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Jet observables in anisotropic QCD matter

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Based on work done with G. Milhano , A. Sadofyev

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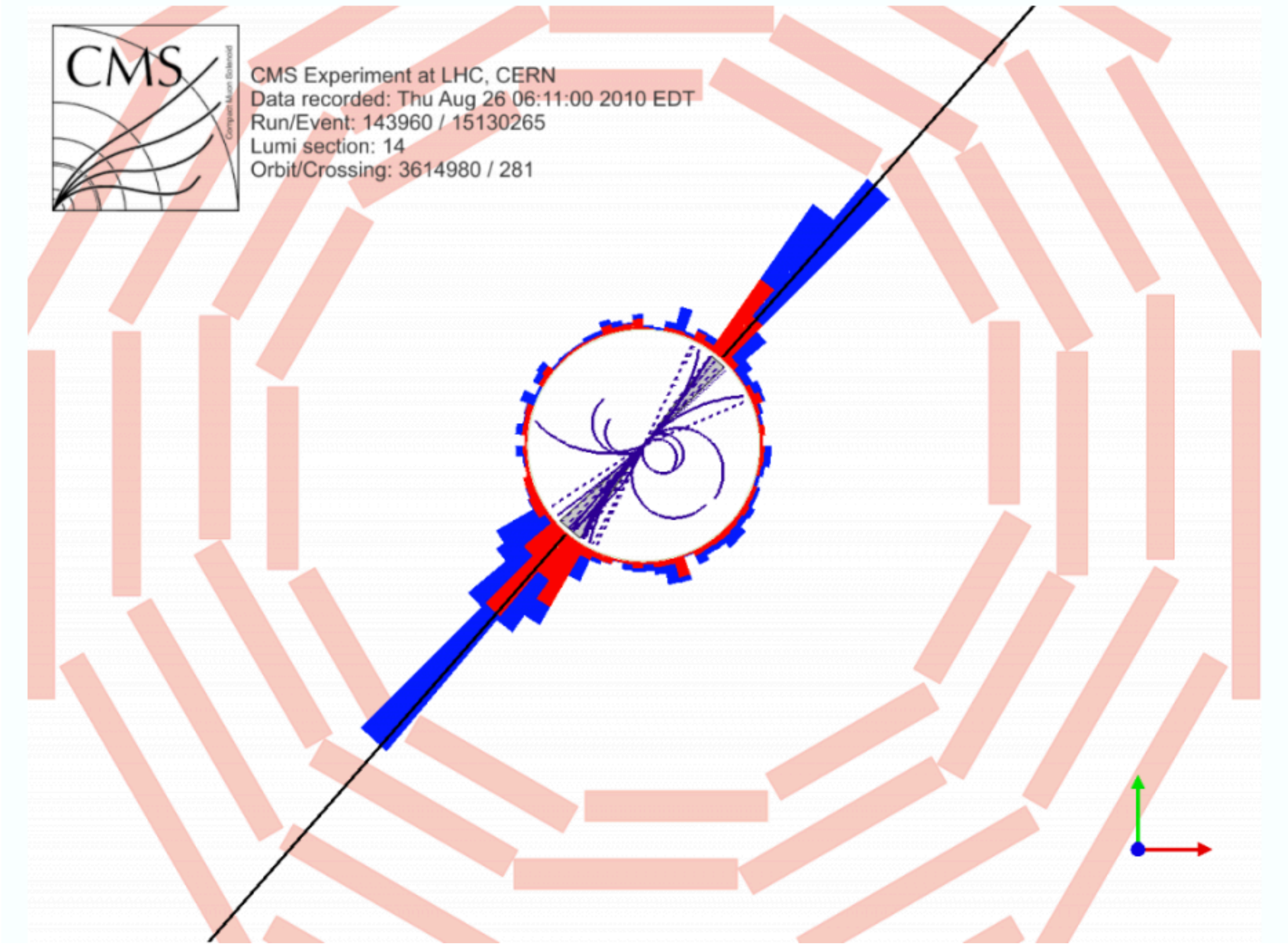
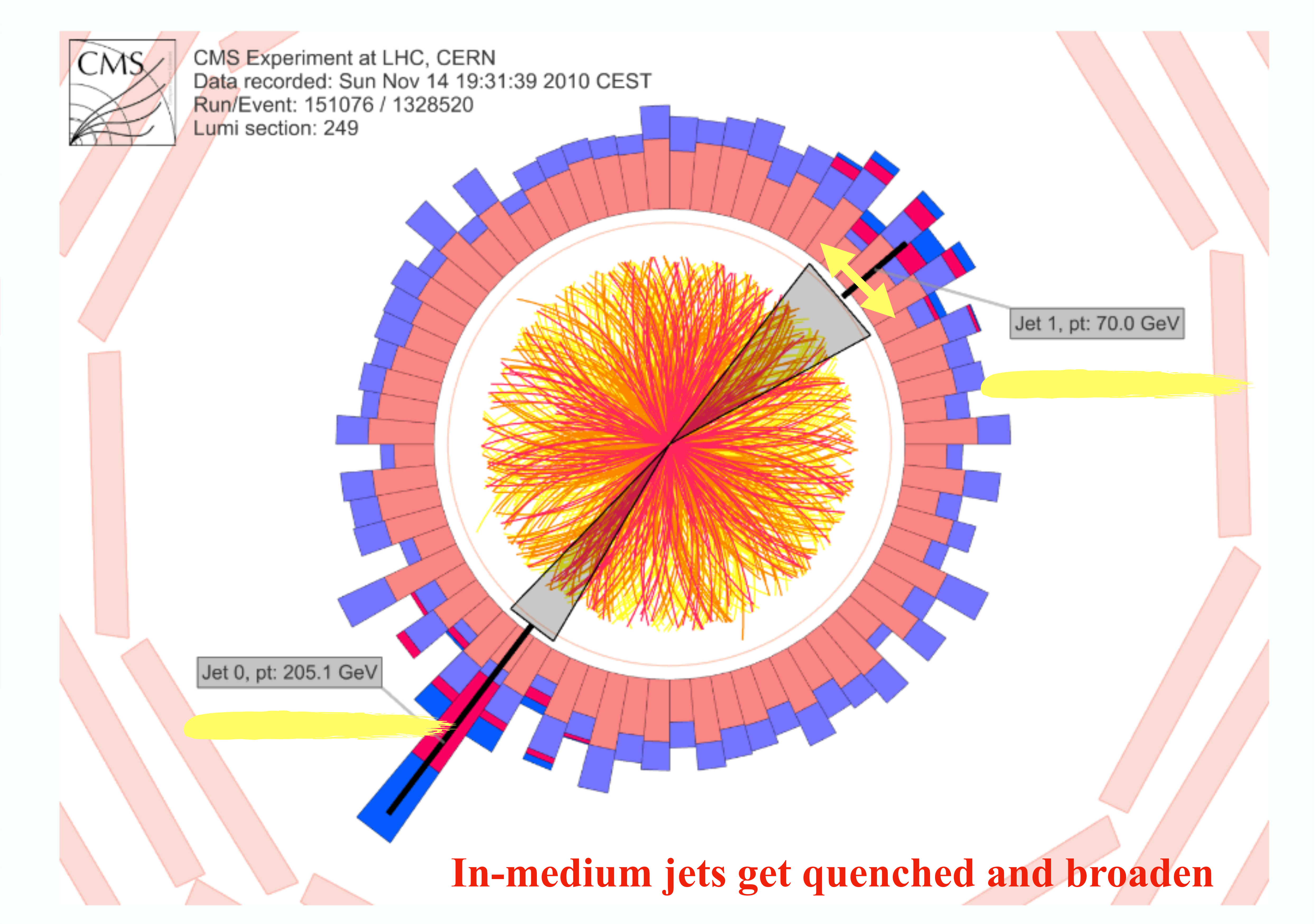
Jets in hot plasmas



pp dijet event in CMS



PbPb dijet event in CMS

Jets in hot plasmas

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How do we treat jet evolution in theory?

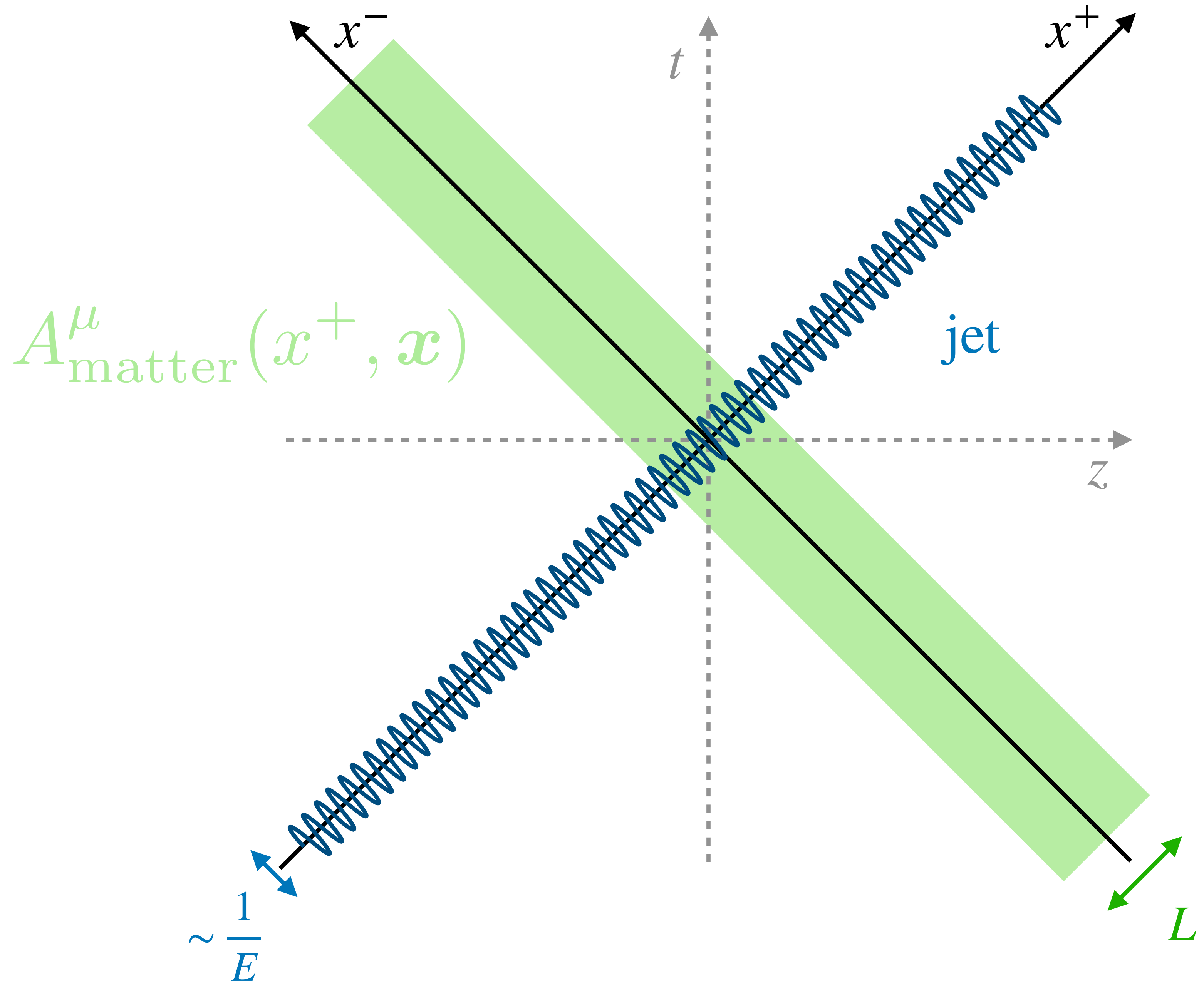
1) Use eikonal expansion, i.e. expansion in inverse powers of jet energy; keep kinetic phases

$$k^- L \sim \frac{\boldsymbol{k}^2}{2E_{\text{jet}}} L$$

2) Matter enters through classical background field; usually assumed: homogeneous, infinitely long, static, …

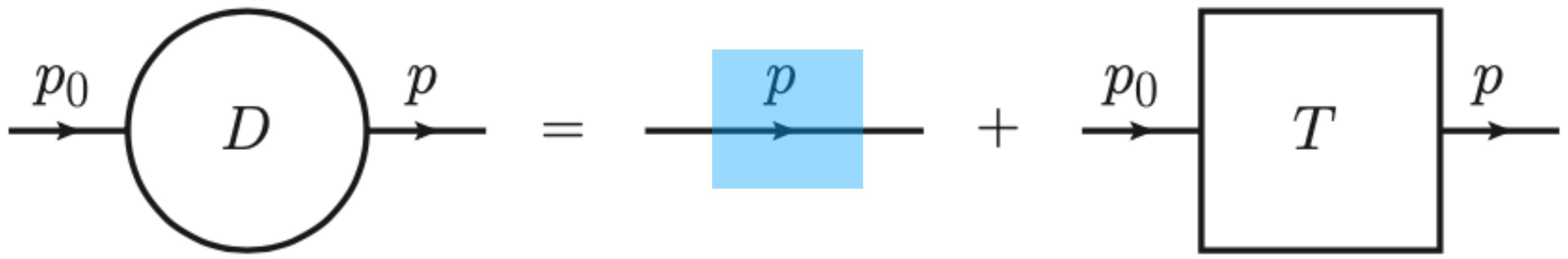
$$A^\mu(x^+, x^-, \boldsymbol{x}) \approx A^\mu_{\text{matter}}(x^+, \boldsymbol{x}) + \delta A^\mu(x^+, x^-, \boldsymbol{x})$$

$$\langle A_{\text{matter}}(x) A_{\text{matter}}(y) \rangle \sim \delta(x - y)$$

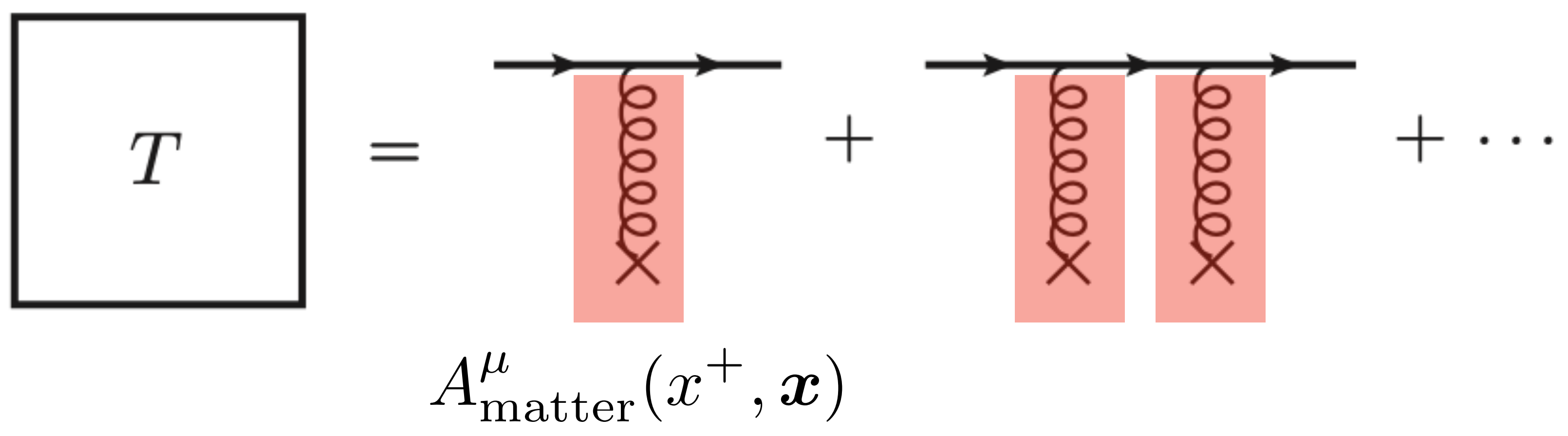


Jets in hot plasmas

3) Any cross-section is constructed from



where



The single particle propagator becomes at **high energies**

$$\mathcal{G}(\boldsymbol{x}_2, t_2; \boldsymbol{x}_1, t_1) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r} \exp\left(\frac{i\omega}{2}\int_{t_1}^{t_2} dt\, \dot{\boldsymbol{r}}^2\right) \mathcal{W}_{\boldsymbol{r}}$$

Wilson line along forward light-cone

Brownian motion in momentum space

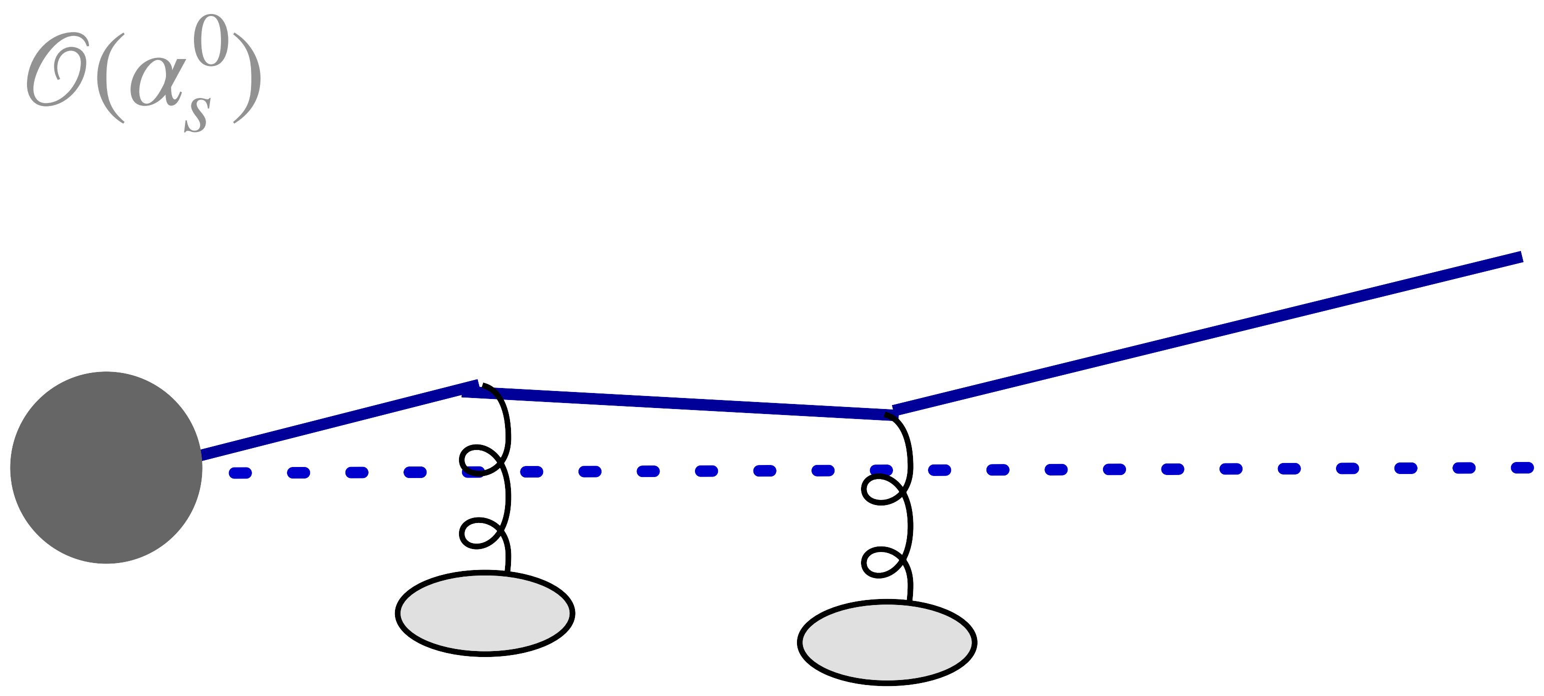
Then any process reduces to computing correlators of the form

vertices

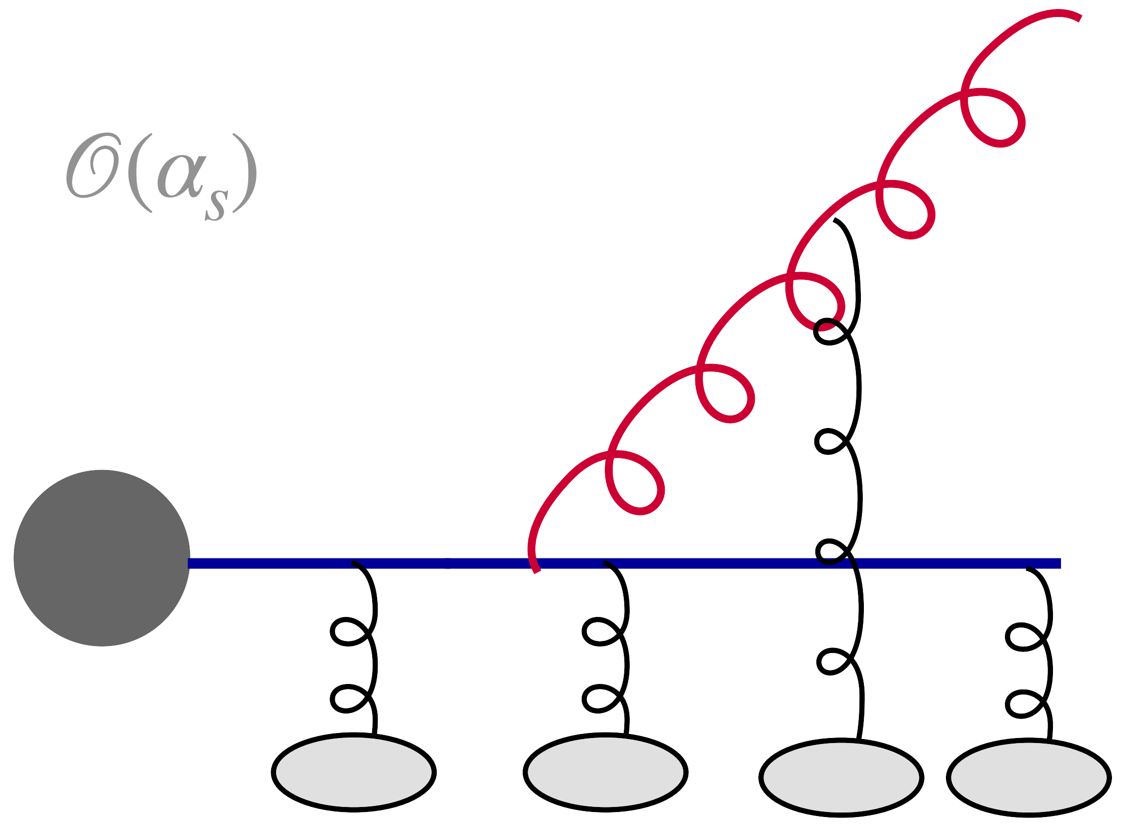
$$d\sigma \sim \langle \mathcal{T} \prod \{\mathcal{G}, \Gamma\} \rangle_{\rm matter}$$

Jets in hot plasmas

Even with these approximations this is a challenging problem! Focus on lowest order processes



“momentum broadening”



“medium induced gluon emission”

✓ **One can gain analytical insight into the problem; covers all main approaches to jet quenching**

✗ **Jets decouple more from plasma evolution: less sensitivity to medium properties**

Momentum broadening in anisotropic matter

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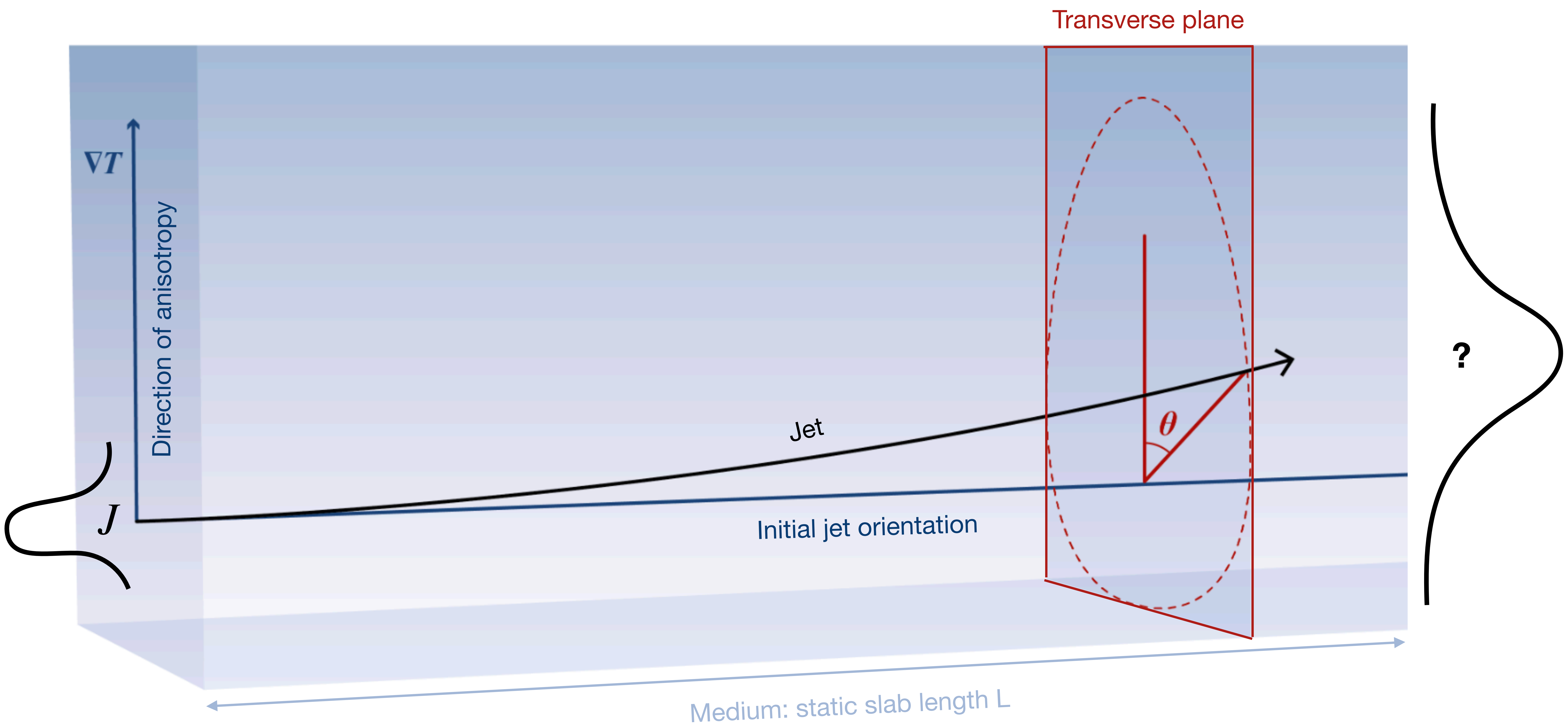

Momentum broadening in anisotropic matter

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The final distribution has the form

Single particle broadening distribution (when Fourier transformed)

Usually a unit operator, but now it acts with ∇ on initial distribution

$$\frac{d\mathcal{N}}{d^2\boldsymbol{x}dE} = \mathcal{P}\left(\boldsymbol{x}\right)\hat{\mathsf{S}}\left(\boldsymbol{x}\right)\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}$$

$$\int d^2\boldsymbol{p}\,\frac{d\mathcal{N}}{d^2\boldsymbol{p}\,dE} = \frac{d\mathcal{N}}{d^2\boldsymbol{x}dE}\bigg|_{\boldsymbol{x}=0}$$

Self normalized (particle number conservation)

Consider the case of a source with finite width $E\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{p}\,dE} = \frac{f(E)}{2\pi w^2}e^{-\frac{\boldsymbol{p}^2}{2w^2}}$

higher odd moments can be generated, for example

$$\langle p^\alpha\,\boldsymbol{p}^2\rangle = \frac{w^2L^2\mu^2}{E\,\lambda}\frac{\nabla^\alpha\rho}{\rho}\ln\frac{E}{\mu} + \frac{L^3\mu^4}{6E\,\lambda^2}\frac{\nabla^\alpha\rho}{\rho}\left(\ln\frac{E}{\mu}\right)^2$$

$N = 1$ $\qquad$ $N = 2$

Coulomb logarithm

Higher N terms dominate due to diverging potential at large momenta

Momentum broadening in anisotropic matter

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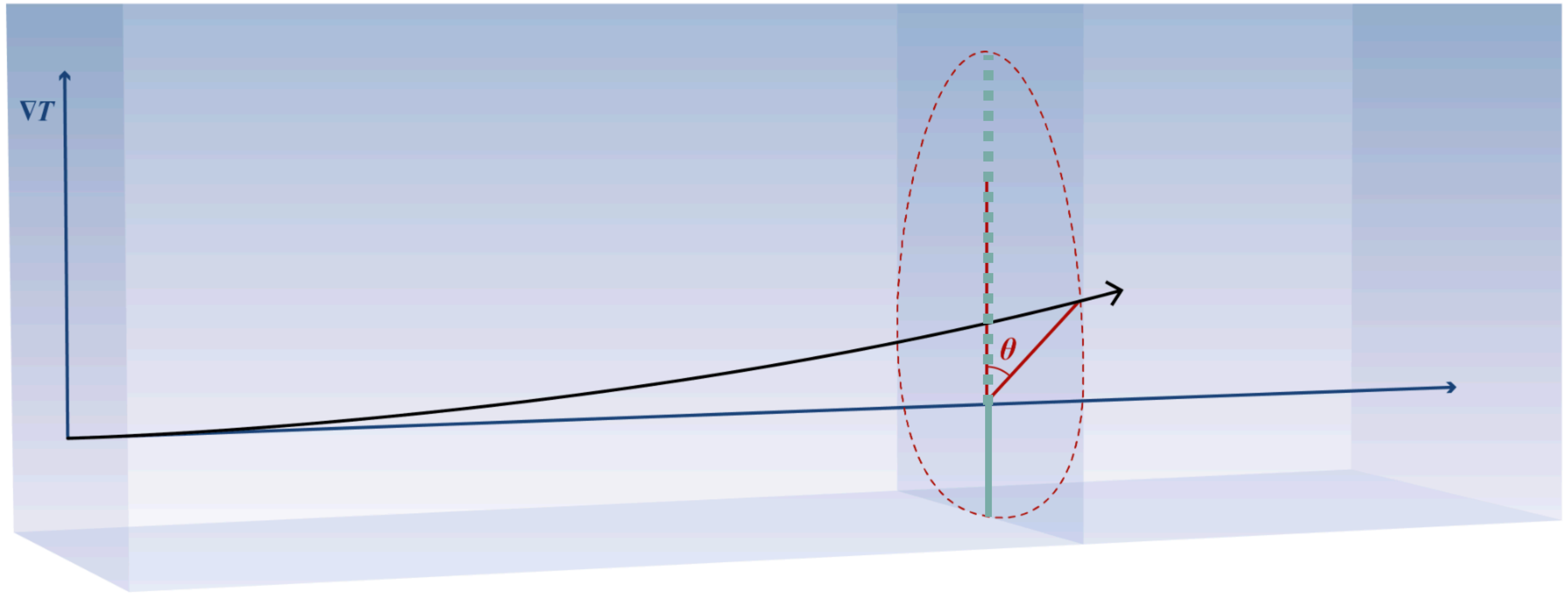
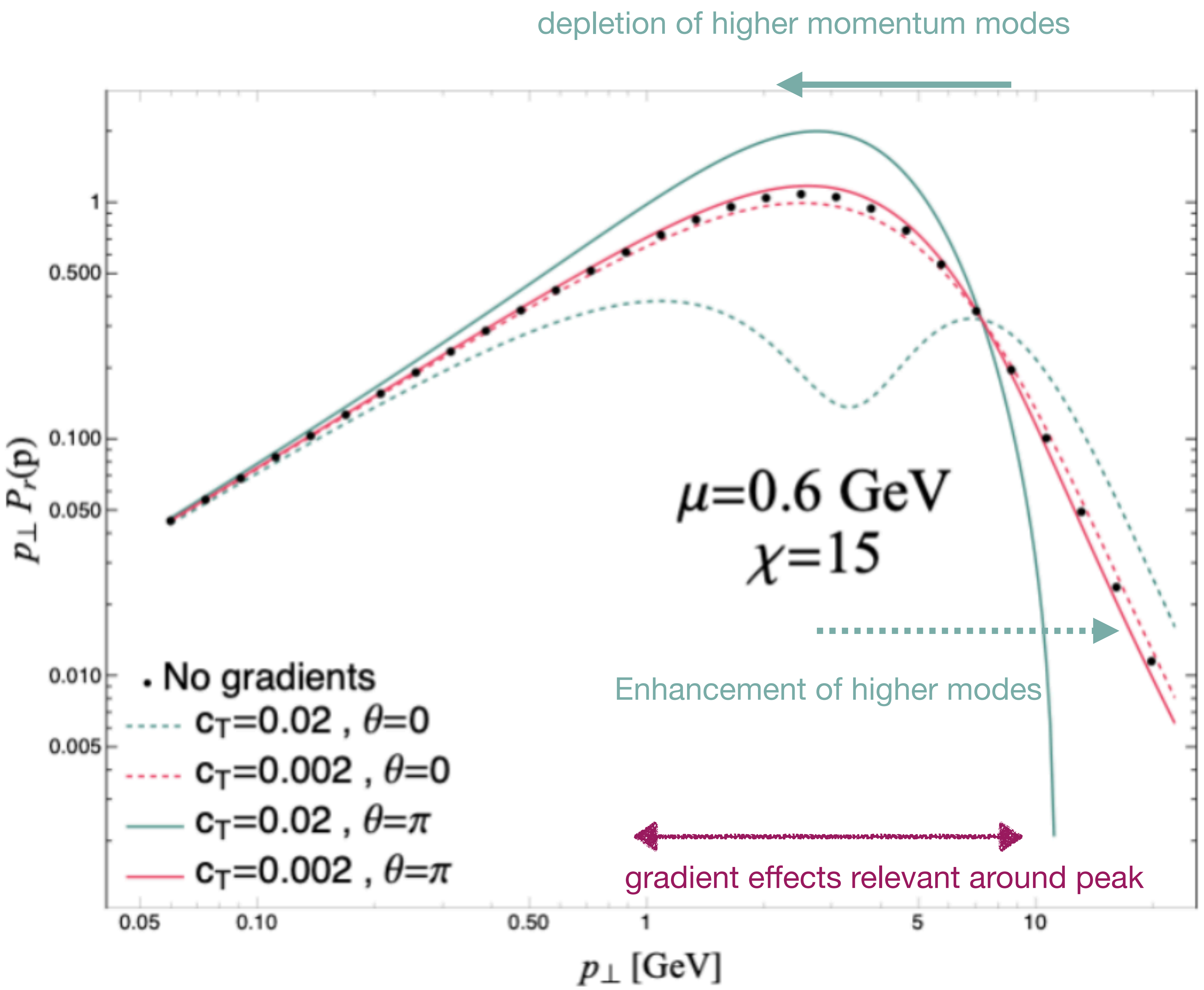
Some simple numerical results





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

Radiative energy loss in dense anisotropic matter

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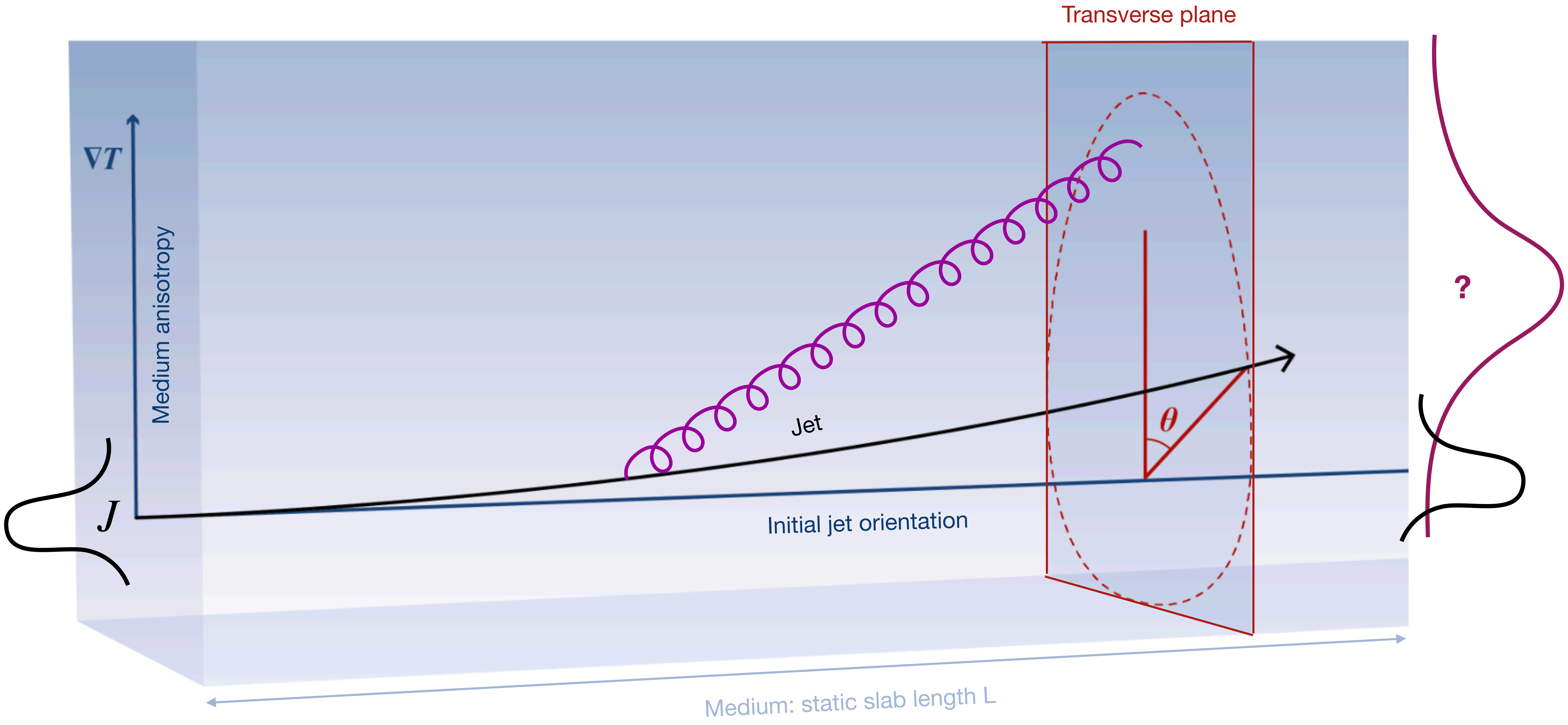

Radiative energy loss in dense anisotropic matter

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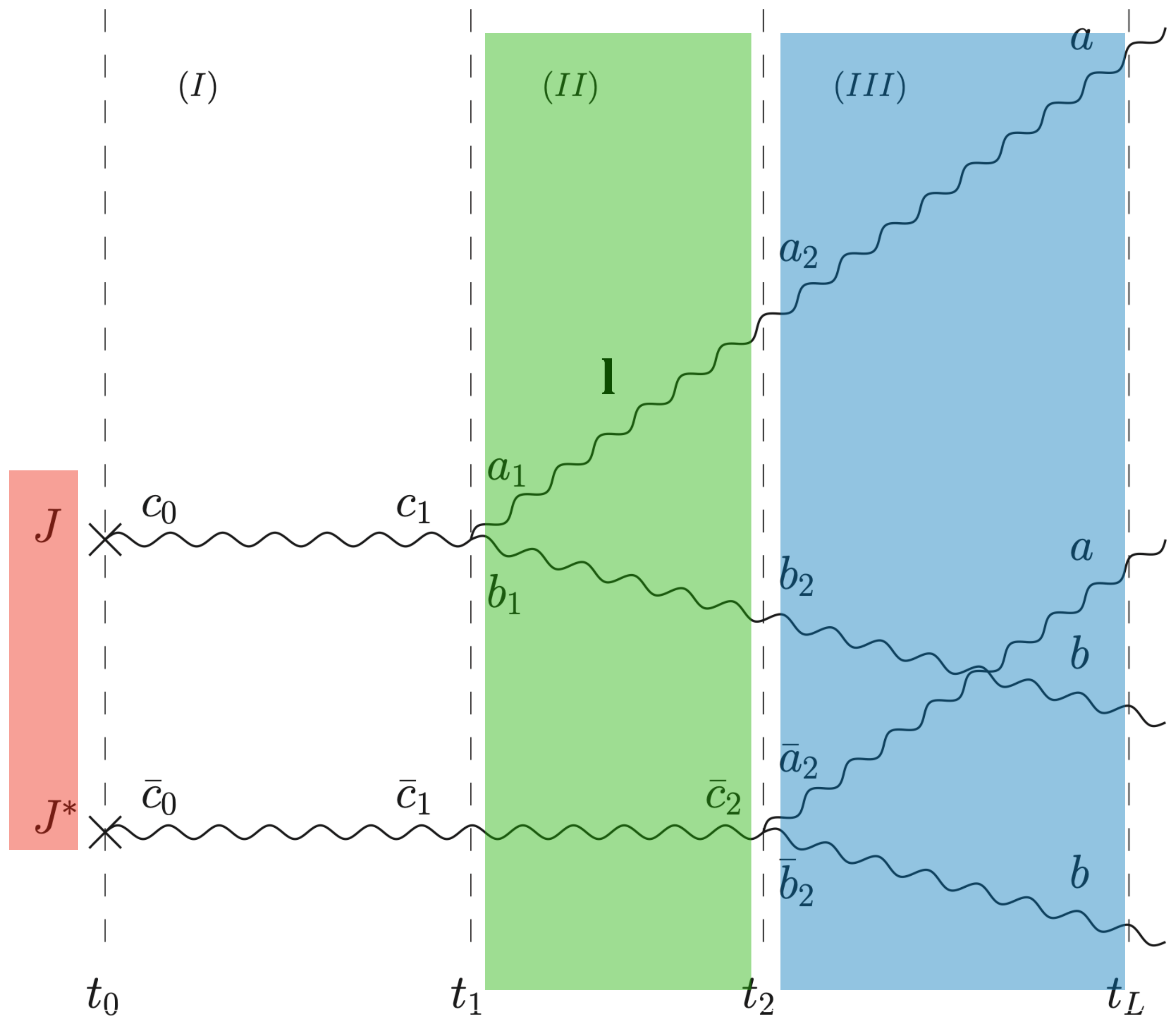

The distribution can be written as

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dE d^2\boldsymbol{k}} = \frac{2\alpha_s C_F}{\omega^2}\text{Re}\int_0^\infty d\bar{z}\int_0^{\bar{z}} dz \int_{\boldsymbol{x}_{in},\boldsymbol{y}} |J(\boldsymbol{x}_{in})|^2 \Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}\; S_2(\boldsymbol{k},\boldsymbol{k},\infty;\boldsymbol{y},\bar{\boldsymbol{x}},\bar{z})\,\mathcal{K}(\boldsymbol{y},\boldsymbol{x}_{in},\bar{z};\boldsymbol{x},\boldsymbol{x}_{in},z)\Big]\Big|_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

Solved!

Expanding to first order in gradients allows to perturbatively compute the spectrum in the form

$$\omega\frac{dI}{d\omega d^2\boldsymbol{k}} = \omega\frac{dI_0}{d\omega d^2\boldsymbol{k}} + (\hat{\boldsymbol{g}}\cdot\boldsymbol{k})\,\omega\frac{dI_1}{d\omega d^2\boldsymbol{k}} + \mathcal{O}(\hat{\boldsymbol{g}}^2)$$

$$\omega\frac{dI}{d\omega d^2\boldsymbol{k}} = \omega\frac{dI_0}{d\omega d^2\boldsymbol{k}} + \omega\frac{dI_{\mathcal{P}}}{d\omega d^2\boldsymbol{k}} + \omega\frac{dI_{\mathcal{K}}}{d\omega d^2\boldsymbol{k}} + \omega\frac{dI_{\hat{\mathbb{S}}}}{d\omega d^2\boldsymbol{k}}$$

Radiative energy loss in dense anisotropic matter

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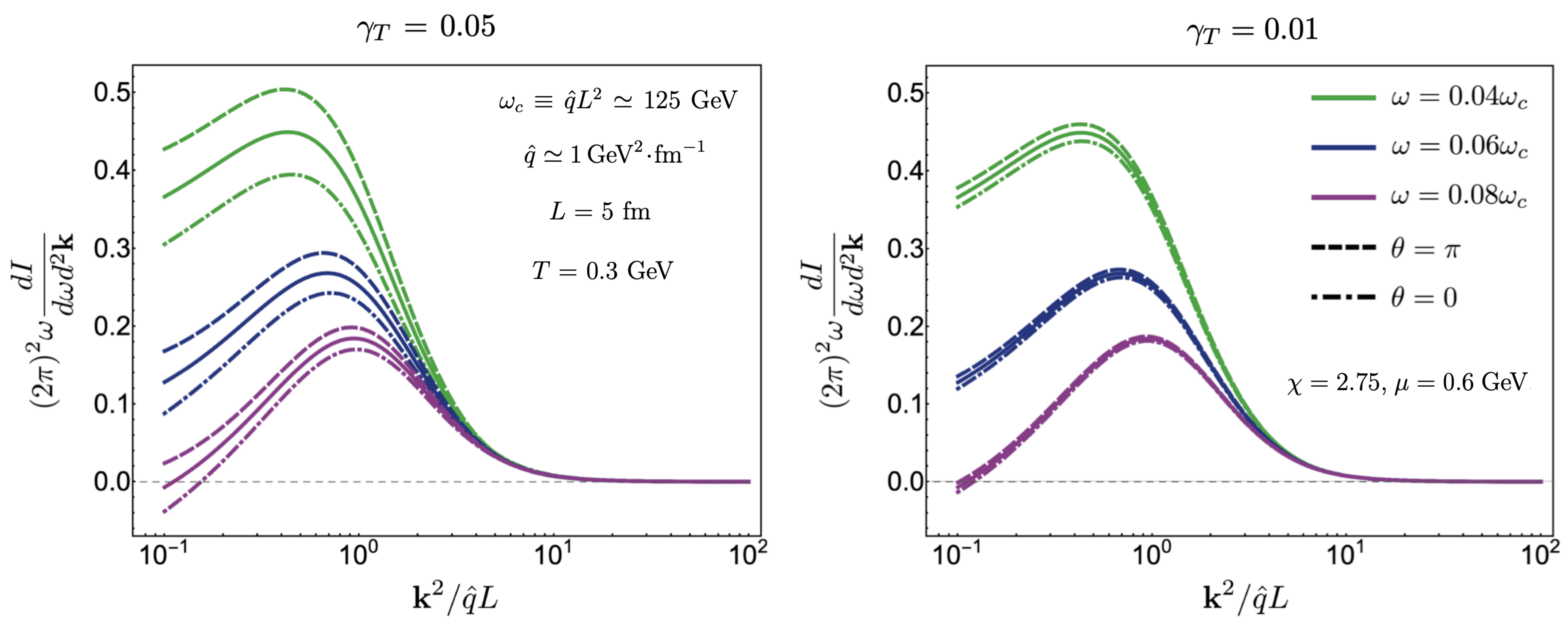
Numerical results, in the harmonic approximation for the in-medium scattering cross-section



$$\gamma_T = |\nabla T/T^2|$$

Jet observables in inhomogeneous matter

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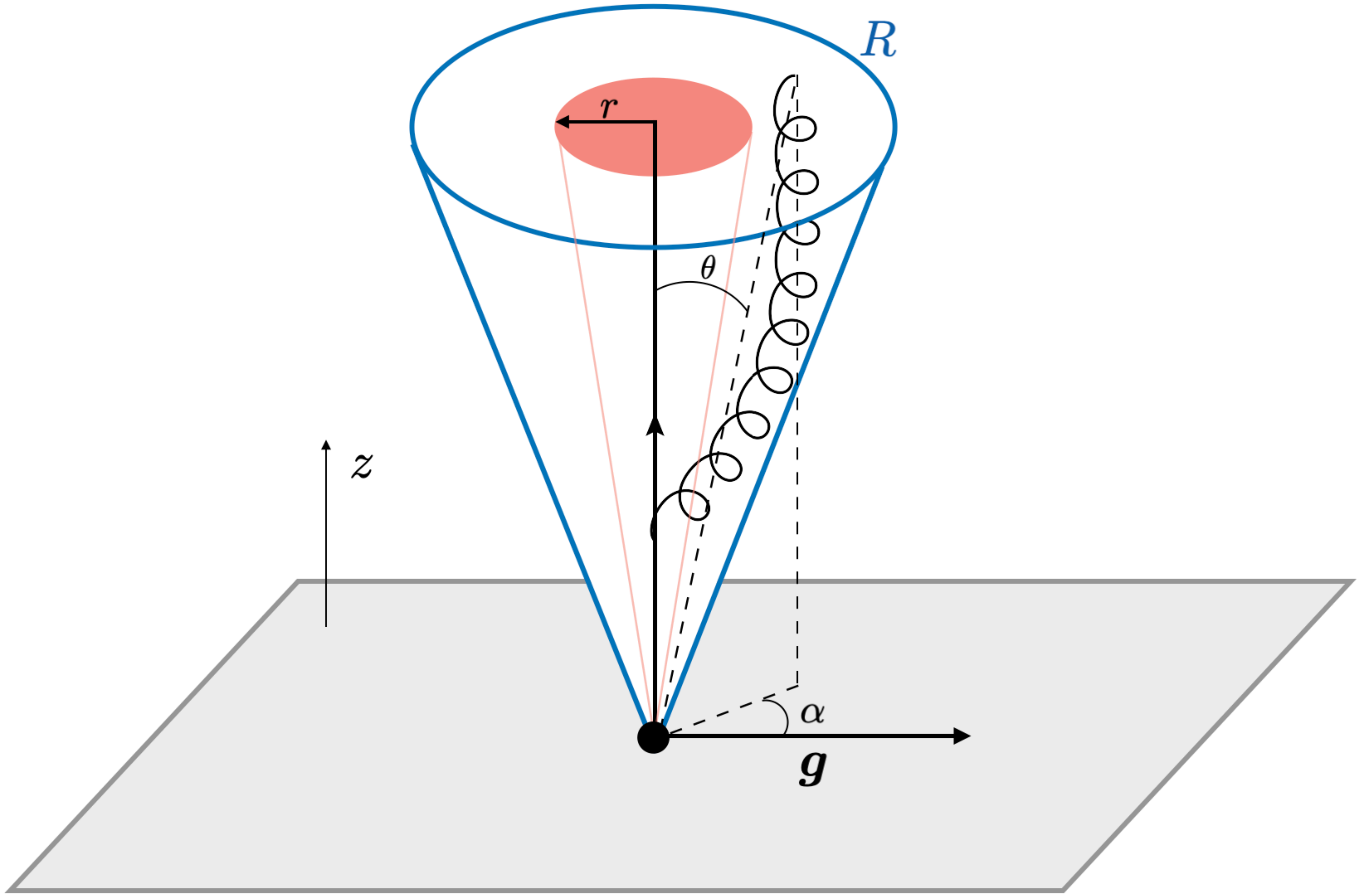

Jet observables in inhomogeneous matter

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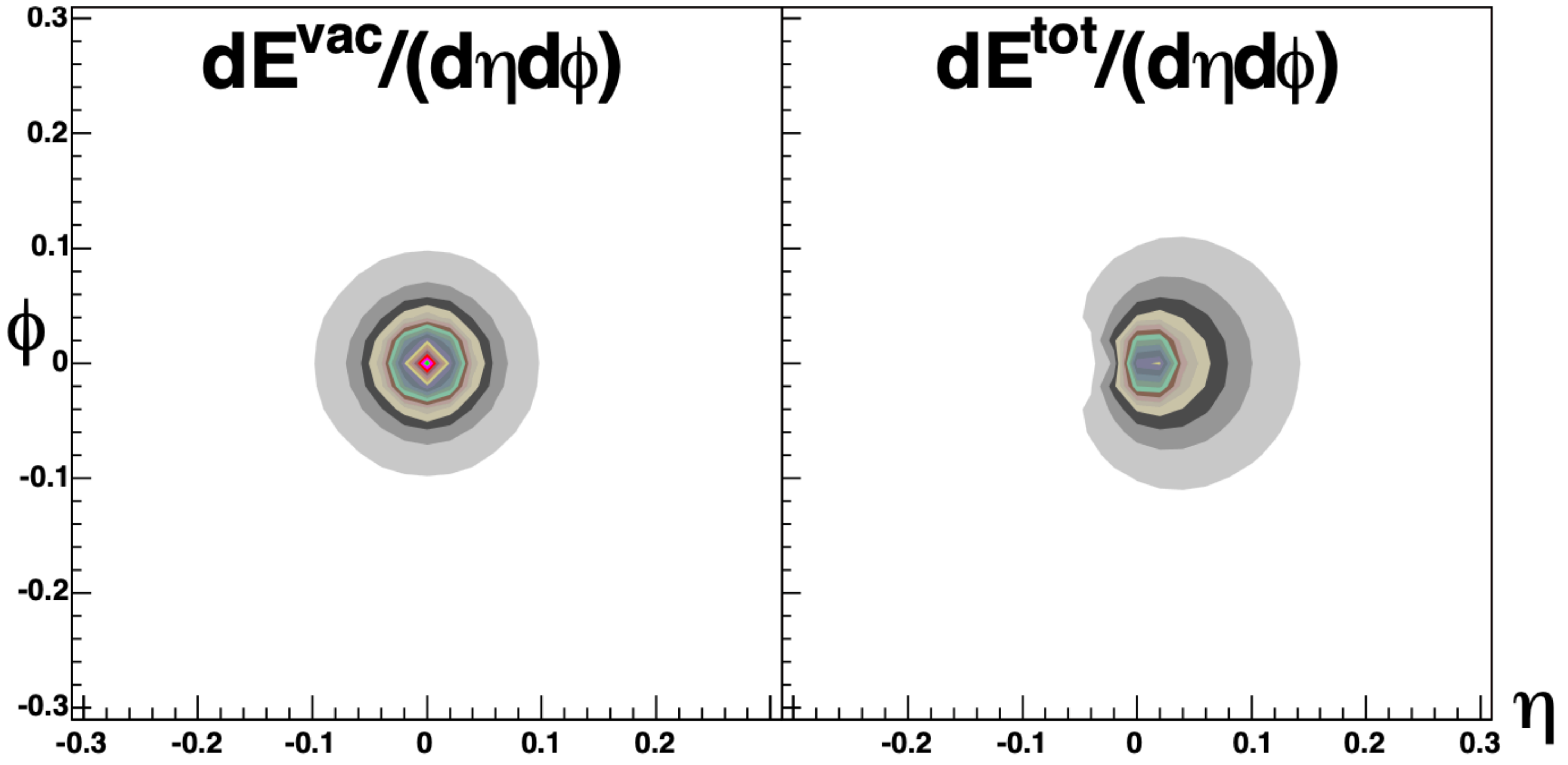
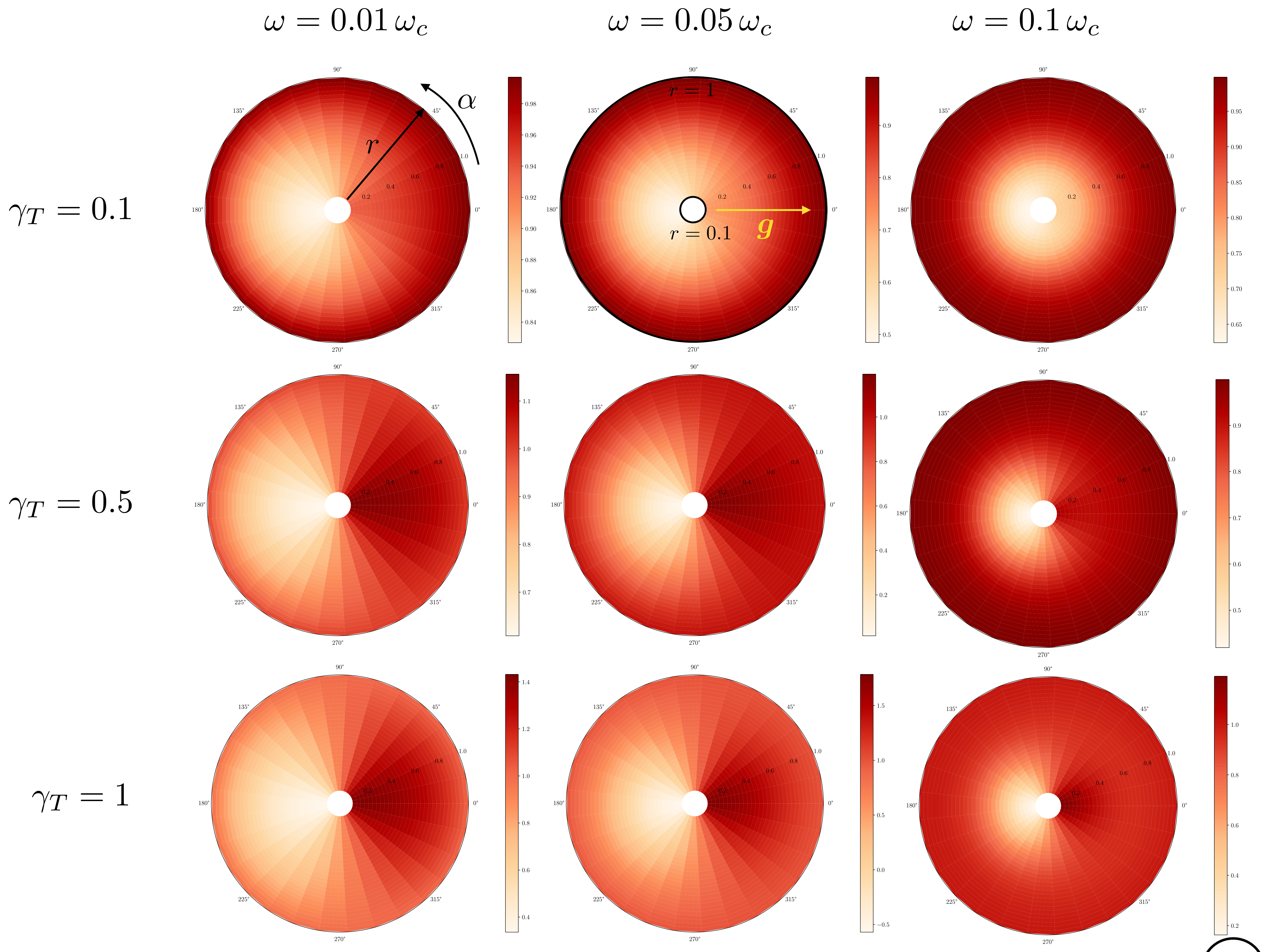
We have now the tools to compute jet observables (at least at leading order in the strong coupling)

Observable 1: jet shape

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

2004, Armesto, Salgado, Wiedemann





Jet observables in inhomogeneous matter

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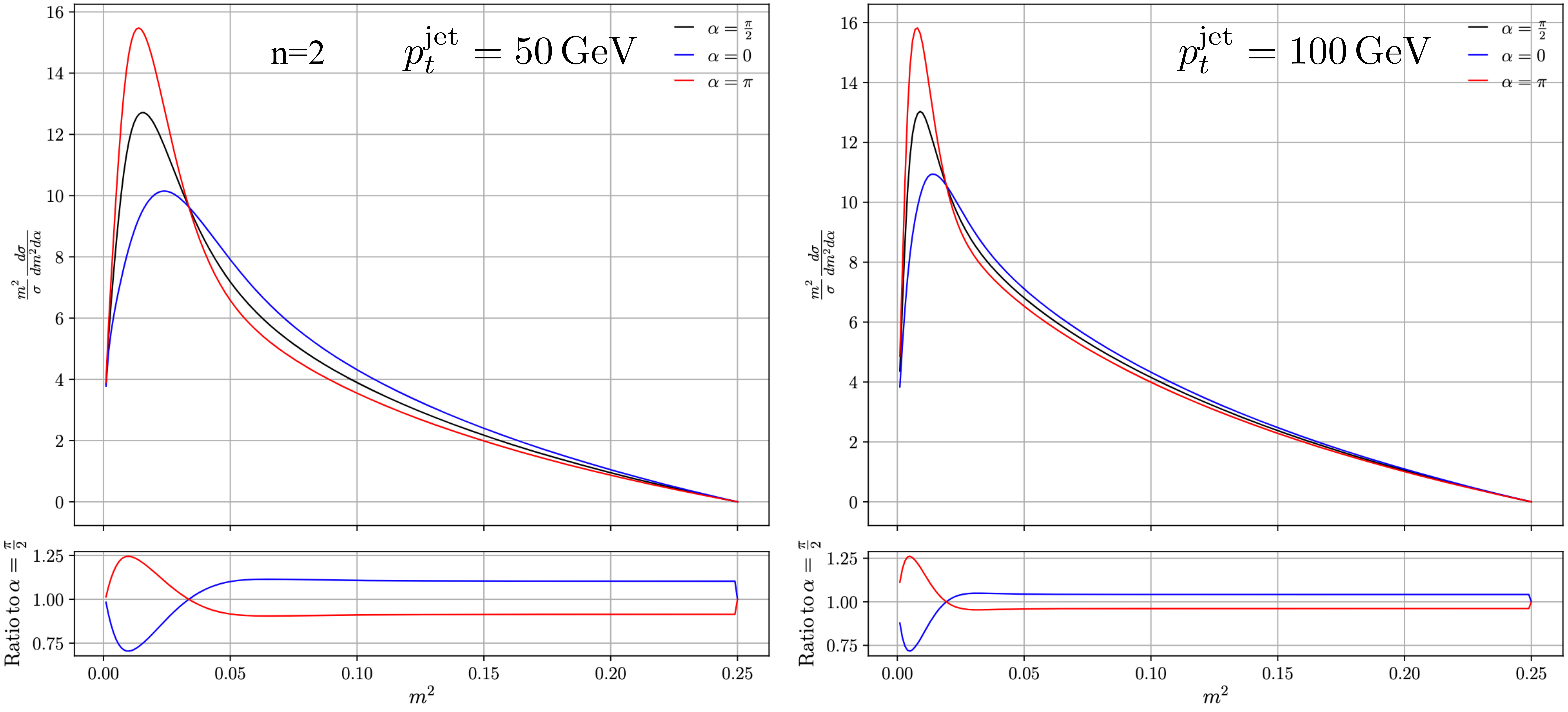
Observable 2: jet angularities

$$G_n = \sum_{i \in \text{jet}} \frac{p_t^i}{p_t^{\text{jet}}} g^{(n)}(r_i)$$

At leading logarithmic accuracy we have

$$\frac{g_n}{\sigma}\frac{d\sigma}{dg_n d\alpha} = \left(\int_{\frac{g_n}{R^n}}^{1} dx \left(\frac{\omega dI}{d\omega d^2\boldsymbol{k}} \frac{(p_t^{\text{jet}})^2 x^{1-\frac{2}{n}} g_n^{\frac{2}{n}}}{n} \right)_{\theta^n = \frac{g_n}{x}} + \frac{\alpha_s C_F}{\pi^2 n} \log \frac{R^n}{g_n} \right) e^{-\frac{\alpha_s C_F}{n\pi} \log^2 \frac{R^n}{g_n}}$$



Jet observables in inhomogeneous matter

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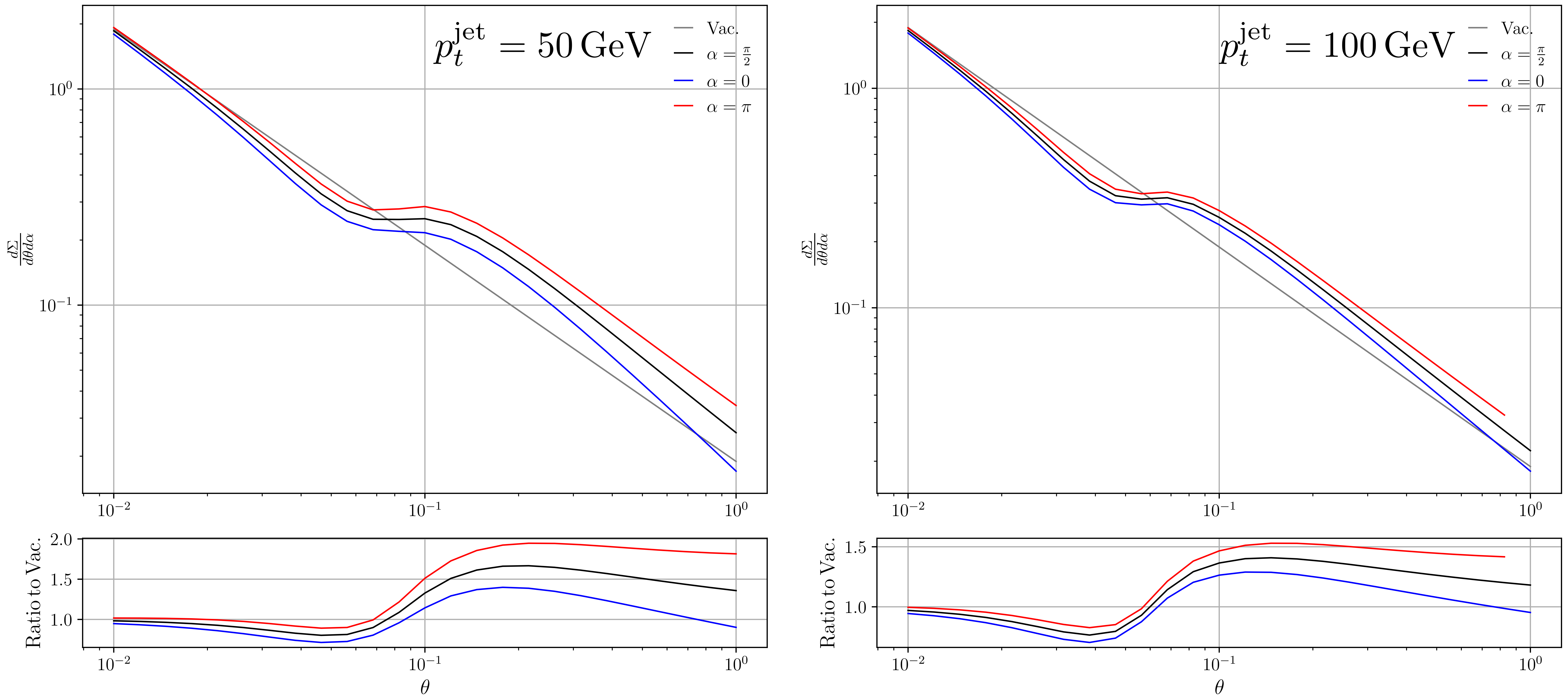
Observable 3: ENCs

Ideally we would need E3C, but already with EEC we have

$$\frac{d\Sigma}{d\theta d\alpha} = \int d\vec{n}_1 d\vec{n}_2 \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle}{(p_t^{\text{jet}})^2}\delta(\cos(\theta_2-\theta_1)-\cos(\theta))\,\delta(\alpha-(\alpha_1-\alpha_2))$$



Outlook

- **To go beyond we need MC with realistic geometry:**

LBT model in equivalent setup to before