Imprints of jet-induced medium response on identical particle (HBT) correlations (a preliminary estimation)

Jet Modification and Hard-Soft Correlations (SoftJet 2024), University of Tokyo

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In collaboration with Zhong Yang, Xin-Nian Wang, De-Xing Zhu

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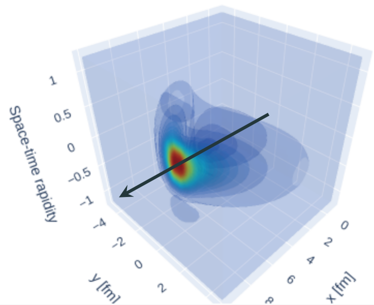
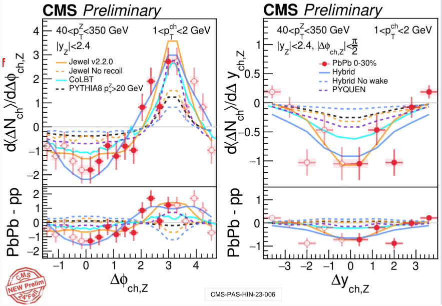
Jet-induced medium response



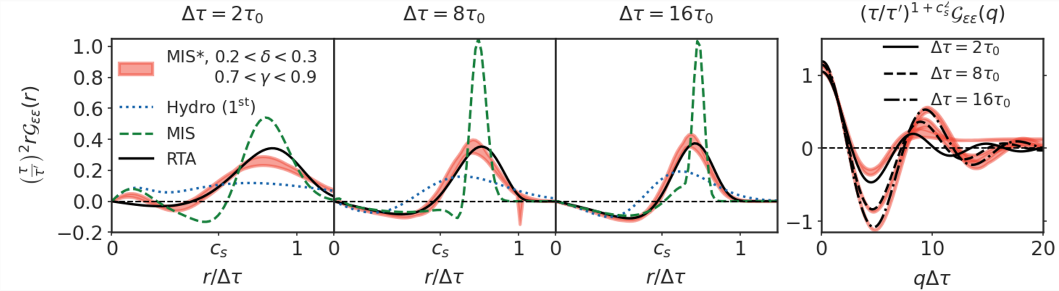


A demonstration using the linearized relaxation-time-approximation of the Boltzmann Eq.

First unambiguous evidence of diffusion wake from CMS! Compared to simulation in a realistic medium.

- Medium response: a natural consequence of jet quenching + medium dynamics.
- Will it tell something about medium dynamics? We only access momentum space.

Medium response in the spatial coordinates and response functions



[Weiyao Ke and Yi Yin PRL130(2023)212303]

- Jet excites QGP at "all" wave-length $\delta(x) \to f(k) = 1$. Small perturbations are characterized by linear response $\Leftrightarrow G^{\mu\nu}_{\alpha\beta} = \langle T^{\mu\nu}(t,x) T_{\alpha\beta}(t',x')\rangle$.
- Are the response at large gradient (k) described by quasi-particle or hydro modes (if so, what type of hydro)? Maybe jet-induced medium response can tell.

How are information encoded in one-particle angular distribution? (toy study)

Background: a Bjorken flow

Response: some small perturbation ($\delta \ll 1$) on top of that.
Study the impact on particle production at freeze out defined by $e(\tau, x, y, \eta_s) = e_f$.

$$\epsilon = \epsilon_0(\tau) + \delta e(\tau, x, y, \eta_s)$$

$$u^\mu = u_0^\mu + \delta u(\tau, x, y, \eta_s) = u_0^\mu + \frac{\delta g(\tau, x, y, \eta_s)}{\epsilon + P(\epsilon)}$$

$$\pi^{\mu\nu} = \pi_0^{\mu\nu} + \delta \pi^{\mu\nu}(\tau, x, y, \eta_s)$$

Linearize the Cooper-Frye formula:

$$\underbrace{\frac{d\delta N}{m_T dm_T dy d\phi}}_{\text{Induced production}} = \underbrace{\frac{1}{(2\pi)^3}\int_\Sigma p \cdot d^3\sigma(x)\delta f(x,p)}_{\text{Perturbed distribution}} + \underbrace{\frac{1}{(2\pi)^3}\int_\Sigma p \cdot d^3\delta\sigma(x) f(x,p)}_{\text{Perturbed hypersurface}} + \mathcal{O}(\delta^2)$$

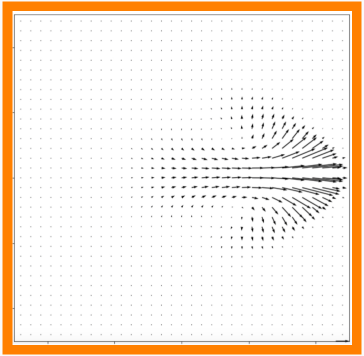
How are information encoded in one-particle angular distribution? (toy study)

$$\frac{d\delta N}{dm_T dy d\phi} = \frac{p^\tau \tau_{\mathrm{frz},0} f_{eq}(\tilde{p}^\tau)}{(2\pi)^3} \left(N_0 + \tilde{p}_\mu N_1^\mu + \tilde{p}_\mu \tilde{p}_\nu N_2^{\mu\nu} + \tilde{p}_\mu \tilde{p}_\nu \tilde{p}_\rho N_3^{\mu\nu\rho} \right) + \mathcal{O}\left(\delta^2\right), \quad \tilde{p}^\mu = \frac{p^\mu}{T}$$

The possible angular structure is quite restricted in this case (No background radial flow, with flow it will be more interesting). Perturbation encoded in the coefficients.

$$\begin{aligned}
N_0 &= \int dx dy d\eta_s \left[c_s^2 \tilde{p}^\tau \delta\tilde{\epsilon} + \delta\tilde{\epsilon} - v^\eta \partial_\eta \delta\tilde{\epsilon} - \tau_f v_\perp \cdot \partial_\perp \delta\tilde{\epsilon} \right], \\
N_1^\mu &= \int dx dy d\eta_s \left[-\delta\tilde{g}^\mu - \tilde{p}^\tau \tilde{\pi}^{\mu\nu} \delta\tilde{g}_\nu \right], \\
N_2^{\mu\nu} &= \int dx dy d\eta_s \left[\frac{1}{2} \tilde{\pi}^{\mu\nu} \left[c_s^2 \tilde{p}^\tau \delta\tilde{\epsilon} + \delta\tilde{\epsilon} - v^\eta \partial_\eta \delta\tilde{\epsilon} - \tau_f v_\perp \cdot \partial_\perp \delta\tilde{\epsilon} \right] + \frac{1}{2} \Delta^{\mu\nu}_{\alpha\beta} \delta\tilde{\pi}^{\alpha\beta} \right], \\
N_3^{\mu\nu\rho} &= \int dx dy d\eta_s \frac{1}{2} \tilde{\pi}^{\mu\nu} (-\delta\tilde{g}^\rho) \quad \text{where} \quad \delta\tilde{\epsilon} = \frac{\delta\epsilon}{\epsilon + P}, \quad \delta\tilde{g}^\mu = \frac{\delta g^\mu}{\epsilon + P} = \delta u^\mu.
\end{aligned}$$

How are information encoded in one-particle angular distribution? (toy study)

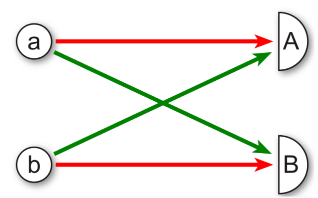


$$\frac{\frac{d\delta N}{dm_T dy d\phi}}{\frac{dN_0}{dm_T dy d\phi}} = 1 + \tilde{p}_\mu \frac{N_1^\mu}{N_0} + \tilde{p}_\mu \tilde{p}_\nu \frac{N_2^{\mu\nu}}{N_0} + \tilde{p}_\mu \tilde{p}_\nu \tilde{p}_\rho \frac{N_3^{\mu\nu\rho}}{N_0}$$

$$= 1 + \sum_{m=0,\pm1} C_{1m}\left(\tilde{p}^\tau\right) Y_1^m(\Omega) + \sum_{m=0,\pm1,\pm2} C_{2m}\left(\tilde{p}^\tau\right) Y_2^m(\Omega) + \sum_{m=0,\pm1,\pm2,\pm3} C_{3m}\left(\tilde{p}^\tau\right) Y_3^m(\Omega) + \mathcal{O}(\delta^2)$$

- Is this toy example, it seems that interested stuff are being integrated out C_{lm}, with conservation effect dominating lowest order of angular structure.
- **Can we access spatial perturbation $\delta\epsilon(\tau, x, y, \eta_s)$ more directly?**

Hanbury-Brown–Twiss (HBT) correlation and spatial information



- Identical bosons are symmetrized

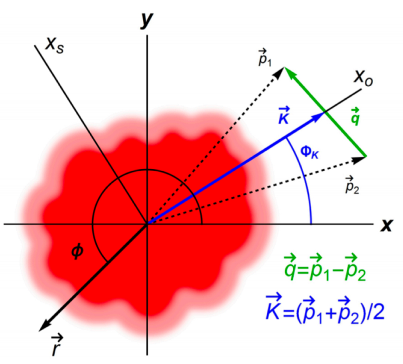
$$\langle x_1, x_2 | a^\dagger_{p_1} a^\dagger_{p_2} | 0 \rangle = \frac{e^{ip_1 \cdot x_1 + ip_2 \cdot x_2} + e^{ip_2 \cdot x_1 + ip_1 \cdot x_2}}{\sqrt{2}}$$

- The intensity to observe one or two identical bosons from a system specified by a density matrix $\hat{\rho}$

$$n(p) = \mathrm{Tr}\left\{\hat{\rho}\hat{n}_p\right\} = \mathrm{Tr}\left\{\hat{\rho}\hat{a}^\dagger_{p_1}\hat{a}_{p_1}\right\}$$

$$n(p_1, p_2) = \mathrm{Tr}\left\{\hat{\rho}\hat{n}_{p_1}\hat{n}_{p_2}\right\} = \mathrm{Tr}\left\{\hat{\rho}\hat{a}^\dagger_{p_1}\hat{a}_{p_1}\hat{a}^\dagger_{p_2}\hat{a}_{p_2}\right\}$$

Earlier focus of HBT measurements



$$q^\mu = p_1^\mu - p_2^\mu, \quad K^\mu = (K_1^\mu + K_2^\mu)/2,$$

$$C\left(\vec{q},\vec{K}\right) = \frac{N(p_1,p_2)}{N(p_1)N(p_2)} \approx 1 + \frac{|S(q,K)|^2}{|S(0,K)|^2}$$

$$S(q,K) = \int d^4x F(x,K) e^{iqx}$$

$$= \underbrace{\int_\Sigma K\cdot d^3\sigma f(x,K)e^{iqx}}_{\text{Production on surface}} \underbrace{+\cdots}_{\text{decays, etc}}$$

- $C(q,K)$ contains power spectrum of a Fourier transform on the freeze out surface.

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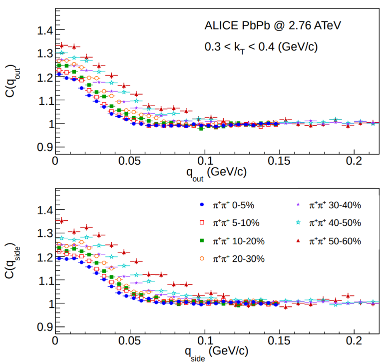

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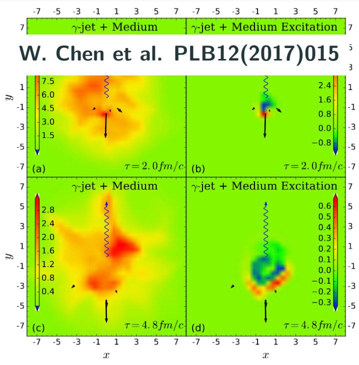
- $C(q, K)$ contains power spectrum of a Fourier transform on the freeze out surface.
- Larger-$q \Leftrightarrow$ finer structures on hypersurface. Study fireball size and inhomogenity.

With a jet passing through, what may change?



W. Chen et al. PLB12(2017)015

$$S'(q,K) = \underbrace{\int_\Sigma K\cdot d^3\sigma f'(x,K)e^{iqx}}_{\textbf{A}:\text{“Production on \textbf{perturbed} surface”}}$$

$$+\ \textbf{B:}\ \text{Production from decays}$$

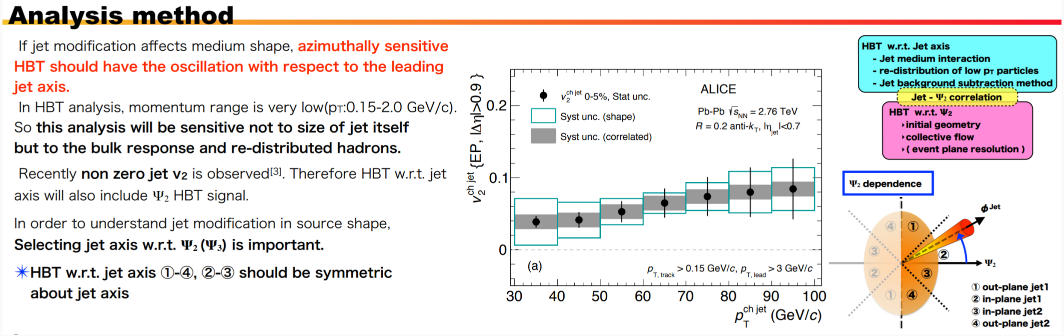
$$+\ \textbf{C:}\ \text{Fragmentations from jet}$$

$$C'\left(\vec{q},\vec{K}\right) \approx 1 + \frac{|S'(q,K)|^2}{|S'(0,K)|^2} \supset |A|^2 + |B|^2 + |C|^2 + 2\mathfrak{Re}(A^*B)\cdots$$

- Tuning q, we scan perturbation with $\lambda \sim 1/q$ on the hypersurface.
- Compare $C'(q,K)$ in hard-triggered events and $C(q,K)$ in un-triggered events.
- Or, to reduce trigger biases, compare $C'(q,K)$ in different directions of $\vec{K}$.

An interesting poster from QM2015 in Japan

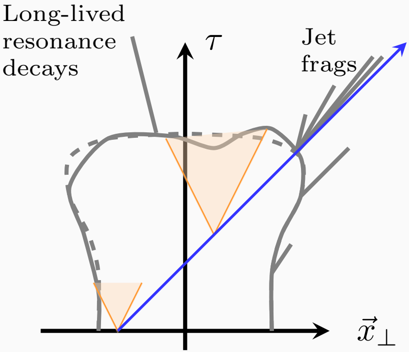
Poster by Naoto Tanaka, University of Tsukuba



Not sure if there were any experimental tries following it, or what difficulty they found.

Now, we have (partly) the tools to do theoretical estimations.

Available tools

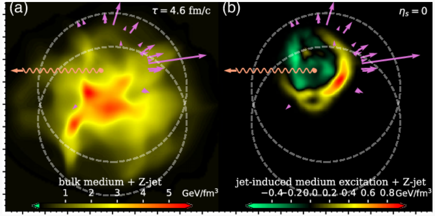


- *A*. Hadrons produced on the bulk hypersurface.
- $B. + C.$ Resonance decay, jet fragmentation.

We have three types of two-particles correlations

- $|A|^2$ Surface-surface correlation, can be treated with Cooper-Frye prescription (✓).
- $|B + C|^2$ Jet-jet (like) correlation. Pythia Lund string has an implementation in the vacuum.
- $\mathfrak{Re}(2A^*(B + C))$ Surface-jet corr., complicate.

Simulation framework: LBT/CoLBT



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T. Luo et al. PRC109(2024)034919

[W. Chen et al. PLB12(2017)015]

$$\partial_\mu T^{\mu\nu} = J^\nu, \quad D_\tau \pi^{\mu\nu} = \cdots$$

$$J^\nu = -\frac{\partial}{\partial t} \int f_{\mathrm{hard}}(t, x, p) p^\nu \Theta(p \cdot u > E_c) \frac{d^3 p}{(2\pi)^3}$$

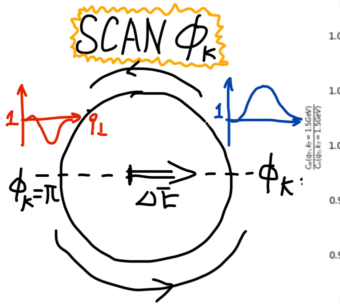
$$(\partial_t + v \cdot \nabla_x) f_{\mathrm{hard}}(t, x, p) = \mathcal{C}_{2\leftrightarrow 2}[f_{\mathrm{hard}}] + \mathcal{R}^{\mathrm{eff}}_{1\to 2}[f_{\mathrm{hard}}]$$

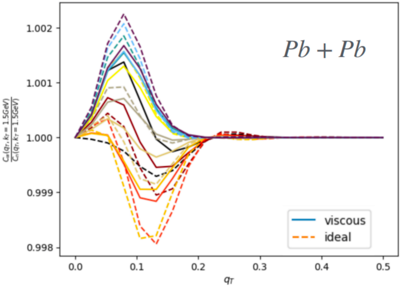
Estimate surface-surface HBT correlation from CoLBT

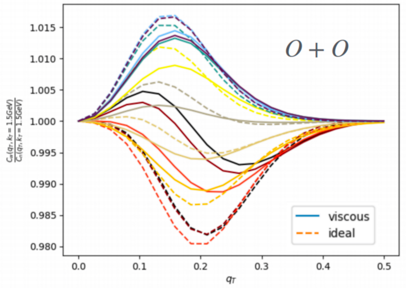
- CoLBT simulation set up (Z. Yang): controlled deposition of energy momentum along a trajectory $dp^\mu/dt \propto \delta(\eta_s)\delta(x-t)\delta(y)[1,1,0,0]$.
- For simplicity, we first neglect viscous correction to the Bose-Einstein distribution function f_{BE} at freeze out.
- Consider collinear limit of the pair $|K| \gg |q|$, and focus on the region where $q^\mu = (0, q_x, q_y, 0)$ and $\vec{K}_\perp \perp \vec{q}_\perp$, then

$$S_{\mathrm{surface}}(q,K) = \frac{g}{(2\pi)^2} \sum_{t_f, \vec{x}_f} K^\mu \sigma_\mu(t_f, \vec{x}_f) f_{\mathrm{BE}}\left(\frac{K \cdot u_f}{T_{\mathrm{frz}}}\right) J_0\left(q_T |\vec{x}_f - \vec{v}_K t_f|\right)$$

Surface-surface contribution. A single event







$$R(q,K) = \frac{C_{\text{with jet}}(q,K)}{C_{\text{no jet}}(q,K)}$$

$\pi^+\pi^+, \quad K = 1.5\text{GeV}.$

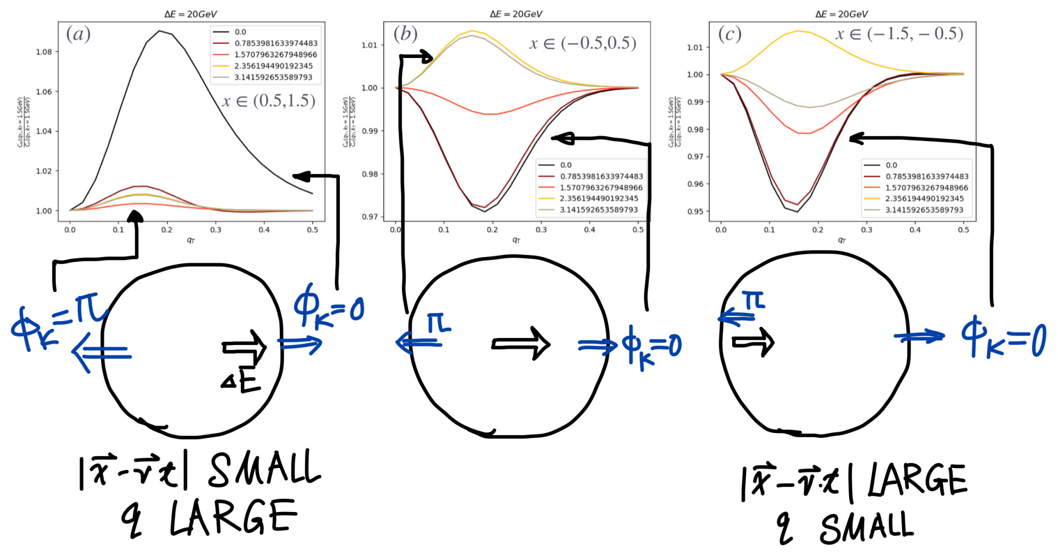
- Central Pb+Pb and O+O at LHC.
- Dashed: ideal hydro. Solid: viscous hydro.
- Colors: rotating $\vec{K}$ from 0 to 2π around jet.

How to understand the signal?

$$
\begin{aligned}
S(q,K) &= S_{bg} + S_{\text{pert}} \\
&\propto \sum_{t_f,\vec{x_f}} K^{\mu}\sigma_{\mu}(t_f,\vec{x_f}) f_{BE}\left(\frac{K\cdot u}{T_{\text{frz}}}\right) J_0\left(q_T\,|\vec{x_f}-\vec{v}_K t_f|\right) \\
&+ \sum_{t_f,\vec{x_f}} K^{\mu}\sigma_{\mu}(t_f,\vec{x_f}) f'_{BE}\frac{K\cdot\delta u}{T_{\text{frz}}} J_0\left(q_T\,|\vec{x_f}-\vec{v}_K t_f|\right) \\
&+ \sum_{t_f,\vec{x_f}} K^{\mu}\delta\sigma_{\mu}(t_f,\vec{x_f}) f_{BE} J_0\left(q_T\,|\vec{x_f}-\vec{v}_K t_f|\right)
\end{aligned}
$$

- What determines the sign of correction. K parallel/anti-parallel to flow or freeze-out element corrections.
- What tells the q_T location of the peak. Inversely related to $|x - vt|$, whether the jet's trace on the surface is short or long.

How to understand the signal?

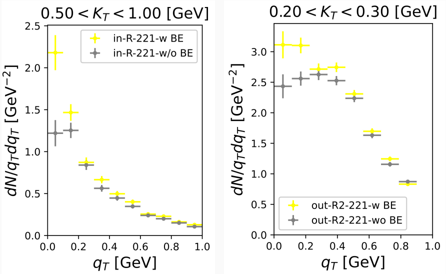


Current problems and possible solutions

Problem 1: some part of the signal cancels when averaging over jet-production vertex.

- One can try selection with Z-jet event, event engineering, etc.
- Try the back-to-back limit (instead of collinear limit): $K^0 \neq 0, \vec{K} = 0$.
- Try three-particle correlation to see if that breaks the symmetry.

Problem 2: how to consistently estimate jet-jet and jet-surface correlation.



- Pythia8 has a implementation of Bose-Einstein correlation in Lund-string hadronization (Left).
- Need to combine it with space-time information in medium-modified jet shower.

Simulations from D.-X. Zhu

Summary

- Is it possible to use the jet-induced medium response phenomena to study the nature of QGP response at large gradient?
- It would be helpful if we have more direct access to the spatial perturbation. HBT correlation may be useful.
- Preliminary studies using CoLBT reveals interesting structure in surface-surface HBT: interplay of direction of flow, jet, and the HBT pair.
- To do: think about an observable/trigger condition to preserve a large signal.
- To do: estimate jet-jet and jet-surface HBT correlations.