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Elliptic Flow in Pb+Pb Collision at $\sqrt{s_{NN}} = 5.02\ TeV$

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Abstract. Elliptic flow signal, v_2, is widely studied in heavy ion collisions. Researches have been done to obtain the pseudorapidity dependence of v_2, while the measurement of transverse momentum dependence is relatively few. This paper presents the transverse momentum dependence of v_2 in Pb+Pb collision at $\sqrt{s_{NN}} = 5.02\ TeV$. The measurement is performed in the region with pseudorapidity $|\eta| < 2.8$ and transverse momentum $0.2 < p_T < 6.0 GeV$. In this work, we use sub-event method to measure elliptic flow for the collisions in different ranges of transverse momentum. The result shows a polynomial relation between elliptic flow signal and transverse momentum. In Section 4, the limitation of our measurement is also discussed.

Keywords: perfect fluid, elliptic flow, subatomic physics, transverse momentum.

1. Introduction

It is known that elliptic flow is created at the central of the collision of heavy nuclear ions, such as Au+Au [1]. To understand the formation of elliptic flow, it is important to investigate the initial condition since the observable is sensitive to the early evolution stages in the collision [2]. In this paper, we present the results on elliptic flow of

Pb+Pb collision at a nucleon-nucleon center of mass energy ($\sqrt{s_{NN}}$) of 5.02 TeV. Wide-range studies of angular correlations in Pb+Pb collision have been made [3, 4], yet, the transverse momentum dependence of the elliptic flow signal, v_2, remains less understood. We start with the Pb+Pb collision at the Relativistic Heavy-Ion Collider (RHIC), and we analyze the transverse momentum, pseudorapidity, and azimuthal angle of 22948 collision events. We calculated the elliptic flow vector Q by summing up the cosine of azimuthal angles in each event. Then we average Q over $\sqrt{M}$, the square root of the number of particles, to remove fluctuations. We use sub-event method to demonstrate the correlation of the elliptic flow in corresponding sub-events. We measure the difference between the measured azimuthal angle and the azimuth of the event plane, $\Delta\phi$. We fit cosine curves to the distribution of $\Delta\phi$ to get v_2 in different transverse momentum. Lastly, we present the transverse momentum dependence of v_2.

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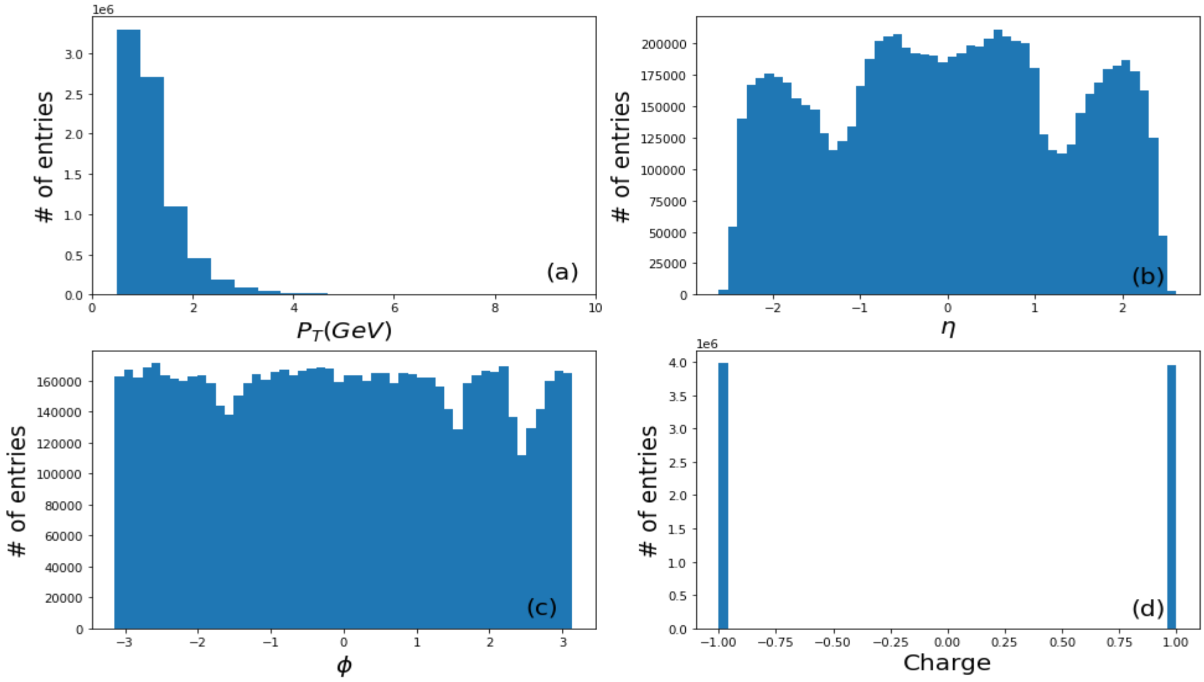

Figure 1. The raw data of all 22948 events displayed in histograms. Top Left: p_T is the transverse momentum of each particle measured in GeV. Top Right: η is the pseudorapidity. Bottom Left: ϕ is the azimuthal angle. Bottom Right: The charge represents the electric charge of different particles.

2. Method

The raw data for the Pb+Pb collision obtained by RHIC contains four parameters: transverse momentum (p_T) in GeV, pseudorapidity (η), azimuthal angle (ϕ), and electric charge. We use the measured azimuthal angles to calculate the flow vector and to estimate the azimuth of the real reaction plane in each event. The complete distributions of all four parameters are shown in Figure 1. We apply the sub-event method to each event to get $\Delta\varphi$. The distribution of $\Delta\varphi$ affects the elliptic flow signal, v_2.

Anisotropic flow of selected particles in the collision is defined as the average azimuthal correlation over particles and planes [5]:

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

where the integer n represents the shape of anisotropic flow such that v_1 is direct flow, v_2 is elliptic flow, and v_3 is triangular flow [6]. ϕ is the azimuthal angle of interest, and Ψ is the azimuthal angle of the reaction plane that cannot be measured experimentally.

2.1. Flow Vector

The elliptic flow is related to the anisotropic state in the collision. Anisotropic transverse flow, $\Delta\phi$, is describe as $\Delta\phi = \phi - \psi$, where ϕ is the azimuthal angle and ψ is the estimation of the reaction event plane. Independent ψ is obtain from the flow vector Q for each measurable harmonic. For an n-th harmonic of the distribution, the event flow vector Q_n over event plane angle ψ_n is defined as [7]:

$$Q_n \cos n\psi_n = \sum_i \cos n\phi_i \tag{2}$$

$$Q_n \sin n\psi_n = \sum_i \sin n\phi_i \tag{3}$$

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where the sum is taken over all tracks in a single event. The anisotropic flow is elliptic, so the integer n is chosen to be 2 with event plane ψ_2 and flow vector Q_2. The distribution of Q_2 is overall normal with minor fluctuations. We reduce Q_2 to q_2 to remove the fluctuation of particles:

$$q = \frac{Q}{\sqrt{M}} \tag{4}$$

where M is the number of particles in a given event plane in the calculation of Q. Fig.2 presents the distribution of $|q_2|$.

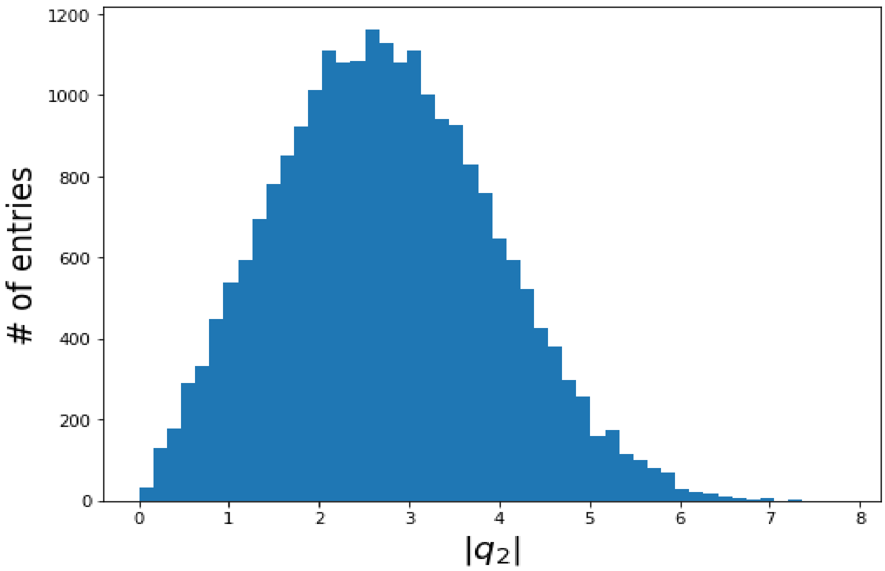

Figure 2. The distribution of reduced flow vector $|q_2|$ for all event planes. The y-axis is the number of entries, and the x-axis is the value for $|q_2|$.

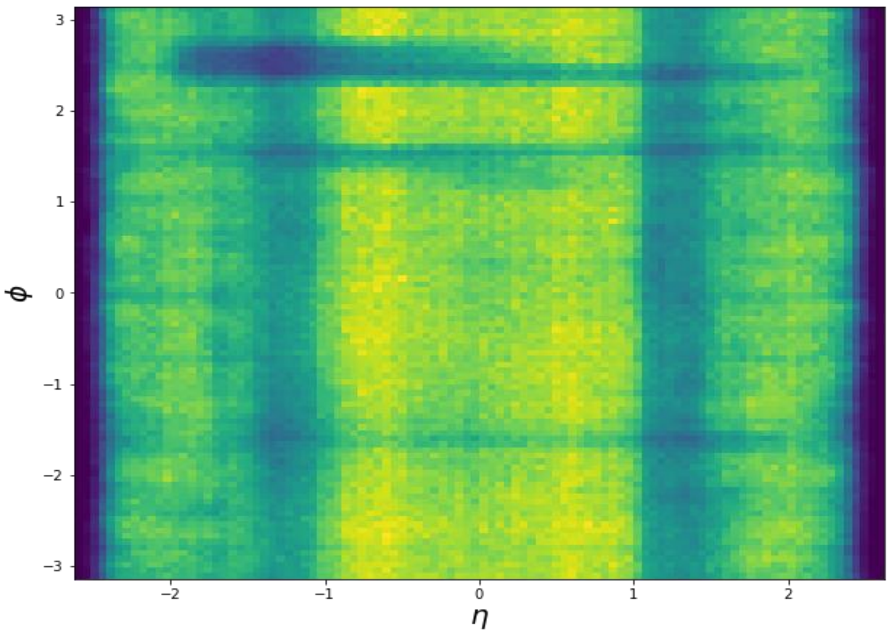

Figure 3. The 2-Dimension histogram that presents the correlation between η (x-axis) and ϕ (y-axis). The color indicates the number of particles in the corresponding η and ϕ. The entries with greater amount are shown in brighter colors.

2.2. *Sub-event method*

One of the most common approaches to measure anisotropic flow v_n is the event plane method. In each event, an estimation of the reaction plane Ψ is measured. The estimated reaction plane is called the event plane ψ [7].

Ideally, ψ_2 is measured over all particles in each event plane. However, the finite number of detected particles limits resolution in the measurement of event plane angles. As shown in Figure 1(b), the correlation slightly breaks down around $\eta = 0$. To improve the resolution, observed particles are divided into independent sub-events [8]. In each event plane, there exists two sub-events: one is at the positive end of η, and the other is at the negative end of η. A gap is generated in the distribution of η so that the two sub-events satisfy $|\eta| > m$ where m is the acceptance (width of the gap). Figure 4 shows two possible acceptances: (a) all particles are included, the acceptance is $|\eta| > 0$; and (b) only particles with $|\eta| > 0.5$ are included, the acceptance is $|\eta| > 0.5$. The most informative gap is the one that has a fine correlation as well as an adequate number of particles. After examining several gap widths, the acceptance of $|\eta| > 0.5$ is optimal. The particles with $\eta > 0.5$ is defined to be in the "positive" region, and the particles with $\eta < -0.5$ is in the "negative" region.

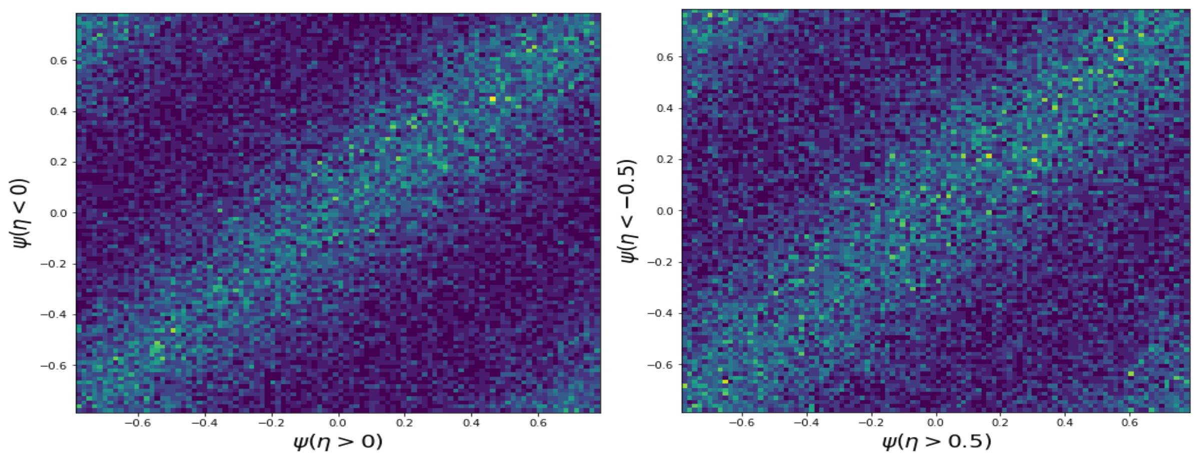

Figure 4. The 2-dimension histograms for ψ in correlated sub-events. The color indicates the number of particles in the corresponding ψ. The entries with greater amount are shown in brighter colors. Top: the correlation for particles with |η| > 0. Bottom: the correlation for particles with |η| > 0.5.

2.3. *Extracting v2*

We examine the distribution of azimuthal angle pairs, $\Delta\phi$, which is calculated through $\phi - \psi$. Figure 5 shows the distribution of $\Delta\phi$ for all particles with the target pseudorapidity acceptance ($|\eta| > 0.5$). $\Delta\phi$ is calculated using the following equations,

$$\Delta\phi_{np} = \phi_{negative} - \psi_{positive} \quad (5)$$

$$\Delta\phi_{pn} = \phi_{positive} - \psi_{negative} \quad (6)$$

where $\phi_{negative}$ is the measured azimuthal angle of negative η particles and $\psi_{positive}$ is the event plane of positive η particles, vice versa. The distribution of $\Delta\phi$ has a cosine dependence in the elliptic flow signal, v_2. The distribution is fitted with a cosine function,

$$f(\Delta\phi) = C(1 + 2v_2 \cos 2\Delta\phi) \quad (7)$$

where C is the weight in the y-axis. The fitting function is represented as the orange curve in Figure 5. The calculation averages the v_2 from $\Delta\phi_{np}$ and $\Delta\phi_{pn}$ to reduce the systematic error. The procedure is repeated for particles with different transverse momentum acceptance, and the change in v_2 is measured as the transverse momentum increases.

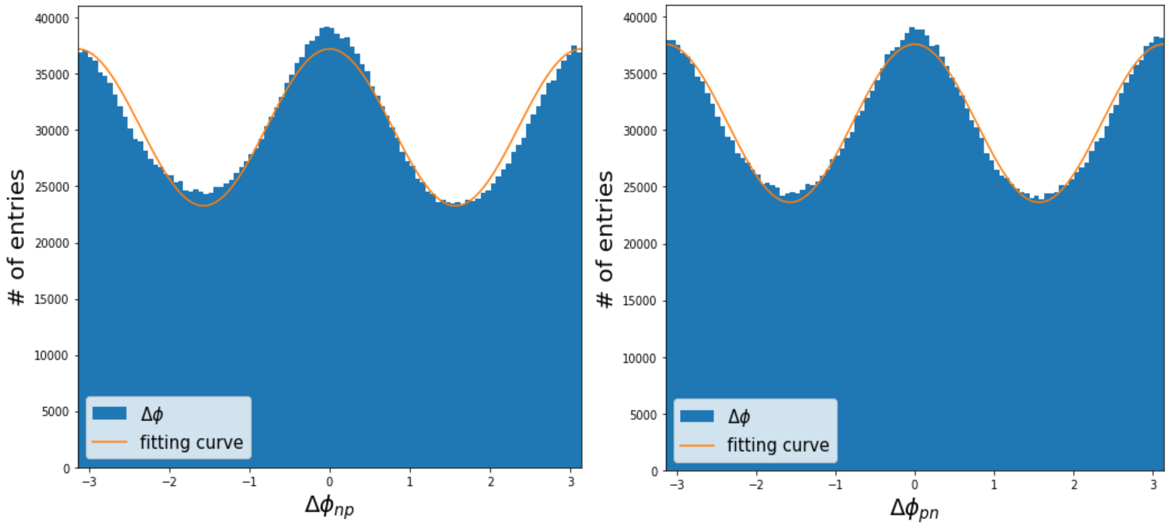

Figure 5. The distribution of Δϕ. The orange curve is the fitting function to the distribution using Eqn. 5. Left: Δϕ calculated by subtracting ϕ of negative particles with ψ of positive particles. Right: $\Delta\phi$ calculated by subtracting ϕ of positive particles with ψ of negative particles.

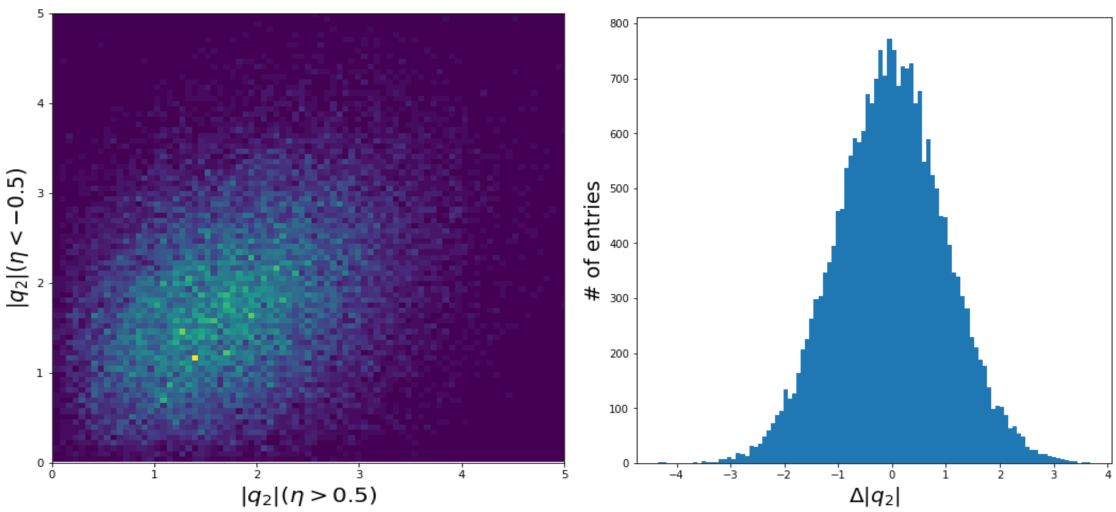

Figure 6. The correlation of $|q_2|$ in positive and negative regions of η. Left: The number of entries is indicated by the brightness of the color. The pixels with brighter color have greater number of entries. Right: $\Delta|q_2|$ is the difference between $|q_2|$ in the two regions.

3. Results

We will now present the results of the elliptic flow. Figure 1 demonstrates the raw data generated from the collider. The collider generated 22948 events and observed 345 particles on average for each event. Figure 1(a) is the transverse momentum (p_T) of the particles. The number of particles decreases exponentially as p_T increases. When the transverse momentum goes above 5 Tev, only few particles are observed. Figure 1(b) is the pseudorapidity (η). The plot shows the particles to be correlated in positive and negative regions of η. The best correlation, as stated in section 2, occurs at $|\eta| > 0.5$. Figure 1(c) is the azimuthal angle (ϕ) for each particle. It is expected that the distribution of ϕ to be uniform throughout the region. The concavities are caused by the inefficiency of the detector. Figure 1(d) shows that positive and negative charges are equally distributed in particles so that the electric charge of the system is approximately neutral. To better observe the correlation between η and ϕ, a 2-dimension

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histogram of the two parameters is plotted as shown in Figure 3. The plot is mostly uniform with a few outliers at ϕ = 2.5, 1.6, and -1.6.

The reduced flow vector q displays a fine correlation to the normal distribution as shown in Figure 2. Figure 6 shows the correlation of q_2 in two different regions in the pseudorapidity acceptance of $|\eta| > 0.5$. The overall correlation is good except a few outliers around $|q_2| = 1.5$.

Figure 7 presents the transverse momentum dependence of the elliptic flow vector, v_2. It is observed that the trend of v_2 is close to a polynomial function, shown as the orange curve in the figure. As p_T increases, v_2 fluctuates around the fitting curve. Moreover, the error in v_2 becomes significant in the high p_T region.

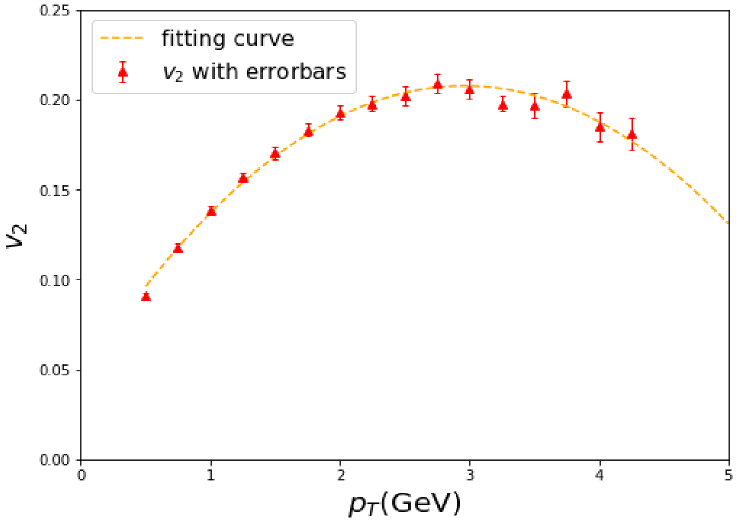

Figure 7. The transverse momentum (p_T) dependence of the elliptic flow signal, v_2. The orange curve is the fitting function of v_2.

4. Discussion

Despite the p_T dependence of v_2 measured, our sub-event method has its limitations. It is expected that the increase in transverse momentum p_T causes a larger elliptic flow [9]. Our results, however, fluctuates and generates error as p_T increases. At the high transverse momentum region where $p_T >$ 3GeV, the distribution of $\Delta\phi$ breaks down and distinguishes itself from the cosine fitting function.
Furthermore, our method does not return a good correlation in higher harmonic anisotropic flow. Previous research shows that elliptic flow, v_2 and triangular flow v_3 have similar magnitudes in the most central events, and triangular flow can be characterized in terms of the initial spatial anisotropy and its fluctuations [10]. In this work, the measurement of higher harmonic flow is not correlated with elliptic flow.

5. Conclusion

In conclusion, we have presented the transverse momentum dependence of v_2 in Pb+Pb collision at $\sqrt{s_{NN}} = 5.02$TeV, which shows a good correlation to a polynomial function. In our sub-event method, the particles in each event plane are divided into two sub-events with a pseudorapidity acceptance of $\eta < -0.5$. The particles with $\eta > 0.5$ are called the positive region, and the particle with $\eta < -0.5$ is called the negative region. The two regions have a good correlation in the flow vector q_2. The result fluctuates and generates error in v_2 as p_T increases because the $\Delta\phi$ distribution at high transverse momentum ($p_T >$ 3GeV) fail to correlate the cosine fitting function. Overall, our method makes a reasonable measurement for 2nd order harmonic flow, v_2. Future research will focus on improving the accuracy for high p_T particles and applying the measurement to higher harmonic anisotropic flow.

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