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Abstract. We present the first measurement of directed flow (v_1) at the Relativistic Heavy Ion Collider (RHIC). v_1 is found to be consistent with zero at pseudorapidities η from -1.2 to 1.2, then rises to the level of a couple of percent over the range $2.4 < |\eta| < 4$. The latter observation is similar to that from NA49 if the SPS rapidities are shifted by the difference in beam rapidity between RHIC and SPS. We studied the evolution of elliptic flow from p+p collisions through d+Au collision, and onto Au+Au collisions. Measurements of higher harmonics are presented and discussed.

Keywords: RHIC, anisotropic flow, STAR
PACS: 25.75.Ld

1. Introduction

Study of anisotropic flow is widely recognized as an important tool to probe the hot, dense matter that is created by the heavy ion collisions [1]. Anisotropic flow means that, in non-central heavy ion collisions, the azimuthal distribution of outgoing particles with respect to the reaction plane is not uniform. It can be characterized [2] by Fourier coefficients

$$v_n = \langle \cos n(\phi - \psi) \rangle \tag{1}$$

where ϕ denotes the azimuthal angle of an outgoing particle, ψ is the orientation of the reaction plane, and n denotes the harmonic. The first Fourier coefficient, v_1, referred to as *directed flow*, describes the sideward motion of the fragments in ultra-relativistic nuclear collisions and it carries early information from the collision. Its shape at midrapidity is of special interest because it might reveal a signature of a possible phase transition from normal nuclear matter to a quark-gluon plasma [3]. Elliptic flow (v_2) is caused by the initial geometric deformation of the reaction region in the transverse plane. At low transverse momentum, roughly speaking, large values of elliptic flow are considered signatures of hydrodynamic behavior. At large transverse momentum, in a *jet quenching* picture [4], elliptic flow results from jets emitted out-of-plane suffer more energy loss than those emitted in-plane.

Higher harmonics reflect the details of the initial geometry. Recently it is reported [5] that the magnitude and even the sign of v_4 are more sensitive than v_2 to initial conditions in the hydrodynamic calculations.

2. Data set

The data come from the second year of operation of Relativistic Heavy Ion collider (RHIC) at its top energy $\sqrt{s_{\rm NN}} = 200$ GeV. The STAR detector [6] main Time Projection Chamber (TPC [7]) and two forward TPCs (FTPC [8]) were used in the analysis. The data set consists of about 2 million minimum bias and 1.2 million central trigger Au+Au events , 7 million d+Au minimum bias events and 11 million p+p minimum bias events. For v_1 analyses there were 70 thousand events available which included the FTPCs. The centrality definition in this paper is the same as used previously by STAR [9]. Tracks used to reconstruct the flow vector, or generating function in case of cumulant method, were subject to the same quality cuts that were used in $\sqrt{s_{\rm NN}} = 130$ GeV analysis [10], except for the low transverse momentum cutoff, which for this analysis is 0.15 GeV/c instead of 0.1 GeV/c. For the scalar product analysis (introduced later in this paper), a tight cut on η (from $-1.$ to 1.) is applied on the flow vector, as well as a tight cut on distance of the closest approach (DCA) (from 0 to 1 cm).

3. Results

3.1. Directed flow at RHIC

The difficulties in studying directed flow are that the signal is small and the non-flow contribution to the two-particle azimuthal correlations can be comparable or even larger than the correlations due to flow. We use the three-particle cumulant method [11] and event plane method with mixed harmonics [2] in v_1 analysis and the results agree with each other [12]. Both methods are less sensitive to two-particle non-flow effects because they measure three-particle correlations

$$\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle = v_{1,a} v_{1,b} v_{2,c}, \tag{2}$$

in which there are no two-particle correlation terms and thus no non-flow contributions from them. The remaining non-flow is expected to cause a relative error of 20%, which is the major systematic uncertainty in this analysis.

Fig. 1 shows v_1 from three-particle cumulants ($v_1\{3\}$) along with corresponding results from NA49 [13]. The RHIC $v_1(\eta)$ results differ greatly from the directly-plotted SPS data in that they are flat near midrapidity and only become significantly different from zero at the highest rapidities measured. However, when the NA49 data is re-plotted in terms of rapidity relative to beam rapidity, they look similar. In the pseudorapidity region $|\eta| < 1.2$, $v_1(\eta)$ is approximately flat with a slope of (-0.25 ± 0.27)% per unit of pseudorapidity, which is consistent with predictions [3]. Within errors we do not observe a wiggle in $v_1(\eta)$ at midrapidity. The quoted error is statistical only.

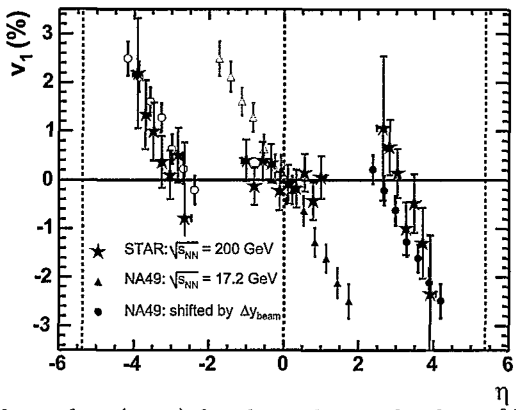

Fig. 1. The values of v_1 (stars) for charged particles for 10% to 70% centrality plotted as a function of pseudorapidity. Also shown are the results from NA49 (solid triangles) for pions from 158A GeV Pb+Pb midcentral (12.5% to 33.5%) collisions plotted as a function of rapidity. The measured NA49 points have also been shifted forward (solid circles) by the difference in the beam rapidities of the two accelerators. The open points have been reflected around midrapidity. The dashed lines indicate midrapidity and RHIC beam rapidity. Both results are from analyses involving three-particle cumulants, $v_1\{3\}$. This plot is taken from [14].

3.2. The evolution of elliptic flow

It is interesting to see how elliptic flow evolves from p+p collisions, in which non-flow dominates, through d+Au collisions, where some correlation with the reaction plane might develop, and finally to Au+Au collisions, where flow dominates. To do such a comparison, we calculate the azimuthal correlation of particles as a function of p_t with the entire flow vector of all particles used to define the reaction plane (scalar product [10]). The correlation in Au+Au collisions, under the assumption that non-flow effects in Au+Au collisions are similar to those in p+p collisions, is the sum of the flow and non-flow contribution and are given by:

$$\langle u_t Q^* \rangle_{AA} = M_{AA}\, v_t\, v_Q + \langle u_t Q^* \rangle_{pp}, \tag{3}$$

where $Q = \sum u_j$ and Q^* its complex conjugate, $u_j = e^{2i\phi_j}$, v_t is flow of particles with a given p_t, and v_Q is the average flow of particles used to define Q. The first term in the r.h.s. of Eq. 3 represents the flow contribution; M_{AA} is the multiplicity of particles contributing to the Q vector. This type of variable also can be extracted from the cumulant approach [11, 16]: If we change the generating function that is used in the cumulant calculation [15] to

$$G(z) = \prod_{j=1}^{M} \left(1 + z^* u_j + z u_j^*\right), \tag{4}$$

where z is an arbitrary complex number and z^* denotes its complex conjugate. Then for a system that is a superposition of two independent system 1 and 2, and only "non-flow" correlations are present, we have

$$G(z) = G_1(z)G_2(z). \tag{5}$$

So if a nucleus-nucleus collision is a simple superposition of N independent p+p collisions, then

$$G(z) = [G_{pp}(z)]^N. \tag{6}$$

We can readily see from Eq.(6) that $Log(G(z))$ should scale linearly with N, so also should cumulants, which is the coefficient of z of $Log(G(z))$. In the case of a second order cumulant, this is

$$M^2\langle u_i u_j^*\rangle = M\langle uQ^*\rangle, \tag{7}$$

dividing it by the scale factor (which is the multiplicity) one recovers Eq. 3 in the case if there is only non-flow.

The scalar product is a convenient quantity for this purpose because it is independent of multiplicity, which is very different in three collision systems. In the case of that only "non-flow" is present, scalar product should be the same for all three collision systems regardless of their system sizes. Any deviation from fundamental p+p collisions for the scalar product results from collective motions and/or effects from medium modification.

Fig. 2 shows the azimuthal correlation as a function of transverse momentum for three different centrality ranges in Au+Au collisions compared to minimum bias d+Au collisions and minimum bias p+p collisions. The difference at low p_t between d+Au collisions and p+p collisions increases as a function of centrality (not shown) that is defined by the multiplicity in Au side, indicating that more collective motion is developed among soft particles in central d+Au collisions. This is consistent with Cronin effect in d+Au collisions, in which one expects that more scattering with soft particles is needed in order to generate a relative high p_t particle. For Au+Au collisions, in middle central events we observe big deviation from p+p collisions that is due to the presence of elliptic flow, while in peripheral events, collisions are more like fundamental p+p collisions. At p_t beyond 5 GeV/c in central collisions, the azimuthal correlation in Au+Au collisions starts to follow that in p+p collisions, indicating a possible recovery of independent fragmentation. The centrality dependence of the azimuthal correlation in Au+Au collisions is clearly non-monotonic, being relatively small for very peripheral collisions, large for mid-central collisions, and relatively small again for central collisions. This non-monotonic centrality dependence is strong evidence that in mid-central collisions (60%-20%) the measured finite v_2 for p_t up to 7 GeV/c is due to real correlations with the reaction plane.

3.3. Higher harmonics

Fig. 3 shows the centrality dependence for p_t-integrated v_2, v_4, and v_6 with respect to the second harmonic event plane and also v_4 from three-particle cumulants ($v_4\{3\}$). The five-particle cumulant, $v_4\{5\}$, is consistent with both methods but

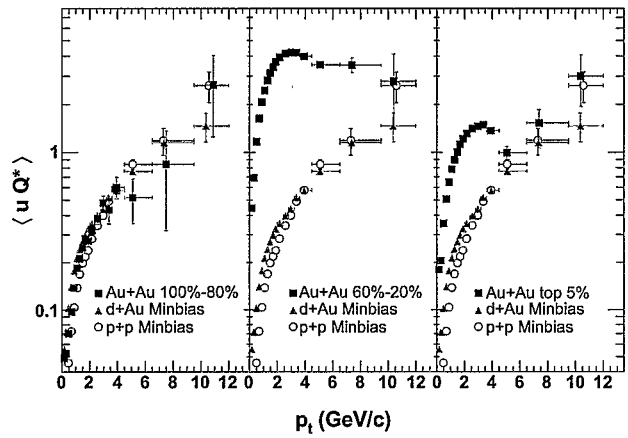

Fig. 2. Azimuthal correlations in Au+Au collisions (squares) as a function of centrality (peripheral to central in the panels from left to right) compared to azimuthal correlations in minimum bias p+p collisions (circles) and d+Au collisions (triangles).

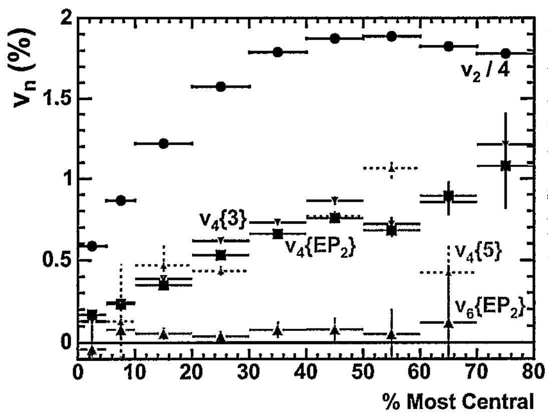

Fig. 3. The p_t- and η- integrated values of v_2, v_4, and v_6 as a function of centrality. The v_2 values have been divided by a factor of four to fit on scale. Also shown are the three particle cumulant value ($v_4\{3\}$) and five particle cumulant value ($v_4\{5\}$).

the error bars are about two times larger. The v_6 values are close to zero for all centralities. These results are averaged over p_t, thus reflecting mainly the low p_t region where the yield is large, and also averaged over η for the midrapidity region accessible to the STAR TPC ($|\eta|<1.2$). There has been a long history of searching for higher harmonics and this is the first successful attempt of measuring higher harmonics in heavy ion collisions. Such detailed measurement of the shape of the event challenges in ever more detail the models describing the reaction.

4. Conclusions

We have presented the first measurement of v_1 at RHIC energies. Within errors $v_1(\eta)$ is found to be approximately flat in the midrapidity region, which is consistent with microscopic transport models, as well as hydrodynamical models where the flatness is associated with the development of the expansion in the direction opposite to the normal directed flow. Using the scalar product method, we studied the evolution of elliptic flow from elementary collisions (p+p) through collisions involving cold nuclear matter (d+Au), and then onto hot, heavy ion collisions (Au+Au). Measurements of higher harmonics are presented and discussed.

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