Particle Interferometry
for Hydrodynamics and Event Generators

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COST Workshop, Lund University

February 28, 2019

The Big Question:

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But why haven't we seen jet quenching in small systems?
Consider the space-time geometry!

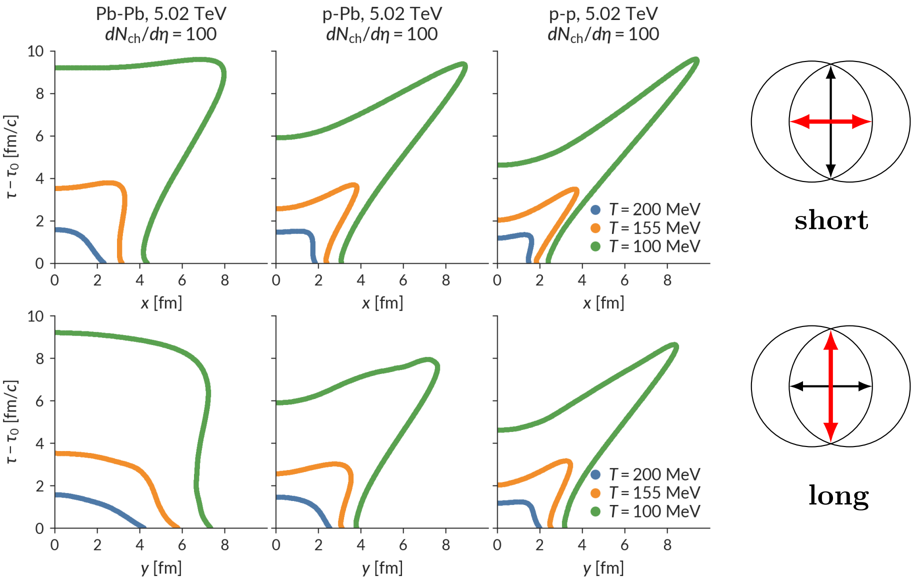
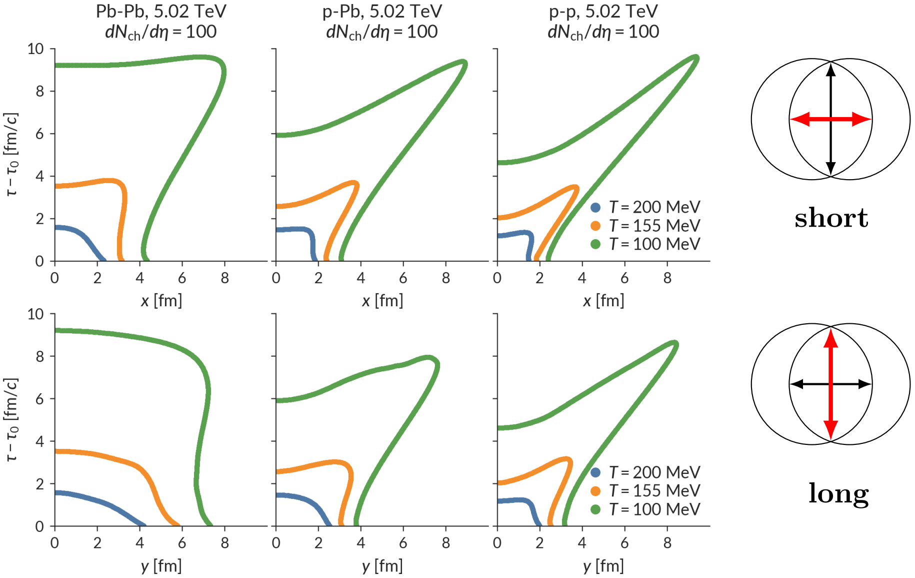


Fig credit: Ulrich Heinz and Scott Moreland



Freeze-out volume constant, but space-time volume changes significantly!

Fig credit: Ulrich Heinz and Scott Moreland

How can we probe the space-time geometry?

[1] HBT≡Hanbury Brown-Twiss

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Today:

- Particle interferometry: basics
- Particle interferometry with hydrodynamics
- Particle interferometry with Pythia 8

[1] HBT≡Hanbury Brown-Twiss

Correlation functions and HBT radii

$$C(\vec{p}_1, \vec{p}_2) \equiv E_{p_1} E_{p_2} \frac{d^6 N}{d^3 p_1 d^3 p_2} \Big/ \left(E_{p_1} \frac{d^3 N}{d^3 p_1} E_{p_2} \frac{d^3 N}{d^3 p_2} \right)$$

Correlation functions and HBT radii

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\to C_{\text{fit}}(\vec{q}, \vec{K}) &\equiv 1 + \lambda \exp\left(- \sum_{i,j=o,s,l} R_{ij}^2(\vec{K}) q_i q_j \right) \\
\vec{q} &\equiv \vec{p}_1 - \vec{p}_2, \; \vec{K} \equiv \frac{1}{2} \left(\vec{p}_1 + \vec{p}_2 \right)
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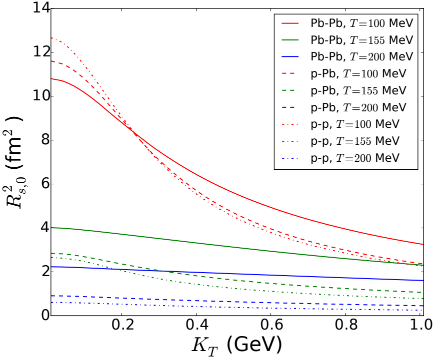
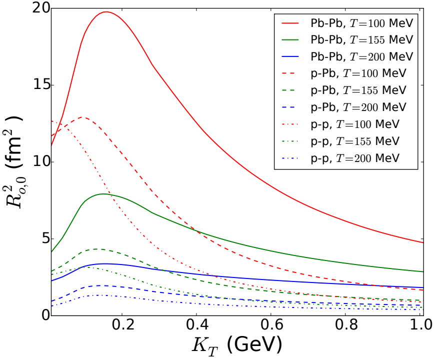
For Gaussian sources:

$$
\begin{aligned}
\Longrightarrow R^2_{ij}(\vec{K}) &\equiv \left\langle (\tilde{x}_i - \beta_i \tilde{t})(\tilde{x}_j - \beta_j \tilde{t}) \right\rangle_S, \\
\langle f(x) \rangle_S &\equiv \frac{\int d^4x\, f(x) S(x,K)}{\int d^4x\, S(x,K)} \\
\tilde{x}_i &\equiv x_i - \langle x_i \rangle_S,\ \tilde{t} \equiv t - \langle t \rangle_S,\ \vec{\beta} \equiv \vec{K}/K^0
\end{aligned}
$$

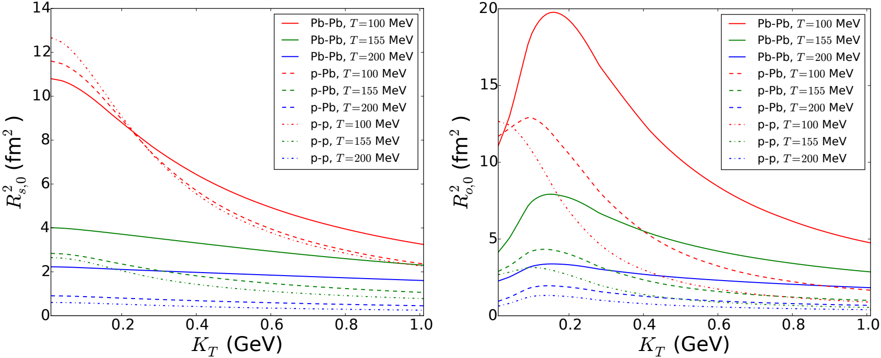
Space-time evolution in Hydrodynamics





Steeper scaling at large K_T

Space-time evolution in Hydrodynamics



Steeper scaling at large K_T

$\Longrightarrow$ pp has *more* flow than pPb or PbPb!

Conclusion: particle interferometry may help constrain the system's geometry in relation to jet quenching, but quantitative studies are still needed.

So how do we do this with event generators?

HBT and Pythia8

Method 1: *momentum-space modifications*

- The idea: modify pairwise correlations in particle momenta to emulate Bose-Einstein (BE) enhancement

[2] The precise form depends on the algorithm being used

HBT and Pythia8

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- The idea: modify pairwise correlations in particle momenta to emulate Bose-Einstein (BE) enhancement
- Strategy: perturb final-state momenta of identical particle pairs by some amount δQ, where

$$\int_0^Q \frac{q^2 dq}{\sqrt{q^2+4m}} = \int_0^{Q+\delta Q} f_2(q)\, \frac{q^2 dq}{\sqrt{q^2+4m}}$$

and $f_2(Q) \sim 1 + \lambda \exp\left(-Q^2 R^2\right)$ is the Bose-Einstein enhancement factor,[2] and λ and R are (user-defined) coherence and radius parameters, respectively, and $Q^2 = -\left(p_1 - p_2\right)^2$

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- Net shift for a hadron is vector sum of shifts in all pairs it belongs to
- Implements BE correlations directly into spectra; all space-time information contained in R

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Output: List of particle momenta with BE effects included

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Method 2: *space-time vertex tracking*[3]

- Assume $q\bar{q}$ string with linear confinement potential, for simplicity
- Hadrons formed by multiple string breaks

[3] *S. Ferreres-Solé and T. Sjöstrand, Eur. Phys. J. C* **78**, *983 (2018).*

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- For a ith break:
  - Longitudinal coordinates fixed by choosing momentum fraction z and requiring new system to have invariant mass $m_{h,\perp}$
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- This process can be generalized to more complex string topologies
- Space-time information determined explicitly by string fragmentation geometry; spectra remain unperturbed

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Output: List of particle momenta with *no* BE effects, together with space-time locations of hadron production vertices

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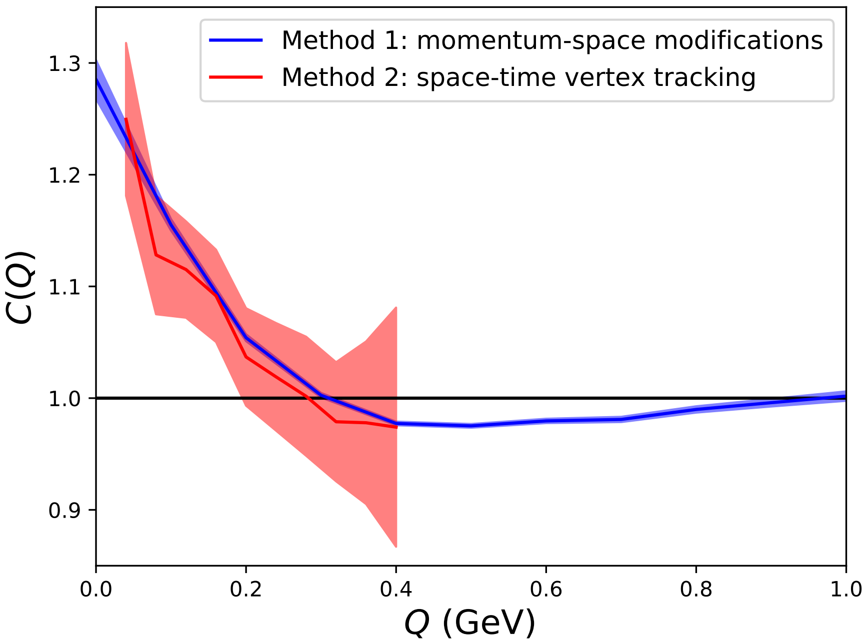
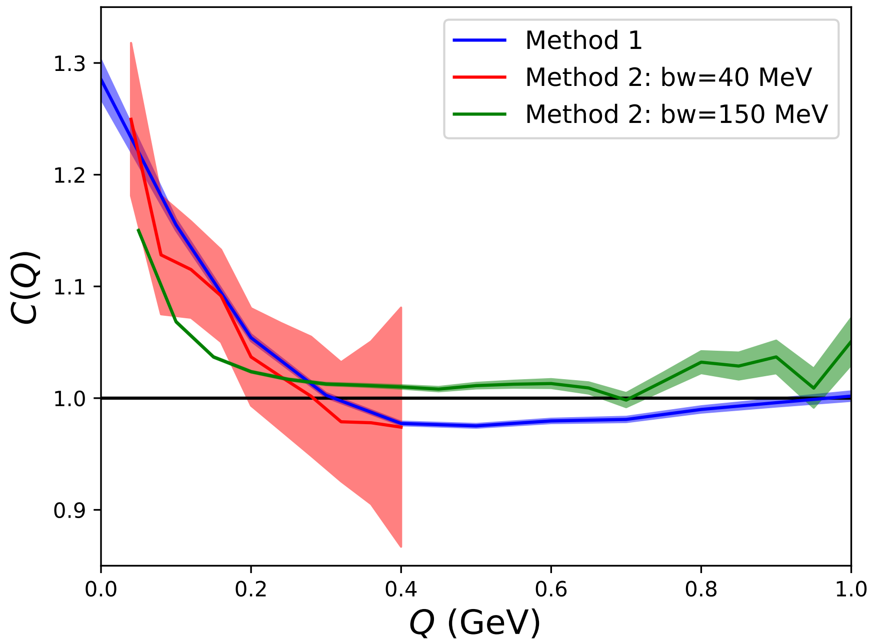


Method 1: momentum-space modifications
Method 2: space-time vertex tracking
$C(Q)$
Q (GeV)
1.3
1.2
1.1
1.0
0.9
0.0
0.2
0.4
0.6
0.8
1.0



Method 1
Method 2: bw=40 MeV
Method 2: bw=150 MeV
$C(Q)$
Q (GeV)
0.9
1.0
1.1
1.2
1.3
0.0
0.2
0.4
0.6
0.8
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Conclusions

Existence of jet quenching in small systems remains an open question

- Could be a consequence of the collision geometry
- Or the lack of QGP formation
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Particle interferometry provides valuable insight into space-time evolution and collision geometries relevant to jet-quenching models

- Already existing infrastructure for addressing this question within hydrodynamics
- Ongoing work to equip Pythia8 with same capability
- Explore effects related to string shoving, rope hadronization, and more
- Stay tuned!

Thanks for your attention!