HBT correlation in HIC with a hard process (preliminary)

Workshop on Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics, Wuhan, China

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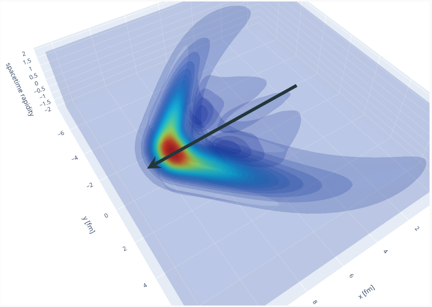
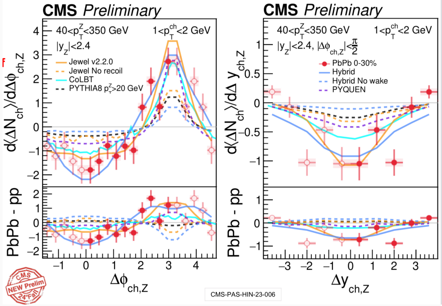
Medium response to the passage of a parton (jet, heavy quark, etc)



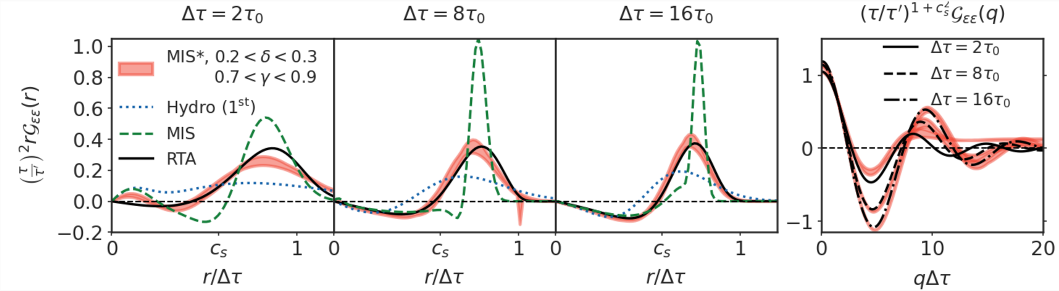
A demonstration using linearized MIS-type hydrodynamics



First unambiguous evidence of diffusion wake at HP2024! Compared to simulations.

- Medium response: a natural consequence of jet quenching + medium dynamics.
- Will it tell something about the medium dynamics?

Medium response in the spatial coordinates



[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 functions** $\Leftrightarrow G^{\mu\nu}_{\alpha\beta} = \langle T^{\mu\nu}(t,x)T_{\alpha\beta}(t',x')\rangle$.
- Kineitc v.s. hydro responses give fairly different spatial strucuters.

  However, we can only access momentum space, e.g., single-hadron spectra.

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

Background is a Bjorken flow. **Response** creates some small perturbations ($\delta \ll 1$)

$$\epsilon = \epsilon_0(\tau) + \delta e(\tau, x, y, \eta_s)$$
$$u^\mu = u_0^\mu + \delta u(\tau, x, y, \eta_s)$$
$$\pi^{\mu\nu} = \pi_0^{\mu\nu} + \delta\pi^{\mu\nu}(\tau, x, y, \eta_s)$$

Study the impact on particle production at freeze out defined by $e(\tau, x, y, \eta_s) = e_f$.

Linearize the Cooper-Frye formula:

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

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

The possible angular structure is quite restricted.

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

All information of perturbations are encode in the **spatially-integrated** coefficients N.

$$N_0 = \int dxdyd\eta_s \left[c_s^2 \tilde{p}^\tau \delta\tilde{\epsilon} + \delta\tilde{\epsilon} - v^\eta \partial_\eta \delta\tilde{\epsilon} - \tau_f v_\perp \cdot \partial_\perp \delta\tilde{\epsilon}\right],$$

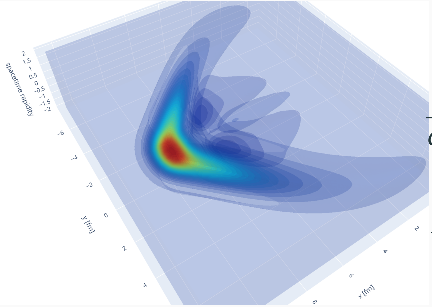
$$N_1^\mu = \int dxdyd\eta_s \left[-\delta\tilde{g}^\mu - \tilde{p}^\tau \tilde{\pi}^{\mu\nu} \delta\tilde{g}_\nu\right],$$

$$N_2^{\mu\nu} = \int dxdyd\eta_s \left[\frac{1}{2}\tilde{\pi}^{\mu\nu}\left[c_s^2 \tilde{p}^\tau \delta\tilde{\epsilon} + \delta\tilde{\epsilon} - v^\eta \partial_\eta \delta\tilde{\epsilon} - \tau_f v_\perp \cdot \partial_\perp \delta\tilde{\epsilon}\right] + \frac{1}{2}\Delta^{\mu\nu}_{\alpha\beta}\delta\tilde{\pi}^{\alpha\beta}\right],$$

$$N_3^{\mu\nu\rho} = \int dxdyd\eta_s \frac{1}{2}\tilde{\pi}^{\mu\nu}(-\delta\tilde{g}^\rho) \quad \text{where} \quad \delta\tilde{\epsilon} = \frac{\delta\epsilon}{\epsilon + P}, \quad \delta\tilde{g}^\mu = \frac{\delta g^\mu}{\epsilon + P} = \delta u^\mu.$$

No background radial flow, it will be more interesting with radial flow.

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



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

$$= C_{00}\left(\tilde{p}^\tau\right) + C_{1m}\left(\tilde{p}^\tau\right) Y_1^m(\Omega)$$

$$+ C_{2m}\left(\tilde{p}^\tau\right) Y_2^m(\Omega) + C_{3m}\left(\tilde{p}^\tau\right) Y_3^m(\Omega) + \mathcal{O}(\delta^2)$$

- In this toy example, it seems that interested stuff are being integrated out. Energy-momenutm conservation dominates lowest order of the angular structure.
- So how can we access the spatial information in $\delta\epsilon(\tau, x, y, \eta_s)$?

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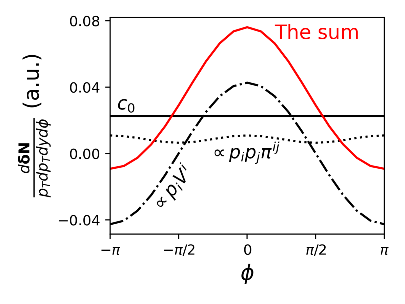

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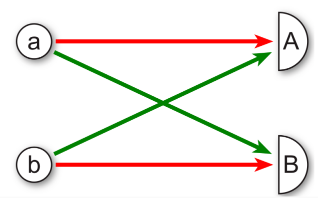
Hanbury-Brown–Twiss (HBT) correlation and spatial information



- Identical bosons are symmetrized

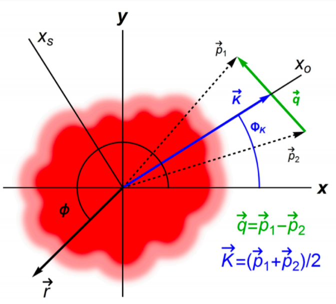
$$\langle x_1, x_2 | a^\dagger_{p_1} a^\dagger_{p_2} | 0 \rangle = \frac{e^{ip_1\cdot x_1 + ip_2 \cdot x_2} + e^{ip_2\cdot x_1 + ip_1 \cdot x_2}}{\sqrt{2}}$$

- 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



[C. Plumberg, U. Heinz PRC98(2018)034910]

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

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

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

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

- The two-particle correlation function $C(q,K)$ contains power spectrum of the Fourier transformed freeze-out surface.

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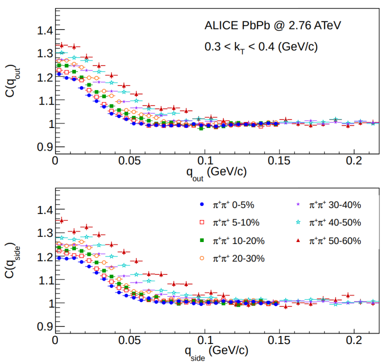

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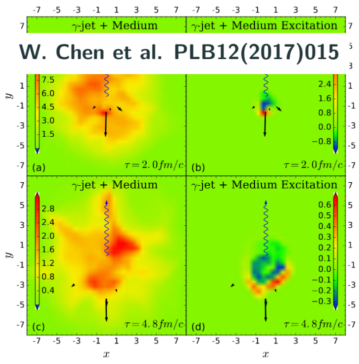
- The two-particle correlation function $C(q,K)$ contains power spectrum of the Fourier transformed freeze-out surface.
- Larger-q $\Leftrightarrow$ finer structures on hypersurface. Study fireball size and inhomogenity.

With a jet passing through, what may change?



$$S'(q,K) = \underbrace{\int_\Sigma K\cdot d^3\sigma f'(x,K)e^{iqx}}$$

A: "Production on **perturbed** surface"

$+$ **B:** Production from decays

$+$ **C:** 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 vs $C(q,K)$ in events w/o hard trigger.
- 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

Analysis method

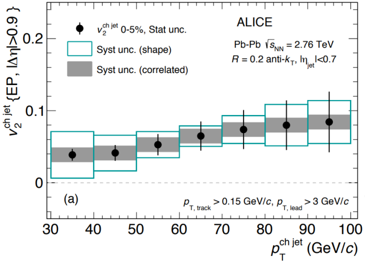
If jet modification affects medium shape, **azimuthally sensitive HBT should have the oscillation with respect to the leading jet axis.**

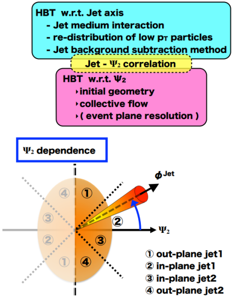
In HBT analysis, momentum range is very low(p_T:0.15-2.0 GeV/c). So **this analysis will be sensitive not to size of jet itself but to the bulk response and re-distributed hadrons.**

Recently **non zero jet v_2** is observed[3]. Therefore HBT w.r.t. jet axis will also include Ψ_2 HBT signal.

In order to understand jet modification in source shape, **Selecting jet axis w.r.t. Ψ_2 (Ψ_3) is important.**

✳**HBT w.r.t. jet axis ①-④, ②-③ should be symmetric about jet axis**

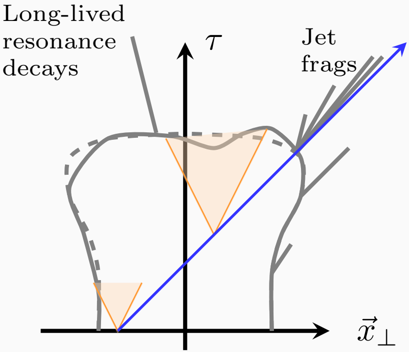




Not sure if this was pursued, and what difficulty was found.

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

Status of the theoretical tools

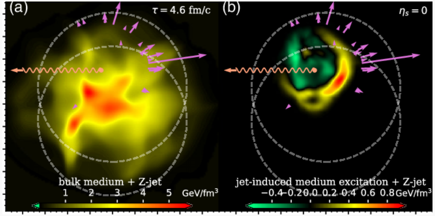


- A. Hadrons produced on the bulk hypersurface.
- $B. + C$. Resonance decay, jet fragmentation.

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, and $\mathfrak{Re}(2A^*(B + C))$ Surface-jet correlation.
  $\Rightarrow$ Maybe can generalize treatments of resonance decay in [Plumberg, Heinz PRC98(2018)034910].

Simulation framework: LBT/CoLBT



W. Chen et al. PRL127(2022)082301,
Y. He et al. Phys. Rev. C 91, 054908,
S. Cao el al. PRC94(2016)014909,
T. Luo et al. PRC109(2024)034919

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

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

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

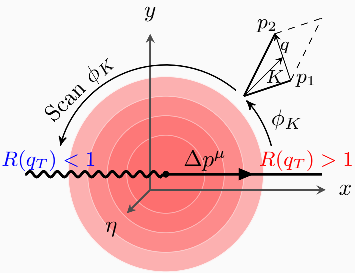
$$(\partial_t + v \cdot \nabla_x) f_{\mathrm{hard}}(t, x, p) = \mathcal{C}_{2\leftrightarrow 2}[f_{\mathrm{hard}}] + \mathcal{R}^{\mathrm{eff}}_{1\to 2}[f_{\mathrm{hard}}]$$

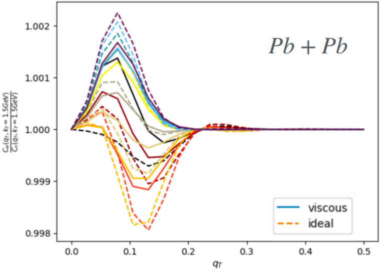
Estimate surface-surface HBT correlation from CoLBT

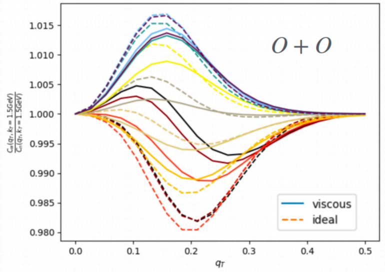
- CoLBT simulation set up (Z. Yang): controlled deposition of energy momentum along a trajectory $dp^\mu/dt \propto \delta(\eta_s)\delta(x-t)\delta(y)[1,1,0,0]$.
- For simplicity, we first neglect viscous correction to the Bose-Einstein distribution function f_{BE} at freeze out.
- Consider collinear 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 correlation from a single event







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

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

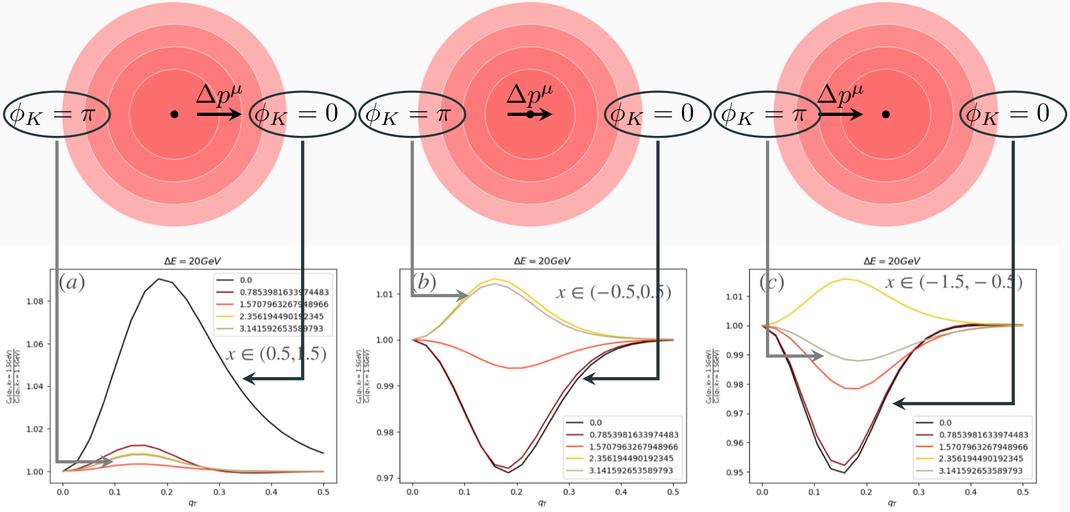
- Central Pb+Pb and O+O at LHC.
- Dashed: ideal hydro. Solid: viscous hydro.
- Colors: rotating $\vec{K}$ from 0 (jet direction) to 2π.

How to understand the signal?

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

- 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?

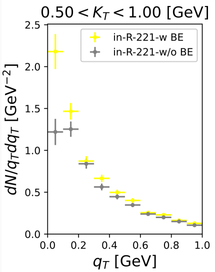


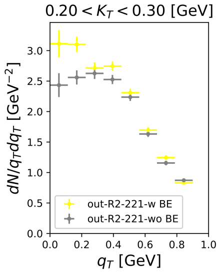
Small $|x_f - v_K t_f|$, large q_T

Large $|x_f - v_K t_f|$, small q_T

Towards a more realistic estimation for phenomenology

1. To consistently include 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

2. How to reduce signal cancellation when averaging over jet production vertex.

- Select events that bias jet production location, e.g. [Z. Yang et al. PJC83(2023)652]
- Try the back-to-back limit (instead of collinear limit): $K^0 \neq 0, \vec{K} = 0$.

Summary

- Is it possible to use the jet-induced medium response phenomena to study the nature of QGP response?
- We need spatial information. HBT correlation may be useful.
- Preliminary studies using CoLBT reveals interesting structure in surface-surface HBT: interplay of direction of flow, jet, and the direction of the pair.
- Need a careful event selection to preserve a large signal.
- Need to estimate jet-jet and jet-surface HBT correlations.
- Need more discussion and feedback on the feasibility!