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Femtoscopic Signature of Strong Radial Flow in High-multiplicity *pp* Collisions

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Abstract.
We report on the results of the pion HBT radii for high-multiplicity *pp* collisions calculated in relativistic hydrodynamics. By comparison with the ALICE data, we make an estimate of he magnitude of the radial flow and initial size of the system.

1 Introduction

The Hanbury-Brown-Twiss (HBT) interferometry, that originally comes from radio astronomy, is a way to measure the space-time extent of a radiation source using the influence of Bose symmetrization of the wave functions of observed particles. This technology has been extensively used in heavy-ion collision experiments, to gain information about the size and the time evolution of the created matter. The advent of LHC made it possible to trigger on high-multiplicity events. It is reported that flow anisotropies quantified by v_n show similar magnitude to those at heavy-ion collisions, suggesting the formation of a liquid-like matter. However, the interpretation of those results are under debate.

In this contribution, we look at this problem from a different angle. We use the data of HBT radii from ALICE collaboration [1], and try to extract the magnitude of the radial flow and the initial size of the system in high-multiplicity event of *pp* collisions. For the details of the analysis, please look at Ref. [2].

2 Method

Unlike the heavy-ion collisions, we do not have a good quantitative model to describe the initial condition for high-multiplicity *pp* collisions. To parametrize the solution, a particularly convenient way is to use the analytic solutions found by Gubser [3]. In those solutions, the energy density and velocity is written as

$$\epsilon(\tau, r) = \frac{\epsilon_0 (2q)^{8/3}}{\tau^{4/3}[1 + 2q^2(\tau^2 + r^2) + q^4(\tau^2 - r^2)^2]^{4/3}}, \tag{1}$$

$$v_\perp(\tau, r) = \frac{2q^2 \tau r}{1 + q^2\tau^2 + q^2 r^2}. \tag{2}$$

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The space-time profiles are characterized by two parameters, q [fm^{-1}] and ϵ_0. The parameter ϵ_0 is related with the entropy per unit rapidity as

$$\epsilon_0 = f_*^{-1/3}\left(\frac{3}{16\pi}\frac{dS}{d\eta}\right)^{4/3}, \tag{3}$$

where $f_* = 11$ is the number of effective degrees of freedom in QGP [3]. We can infer the entropy per unit rapidity from the charge particle multiplicity,

$$\frac{dS}{d\eta} \simeq 7.5\frac{dN_{\rm ch}}{d\eta}. \tag{4}$$

In this way, the values of ϵ_0 are fixed from the charged particle multiplicity of the events of interest.

The other parameter q is related to the initial size of the system. As can be inferred from its dimension, a large q corresponds to a small initial size. In Fig. 1, we show two temperature profiles as functions of the radial coordinate r for $\tau = 0.6$ fm. The solution with larger q (dotted line) is more compressed and has a larger pressure gradient, which results in stronger radial flow at the freezeout.

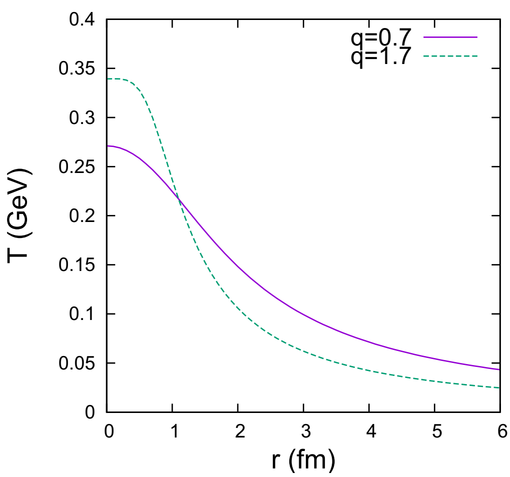

Figure 1. (Color online) Temperature profiles of the Gubser solutions for different values of the parameter q, at $\tau = 0.6$ fm. Plotted as a function of the radial coordinate r.

Although the Gubser solution can be a good description for the early stage of the time-evolution, it cannot be used at later stages close to freezeout. Near the phase transition temperature, the number of degree of freedom changes drastically, which affect the freezeout volume. The analytic Gubser solution is for a conformal EOS, and this change of degrees of freedom cannot be accommodated. Therefore, we start with the Gubser solution, and then, at certain time $\tau_0 = 0.6$ fm, we switch to the numerical evolution using a realistic EOS calculated from the lattice QCD calculations [4]. The system is evolved with the ideal relativistic hydrodynamic equations,

$$\partial_\mu T^{\mu\nu} = 0, \tag{5}$$

where $T^{\mu\nu}$ is the energy-momentum tensor. For a perfect fluid, $T^{\mu\nu}$ is expressed as

$$T^{\mu\nu} = (\epsilon + p)u^{\mu}u^{\nu} - p\eta^{\mu\nu}, \tag{6}$$

where ϵ is the energy density, p is the pressure, u^{μ} is the fluid four-velocity.

After solving the hydrodynamic equation, we use the standard Cooper-Frye prescription [5] to get the particle distributions,

$$p^0 \frac{d^3N}{d\eta dp_T^2} = \frac{1}{(2\pi)^3} \int \frac{p^{\mu} d\sigma_{\mu}(x)}{\exp\left[p \cdot u/T\right] \mp_{\rm BF} 1}. \tag{7}$$

The formula above is applied on an isothermal hypersurface with the freezeout temperature $T_{\rm f}$. We do the Monte-Carlo sampling of pions, according to the distribution (7).

Finally, we calculate the correlations functions using the momenta and emission coordinates of pions from the sampling procedure. The two-particle correlations coming from Bose symmetrization is introduced as

$$C(k_{\rm T}, \boldsymbol{q}) = \frac{\sum_{<i,j>\in[k_{\rm T}]} \left[1 + \cos\left(q_{\mu}\Delta x^{\mu}\right)\right]}{\sum_{<i,j>\in[k_{\rm T}]} 1}, \tag{8}$$

where $\boldsymbol{k}_{\rm T} \equiv (\boldsymbol{p}_{1\rm T} + \boldsymbol{p}_{2\rm T})/2$ is the pair transverse momentum, $< i, j > \in [k_{\rm T}]$ indicates a pair of pions in a particular $k_{\rm T}$ bin, $q^{\mu} = p_1^{\mu} - p_2^{\mu}$ is four-momentum difference of a pion pair, and $\Delta x^{\mu} \equiv x_1^{\mu} - x_2^{\mu}$ is space-time distance of the pair. We evaluate the correlation function in the "longitudinally comoving frame", where $k_z = 0$ for each pair. We use a pseudo-rapidity cut $|\eta| < 1.0$.

The three-dimensional correlation functions are characterized by the so0-called "out-side-long" parametrization [6, 7],

$$C(k_{\rm T}, \boldsymbol{q}) = 1 + \lambda \exp\left[-R_o^2 q_o^2 - R_s^2 q_s^2 - R_\ell^2 q_\ell^2\right], \tag{9}$$

where $R_{o,s,\ell} = R_{o,s,\ell}(k_{\rm T})$ are the HBT radii, q_o is the momentum parallel to the pair transverse momentum, q_ℓ is the one parallel to the beam direction, and q_s is the one perpendicular to out and long direction. We determine the HBT radii for each $k_{\rm T}$ by χ^2 fitting.

3 Results

Figure 2 shows the HBT volume, $R_o R_s R_\ell$, as a function of $k_{\rm T}$ for several values of q. The experimental data from ALICE is also plotted. The HBT radii with $q = 1.5$ to 1.7 fm^{-1} reproduce the volume in the ALICE experiment pretty well.

In Fig. 3, the ratio R_o/R_s is plotted as a function of $k_{\rm T}$. The ratio R_o/R_s is a decreasing function of $k_{\rm T}$. For small q, R_o/R_s is almost flat. As q becomes larger, the slope becomes steeper, and R_o/R_s gets suppressed for large $k_{\rm T}$. This suggests that R_o/R_s is indicative of the strength of the radial flow. The data ALICE shows even stronger suppression, which means that the initial size is very small and the expansion is strong.

The suppression of R_o/R_s is driven by correlation between emission time difference and the displacement in the out direction. For a weak flow (small q), this correlation is weak for the all region of $k_{\rm T}$. As the flow gets stronger (larger q), it becomes a linear increasing function of $k_{\rm T}$ Since this term contributes to R_o/R_s with a negative sign, it leads to the suppression of R_o/R_s at large $k_{\rm T}$. The discussion in detail can be found in Ref. [2]

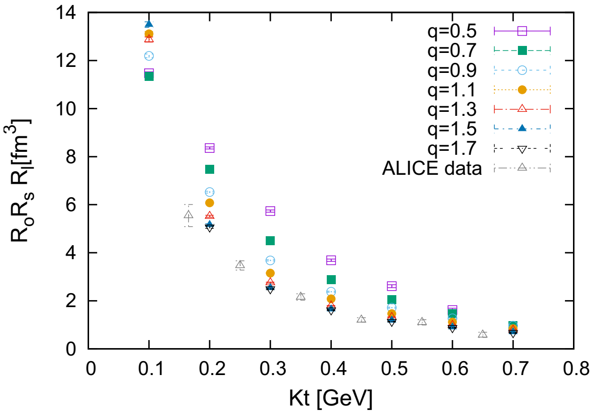

Figure 2. (Color online) HBT volume as a function of the pair transverse momentum k_{T} for various values of the parameter q. $dN_{\mathrm{ch}}/d\eta = 27$, $T_{\mathrm{f}} = 120$ MeV.

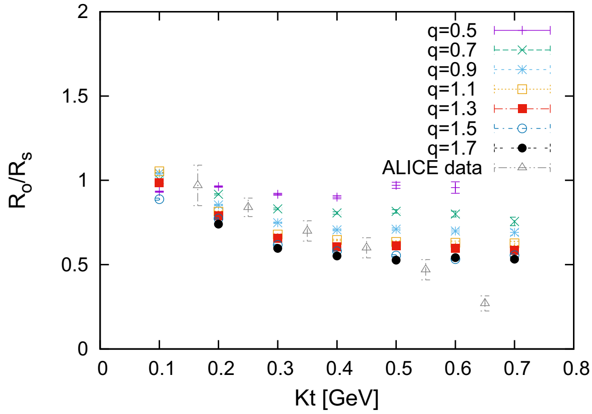

Figure 3. (Color online) The ratio R_o/R_s as a function of k_{T} for multiple values of q.

4 Summary

The data of HBT radii from the ALICE collaboration [1] provided a striking feature that the high multiplicity events of *pp* collisions at the LHC is different from others. It shows an evidence of a strong radial flow. We performed simulations of such system, basing on an ideal relativistic hydrodynamics. The early-time evolution is described by a Gubser solution, complemented by a numerical one, with a realistic EOS at later stages. Comparison of the resulting HBT radii with high multiplicity data shows the best agreement for the smallest initial fireball we study, with Gubser parameter $q = 1.5 - 1.7\ \text{fm}^{-1}$. It confirms that one in fact observes the presence of collective hydrodynamical flow in an unprecedented small system, smaller than 1 fm initially.

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