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### **Author**

Oldenburg, Markus D.

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# Anisotropic flow in the forward directions at $\sqrt{s_{NN}} = 200$ GeV

Markus D. Oldenburg\*  
(for the STAR Collaboration)

Lawrence Berkeley National Laboratory  
Nuclear Science Division  
MS70R0319, One Cyclotron Road  
Berkeley, California, 94720, USA  
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The addition of the two Forward TPCs to the STAR detector allows one to measure anisotropic flow at forward pseudorapidities. This made possible the first measurement of directed flow at collision energies of  $\sqrt{s_{NN}} = 200$  GeV. PHOBOS' results on elliptic flow at forward rapidities were confirmed, and the sign of  $v_2$  was determined to be positive for the first time at RHIC energies. The higher harmonic,  $v_4$ , is consistent with the recently suggested  $v_2^2$  scaling behavior.

This write-up contains results presented as a poster at the Quark Matter conference in Oakland, California in January 2004.

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## I. INTRODUCTION

In non-central heavy-ion collisions the initial spatial anisotropy of the collision region translates into a final state anisotropy in momentum space. In a hydrodynamical picture this is believed to be due to pressure gradients in the dense medium which lead to collective motion — so called transverse flow — of the generated particles.

The simplest way of characterizing these final state anisotropies is to perform a Fourier decomposition on the particle's emission angles  $\phi$  with respect to the reaction plane  $\Psi_{RP}$  [1]. The reaction plane is given by the incident beam direction and the impact parameter and it is experimentally not known *a priori*. It has to be estimated for every event by looking at the anisotropy of particle emission itself [2]. This leads to a finite resolution of the measured event plane which one has to correct for.

Spurious contributions to the measured transverse flow signal are particle correlations due to non-flow effects (e.g. resonance decays). To cope with these, several new methods of the anisotropic flow analysis, based either on cumulants [3, 4] or on Lee-Yang zeros [5], have been proposed.

## II. EXPERIMENTAL SETUP

The two Forward TPCs (FTPCs [6]) of the STAR experiment [7] extend the pseudorapidity coverage of STAR into the region  $2.5 < |\eta| < 4.0$ . The pseudorapidity resolution of these radial drift chambers is better than 5% for their full acceptance. During RHIC run 2 about 70 thousand Au+Au collisions at a center of mass energy

of  $\sqrt{s_{NN}} = 200$  GeV were taken with both FTPCs and the STAR TPC [8].

## III. MEASUREMENTS

### A. Directed Flow $v_1$

The first measurement of directed flow at RHIC energies was recently published [9] (see Fig. 1). It showed that while  $v_1(\eta)$  is close to zero at mid-rapidities, the signal rises to a couple of percent near pseudorapidity  $|\eta| \approx 4$ .

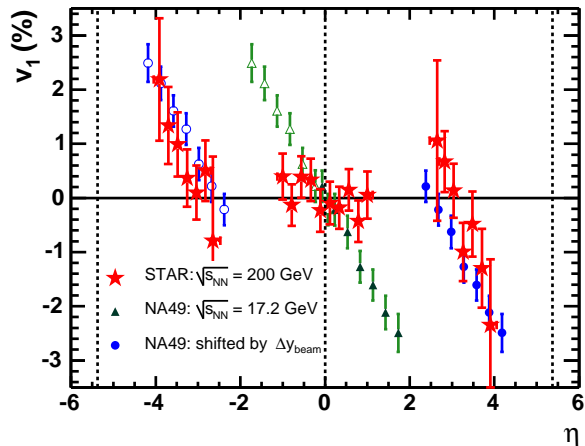


FIG. 1: Directed flow measured at  $\sqrt{s_{NN}} = 200$  GeV compared to results measured by NA49 in fixed-target collisions at 158A GeV. The red stars show our measurement of  $v_1\{3\}$ . We see a clear signal of directed flow at forward pseudorapidities. While our signal differs greatly from the measured result by NA49 [10] (green triangles), there is a good agreement between the two signals in the projectile frame.

\*Electronic address: MD01denburg@lbl.gov

It was noted that our measurement greatly differs from the NA49 results [10] at lower beam energies of 158A GeV. But if the NA49 data are shifted and both measurements are seen in the projectile frame, they look similar.

## B. Elliptic flow $v_2$

The comparison of our new measurement on elliptic flow  $v_2(\eta)$  at forward pseudorapidities confirms the published result [11] obtained by the PHOBOS collaboration (see Fig. 2) at high  $\eta$ . We observe a similar fall-off by a factor of 1.8 comparing  $v_2(\eta = 0)$  with  $v_2(\eta = 3)$ . Both measurements were done using the event plane method.

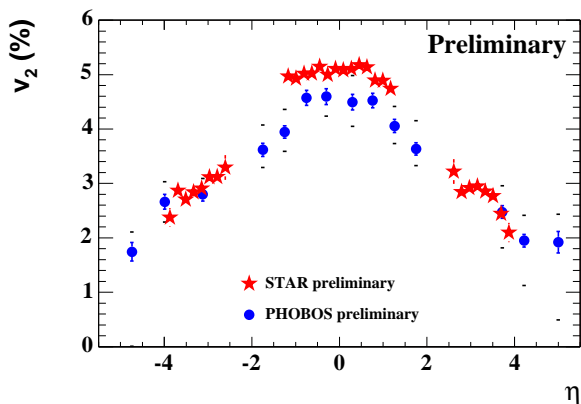


FIG. 2: Elliptic flow  $v_2$  vs. pseudorapidity  $\eta$  at  $\sqrt{s_{NN}} = 200$  GeV. The measured  $v_2(\eta)$  from the STAR collaboration (red stars) agrees very well with the published [11] (but preliminary) results by PHOBOS at forward pseudorapidities: the fall-off from  $\eta = 0$  to  $|\eta| = 3$  is confirmed.

If we compare our results for  $v_2$  obtained with the method of two-particle cumulants,  $v_2\{2\}$ , to the four-particle cumulants,  $v_2\{4\}$ , we observe almost no difference in the FTFC region, while the two-particle cumulant measurement gives a 15% higher signal in the TPC. Since four-particle cumulants are much less prone to non-flow contributions we conclude that non-flow effects are less strong in the forward regions.

## C. A new method to measure directed flow

From the above measurements it became clear that the STAR TPC sitting at mid-rapidity has very good capabilities to measure elliptic flow, while the Forward TPCs allow to measure directed flow (which appears to be close to zero at mid-rapidities).

### 1. $v_1\{EP1, EP2\}$

In order to utilize the method of Fourier decomposition but to reduce non-flow contributions at the same time, we measured  $v_1$  with respect to the first and second order reaction plane  $\Psi_1$  and  $\Psi_2$ , where  $\Psi_1$  was determined in the FTFCs while  $\Psi_2$  was measured in the TPC. Within the recently proposed notation (see [9]) we denote this measurement as  $v_1\{EP1, EP2\}$ .

$$v_1\{EP1, EP2\} = \frac{\langle \cos(\phi + \Psi_1^{\text{FTFC}} - 2\Psi_2^{\text{TPC}}) \rangle}{\sqrt{\langle \cos(\Psi_1^{\text{FTFC}_1} + \Psi_1^{\text{FTFC}_2} - 2\Psi_2^{\text{TPC}}) \rangle \cdot \text{Res}(\Psi_2^{\text{TPC}})}}. \quad (1)$$

As shown in Fig. 3, the results are in reasonable agreement with the published measurement obtained by the three-particle cumulant method  $v_1\{3\}$ .

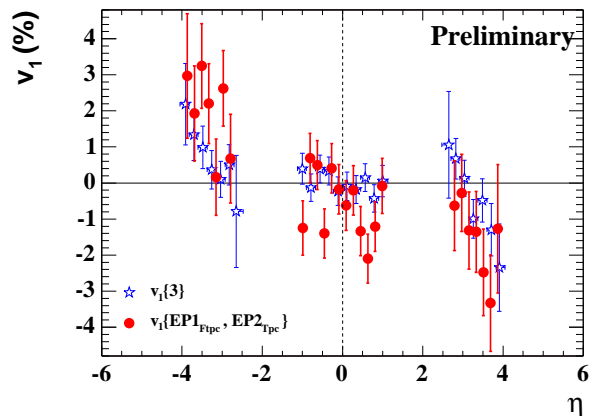


FIG. 3: Directed flow with respect to the first and second order reaction plane as a function of pseudorapidity. The measurements of  $v_1\{EP1, EP2\}$  (red circles; centrality 20–60%) agree within the errors with the published results of  $v_1\{3\}$  (centrality 10–70%).

### 2. The sign of $v_2$

This new method provides an elegant tool to measure the sign of  $v_2$ , which was assumed to be positive but had not yet been determined at RHIC energies. One of the quantities involved in the measurement of  $v_1\{EP1, EP2\}$  is approximately equal to the product of integrated values of  $v_1^2$  and  $v_2$ :

$$v_1^2 \cdot v_2 \approx \frac{\langle \cos(\Psi_1^{\text{FTFC}_1} + \Psi_1^{\text{FTFC}_2} - 2\Psi_2^{\text{TPC}}) \rangle}{\sqrt{M_{\text{FTFC}_1} \cdot M_{\text{FTFC}_2} \cdot M_{\text{TPC}}}}, \quad (2)$$

where  $M_{\text{FTFC}_1}$ ,  $M_{\text{FTFC}_2}$ , and  $M_{\text{TPC}}$  denote the multiplicities for a given centrality bin in the two FTFCs and the TPC, respectively. Since  $v_1^2$  is always positive, the sign of  $v_1^2 \cdot v_2$  determines the sign of  $v_2$ .

Averaged over centralities 20–60% we measure  $v_1^2 \cdot v_2$  in Fig. 4 to be  $(1.08 \pm 0.46) \cdot 10^{-5}$ . In this region the expected non-flow contributions are much smaller than for the most central and peripheral centrality bins. Therefore the sign of  $v_2$  is determined to be positive: *In-plane* elliptic flow is confirmed. (This stated value for  $v_1^2 \cdot v_2$  and its uncertainty is based on an approximation that does not affect the statistical significance of the conclusion that  $v_2$  is *in-plane*.)

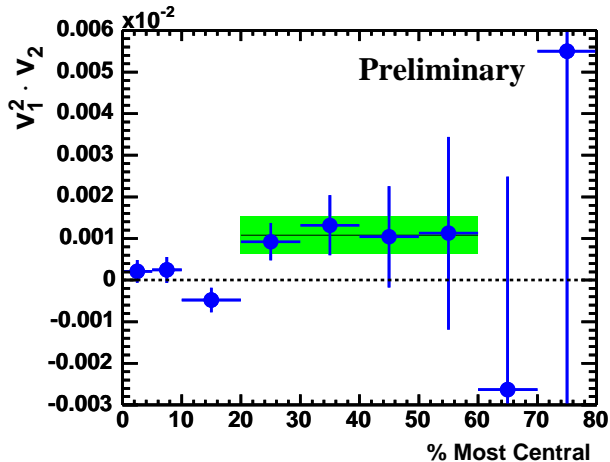


FIG. 4: The product of  $v_1^2$  and  $v_2$ . Since the mean value of this quantity, averaged over centralities 20–60%, is  $(1.08 \pm 0.46) \cdot 10^{-5}$ , elliptic flow is measured to be *in-plane*.

#### D. The fourth harmonic $v_4$

Since elliptic flow  $v_2$  is strong, the second order reaction plane  $\Psi_2$  can be estimated with high precision at RHIC energies. This makes the study of higher order flow feasible [9].

The fourth harmonic  $v_4$  shows an average value of  $(0.4 \pm 0.1)\%$  in pseudorapidity coverage of the TPC ( $|\eta| < 1.2$ ), see Fig. 5. In contrast, its value of  $(0.06 \pm 0.07)\%$  in the forward regions is consistent with zero and we place a  $2\sigma$  upper limit of 0.2%. Therefore the fall-off of  $v_4$

from mid-rapidities to forward rapidities appears to be stronger than for  $v_2$ . This behavior is consistent with scaling like  $v_4 \sim v_2^2$ .

#### IV. FUTURE DEVELOPMENTS

First attempts to make use of the newly proposed method [5] utilizing Lee-Yang zeros are encouraging. This method eliminates higher order non-flow contributions by construction. It is mathematically equivalent to the *all-particle* cumulant method  $v\{\infty\}$  which takes into account all higher order non-flow effects. The great

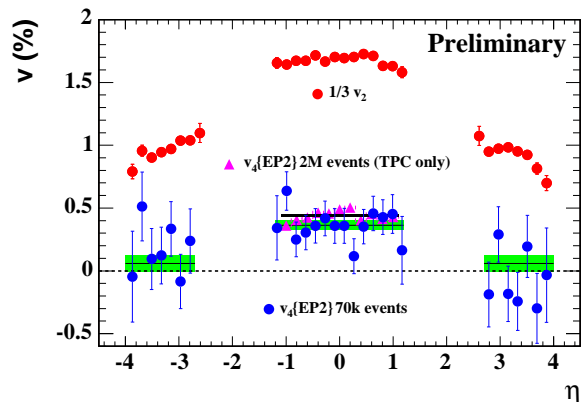


FIG. 5: Comparison of  $v_2$  to  $v_4\{\text{EP2}\}$ . The fourth harmonic (blue circles) is consistent with zero at forward pseudorapidities while it reaches  $(0.4 \pm 0.1)\%$  at mid-rapidities. Compared to the measurement of elliptic flow  $v_2$  (red circles, scaled by a factor of 1/3 to fit on the plot) the fall-off from  $\eta = 0$  to  $|\eta| = 3$  is stronger. The larger dataset available for the TPC only (magenta triangles) confirms our measurement of  $v_4\{\text{EP2}\}$  at mid-rapidities.

advantage of the new method is its simplicity and speed compared to the evaluation of the cumulants.

The upcoming RHIC run 4 will greatly enhance our data sample. With it we will reduce our statistical uncertainties in the forward pseudorapidity region significantly.

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