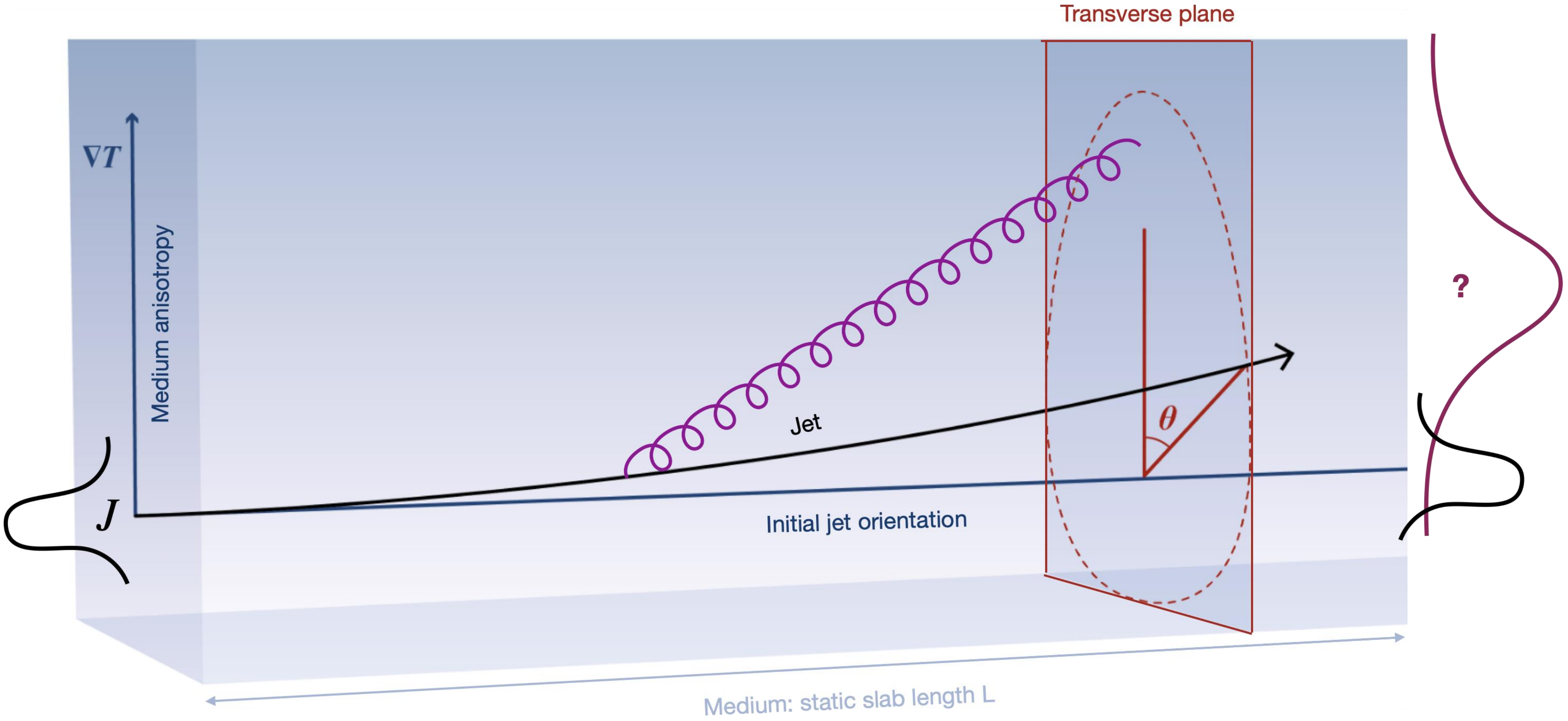


$\omega \sim 10$ GeV and $\langle\theta\rangle \sim 15^o$

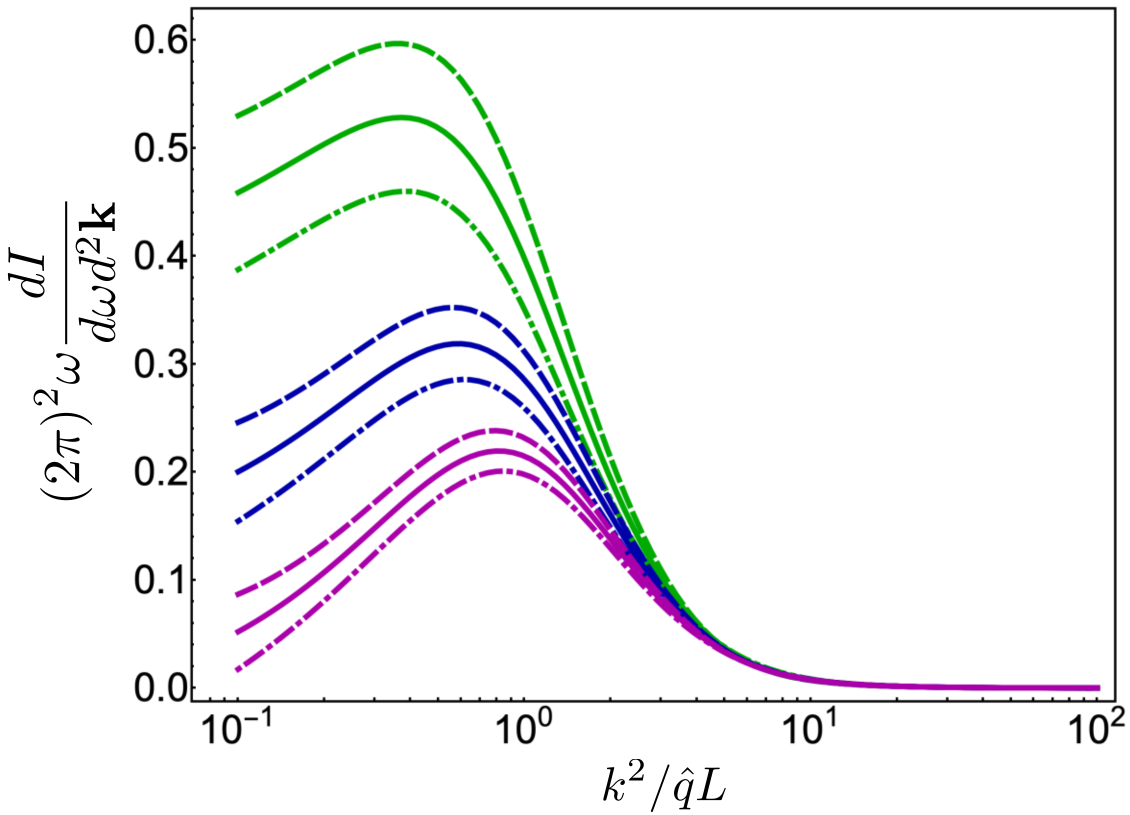
Gluon emission



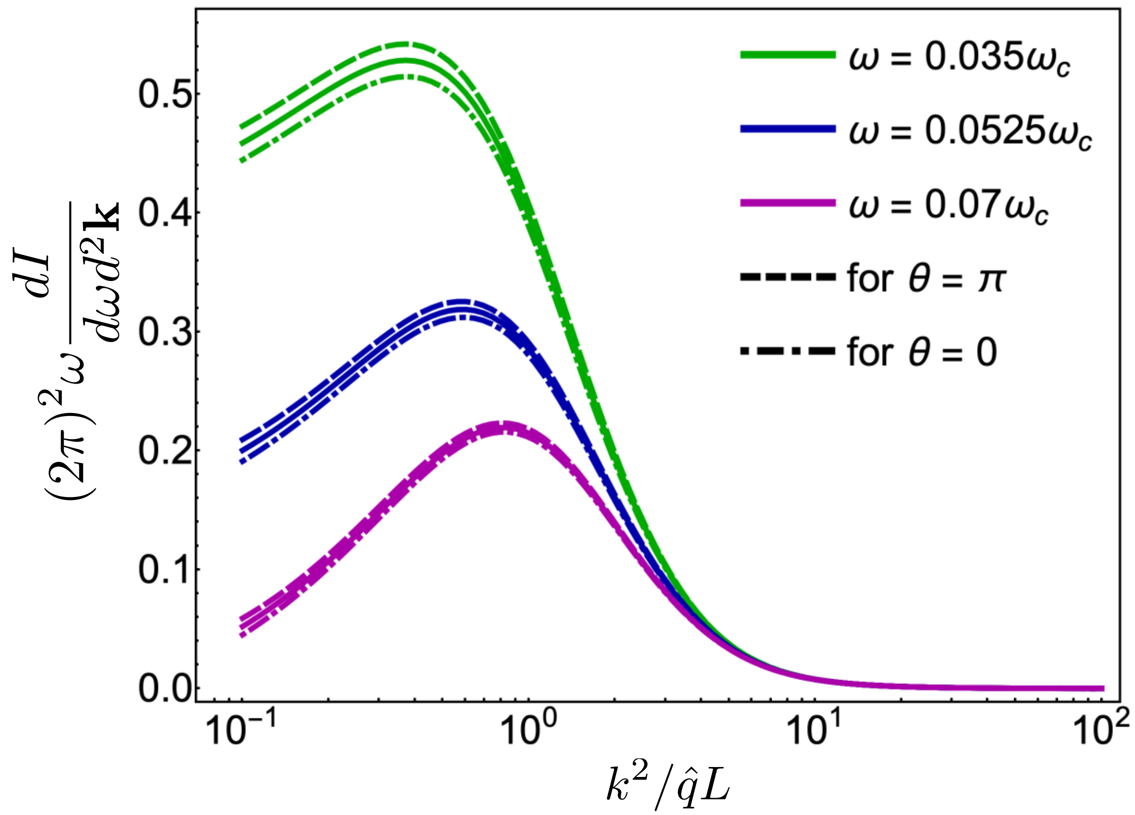
Gluon emission



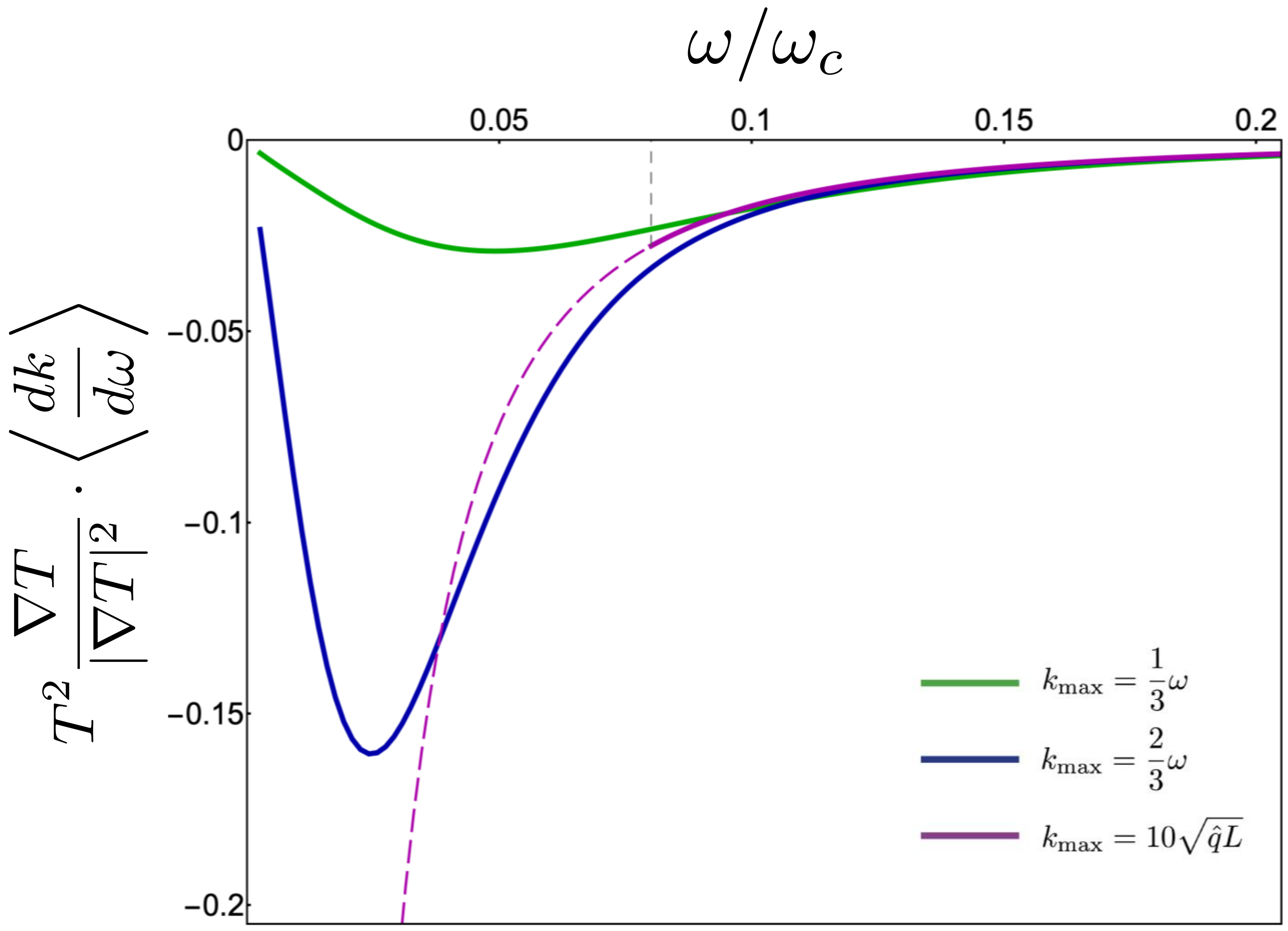
$$\left|\frac{\nabla T}{T^2}\right| = 0.05$$



$$\left|\frac{\nabla T}{T^2}\right| = 0.01$$

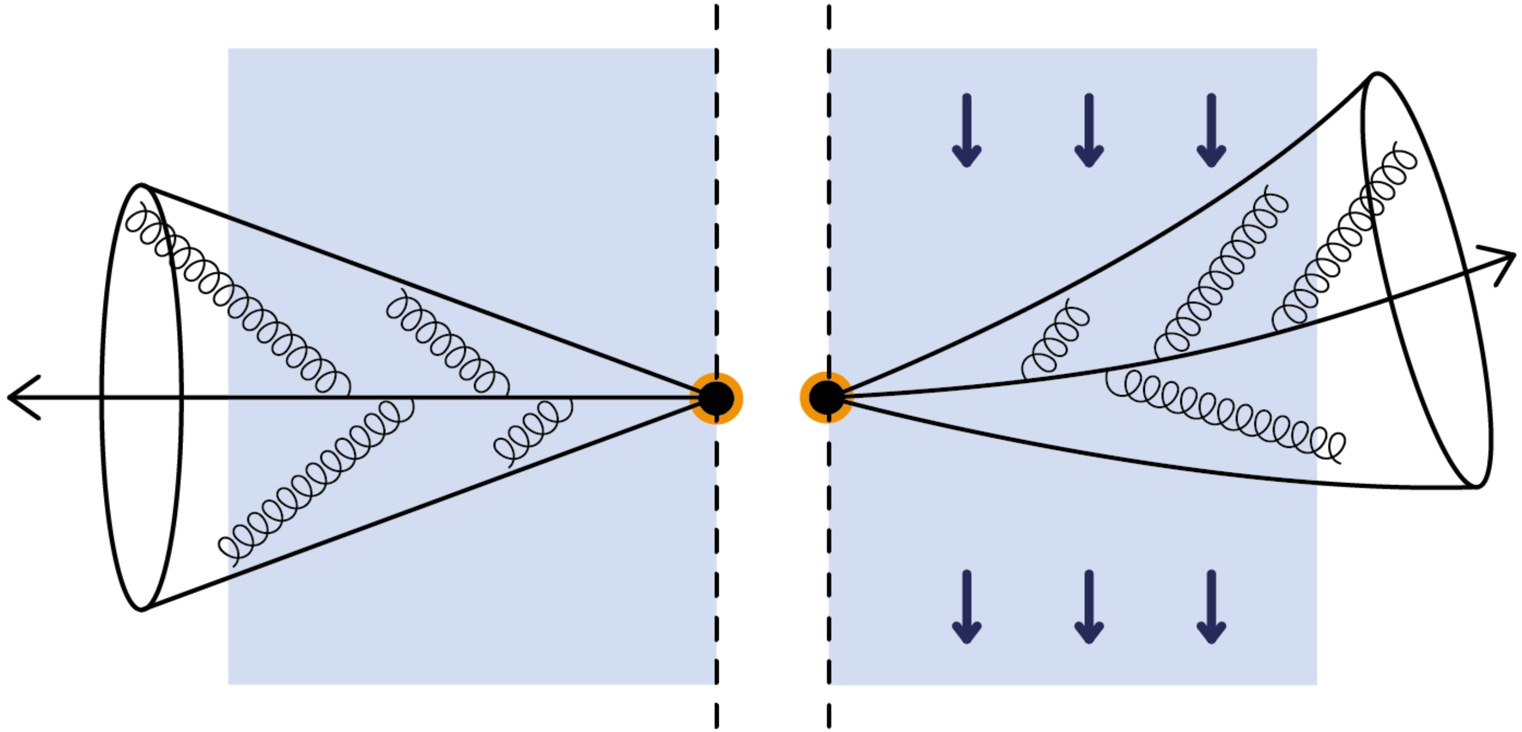


$$L = 5\text{fm}, \quad T = 0.3\text{GeV}, \quad \hat{q} = 1\text{GeV}^2 \cdot \text{fm}^{-1}$$

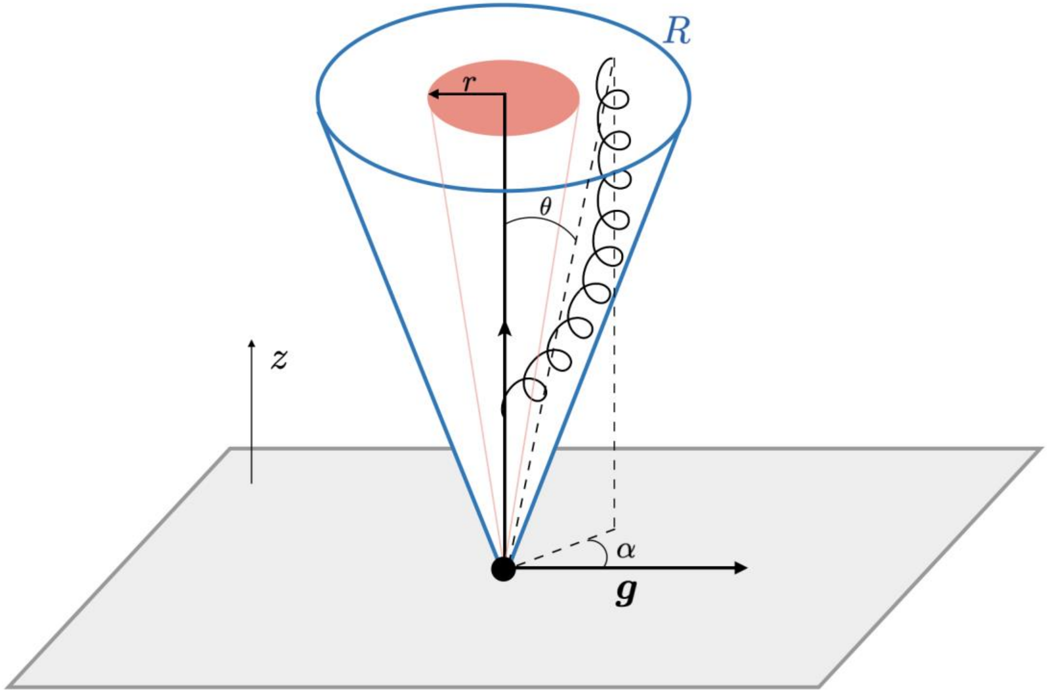


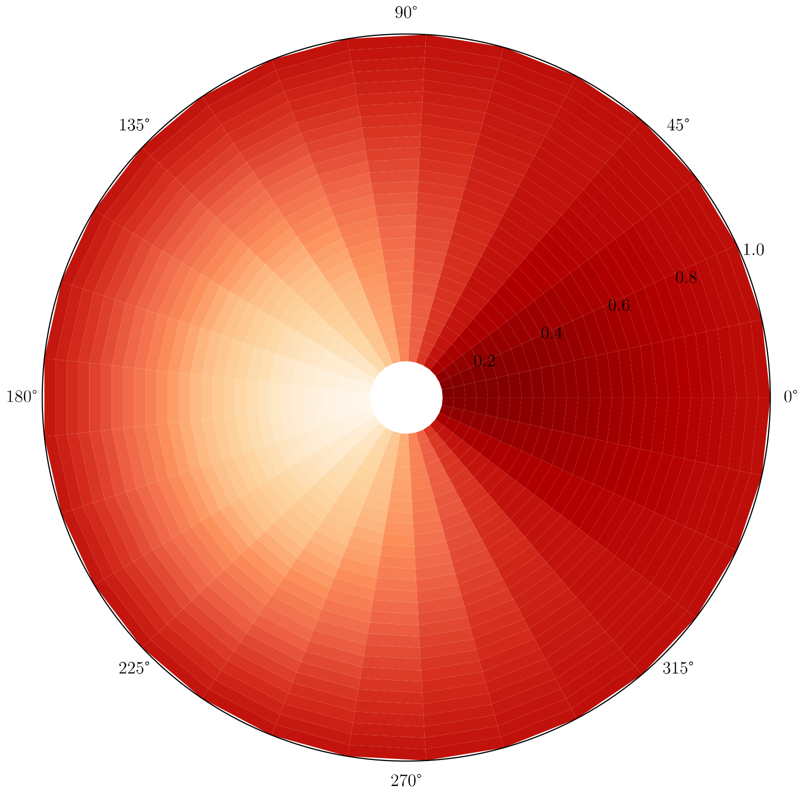
$$\left\langle \frac{d\mathbf{k}}{d\omega} \right\rangle \equiv \int_\Gamma d^2\mathbf{k}\,\mathbf{k}\,\frac{dI}{d\omega d^2\mathbf{k}}$$

Jets in evolving matter



Jets in evolving matter

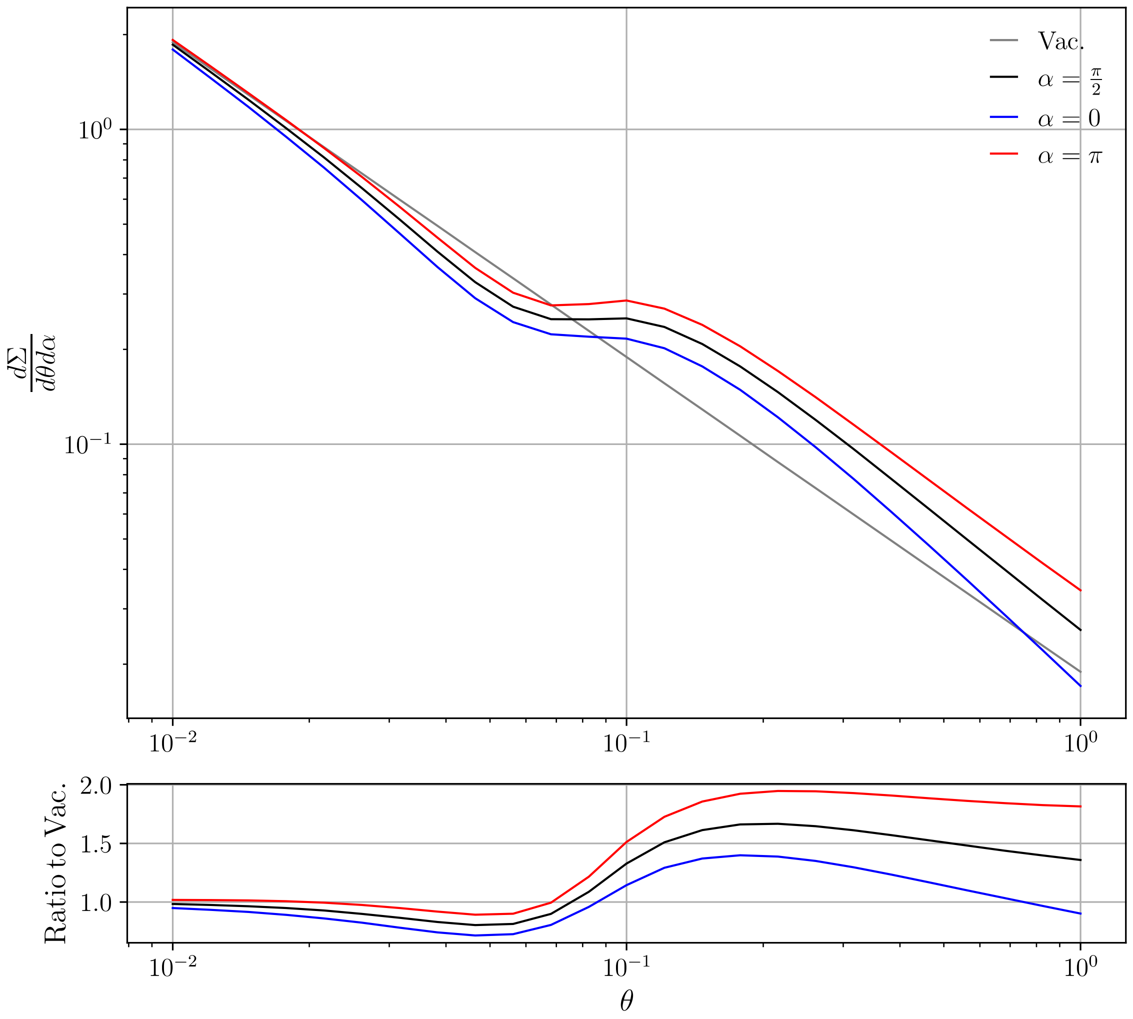




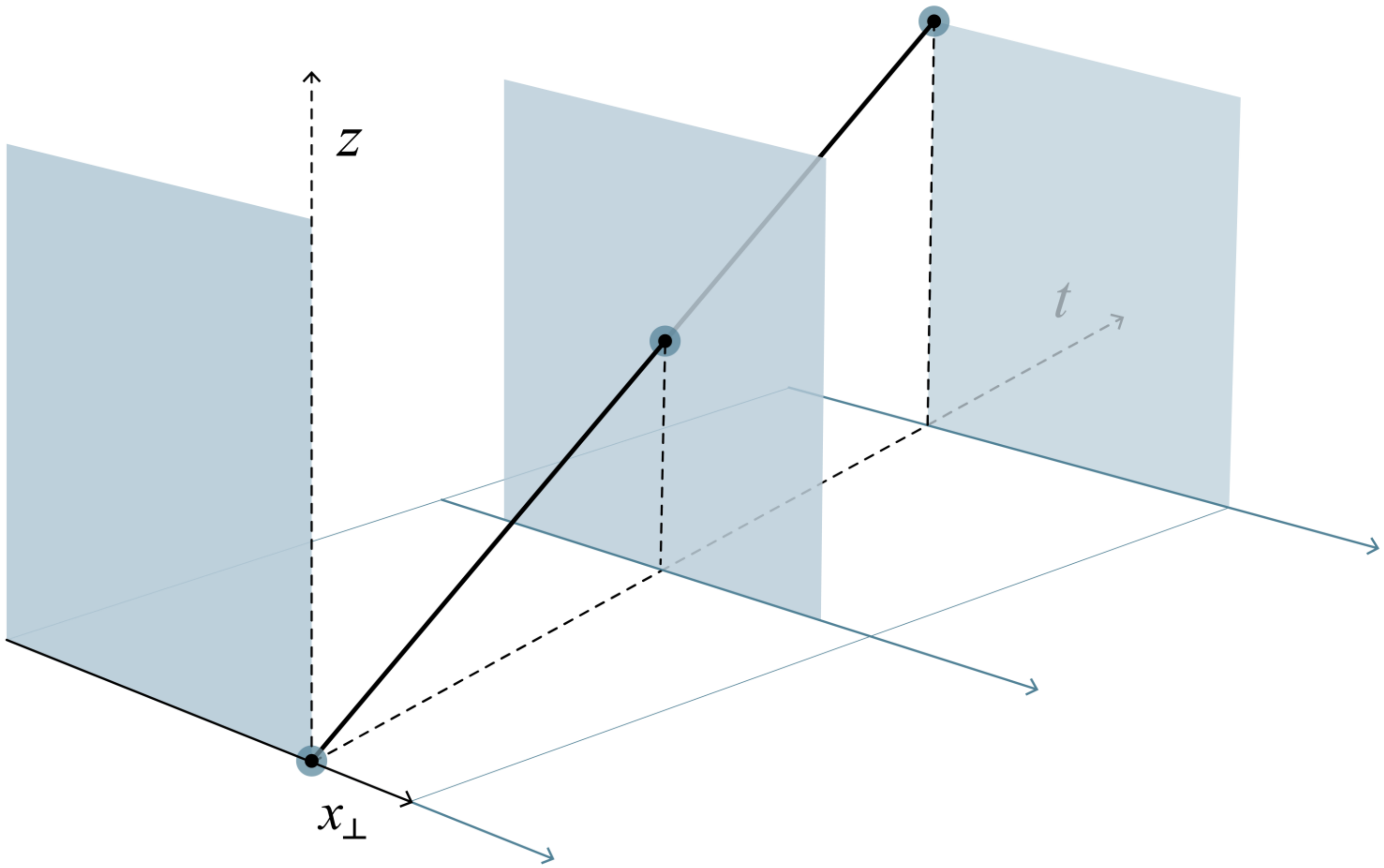
Estimates

$$\frac{d\Sigma}{d\theta d\alpha} = \int_0^1 dx\, \frac{d\sigma}{\sigma dz d\theta d\alpha} x(1-x)$$
$$= \int_0^1 dz \left(\frac{\alpha_s C_F}{\pi^2} \frac{1}{x\theta} + \omega \frac{dI}{d\omega d^2\mathbf{k}} p_t^{\text{jet}} |\mathbf{k}| \right) x(1-x)$$

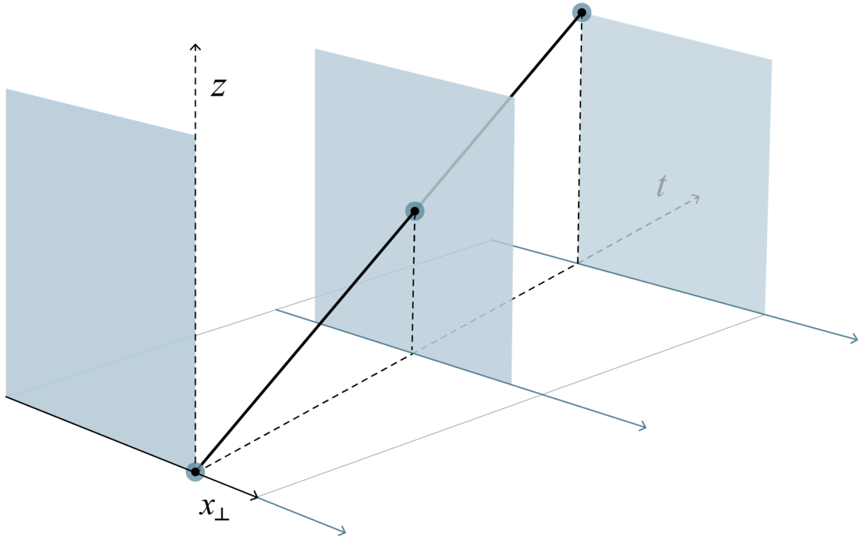
- The anisotropy leave traces in the shape observables
- At the toy model level, we see how azimuthally differential EEC is affected by the gradients
- The small-x BDMPS-Z formula is not strictly applicable, just an illustration
- The gradient effects can be clearly seen



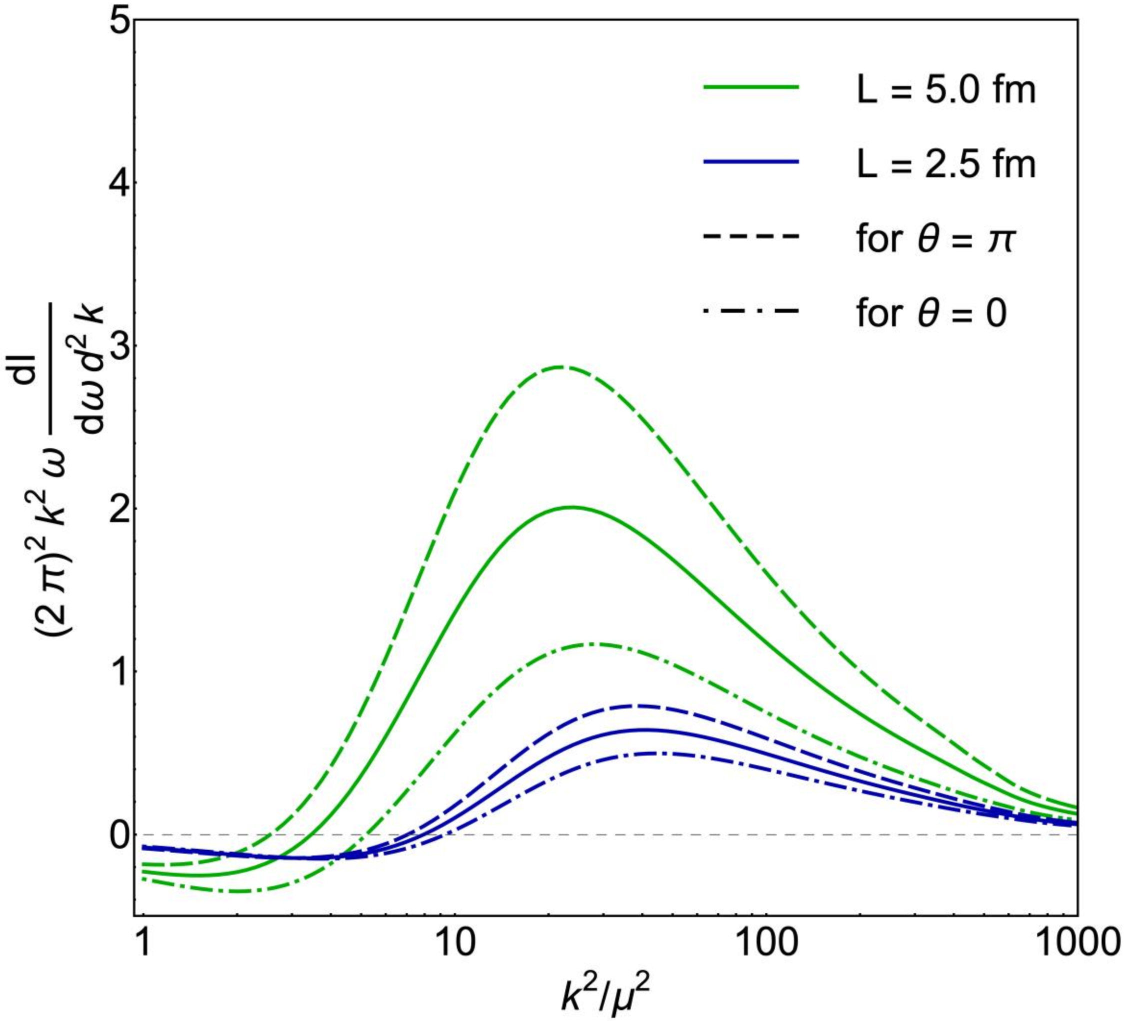
Mixed flow-gradient effects



Jets in evolving matter



$$\hat{q} = \left(1 - z\,\boldsymbol{\nabla}_\perp \frac{\mathbf{u}_\perp}{1-u_z}\right)\hat{q}_0$$



$E = 100\,\mathrm{GeV} \quad L = 5\,\mathrm{fm} \quad |\nabla T|/T^2 = 0.1 \quad \chi = 3 \quad x = 0.1$

Summary

- Energetic partons do feel the transverse flow and anisotropy, and get bended and distorted;
- The transverse flow and anisotropy affect the pattern of the medium-induced radiation, modifying the substructure of jets;
- Some of the effects appear in the eikonal limit, and are sizeable even when compared to the leading contributions;
- These jet modifications can be probed in experiment, leading us towards actual jet tomography;
- One should also expect similar evolution-induced effects for the other probes of nuclear matter, and for the other forms of nuclear matter;