Jet observables in anisotropic QCD matter

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

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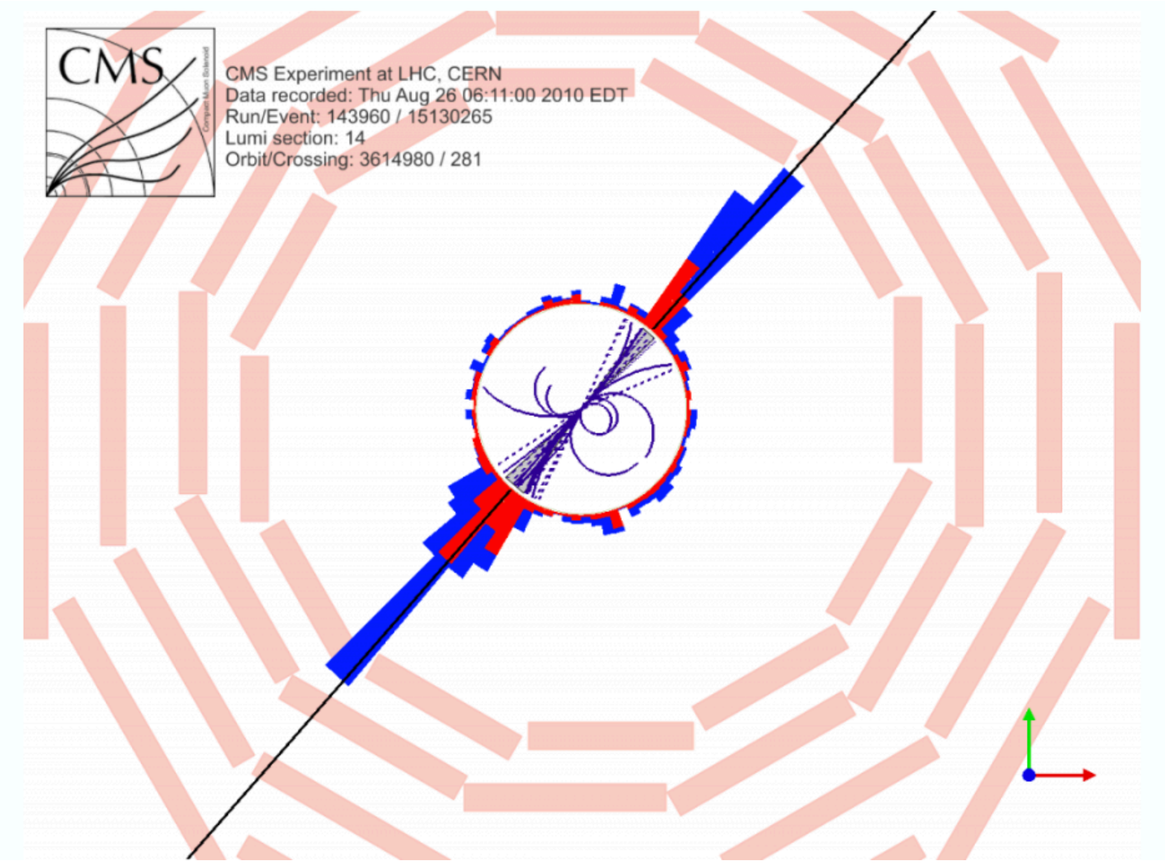
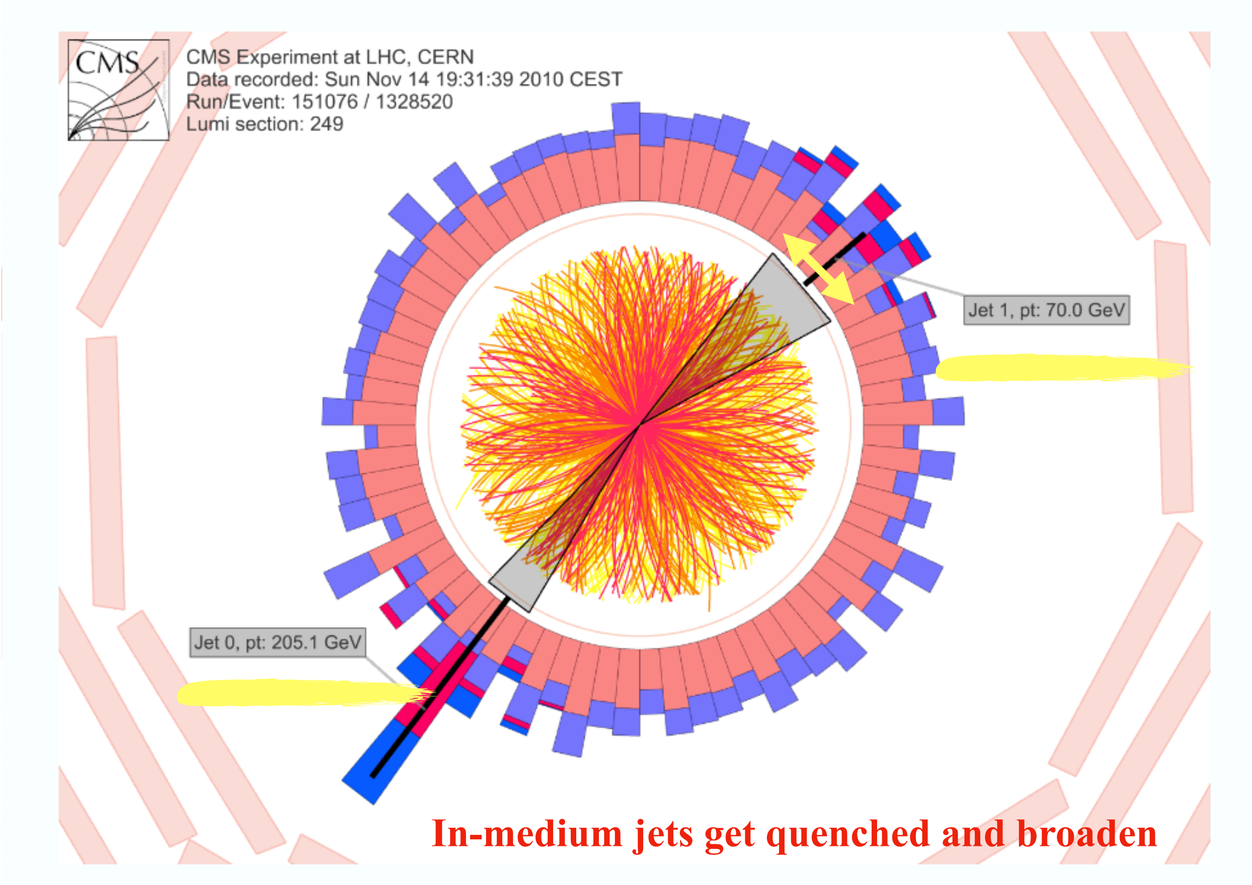
Jets in hot plasmas



pp dijet event in CMS



PbPb dijet event in CMS

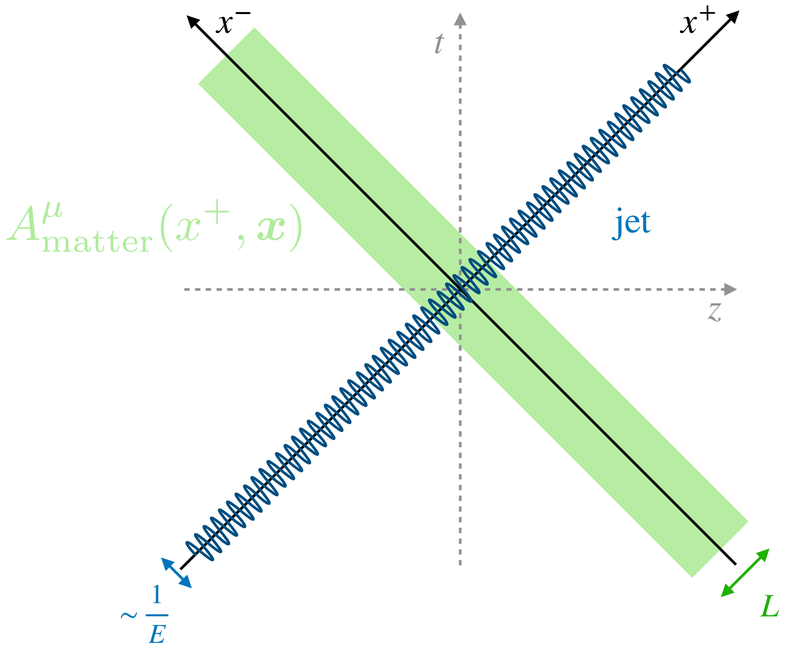
Jets in hot plasmas

How do we treat jet evolution in theory?

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

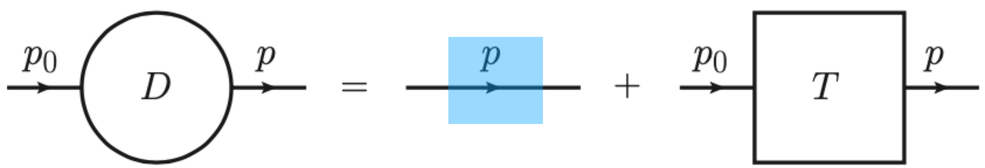
$$A^\mu(x^+, x^-, \boldsymbol{x}) \approx A^\mu_{\text{matter}}(x^+, \boldsymbol{x}) + \delta A^\mu(x^+, x^-, \boldsymbol{x})$$

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

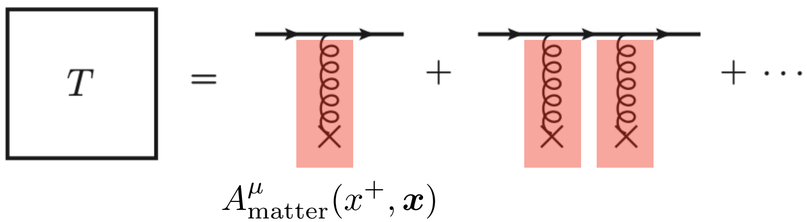


Jets in hot plasmas

2) 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

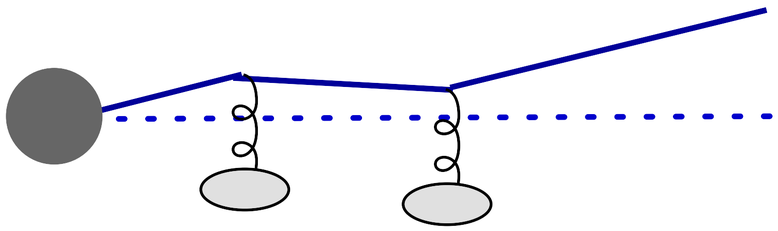
Then any process reduces to computing correlators of the form

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

Jets in hot plasmas

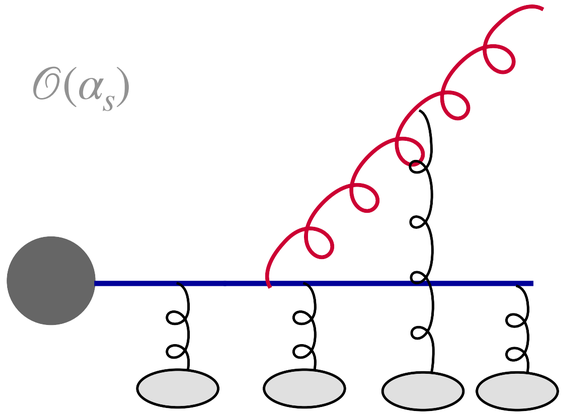
Even with these approximations this is a challenging problem! Focus on lowest order processes

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



"momentum broadening"

$\mathcal{O}(\alpha_s)$



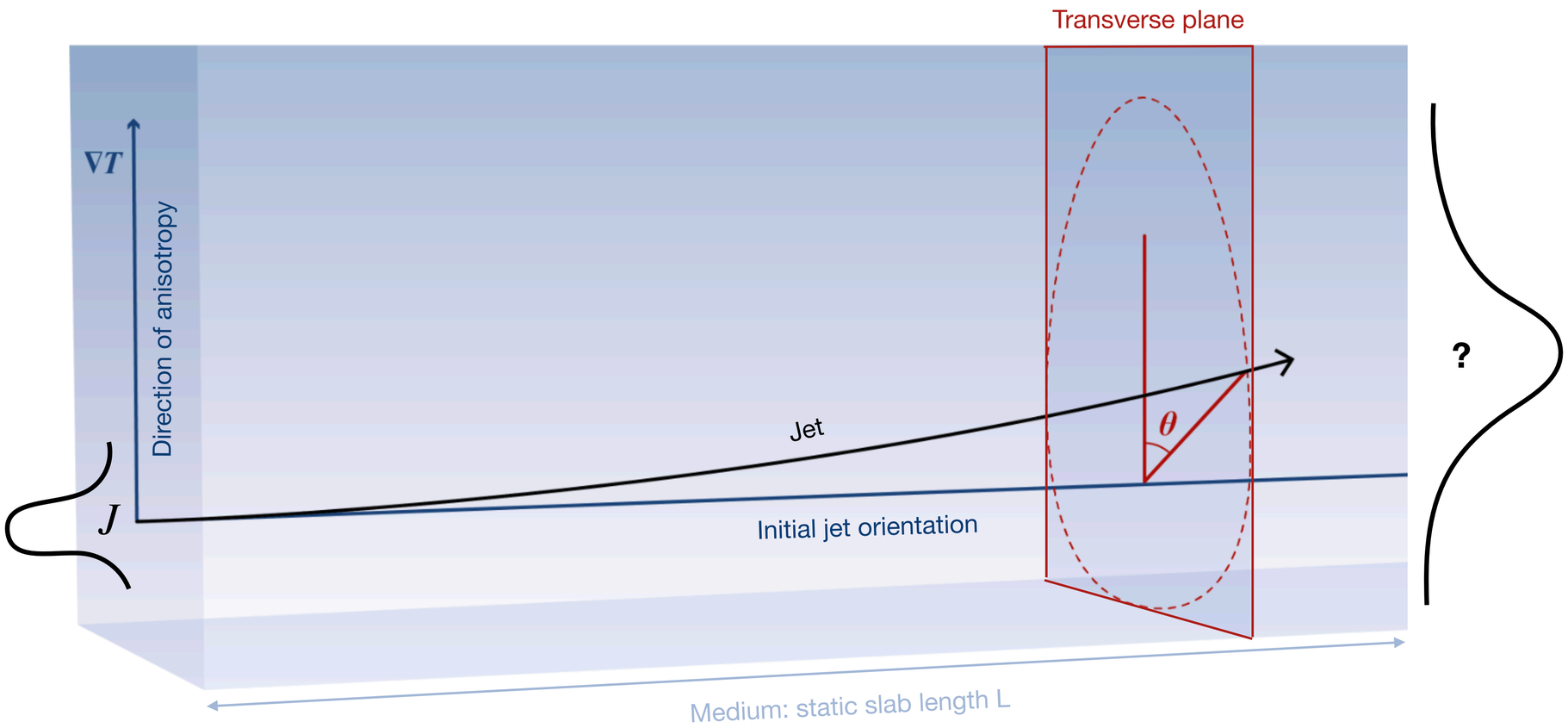
"medium induced gluon emission"

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

2202.08847



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

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

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

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

$$\langle p^\alpha\,\boldsymbol{p}^2\rangle = \underbrace{\frac{w^2L^2\mu^2}{E\,\lambda}\frac{\nabla^\alpha\rho}{\rho}\ln\frac{E}{\mu}}_{N=1} + \underbrace{\frac{L^3\mu^4}{6E\,\lambda^2}\frac{\nabla^\alpha\rho}{\rho}\left(\ln\frac{E}{\mu}\right)^2}_{N=2}$$

Coulomb logarithm

Higher N terms dominate due to diverging potential at large momenta

Momentum broadening in anisotropic matter

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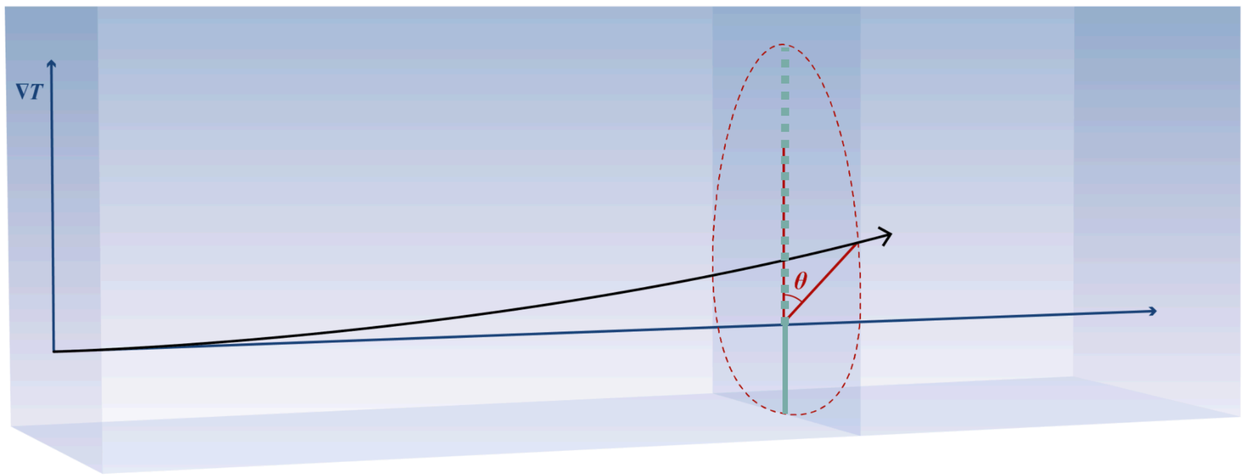
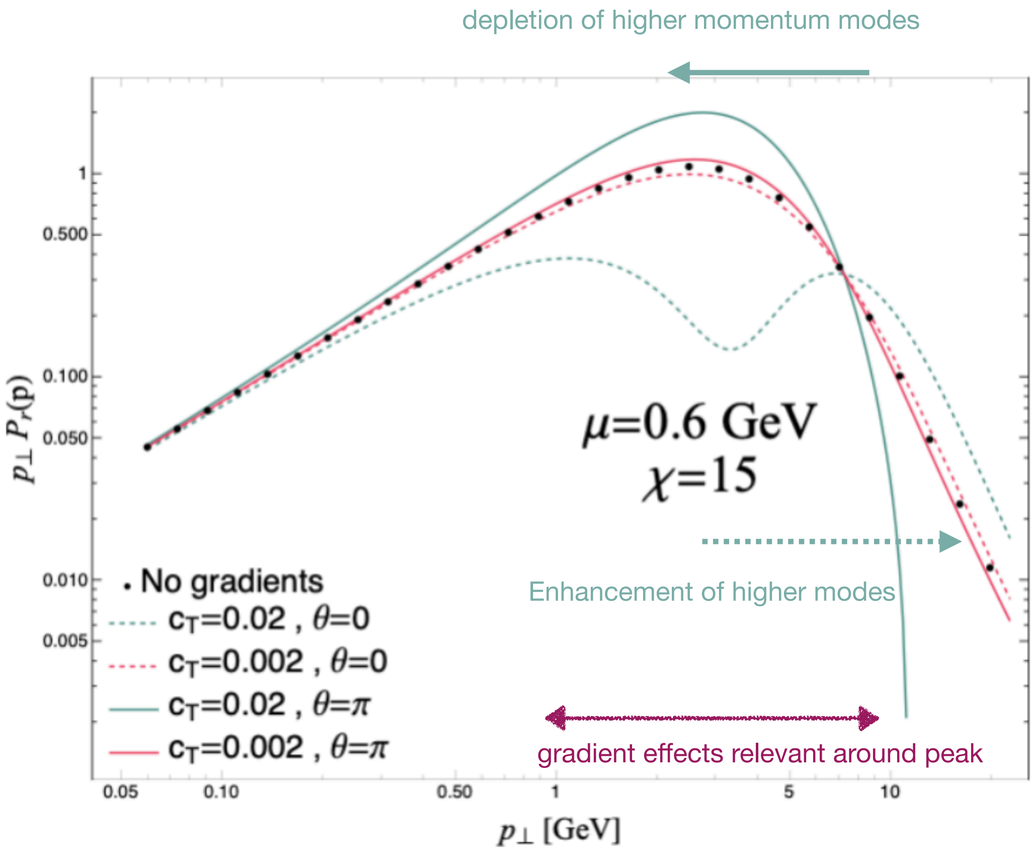
Some simple numerical results

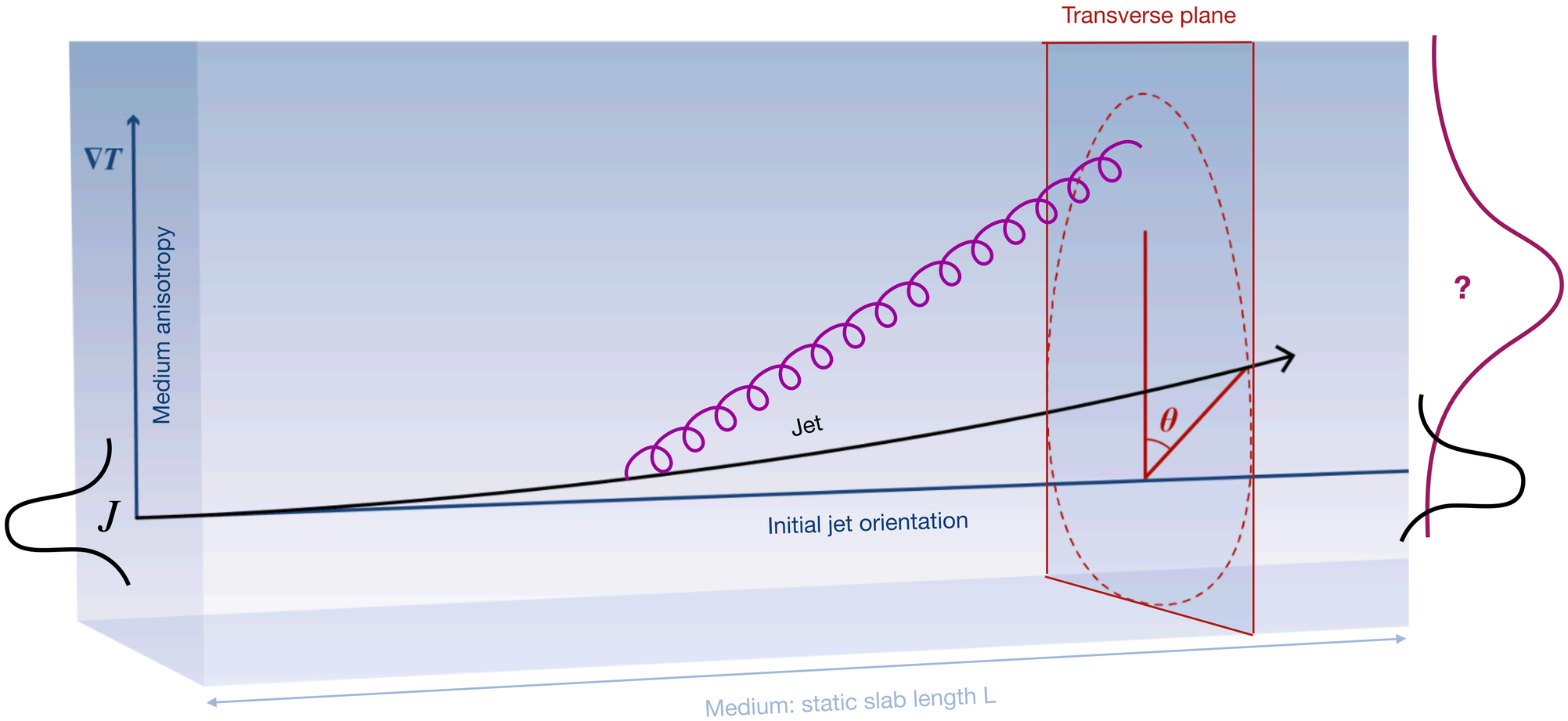


The full distribution is written in terms of the angle θ and parameter $c_T \equiv \left|\frac{\nabla T}{ET}\right|$.



Radiative energy loss in dense anisotropic matter

2304.03712



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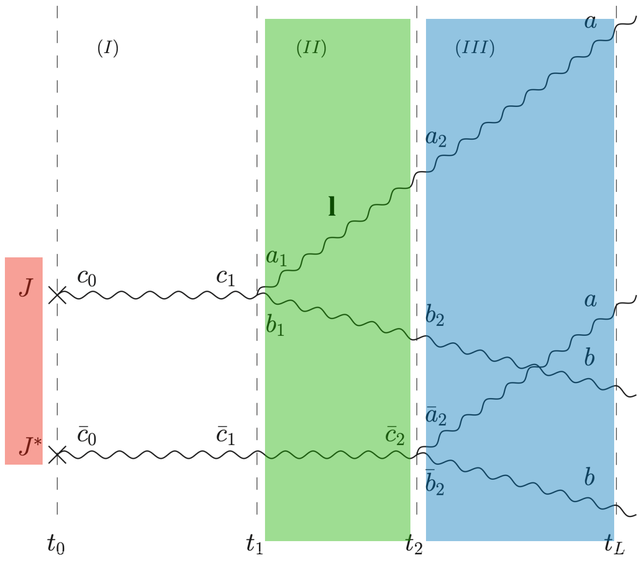

The distribution can be written as

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

Solved!

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

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

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

Radiative energy loss in dense anisotropic matter

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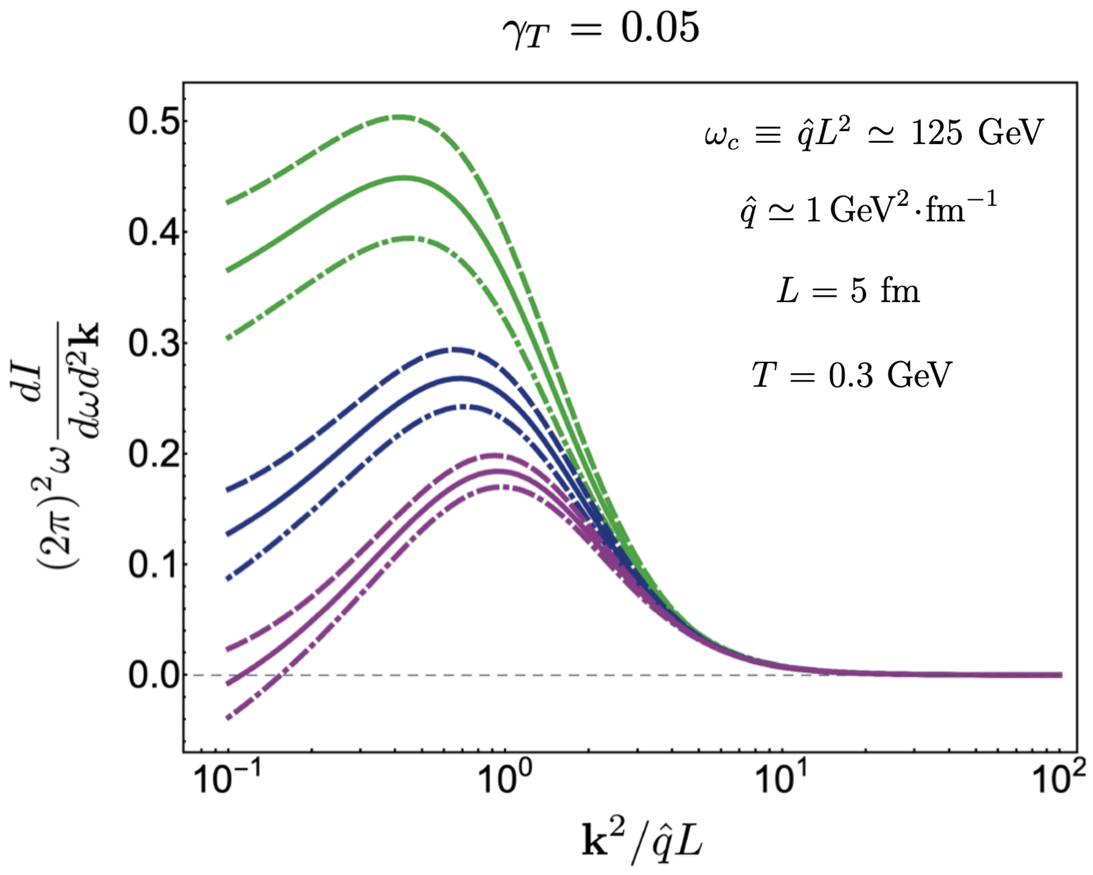
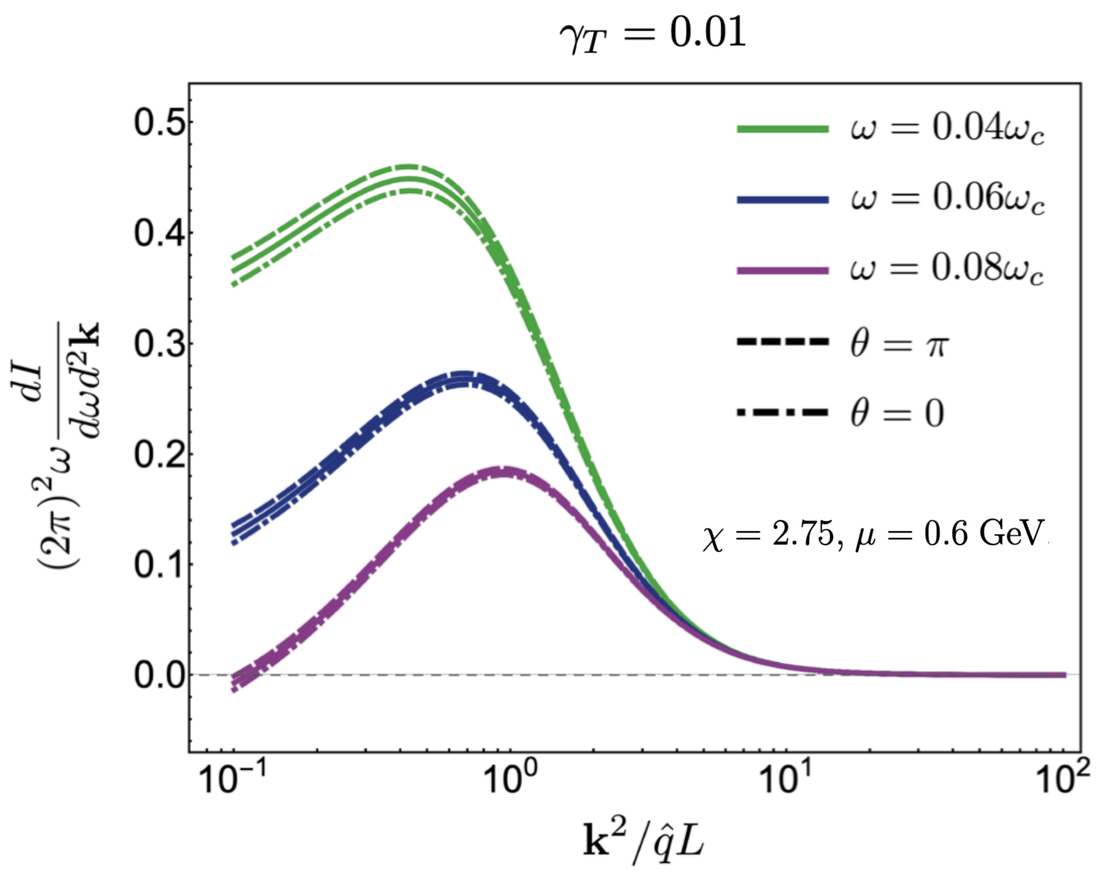
Numerical results, in the harmonic approximation for the in-medium scattering cross-section





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

Jet observables in inhomogeneous matter

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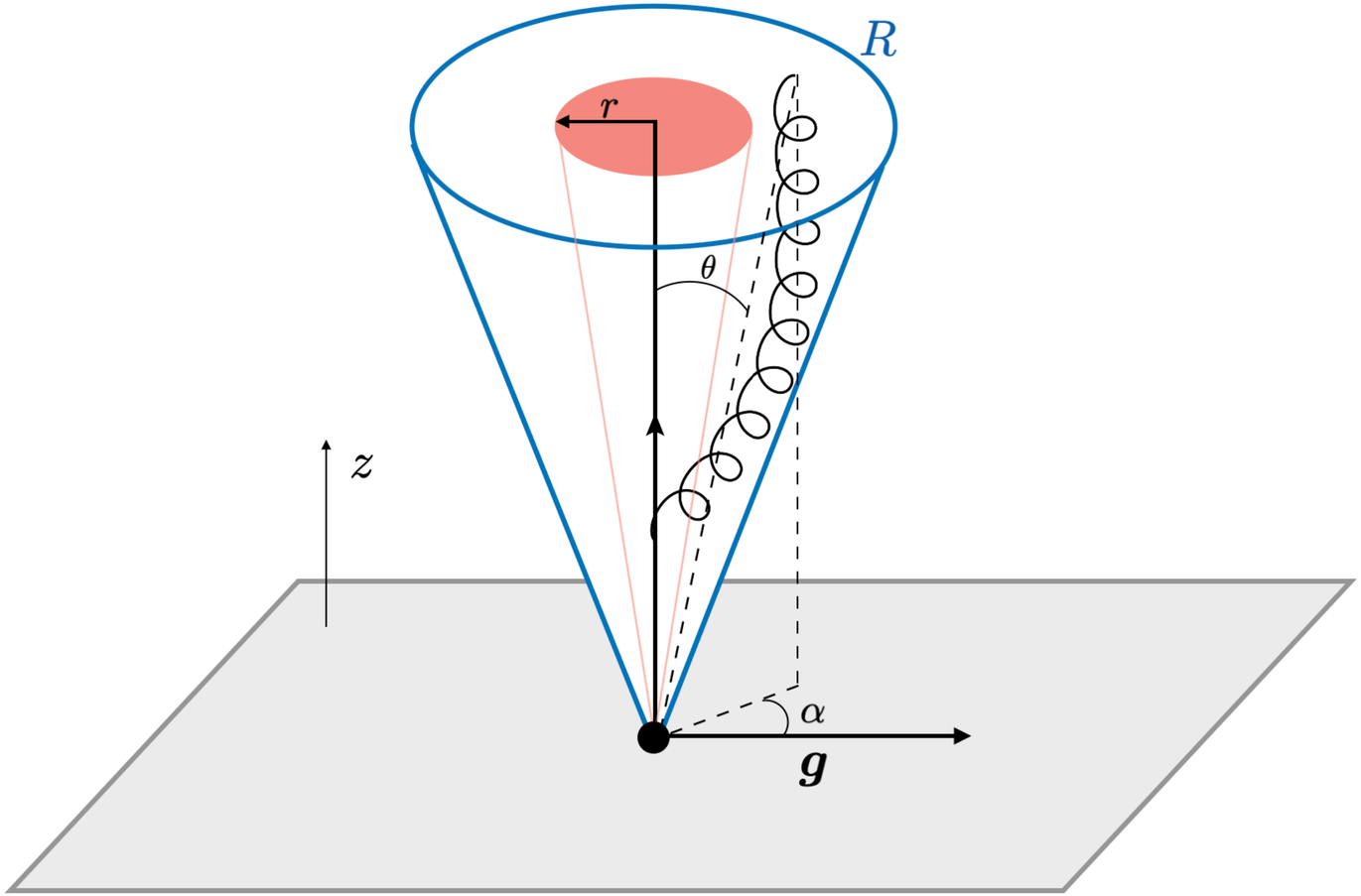

Jet observables in inhomogeneous matter

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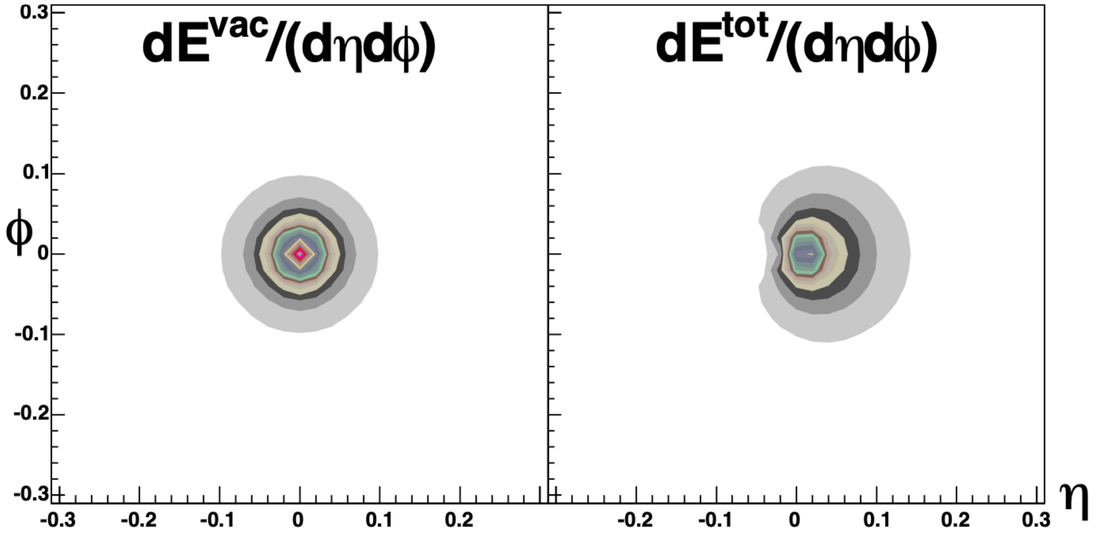
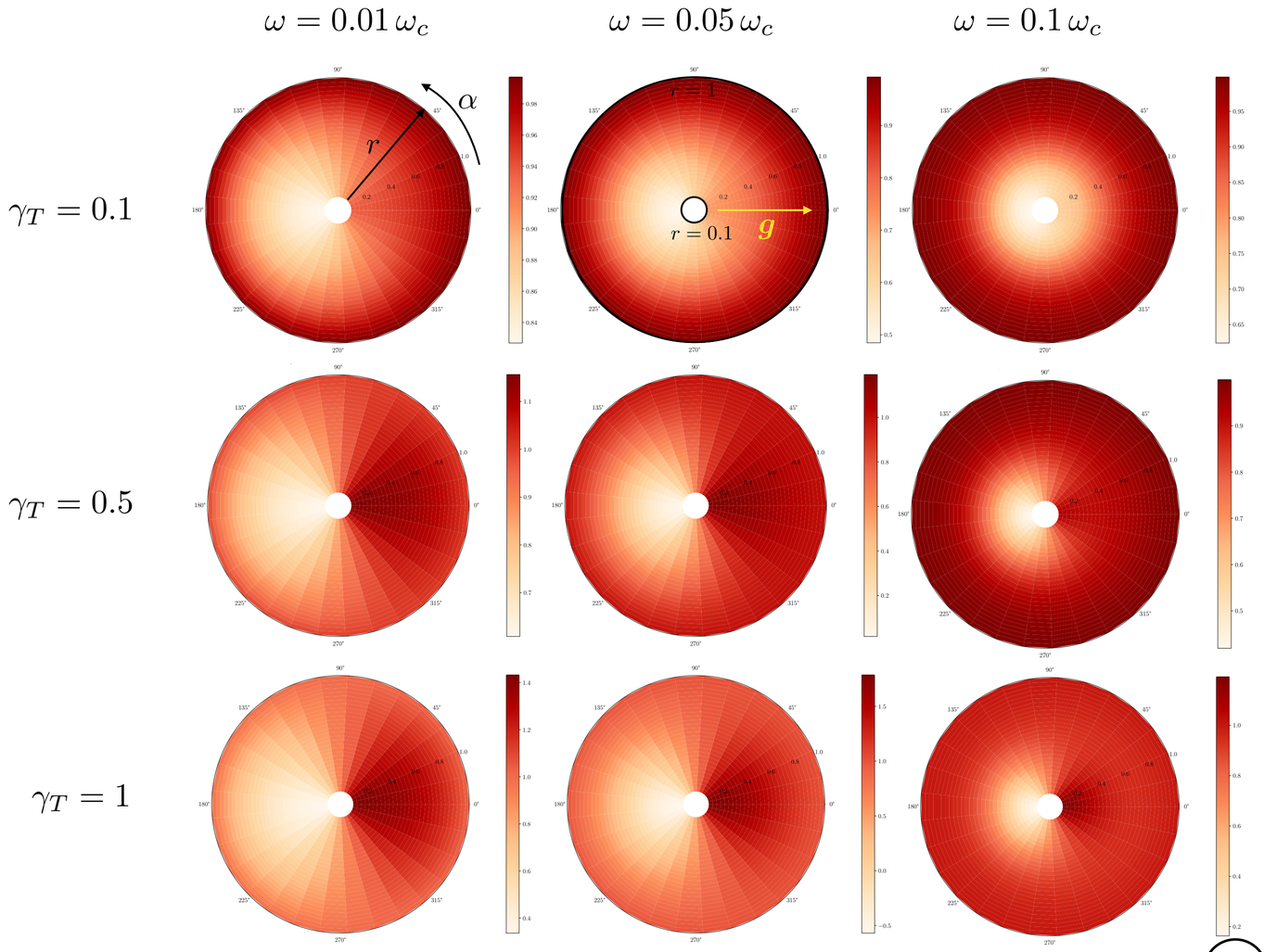
We have now the tools to compute jet observables (at least at leading order in the strong coupling)

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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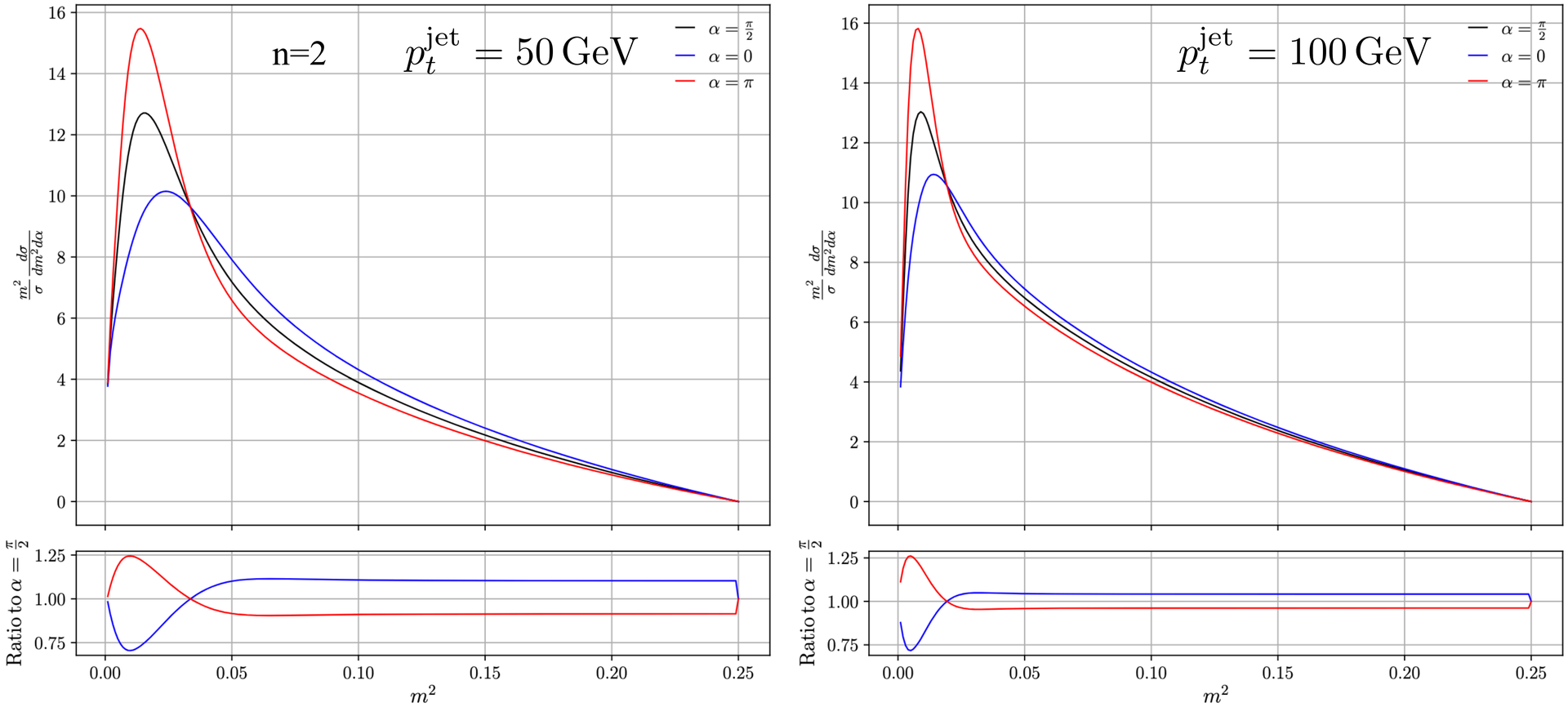
Observable 2: jet angularities $$G_n = \sum_{i\in\text{jet}} \frac{p_t^i}{p_t^{\text{jet}}} g^{(n)}(r_i)$$

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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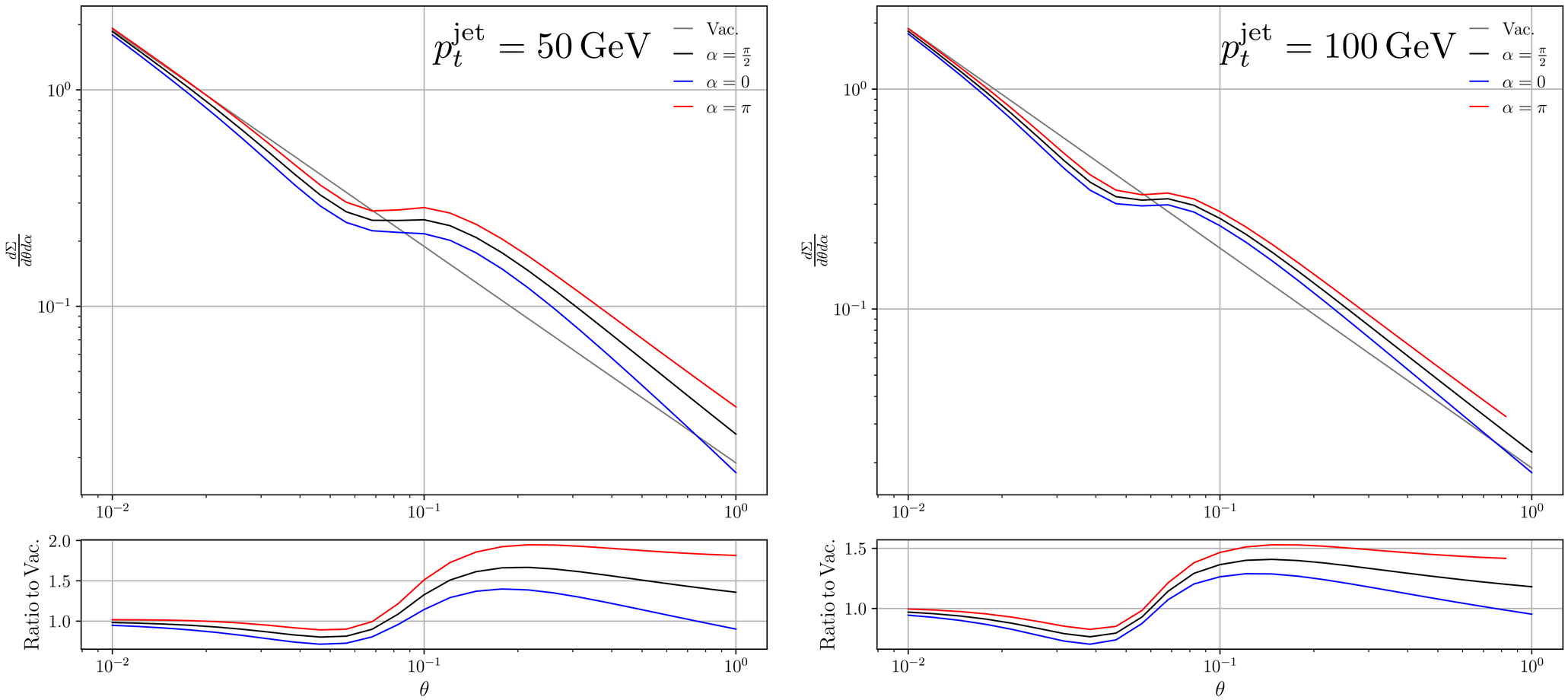
Observable 3: ENCs

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

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



Outlook

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