**Search for Electric Quadrupole Moments in Nuclear Collisions with Finite Net Baryon Density**

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*It is predicted that a Chiral Magnetic Wave (CMW) at finite baryon density can induce an electric quadrupole moment in the quark-gluon plasma produced in heavy ion collisions* [1]*. This electric quadrupole deformation lifts the degeneracy between the elliptic flows ($v_2$) of positive and negative pions leading to $v_2(\pi^+) < v_2(\pi^-)$. We study the difference between $v_2(\pi^+)$ and $v_2(\pi^-)$ measurements from STAR at RHIC for Au+Au collisions at 39 GeV, and investigate the dependence of the $v_2$ difference on the measured net-charge asymmetry of the data sample. Here the $v_2$ difference is expected to be proportional to the net-charge asymmetry in the presence of an Electric Quadrupole Effect. In this work, we present pion elliptic flows as a function of transverse momentum and centrality for Au+Au collisions at 39 GeV, and we will discuss the dependence of the $v_2$ difference on net-charge asymmetry.*

## I. Introduction: Subject and Terminology

At the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratories in Long Island, NY the Solenoidal Tracker At RHIC (STAR) focuses on the study of quark-gluon plasma, which is a new state of matter formed at high temperature and energy density. Quarks and gluons are elementary particles, which under normal circumstances, are confined to hadrons such as protons and neutrons due to the strong force. The strong force is one of the four fundamental forces of nature, which behaves in such a way that as the distance between quarks increase, the force acting upon them also increases. Adding energy to the hadrons results in particle formation, instead of particle separation [2]. Quark-gluon plasma is a newly rediscovered state of matter that is believed to have been present one microsecond after the Big Bang. The data that was analysed was collected with the Time Projection Chamber detector from the STAR experiment at Brookhaven National Laboratory. It has been proposed that there will be a slight electric quadrupole moment in Au+Au collisions at 39 GeV, and that this quadrupole is caused by the coupling of quark charge to the electromagnetic field produced by the incoming nuclei, and may be related to the phenomenon of local parity violations as well[1].

### Elliptic Flow

Elliptic flow is a way to quantify the azimuthal angular anisotropy in transverse motion due to the expansion of the QGP. When the two gold ions collide off-center, the quark-gluon plasma is formed in the overlapping almond shaped region. As the quarks are deconfined, they are able to interact with each other and build up an uneven pressure gradient, which is greater along the minor axis of the QGP region. As the QGP expands, there is greater expansion along the minor axis, resulting in an elliptic azimuthal angular anisotropy [3]. This expansion is called elliptic flow and is calculated from the second harmonic of the Fourier series of the triple differential distribution

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \Sigma_{n=1}^{\infty} 2v_n cos(n(\phi - \psi_r))), \quad (1)$$

or simply as

$$v_2 = \langle cos(2(\phi - \psi_r))\rangle = \frac{\langle cos(2(\phi - \psi_{EP}))\rangle}{EPresolution}. \quad (2)$$

Positive elliptic flow indicates greater expansion along the minor axis of the QGP region and negative elliptic flow is along the major axis.

**Reaction Plane and Event Plane**

We use the charged particle tracks from the TPC to reconstruct the reaction plane of the collisions. This estimated plane is called the Event plane. The event plane angle $\psi_{EP}$ is given by

$$\psi_{EP} = \left(tan^{-1}\frac{\Sigma_i w_i sin(n\phi_i)}{\Sigma_i w_i cos(n\phi_i)}\right)/n, (3)$$

with $n = 2$ as elliptic flow is the second harmonic [4]. The event plane for this analysis was calculated using two sub-event planes. The data was divided based on positive or negative pseudo-rapidity. This was done to avoid auto-correlation in the data.

**Electric Quadrupole Moment**

It is proposed that there is an electric quadrupole moment present in the QGP. The quadrupole is an uneven charge distribution, with a slight excess of positive charge at the top and bottom of the QGP region and a slight excess of negative charge found in the center of the QGP region. There will be a slight excess of positive quarks in the upper and lower regions of the QGP and a slight excess of negative quarks in the center of the QGP region. As the quarks interact with each other and form hadrons, it has been predicted that there will be a slightly higher $v_2$ for negative hadrons than for positive hadrons, as shown in Fig. 1 [1].

The elliptic flow of positive and negative pions was studied to observe this effect. The quadrupole is predicted to effect the elliptic flow so that

$$v_2^{\pm} = v_2 \mp \frac{q_e}{\rho_e}A_{\pm} \quad (4)$$

where $q_e$ is the electric quadrupole moment, $\rho_e$ is the charge density, and $A_{\pm}$ is the charge asymmetry [1].

$$A_{\pm} = \frac{N^+ - N^-}{N^+ + N^-} \quad (5)$$

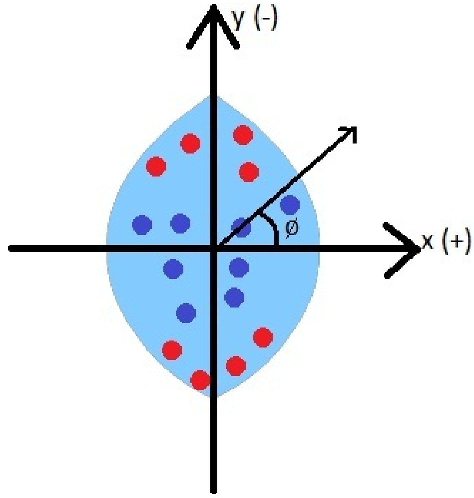


Figure 1: Elliptic flow of positive and negative hadrons in a quadrupole. Here red corresponds to positive charge and blue corresponds to negative charge.

**II. Experimental Setup and Data Collection**

The data was collected at STAR during the 2010 runs at $\sqrt{s_{NN}} = 39$ GeV incident energy. The tracks of the charged particles were reconstructed using the cylindrical TPC, a 4.2 m long barrel with a 2 m radius operated in a 0.5 T solenoidal magnetic field [5-7]. There were 125 million accepted events after event selections. The position of the collisions in the transverse direction $\sqrt{V_x^2 + V_y^2}$ or $V_r < 2$ cm to remove pile-up or fake events. The position in the beam direction $|V_z| < 40$ cm to insure that the events occur near the middle of the TPC, and that the pseudo-rapidity distribution of tracks in an event is roughly symmetric. The distance of closest approach, or DCA, which is the distance between the track and the vertex must be less than two centimetres to remove secondary particles and fake particles. If the DCA is greater than this, then the particle is likely from weak decay particles or pile up events. The number of TPC hits that make up the track was greater than 15, the pseudo-rapidity $|\eta| < 1$, and $0.15 < p_T < 0.5$ GeV/c for TPC. The events were also separated based on different centralities, or amount of overlap in the collision, according to the STAR official centrality definition, based on charged particle multiplicities measured in the TPC. This separation was done as it is hypothesised that at high centralities (small amounts of overlap) the QGP region is to small for there to be a EQM effect, and that at low centralities (large amounts of overlap) the QGP region is too spherical for there to be a noticeable difference in the elliptic flow of positive and negative particles. We present our analysis results from the $40\% - 50\%$, $30\% - 40\%$, and $20\% - 30\%$ centralities.

## III. Analysis and Results

The net-charge asymmetry distribution was divided into five segments of roughly equal size, with divisions at the mean$\pm 0.3\sigma$ and $\pm 1\sigma$, when fit with a Gaussian, as shown in Fig. 2 As the elliptic flow of all charged particles is dependent on transverse moment for low $p_T$ values, the elliptic flow was integrated over the transverse momentum from $0.15 < p_T < 0.5$. GeV/c for each of these five segments. This was then graphed against the average charge asymmetry for the segment, as shown in Fig. 3. The elliptic flow of the negative pions is higher than that of the positive pions at positive observed charge asymmetries. The difference between the $\pi^-$ elliptic flow and $\pi^+$ elliptic flow is shown in Fig. 4. Eq. 4 gives

$$v_2^- - v_2^+ = \left(v_2 + \frac{q_e}{\rho_e} A_\pm\right) - \left(v_2 - \frac{q_e}{\rho_e} A_\pm\right) \tag{6}$$

or simply

$$v_2^- - v_2^+ = 2\frac{q_e}{\rho_e} A_\pm. \tag{7}$$

The slope of the difference between $\pi^-$ elliptic flow and $\pi^+$ elliptic flow therefore corresponds to $2\frac{q_e}{\rho_e}$. This is not a direct correspondence, as the linear fit of the data was found using an observed charge asymmetry, and not the true charge asymmetry.

## IV. Summary

An analysis using elliptic flow of pions in heavy ion collisions has been presented for Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV. Our measurements for the $40\% - 50\%$, $30\% - 40\%$, and $20\% - 30\%$ centralities are consistent with the possible existence of electric quadrupole moments in these collisions. The $20\% - 30\%$ centrality had the largest quadrupole effect, then the $30\% - 40\%$ centrality, followed by the $40\% - 50\%$ centrality. Future measurements from other collision centralities and beam energies are needed to shed more light on the physical origin of the observed elliptic flow difference between charged pions.

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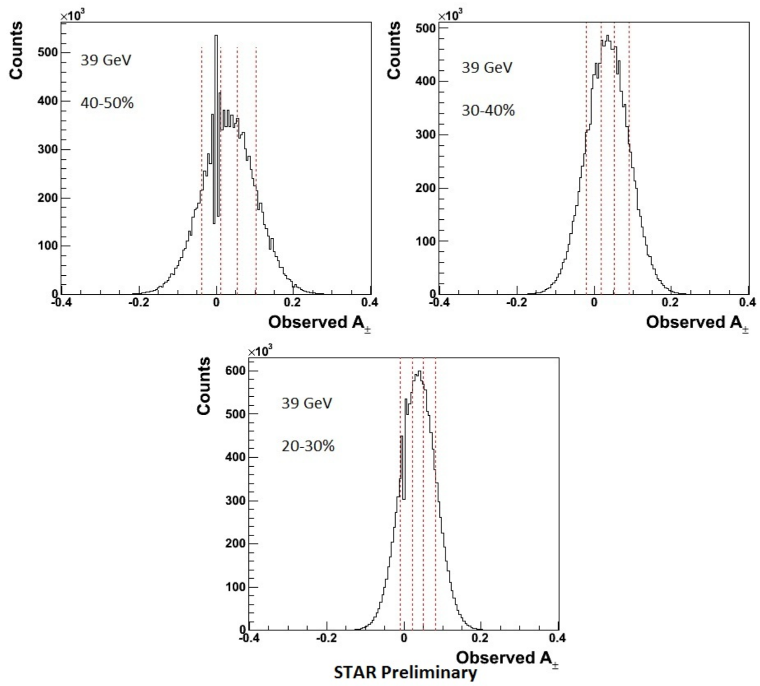


Figure 2: Net-charge asymmetry distribution

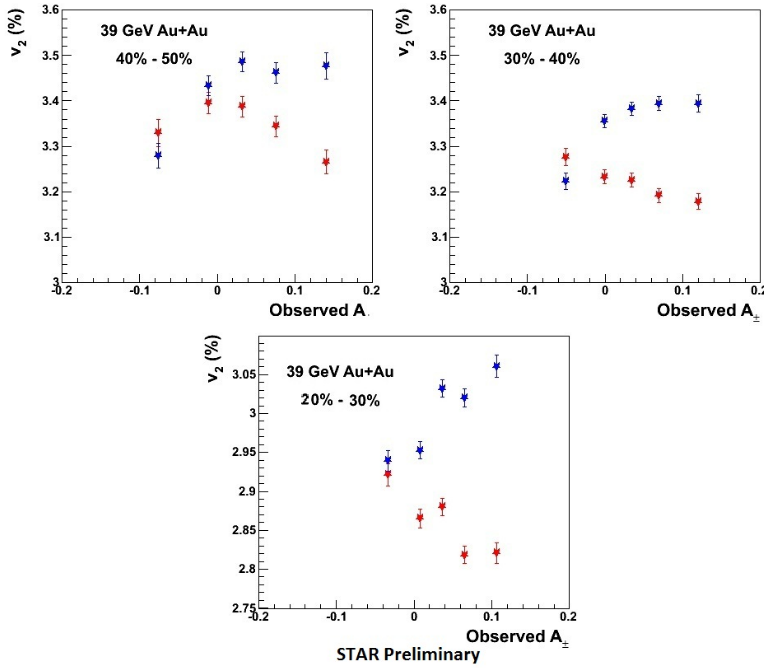


Figure 3: Elliptical flow of positive and negative pions, with red corresponding to positive pions and blue corresponding to negative pions.

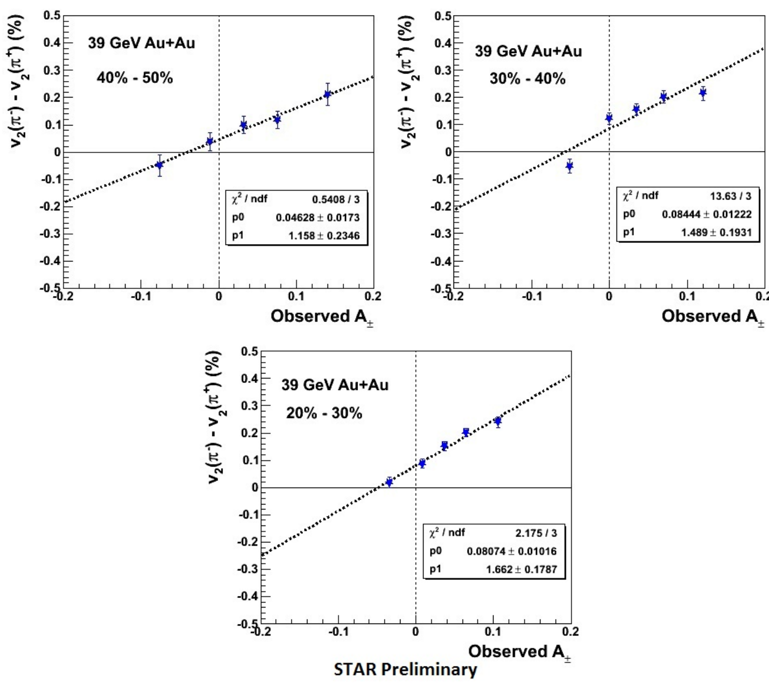


Figure 4: Difference in elliptical flow of negative and positive pions