Ab Initio Coupling of Jets to Collective Flow in the Opacity Expansion Approach

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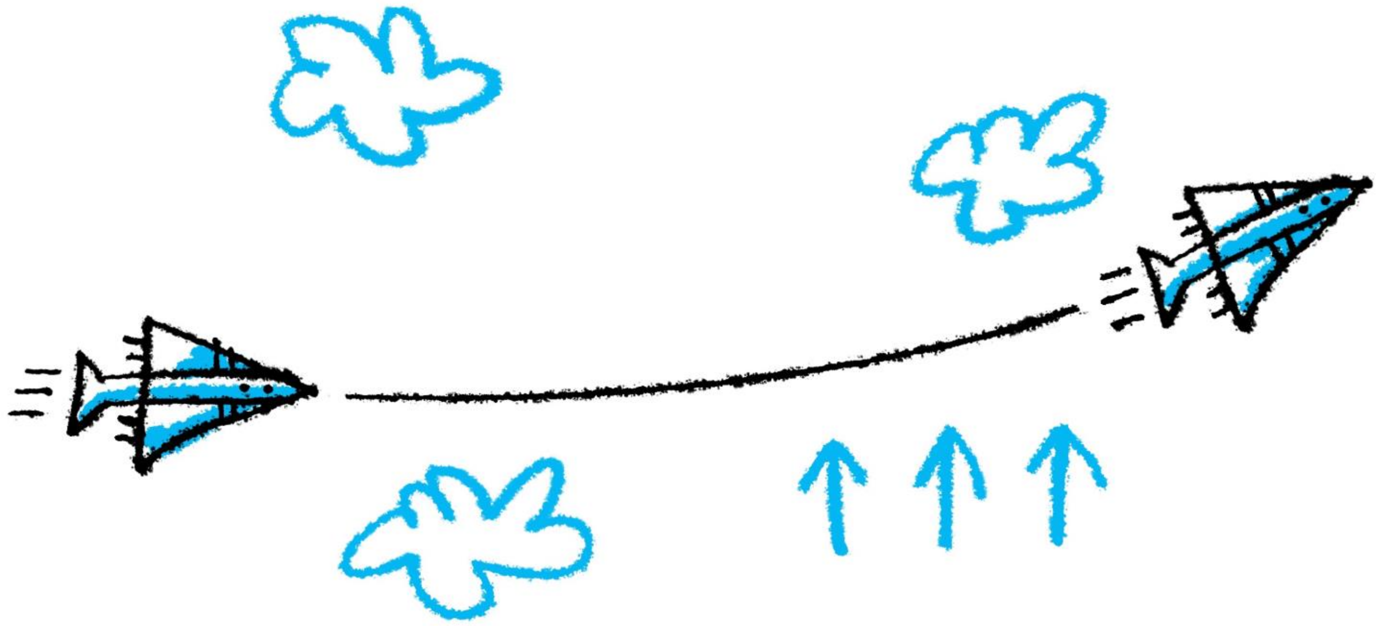
Jet Tomography

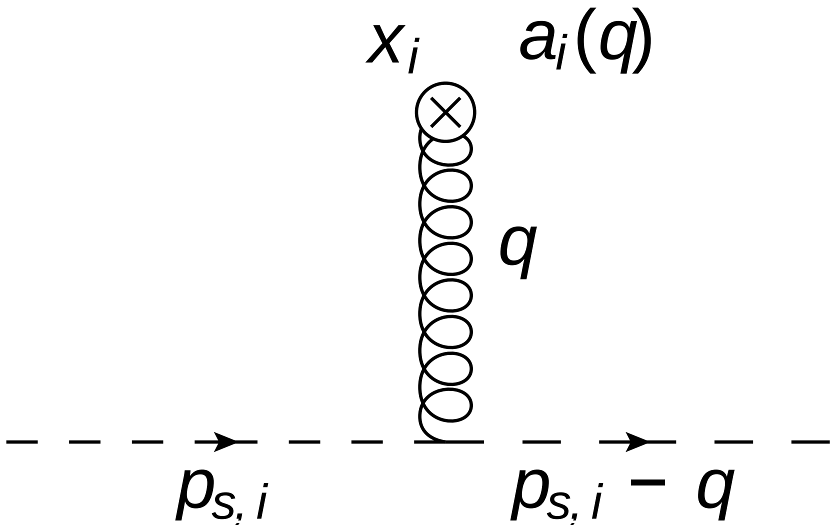
- Jets are main available probes of the matter in HIC;
- The hot nuclear matter in HIC undergoes multi-phase evolution and its details are hard to access through the soft sector. In turn, jets see the matter at multiple scales, and essentially X-ray it;
- However, most approaches to the jet-medium interaction are either empirical or based on multiple simplifying assumptions – static matter, no fluctuations, etc;
- In what follows I will highlight our recent progress on the medium motion effects in the QCD calculations for jet broadening and gluon emission;
- The developed formalism can be also applied to include orbital motion of nucleons and some of in-medium fluctuations (e.g. spatial inhomogeneities) in the DIS context;

Jets

Does a jet feel the flow?



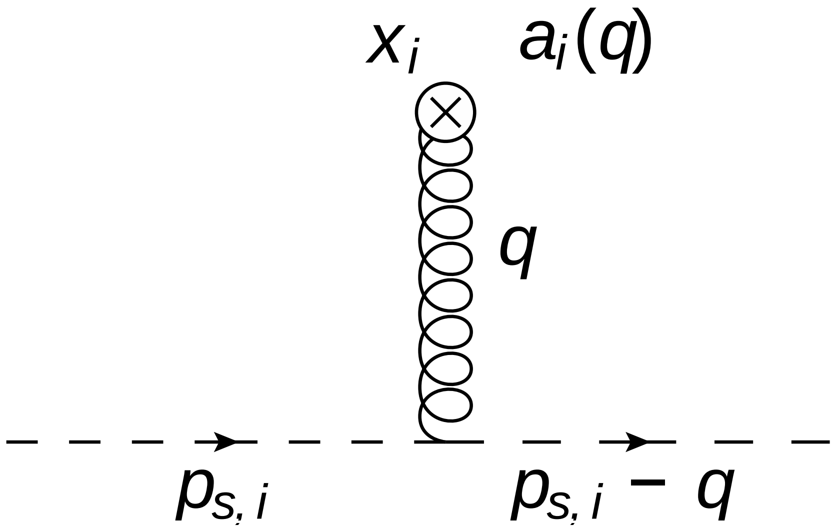
Color Potential



$$a_i^{\mu a}(q) = (ig\, t_i^a)\,(2p_{s\,i} - q)_\nu \left(\frac{-ig^{\mu\nu}}{q^2 - \mu^2 + i\epsilon}\right)\,(2\pi)\,\delta\Big((p_{s\,i} - q)^2 - M^2\Big)$$

$v(q^2)$ -- **the Gyulassy-Wang potential**

Color Potential



the four-vector of the fluid non-relativistic velocity

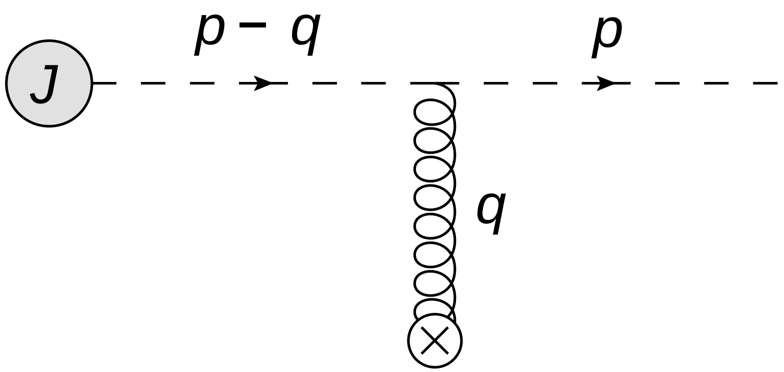
$$a_i^{\mu a}(q) = g\, t_i^a \left(\frac{u_i^\mu}{q^2 - \mu^2 + i\epsilon} \right) (2\pi)\, \delta\left(q^0 - \vec{u}_i \cdot \vec{q}\right)$$

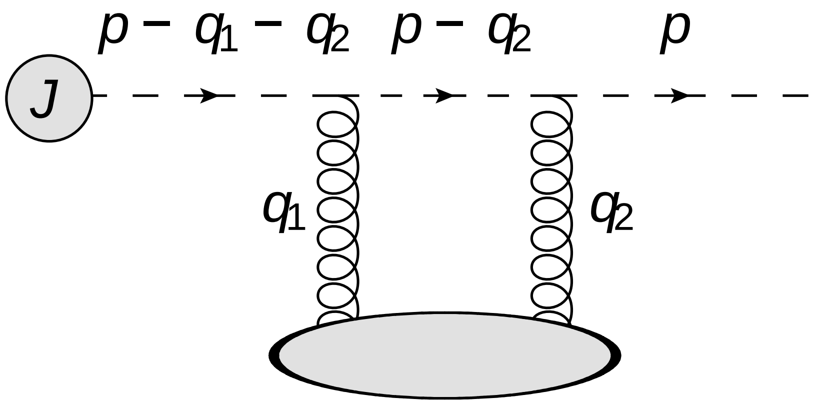
finite energy transfer!!!

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

color neutrality

Jet Broadening





the static case:

the 1st order in opacity

$$E\frac{dN^{(1)}}{d^3p} = \int dz\, d^2q_\perp\, \rho(z)\, \frac{d\sigma}{d^2q_\perp}\left[\left(E\frac{dN^{(0)}}{d^2(p-q)_\perp\, dE}\right) - \left(E\frac{dN^{(0)}}{d^2p_\perp\, dE}\right)\right]$$

elastic scattering cross section

Jet Broadening

with flow:

$$E\frac{dN^{(1)}}{d^3p} = \int dz\, d^2q_\perp\, \rho(z)\, \frac{d\sigma}{d^2q_\perp}\Bigg[\left(E\frac{dN^{(0)}}{d^2(p-q)_\perp\, dE}\right)\left(1+\vec{u}_\perp(z)\cdot\vec{\Gamma}(\vec{q}_\perp)\right)$$
$$-\left(E\frac{dN^{(0)}}{d^2p_\perp\, dE}\right)\left(1+\vec{u}_\perp(z)\cdot\vec{\Gamma}_{DB}(\vec{q}_\perp)\right)\Bigg] + \mathcal{O}\left(\partial_\perp\right)$$

$$\vec{\Gamma}(\vec{q}_\perp) = -2\frac{\vec{p}_\perp-\vec{q}_\perp}{(1-u_{i\,z})E} + \frac{2\vec{q}_\perp}{(1-u_{i\,z})E}\left(\frac{(p-q)_\perp^2-p_\perp^2}{v(q_\perp^2)}\right)\frac{\partial v}{\partial q_\perp^2}$$
$$-\frac{\vec{q}_\perp}{1-u_z}\left(\frac{1}{\bar{N}_0(E,\vec{p}_\perp-\vec{q}_\perp)}\frac{\partial \bar{N}_0}{\partial E}\right)$$

Jet Broadening

An illustration:

assuming a model source

$$E\frac{dN^{(0)}}{d^3p} \propto \delta^{(2)}(\vec{p}_\perp)$$

and ignoring z-dependence, we find

the distribution in energies

$$\langle \boldsymbol{p}_\perp (p_\perp^2)^k \rangle = -\frac{\boldsymbol{u}_\perp}{(1-u_z)}\frac{L}{2\lambda}(\mu^2)^{k+1}\left(-\frac{2}{E}\int_0^\infty d\xi \frac{\xi^{k+2}}{(1+\xi)^3} + \frac{1}{f(E)}\frac{\partial f}{\partial E}\int_0^\infty d\xi \frac{\xi^{k+1}}{(1+\xi)^2}\right)$$

$1/\rho\sigma_0$ **the mean free path**

while even moments are unmodified

A family of velocity-sensitive observables!

Jet Broadening

An illustration:

assuming a model source

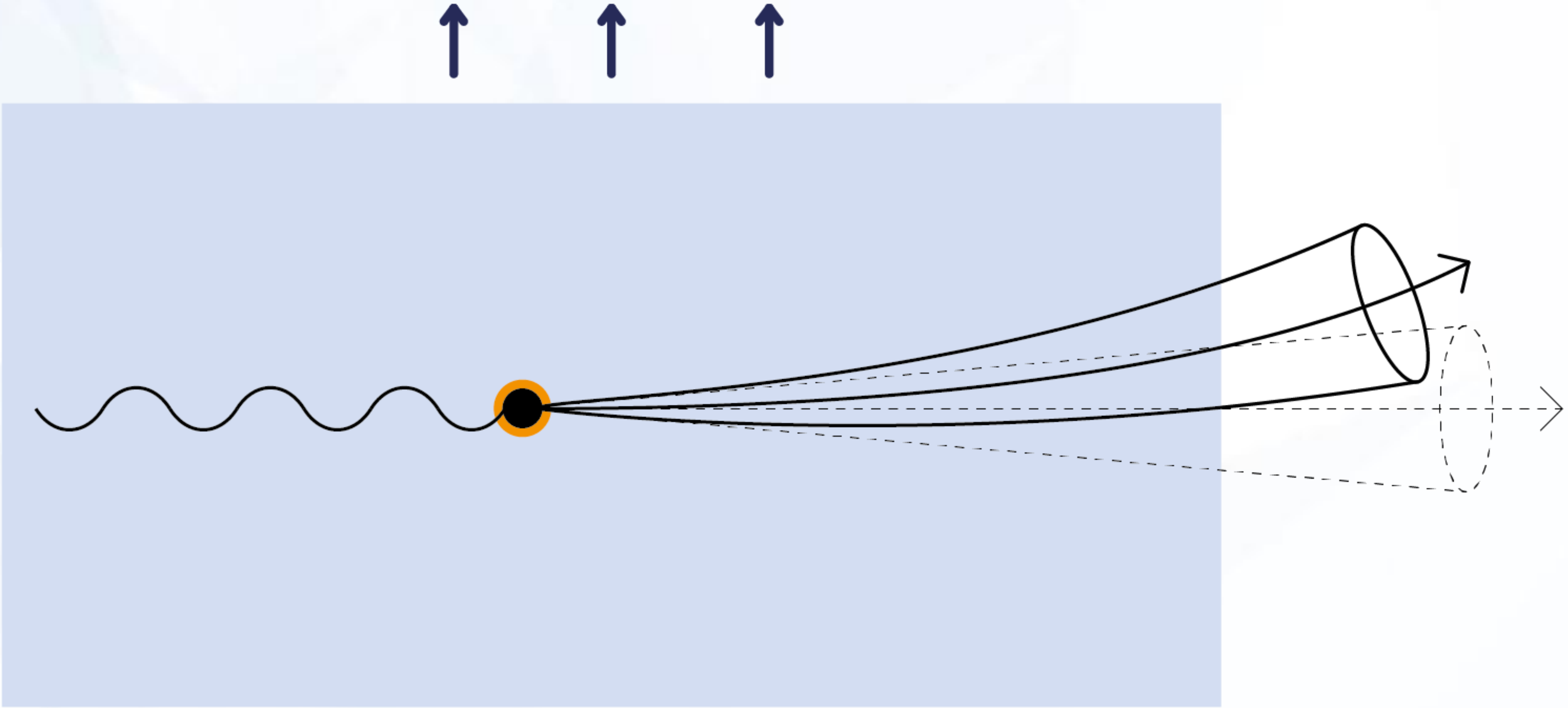
$$E\frac{dN^{(0)}}{d^3p} \propto E^{-4}\,\delta^{(2)}(\vec{p}_\perp)$$

and ignoring z-dependence, we find

$$\left\langle \frac{\vec{p}_\perp}{p_\perp^2} \right\rangle = \frac{5}{2}\frac{\vec{u}_\perp}{(1-u_z)}\frac{L}{\lambda}\frac{1}{E} \;, \quad \frac{\langle \vec{p}_\perp \rangle}{\mu^2} = 3\frac{\vec{u}_\perp}{(1-u_z)}\frac{L}{\lambda}\frac{1}{E}\ln\frac{E}{\mu}$$

while even moments are unmodified

A family of velocity-sensitive observables!



Jet Broadening

gradient expansion

$$E\frac{dN^{(0)}}{d^3p} = \frac{1}{2(2\pi)^3}|J(p)|^2 = \frac{f(E)}{2\pi w^2}\, e^{-\frac{p_\perp^2}{2w^2}}$$

$$\downarrow$$

$$\langle \vec{p}_\perp\, p_\perp^2 \rangle^{(linear)} \simeq \frac{L}{\lambda}\frac{L}{E} w^2 \mu^2 \frac{\vec{\nabla}_\perp \rho}{\rho} \ln\frac{E}{\mu}$$

the leading gradient correction at the first order in opacity

Summary

- We have constructed a generalization of the GLV approach which includes the medium motion effects. With this tool one can study general flow, temperature, and source density profiles in the context of HIC;

- It is shown that the odd moments of the jet momentum are modified by the medium motion, and the jet is bended by the flow and gradients;

- We have also derived the gluon emission spectrum in the case of uniformly flowing matter, which cannot be discussed in details in a short talk (see the paper);

- In the context of DIS our formalism can be used to study nucleon orbital motion and spatial inhomogeneities in the system (a relation to GPDs and TMDs?);