Collective Dynamics at RHIC

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Abstract. The property of the “perfect liquid” created at RHIC is probed with anisotropic flow measurements. Different initial conditions and their consequences on flow measurements are discussed. The collectivity is shown to be achieved fast and early. The thermalization is investigated with the ratio of $v_4/v_2^2$. Measurements from three sectors of soft physics (HBT, flow and strangeness) are shown to have a simple, linear, length scaling. Directed flow is found to be independent of system size.

1. Introduction: the perfect liquid

As the world’s first heavy ion collider, RHIC has initiated new opportunities for studying nuclear matter under extreme conditions. After six years of successful operations, the discovery of the existence of a perfect liquid in ultra-relativistic heavy ion collisions was announced[1]. Indications of liquid-like behavior of the matter that RHIC has created came in the form of large elliptic flow. Because of the pressure developed early in the collision, the initial spatial deformation due to geometry, which is quantified by eccentricity ($\epsilon$), is converted into the asymmetry in the momentum space, which is quantified by elliptic flow ($v_2$)[2]. This conversion process is directly related to the thermalization, equation of state, etc. The wealth of data collected and analyzed in many aspects, including but not limited to elliptic flow, indicates that central Au+Au collisions can be well described by ideal Hydrodynamics[3]. It suggests that particles in the medium interact with one another rather strongly, which surprised many theoretists who had anticipated an almost ideal, weakly interacting gas. What is more interesting is that, this liquid has little viscosity and acts like a perfect one[4]. This is shown in Fig. 1 in which $v_2$ from data as a function of transverse momentum ($p_T$) is compared to the calculation with sound attenuation length ($\Gamma_s$) scaled by the time scale of the expansion $\tau_o$. The sound attenuation length is related to the shear viscosity ($\eta$) by $\Gamma_s = \frac{4}{3}s\eta(e+p)$, where $e$ and $p$ are energy density and pressure, respectively. We can see that as expected, viscosity reduces $v_2$. The calculation shows that in order to explain the large $v_2$ observed at RHIC, one has to assume that the medium has an extremely small viscosity – the characteristic feature of a perfect liquid.
2. The initial condition

The viscosity is so small that the initial spatial eccentricity is converted to momentum anisotropy with a high efficiency, and this process results in large amount of $v_2$ as reported by RHIC experiments. In this explanation one assumes that the initial spatial eccentricity is from Glauber source[6]. Recent theoretical work (Fig. 2) shows that a different initial condition like Color Glass Condensate (CGC) will give a much larger initial spatial eccentricity than that is from Glauber source. As a consequence of that, the viscosity has to be finite, as opposed to the close-to-zero viscosity in a perfect liquid, in order to reduce the $v_2$ to the level that matches the data. Thus the matter that RHIC has created can be explained either by a perfect liquid with a Glauber source or, a viscous matter with a CGC source. To distinguish between the two, one has to understand the initial condition. However it is not easy to trace the initial condition, because with it
the system starts, and after that the system has gone through thermalization, a possible QGP phase, hadronic interactions and freeze out. A lot of early information can be easily washed out or completely lost due to various effects at later stages. Nevertheless, both theorists and experimentalists begin to realize the importance of the initial condition, and starts to trace its footprints. Fig. 3 shows that for high $p_T$ particles the $v_1$ (solid lines) from CGC flips sign at $\eta \simeq 1.2$, and becomes positive for higher values of rapidity. That means particles are flowing in the same direction as the projective spectator. In the conventional factorized jet production (dashed line), the high $p_T$ $v_1$ is negative and in the same direction as the low $p_T$ bulk directed flow. It would be interesting for experimentalists to test this novel prediction from CGC in the future. One can also exam the initial condition by studying the fluctuation of elliptic flow. Both STAR and PHOBOS collaboration has measured (see Fig. 4) the $v_2$ fluctuation and compared it to the fluctuation from initial conditions assuming Glauber sources. The $v_2$ fluctuation is found to be significant ($\sim 40\%$ relatively), and most of it can be explained by the fluctuation from the Glauber model as the initial condition. It means that, again, the conversion process from the initial spatial eccentricity to momentum anisotropy is so complete that little room is left for fluctuations of other dynamic processes.
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3. Collectivity and thermalization

After the initial collision, particles begin to exchange momentum and the system begins to build up collectivity. Knowing when and how the collectivity is achieved is the first step towards understanding the dynamics in a hot and dense environment. This can be addressed by studying the $v_2$ of $\phi$ and $\Omega$. Both of them are expected to have small hadronic cross section\cite{10} thus are less affected by hadronic interactions. The other reason to choose $\phi$ for this purpose is because of its long lifetime – it decays outside of the fireball and is not formed by $k^+k^-$ coalescence, thus it picks up little information from a later stage. Fig. 5 shows that, although $\phi$ and $\Omega$ tends to suffer much less rescatterings in the hadronic stage of the collision, their $v_2$ are found to be as high as other hadrons at a given $p_T$. Hence the collectivity must be developed fast at a pre-hardonic stage.

Building up collectivity does not necessarily mean that the system is thermalized. In order for the system to be thermalized, particles in the system have to “talk” to each other intensively so that the information like the initial spatial anisotropy can be passed on to all particles. This process depends on number of collisions encountered by each particle. It is expected that both $v_2$ and $v_4$ are proportional to the number of collisions per particle, and thus the ratio of $v_4/v_2^2$ decreases with it\cite{12}. In Fig.6, this ratio is plotted against $p_T$ and compared to theoretical calculations. The Hydro calculation done by Borghini and Jean-Yves\cite{12} suggests that in ideal hydrodynamics, this ratio decreases as a function of $p_T$. Another version of Hydrodynamic calculation\cite{13} shows a similar trend with smaller magnitude. The calculation from the AMPT\cite{14} model shows a more or less flat shape. The data points are higher than theoretical calculations but the systematical errors are also large. It is desirable that in the future the uncertainty from both experiment measurement and theoretical calculation can be reduced, so that the degree of thermalization can be tested.

4. Scaling of soft physics

The number of collisions encountered by each particle on its way out not only plays an important role in thermalization, but also leads to a simple, but interesting scaling of soft physics. Fig. 7 shows that for different collision energies and over a wide range of
collision systems, the HBT radii show a nice linearity if plotted against $dN/dy^{1/3}$, which is proportional to the source’s length, and in turn relates to the number of interactions for a particle on its way out. $R_{out}$ is an exception because it includes both space and time information thus the simple scaling with length is not expected. A similar $dN/dy^{1/3}$ scaling is also observed [17] in the strangeness yield relative to pp. Fig. 8 shows a good linearity if the relative yield of $\Omega$ and $\Xi$ are plotted as a function of $dN/dy^{1/3}$. Also shown in the figure is the theoretical calculation of the enhancement with the correlation volume $V = (N_{part}/2)^{\alpha}V_0$, where $V_0 = 4/3\pi R^3$ and $R$ is the radius of the proton. The curve which fits the shape of the data the best is for the case of $\alpha = 1/3$, which indicates that length plays an important role in strangeness production. Such linearity can be seen in flow measurements as well. In Fig. 9, the $v_2$ is scaled by the initial eccentricity and plotted as a function of particle’s density $1/SdN/dY$, which is also proportional to the length of the system because $dN/dY$ is proportional to the volume and $S$ is the overlap area. Over a broad range of collision energies and system sizes, we observe a good linear relationship between $v_2/\epsilon$ and $1/SdN/dY$. This linear relation disappears if the same quantity plotted against $N_{part}$ (Fig. 10), which is directly related to the volume.
The simple linear scaling from three important sectors of soft physics (HBT, strangeness, flow) suggests that the number of collisions encountered by each particle plays an important role in soft physics. One may venture to predict \( v_2 \), HBT radii and the relative strangeness yield based on this simple scaling, without knowing anything about the collision (energy, system size etc.).
5. Directed flow

Directed flow \((v_1)\) describes the “bounce-off” motion of particles away from midrapidity. As an important tool to probe the system at forward rapidity, it complements our understanding of the dynamics at midrapidity. Directed flow from different energies at SPS has been studied in [21], however its system size dependence has not been well explored. \(v_1\) for Au+Au collisions at both \(\sqrt{s_{NN}} = 62.4\) and 200 GeV have been measured[22], the Cu+Cu data that RHIC experiments collected in year 2005 at the same two energies gives us a good opportunity to study the system size dependence. The left plot in Fig. 11 presents \(v_1\) as a function of pseudorapidity measured by the STAR Collaboration. Data from Cu+Cu collisions and Au+Au collisions at both energies \((\sqrt{s_{NN}} = 62.4 \text{ and } 200 \text{ GeV})\) are shown. The data points fall into two bands, one is for \(\sqrt{s_{NN}} = 62.4\) GeV and the other one is for \(\sqrt{s_{NN}} = 200\) GeV. From Au+Au collision to Cu+Cu collision the system size is reduced by 1/3, however the \(v_1\) does not change. This is true even for the region near midrapidity, where \(v_2\) for Cu+Cu collisions is considerably lower that that for Au+Au collisions [19]. Unlike \(v_2/\epsilon\) which scales with system length, \(v_1\) is found to be independent of system size. Instead, it scales with the incident energy. A possible explanation to the different scalings for \(v_2/\epsilon\) and \(v_1\) might comes from the way in which they are developed : To produce \(v_2\), intensive momentum exchanges among particles are needed (and remember number of momentum exchanges is related to the length), while to produce \(v_1\), one in principle needs only different rapidity losses, which has a connection to the incident energy, for particles having different distances away from the central point of the collision.

One may also test the limiting fragmentation hypothesis [24], which has successfully described particle’s yield and flow at forward rapidity, with different system sizes. The right plot in Fig. 11 re-plotted the same \(v_1\) results as a function of \(\eta - y_{beam}\). We can see that within three units from beam rapidity, most data points fall into a universal curve. This extends the validity of limiting fragmentation to different collision system

![Figure 11. Left: Charged-hardon \(v_1\) vs. \(\eta\) for Au+Au and Cu+Cu collisions at \(\sqrt{s_{NN}} = 62.4\) and 200 GeV. Right: The same data but plotted as a function of \(v_1\) vs. \(\eta - y_{beam}\). Both plots are from [23].](image)
sizes. There are evidences\cite{15} show that limiting fragmentation also works for higher harmonics like $v_4$.

6. Summary

In summary, rich results from RHIC support a Hydrodynamic expansion of a thermalized fluid, in which the collectivity is achieved fast and at the very early time. Understanding the initial condition plays a key role in understanding what happens thereafter. Studying elliptic flow fluctuation, as well as directed flow for high $p_T$ particles, may help us constraint the initial condition. A few key observables from soft physics are found scaling with system length, which is directly related to the average number of interactions for a particle on its way out. Directed flow is found to depend on the incident energy but not on the system size. Limiting fragmentation holds for different collision energies, systems and flow harmonics.

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