Jet quenching in evolving matter

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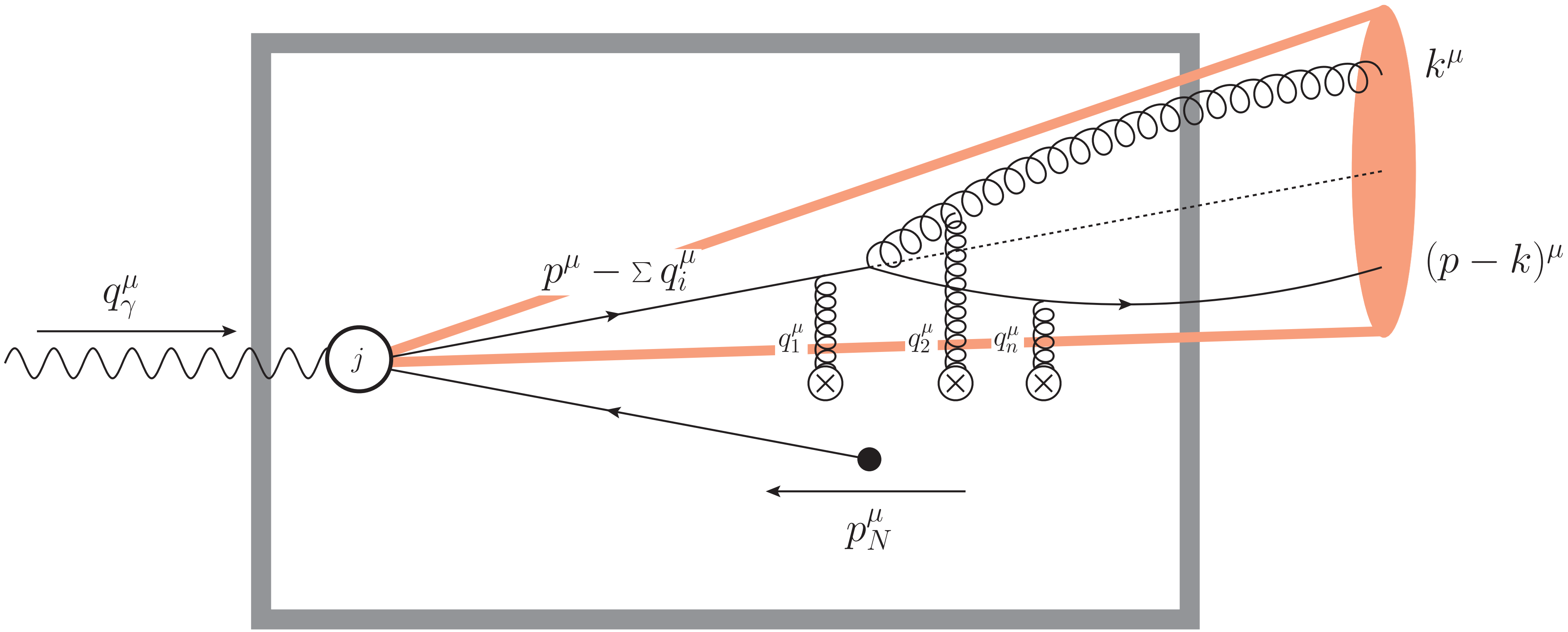
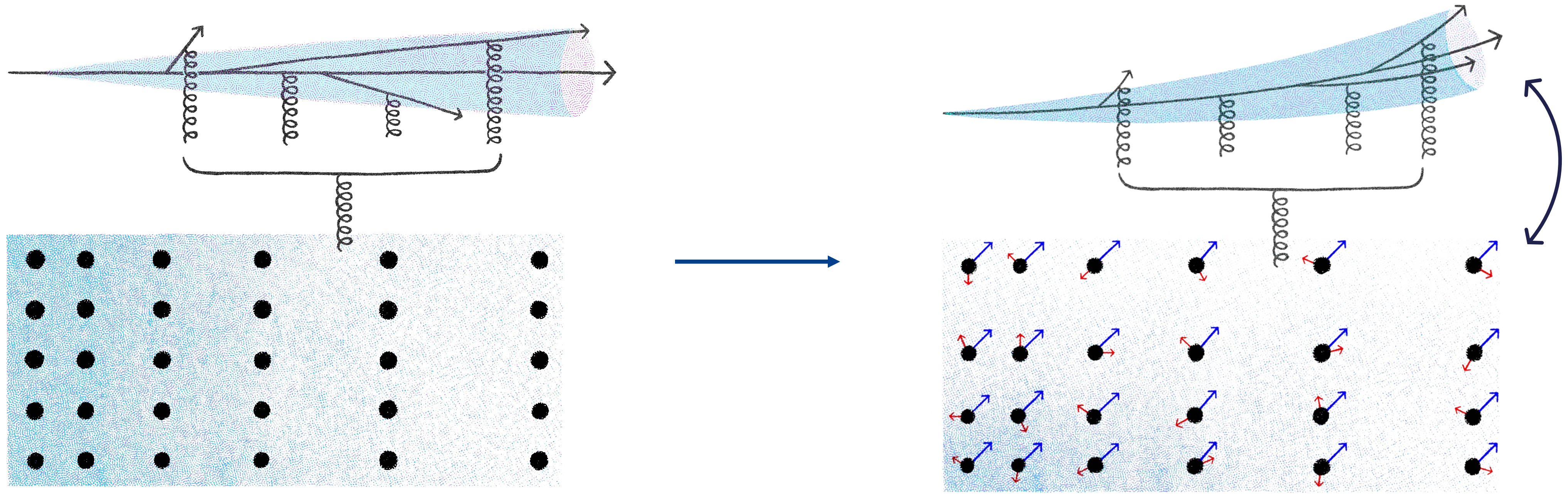
Jet tomography

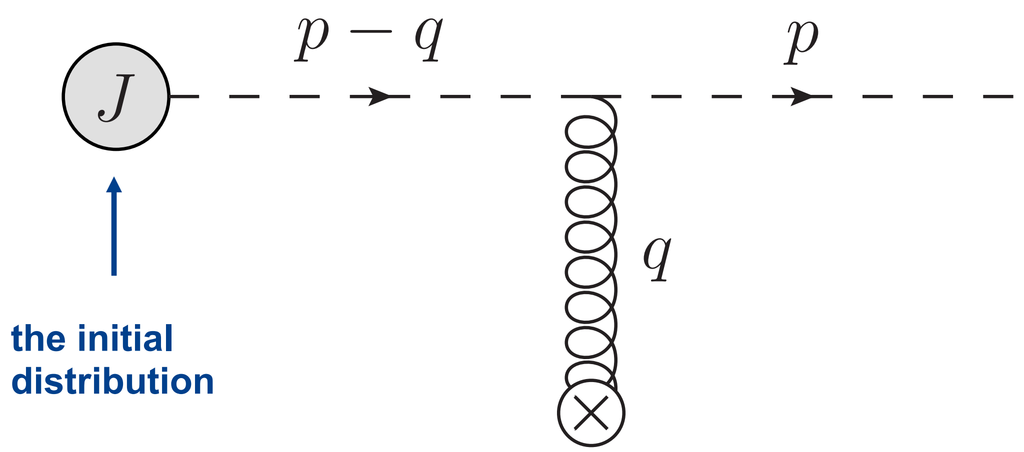
- Jets see the matter in HIC at multiple scales, and essentially X-ray it;
- The existing jet quenching theory is based on multiple simplifying assumptions: large parton energy, static matter, no fluctuations, etc;
- There is a very recent progress on the medium motion and structure effects in jet quenching 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 in the DIS context;

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

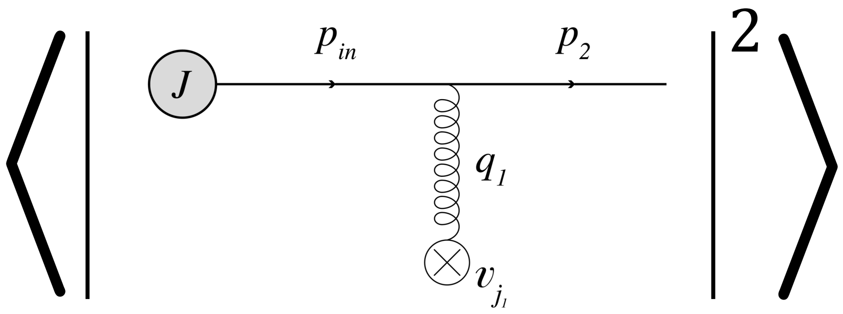


$$gA^{\mu a}_{ext}(q) = \sum_i e^{iq\cdot x_i}\, t^a_i\, u^\mu_i\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \vec{u}_i \cdot \vec{q}\right)$$

inhomogeneity

the fluid velocity

Medium averaging



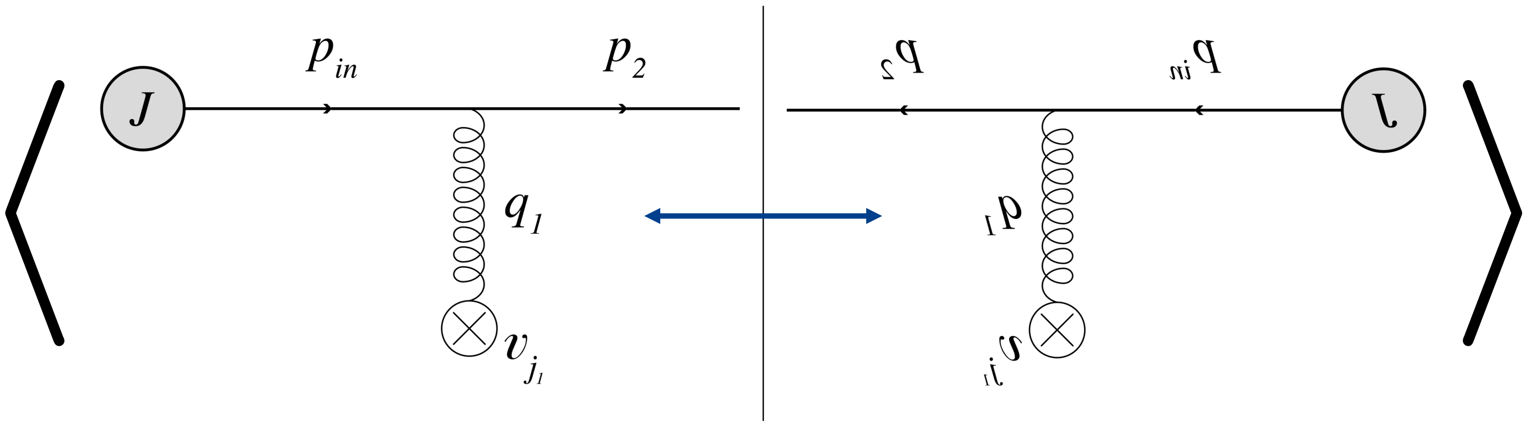
$$\langle t_i^a t_j^b \rangle = \mathcal{C}\delta_{ij}\delta^{ab}$$

color neutrality

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

source averaging

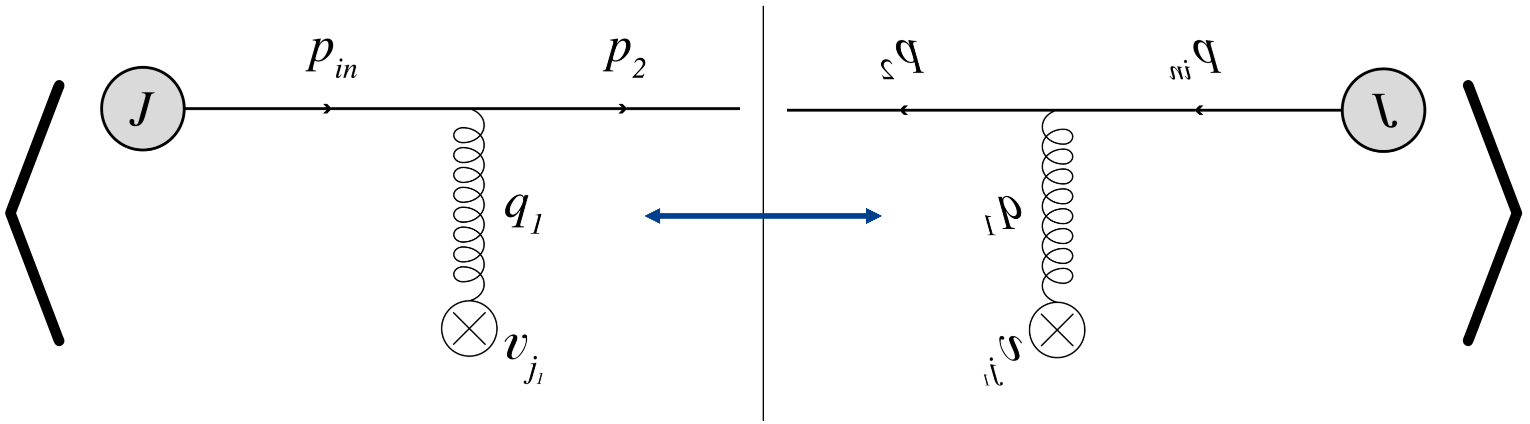
Medium averaging



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

$$\rho \sim T^3$$

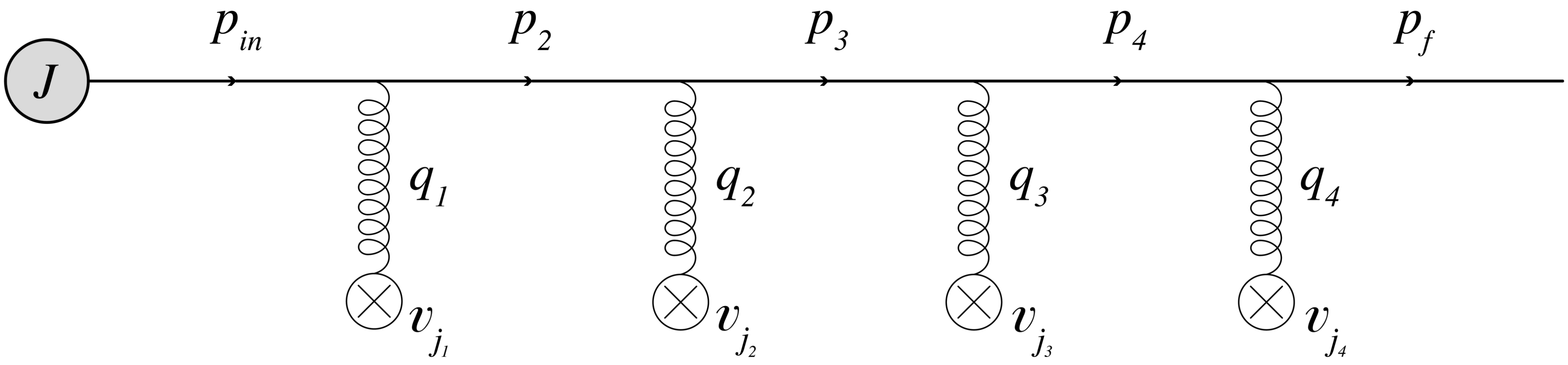
Medium averaging



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

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

Jet broadening



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

$$\mathbf{\Omega} = -\frac{\mathbf{p}-\mathbf{q}}{E} + \frac{\mathbf{q}}{E}\frac{(\mathbf{p}-\mathbf{q})^2-\mathbf{p}^2}{v(\mathbf{q}^2)}\frac{\partial v}{\partial \mathbf{q}^2}$$

Jet broadening

$$\frac{\partial}{\partial L}\mathcal{G}(\mathbf{p},L;\mathbf{p}_0,z_0) = i\left(\mathbf{u}\cdot\mathbf{p} - \frac{p_\perp^2}{2E}\right)\mathcal{G}(\mathbf{p},L;\mathbf{p}_0,z_0) + i\int\frac{d^2\mathbf{q}}{(2\pi)^2}\,[1+\mathbf{u}\cdot\mathbf{\Omega}(\mathbf{p},\mathbf{q})]\,v(q_\perp^2)\,\hat{\rho}^a(\mathbf{q},L)\,t^a\,\mathcal{G}(\mathbf{p}-\mathbf{q},L;\mathbf{p}_0,z_0)\,,$$

not a convolution anymore

$$\mathcal{G}(\mathbf{p},L;\mathbf{p}_0,z_0) = \mathcal{G}^{(0)}(\mathbf{p},L;\mathbf{p}_0,z_0) + \mathcal{G}^{(1)}(\mathbf{p},L;\mathbf{p}_0,z_0) + \mathcal{O}\left(\frac{\perp^2}{E^2}\right)$$

still can be solved analytically

Broadening probability

$$\frac{1}{d_{proj}} \left\langle \mathrm{Tr}\left[\mathcal{G}^{\dagger}(\boldsymbol{p}_0', 0; \boldsymbol{p}, L)\, \mathcal{G}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0) \right] \right\rangle \equiv (2\pi)^2 \delta^{(2)}(\boldsymbol{p}_0 - \boldsymbol{p}_0')\, \mathcal{P}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0)$$

$$\frac{\partial}{\partial L} \mathcal{P}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0) = -\int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\, \sigma(\boldsymbol{p}, \boldsymbol{q}; L)\, \mathcal{P}(\boldsymbol{p} - \boldsymbol{q}, L; \boldsymbol{p}_0, 0)$$

$$\mathcal{P}(\boldsymbol{p}, 0; \boldsymbol{p}_0, 0) = (2\pi)^2 \delta^{(2)}(\boldsymbol{p} - \boldsymbol{p}_0)$$

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Broadening probability

$$\mathcal{P}^{(0)}(\boldsymbol{r}, L; \boldsymbol{r}_0, 0) = e^{-\mathcal{V}(\boldsymbol{r})L}\delta^{(2)}(\boldsymbol{r}-\boldsymbol{r}_0)$$

$$\mathcal{V}(\boldsymbol{q}, z) \equiv -\mathcal{C}\,\rho(z)\left(\left|v(q_\perp^2)\right|^2 - \delta^{(2)}(\boldsymbol{q})\int d^2\boldsymbol{l}\,\left|v(l_\perp^2)\right|^2\right)$$

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Broadening probability

$$\mathcal{P}^{(1)}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0) = \int d^2\boldsymbol{r}\, e^{-i(\boldsymbol{p}-\boldsymbol{p}_0)\cdot\boldsymbol{r}} e^{-\mathcal{V}(\boldsymbol{r})L}\, \frac{u_\alpha}{E} \Big[2L\, \boldsymbol{p}_{0\beta} \Big(\mathcal{V}(\boldsymbol{r})\delta_{\alpha\beta} + \mathcal{V}_{\alpha\beta}(\boldsymbol{r})\Big) - iL\, \nabla_\beta \mathcal{V}_{\alpha\beta}(\boldsymbol{r}) + iL^2 \Big(\mathcal{V}(\boldsymbol{r})\delta_{\alpha\beta} + \mathcal{V}_{\alpha\beta}(\boldsymbol{r})\Big)\nabla_\beta \mathcal{V}(\boldsymbol{r})\Big]$$

$$\mathcal{V}_{\alpha\beta} = \mathcal{C}\,\rho \left[-\boldsymbol{q}_\alpha \boldsymbol{q}_\beta \frac{\partial v^2}{\partial q_\perp^2} - (2\pi)^2 \delta^{(2)}(\boldsymbol{q}) \frac{\delta_{\alpha\beta}}{2} \int \frac{d^2\boldsymbol{l}}{(2\pi)^2}\, v(l_\perp^2)^2\right]$$

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Jet broadening

$$E\frac{d\mathcal{N}}{d^2\boldsymbol{p}\,dE} = \int \frac{d^2\boldsymbol{p}_0}{(2\pi)^2}\,\mathcal{P}(\boldsymbol{p},L;\boldsymbol{p}_0,0)\left[1-\boldsymbol{u}\cdot(\boldsymbol{p}-\boldsymbol{p}_0)\frac{\partial}{\partial E}\right]E\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{p}_0\,dE}$$

- The odd moments are proportional to the transverse flow velocity, the even moments are unmodified;

- The initial and final distributions are not factorized anymore in coordinate space (due to the energy derivative);

Jet broadening

uniform matter

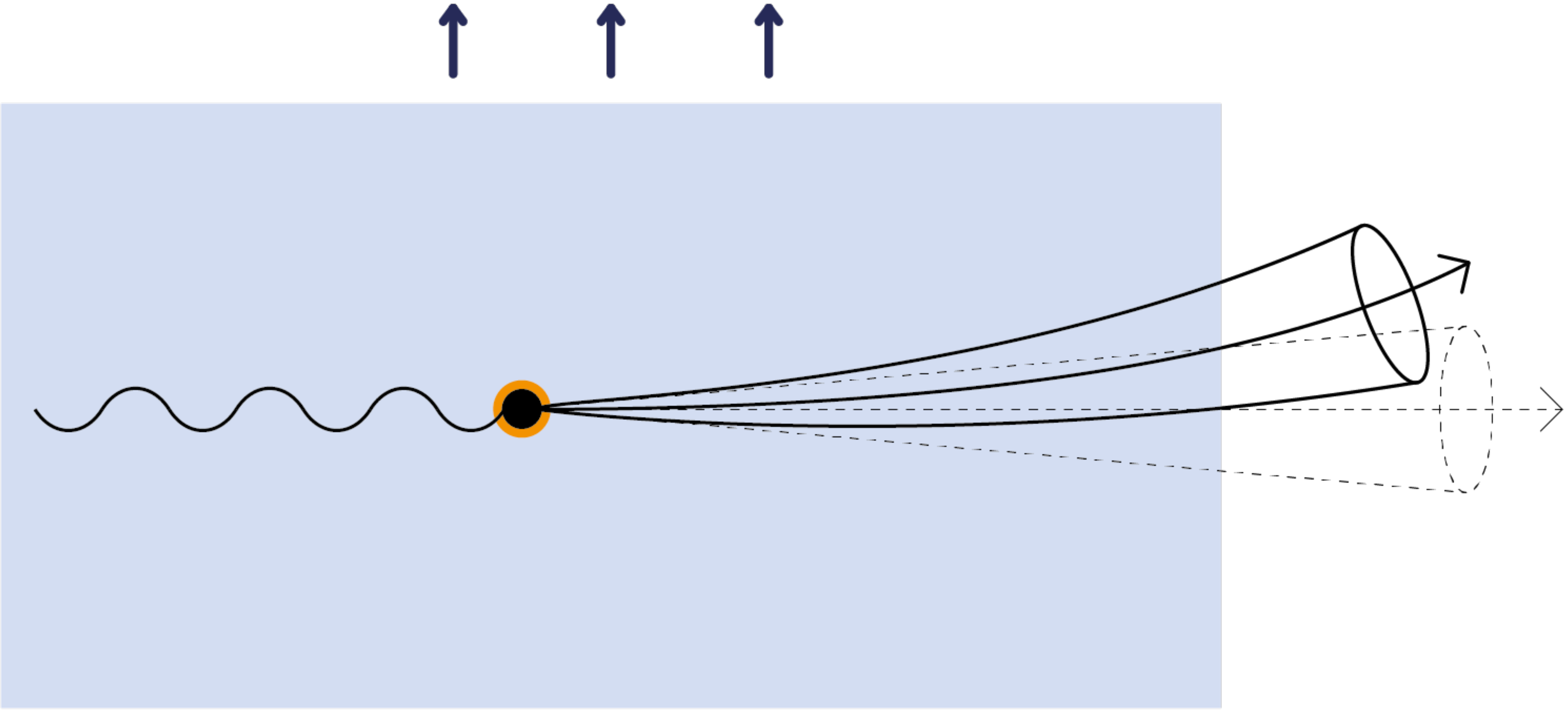
$$E\frac{d\mathcal{N}^{(0)}}{d^2\mathbf{p}_0 dE} = f(E)\delta^{(2)}(\mathbf{p}_0)$$

Eikonal approximation -- $E \to \infty$

$$\langle p_\perp^{2k}\boldsymbol{p}\rangle = \int \frac{d^2\boldsymbol{p}\, d^2\boldsymbol{r}}{(2\pi)^2}\, p_\perp^{2k}\boldsymbol{p}\, e^{-i\boldsymbol{p}\cdot\boldsymbol{r}} e^{-\mathcal{V}(\boldsymbol{r})L} = 0 + \mathcal{O}\left(\frac{\perp}{E}\right)$$

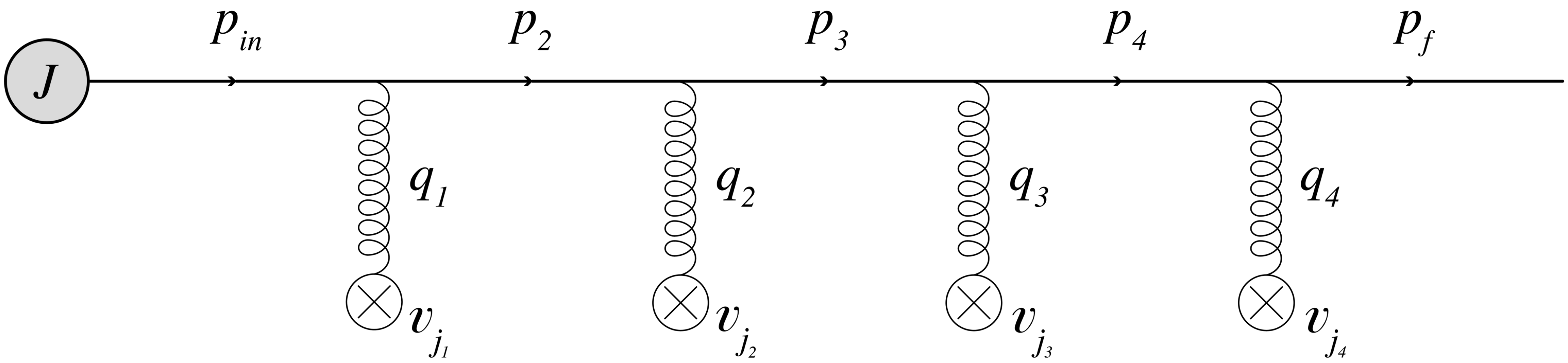
Opacity expansion -- $\chi \equiv \mathcal{C}\frac{g^4\rho}{4\pi\mu^2}L \ll 1$

$$\langle p_\perp^{2k}\boldsymbol{p}\rangle \simeq -\frac{\boldsymbol{u}}{2E}\mathcal{C}\rho L \int \frac{d^2\boldsymbol{p}}{(2\pi)^2}\, p_\perp^{2k+2}\left[E\frac{f'(E)}{f(E)}\, v(p_\perp)^2 + p_\perp^2\,\frac{\partial v^2}{\partial p_\perp^2}\right]$$



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

The propagator



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

Medium averaging

$$\left\langle \mathcal{P}\exp\left(-i\int_0^L d\tau\, t^a_{\text{proj}} v^a(\boldsymbol{r}(\tau),\tau)\right)\mathcal{P}\exp\left(i\int_0^L d\bar{\tau}\, t^b_{\text{proj}} v^b(\overline{\boldsymbol{r}}(\bar{\tau}),\bar{\tau})\right)\right\rangle$$
$$= \exp\left\{-\int_0^L d\tau\left[1+\frac{\boldsymbol{r}(\tau)+\overline{\boldsymbol{r}}(\tau)}{2}\cdot\hat{\boldsymbol{g}}\right]\mathcal{V}(\boldsymbol{r}(\tau)-\overline{\boldsymbol{r}}(\tau))\right\}$$

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

$$\langle G(\boldsymbol{x}_L,L;\boldsymbol{x}_0,0)G^\dagger(\overline{\boldsymbol{x}}_L,L;\overline{\boldsymbol{x}}_0,0)\rangle$$
$$= \int^{\boldsymbol{u}_L}\mathcal{D}\boldsymbol{u}\int^{\boldsymbol{w}_L}\mathcal{D}\boldsymbol{w}\,\exp\left\{\int_0^L d\tau\left[iE\,\dot{\boldsymbol{u}}\cdot\dot{\boldsymbol{w}}-(1+\boldsymbol{w}\cdot\hat{\boldsymbol{g}})\,\mathcal{V}(\boldsymbol{u}(\tau))\right]\right\}$$

Jet broadening

$$E\frac{d\mathcal{N}^{(0)}}{d^2\mathbf{p}_0 dE} = f(E)\delta^{(2)}(\mathbf{p}_0)$$

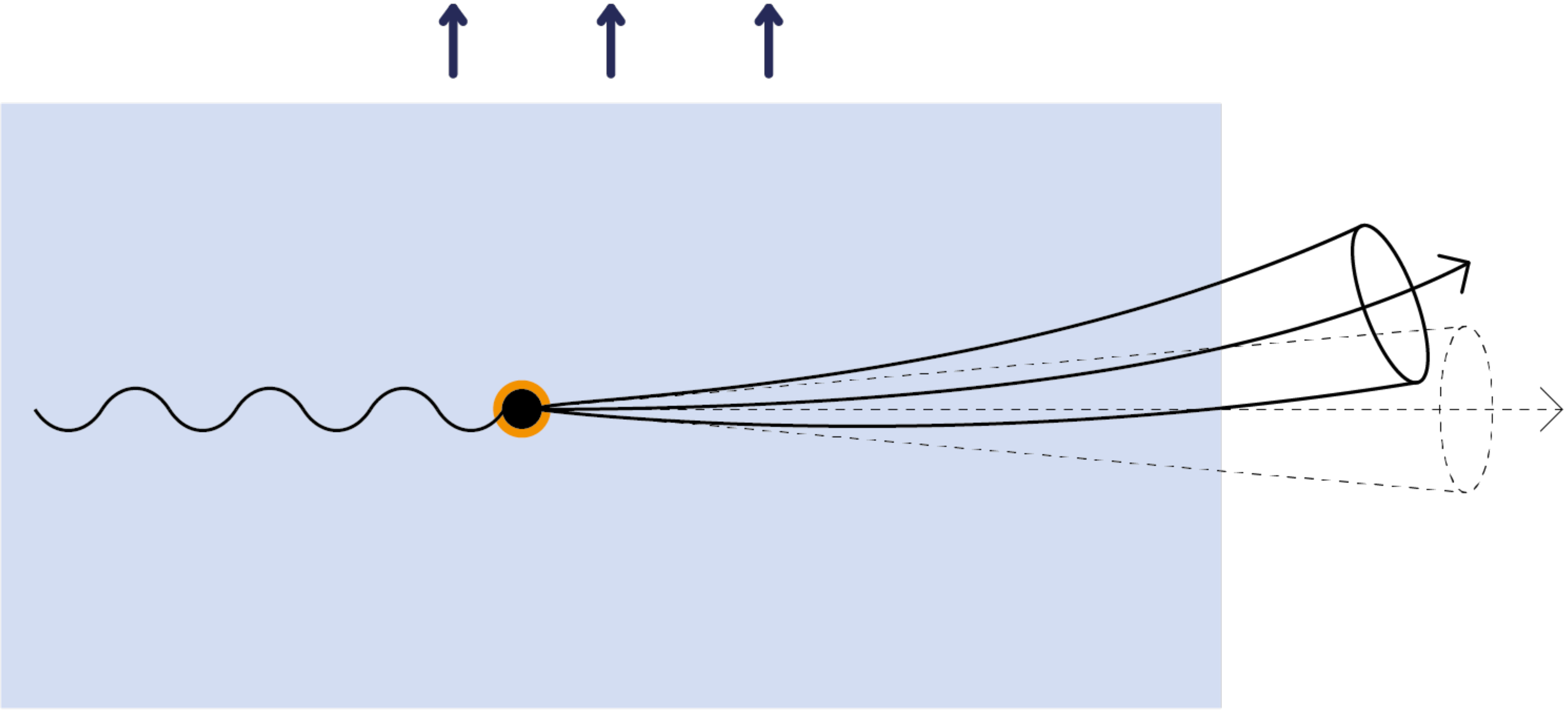
inhomogeneous matter

$$\frac{d\mathcal{N}}{d^2\boldsymbol{x}dE} \simeq \exp\{-\mathcal{V}(\boldsymbol{x})L\}\left\{\left[1-\frac{iL^3}{6E}\boldsymbol{\nabla}\mathcal{V}(\boldsymbol{x})\cdot\hat{\boldsymbol{g}}\,\mathcal{V}(\boldsymbol{x})\right]\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}+\frac{iL^2}{2E}\hat{\boldsymbol{g}}\,\mathcal{V}(\boldsymbol{x})\cdot\boldsymbol{\nabla}\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}\right\}$$

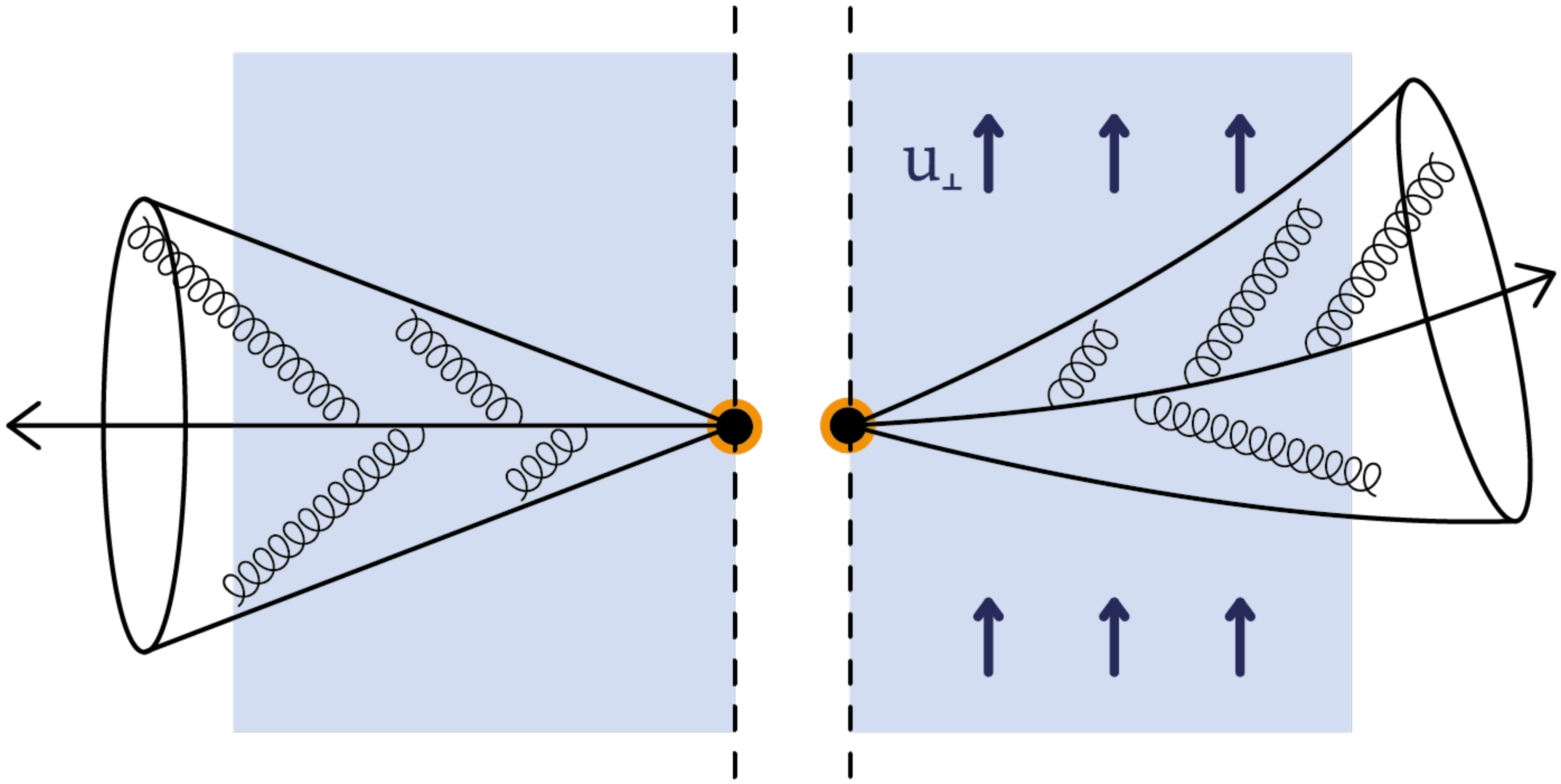
$$\hat{\boldsymbol{g}} \equiv \left(\boldsymbol{\nabla}\rho\frac{\delta}{\delta\rho}+\boldsymbol{\nabla}\mu^2\frac{\delta}{\delta\mu^2}\right)$$

$\rho \sim T^3$

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



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


$u_\perp$

Summary

- Jets do feel the transverse flow and anisotropy, and get bended;
- The transverse flow and anisotropy are expected to 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;
- The initial and final state effects are not factorized anymore;
- One may also expect similar evolution-induced effects for other probes of nuclear matter, e.g. quarkonium;