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ELLIPTIC FLOW FLUCTUATIONS IN NUCLEUS–NUCLEUS COLLISIONS*

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Measurements of elliptic flow in high-energy nucleus–nucleus suggest that in these collisions a strongly interacting medium is formed. The expansion of this medium appears to be well described by ideal hydrodynamics. Further information about the properties of the medium and the hydrodynamic evolution can be obtained by studying not just the average strength of elliptic flow, $\langle v_2 \rangle$, but also event-by-event fluctuations in the elliptic flow coefficient, v_2. However, the quantitative interpretation of current measurements of v_2 fluctuations is complicated by the presence of multi-particle correlations between final state hadrons. We will discuss the status of v_2 fluctuation measurements, the influence of non-flow particle correlations and possible approaches to obtain the "true" v_2 fluctuation strength.

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1. Flow, hydrodynamics and initial geometry

The first study of the final state anisotropy of charged hadron production at RHIC was performed by the STAR Collaboration [1]. In that paper, the second Fourier-coefficient, $\langle v_2 \rangle$, of the azimuthal distribution of charged particles relative to the reaction plane ("elliptic flow") was measured as a function of collision centrality. For the most peripheral collisions, $\langle v_2 \rangle$ was shown to reach a value bigger than 6%. Since then, measurements of elliptic flow as a function of pseudo-rapidity, p_{T} and particle species have been performed by the four RHIC collaborations. The data on elliptic flow formed a central part of the argument that in RHIC Au+Au collisions a strongly interacting medium is formed, undergoing an expansion following near-ideal hydrodynamics [2]. In this interpretation of the Au+Au data, the average initial eccentricity of the interaction zone is directly reflected in the average final state angular distribution of produced hadrons relative to the reaction plane.

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An indication that this picture needed to be refined was given by the first data on elliptic flow in Cu+Cu collisions at RHIC, shown in 2005. Even for the most central Cu+Cu collisions, a large value of $\langle v_2 \rangle \approx 0.03$ is observed, whereas the azimuthal distribution of participant nucleons relative to the reaction plane is nearly isotropic, when *averaged* over many of these central collision events. This points to the importance of event-by-event fluctuations in the initial geometrical shape. As Fig. 1 demonstrates, the elliptic flow results for Cu+Cu and Au+Au collisions can be plotted consistently as a function of initial density, when normalized by the so-called participant eccentricity, $\epsilon_{\rm part}$, obtained from Glauber MC calculations [4]. The participant eccentricity is defined as $\epsilon_{\rm part} \equiv \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4(\sigma_{xy})^2}}{\sigma_y^2+\sigma_x^2}$. This definition takes event-by-event fluctuations in the distribution of participant nucleons into account [5] and therefore does not approach zero even for collisions with impact parameter $b = 0$.

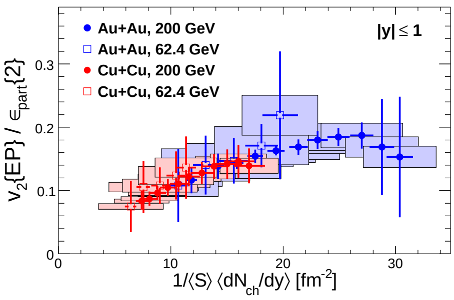

Fig. 1. Elliptic flow parameter $\langle v_2 \rangle$ normalized to $\epsilon_{\rm part}$ for Cu+Cu and Au+Au collisions, as a function of particle area density [3].

The comparison of Cu+Cu and Au+Au data suggests, that fluctuations in the initial geometry are reflected in the average values of $\langle v_2 \rangle$ in the respective systems. In a hydrodynamic picture, the eccentricity fluctuations should also be reflected in v_2 event-by-event, as each single event undergoes hydrodynamic expansion from a given initial geometry [6].

2. v_2 fluctuations and particle correlations

Measurements of non-statistical v_2 fluctuations have been performed by the PHOBOS and STAR experiments and reported at QM 2006 [8]. A detailed description of the rather sophisticated analysis required to extract the relevant fluctuation signal can be found in [9]. The results reported by the two collaborations are shown in Fig. 2 as a function of collision centrality. The data show good agreement between the two experiments, and surprisingly also quantitative agreement with the eccentricity fluctuations calculated in a Glauber MC simulation.

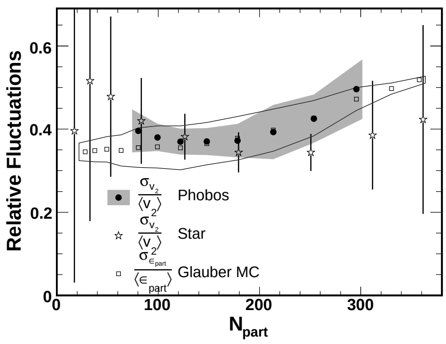

Fig. 2. Elliptic flow fluctuations $\sigma(v_2)/\langle v_2 \rangle$ for Au+Au collisions at 200 GeV as a function of collision centrality. Solid symbols show PHOBOS data, open stars show preliminary STAR data. Also shown are the expected participant eccentricity fluctuations in a Glauber calculation. See text regarding the corrections for non-flow effects for the two data sets.

However, the quantitative interpretation of the data is complicated by the fact that final-state hadrons are not produced independently, but exhibit strong correlations in momentum space. This is readily visible in two-particle correlation functions such as that shown in Fig. 3 for mid-central Cu+Cu collisions. The correlation function exhibits a clear flow signal ($\cos(2\Delta\phi)$ modulation), with superimposed short range correlations closer to $\Delta\eta = 0$. The detailed origin of the short-range correlations is not understood at this time, with contributions expected from resonances, fragmentation of strings and (mini-)jets, as well as Bose–Einstein– and Coulomb-correlations. Due to this uncertainty, STAR now regards the result shown in Fig. 2 as an upper limit for the true underlying v_2 fluctuations.

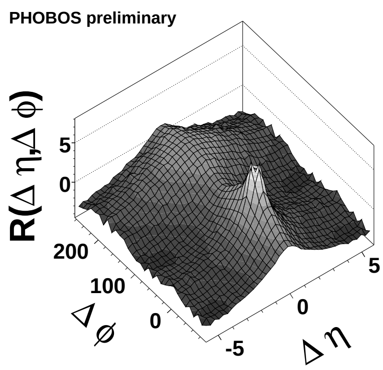

Fig. 3. Two-particle angular correlation function for mid-central Cu+Cu collisions at 200 GeV [7].

The presence of the correlations distorts the measurement of non-statistical v_2 fluctuations in several ways. First, the effective number of degrees of freedom determining the expected statistical variation of v_2 from event to event depends on the strength of non-flow particle correlations. Secondly, the event-by-event v_2 measurement effectively includes a measurement of the event-by-event reaction plane, which again is distorted by the presence of two-particle correlations.

As Sorensen *et al.* [8] have pointed out, the relevant quantity characterizing the influence of particle correlations on v_2 fluctuation measurements, is the $\langle\cos(2\Delta\phi)\rangle$ term of the (flow-subtracted) correlation function, *i.e.* a term that looks exactly like the elliptic flow effect. Obviously, a data-based correction for such an effect is non-trivial. Studies based on correlations in $p+p$ data or MC generators like `HIJING` yield rather small corrections for the v_2 fluctuations. However, as the origin of the correlation signal is not understood well, it is not clear whether such $p+p$ based corrections are sufficient for the Au+Au data.

There are several efforts underway to correct the present measurement of v_2 fluctuations of final state hadrons to obtain the underlying true event-by-event variation of v_2. Using a azimuthally segmented forward calorimeter, STAR will be able to get a reaction plane measurement that is independent of the mid-rapidity hadrons used for the v_2 measurement. PHOBOS is investigating a separation of flow effects and non-flow correlations using its large rapidity coverage and the short-range nature in $\Delta\eta$ of the non-flow correlations. First results from these new approaches should be shown at the QM2008 conference and should bring us a step closer to using v_2 fluctuation results to further constrain the hydrodynamic description of heavy-ion collisions.

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