Interferometry probe of the space-time structure of jet-induced medium response

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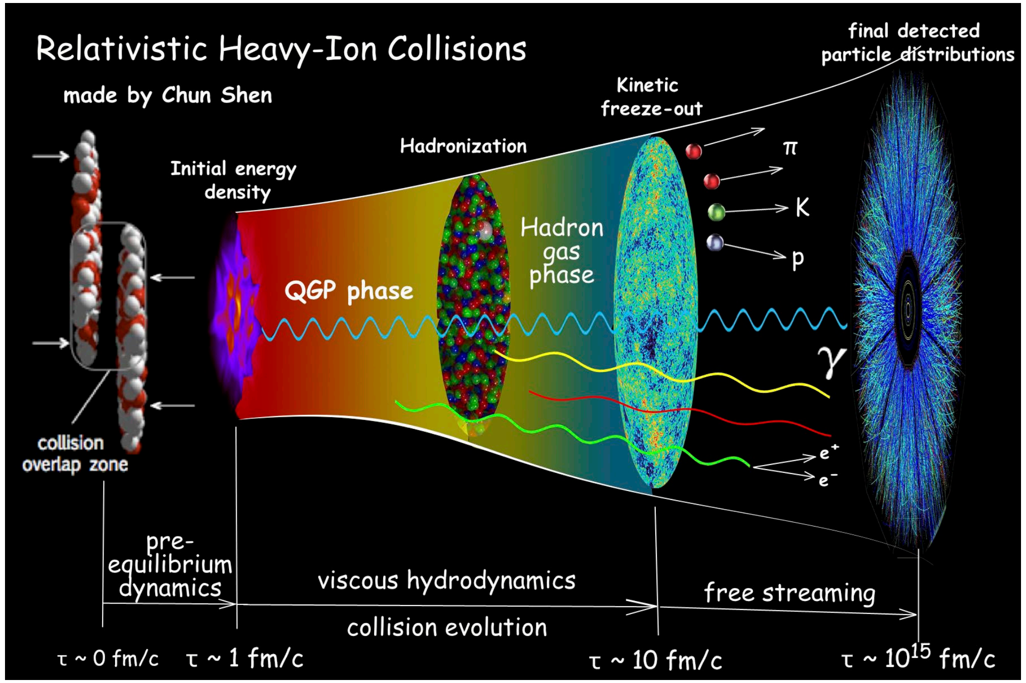
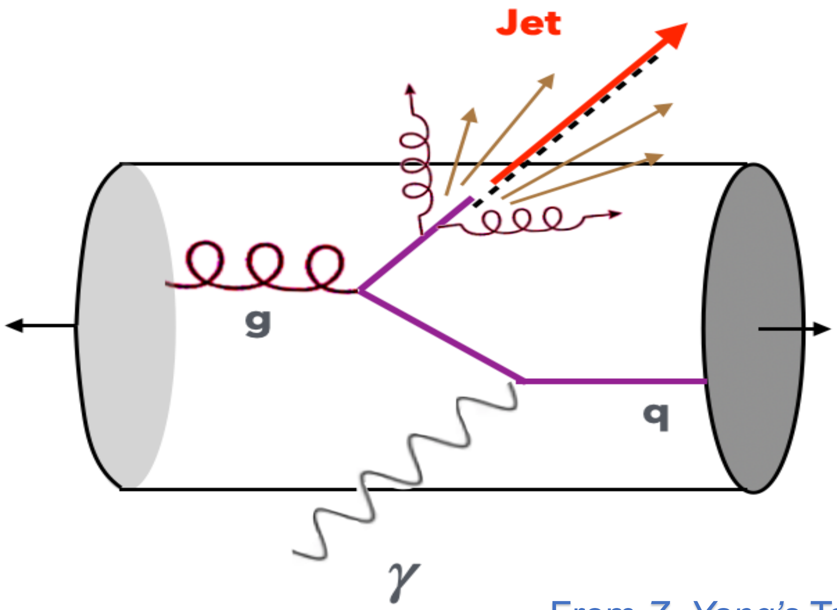
Outlines

- *Traditional observables may be inadequate to characterize medium response.*
- *HBT correlation is a potential probe of space-time structure of medium response.*
- *Preliminary results: estimation of HBT modifications due to jet medium response.*

Heavy-ion collision, jet propagation, and medium response





From Z. *Yang's* Talk

What one can learn from HIC

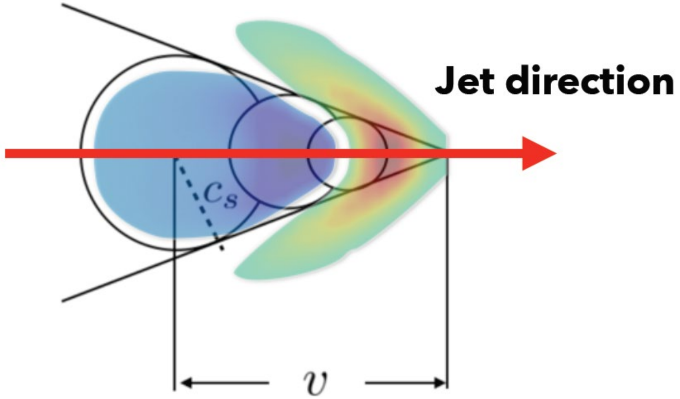
a) Parton distributions in nuclei.
b) Initial conditions of the collision.
c) Properties of the new state of matter – QGP.
d) Hadronization in environment.

Jet propagation in the QGP medium

a) Parton energy loss.
b) Medium response: medium constituents get excited by the jet, search for the possible collective response.

The jet-induced medium response: Medium ⇄ Jets

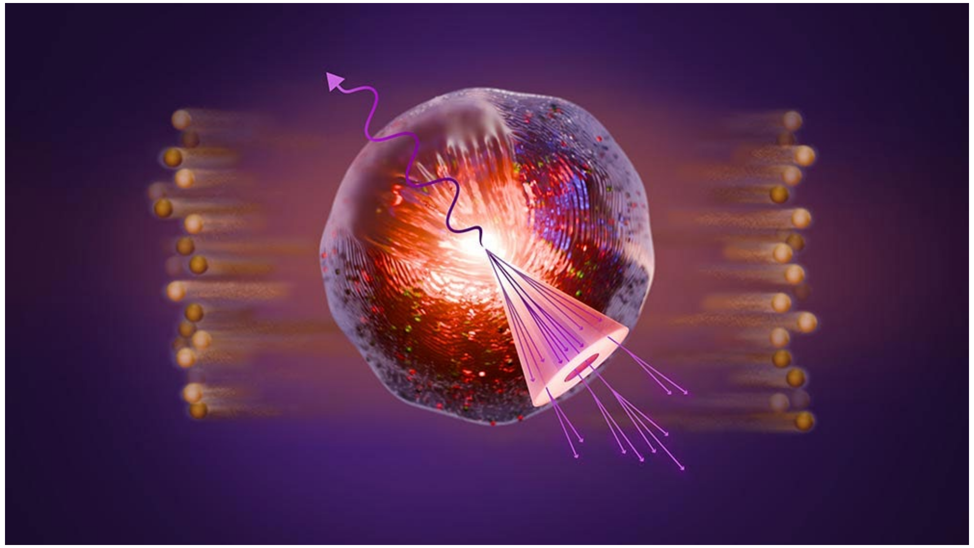
Mach Cone

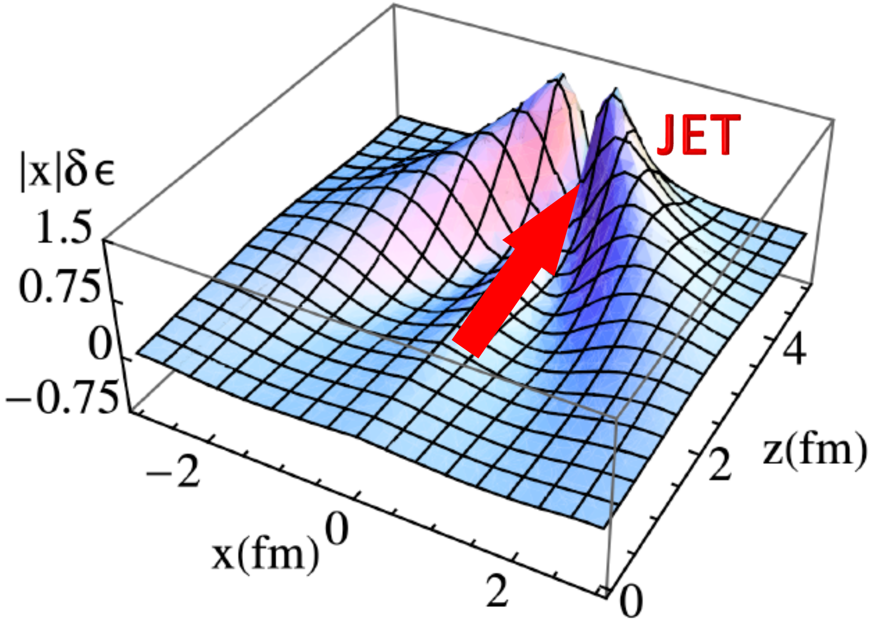


As jets are modified by medium, the medium is also affected by jets!

Mach cone, diffusion wake, …

1. Energy momentum lost to medium
2. Medium response could be collective or particle-like in nature



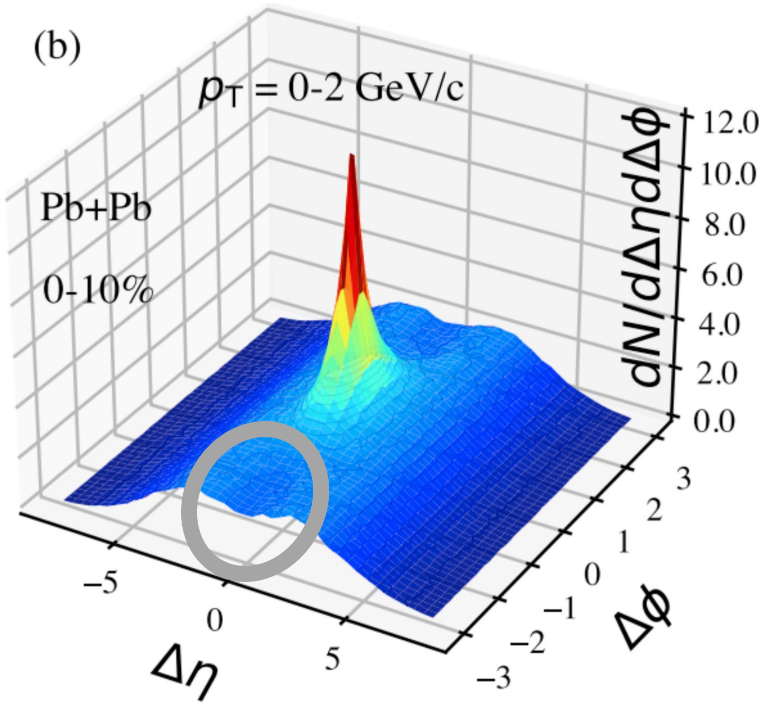


Z. Yang et al, PRL 127, 082301 (2021) , *Z. Yang et al, PRL* 130, 052301 (2023), *G.-Y. Qin et al, PRL* 103,152303 (2009)*, R. B. Neufeld et al, PRC* 78*,* 041901 (2008)

Search for medium response in the final-state momentum space

Simulations from CoLBT-hydro model: Right: coordinate space, Left: momentum space.

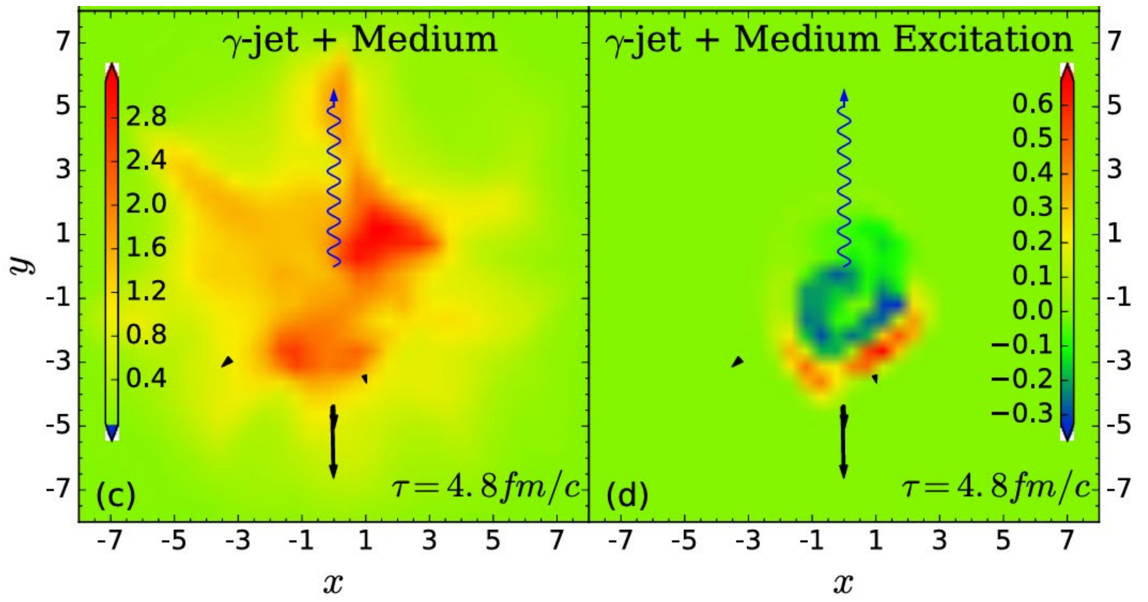
jet-hadron correlations



$$\Delta\eta = \eta_h - \eta_{jet}, \Delta\phi = \phi_h - \phi_{jet}$$

Zhong Yang et al. PRL 130, 052301 (2023)

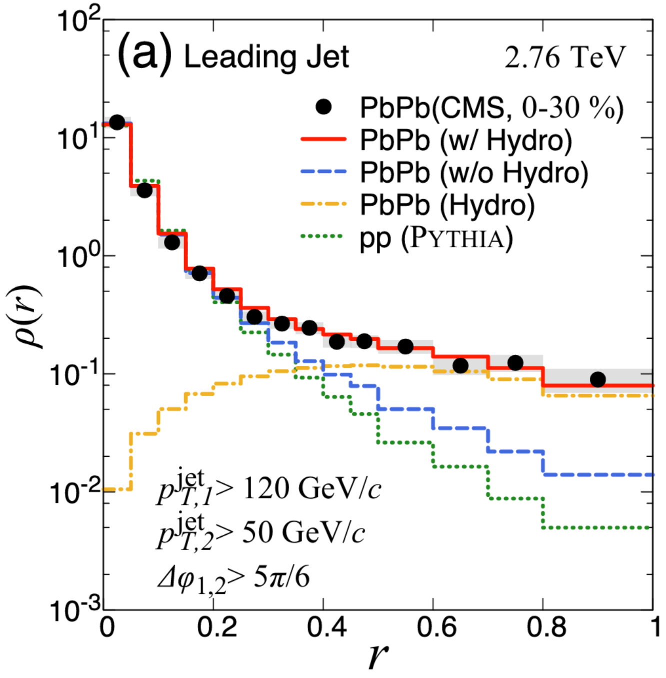
transverse distributions of the energy density



0–12% Au+Au $\sqrt{s} = 200GeV$

Wei Chen et al. PLB 777, 86 (2018)

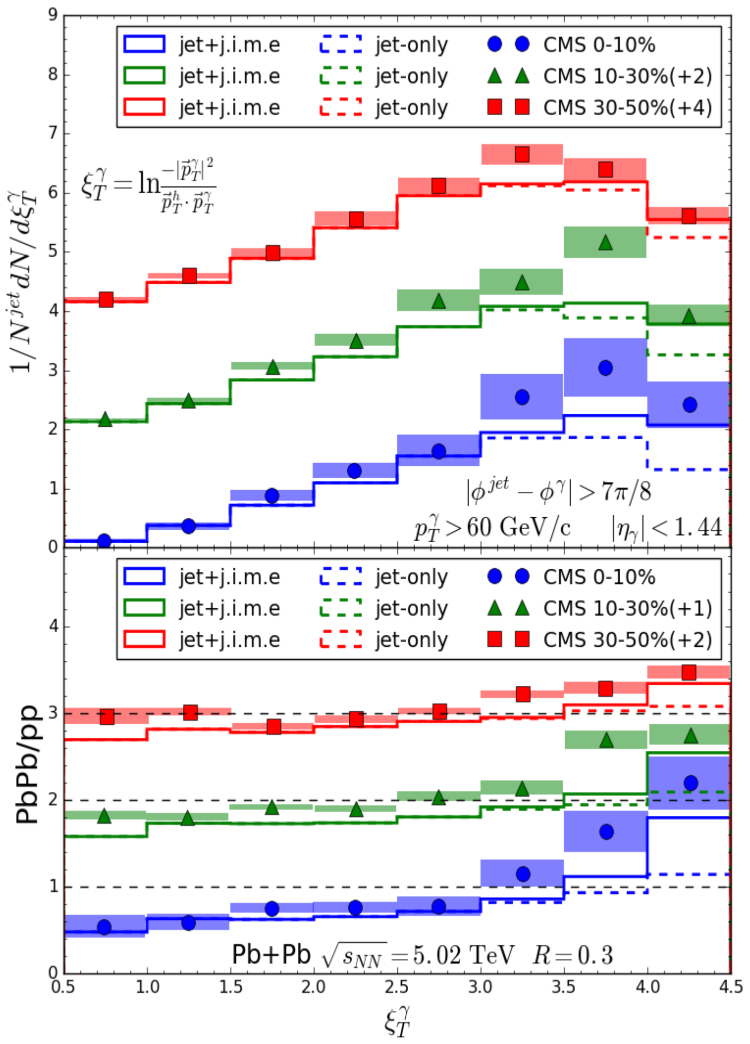
Medium response signals are often convolved with many effects



Why the wake is hard to see

• Soft hadrons from the wake are overwhelmed by the HIC background.

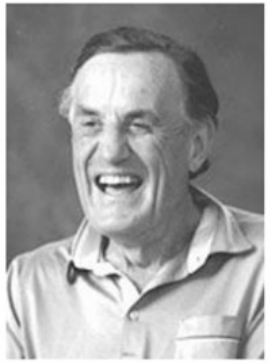
• Collective response are essentially structure in space time distribution.
But we can only observe the momentum space.
→ freeze-out wipe out a lot of information.



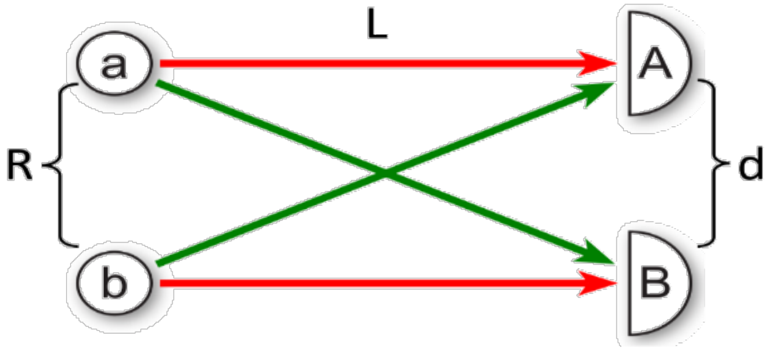
Phys.Rev.C 95,044909 (2017), *Phys.Lett.B 810, 135783 (2020)*

Hanbury Brown Twiss (HBT) interferometry

Richard Twiss (Springer International Publishing)



Robert Hanbury Brown (Australian Academy of Sciences)



Why HBT helps

- The wake is fundamentally a space-time distortion.
- HBT measures source geometry at the femtometer scale.

Single particle plane waves

$$\Psi_B^b = e^{ikr_{bB}+i\Phi_b}\ , \quad \Psi_A^a = e^{ikr_{aA}+i\Phi_a}$$

Identical boson wave function:

$$\Psi_{AB} = \frac{1}{\sqrt{2}}\left(\Psi_A^a\Psi_B^b + \Psi_B^a\Psi_A^b\right)$$ indistinguishability

Hence the correlation functions is:

$$C_{AB} = \frac{P(A,B)}{P(A)P(B)} = \frac{1}{2}\left\langle\left|\left(\Psi_A^a\Psi_B^b + \Psi_B^a\Psi_A^b\right)\right|^2\right\rangle$$

$$C_{AB} \approx 1 + \cos k\frac{Rd}{L}$$ Spaital inhomogeneity enters!

If medium response modify QGP inhomogeneity, we should see it in HBT!

Nature 178, 1046 (1956), *Phys. Rev* 120, 300 (1960)

CoLBT-hydro model

LBT: Linear Boltzmann Transport Model

CLVisc: CCNU-LBNL (3+1)D Viscous hydro model

1. LBT for energetic partons (jet shower and recoil)
2. Hydrodynamic model for bulk and soft particles: CLVisc
3. Sorting jet and recoil partons according to a cut-off parameter (p^0_{cut})

   Hard partons: $p\partial f(p) = -C(p)\ \left(p \cdot u > p^0_{cut}\right)$

   Soft and negative partons:

$$j^\nu = \sum_i p_i^\nu\ \delta^{(4)}(x - x_i)\,\theta\left(p^0_{cut} - p \cdot u\right)$$

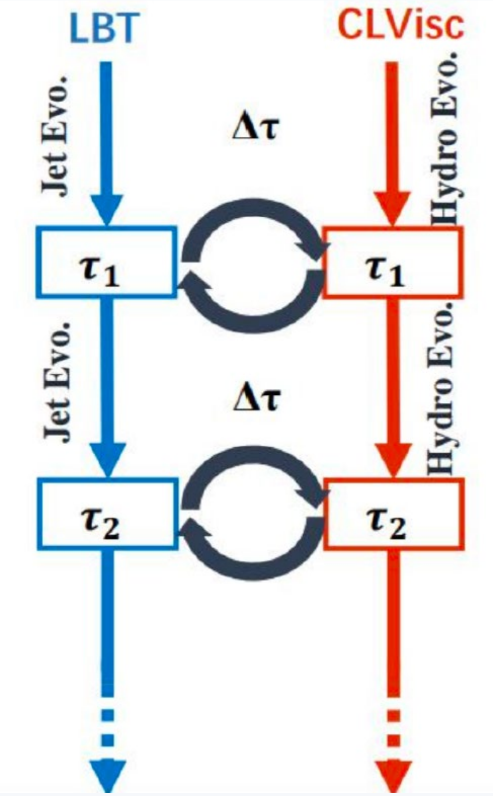
4. Updating medium information by solving the hydrodynamics equation with source term :

$$\partial_\mu T^{\mu\nu} = j^\nu$$

j^ν: energy-momentum deposited by jet

5. The final hadron spectra:
 (1) hadronization of hard partons within a parton recombination model
 (2) jet-induced hydro response via Cooper-Frye freeze-out

Workflow



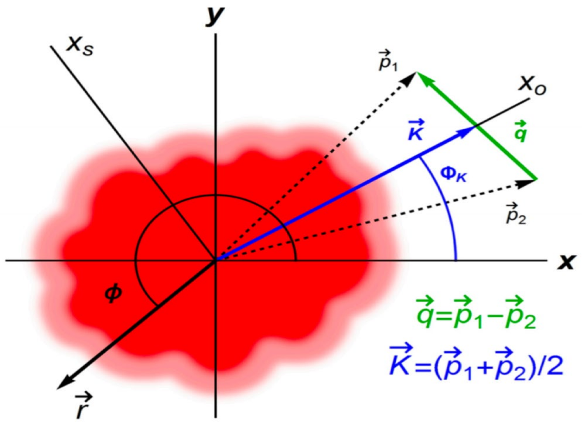
Further details can be found in Zhong Yang's presentation on March 23.

Y. He et al, Phys. Rev. C 91, 054908 (2015), *L. Pang et al, Phys. Rev. C* 86, 024911 (2012) & *W. Chen et al, Phys. Lett. B* 777, 86 (2018).

A simple estimation of HBT using the jet-perturbed freeze-out surface

Institute of Particle Physics 粒子物理研究所

Isolating geometry and flow effects from a localized jet-induced perturbation



- **Jet-induced source**

Energy-momentum deposited along a fixed trajectory

$$J^\mu \propto \frac{dp^\mu}{dt}\delta(\eta_s)\delta(x-t)\delta(y)[1,1,0,0]$$

Propagating source along $+x$ direction at mid-rapidity
Drives **medium response**

- **Simplification at freeze-out**

Use equilibrium Bose-Einstein distribution f_{BE}
Neglect viscous correction δf
Focus on **geometry + flow effects**

- **Pair kinematics (HBT limit)**

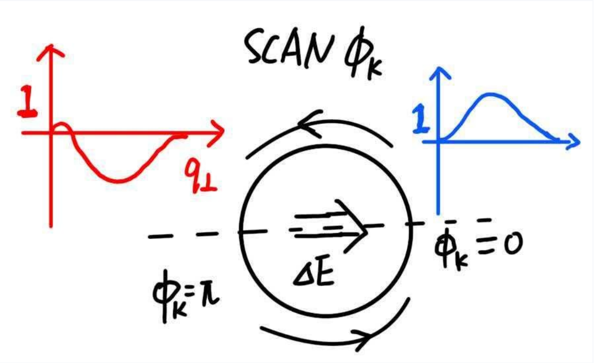
Collinear limit: $|K| \gg |q|$
Study the special case where $q^\mu = (0, q_x, q_y, 0)$
Orthogonal configuration: $\vec{K} \perp \vec{q}$

Surface emission kernel

$$S_{surface}(q,K) = \frac{g}{(2\pi)^2}\sum_{t_f,\overrightarrow{x_f}} K^\mu\,\sigma_\mu(t_f,\overrightarrow{x_f})f_{BE}\left(\frac{K\cdot u_f}{T_{frz}}\right) \times J_0\left(q_T\left|\overrightarrow{x_f}-\overrightarrow{v_K}t_f\right|\right)$$

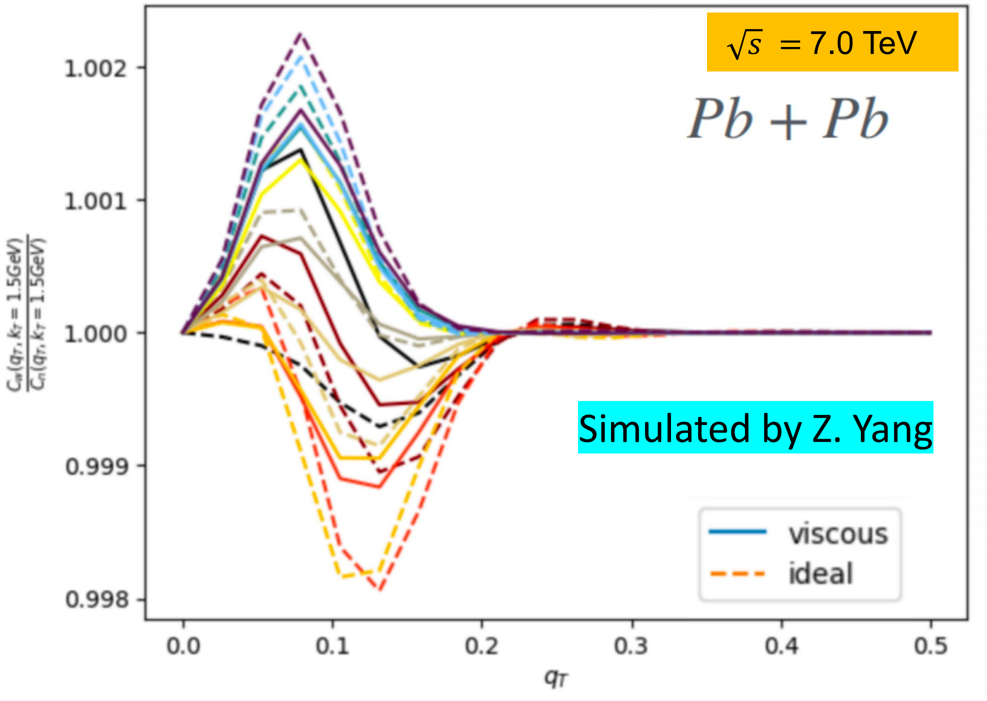
$K^\mu\sigma_\mu$:freeze-out surface weighting
f_{BE} :thermal occupation
$J_0\left(q_T\left|\overrightarrow{x_f}-\overrightarrow{v_K}t_f\right|\right)$: **HBT sensitivity to spatial structure**

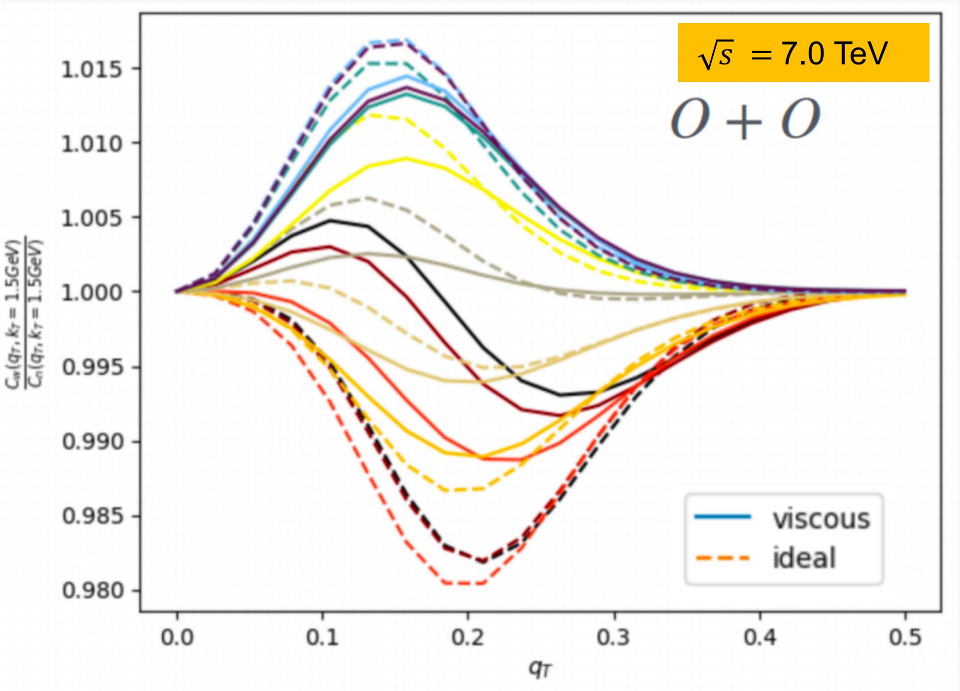
A simple estimation: Surface-surface contribution for a SINGLE event



$\pi^+\pi^+$ pairs , K=1.5 GeV

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



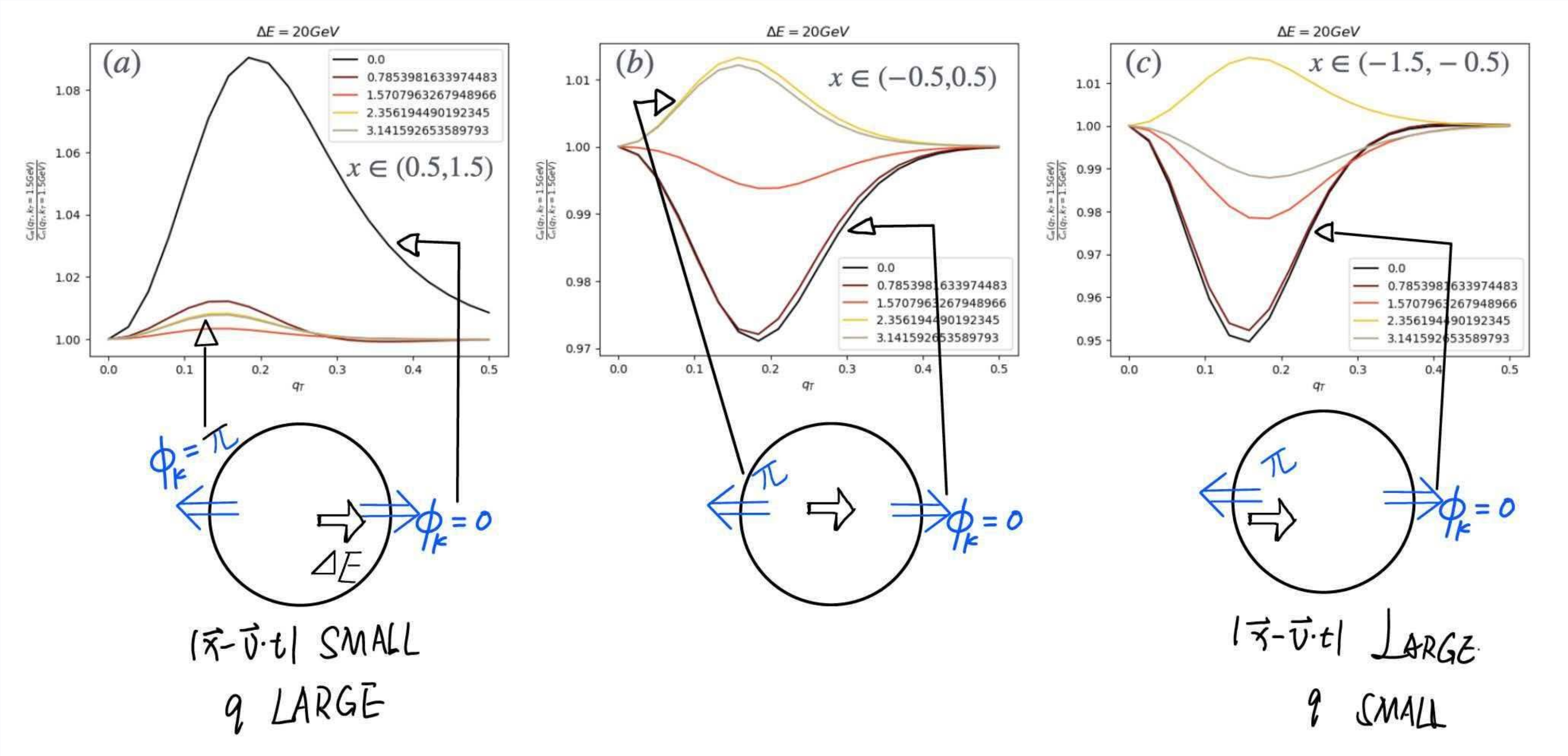


- Central (0-5%) Pb+Pb and O+O at LHC.
- Dashed: ideal hydro / Solid: viscous hydro.
- Colors: rotating ***K*** from 0 to 2π around jet.

- Positive and negative correction, depending whether jet going along/against the flow.
- Correction also sensitive to viscous effect.
- Relative signal in O+O is larger than Pb+Pb.

The correction to HBT depends on the direction of K.

A simple estimation from Cooper-Fyre: What Kind of Structure Does HBT See?



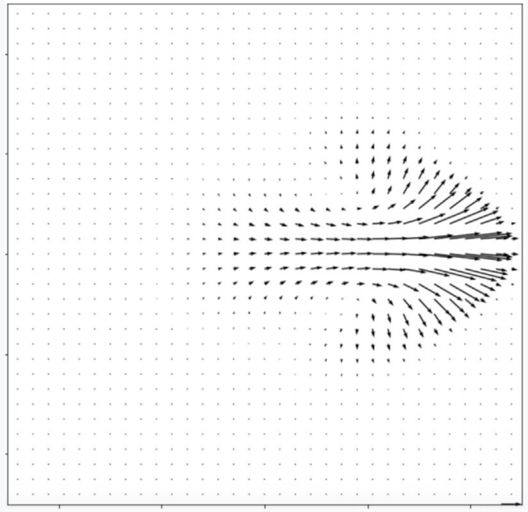
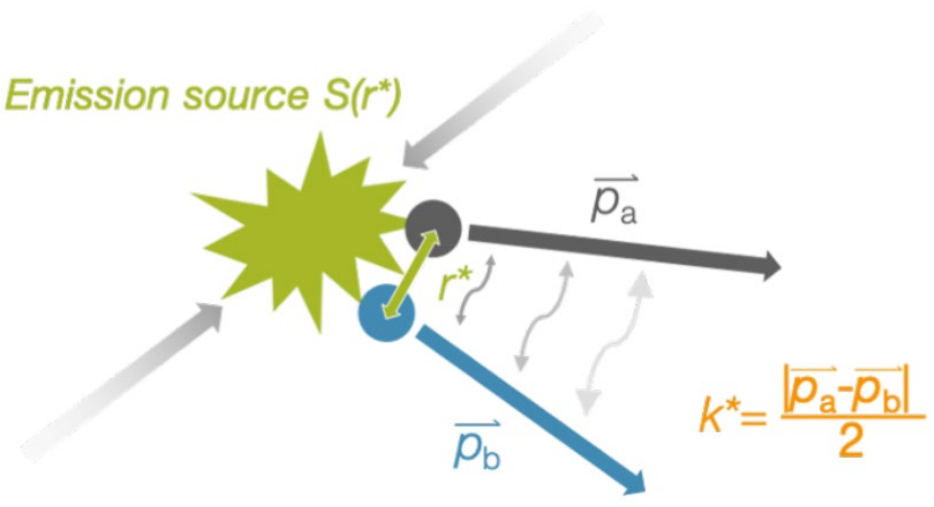


fig.a, the particles will go along the flow direction, the HBT are almost positive when we vary ϕ_k.
fig.b, particles can travel along or against the flow, the HBT has positive and negative results when we vary ϕ_k.
fig.c, the particles will go against the flow, the HBT are almost negative.

A more refined estimate of HBT using the Lednicky Lyuboshits Model



Femtoscopy is inspired by Hanbury Brown and Twiss (HBT) interferometry, but different scale (~several fm)

→ Spatial and temporal extent of emission source
→ Final-state Interactions (Coulomb, Strong interaction)
→ Bound state

Two-particle correlation function:

Model — *Experimental*

$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$S(\vec{r})$: *Source function*
$\Psi(\vec{k}^*,\vec{r})$: *Pair wave function*
$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, *relative momentum*
$\vec{r}$: *relative distance*

For this study, the LL model is governed by Fudan university

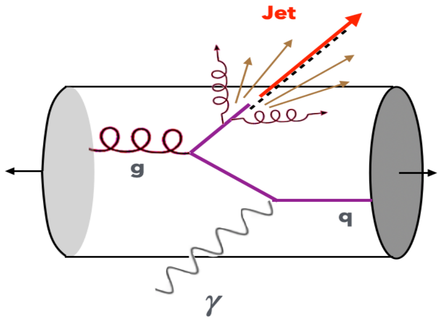
Baoshan Xi et al,Nucl. Sci. Tech. 36, 228 (2025)

R. Lednicky, V.L. Lyuboshits, Yad. Fiz. 35, 1316 (1981),
R. Lednicky, et al. Phys. Rev. C 61, 034901 (2000)

Prepare particles to be used in L-L calculation

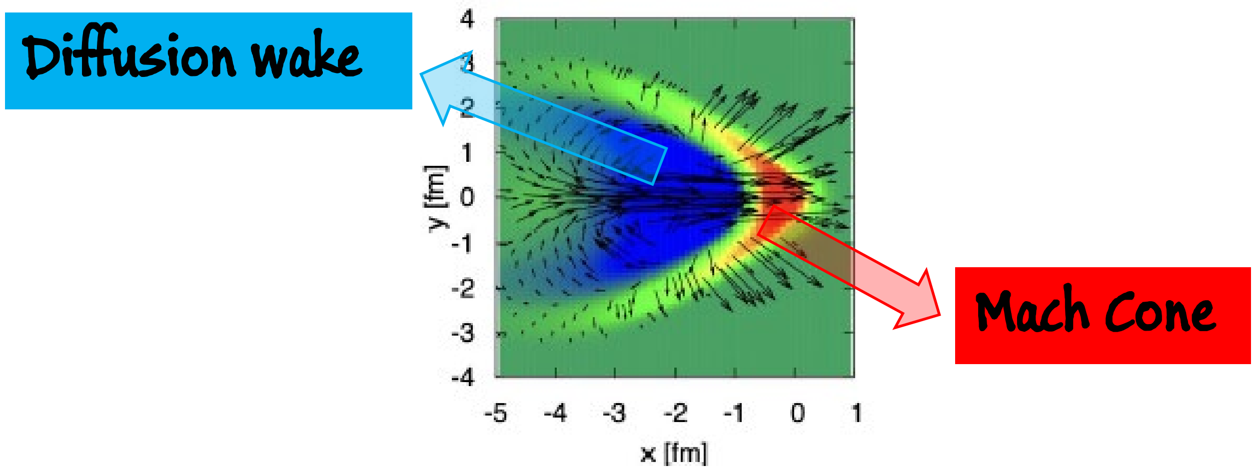
Settings for CoLBT-hydro

- O+O system γ-jet event
- 0-10% Centrality
- $\sqrt{s} = 5.36$ TeV
- $p_T^{\gamma} = 100$ GeV



How to select the pairs for investigating the jet induced medium response?

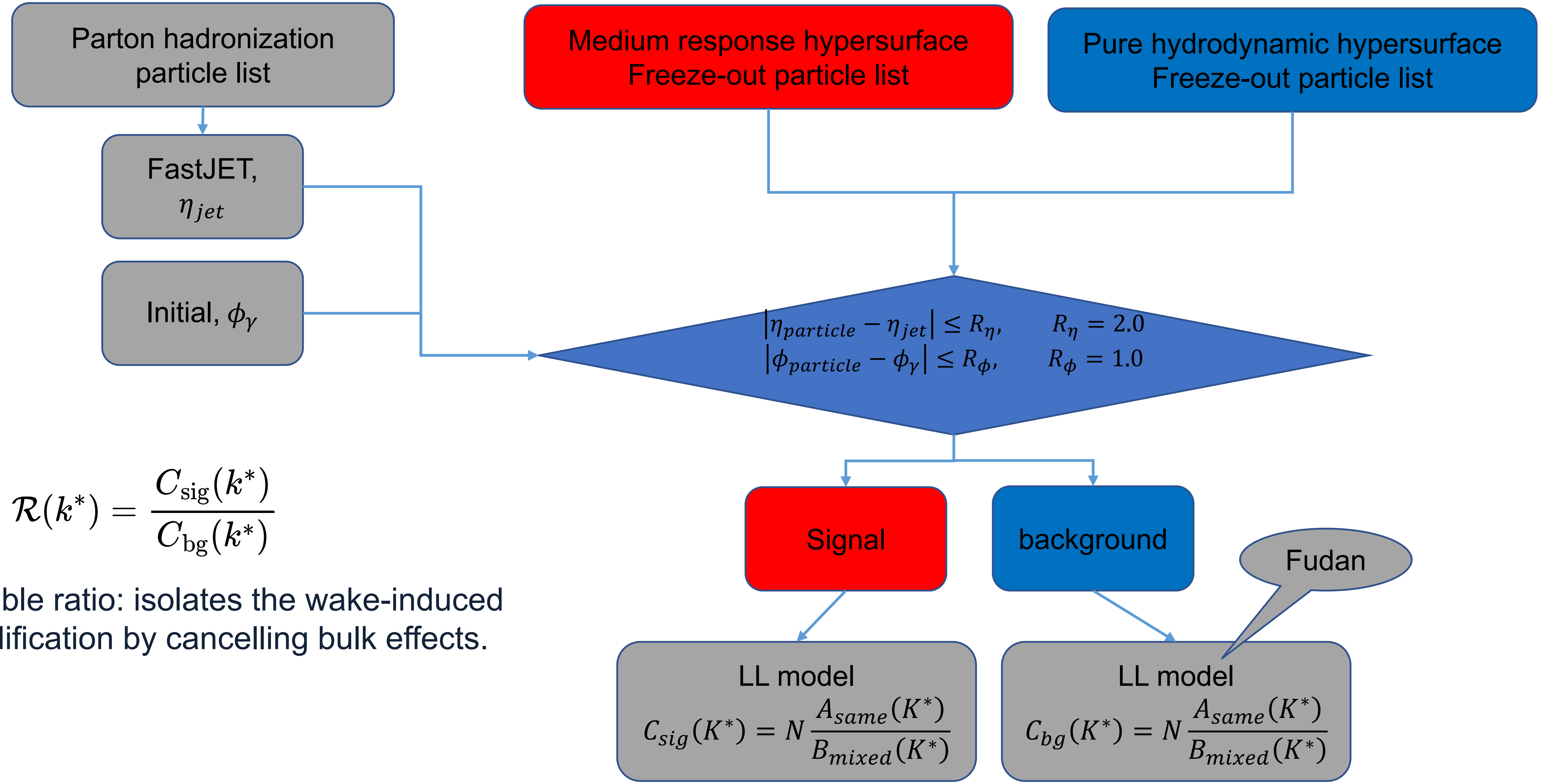
Phase space selection



- Signal: particles from jet+hydro CoLBT-model, contain jet-induced medium response.
- Background: particles from no-jet hydrodynamic simulation.

Betz Barbara et al.
PRC 79, 034902 (2009)

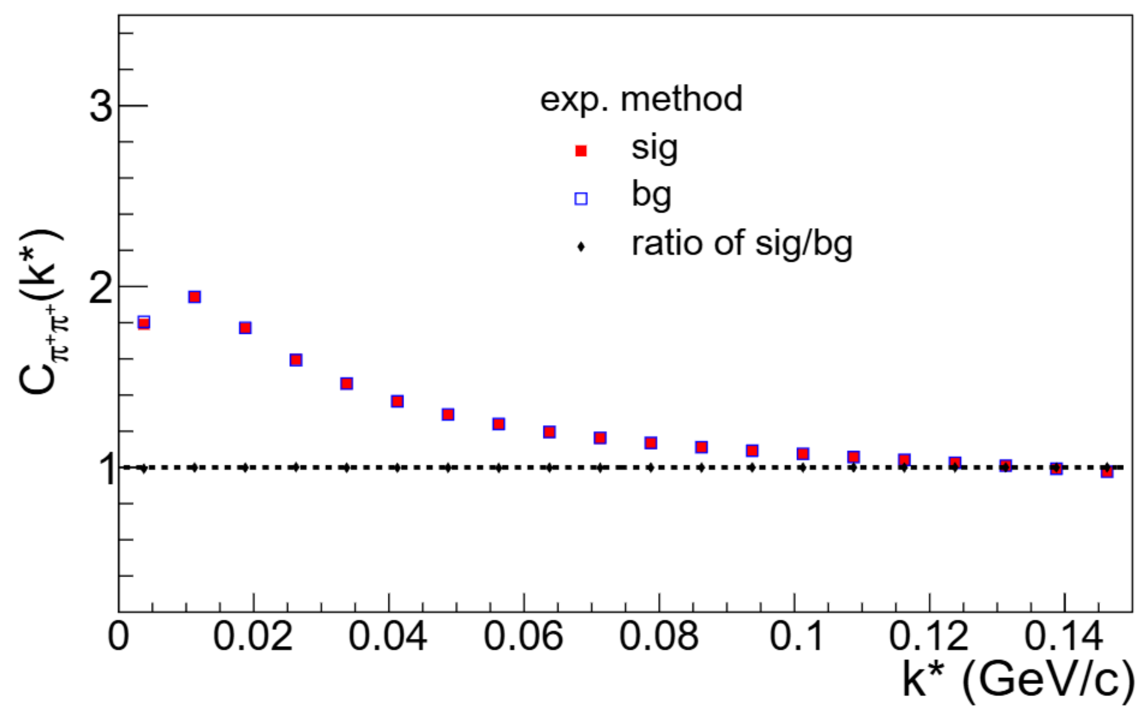
The work flow for this study

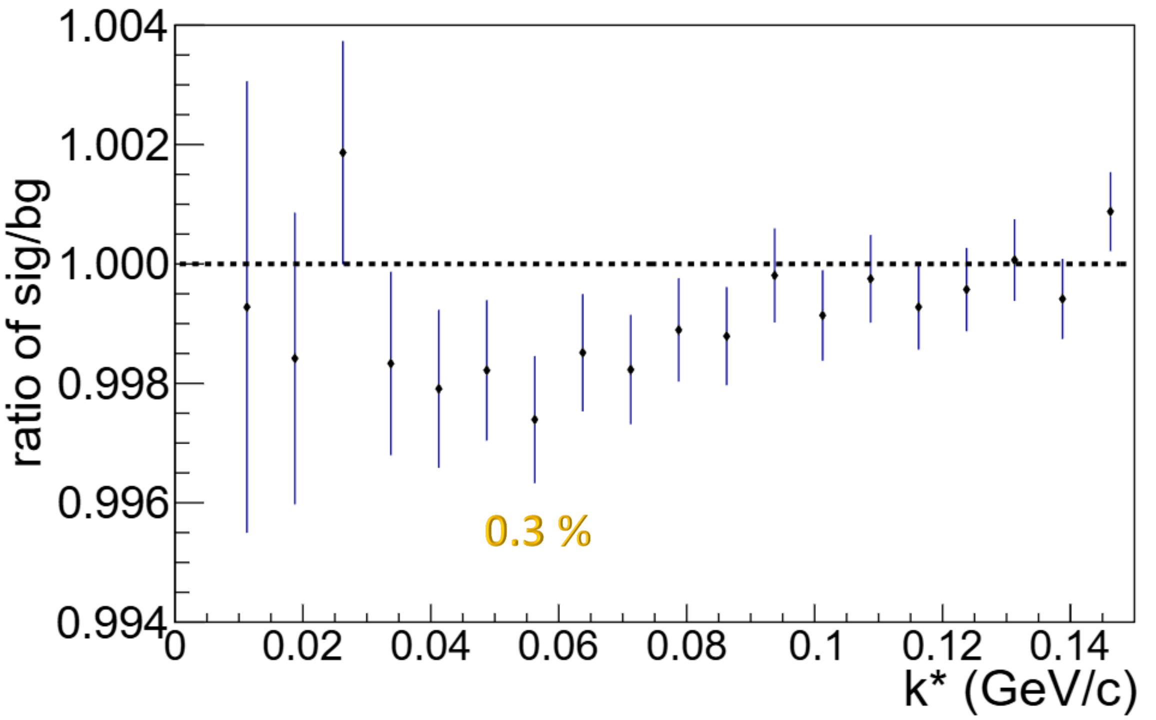


$$\mathcal{R}(k^*) = \frac{C_{\text{sig}}(k^*)}{C_{\text{bg}}(k^*)}$$

Double ratio: isolates the wake-induced modification by cancelling bulk effects.

A more refined Estimation (Preliminary Results): medium pairs

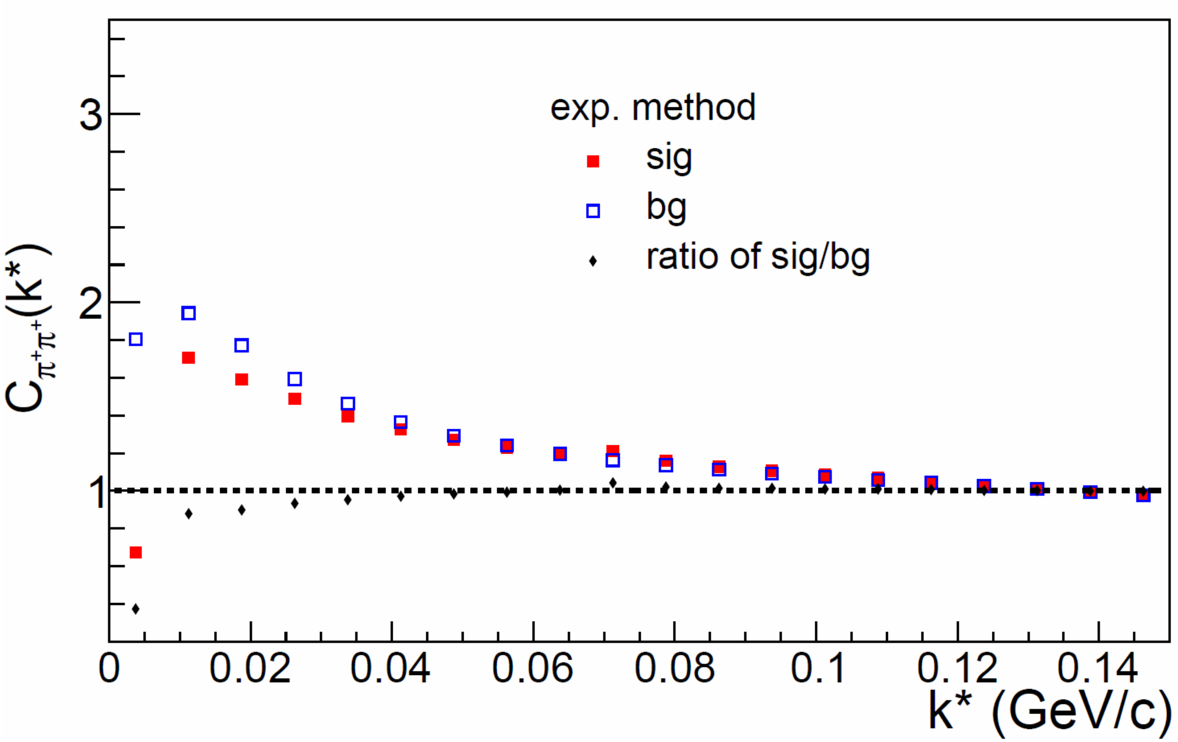


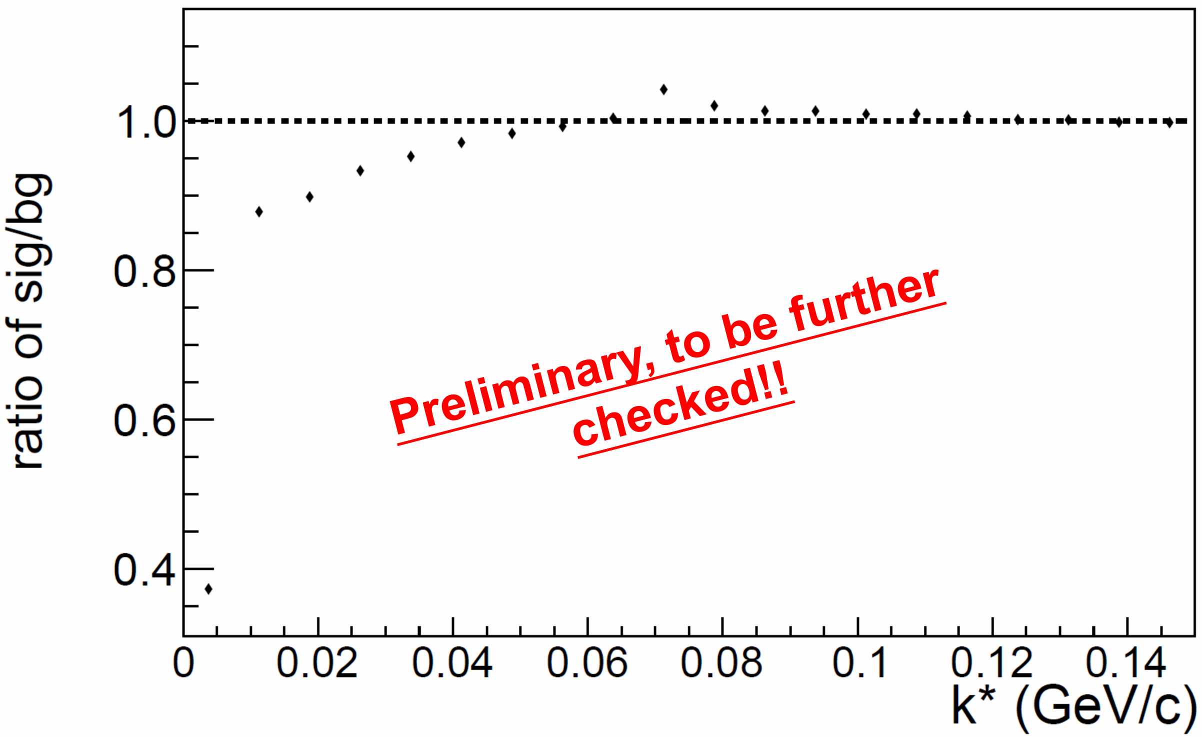


theory-isolated / model-isolated

- Left: the signal and background correlations almost overlap: medium response is small.
- Right: ratio of HBT from events with jets to that without jets. Correction is on the order of 0.3%, with a non trivial k* dependence, i.e., medium response has a finite spatial gradient.
- However, we have not included contributions between jet-medium pairs yet.

However, it seems that jet-medium pairs are order of magnitude larger





Once we consider the particles contributed by the jet fragmentation, the correlation will be further modified. How to distinguish the particles come from the **hydro-hydro, jet-hydro correlation?**

Of course, jet-med HBT correlation is also useful: it tells the hadronization space-time picture of jet in HIC.

Summary

- Collective medium response are essentially space-time perturbation structure on top of QGP.
- However, freeze-out wipe out a lot of spatial information.
- HBT seem to be the only observable directly sensitivity to spatial inhomogeneity.
- Using the CoLBT model, we estimate the correction to HBT due to the presence of jet-medium response.
- The interested signal come form medium-medium pair correlation, in O-O, it comes with typical $k^* \approx 0.06$ GeV/c with a magnitude of 0.3%.
- However, if one further include jet-medium pair correlation, the correlation function may be significantly changed → could be used to study the jet hadronization space-time structure in HIC.