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Pseudorapidity correlations in heavy ion collisions from viscous fluid dynamics

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ABSTRACT

We demonstrate by explicit calculations in 3+1 dimensional viscous relativistic fluid dynamics how two-particle pseudorapidity correlation functions in heavy ion collisions at the LHC and RHIC depend on the number of particle producing sources and the transport properties of the produced medium. In particular, we present results for the Legendre coefficients of the two-particle pseudorapidity correlation function, $a_{n,m}$, in Pb+Pb collisions at 2760 GeV and Au+Au collisions at 200 GeV from viscous hydrodynamics with three dimensionally fluctuating initial conditions. Our results suggest that the $a_{n,m}$ provide important constraints on initial state fluctuations in heavy ion collisions.

1. Introduction

The study of the Fourier coefficients v_n of the azimuthal particle distribution in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) has led to great insight into the initial state fluctuations and hydrodynamic evolution of the produced system [1]. In particular, it has led to the conclusion that the system has a very small viscosity, close to the lower bound conjectured using AdS/CFT correspondence [2].

Recently, the ATLAS collaboration has presented results on the expansion of two-particle pseudorapidity correlations into Legendre polynomials [3]. The obtained coefficients contain important information on the fluctuations of the particle multiplicity in pseudorapidity.

In this letter we explore how two-particle pseudorapidity correlations from hydrodynamic calculations can give insight into the number of sources for particle production and their correlations, as well as the shear and bulk viscosity of the system. To achieve this, we introduce a simple initial state model that extends the conventional Monte Carlo (MC) Glauber model [4] to include fluctuations of valence quarks in rapidity and thus produces three dimensional fluctuating distributions of net baryon number and entropy density. We then use this model to generate the input for 3+1 dimensional viscous hydrodynamic calculations and compute rapidity distributions of charged hadrons and two-particle rapidity correlations. We then analyze the effect of i) the number of sources and ii) the shear and bulk viscosity of the system on the Legendre coefficients.

2. Initial state model and hydrodynamic evolution

Fluctuations in rapidity have been included in hydrodynamic calculations via UrQMD [5,6], EPOS [7], or AMPT [8] initial conditions. To study the effect of fluctuations in rapidity in addition to fluctuations in the transverse plane without being dependent on a complicated string with many parameters, we introduce a simple model that is a straightforward extension to the MC Glauber model to include longitudinal fluctuations. In particular, we will employ a Monte Carlo implementation of the Lexus model [9] to provide a simple parametrization of the rapidity distribution of wounded nucleons (or constituent quarks), which is based on experimental observations in proton–proton collisions.

3DMC-Glauber model. For each nucleus we sample the three-dimensional spatial distribution of nucleons from a Woods–Saxon distribution. We then sample valence quark positions within each nucleon from an exponential distribution. After overlaying the two nuclei in the transverse plane, separated by the sampled impact parameter b, wounded quarks are determined using the quark–quark inelastic cross-section σ_{qq}, which can be obtained geometrically by requiring that the experimentally determined nucleon–nucleon cross section is recovered. We do, however,

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treat the quark–quark cross section in heavy ion collisions as an independent, free parameter. When we choose $\sigma_{qq} = 3$ mb at $\sqrt{s} = 200$ GeV, we can reproduce the experimental multiplicity and pseudorapidity distribution of charged hadrons without including additional negative binomial fluctuations. We employ a Gaussian wounding where quarks are determined to be participants with a Gaussian probability [10,11].

As mentioned above, to obtain the longitudinal distribution of the initial baryon number we employ the Lexus model [9]. Here, the idea is that the rapidity distribution of nucleons in heavy ion collisions can be obtained by linear extrapolation from the distribution in p+p collisions. That distribution is parametrized and fit to experimental data. We use this model for valence quarks such that the probability for a quark with rapidity y_P to end up with rapidity y after a collision with a quark with rapidity y_T (from the other nucleus) is given by [9]:

$$Q(y - y_T, y_P - y_T, y - y_P) = \lambda \frac{\cosh(y - y_T)}{\sinh(y_P - y_T)} + (1 - \lambda)\delta(y - y_P), \quad (1)$$

which corresponds to a flat distribution in longitudinal momentum p_L. In the original work [9] λ is the fraction of nucleon–nucleon scatterings that result in a hard collision. Here, we treat λ as a free parameter, regulating the stopping power of the collision. It can be fixed by fitting the net baryon distribution to experimental data. Generally, we find a good fit to the net baryon rapidity distribution when $\sigma_{qq}\lambda \approx 2$ mb.

The initial rapidities are distributed according to the quarks' x value, which is determined by the valence quark parton distribution functions (PDFs).[1] Initial rapidities are thus $y = \pm\ln(x\sqrt{s}/2m_q)$, with the sign depending on whether it is a quark in the projectile (+) or the target (−). We employ a valence quark mass of $m_q = 0.34$ GeV and assume zero transverse momentum initially.

To systematically organize the collisions of all quarks, we have quark pairs collide subsequently with increasing inter-quark distance Δz. We then convert rapidity to space–time rapidity η_s to obtain a three dimensional event-by-event distribution of quarks. To assign a baryon density, this distribution needs to be smeared and we do this by introducing Gaussians in the transverse plane with width $\sigma_T = 0.4$ fm, and width in space–time rapidity of $\sigma = 0.2$.

Next we determine the entropy density distribution. We deposit a fixed entropy between the rapidities of each wounded quark and its last collision partner and smear the edges with half Gaussians of the same width as used for the baryon density distribution. This leads to the following form of the rapidity dependence of the entropy density per wounded quark pair

$$\begin{aligned} s(y, y_P, y_T) = \mathcal{N} \exp[&-\theta(-y + \min(y_P, y_T)) \\ &\times (y - \min(y_P, y_T))^2/2\sigma^2 \\ &- \theta(y - \max(y_P, y_T)) \\ &\times (y - \max(y_P, y_T))^2/2\sigma^2] \\ \times \Big(\max(y_P, y_T) &- \min(y_P, y_T) + \sqrt{2\pi}\sigma\Big)^{-1}, \end{aligned} \quad (2)$$

where y_T and y_P are the rapidities of the colliding quarks, and $\mathcal{N}$ determines the normalization, which is the same for every "tube" and adjusted to fit the experimental data.

In the transverse plane, we smear the entropy density around the center of mass position of each pair by a Gaussian of width $\sigma_T = 0.4$ fm. This way of initializing the entropy density leads to the correct centrality dependence of the total multiplicity.

We note that energy and momentum conservation is not explicitly fulfilled, however, we are not including any transverse momentum production or very high momentum partons, which will carry away some of the energy and momentum of the collision and are not part of the bulk medium we are describing.

A different initial state model using random rapidities for wounded nucleons was employed in [17].

Hydrodynamics. We integrate the above initial condition into the 3+1 dimensional viscous relativistic fluid dynamic simulation MUSIC [18–21]. In addition to numerically solving the equations for the conservation of energy and momentum $\partial_\mu T^{\mu\nu} = 0$, and the baryon current $\partial_\mu J^\mu_B = 0$, we solve the relaxation-type equations derived from kinetic theory [22,23]

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \quad (3)$$

$$\begin{aligned} \tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \phi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} \\ - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}. \end{aligned} \quad (4)$$

The transport coefficients τ_Π, $\delta_{\Pi\Pi}$, $\lambda_{\Pi\pi}$, τ_π, $\delta_{\pi\pi}$, ϕ_7, $\tau_{\pi\pi}$, and $\lambda_{\pi\Pi}$ are fixed using formulas derived from the Boltzmann equation near the conformal limit [23]. At zero baryon chemical potential the ratio η/s will be chosen to be constant in this work, and the temperature dependence of the ratio of bulk viscosity to entropy density ζ/s is parametrized as in [24,25], except that we gradually reduce the constant value at low temperature such that effects of the bulk δf corrections [26] are kept to a minimum. Because we include finite baryon chemical potential $\mu_B > 0$, we replace s in the above expressions by $(\varepsilon + P)/T$, motivated by the relativistic limit of the fluidity measure introduced in [27].

The equation of state, which includes finite baryon chemical potential, is constructed by interpolating the pressures of hadronic resonance gas and lattice QCD [28,29].

We leave a detailed description of the initial state model and the newly constructed equation of state for a longer paper in the future.

After Cooper–Frye freeze out at an energy density of 0.1 GeV/fm^3, the calculation of thermal spectra including δf corrections [26] for shear and bulk viscosities, and resonance decays, we obtain the final hadron spectra as functions of transverse momentum p_T and pseudo-rapidity η_p.

3. Two particle rapidity correlations

The p_T integrated ($p_T > 0.5$ GeV) event-by-event rapidity distributions $dN/d\eta_p$ are then used to determine the two-particle rapidity correlation function [30]

$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle}, \quad (5)$$

where $N(\eta) = dN/d\eta_p$. We follow the ATLAS collaboration [3] and remove the effect of residual centrality dependence in the average shape $\langle N(\eta)\rangle$ by redefining the correlation function as [31]

$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1)C_p(\eta_2)}, \quad (6)$$

where

$$C_p(\eta_{1/2}) = \frac{1}{2Y}\int_{-Y}^{Y} C(\eta_1, \eta_2)d\eta_{2/1}. \quad (7)$$

Importantly, the resulting distribution is then normalized such that the average value of $C_N(\eta_1, \eta_2)$ is one.

[1] The x values are sampled from CT10 NNLO parton distribution functions [12] at $Q^2 = 1$ GeV^2 with EPS09 nuclear correction [13] using LHAPDF 6.1.4 [14].