Interferometry signatures of hydrodynamic sources with fluctuating initial conditions postprint

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Full Text

Preamble

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Interferometry Signatures of Hydrodynamic Sources with Fluctuating Initial Conditions

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Abstract

We investigate the space-time evolution of hydrodynamic particle-emitting sources with fluctuating initial conditions generated by the Heavy Ion Jet Interaction Generator (HIJING). To detect the event-by-event inhomogeneity of the sources, we examine the distribution of the error-inverse-weighted fluctuations, f, between the two-pion Bose-Einstein correlation functions of single and mixed events. We find that the distribution of f becomes wide for fluctuating initial conditions. The large values of the distribution width and the root-mean-square f_{rms} are signatures of hydrodynamic particle-emitting sources with fluctuating initial conditions.

Key words: Hydrodynamic source, Fluctuating initial condition, Interferometry signature, Event-by-event analysis

Introduction

Relativistic hydrodynamics has been widely used to describe system evolution in high-energy heavy ion collisions \cite{1-3}. It provides the link between the initial and final states of systems produced in these collisions. In general, the initial systems produced in relativistic heavy ion collisions are not spatially uniform, and there are event-by-event fluctuations of the initial quantities [?]. These initial fluctuations may affect the space-time evolution of the system and lead to changes in final particle observables relative to those associated with smoothed initial conditions \cite{4-8}.

Hanbury-Brown-Twiss (HBT) interferometry is a useful tool for probing the space-time structure of particle-emitting sources in high-energy heavy ion collisions \cite{9-12}. Previous studies indicate that the single-event HBT correlation functions of final identical pions exhibit event-by-event fluctuations in both the granular source model [?, ?] and the Smoothed Particle Hydrodynamics (SPH) model [?]. Investigating the propagation of initial fluctuations through system evolution and detecting their effects on HBT measurements in relativistic heavy ion collisions are interesting issues. In this work, we use the Heavy Ion Jet Interaction Generator (HIJING) [?] to generate the initial states of the systems event-by-event, at the energies of the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). We then model the evolution of the particle-emitting sources with (2+1)-dimensional relativistic hydrodynamics using these fluctuating initial conditions. Using HBT techniques based on event-by-event analysis [?, ?], we investigate the effects of fluctuating initial conditions on particle-emitting sources. We find that particle-emitting sources with HIJING fluctuating initial conditions are inhomogeneous in space, and the single-event two-pion correlation functions exhibit event-by-event fluctuations. The large width of the distribution of the error-inverse-weighted fluctuations, f, between the correlation functions of single and mixed events, and the large values of the root-mean-square f_{rms}, are signatures of particle-emitting sources with fluctuating initial conditions.

2. Hydrodynamic Evolution of the Systems with Fluctuating Initial Conditions

In heavy ion collisions at RHIC and LHC energies, the net baryon density of the system is approximately zero due to collision transparency. The ideal hydrodynamic description for a system with zero net baryon density is defined only by local energy and momentum conservation [?, ?]. Under the assumption of Bjorken longitudinal boost invariance [?], hydrodynamics in (3+1) dimensions reduces to (2+1) dimensions, and we need only to solve the equations of motion in the transverse plane [?]. Assuming that the system achieves local equilibrium at time τ_0, we can use HIJING to construct the event-by-event hydrodynamic initial energy density distribution in the transverse plane at $z = 0$ as [?, ?]:

$$\epsilon(x, y, \tau_0) = K \sum_{\alpha} \frac{p_{\alpha\perp}}{\tau_0} \exp\left[-\frac{(x - x_\alpha)^2 + (y - y_\alpha)^2}{2\sigma_\perp^2}\right]$$

where $p_{\alpha\perp}$ is the transverse momentum of parton α, x_α and y_α are the transverse coordinates of the parton at τ_0, $\sigma_\perp$ is a transverse width parameter, and K is a scale factor that can be adjusted to fit experimental data for produced hadrons.

Figure 1 [Figure 1: see original paper] shows the transverse distributions of energy density for two single events constructed with HIJING for $\sqrt{s_{NN}} =$ 200 GeV Au+Au collisions with impact parameters $b = 4$ fm and $b = 8$ fm, respectively. The parameters $\sigma_\perp$ and K are taken to be 0.5 fm and 0.8. One can see clearly that the transverse distribution of energy density for each event exhibits large fluctuations, which leads to the formation of "hot spots" in the initial sources. The number and maximum values of these spots decrease with increasing impact parameter.

To solve the hydrodynamic equations of motion, we also need the equation of state (EOS) to close the system. In our calculations, we use the parameterized EOS named s95p-PCE [?], which combines a hadron resonance gas at low temperature with lattice QCD results at high temperature.

Once the initial conditions and EOS are determined, we can solve the hydrodynamic equations numerically. Figures 2(b1)-(d1) and (b2)-(d2) show the solutions for the transverse distributions of energy density at $z = 0$ and $t = 3$, 6, and 9 fm/c, for the two single-event initial conditions presented in Figures 1(a1) and (a2), respectively. In the calculations, we use the HLLE scheme [?, ?] and Sod' s operator splitting method [?, ?, ?] to solve the hydrodynamic equations in the transverse plane at $z = 0$, and obtain the hydrodynamic solutions at $z \neq 0$ using the longitudinal Bjorken hypothesis [?, ?]. The grid size for the HLLE scheme is taken to be $\Delta x = \Delta y = 0.1$ fm, and the time step is taken to be $\Delta t = 0.1 \cdot \Delta x$ for the Courant-Friedrichs-Lewy (CFL) criterion, with $\Delta t/\Delta x < 1$ [?, ?]. From Figure 2, it can be seen that the transverse distributions of energy density exhibit large event-by-event fluctuations in space. These fluctuations persist even at the late stage of evolution at $t = 9$ fm/c.

3. HBT Signatures of Inhomogeneous Particle-Emitting Sources

The HBT correlation function of identical pions is defined as the ratio of the two-pion momentum distribution $P(p_1, p_2)$ to the product of single-pion momentum distributions. Assuming that final identical pions are emitted from a space-time configuration characterized by a freeze-out temperature T_f, we can generate pion momenta according to Bose-Einstein distribution and then construct the single-event and mixed-event two-pion correlation functions [?, ?].

In order to observe the event-by-event fluctuations, we investigate the ratio of signal to noise of the fluctuations between the correlation functions of single and mixed events [?, ?]:

$$f_i = \frac{C_{\text{single}}(q_i) - C_{\text{mixed}}(q_i)}{\sigma_i}$$

where i is the index of the component of relative momentum q, and σ_i is the error of the fluctuation.

Figure 3 [Figure 3: see original paper] shows our model-calculated two-pion correlation functions, $C(q_{\text{side}}, q_{\text{out}}, q_{\text{long}})$, for single and mixed events with HIJING initial conditions for $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions with $b = 4$ fm (upper panels) and $b = 8$ fm (lower panels). Here q_{side}, q_{out}, and q_{long} are the "side" , "out" , and "long" components of the relative momentum of pion pairs [?, ?]. The dashed lines in each panel show results for three different single events, while the solid line shows the mixed event constructed from 80 single events. In the calculations, the freeze-out temperature is taken to be $T_f = 120$ MeV, and the total number of correlated pion pairs in each event is $N_{\pi\pi} = 10^6$. One can see from Figure 3 that the correlation functions for single events exhibit fluctuations relative to those for mixed events, particularly for the larger impact parameter. This occurs because the smaller number of hot spots in systems with larger impact parameters may increase source granularity [?, ?] and lead to larger fluctuations [?, ?].

Figure 4 [Figure 4: see original paper] shows the distributions of dN/df in the side, out, and long directions obtained from 80 events with impact parameters $b = 4$ fm and $b = 8$ fm. In the calculations, we take the width of the relative momentum bin Δq_i to be 10 MeV/c and use bins in the region $20 < q_i < 80$ MeV/c. The number of correlated pion pairs for each event is taken to be $N_{\pi\pi} = 10^6$. In Figure 4, the solid lines show results for fluctuating initial conditions (FIC). For comparison, the corresponding distributions for events with smoothed initial conditions (SIC), obtained by averaging over 400 random HIJING events, are shown with dashed lines. One can see that the f distributions for FIC are wider than the corresponding results for SIC. The widths of the distributions for FIC increase with impact parameter, while the widths for SIC remain small and almost invariant with increasing impact parameter. This is because the fluctuations of the single-event correlation functions for SIC are always small.

For a limited $N_{\pi\pi}$, we can reduce the number of analysis variables to decrease the noise in Eq. (2) and increase the signal-to-noise ratio f, although this may sacrifice some details. In Figure 5 [Figure 5: see original paper], we show the distributions of f calculated using the variables of transverse relative momentum q_T [panels (a) and (b)] and relative momentum q [panels (c) and (d)] of pion pairs. The impact parameter is $b = 8$ fm. One can see that the widths of the f distributions for FIC increase with the number of pion pairs in an event, $N_{\pi\pi}$. Even for $N_{\pi\pi} = 10^5$, the widths for FIC are visibly larger than those for SIC.

We next examine quantitatively the widths of the distributions dN/df for relativistic heavy ion collisions at RHIC and LHC energies. Figure 6 [Figure 6: see original paper] shows the root-mean-square (RMS) of f as a function of $N_{\pi\pi}$ calculated from 40 simulated events for $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC and $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at LHC. From Figure 6, we can see that the values of $f_{\rm rms}$ for FIC increase with $N_{\pi\pi}$, while for SIC the values of $f_{\rm rms}$ are almost independent of $N_{\pi\pi}$. The reason is that for FIC the errors in Eq. (2) decrease with $N_{\pi\pi}$, while for SIC both the differences and their errors decrease with $N_{\pi\pi}$. For larger impact parameters, $f_{\rm rms}$ for FIC increases more rapidly with $N_{\pi\pi}$ because the number of hot spots is smaller in this case. At LHC energy, we find that the number of hot spots in the source is larger than at RHIC energy for the same impact parameter, which leads to smaller $f_{\rm rms}$ for FIC at LHC energy compared to RHIC energy.

In experiments, the number of correlated pion pairs in one event, $N_{\pi\pi}$, is limited. For central collisions at RHIC energy, the event multiplicity of identical pions, M_π, is about several hundred and $N_{\pi\pi}$ is about 10^5 ($\sim M_\pi^2$). At LHC energy, M_π is about several thousand and $N_{\pi\pi}$ may reach 10^6. From Figure 6 [Figure 6: see original paper], one can see that in these cases the $f_{\rm rms}$ values for FIC are visibly larger than those for SIC. Therefore, signatures of inhomogeneous particle-emitting sources can hopefully be detected in heavy ion collisions at RHIC and LHC.

4. Conclusion

Using a hydrodynamic model with HIJING fluctuating initial conditions, we have investigated particle-emitting sources in relativistic heavy ion collisions. The results indicate that the space-time evolution of sources with fluctuating initial conditions is inhomogeneous, and the single-event two-pion correlation functions exhibit event-by-event fluctuations. However, in usual HBT analyses performed with mixed events, these event-by-event fluctuations of single-event correlation functions are smoothed out.

To observe the fluctuations of correlation functions, we have investigated the distributions of f, the error-inverse-weighted fluctuations between correlation functions of single and mixed events. We find that the widths of the distributions dN/df for FIC are much wider than those for SIC, and correspondingly, the root-mean-square $f_{\rm rms}$ values for FIC are larger. For FIC, $f_{\rm rms}$ increases with the impact parameter of collisions because the smaller number of hot spots in systems with larger impact parameters may lead to greater source granularity. The values of $f_{\rm rms}$ for FIC increase with the number of correlated pion pairs,

$N_{\pi\pi}$, while the values of f_{rms} for SIC are almost independent of $N_{\pi\pi}$. The large values of the distribution width and the root-mean-square f_{rms} are signatures of particle-emitting sources with fluctuating initial conditions. Our calculations indicate that these signatures can hopefully be detected in heavy ion collisions at RHIC and LHC.

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Note: Figure translations are in progress. See original paper for figures.