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FEMTOSCOPY OVERVIEW AND THE HBT PUZZLE* **

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In this overview of heavy ion femtoscopy, we emphasize the dramatic progress during the last year in understanding the HBT puzzle.

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In nuclear and particle physics, measurements are confined to the asymptotic trajectories of out-going particles. Given that many of the pressing issues facing heavy ion physics concern the dynamics and space-time evolution of the exploding fireball, correlation analyses play a critical role as they furnish our most direct insight into space-time aspects of the source. In particular, they are related to the source function $S(\boldsymbol{P},\boldsymbol{r}')$, *i.e.* the probability to emit two particles separated by a distance $\boldsymbol{r}'$,

$$C(\boldsymbol{P},\boldsymbol{q}) = \int d^3r'\ S(\boldsymbol{P},\boldsymbol{r}')\left|\phi(\boldsymbol{q},\boldsymbol{r}')\right|^2 . \tag{1}$$

Here, $\boldsymbol{r}'$ is the difference between two particles of the same velocity whose total momentum is $\boldsymbol{P}$, where $\boldsymbol{r}'$ is measured by an observer in the two-particle rest-frame. The correlation function $C(\boldsymbol{P},\boldsymbol{q})$ is constructed by taking the ratio of same-event and mixed-event distributions, which are binned by the total momentum $\boldsymbol{P} = \boldsymbol{p}_1 + \boldsymbol{p}_2$ and relative momentum $\boldsymbol{q} = (\boldsymbol{p}'_1 - \boldsymbol{p}'_2)/2$, and $\phi(\boldsymbol{q},\boldsymbol{r})$ is the outgoing scattering wave function. The approximations entailed in justifying Eq. (1) are delineated in a recent review [1], as well as in many of the references in that review.

Here, we review the progress made during the last year with an emphasis on the current status of the "HBT puzzle". Before describing the HBT puzzle, it is necessary to define the dimensions $R_{\rm out}$, $R_{\rm side}$ and $R_{\rm long}$ used to

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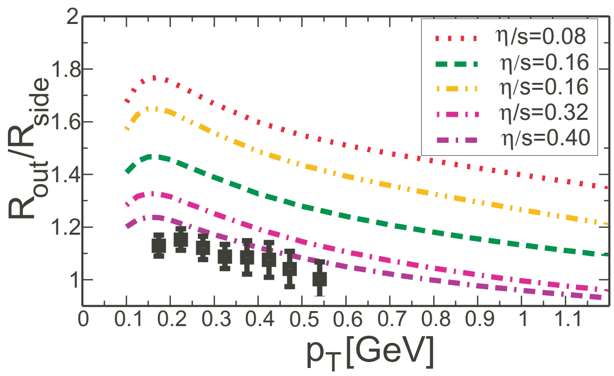
parameterize the source function described in Eq. (1). After boosting along the beam axis to a frame where the longitudinal component of $\boldsymbol{P}=0$, the "outwards" direction is parallel to the total momentum, and the "sideward" dimension is perpendicular to the other two. The source function is usually represented by a Gaussian form, $S\sim\exp\{-r'^{,2}_{\rm out}/4R'^{,2}_{\rm out}-r^2_{\rm side}/4R^2_{\rm side}-r^2_{\rm long}/4R^2_{\rm long}\}$. In the usual convention the dimension $R_{\rm out}$ refers to the size of the Gaussian probability cloud as measured by an observer with no transverse momentum, *i.e.*, $R_{\rm out}=R'_{\rm out}/\gamma_\perp$, where $\gamma_\perp$ is the Lorentz factor for the transverse boost. Each dimension is a function of transverse momentum, and has been extracted experimentally at the level of 10% or better. The Gaussian form implies that the principal axes of the Gaussian cloud coincide with the beam axis and $\boldsymbol{P}$. Symmetry only constrains this to be the case for central collisions at mid-rapidity. Realignments of the principal axes are often described as cross-terms and can depend on the direction of $\boldsymbol{P}$ relative to the reaction plane as measured in [2]. Cross terms involving the longitudinal direction are related to boost invariance, and have been analyzed through Yano–Koonin parameterizations for the SPS [3].

The HBT puzzle refers to the failure of transport models to reproduce measurements of $R_{\rm out}$, $R_{\rm side}$ and $R_{\rm long}$. Parameterizations based on blast-wave geometries suggest a rapid dissolution of the fireball at 9–10 fm$/c$, with a transverse radius of greater than 10 fm [4, 5]. This picture was reinforced by detailed analysis of the non-Gaussian features of the source function, which corroborated the expected resonance fraction and the longitudinal semi-Boost-invariant dynamics [5, 6]. In addition to parametric models, parameterized Buda–Lund hydrodynamics can reproduce the data, but not without assuming questionable initial conditions. None of the full simulations (where "full" refers to beginning with a pancake geometry with no initial transverse flow) has provided a fully satisfactory fit to the data. The averaged source volume is related to the total entropy of the system [7], and there is little difficulty in reproducing it if one adjusts the equation of state. The most common difficulty has come with reproducing the $R_{\rm out}/R_{\rm side}$ ratio, which experimentally are close to unity, but in the failing models were often higher by tens of percent. Physically, models failed because their expansions were insufficiently rapid and allowed too high a fraction of particles to escape from the surface, which extends the outward dimension of the phase-space cloud of outgoing particles, and results in $R_{\rm out}/R_{\rm side}>1$. A second smaller aspect of the puzzle involves $R_{\rm long}$, but is probably rectified by including longitudinal acceleration [8].

One possible solution to $R_{\rm out}/R_{\rm side}$ puzzle is that outgoing trajectories are bent by mean fields [9], which distort the outgoing phase space cloud. However, fields must be enormously strong at breakup densities to explain the data [10]. A second idea [11] is that matter super-cools near the phase transition which might inhibit emission from the surface. Indeed, adding a bulk viscosity for energy densities near T_c, which is similar to super-cooling, leads to minor improvements [12].

It now seems that the principal factor in the solution of the HBT puzzle is early acceleration. This was pointed out qualitatively [13], then shown quantitatively by providing an initial boost as an initial condition to hydrodynamics [14]. Now, it has been quantitatively demonstrated that the initial boost could arise from a high initial shear [12, 15, 16], in the context of hydrodynamics, or from a stiff repulsive potential [17], in the context of a microscopic simulation. Fig. 1 displays hydrodynamic calculations of the $R_{\text{out}}/R_{\text{side}}$ ratio from [15] which show how a fairly large viscosity can reproduce the experimentally observed result of $R_{\text{out}}/R_{\text{side}} \sim 1$. Shear increases the transverse components of the stress-energy tensor $T_x x$ and $T_y y$ relative to the longitudinal component T_{zz}, which increase transverse acceleration at early times when the shears are large. However, the viscosity required to reproduce the data in Fig. 1 is approximately five times the KSS bound [18] and is inconsistent with elliptic flow analyses. Similar success was found with microscopic URQMD calculations [17] displayed in the right panel, after the implementation of a repulsive mean field for the early stage where the hadrons are treated as “pre-formed” in URQMD.



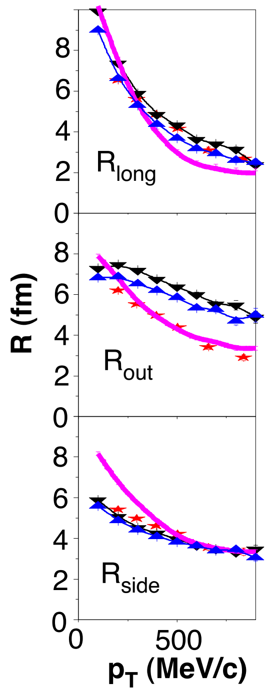


Fig. 1. Hydrodynamic calculations of $R_{\text{out}}/R_{\text{side}}$ from [15] are displayed above alongside data from STAR. Data are approached with increasing shear viscosity. Microscopic simulations from [17] are shown to the right for three cases: no mean field (down triangles), mean field only for pre-formed baryons (up triangles) and a repulsive field for all pre-formed hadrons (heavy lines) which also approaches STAR data (stars).

Although questions remain, the success of the landmark calculations displayed in Fig. 1 brings a consistent solution of the HBT puzzle within sight. Most importantly, early acceleration caused by adjusting the equation of state or viscosity must be reconciled with measurements of elliptic flow and spectra. This might be accomplished by adjusting the initial conditions for the stress-energy tensors, which in Israel–Stewart treatments of hydrodynamics are dynamic objects which relax toward Navier–Stokes values [19]. In [15] the initial stress-energy tensor was isotropic, but with anisotropic initial conditions, the same $R_{\rm out}/R_{\rm side}$ ratios might be reached with less viscosity [12]. Such conditions might result from longitudinal color fields [13, 20]. Finally, we emphasize that fitting the low-$p_{\rm t}$ RHIC data set does not rigorously verify any of the aspects of the equation of state or viscosity. However, it would demonstrate that a rigorous exploration of a model's parameter space will uncover at least one region of acceptable solutions.

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