**Centrality dependence of $v_2$ in Au + Au at $\sqrt{s_{NN}} = 200$ GeV unidentified charged hadron $v_2$ with respect to the first harmonic ZDC-SMD event plane**

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**Abstract.** One of the most striking results is the large elliptic flow ($v_2$) at RHIC. Detailed mass and transverse momentum dependence of elliptic flow are well described by ideal hydrodynamic calculations for $p_T < 1$ GeV/c, and by parton coalescence/recombination picture for $p_T = 2 - 6$ GeV/c. The systematic error on $v_2$ is dominated by so-called "non-flow effects", which is the correlation not originated from reaction plane. It is crucial to understand and reduce the systematic error from non-flow effects in order to understand the underlying collision dynamics. In this paper, we present the centrality dependence of $v_2$ with respect to the first harmonic event plane at ZDC-SMD ($v_2\{\text{ZDC-SMD}\}$) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Large rapidity gap ($|\Delta \eta| > 6$) between midrapidity and the ZDC could enable us to minimize possible non-flow contributions. We compare the results of $v_2\{\text{ZDC-SMD}\}$ with $v_2\{\text{BBC}\}$, which is measured by event plane determined at $|\eta| = 3.1 - 3.9$. Possible non-flow contributions in those results will be discussed.

**PACS.** 25.75.-q Relativistic heavy-ion collisions – 25.75.Ld Collective flow

1 Introduction

Elliptic flow is expected to be one of the key observables to study an early stage of heavy ion collisions [1]. It is defined by the second harmonic Fourier coefficient

$$v_2 = \langle \cos(2[\phi - \Psi_{RP}]\rangle, \quad (1)$$

where $\phi$ is the azimuthal angle of emitted particles, $\Psi_{RP}$ is the azimuthal angle of reaction plane and brackets denote the average over all particles and events.

The PHENIX experiment at Relativistic Heavy Ion Collider (RHIC) have measured the $v_2$ for identified charged hadrons [2,3], $\phi$ mesons and deuterons [4], $\pi^0$'s and photons [5] as well as electrons from heavy flavor decays [6] at midrapidity. The mass ordering of $v_2$ for identified hadrons were qualitatively explained by ideal hydrodynamics in transverse momentum $p_T < 2$ GeV/c [2]. For intermediate $p_T = 2 - 6$ GeV/c, a universal parton $v_2$ were obtained by dividing $v_2$ and $p_T$ by constituent quarks for each hadron [2,3]. The $v_2$ for $\phi$ meson was also found to follow the quark number scaling, which support that the parton $v_2$ have already developed prior to the hadronization [4]. Because the cross section of $\phi$ meson to non-strange hadrons are small, $\phi$ meson $v_2$ is less sensitive to the late hadronic stage. The finite $v_2$ for electrons from heavy flavor decays implied the non-zero charm $v_2$ [3]. Comparison of $v_2$ with transport model calculation suggest that the viscosity to entropy density ratio is close to the quantum lower bound $1/4\pi$ [7].

These measurements were done by using an event plane determined from the Beam-Beam Counter (BBC) located at pseudorapidity $|\eta| = 3.1 - 3.9$. The large pseudorapidity separation $|\Delta \eta| \sim 3$ from midrapidity would reduce non-flow effects, which are correlations not originated from the reaction plane such as jets, resonance decays and so on. Fluctuations of $v_2$ were also considered as the non-flow contributions [3], which would become more important in smaller system, such as Cu + Cu collisions. It is crucial to understand how non-flow contributions affect the event plane determined at the BBC so that we could validate a sensitivity to real collective flow on our measured $v_2$ based on the BBC.

In this paper, we present the $v_2$ with respect to the event plane from directed flow determined at the Shower Maximum Detector (SMD), which is located at $|\eta| > 6$. The larger rapidity separation could reduce the possible non-flow effects on our measured $v_2$. We will compare the $v_2$ results from the event planes determined at the BBC and SMD and discuss the possible non-flow contributions on the $v_2$.

2 Data Analysis

In this study, we analyzed $\sim 650$ M events collected by the PHENIX experiment in Au + Au at $\sqrt{s_{NN}} = 200$ GeV. Minimum bias events were selected within a collisions z-vertex $\pm 30$ cm. Event centrality was determined by the...
correlation between the energy deposit at the Zero Degree Calorimeter (ZDC) and number of charged particles at the BBC. Tracking were done by the Drift Chamber (DC) and Pad Chambers (PCs) at the central arm $|\eta| < 0.35$. Transverse momentum were determined by the incident angle at the DC. The polar angle of the tracks were obtained by the hit at the inner PC (PC1) and the collision vertex from the BBC. Track associations were made by comparing hit positions with the projection of the DC tracks to the outer Pad Chamber (PC3). Tracks were required to have a hit on the PC3 within $\pm 3\sigma$ of the expected hit location in both azimuthal and beam directions. Large energy deposit $E/p > 0.2$ at the Electromagnetic Calorimeter (EMCal) were also required, where $E$ is the energy deposit in EMCal and $p$ is the momentum determined at the DC. It was necessary to eliminate the background mainly from photon conversions and resonance decays so as to improve the signal to background ratio for $p_T > 4$ GeV/$c$.

The $v_2$ was measured by an event plane method \cite{9} and was obtained by dividing the measured $v_2$ by the event plane resolution

$$v_2 = \frac{v_2^{obs}}{\text{Res}\{\Psi_n\}} = \frac{\langle \cos (2(\phi - \Psi_n)) \rangle}{\langle \cos (2(\Psi_n - \Psi_{RP})) \rangle}, \quad (2)$$

where $\phi$ is the azimuth of charged hadrons at the central arm ($|\eta| < 0.35$), $\Psi_n$ is the event plane from the $n$-th harmonic flow ($n = 1$ for the ZDC-SMD, $n = 2$ for the BBC) and $v_2^{obs}$ is the measured $v_2$ with respect to the event plane $\Psi_n$. Event planes were determined from the $v_2$ at the BBC and the central arm as well as the directed flow $v_1 = \langle \cos (\phi - \Psi_{RP}) \rangle$ at the Shower Maximum Detector (SMD). The central arm event plane is only used to evaluate the event plane resolutions. The SMDs are located at the same acceptance of the ZDCs, $|\eta| > 6$, and measure transverse positions of spectator neutrons. The measured $v_2$'s are denoted as $v_2\{\text{ZDC-SMD}\}$ and $v_2\{\text{BBC}\}$ for the ZDC-SMD and BBC event planes, respectively.

The event plane determined at the ZDC-SMD can minimize non-flow correlations as well as $v_2$ fluctuations because of the cause of the following reasons. First, the pseudorapidity gap from midrapidity is 6, which is higher than what we have previously studied the $v_2$ by using the BBC. Second, the ZDC-SMD event plane is determined from directed flow. This mixed harmonic method involves three particle correlations and thus direct two particle correlations, which is dominant contributions from non-flow effects, do not affect the measured $v_2$. Third, ZDC-SMD measures spectator neutrons rather than participants. Therefore, $v_2$ fluctuations are suppressed up to the fluctuation of spectator neutrons.

Fig. 1 shows the event plane resolutions as a function of centrality for the ZDC-SMD event plane (solid circles) and the BBC (open diamonds) by Eq. (3). Dashed lines represent the resolutions calculated by Eq. (4).

A constant parameter $C$ is very close to $\sqrt{2}$ for both BBC and ZDC-SMD due to low resolution \cite{9}. The ZDC-SMD resolution is about factor 4 smaller than that of BBC because the ZDC-SMD event plane is determined from directed flow. It is approximately proportional to $v_2^2 M^{SMD}$, where $M^{SMD}$ is multiplicity used to determine the ZDC-SMD event plane, whereas the BBC resolution is roughly proportional to $v_2\sqrt{M^{BBC}}$.

The resolutions were also evaluated by adding a reference event plane

$$\text{Res}\{\Psi_n\} = \sqrt{\frac{\langle \cos (2(\Psi^A - \Psi_n)) \rangle \langle \cos (2(\Psi_n - \Psi^B)) \rangle}{\langle \cos (2(\Psi^B - \Psi^A)) \rangle}}, \quad (4)$$

where $l$, $m$ and $n$ denote the harmonics for event plane $\Psi^A$, $\Psi^B$ and $\Psi$, respectively. Dashed lines in Fig. 1 show the resolutions calculated by Eq. (4). For example, the BBC resolution was calculated by inserting $\Psi_n = \Psi_2^{BBC}$, $\Psi^A = \Psi_1^{ZDC-SMD}$, and $\Psi^B = \Psi_2^{CNT}$ where CNT denote the central arm. One can find that the dashed lines are systematically lower for the ZDC-SMD, and higher for the BBC. The comparison of $v_2$ from two different resolutions will be presented in the next section.

3 Results

We will present the preliminary results of $v_2\{\text{BBC}\}$ as well as $\{\text{ZDC-SMD}\}$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured at the PHENIX experiment. Section 3.1 will give comparison of the $v_2$ between BBC and ZDC-SMD event planes. Results between PHENIX and STAR experiments will be compared in Section 3.2. In Section 3.3 centrality dependence of the $v_2\{\text{ZDC-SMD}\}$ will be compared with the $v_2\{\text{BBC}\}$.
3.1 Comparison of $v_2\{\text{BBC}\}$ with $v_2\{\text{ZDC-SMD}\}$

Fig. 2 shows the $v_2\{\text{ZDC-SMD}\}$ as a function of $p_T$ in 20 - 60 % centrality. For comparison, the $v_2\{\text{BBC}\}$ is also plotted by open diamonds. The $v_2$ increases linearly up to $p_T \sim 3$ GeV/$c$, reach maximum $\sim 0.2$ and then start decreasing for higher $p_T$. The $v_2\{\text{ZDC-SMD}\}$ (S-N), which is obtained from the resolution in Eq. (3), is about 7 % systematically lower than the $v_2\{\text{BBC}\}$, while the results are consistent within systematic uncertainties. We also plot the $v_2\{\text{ZDC-SMD}\}$ (ZDC-BBCS-BBCN) as shown by solid circles, which is obtained from the resolution in Eq. (1) by inserting $\Psi_n = \Psi_{2\text{ZDC-SMD}}$, $\Psi_n^A = \Psi_{2\text{BBCS}}$ and $\Psi_n^B = \Psi_{2\text{BBCN}}$. The BBCS and BBCN denote the backward and forward BBC, respectively. The $v_2\{\text{ZDC-SMD}\}$ from two different resolutions are in good agreement within systematic uncertainties. Bottom panel shows the ratio of $v_2\{\text{ZDC-SMD}\}$ to $v_2\{\text{BBC}\}$ as a function of $p_T$. One can see that the ratio is constant within systematic errors in the measured $p_T$ range.

3.2 PHENIX vs STAR

Fig. 3 show the comparison of the PHENIX $v_2\{\text{ZDC-SMD}\}$ with STAR result [10] in 20 - 60 % centrality bin. Only statistical errors are shown for the STAR $v_2$. Both PHENIX and STAR results are obtained by the resolution in Eq. (2) and thus the results of $v_2\{\text{ZDC-SMD}\}$ are extracted by the exactly same method. Data symbols (open diamonds and open crosses) are the same as shown in Fig. 2. For a quantitative comparison, the ratio of $v_2$ to the $v_2\{\text{BBC}\}$ is plotted in bottom panel in Fig. 3. The denominator of the ratio is fitting result of the $v_2\{\text{BBC}\}$ by fourth polynomial function. One can see that the results agree very well within systematic errors.

3.3 Centrality dependence of $v_2$

Fig. 4 show the $v_2(p_T)$ for 10 % step centrality bin in 20 - 60 %. In left figures, the $v_2\{\text{ZDC-SMD}\}$ is essentially consistent with the $v_2\{\text{BBC}\}$ within systematic errors. In peripheral 40 - 60 %, we find that the $v_2\{\text{ZDC-SMD}\}$ is 5 - 10 % lower than the $v_2\{\text{BBC}\}$. The lower $v_2\{\text{ZDC-SMD}\}$ could suggest possible non-flow contributions on the $v_2\{\text{BBC}\}$.

In right figures, both BBC and ZDC-SMD resolutions are calculated by ZDC-SMD, BBC and CNT combinations in Eq. (3). Since the non-flow effects are expected to be maximum at the midrapidity, the CNT event plane could have maximal sensitivity to the non-flow contributions. Therefore, by including the CNT event plane reso-
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![Graph](image)

Fig. 4. Comparison of $v_2$ (ZDC-SMD) to $v_2$ (BBC) as a function of $p_T$ for 10% step centrality bin in 20 - 60%. Left (a) and right (b) figures show the results without and with the central arm (CNT) event plane resolution, respectively.

4 Conclusion

In summary, we have measured unidentified charged hadron elliptic flow with respect to the ZDC-SMD event plane from directed flow in Au + Au at $\sqrt{s_{NN}} = 200$ GeV. The $v_2$ (ZDC-SMD) was compared with the $v_2$ (BBC) measured with respect to the event plane determined at the BBC. We found that the $v_2$ (ZDC-SMD) was basically consistent with the $v_2$ (BBC) within systematic uncertainties in 20 - 60% centrality. Several different choice of event plane resolutions were studied. We found that resulting $v_2$ (ZDC-SMD) was still consistent with the $v_2$ (BBC) even if the CNT event plane was included in the event plane resolution. The difference of $v_2$ between BBC and ZDC-SMD event plane, $\sim 5 - 10\%$, at 40 - 60% centrality bins could attribute to the possible non-flow effects. This result indicates that the non-flow effects are essentially minimal on the $v_2$ (BBC) in 20 - 60% centrality because the $v_2$ (ZDC-SMD) is expected to be unbiased by the non-flow contributions.

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