Jet quenching in evolving anisotropic matter

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AS, M. Sievert, I. Vitev, PRD, 2021
J. Barata, AS, C. Salgado, PRD, 2022
C. Andres, F. Dominguez, AS, CS, PRD, 2022
J. Barata, AS, X.-N. Wang, PRD, 2023
J. Barata, X. Mayo, AS, CS, arxiv, 2023
J. Barata, G. Milhano, AS, TBA, 2023
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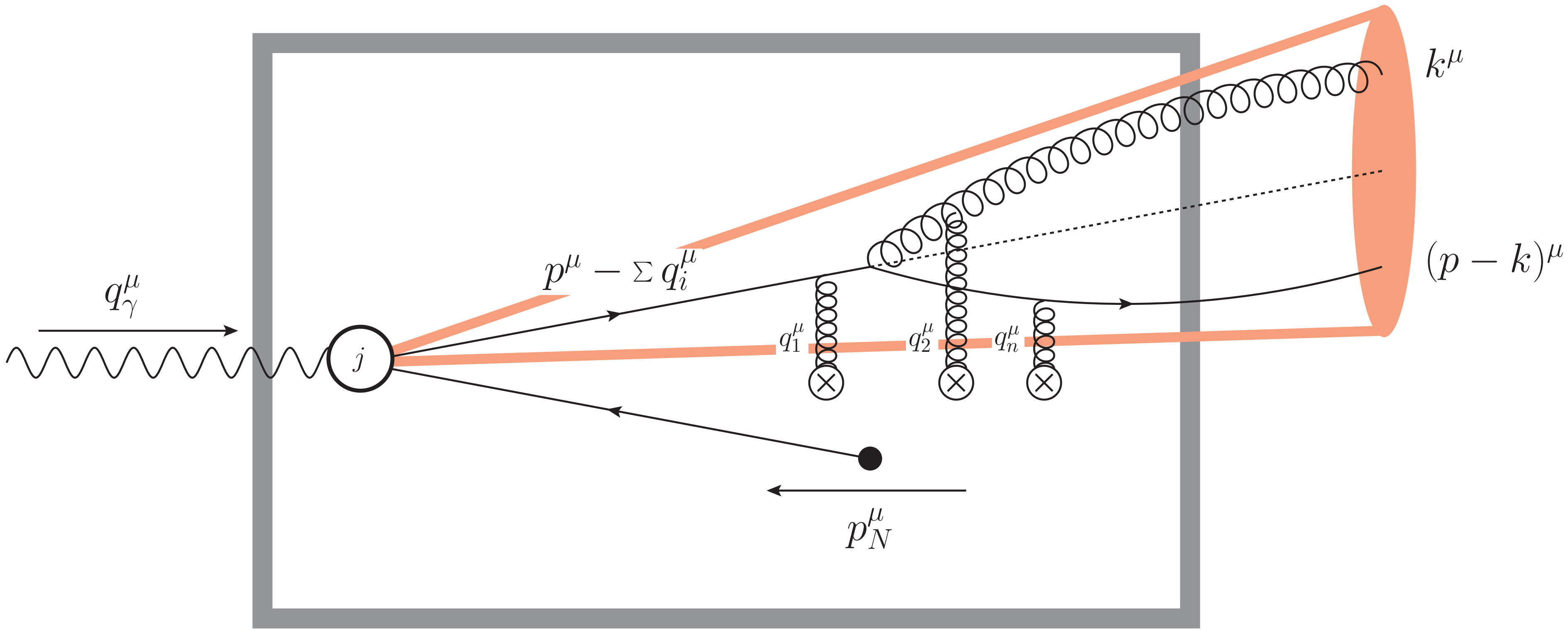
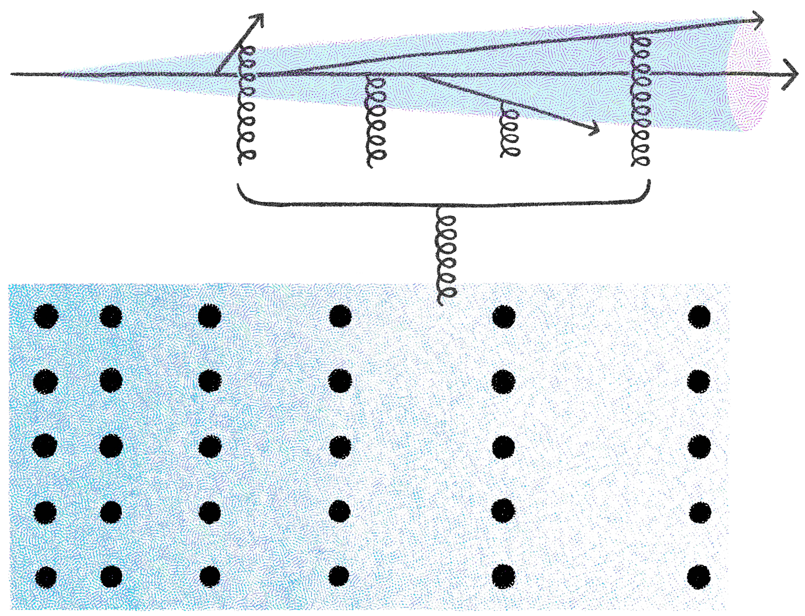
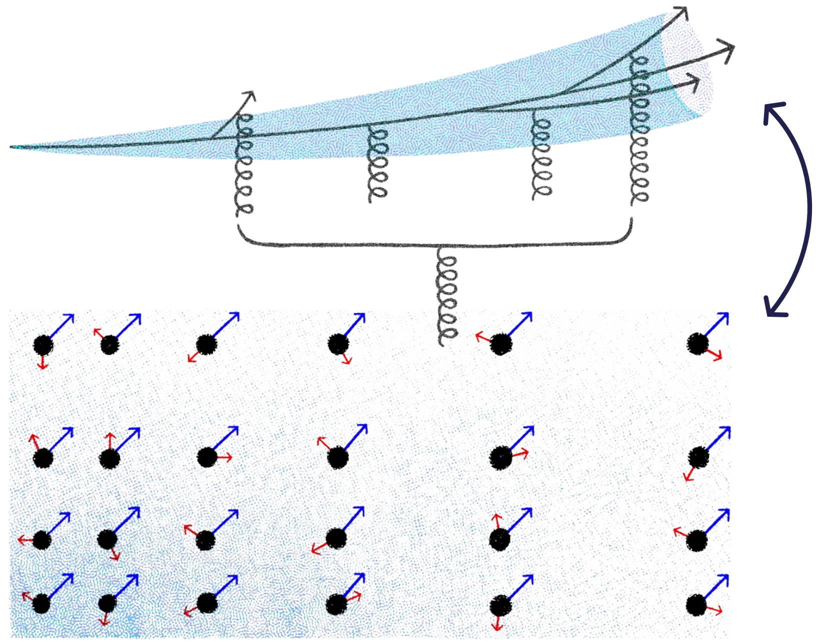
Jet tomography

- Jets see the matter in HIC at multiple scales, and essentially X-ray it;
- The existing jet quenching theory is based on multiple simplifying assumptions: large parton energy, static matter, no fluctuations, etc;
- There is a very recent progress on the medium motion and structure effects in jet quenching and this is the focus of this talk;
- The developed formalism can be also applied to include orbital motion of nucleons and some of the in-medium fluctuations to the energy loss in cold nuclear matter;

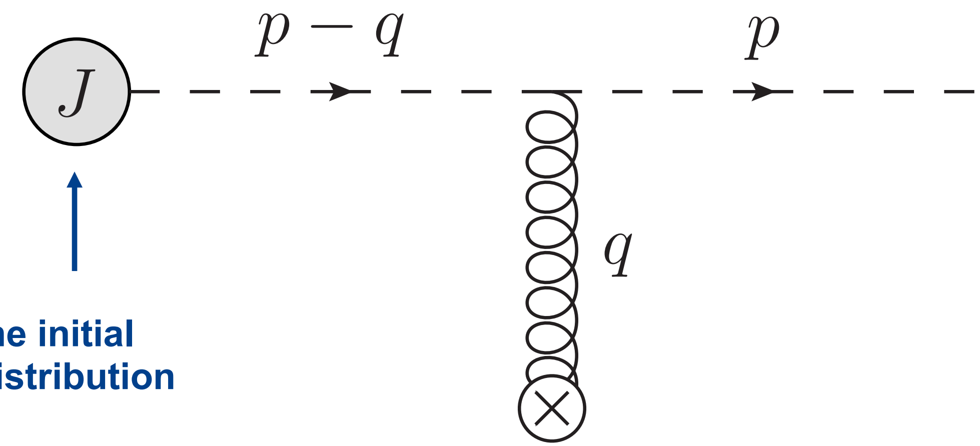
R. Baier et al, NPB, 1997
B. G. Zakharov, JETP, 1997
R. Baier et al, NPB, 1998
M. Gyulassy et al, NPB, 2000
M. Gyulassy et al, NPB, 2001







Color potential



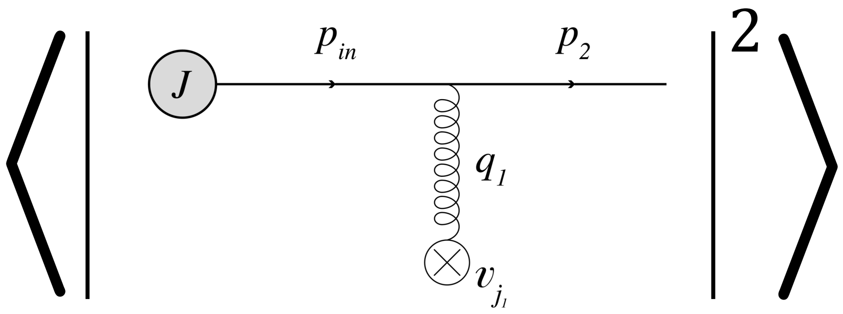
the initial distribution

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

inhomogeneity

the fluid velocity

Medium averaging



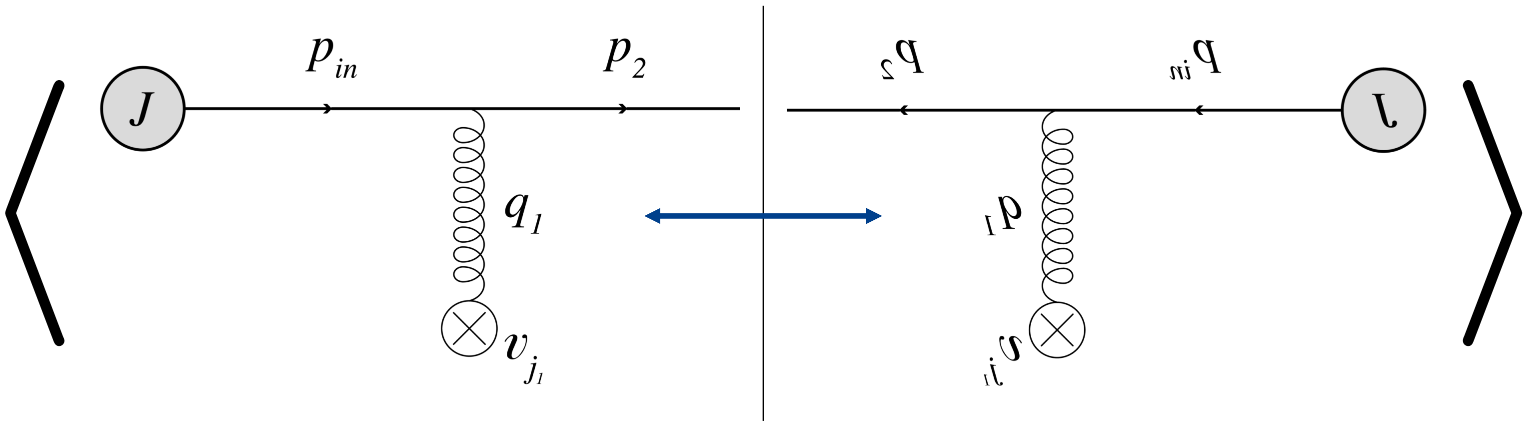
$$\langle t_i^a t_j^b \rangle = \mathcal{C}\delta_{ij}\delta^{ab}$$

color neutrality

$$\sum_i = \int d^3x\, \rho(\vec{x})$$

source averaging

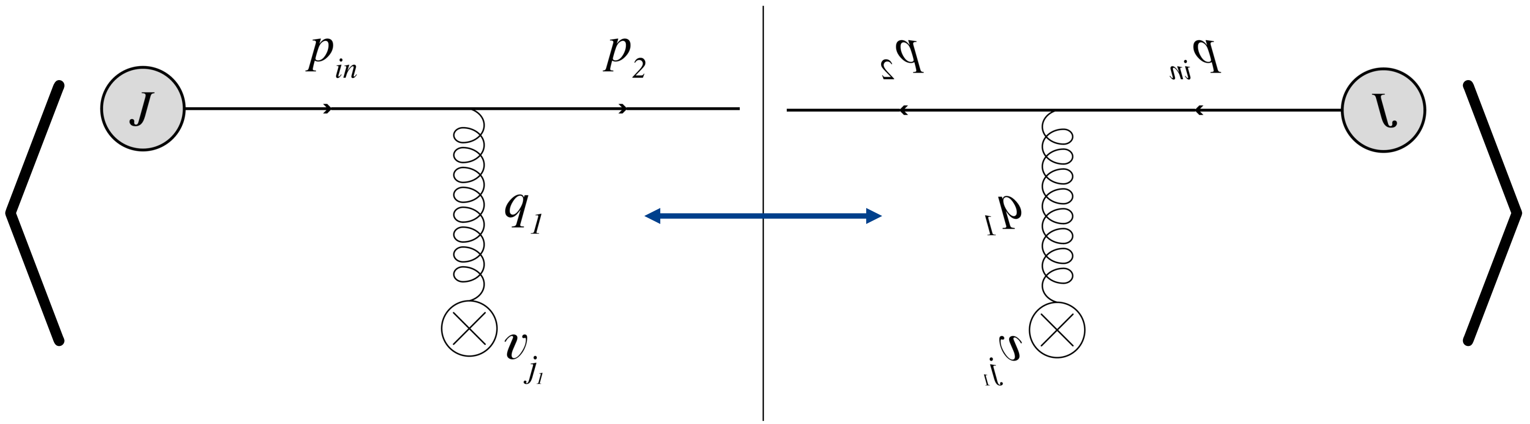
Medium averaging



$$\int d^2\mathbf{x}_n\, e^{-i(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)\cdot \mathbf{x}_n} = (2\pi)^2\, \delta^{(2)}(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)$$

$$\rho \sim T^3$$

Medium averaging



$$\int d^2\mathbf{x}_n \, e^{-i(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)\cdot \mathbf{x}_n} = (2\pi)^2 \, \delta^{(2)}(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)$$

$$\int d^2\mathbf{x}_n \, x_n^{\alpha} \, e^{-i(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)\cdot \mathbf{x}_n} = i\,(2\pi)^2 \, \frac{\partial}{\partial(q_n \pm \overline{q}_n)_\alpha} \, \delta^{(2)}(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)$$

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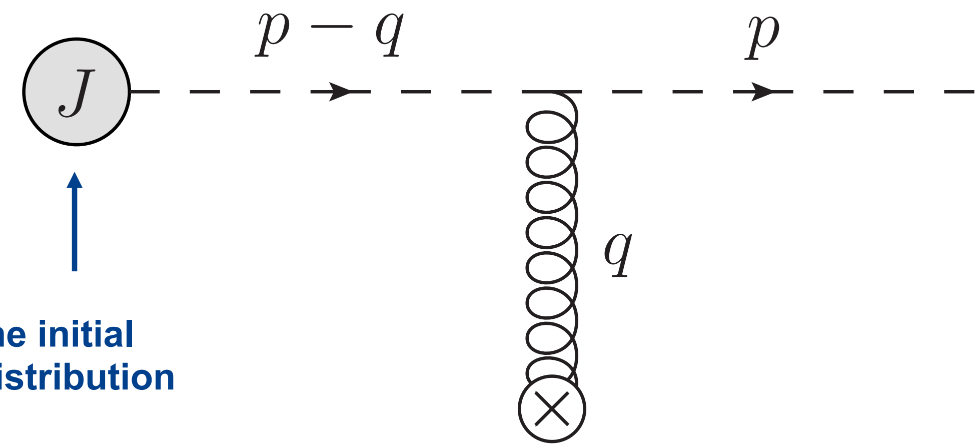
Color potential



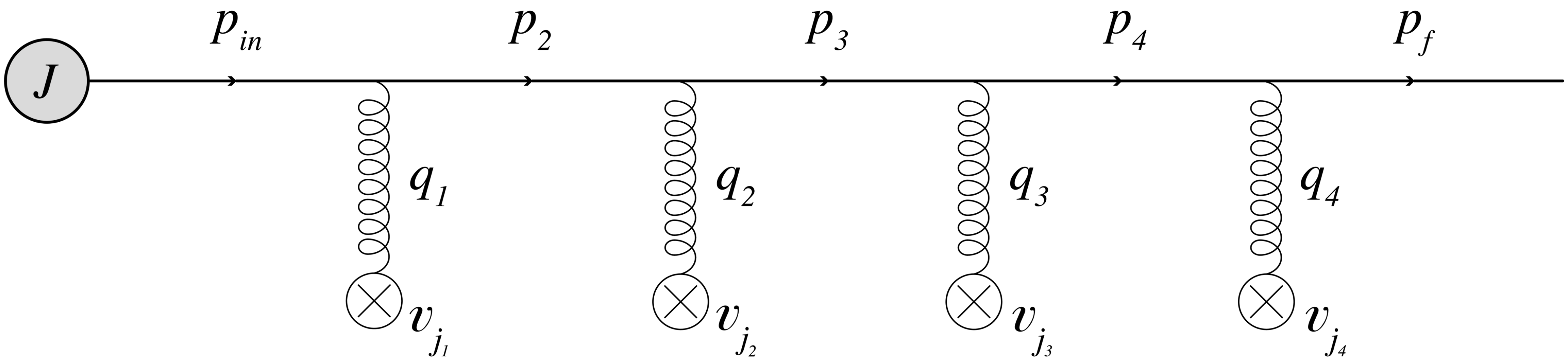
the initial distribution

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

inhomogeneity

(1,0,0,0)

The broadening



$E \to \infty$

$v(q)$

$\mu \ll E \quad \mu z \gg 1$

$$iM(p) = \int \frac{d^2\mathbf{p}_{in}}{(2\pi)^2} e^{i\frac{\mathbf{p}_f^2}{2E}L}\, G(\mathbf{p}_f, L; \mathbf{p}_{in}, 0)\, J(E, \mathbf{p}_{in})$$

single particle propagator

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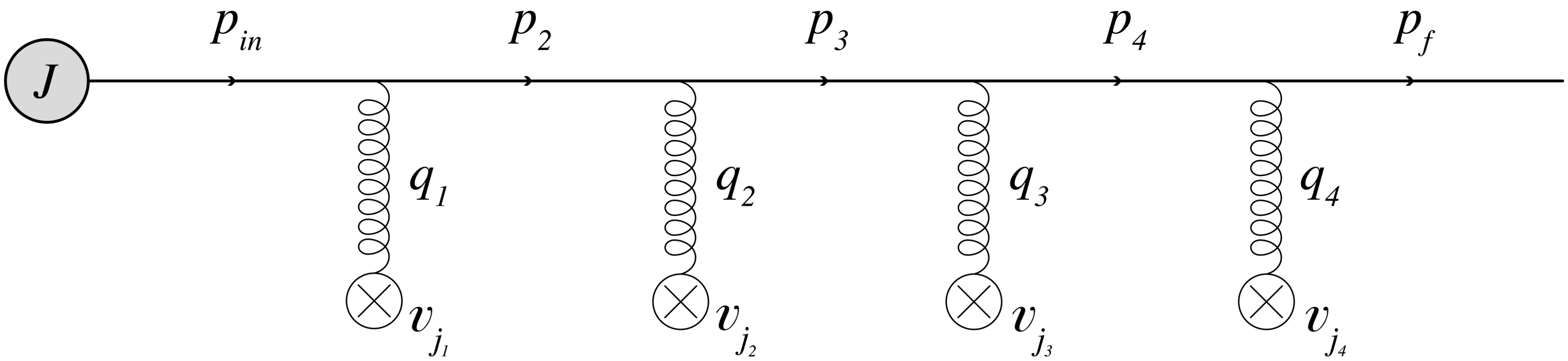
The broadening



$$G(\mathbf{x}_L, L; \mathbf{x}_0, 0) = \int_{\mathbf{x}_0}^{\mathbf{x}_L} \mathcal{D}\mathbf{r} \exp\left(\frac{iE}{2}\int_0^L d\tau\, \dot{\mathbf{r}}^2\right) \mathcal{P}\exp\left(-i\int_0^L d\tau\, t^a_{\mathrm{proj}} v^a(\mathbf{r}(\tau),\tau)\right)$$

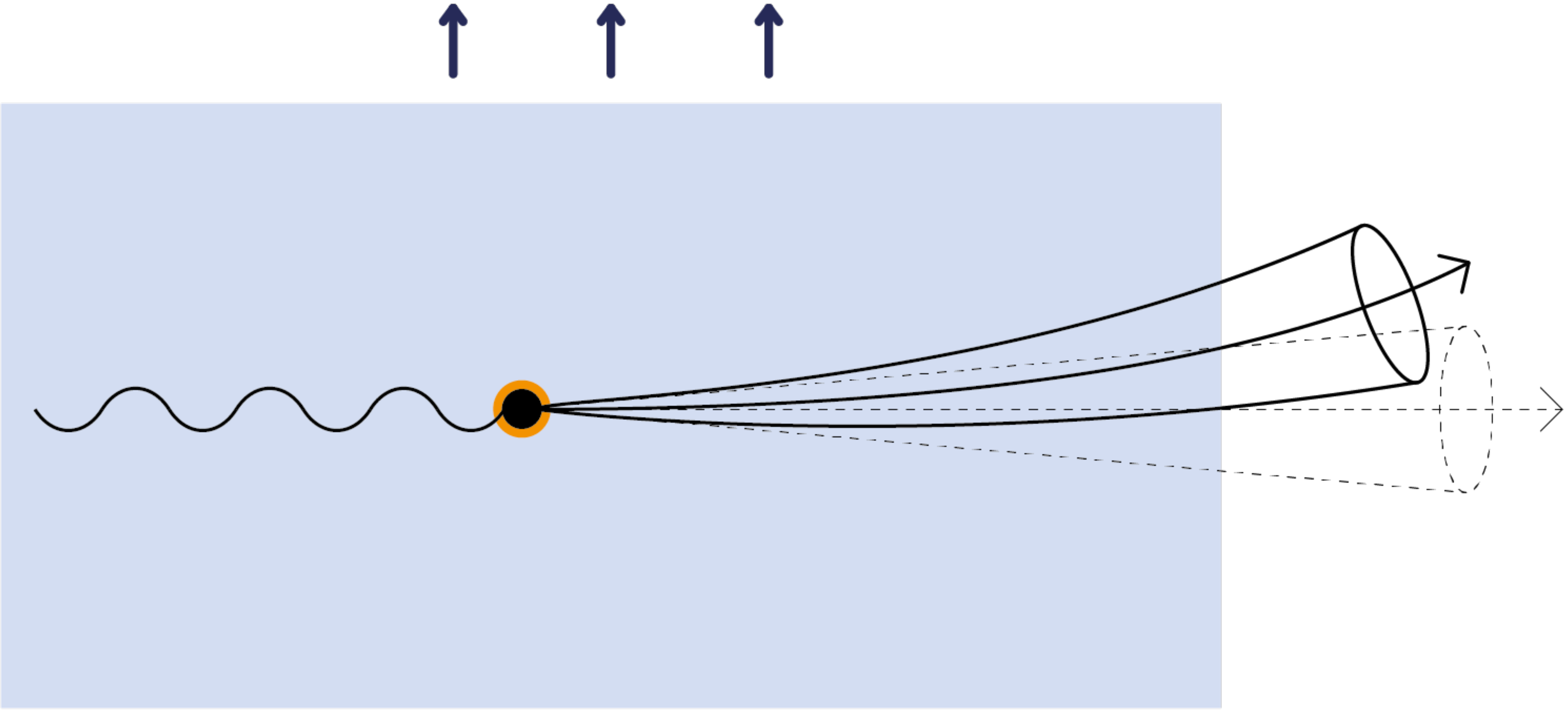
$$\left\langle \mathcal{P}\exp\left(-i\int_0^L d\tau\, t^a_{\mathrm{proj}} v^a(\boldsymbol{r}(\tau),\tau)\right)\mathcal{P}\exp\left(i\int_0^L d\bar{\tau}\, t^b_{\mathrm{proj}} v^b(\bar{\boldsymbol{r}}(\bar{\tau}),\bar{\tau})\right)\right\rangle$$

$$= \exp\left\{-\int_0^L d\tau \left[1 + \frac{\boldsymbol{r}(\tau)+\bar{\boldsymbol{r}}(\tau)}{2}\cdot\hat{\boldsymbol{g}}\right]\mathcal{V}\left(\boldsymbol{r}(\tau)-\bar{\boldsymbol{r}}(\tau)\right)\right\}$$

$$\hat{\boldsymbol{g}} \equiv \left(\boldsymbol{\nabla}\rho\frac{\delta}{\delta\rho} + \boldsymbol{\nabla}\mu^2\frac{\delta}{\delta\mu^2}\right)$$

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

$$\frac{\mathcal{N}}{d^2\mathbf{p}dE} \qquad\qquad \frac{\mathcal{N}^{(0)}}{d^2\mathbf{p}dE}$$



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

$$W_L(\mathbf{Y},\mathbf{p}) \equiv \int_{\mathbf{y},\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{y}} \left\langle G\left(\mathbf{Y}+\frac{\mathbf{y}}{2};\frac{\mathbf{x}}{2}\right) G^\dagger\left(\mathbf{Y}-\frac{\mathbf{y}}{2};-\frac{\mathbf{x}}{2}\right)\right\rangle$$

$\downarrow$

a limit of AMY KT (JHEP 2002/2003) $\longrightarrow$

$$\left(\partial_L + \frac{\mathbf{p}}{E}\cdot\nabla_{\mathbf{Y}} - \frac{\hat{q}}{4}\partial^2_{\mathbf{p}}\right) W_L(\mathbf{Y},\mathbf{p}) = 0$$

in the harmonic approximation

$$W_L(\mathbf{Y},\mathbf{p}) \equiv \int_{\mathbf{y},\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{y}} \left\langle G\left(\mathbf{Y}+\frac{\mathbf{y}}{2};\frac{\mathbf{x}}{2}\right) G^\dagger\left(\mathbf{Y}-\frac{\mathbf{y}}{2};-\frac{\mathbf{x}}{2}\right)\right\rangle$$

$$\downarrow$$

$$\left(\partial_L + \frac{\mathbf{p}}{E}\cdot\nabla_{\mathbf{Y}} - \frac{\hat{q}(\mathbf{Y})}{4}\partial^2_{\mathbf{p}}\right) W_L(\mathbf{Y},\mathbf{p}) = \boxed{\nabla_i\nabla_j\rho}$$
$$\underbrace{\times \boxed{\int_{\mathbf{q}}\left[\kappa\frac{\partial^2}{\partial p_i\partial p_j}\delta^{(2)}(\mathbf{q}) - V_{ij}(\mathbf{q})\right] W_L(\mathbf{Y},\mathbf{p}-\mathbf{q})}}_{\text{quantum corrections to the Boltzmann-diffusion equation}}$$

cannot be obtained from local collision kernel $\longrightarrow$

quantum corrections to the Boltzmann-diffusion equation

$$W_L(\mathbf{Y},\mathbf{p}) \equiv \int_{\mathbf{y},\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{y}} \left\langle G\left(\mathbf{Y}+\frac{\mathbf{y}}{2};\frac{\mathbf{x}}{2}\right) G^{\dagger}\left(\mathbf{Y}-\frac{\mathbf{y}}{2};-\frac{\mathbf{x}}{2}\right)\right\rangle$$

$$\downarrow$$

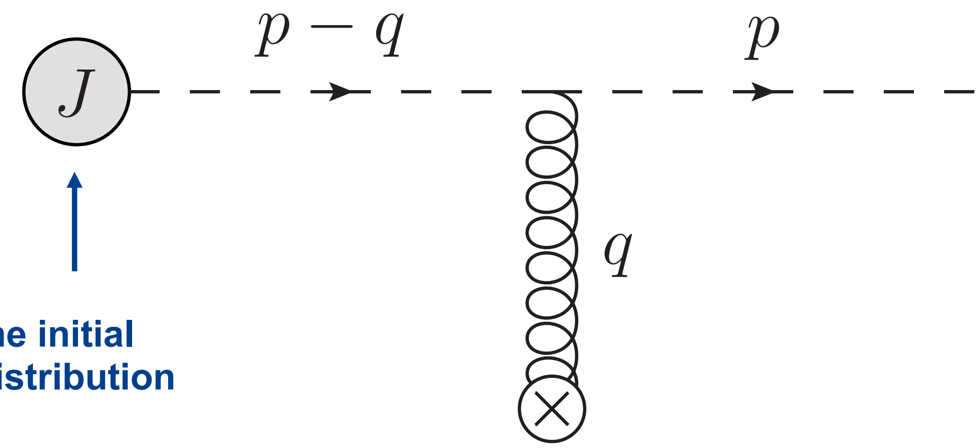
$$\left(\partial_L + \frac{\mathbf{p}}{E}\cdot\nabla_{\mathbf{Y}} - \frac{\hat{q}(\mathbf{Y})}{4}\partial^2_{\mathbf{p}}\right) W_L(\mathbf{Y},\mathbf{p}) = \nabla_i\nabla_j\rho$$

$$\times \int_{\mathbf{q}} \left[\kappa\frac{\partial^2}{\partial p_i \partial p_j}\delta^{(2)}(\mathbf{q}) - V_{ij}(\mathbf{q})\right] W_L(\mathbf{Y},\mathbf{p}-\mathbf{q})$$

$$\downarrow$$

$$\hat{q}_r = \hat{q} + \nabla^2\hat{q}\left(\frac{\hat{q}L^3}{12E^2} + \eta\right)$$

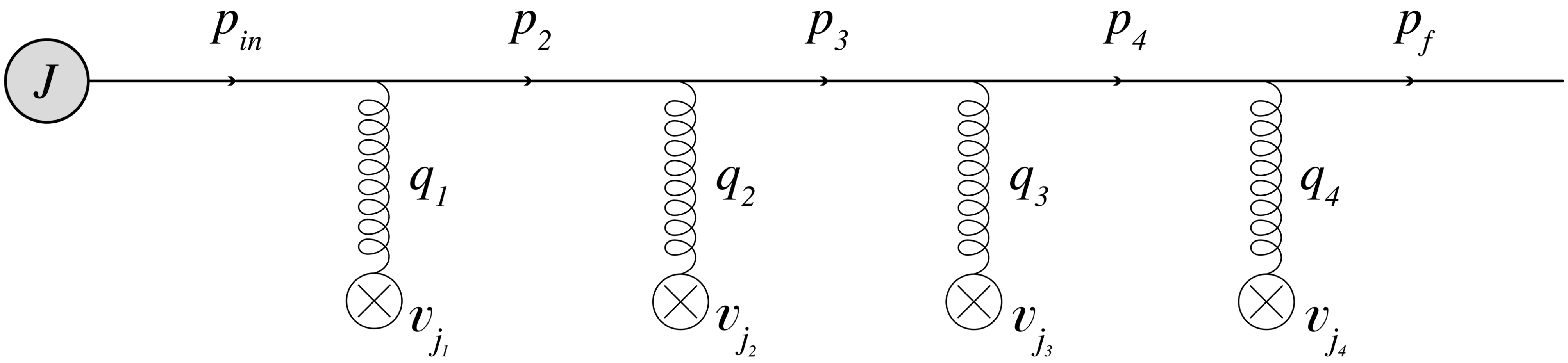
Color potential



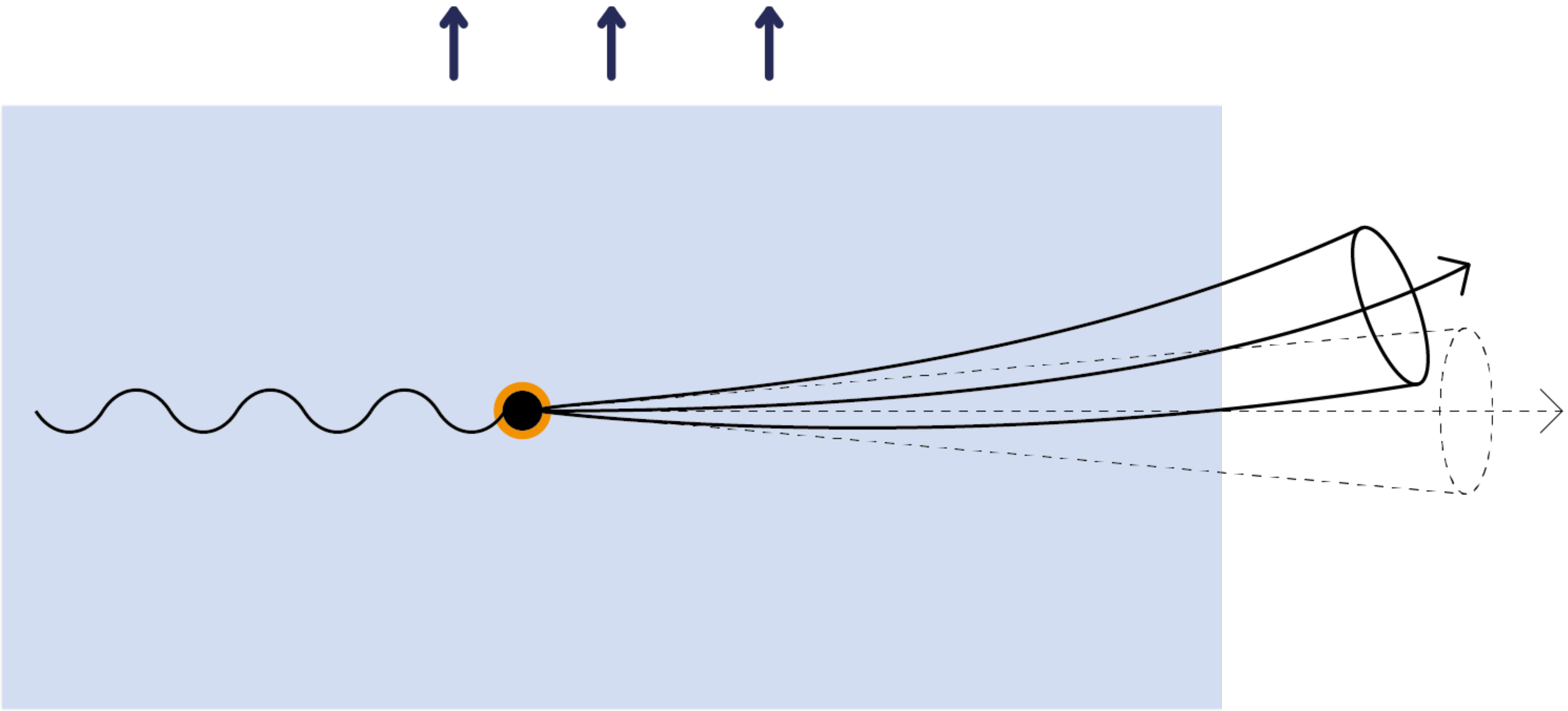
the initial distribution

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

Jet broadening

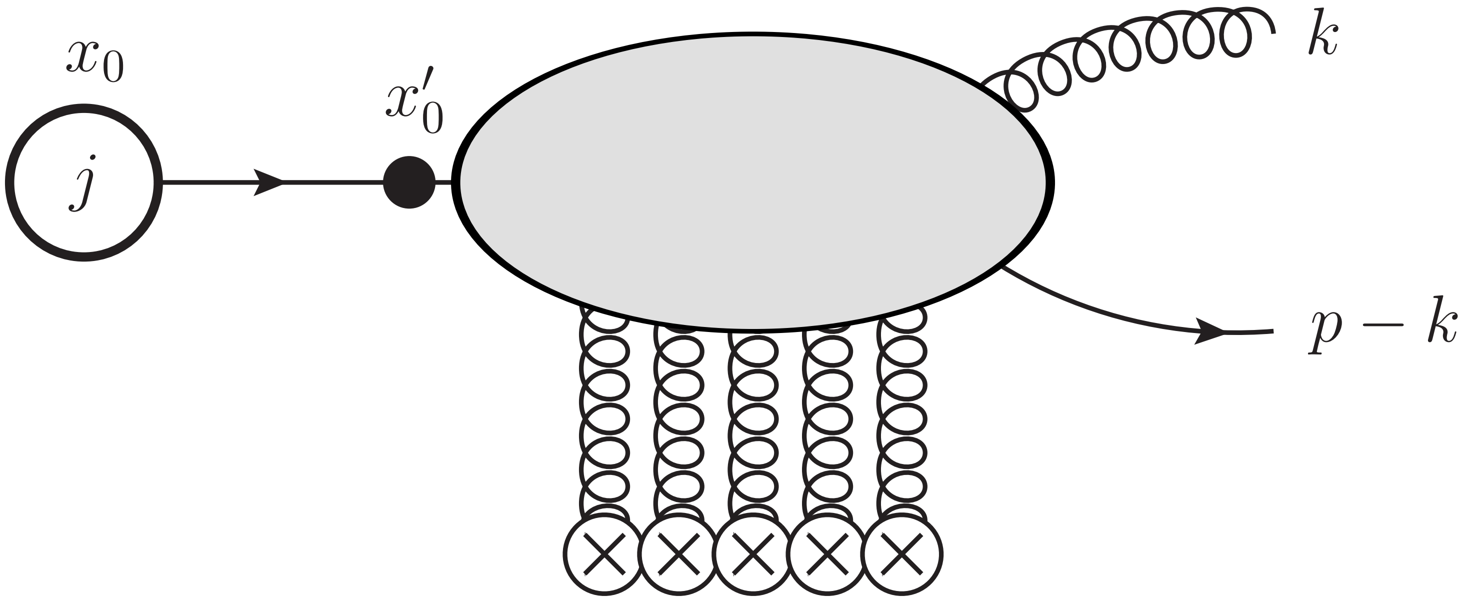


$$i\mathcal{M}_n(p) = e^{-i\left(\mathbf{u}\cdot\mathbf{p}-\frac{p_\perp^2}{2E}\right)L}\int\frac{d^2\mathbf{p}_0}{(2\pi)^2}\,\mathcal{G}_n(\mathbf{p},L;\mathbf{p}_0,0)\,J\big(E-\mathbf{u}\cdot(\mathbf{p}-\mathbf{p}_0),\mathbf{p}_0\big)\,,$$



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

Gluon emission



Gluon emission

$$iR \simeq -\frac{g}{xE} \lim_{z_f \to \infty} \int_0^\infty dz_s \int d^2x_0 \, e^{-i\mathbf{x}_0 \cdot \mathbf{l}_f} J(\mathbf{x}_0)$$

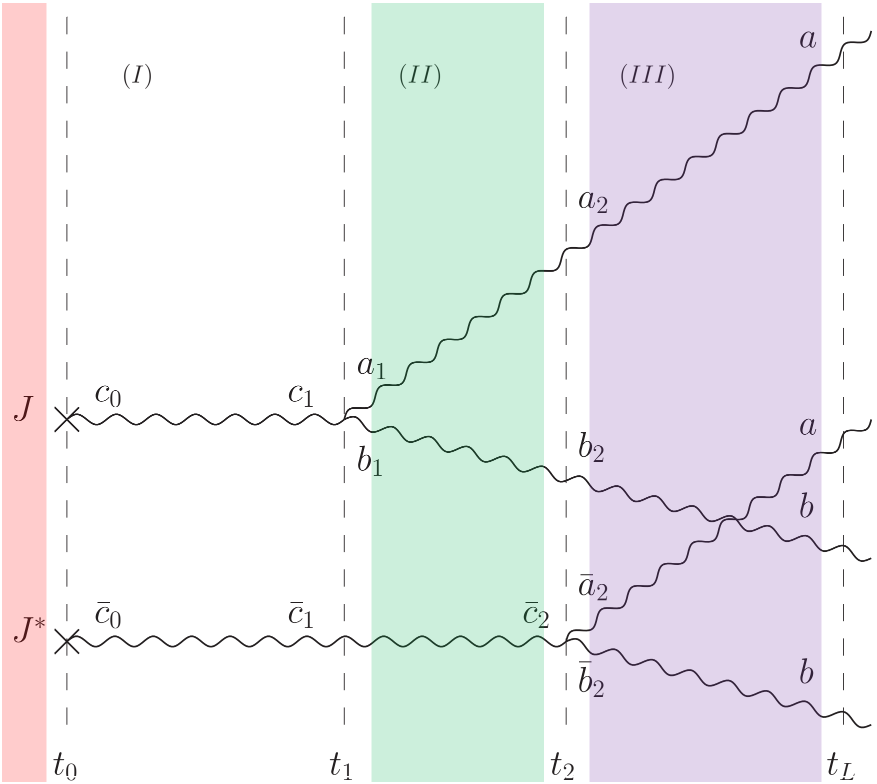
$$\times \, \mathcal{W}(\mathbf{x}_0; \infty, z_s) \, t^a_{proj} \, \mathcal{W}(\mathbf{x}_0; z_s, 0) \; e^{i\frac{\mathbf{k}_f^2}{2\omega} z_f} \left[\epsilon \cdot \vec{\nabla}_{\mathbf{x}_0} \mathcal{G}^{ba} \left(\mathbf{k}_f, z_f; \mathbf{x}_0, z_s \right) \right]$$

energy fraction

Wilson line ($x \ll 1$)

the gluon (single-particle) propagator

Gluon emission



$$(2\pi)^2\omega\frac{d\mathcal{N}}{d\omega d^2\mathbf{k}} = \frac{\alpha_s}{N_c\,\omega^2}\mathrm{Re}\int_0^L d\bar{z}\int_0^{\bar{z}} dz\int_{\mathbf{x}_0,\mathbf{y}} |J(\mathbf{x}_0)|^2\Big[(\nabla_{\mathbf{x}}\cdot\nabla_{\bar{\mathbf{x}}})$$

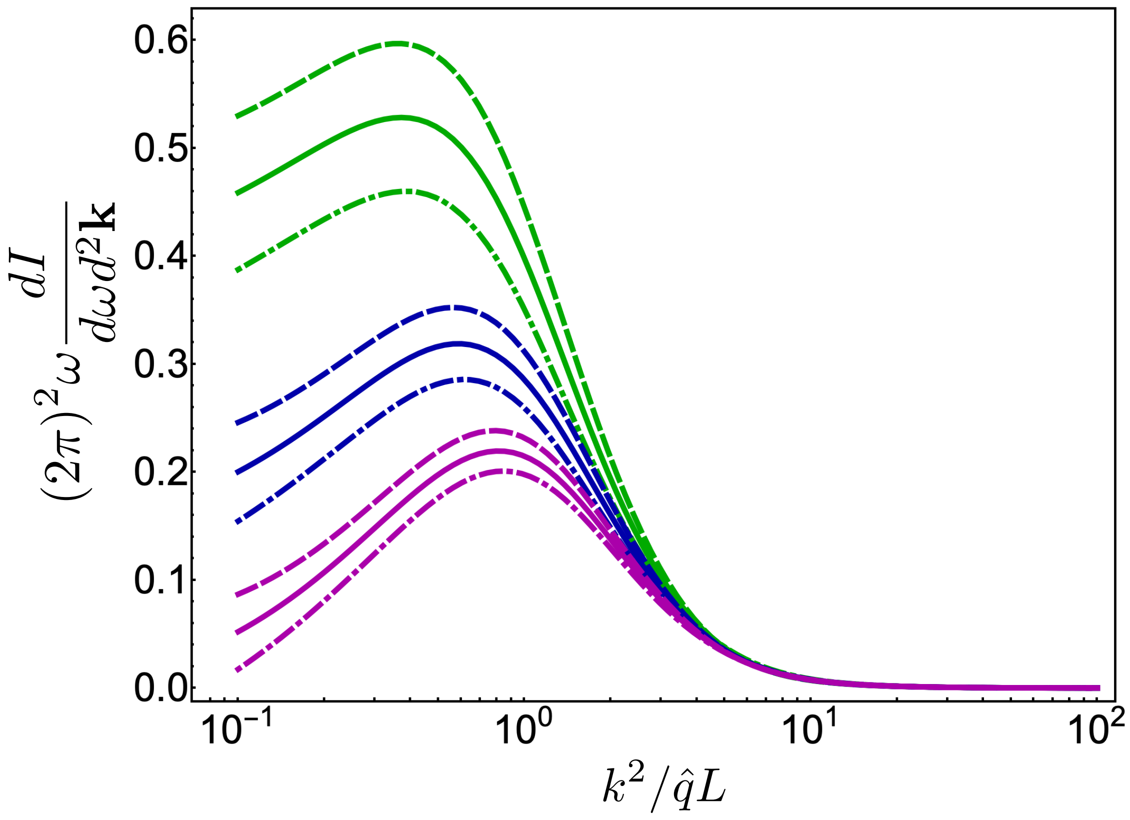
$$\times\left\langle\mathcal{G}^{bc}(\mathbf{k},L;\mathbf{y},\bar{z})\,\mathcal{G}^{\dagger\,\bar{a}b}(\mathbf{k},L;\bar{\mathbf{x}},\bar{z})\right\rangle\left\langle\mathcal{G}^{ca}(\mathbf{y},\bar{z};\mathbf{x},z)\,\mathcal{W}_A^{\dagger\,a\bar{a}}(\mathbf{x}_0;\bar{z},z)\right\rangle\Big]\Big|_{\mathbf{x}=\bar{\mathbf{x}}=\mathbf{x}_0}$$

broadening of the gluon (already have it with ∇)

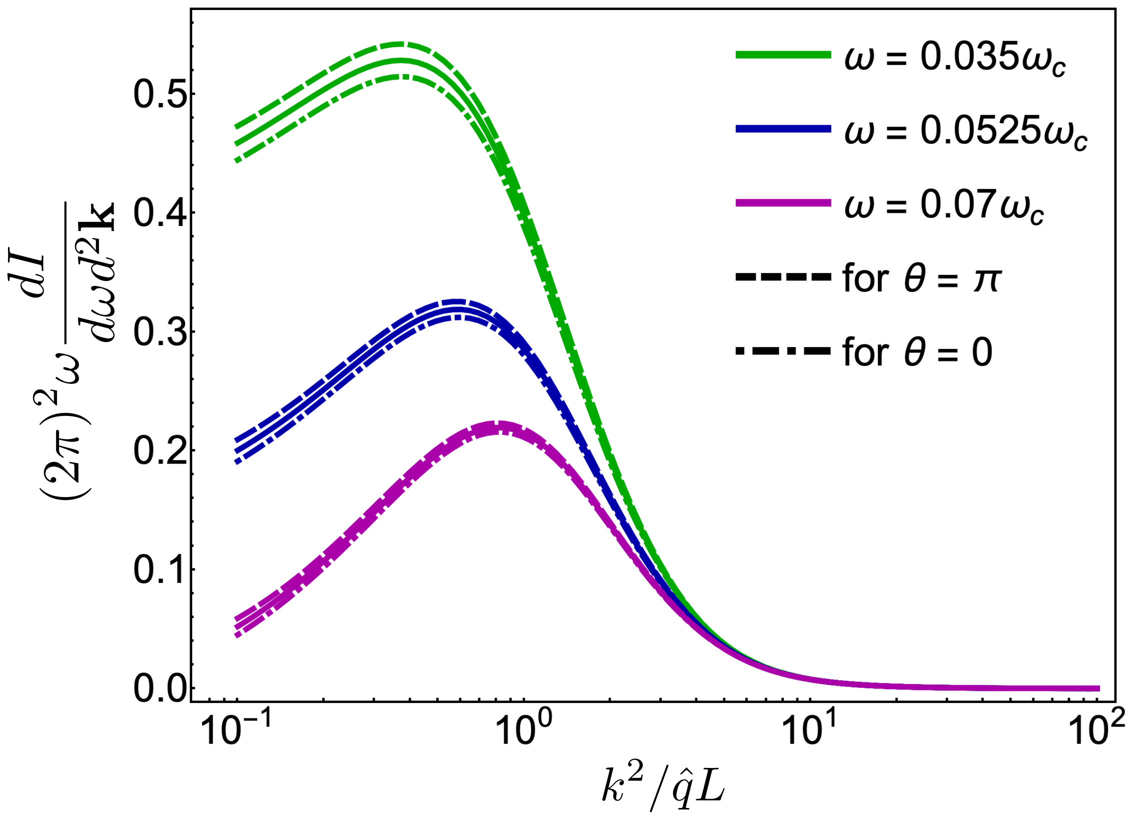
emission kernel

$$\delta\mathcal{K}(\mathbf{y},\bar{z};\mathbf{x},z) = -\int_z^{\bar{z}} ds\int_{\mathbf{w}}\mathcal{K}_0(\mathbf{y},\bar{z};\mathbf{w},s)\delta\mathcal{V}(\mathbf{w},s)\mathcal{K}_0(\mathbf{w},s;\mathbf{x},z)$$

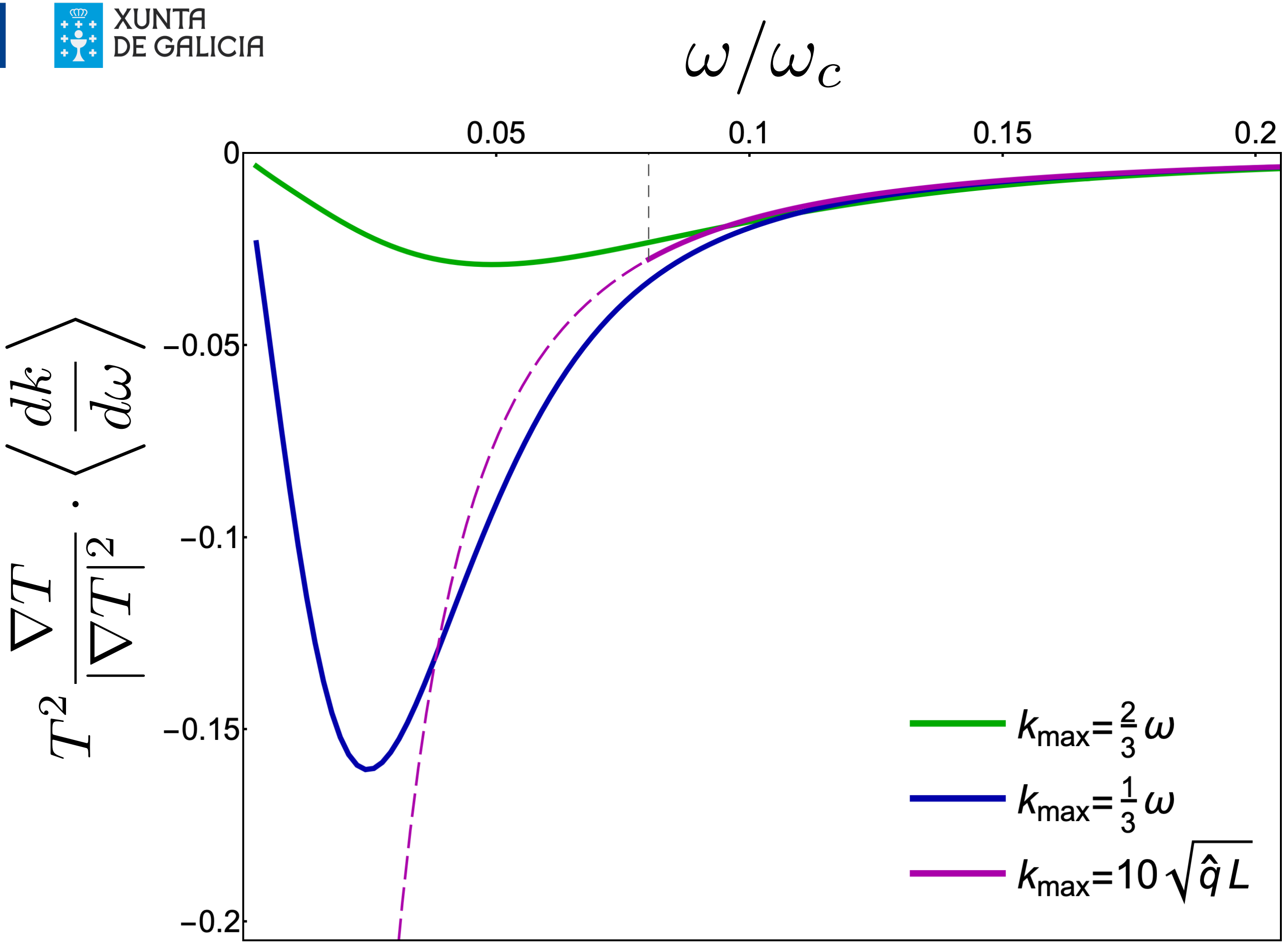
$$\left|\frac{\nabla T}{T^2}\right| = 0.05$$



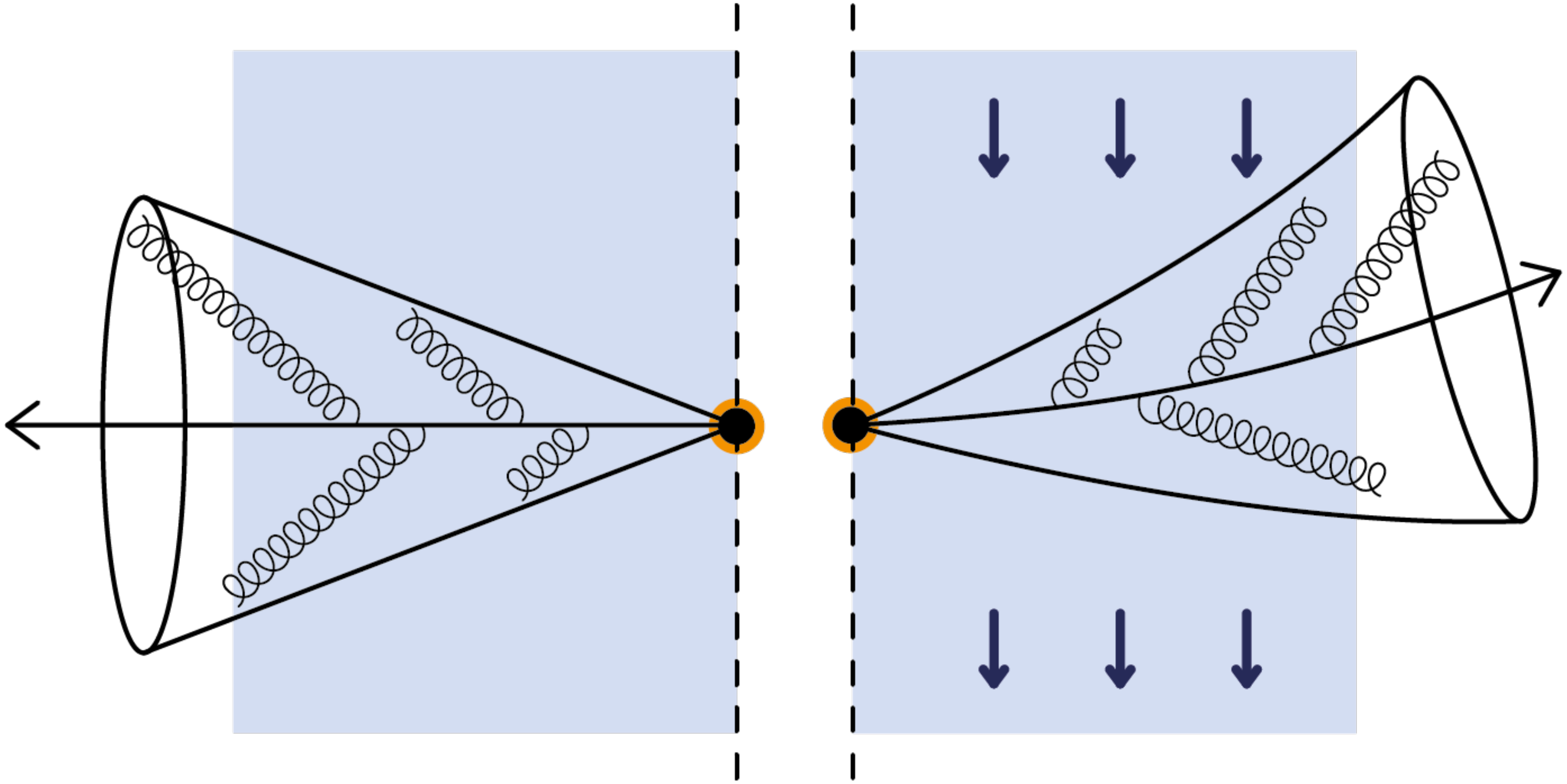
$$\left|\frac{\nabla T}{T^2}\right| = 0.01$$



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



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



Summary

- Jets do feel the transverse flow and anisotropy, and get bended and distorted;
- The transverse flow and anisotropy do affect the medium-induced radiation, bending the substructure of jets;
- These effects can be in principle probed in experiment, leading us towards actual jet tomography;
- One should also expect similar evolution-induced effects for the other probes of nuclear matter;

Jet broadening

uniform matter

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

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

What jet energy corresponds to $\langle\theta\rangle \approx 1^o$?

$$\downarrow$$

$$E{\sim}50\ \text{GeV}$$

Jet broadening

inhomogeneous matter

- Opacity $\chi \approx 4$
- $\mu = gT$ with $g \approx 2$ and $T \approx 500\ MeV$
- $L\nabla T > T$

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

What jet energy corresponds to $\langle \text{"}\theta\text{"} \rangle \approx 1^o$?

$\downarrow$

Jet energies: $E < 100\ \mathrm{GeV}$

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Energy-energy correlators

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

- EEC for jets, see K. Lee et al, 2022
- EEC in HIC, see Carlota's slides
- The small-x BDMPS-Z formula is not strictly applicable, just an illustration
- The gradient effects can be clearly seen