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THE INITIAL STATE FOR HYDRO AT RHIC*

Adrian Dumitru

Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität
Max-von-Laue Str. 1, 60438 Frankfurt am Main, Germany

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It is well known that perturbative saturation of small-x gluons modifies the transverse momentum distribution in high-energy heavy-ion collisions. Near the unitarity limit, their distribution in coordinate space also differs from the one predicted by leading-twist perturbative QCD or soft particle production models. This implies a different initial condition for the hydrodynamic expansion of the hot plasma formed in such collisions, and thus affects the equation of state and the transport coefficients extracted from RHIC flow data. Accurate data on relative flow fluctuations could help to constrain models for the initial state.

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1. Distribution of produced particles in coordinate space

Consider a collision of two highly relativistic heavy ions at non-zero impact parameter. Their overlap area in the transverse plane has a short axis, parallel to the impact parameter, and a long axis perpendicular to it. This asymmetry of the initial profile is converted by the pressure gradient into a momentum asymmetry called "elliptic flow" [1]. It is characterized by

$$v_2 \equiv \langle \cos 2\varphi \rangle \,, \tag{1}$$

where φ is the azimuthal angle of a particle relative to the reaction plane, and angular brackets denote an average over many particles and many events. The large magnitude of elliptic flow at RHIC [2] has generated a lot of activity in recent years. If the produced matter equilibrates, it behaves as a fluid. Hydrodynamics predicts that at a given energy, v_2 scales like the eccentricity ε of the overlap area [1], $\varepsilon = \langle r_y^2 - r_x^2 \rangle / \langle r_y^2 + r_x^2 \rangle$. The average is taken with respect to the distribution of produced gluons in the transverse plane, which needs to be calculated.

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A common assumption [3] is that by analogy to the Glauber model for soft particle production $dN/dy\, d^2r_\perp \sim \rho^{\mathrm{ave}}_{\mathrm{part}}(r_\perp) \equiv (\rho^A_{\mathrm{part}}(r_\perp)+\rho^B_{\mathrm{part}}(r_\perp))/2$, where ρ^i_{part} is the density of participants of nucleus i per unit transverse area. A $\sim 20\%$ contribution of hard particles needs to be added in order to fit the centrality dependence of dN/dy; their transverse density scales like $n_{\mathrm{coll}} \equiv \sigma_{pp}\, T_A T_B$.

Collisions of large nuclei at high energies may exhibit perturbative gluon saturation, implying that the $\sim 1/k_\perp^2$ growth of the unintegrated gluon distribution (uGD) saturates below a semi-hard scale $Q_{\mathrm{s}}(x)$. The $p_\perp$-integrated multiplicity could then be determined from weak-coupling QCD without additional models for soft particle production. High-density QCD (the "Color-Glass Condensate") predicts a different distribution of gluons in the transverse plane, corresponding to a higher eccentricity ε for intermediate impact parameters. This has been noted first in Ref. [4], using the KLN-ansatz [5] for the uGD. The relation to unitarization of the scattering amplitude from a dense target was pointed out in [6].

Recall that for a semi-central collision, within the Glauber model the transverse density of produced particles is proportional to the *symmetrized* participant density of the two nuclei. In the CGC framework this symmetrization is absent when either A or B is dense: the number of produced particles is linearly proportional only to the density of the dilute collision partner, whose partons add up linearly. Hence, *in the reaction plane*, $dN/dyd^2r_\perp \sim \min(Q\mathrm{s}, A^2, Q^2_{\mathrm{s},B}) \sim \min(\rho^A_{\mathrm{part}}, \rho^B_{\mathrm{part}})$ drops more rapidly towards the edge than $dN/dyd^2r_\perp \sim \rho^{\mathrm{ave}}_{\mathrm{part}}$. This leads to a higher eccentricity [6]. On the other hand, the $Q_{\mathrm{s},A} \leftrightarrow Q_{\mathrm{s},B}$ asymmetry disappears for peripheral collisions; in this limit, therefore, $\varepsilon_{\mathrm{CGC}} \to \varepsilon_{\mathrm{Glauber}}$. This can be checked by quantitative numerical computations, see Fig. 7 in [7]. For this to work, the nuclear uGD has to be constructed rather carefully in such a way that in the surface region $Q_{\mathrm{s}}(r_\perp)$ does not drop below the saturation scale for a single nucleon; it should also account for the fact that the probability of finding one or more nucleons at a given $r_\perp$ becomes small [7].

2. Centrality dependence of v_2

A direct experimental measurement of the initial ε is of course impossible. Although the final momentum-space asymmetry is approximately proportional to the initial coordinate-space asymmetry, $v_2 \simeq c\,\varepsilon$, the coefficient c depends on the viscosity and on the speed of sound, *i.e.*, on the equation of state (EoS) of the plasma. There are (at least) two possible ways to disentangle the effects: *(i)* one can analyze the event-by-event *relative* flow fluctuations $\delta v_2/v_2$; if c is fixed then it drops out from the ratio and $\delta v_2/v_2 = \delta\varepsilon/\varepsilon$ reveals the relative fluctuations of the initial eccentricity. And *(ii)*, one can scrutinize the centrality dependence of v_2 to separate dissipative corrections and EoS. We begin with the latter. In ideal hydrodynamics, v_2/ε is independent of the transverse dimension of the overlap zone, which follows from the scale invariance of ideal-fluid dynamics (with a simple EoS of the form $p = c_s^2 e$). On the other hand, if equilibration is incomplete, then eccentricity scaling is broken and v_2/ε also depends on the Knudsen number $K = \lambda/R$, where λ is the mean-free path. One may therefore attempt to describe the centrality dependence of v_2/ε by the following simple formula [8] (see Fig. 1):

$$\frac{v_2}{\varepsilon} = \frac{v_2^{\rm hydro}}{\varepsilon} \frac{1}{1 + K/K_0} \,, \tag{2}$$

with $K_0 \simeq 1$. Assuming that the relevant time-scale for flow is given by $R/c_{\rm s}$ one can rewrite $1/K = c_{\rm s}\,(\sigma/S)\,dN/dy$, where S is the transverse area. Plotting the measured v_2 divided by ε (from one of the models) *versus* the transverse density displays the approach to the hydrodynamic limit [11].

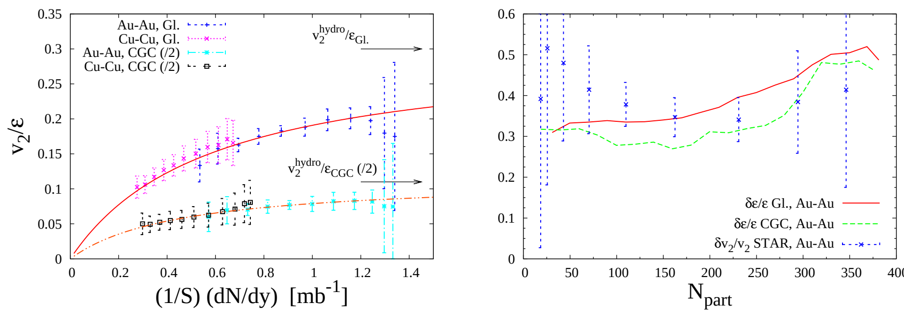

Fig. 1. Left: v_2/ε *versus* the transverse density [9]; $v_2/\varepsilon_{\rm CGC}$ has been scaled by $1/2$ for better visibility. v_2 data from [10]. Right: measured $\delta v_2/v_2$ [13] compared to the calculated fluctuations of the participant eccentricity [14].

Fits of the form (2) give $v_2^{\rm hydro}/\varepsilon_{\rm CGC} = 0.22$ *versus* $v_2^{\rm hydro}/\varepsilon_{\rm Glauber} = 0.3$, *i.e.* the speed of sound associated with the CGC initial conditions is only $0.22/0.3 \simeq 73\%$ of that predicted by the Glauber-like initial state. On the other hand, the effective parton cross-section, $\sigma_{\rm CGC}/\sigma_{\rm Glauber} \simeq 1.77$, is larger by about 77%. This is a direct consequence of $\varepsilon_{\rm CGC} \simeq \varepsilon_{\rm Glauber}$ for peripheral and $\varepsilon_{\rm CGC} > \varepsilon_{\rm Glauber}$ for semi-central collisions, which results in a weaker dependence of v_2/ε on the transverse density and so in a lower Knudsen number K. The parton cross-sections translate into a shear viscosity to entropy density estimate of $\eta/s \simeq 0.11$ for CGC-IC *versus* $\eta/s \simeq 0.19$ for the Glauber model [9]. The $\sim 30\%$ reduction of v_2/ε for central Au–Au collisions relative to the asymptotic (ideal-fluid) $v_2^{\rm hydro}/\varepsilon$ agrees quite well with recent results from dissipative hydrodynamics [12].

The measured upper limits for $\delta v_2/v_2$ [13] are nearly saturated by the expected eccentricity fluctuations [14]. This points at an event-by-event correspondence of the flow with the shape of the overlap zone, which is consistent with the assumption that a large fraction of the observed final-state entropy (or multiplicity) is present already in the early stage (see, also [15]). Moreover, $\delta\varepsilon/\varepsilon$ is smaller for CGC-IC, mainly because the average eccentricity ε is larger. Precise data for $\delta v_2/v_2$ for intermediate centralities may help constrain the models for the initial state, in particular if other contributions to $\delta v_2/v_2$ besides eccentricity fluctuations can be estimated.

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