Particle Interferometry from pp to AA

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Overview and Motivation

A central goal of the heavy-ion program is to create and study the quark-gluon plasma (QGP). The QGP should behave like a strongly coupled fluid of deconfined color charges, so it is normally identified by looking for fluid-like signatures. Such signatures include collective motion (defined by strong correlations between position-space and momentum-space) and jet-quenching (implying directional suppression high-p_T partons).

Intriguingly, some (but not all) of these same signatures have been observed in small collision systems (e.g., p+p vs. Pb+Pb) which were traditionally thought to be too small to permit the formation of QGP. A wide variety of models, including "initial-state models" (e.g., color-glass condensate [CGC] physics [1]), event generators (e.g., Pythia/Angantyr [2]), and "final-state models" (e.g., hydrodynamics [3]) have been proposed to explain these features. The challenge is to understand how one can discriminate experimentally between different competing models.

The proposal of this work is that particle interferometry – also known as Hanbury Brown-Twiss (HBT) interferometry – is ideally suited to this task. Moreover, I argue that hydrodynamics, in addition to explaining more conventional QGP-signatures such as anisotropic flow $v_n(p_T)$, also models correctly the space-time evolution of nuclear collisions, such as is probed by interferometric observables. This implies that HBT interferometry could provide information which is useful in distinguishing between the different approaches to modeling nuclear collisions.

Building Blocks of Interferometry

Particle production in nuclear collisions can be characterized by an emission density $S(x, K)$, which gives the probability to emit a particle from a point x^μ with four-momentum K^μ. In terms of $S(x, K)$, the HBT radii may be computed by

$$R^2_{ij}(\vec{K}) \equiv \left\langle (\tilde{x}_i - \beta_i \tilde{t})(\tilde{x}_j - \beta_j \tilde{t}) \right\rangle_S$$

where the "source average" is

$$\langle f(x) \rangle_S \equiv \frac{\int d^4x\, f(x) S(x, K)}{\int d^4x\, S(x, K)}$$

and

$$\tilde{x}_i \equiv x_i - \langle x_i \rangle_S,\ \tilde{t} \equiv t - \langle t \rangle_S,\ \vec{\beta} \equiv \vec{K}/K^0$$

In this way, HBT radii probe spatio-temporal properties of the particle production process in nuclear collisions.

From pp to AA in hydrodynamics

Consider three separate collision systems – Pb+Pb, p+Pb, and p+p – at fixed $\sqrt{s_{NN}} =$ 5.02 TeV and $dN^{\mathrm{ch}}/d\eta = 100$, as modeled by hydrodynamics [3]. What does the space-time evolution look like in these cases?

We find:

✓ Similar freeze-out volumes $\Longrightarrow$ similar multiplicities

✓ Strong time-position correlations in smaller systems $\Longrightarrow$ stronger collective flow!

✓ Very different space-time volumes

These effects should be visible in the HBT radii.

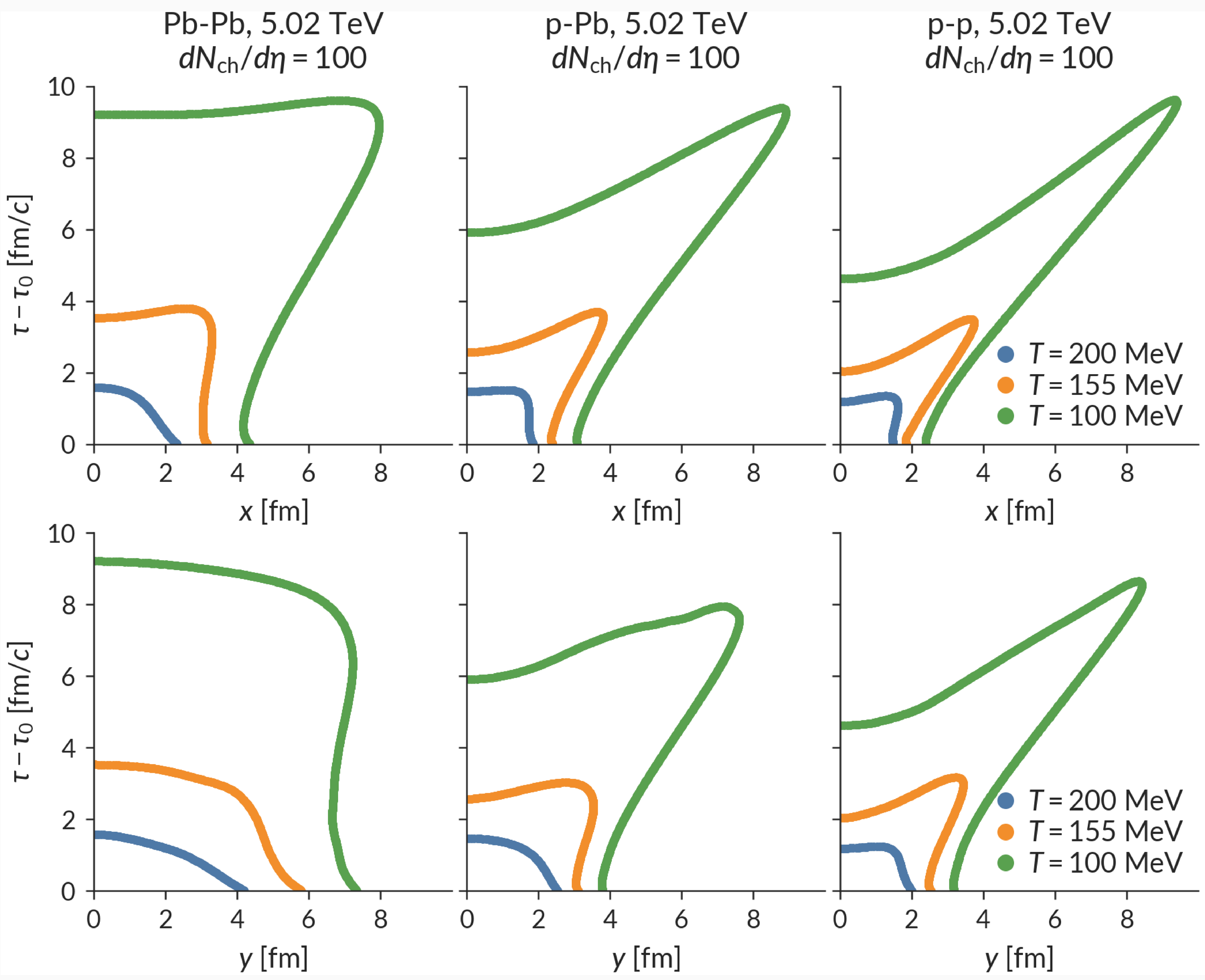

Fig. 1: Isotherms in Pb+Pb, p+Pb, and p+p collisions at fixed $dN^{\mathrm{ch}}/d\eta = 100$. Taken from Ref. [4] with permission.

Interferometry and Model Studies

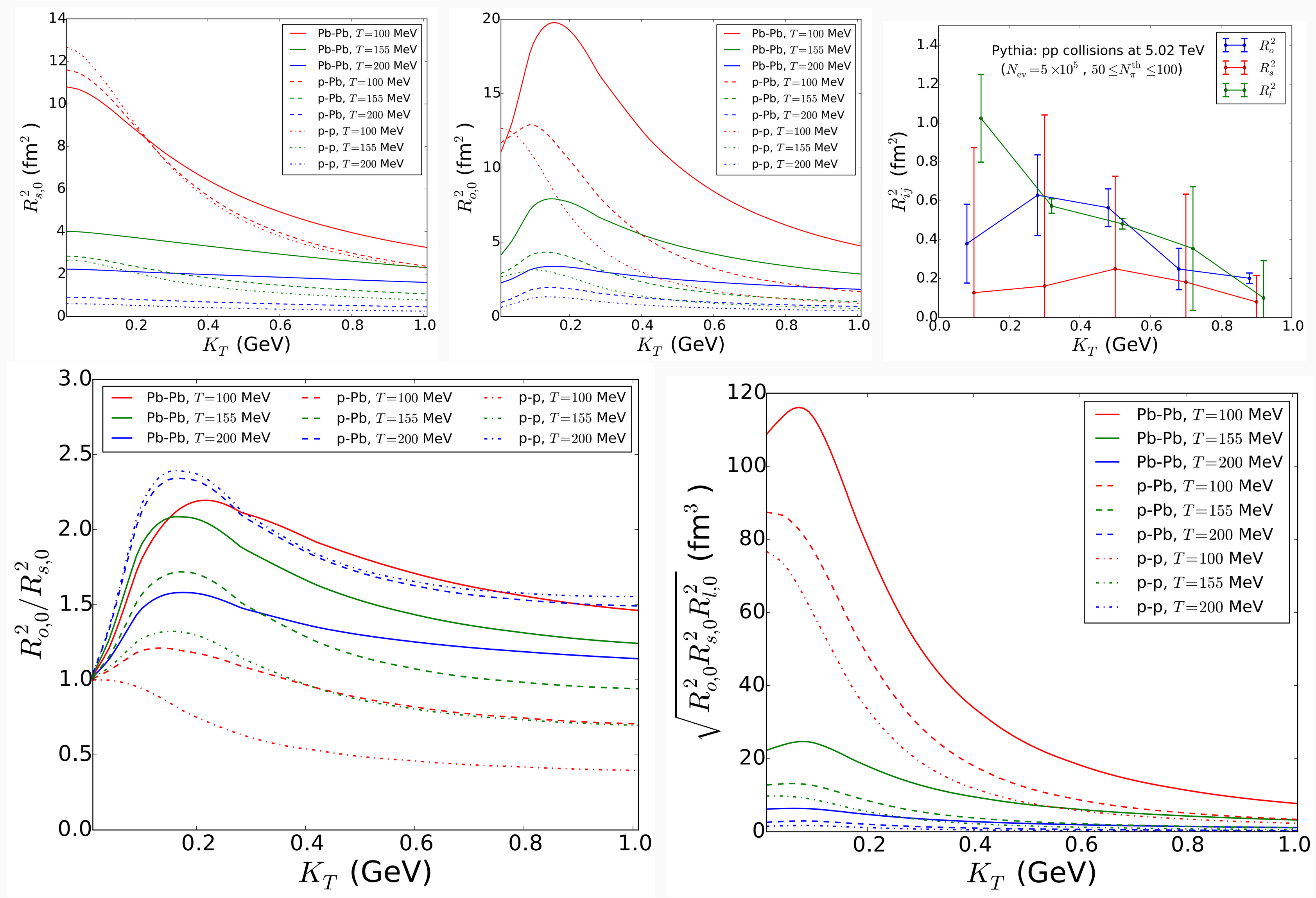

Fig. 2: The top row shows K_T-dependence of side (left) and out (center) radii in p+p, p+Pb, and Pb+Pb collisions, on the isotherms contained in Fig. 1.
The righthand plot in the top row shows for comparison the three radii R^2_o, R^2_s, and R^2_l obtained using the new space-time picture of hadronization available in Pythia [2], without any collective effects [5]. Although the latter shows large uncertainties (especially in R^2_s), we find that pp collisions tend to have $R^2_o/R^2_s < 1$ and $R^2_s \sim$ const., both of which are consistent with an absence of collective motion. This is likely to change once collective effects are included.
The bottom row shows the corresponding ratio R^2_o/R^2_s (left) and the volume of the freeze-out surface (right) from hydrodynamics. Only thermal pions have been used. The effects of strong collective flow (K_T-scaling of transverse $R^2_{ij} \sim K_T^{-1}$ and $R^2_o/R^2_s < 1$) and very different freeze-out volumes (factors of 2-3 between p+p and Pb+Pb) are apparent.

Discussion

This discussion allows us to formulate some focused questions for better constraining the various modeling approaches of nuclear collisions using HBT.

- How well do CGC-based models and event generators exhibit K_T-scaling in the transverse HBT radii?
- Which models best describe the $dN^{\mathrm{ch}}/d\eta$-dependence of the HBT radii and volume? In particular, how should we understand the weaker dependence in p+p as compared with A+A (cf. [6])?
- Which model yields a space-time picture which allows to understand the non-observation of jet quenching in small collision systems [7]?

A comprehensive description of nuclear collisions requires the ability to model both the dynamical (momentum-space) and kinematical (coordinate-space) evolution of these systems. Correctly describing both aspects simultaneously is clearly a difficult task. The interferometric observables discussed here should therefore allow for much-needed, non-trivial tests of the various approaches to modeling collision systems.

References

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