Systematic Study of Azimuthal Anisotropy in Cu+Cu and Au+Au Collisions at \( \sqrt{s_{NN}} = 62.4 \) and 200 GeV

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The azimuthal anisotropy of particles produced in relativistic heavy ion collisions is a powerful probe for investigating the characteristics of the quark-gluon plasma (QGP) \[1\]-\[4\]. The elliptic azimuthal anisotropy \(v_2\) is defined by the amplitude of the second-order harmonic in a Fourier series expansion of emitted particle azimuthal distributions:

\[
v_2 = \langle \cos \left( 2(\phi - \Psi_{\text{RP}}) \right) \rangle ,
\]

where \(\phi\) represents the azimuthal emission angle of a particle and \(\Psi_{\text{RP}}\) is the azimuthal angle of the reaction plane, which is defined by the impact parameter and the beam axis. The brackets denote statistical averaging over particles and events. Elliptic flow is sensitive to the early stage of heavy ion collisions because pressure gradients transfer the initial geometrical anisotropy of the collision region to an anisotropy in momentum space.

We have studied the dependence of azimuthal anisotropy \(v_2\) for inclusive and identified charged hadrons in Au+Au and Cu+Cu collisions on collision energy, species, and centrality. The values of \(v_2\) as a function of transverse momentum \(p_T\) and centrality in Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV and 62.4 GeV are the same within uncertainties. However, in Cu+Cu collisions we observe a decrease in \(v_2\) values as the collision energy is reduced from 200 to 62.4 GeV. The decrease is larger in the more peripheral collisions. By examining both Au+Au and Cu+Cu collisions we find that \(v_2\) depends both on eccentricity and the number of participants, \(N_{\text{part}}\). We observe that \(v_2\) divided by eccentricity (\(\varepsilon\)) monotonically increases with \(N_{\text{part}}\) and scales as \(N_{\text{part}}^{1/3}\). The Cu+Cu data at 62.4 GeV falls below the other scaled \(v_2\) data. For identified hadrons, \(v_2\) divided by the number of constituent quarks \(n_q\) is independent of hadron species as a function of transverse kinetic energy \(K_{\text{T}} = mT - m\) between 0.1 < \(K_{\text{T}}/n_q\) < 1 GeV. Combining all of the above scaling and normalizations, we observe a near-universal scaling, with the exception of the Cu+Cu data at 62.4 GeV, of \(v_2/(n_q \cdot \varepsilon \cdot N_{\text{part}}^{1/3})\) vs \(K_{\text{T}}/n_q\) for all measured particles.

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I. INTRODUCTION

The azimuthal anisotropy of particles produced in relativistic heavy ion collisions is a powerful probe for investigating the characteristics of the quark-gluon plasma (QGP) \[1\]-\[4\]. The elliptic azimuthal anisotropy \(v_2\) is defined by the amplitude of the second-order harmonic in a Fourier series expansion of emitted particle azimuthal distributions:

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One of the most remarkable findings at the Relativistic Heavy Ion Collider (RHIC) is that the strength of \(v_2\) \[5\] is much larger than what is expected from a hadronic scenario \[6\]. Moreover, a scaling of \(v_2\) by the number of constituent quarks in a hadron in the intermediate transverse momentum region \(p_T = 1-4\) GeV/\(c\) has been found for a broad range of particle species produced in Au+Au at \(\sqrt{s_{NN}} = 200\) GeV \[7\]-\[8\]. Both STAR and PHENIX experiments have observed that \(v_2\) scales better as a function of the transverse kinetic energy of the hadron. These scalings of \(v_2\) are consistent with constituent quark flow at early collision times and recombination as the dominant process of hadronization.

The detailed interpretation of \(v_2\) results requires modeling \[9\]-\[10\] of the wavefunction of the incoming nuclei, fluctuations of the initial geometry, viscous relativistic hydrodynamics, hadronic freeze out and subsequent rescattering, along with various model parameters such as the assumed equation of state and transport coefficients, e.g. viscosity. In recent calculations, the strength of \(v_2\) for hadrons in heavy ion collisions at \(\sqrt{s_{NN}} = 200\) GeV can be reproduced by hydrodynamical models that include shear viscosity and initial fluctuations \[11\]-\[13\].

At the LHC, experiments have measured \(v_2\) as a function of \(p_T\) from Pb+Pb collisions at an order of magnitude higher beam energy, at \(\sqrt{s_{NN}} = 2.76\) TeV \[14\].
These $v_2$ results as a function of $p_T$ for inclusive hadrons are very similar in magnitude and shape to the RHIC measurements at 200 GeV. However, the $v_2$ measurements for identified hadrons at LHC below 3 GeV/$c$ do not scale well with the quark number and transverse kinetic energy of the hadron with deviations up to 40%.

A comparison of measured $v_2$ at the lower beam energies at RHIC ($\sqrt{s}_{NN} = 7.7–200$ GeV) shows that $v_2$ as a function of $p_T$ seems to be saturated above $\sqrt{s}_{NN} = 39$ GeV and decreases below this beam energy [19]. The scaling of $v_2$ with transverse kinetic energy is broken below a beam energy of 19 GeV [19]. Possible explanations for this behavior include rescattering in the later hadronic phase, incomplete thermalization in the initial stage, or the plasma not being formed at these lower beam energies.

Because transverse kinetic energy scaling is broken at energies significantly lower and higher than RHIC’s full energy of 200 GeV, it is important to provide systematic measurements of $v_2$ for identified hadrons as a function of system size, collision energy, and centrality. These systematics are needed in order to make progress on the nature of the QGP at lower energy-density. These systematics are needed in order to make progress on the nature of the QGP at lower energy-density. We report on such a set of measurements in this paper, examining both Au+Au and Cu+Cu collisions at 200 GeV and 62.4 GeV beam energies. This adds to the low-energy Au+Au measurements made by STAR [19] and their Cu+Cu $v_2$ data at 200 GeV and 62.4 GeV beam energies [20]. The system size dependence of flow is particularly important because long-range azimuthal correlations have also been observed in high-multiplicity events from much smaller systems such as $d+Au$ collisions [21] at RHIC, $p+p$ [22], and $p+Pb$ collisions [23] at LHC. The origin of these anisotropies is currently unknown; various competing explanations include parton saturation and hydrodynamic flow.

We expect that the systematic study of $v_2$ for inclusive and identified particles can provide information on the temperature dependence of $\eta/s$ (i.e. the ratio of shear viscosity to entropy density $s$), the impact of viscosity on systems of different sizes, as well as constraining models of the reaction dynamics.

The organization of this paper is as follows: Section II describes the PHENIX detector used for this analysis, Section III describes the experimental method of azimuthal anisotropy analysis, Section IV presents the results of the systematic study for inclusive charged hadron $v_2$, and Section V presents the results of the systematic study for the $v_2$ of identified charged hadrons. The new data published in this paper are the Cu+Cu data at 62.4 GeV, as well the Au+Au $v_2$ results for $p_T > 5$ GeV/$c$. Other data come from prior PHENIX publications. [7, 24]
Details of the TOF construction and performance can be found in [27].

The PHENIX pad chambers (PC) are multi-wire proportional chambers composed of three separate layers of pixel detectors. Each pad chamber detector contains a single plane of wires in a gas volume bounded by two cathode planes. The innermost pad chamber plane, PC1, is located between the DC and a ring-imaging Čerenkov counter (RICH) on both East and West arms, PC2 is placed in back of the RICH on the West arm only, and PC3 is located in front of the Electromagnetic Calorimeters on both East and West arms.

The PC system determines space points outside the magnetic field and hence provides straight-line particle trajectories. They are the only nonprojective detectors in the central tracking system and thus are critical elements of the pattern recognition. PC1 is also essential for determining the three-dimensional momentum vector by providing the z coordinate of each track at the exit of the DC. Details of the PC construction and their performance can be found in [27].

C. Time-of-flight counters

The PHENIX time-of-flight (TOF) detector serves as a particle identification device for charged hadrons. The time resolution for the BBC-TOF system is around 120 ps, which enables 2σ separation of π/K up to 2.0 GeV/c. The length of the flight path of each track from the event vertex to the TOF detector is calculated by the momentum reconstruction algorithm. The length and time of flight are combined to identify the charged particles. The TOF is located between the PC3 and EMCal in the east and about 5.06 m away from the collision vertex. It covers |η| < 0.35 and azimuthal angle, Δφ = 45°. Details of the TOF construction and performance can be found in [26].

D. Electromagnetic calorimeter

The PHENIX EMCal was designed to measure the spatial position and energy of electrons and photons produced in heavy ion collisions. The EMCal covers the full central spectrometer acceptance of |η| < 0.35 and is installed in both arms, each subtending 90° in azimuth, i.e., larger than the TOF acceptance. The EMCal comprises six sectors of lead-scintillator (PbSc) calorimeters and two sectors of lead-glass (PbGl) calorimeters. The PbGl is not used in this analysis, but we note that the TOF detector is in front of the PbGl so no PID coverage is lost. The PbSc is a sampling calorimeter and has a timing resolution of 400 ps for hadrons. The PbSc can be used to separate π/K with 2σ up to 1.0 GeV/c. Details of the PbSc construction and performance are described in [28].

E. RICH

A Ring Imaging Čerenkov Counter (RICH) is installed on each of the PHENIX central arms. Each RICH detector is a threshold gas Čerenkov detector with a high angular segmentation filled with CO2 gas. In this analysis we use the RICH to reject electrons by removing tracks that match to a RICH ring. It is noted that charged pions with pT larger than 4 GeV/c also radiate in the CO2 gas.

III. EXPERIMENTAL METHOD

A. Data sets and event selection

We measured Cu+Cu and Au+Au collisions at √sNN = 62.4 and 200 GeV. The Cu+Cu data were taken during RHIC Run-5 (2005) and Au+Au data were taken during RHIC Run-4 (2004) running periods. We used a minimum bias trigger that was defined by a coincidence between the two BBCs and an energy threshold of one neutron in both ZDCs. The collision vertex along the beam direction, z, was measured by the BBC. The total number of minimum bias events that were analyzed after requiring an offline vertex cut of |z| < 30 cm and selecting good runs are listed in Table I.

| Year  | Species  | Energy [GeV] | # of events |
|-------|----------|--------------|-------------|
| 2004  | Au+Au    | 200          | 8.2 × 10⁸   |
| 2004  | Au+Au    | 62.4         | 2.6 × 10⁷   |
| 2005  | Cu+Cu    | 200          | 8.0 × 10⁸   |
| 2005  | Cu+Cu    | 62.4         | 3.4 × 10⁸   |

TABLE I. Information on the data sets and event statistics.

In Au+Au collisions at 200 GeV the centrality of the collision was determined by using the correlation of the total energy deposited in the ZDCs with the total charge deposited in the BBCs, as described in [29]. However, in 200 GeV Cu+Cu, 62.4 GeV Cu+Cu, and 62.4 GeV Au+Au collisions, the resolving power of the ZDCs is insufficient to significantly contribute to the centrality definition. Therefore, the total charge deposited in the BBCs is used to determine centrality in these collision systems, as described in [29]. A Glauber model Monte-Carlo simulation of the each collision [30, 31] was used to estimate the average number of participating nucleons Npart and participant eccentricity (ε). This simulation

...
includes modeling of the BBC and ZDC response. The eccentricity $\varepsilon$ is also known as the participant eccentricity and includes the effect of fluctuation from the initial participant geometry. Table IV summarizes $N_{\text{part}}$, its systematic uncertainties ($\Delta N_{\text{part}}$), $\varepsilon$ and its systematic uncertainties ($\Delta \varepsilon$).

**B. Track selection**

The analysis was performed for inclusive charged hadrons over the transverse momentum range $0.2 < p_T < 10$ GeV/$c$, and for identified charged particles (pions ($\pi^+ + \pi^-$), kaons ($K^+ + K^-$), and protons ($p + \bar{p}$)) in the momentum range up to $p_T = 2.2$, $3$, and $4$ GeV/$c$ respectively.

The track reconstruction procedure is described in [32]. Tracks reconstructed by the DC which do not originate from the event vertex have been investigated as background to the inclusive charged particle measurement. The main background sources include secondary particles from hadron decays and $e^+e^-$ pairs from the conversion of photons in the material between the vertex and the DC [33]. To minimize background originating from the magnets, reconstructed tracks are required to have a $z$-position less than $\pm 80$ cm when the tracks cross the outer radius of the DC. The DC is outside the central magnet field hence we can approximate reconstructed tracks through the central-arm detectors as straight lines. This enables tracks to be projected to outer detectors and matched to measured hits. Good tracks are required to be matched to a hit in the PC3, as well as in the EMCal, within $2.5 \sigma$ of the expected hit location in both azimuthal and beam directions.

The Ring Imaging Čerenkov detector (RICH) also reduces the conversion background. For tracks with $p_T < 4$ GeV/$c$ we apply a cut of $n_0 < 0$ where $n_0$ is the number of fired phototubes in the RICH ring. For $p_T > 4$ GeV/$c$, we require tracks to have $E/p > 0.2$, where $E$ denotes the energy deposited in the EMCal and $p_T$ is the transverse momentum of particles measured in the DC. Because most of the background from photon conversion are low-momentum particles that were incorrectly reconstructed at higher momentum, when we require a large deposit of energy in the EMCal this suppresses the conversion background [34].

To demonstrate the effectiveness of the $E/p$ cut, Fig. 2 shows the track/hit matching distributions $d\phi/\sigma$ at PC3, where $d\phi$ is the residual between the track projection point and the detector hit position along $\phi$ and $\sigma$ is the standard deviation of the $d\phi$ distribution. The left panel shows the $d\phi/\sigma$ without an $E/p$ cut, and the right panel shows the distribution with a cut of $E/p > 0.2$. Note that the vertical scale between the panels is different. The $E/p > 0.2$ cut substantially reduces the background for high $p_T$ tracks. The residual background remaining after these cuts has been estimated by the fitting the $d\phi/\sigma$ distributions in PC3 with a double Gaussian function (signal and background). The signal and residual background distributions are required to have the same mean. For $p_T < 4$ GeV/$c$ the residual background is less than 5% of the real tracks and reaches 10% for $p_T = 8-10$ GeV/$c$. The efficiency of the $E/p > 0.2$ cut is 0.3 at $p_T = 5-6$ GeV/$c$ and 0.1 at $p_T = 7-9$ GeV/$c$.

**C. Particle identification**

For identified charged hadrons we also require the tracks to have a hit in the TOF detector or EMCal within at most $2 \sigma$ of the expected hit location in both azimuthal and beam directions. Particles are identified by their mass-squared, using the momentum measurement from the DC ($p$), time-of-flight between BBC and TOF/EMCal ($t$), and flight path length ($L$) from the collision vertex point to the hit position on the TOF wall or cluster in the EMCal. The square of the particle’s mass is calculated as

$$m^2 = \frac{p^2}{c^2} \left( \frac{t}{L/c} \right)^2 - 1 \quad (2)$$

The timing resolution of the BBC-TOF and BBC-EMCal systems was determined by examining the timing difference between the measured flight-time $t$ and $t_{\text{expected}}$, the time which is expected under the assumption that the particles are pions. The resulting time distribution is shown in Fig. 3. A narrow peak centered around $t - t_{\text{expected}} \approx 0$ corresponds to pions, and the other two broad peaks are kaons and protons. A Gaussian distribution is fit to the pion peak and yields a resolution of $\sim 120$ ps for the BBC-TOF system and $\sim 400$ ps for the BBC-EMCal system.

The PID is performed by applying momentum-dependent cuts in mass-squared ($m^2$). The $m^2$ distributions are fit with a 3-Gaussian function corresponding to pions, kaons, and protons. The corresponding widths and centroids are extracted from the data as a function of transverse momentum. To select candidate tracks of a particle species, the $m^2$ is required to be within two standard deviations of the mean for the selected particle species and outside $2.5$ standard deviations of the
TABLE II. Number of participants \((N_{\text{part}})\), its uncertainty \((\Delta N_{\text{part}})\), participant eccentricity \((\varepsilon)\) and its uncertainty \((\Delta \varepsilon)\) from Glauber Monte-Carlo calculations for Au+Au and Cu+Cu collisions at 200 and 62.4 GeV.

| Centrality | Au+Au 200 GeV | Au+Au 62.4 GeV | Cu+Cu 200 GeV | Cu+Cu 62.4 GeV |
|------------|--------------|----------------|--------------|----------------|
| Bin        | \(N_{\text{part}}\) | \(\Delta N_{\text{part}}\) | \(\varepsilon\) | \(\Delta \varepsilon\) |
| 0%–10%     | 325.2        | 3.3            | 0.103        | 2.6            |
| 10%–20%    | 234.6        | 4.7            | 0.200        | 2.5            |
| 20%–30%    | 166.6        | 5.4            | 0.284        | 2.1            |
| 30%–40%    | 114.2        | 4.4            | 0.356        | 1.7            |
| 40%–50%    | 74.4         | 3.8            | 0.422        | 1.5            |
| 50%–60%    | 45.5         | 3.3            | 0.491        | 1.1            |
| 60%–70%    | 25.7         | 3.8            | 0.567        | 0.7            |
| 70%–80%    | 13.4         | 3.0            | 0.666        | 1.2            |
| 80%–90%    | 0.726        | 2.8            | 0.740        | 2.2            |

D. Azimuthal anisotropy: event plane method

Because the principal axis of the participants cannot be measured directly in the experiment, the azimuthal angle of the reaction plane is estimated \([35]\). The estimated reaction plane is called the “event plane” and is determined for each harmonic of the Fourier expansion of the azimuthal distribution. The event flow vector \(\vec{Q}_n = (Q_x, Q_y)\) and azimuth of the event plane \(\Psi_n\) for \(n\)-th harmonic of the azimuthal anisotropy can be expressed as

\[
Q_x \equiv |\vec{Q}_n| \cos (n\Psi_n) = \sum_i^M w_i \cos (n\phi_i),
\]

\[
Q_y \equiv |\vec{Q}_n| \sin (n\Psi_n) = \sum_i^M w_i \sin (n\phi_i),
\]

where \(M\) denotes the number of particles used to determine the event plane, \(\phi_i\) is the azimuthal angle of each event.
particle and the weight \(w_i\) is the charge seen in the corresponding channel of the BBC. Once the event plane is determined, the elliptic flow \(v_2\) can be extracted by correlating the azimuthal angle of emitted particles \(\phi\) with the event plane:

\[
v_2(\Psi_n) = \frac{v_{2\text{obs}}}{\text{Res}(\Psi_n)} = \frac{\langle \cos (2[\phi - \Psi_n]) \rangle}{\langle \cos (2[\Psi_n - \Psi_{\text{RP}}]) \rangle},
\]

where \(\phi\) is the azimuthal angle of tracks in the laboratory frame, \(\Psi_n\) is the \(n\)-th order event plane and the brackets denote an average over all charged tracks and events. The denominator \(\text{Res}(\Psi_n)\) is the event plane resolution that corrects for the difference between the estimated event plane \(\Psi_n\) and true reaction plane \(\Psi_{\text{RP}}\). We measure \(v_2\) using the same harmonic event plane \((\Psi_2)\) because this leads to a better accuracy \[25\].

The second-harmonic event planes were independently determined with two BBCs located at forward (BBC South) and backward (BBC North) pseudorapidities \(|\eta| = 3.1–3.9\) \[5\]. The planes were also combined to provide the event plane for the full event. More details study on using the BBC for the reaction plane measurement can be found in \[24\]. The measured \(v_2\) of hadrons in the central arms with respect to the combined second-harmonic BBC event plane will be denoted throughout this paper as \(v_2\).

1. Event plane determination

To determine each event plane we chose the weights at each azimuthal angle to be the charge seen in the corresponding channel of the BBC. Corrections were performed to remove possible biases from small nonuniformities in the acceptance of the BBC. In this analysis we applied two corrections; the re-centering and shift methods \[35\]. In the re-centering method, event flow vectors are shifted and normalized using the mean \(\langle Q \rangle\) and width \(\sigma\) of the \(Q\) vector distribution:

\[
Q' = \frac{Q_x - \langle Q_x \rangle}{\sigma_x}, \quad Q' = \frac{Q_y - \langle Q_y \rangle}{\sigma_y}.
\]

This correction reduces the dependence of the event plane resolution on the laboratory angle. Most acceptance effects are removed by this re-centering method. The shift method was used as a final correction \[35\]. In the shift method the reaction plane is shifted by \(\Delta \Psi_n\) defined by \(k_{\text{max}} = 4\), the difference in the extracted \(v_2\) was negligible and thus we include no systematic uncertainty due to the choice of \(k_{\text{max}}\) in our \(v_2\) results \[24\].

Independent re-centering and shift corrections were applied to each centrality selection, in 5% increments, as well as 20 cm steps in \(z\)-vertex. This optimizes the event plane resolution. The corrections were also performed for each experimental run (the duration of a run is typically 1-3 hours) to minimize the possible time-dependent response of detectors.

2. Event plane resolution

The event plane resolution for \(v_2\) was evaluated by the two-subevent method. The event plane resolution \[35\] is expressed as

\[
\langle \cos (kn[\Psi_n - \Psi_{\text{RP}}]) \rangle = \frac{\sqrt{\pi}}{2 \sqrt{2}} \chi_n e^{-\chi_n^2/4} \times \left[I_{(k-1)/2} \left(\frac{\chi_n^2}{4}\right) + I_{(k+1)/2} \left(\frac{\chi_n^2}{4}\right)\right],
\]

where \(\chi_n = v_n\sqrt{2M}\), \(M\) is the number of particles used to determine the event plane \(\Psi_n\), \(I_k\) is the modified Bessel function of the first kind and \(k = 1\) for the second harmonic BBC event plane.

To determine the event plane resolution we need to determine \(\chi_n\). Because the North and South BBCs have approximately the same \(\eta\) coverage, the event plane resolution of each sub-detector is expected to be the same. Thus, the subevent resolution for south and north event planes can be expressed as

\[
\sqrt{\text{Res}(\Psi_{\text{S(N)}} - \Psi_{\text{RP}})} = \sqrt{\langle \cos (2[\Psi_{\text{S(N)}} - \Psi_{\text{RP}}]) \rangle},
\]

where \(\Psi_{\text{S(N)}}\) denotes the event plane determined by the South (North) BBC. Once the subevent resolution is obtained from Eq. \[10\], one can calculate \(\chi_n\) using Eq. \[9\]. The \(\chi_n\) for the full event can then be estimated by \(\chi_n = \sqrt{2} \chi_n^{\text{sub}}\). This is then substituted into Eq. \[9\] to give the full event resolution. Because the multiplicity of the full event is twice as large as that of the subevent, \(\chi_n\) is proportional to \(\sqrt{M}\).

Figure 4 shows the BBC North-South-combined resolution of the event plane as a function of the centrality in \(\text{Au+Au and Cu+Cu at } 78.2\) and \(200\) GeV. The reaction-plane resolution and its uncertainties in \(\text{Au+Au and Cu+Cu at } 78.2\) and \(200\) GeV are summarized in Table II.

E. Systematic uncertainty for \(v_2\)

The sources of systematic uncertainty on the \(v_2\) measurement include: reaction plane determination, the effects of matching cuts, the effects of the E/p cut, and
TABLE III. Reaction-plane resolution for each centrality in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV and its statistical contribution to the uncertainty on $v_2$. Note: Centrality bins are 10% wide (0%–10%, 10%–20%, etc.) for Au+Au 62.4 GeV.

| Centrality | Au+Au 200 GeV | Au+Au 62.4 GeV | Cu+Cu 200 GeV | Cu+Cu 62.4 GeV |
|------------|---------------|----------------|---------------|----------------|
| Reso- Stat. Uncert. for $v_2$ [%] | Reso- Stat. Uncert. for $v_2$ [%] | Reso- Stat. Uncert. for $v_2$ [%] | Reso- Stat. Uncert. for $v_2$ [%] |
| 0%–5% | 0.212 | 0.20 | 0.128 | 2.0 | 0.139 | 0.55 | 0.053 | 5.6 |
| 5%–10% | 0.312 | 0.09 | 0.155 | 0.44 | 0.061 | 4.3 |
| 10%–15% | 0.405 | 0.05 | 0.155 | 0.94 | 0.073 | 3.0 |
| 15%–20% | 0.414 | 0.05 | 0.155 | 0.97 | 0.073 | 3.0 |
| 20%–25% | 0.407 | 0.05 | 0.155 | 0.97 | 0.073 | 3.0 |
| 25%–30% | 0.387 | 0.06 | 0.163 | 1.3 | 0.068 | 3.5 |
| 30%–35% | 0.357 | 0.07 | 0.118 | 2.4 | 0.060 | 4.4 |
| 35%–40% | 0.320 | 0.12 | 0.118 | 2.4 | 0.051 | 6.1 |
| 40%–45% | 0.278 | 0.16 | 0.079 | 5.4 | 0.054 | 5.6 |
| 45%–50% | 0.234 | 0.25 | 0.044 | 17.5 | 0.044 | 8.2 |
| 50%–55% | 0.189 | 0.40 | 0.044 | 17.5 | 0.044 | 8.2 |
| 55%–60% | 0.150 | 0.70 | 0.044 | 17.5 | 0.044 | 8.2 |
| 60%–65% | 0.113 | 0.70 | 0.044 | 17.5 | 0.044 | 8.2 |
| 65%–70% | 0.078 | 0.70 | 0.044 | 17.5 | 0.044 | 8.2 |

FIG. 4. (Color online) Second-order event plane resolution vs. centrality in Au+Au and Cu+Cu at 200 and 62.4 GeV. The event plane is measured by BBC.

TABLE IV. Systematic uncertainty [%] of the reaction plane determination for each data set and each centrality bin. These are obtained by taking the larger values away from unity of the ratio of $v_2$ with BBC North and South to $v_2$ with BBC North-South combined.

| Centrality | Au+Au | Cu+Cu |
|------------|-------|-------|
| bin       | 200 GeV | 62.4 GeV | 200 GeV | 64 GeV |
| 0%–10%    | 2      | 3      | 3       | 14     |
| 10%–20%   | 3      | 2      | 2       | 9      |
| 20%–30%   | 4      | 2      | 2       | 6      |
| 30%–40%   | 4      | 7      | 2       | 2      |
| 40%–50%   | 3      | 7      | 2       | 3      |
| 50%–60%   | 3      | 5      | 2       | 5      |

occupancy effects for PID $v_2$. These are described below.

The systematic uncertainties due to the reaction plane determination were estimated by comparing the $v_2$ values extracted using three different reaction planes; the BBC North, BBC South, and BBC North-South combined. Figure 5 shows $v_2$ vs. centrality for three reaction planes (BBC South, North, South-North combined) for Au+Au 200 GeV. The bottom panel shows the ratio of $v_2$ with BBC North and South RP to $v_2$ with BBC North-South combined (default). The percentage systematic uncertainty was obtained by taking the largest values away from unity of these ratios. These uncertainties are summarized in Table IV, summarizes for each data set and each centrality bin.

The default matching cuts for tracks projected to PC3 are $-2.5\sigma < (d\phi_{PC3} \text{ and } dz_{PC3}) < 2.5\sigma$. To obtain the systematic uncertainty from the dependence on these matching cuts, we examined different cut windows, e.g. $|d\phi_{PC3}| < 1.0\sigma$ and $1.0\sigma < |d\phi_{PC3}| < 2.5\sigma$, and compared $v_2$ values using these cuts to $v_2$ values from the default cut. The difference between $v_2$ values with these matching cuts determine the systematic uncertainties. Because the alternative cut windows have a smaller sample of data, we extracted the systematic uncertainty from the minimum bias event sample and used these for all centralities. Table V shows the matching systematic uncertainties.

The $E/p$ cut can reject background from conversions, especially for high $p_T$ tracks. The default cut, $E/p > 0.2$, was used for tracks with $p_T > 4$ GeV/c. To test the sensitivity to the value of the cut, we apply cuts of $E/p > 0.1$, 0.2 and 0.3 cuts for tracks $3 < p_T < 4$ GeV/c; a lower momentum was used because we have more statistics there. The ratio of $v_2$ with different $E/p$ cuts contributes to
TABLE V. Systematic uncertainty [%] of the matching and $E/p$ cuts for each data set and each $p_T$ bin for minimum bias event sample, which are obtained by taking the larger values of the ratio of $v_2$ with different matching cut to $v_2$ with the default matching cut.

| $p_T$ (GeV/c) | Au+Au 200 GeV | Au+Au 62.4 GeV | Cu+Cu 200 GeV | Cu+Cu 62.4 GeV |
|--------------|--------------|----------------|--------------|----------------|
|               | Systematic Uncertainty (%) | Systematic Uncertainty (%) | Systematic Uncertainty (%) | Systematic Uncertainty (%) |
| 0.2–1.0       | 1            | 1              | 1            | 2              |
| 1.0–2.0       | 1            | 3              | 1            | 4              |
| 2.0–4.0       | 1            | 2              | 4            | 3              |

The systematic uncertainty due to the $E/p$ cut using the minimum bias event sample, because within the statistics we did not observe any centrality dependence for how $v_2$ changed with different $E/p$ cuts. Table VI lists the systematic uncertainties from the $E/p$ cut.

Both EMCal and TOF detectors are used for particle identification. In the low $p_T$ region both detectors can be used, and the difference between $v_2$ measured with the EMCal and TOF, averaged across $p_T$, is used for the systematic uncertainty due to timing performance. This includes the 1% uncertainty due to background contributions in the particle identification. The values are summarized in Table VI. Note, that the timing systematic uncertainty only affects the identified hadron results.

The values for $v_2$ can be impacted due to finite occupancy which tends to lower the measured $v_2$. The magnitude of this effect has been estimated to be largest for central Au+Au collisions at 200 GeV as a reduction in $v_2$ for PID particles of approximately 0.0013 for the running conditions of the data presented here. This effect is independent of $p_T$. For different centrality and beam-energies we take the systematic uncertainty on PID $v_2$ to linearly decrease with the average charged particle multiplicity in those collisions.

FIG. 5. (Color online) (a) $v_2$ vs. centrality with three different reaction planes (BBC South, North, South-North combined) for Au+Au 200 GeV. (b) The ratio of $v_2$ with BBC South or North reaction plane to $v_2$ with South-North combined.

TABLE VI. Systematic uncertainty [%] for $v_2$ of identified hadrons due to the timing performance of the EMCal and TOF detectors. These are obtained by taking the difference between $v_2$ with EMCal and $v_2$ with TOF merging $p_T$ and centrality bins.

| Collision $\sqrt{s_{NN}}$ | Species | identified hadron |
|---------------------------|---------|------------------|
| Au+Au 62.4                | $\pi$   | 2                |
| Cu+Cu 200                 | K       | 4                |
|                            | p       | 6                |

IV. RESULTS FOR $v_2$ OF INCLUSIVE CHARGED HADRONS

In this section we describe the $v_2$ measurements and how they change as a function of collision energy and system size. We present the measured $v_2$ for inclusive charged particles in Au+Au and Cu+Cu collisions at 62.4 and 200 GeV. For 200 GeV, the $v_2$ results for $p_T < 5$ GeV/c are obtained by re-binning the data published in [24, 30]. The new 200 GeV data published in this paper are $v_2$ results for $p_T > 5$ GeV/c. In addition the 62.4 GeV Cu+Cu data are new results original in this paper.

The centrality selections of each collision system are:

1. Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
   - Minimum Bias ; 0%–92%
   - 10% steps : 0%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, 50%–60%
   - 20% steps ; 0%–20%, 20%–40%, 40%–60%
   - Most peripheral bin ; 60%–92%

2. Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV
   - Minimum Bias ; 0%–83%

The centrality selections of each collision system are:
3. Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV

- Minimum Bias: 0%–88%
- 10% steps: 0%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%

A. $v_2$ vs. $p_T$ results for inclusive charged hadrons

1. Au+Au at $\sqrt{s_{NN}} = 200$ GeV

![Graphs showing $v_2$ vs. $p_T$ for different centralities in Au+Au collisions at 200 GeV.](image)

FIG. 6. (Color online) $v_2$ for inclusive charged hadrons in Au+Au at $\sqrt{s_{NN}} = 200$ GeV for the centralities indicated. The error bars show statistical uncertainties and the bands show systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.

We analyzed 860 million Au+Au collisions at 200 GeV collected during the 2003-04 experimental period, which is more than 20 times larger than the sample of events (30 M) analyzed from the 2001-02 experimental period [5]. Figure 6 shows the $v_2$ for inclusive charged hadrons in Au+Au collisions at 200 GeV.

2. Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV

![Graphs showing $v_2$ vs. $p_T$ for different centralities in Au+Au collisions at 62.4 GeV.](image)

FIG. 7. (Color online) $v_2$ for inclusive charged hadrons in Au+Au at $\sqrt{s_{NN}} = 62.4$ and 200 GeV for the centralities indicated. The error bars show statistical uncertainties and the bands show systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.

For Au+Au collisions at 62.4 GeV, 30 million events were analyzed to study the dependence of $v_2$ on collision center-of-mass energy. The measured $v_2$ results from this collision system are shown in Fig. 7 together with the results from Au+Au 200 GeV collisions. The values of $N_{\text{part}}$ are very similar at these two beam energies. We observe that the $v_2$ measurements for Au+Au collisions at 62.4 GeV are consistent with those for Au+Au at 200 GeV, within the combined statistical and systematic uncertainties.
3. **Cu+Cu at $\sqrt{s_{NN}} = 200 \text{ and 62.4$GeV$}**

For Cu+Cu collisions at 62.4 GeV, 340 million events were analyzed to study the dependence of $v_2$ on collision center-of-mass energy and system size. Figure 5 shows the $v_2$ results at 62.4 GeV in minimum bias events and 10% centrality selections. These are compared with Cu+Cu 200 GeV $v_2$ results [7]. The $v_2$ results for Cu+Cu collisions at 62.4 GeV are clearly smaller than those in 200 GeV collisions, especially at $p_T < 1.5$ GeV/c.

**B. System comparisons**

1. **Centrality and collision energy dependence**

An alternative view of these data is to make separate $p_T$ selections and to plot $v_2$ in a given $p_T$ range as a function of centrality and collision energy. Figure 9 presents the Au+Au data as a function of centrality, where triangles, boxes, and circles correspond to three $p_T$ bins: 0.2–1.0, 1.0–2.0 and 2.0–4.0 GeV/c respectively. The two different beam energies are presented by open and closed symbols for 62.4 and 200 GeV respectively. The data confirms prior results that $v_2$ increases from central to midcentral collisions and then begins to decrease again towards peripheral collisions. The $v_2$ for Au+Au at 62.4 and 200 GeV agree to within statistical and systematic uncertainties for all measured centralities.

A similar $v_2$ comparison has been carried out by the STAR experiment reaching even lower energies from $\sqrt{s_{NN}} = 7.7$ to 200 GeV [10]. Their results show that the $v_2$ ($p_T$) increases slightly from 7.7 up to 39 GeV, then saturates above 39 GeV.

Figure 10 shows the centrality dependence of $v_2$ for charged hadrons emitted at different $p_T$ from Cu+Cu collisions at 62.4 and 200 GeV. The statistical uncertainties are larger due to lower statistics for the Cu+Cu in the 62.4 GeV data sample. The measured $v_2$ values are lower at 62.4 GeV compared with 200 GeV.

We have made a comparison between the measured PHENIX $v_2$ and the previously published STAR $v_2$ measurement [20] in Cu+Cu collisions and found them to be generally consistent. For 200 GeV Cu+Cu the PHENIX $v_2$ are higher by about 10% in the 0-10%, 10-20%, 20-30% and 30-40% centrality bins, and higher by about 20% in 40-50% bin; these differences are within statistical and systematic uncertainties of the PHENIX results in all cases. At 62.4 GeV the PHENIX $v_2$ is lower by approximately 10% in the 0-40% bins and by 20% in 40-50% bin. These differences are within statistical and systematic uncertainties in the 0-20% bins, though they are roughly twice the statistical and systematic uncertainties in 20-50% bins, taking into account errors on the PHENIX measurement alone.

There are two ways to establish the extent that $v_2$ changes with the system size: one is to change the collision centrality, the other is to change the colliding nuclei. As seen in Fig. 11 the measured $v_2$ in Cu+Cu collisions is smaller than that of Au+Au at a comparable $N_{part}$.

Because $\varepsilon$ is different between Au+Au and Cu+Cu collisions at the same $N_{part}$, we can try to normalize $v_2$ by $\varepsilon$. In the lower row of Fig. 11, $v_2$ normalized by $\varepsilon$ is similar in magnitude for both Cu+Cu and Au+Au collisions. This confirms that the eccentricity normalization can account for the effect of the initial geometrical anisotropy [30]. The exception is that the Cu+Cu 62.4 GeV data falls below the other data. Note that the ratio $v_2/\varepsilon$ also depends on centrality ($N_{part}$) and that there is a similar rate of increase of $v_2/\varepsilon$ with $N_{part}$ for all three $p_T$ bins: 0.2–1.0, 1.0–2.0, and 2.0–4.0 GeV/c. This pattern suggests the need for an additional normalization or scaling factor that depends on $N_{part}$.

Figure 12 is a comparison of $v_2$ as a function of $p_T$ for centrality classes that have approximately the same value of $\varepsilon$ but with different values of $N_{part}$. The average $N_{part}$ is 166.6 for 20%-30%, 114.2 for 30%-40% and 45.5 for 50%-60% in Au+Au collisions, while $N_{part}$ is 73.6 for 10%-20%, 53.0 for 20%-30% and 25.4 for 40%-50% in Cu+Cu collisions. It can be clearly seen that $v_2$ increases with $N_{part}$ for similar $\varepsilon$.

3. **Participant $N_{part}^{1/3}$ scaling**

We empirically explore using $N_{part}^{1/3}$ as a potential scaling factor of $v_2$ in addition to $\varepsilon$. We draw on results with a different observable, namely that the HBT source sizes for similar $\varepsilon$ is different between Au+Au and Cu+Cu collisions. It can be clearly seen that the Cu+Cu 62.4 GeV data falls below the other data. Note that the ratio $v_2/\varepsilon$ also depends on centrality ($N_{part}$) and that there is a similar rate of increase of $v_2/\varepsilon$ with $N_{part}$ for all three $p_T$ bins: 0.2–1.0, 1.0–2.0, and 2.0–4.0 GeV/c. This pattern suggests the need for an additional normalization or scaling factor that depends on $N_{part}$.

Figure 13 plots $v_2/(\varepsilon \cdot N_{part}^{1/3})$ for integrated bins of $p_T$ = 0.2–1.0, 1.0–2.0, and 2.0–4.0 GeV/c. This combination of two scaling factors works well, i.e. the scaled data are at comparable values, with the exception of the Cu+Cu data at 62.4 GeV which deviate from this scaling, particularly at $N_{part} \leq 40$. That this empirical $v_2/(\varepsilon \cdot N_{part}^{1/3})$ scaling works well suggests that $v_2$ is determined by both the initial geometrical anisotropy and the number of participants.

Other scalings for the system size dependence have been suggested, particularly $1/S_{xy}dN/dy$ [38] where $S_{xy}$ is the transverse area of the participant zone. Because $dN/dy$ is proportional to $N_{part}$ at a given beam energy and $S_{xy}$ is approximately proportional to $(N_{part})^{2/3}$, $1/S_{xy}dN/dy$ is then proportional to $N_{part}^{1/3}$.
FIG. 8. (Color online) $v_2$ for inclusive charged hadrons in Cu+Cu at $\sqrt{s_{NN}} = 62.4$ GeV compared with 200 GeV [7] for the centralities indicated. The error bars show statistical uncertainties and the bands show systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.

FIG. 9. (Color online) Comparison of integrated $v_2$ at $\sqrt{s_{NN}} = 62.4$ and 200 GeV in Au+Au. Solid symbols indicate $\sqrt{s_{NN}} = 200$ GeV and open symbols indicate $\sqrt{s_{NN}} = 62.4$ GeV. Ranges of $p_T$ integrated are 0.2–1.0 (circles), 1.0–2.0 (squares), and 2.0–4.0 (triangles) GeV/c. The bars indicate the statistical uncertainties and the boxes indicate the systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.

FIG. 10. (Color online) Comparison of integrated $v_2$ at $\sqrt{s_{NN}} = 62.4$ and 200 GeV in Cu+Cu. Open symbols indicate $\sqrt{s_{NN}} = 62.4$ GeV and filled symbols indicate $\sqrt{s_{NN}} = 200$ GeV. Ranges of $p_T$ integrated are 0.2–1.0 (circles), 1.0–2.0 (squares), and 2.0–4.0 (triangles) GeV/c. The bars indicate the statistical uncertainties and the boxes indicate the systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.
V. RESULTS FOR $v_2$ OF IDENTIFIED CHARGED HADRAMS

More information can be obtained by examining $v_2$ for charged pions, kaons and (anti) protons ($\pi/K/p$) each as a function of transverse momentum $p_T$. The charged particles are identified by TOF and EMCal and the data are presented for several classes of collision centrality;

1. Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV
   - 10%–40% (Particles and antiparticles are measured separately.)
   - 10% bins from 0% to 50% (Particles and antiparticles are measured together.)

2. Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
   - 0%–92% (Particles and antiparticles are measured separately.)
   - 10% bins from 0% to 50% (Particles and antiparticles are measured together.)

3. Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV
   - 10% bins from 0% to 50% (Particles and antiparticles are measured together.)

Note we do not present Cu+Cu 62.4 GeV data in this section because there were insufficient statistics to determine $v_2$ for identified particles.

A. Beam energy dependence

Figure 14 shows a summary of $v_2$ measurements of identified particles $\pi/K/p$ for three different data sets; Au+Au at 62.4 and 200 GeV and Cu+Cu at 200 GeV. Figure 15 shows the comparison between 62.4 and 200 GeV for Au+Au collisions. The measured $v_2$ in the 62.4 and 200 GeV data sets are consistent, within the systematic uncertainties, with the exception of proton $v_2$ at 62.4 GeV which is slightly higher than at 200 GeV in the lower $p_T$ region. These small differences could be caused by larger radial flow at higher $\sqrt{s_{NN}}$, especially for heavier particles such as protons.

The observation that the proton $v_2$ is larger at 62.4 GeV than at 200 GeV for Au+Au collisions is opposite to the earlier observation that inclusive charged $v_2$ at...
15

1 2 3
0.2
0.1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure12}
\caption{(Color online) Comparison of $v_2$ ($p_T$) at 200 GeV for two example systems with different collision size (Au+Au or Cu+Cu) but approximately the same $\varepsilon$. Black symbols indicate Au+Au and red symbols indicate Cu+Cu. The average number of participants $N_{\text{part}}$ is 166.6 for 20%–30%, 114.2 for 30%–40% and 45.5 for 50%–60% at Au+Au collisions, and $N_{\text{part}}$ is 73.6 for 10%–20%, 53.0 for 20%–30% and 25.4 for 40%–50% at Cu+Cu collisions.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure13}
\caption{(Color online) Comparison of integrated $v_2/\varepsilon \cdot N_{\text{part}}^{1/3}$ as a function of $N_{\text{part}}$ for two collision energies and two collision systems, Au+Au at 200 GeV, Au+Au at 62.4 GeV, Cu+Cu at 200 GeV and Cu+Cu at 62.4 GeV. Ranges of $p_T$ integration are 0.2–1.0, 1.0–2.0 and 2.0–4.0 GeV/c from left to right panels respectively. All uncertainties from the measured $v_2$, $\varepsilon$, and $N_{\text{part}}$ are included in the error bars.}
\end{figure}

62.4 GeV is lower than that at 200 GeV Cu+Cu. Therefore, the differences in lower $v_2$ for inclusive charged hadrons from Cu+Cu may be caused by different physics than the radial flow effect seen in Au+Au collisions.

\section*{B. Particle-antiparticle comparison}

When we examine identified $v_2$ we will combine opposite charged particles, e.g. $\pi^\pm$, to form $\pi$ $v_2$. Prior results on the ratio of $v_2$ for antiparticles and particles can be found in Refs. \textsuperscript{19, 39}. In this section we compare the particle and antiparticle $v_2$ in Au+Au collisions at 200 and 62.4 GeV in wide centrality classes: a minimum bias sample (0%–92%) for 200 GeV and 10%–40% for 62.4 GeV data. The first and second rows of plots in Fig. \textsuperscript{16} present $v_2$ as a function of $p_T$ for $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$ in Au+Au collisions at 200 and 62.4 GeV. The lines for each point are the statistical uncertainties and the boxes are systematic uncertainties.

At both 200 and 62.4 GeV, the the measured Au+Au $v_2$ values of particle and antiparticle are comparable to each other within uncertainty, though there is a possible indication of a small reduction of anti-proton $v_2$ at lower $p_T$. When we combine particle and anti-particle $v_2$ we average over these differences.

\section*{C. Number of valence quark $n_q$ scaling of $v_2$}

The $v_2$ measurements of identical particles $\pi/K/p$ for three different data sets; Au+Au at 62.4 and 200 GeV...
FIG. 14. (Color online) $v_2$ vs. $p_T$ for $\pi/K/p$ emitted from Au+Au at 62.4 and 200 GeV and Cu+Cu at 200 GeV collisions for the centralities indicated. The lines for each point indicate the statistical uncertainties, and the boxes are systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.

FIG. 15. (Color online) Comparison of $v_2$ between $\sqrt{s_{NN}} = 62.4$ and 200 GeV for $\pi/K/p$ emitted from 0%–10%, 10%–20% and 20%–30% central Au+Au collisions. Both results for all species agree within the errors. The lines indicate the statistical uncertainties at each point and the boxes indicate the systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.
FIG. 16. (Color online) Comparison of the $v_2$ of particles, antiparticles, for a minimum bias sample 0%–92% at 200 GeV and 10%–40% central at 62.4 GeV in Au+Au collisions. The lines for each point indicate the statistical uncertainties, and the boxes are systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.

FIG. 17. (Color online) The ratio $v_2/n_q$ vs. $p_T/n_q$ for $\pi/K/p$ emitted from Au+Au at 62.4 and 200 GeV and Cu+Cu at 200 GeV collisions for the centralities indicated. The lines for each point indicate the statistical uncertainties, and the boxes are systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.
FIG. 18. (Color online) The ratio $v_2/n_q$ vs. $KE_T/n_q$ for $\pi/K/p$ emitted from Au+Au at 62.4 and 200 GeV and Cu+Cu at 200 GeV collisions for the centralities indicated. The lines for each point indicate the statistical uncertainties and the boxes are systematic uncertainties. In many cases, the systematic uncertainties are smaller than the symbols.

FIG. 19. (Color online) The ratio of $v_2/n_q$ to the fit for $\pi/K/p$ emitted from Au+Au at 62.4 and 200 GeV and Cu+Cu at 200 GeV collisions for the centralities indicated. The lines for each point indicate the statistical uncertainties.
and Cu+Cu at 200 GeV collisions are re-plotted in Fig. 17 after scaling by the number of constituent quarks for both \( v_2 \) and \( p_T \) axes as shown. An alternative scaling is to use transverse kinetic energy. We define transverse kinetic energy as \( K_{ET} = m_T - m \), where \( m \) is the mass of the hadron and \( m_T = \sqrt{p_T^2 + m^2} \). The quark number scaled \( v_2 \) are shown as a function of \( K_{ET}/n_q \) for all three data sets in Fig. 18.

Note that at higher values, \( K_{ET}/n_q > 0.7 \), PHENIX has observed significant deviations from \( n_q \) scaling for Au+Au noncentral collisions. Those higher \( K_{ET} \) results indicate that the azimuthal anisotropy of these high \( K_{ET} \) particles are impacted by mechanisms such as parton-energy loss, jet chemistry, and/or different fragmentation functions. For comparison, at the LHC \( K_{ET}/n_q \), \( v_2 \) does not scale well with the quark number and transverse kinetic energy of the hadron in any range of \( K_{ET}/n_q \), with up to 40% deviations observed at low values of \( K_{ET}/n_q \).

To quantify how well the number of quark scaling with \( K_{ET} \) works with the current data, we fit all the hadron species data in Figure 18 with a common polynomial function for each centrality and colliding system. We divide the data by these fits to compare how close different hadron species are to the common scaled shape of \( K_{ET}/n_q \). For Au+Au, Au+Au at 62.4 GeV and Cu+Cu at 200 GeV collisions are re-plotted in Fig. 17, especially for the more central collisions between 0%-10%. For peripheral Cu+Cu collisions, the number of quark scaling with \( K_{ET} \) does not work well. The deviation from \( n_q \) scaling seems to be largest at peripheral collisions, i.e. at 40%-50%, especially between pions and protons.

We examine in more detail the scaling at low \( K_{ET} \) in the 62.4 GeV data in stages. First, the left panel in Fig. 20 summarizes the unscaled \( v_2 \) data from 10%-40% central Au+Au collisions at 62.4 GeV. The \( v_2 \) values are broadly spread in their magnitude. A reduction in spread is observed in the right panel when \( n_q \), the number of valence quarks, is used as a scaling. However the scaled \( v_2 \) values do not collapse to a universal curve. Figure 21 shows a better scaling with \( K_{ET}/n_q \).

Overall, the combined \( n_q - K_{ET} \) scaling works well (typical deviations less than 20%) for 0 < \( K_{ET}/n_q < 1 \) GeV, indicating that the elliptic collective motion is created at a level consistent with constituent quarks both at 62.4 GeV in Au+Au and at 200 GeV in Cu+Cu.

D. Universal \( v_2 \) scaling

We consider a universal \( v_2 \) scaling for all the \( v_2 \) measurements in this paper for identified hadrons between 0.1 < \( K_{ET}/n_q < 1 \) GeV. Within a given collision system, i.e. each centrality bin for each set of Au+Au and Cu+Cu collisions, we first apply quark number \( n_q \) scaling and \( K_{ET} \) scaling. Then we apply the eccentricity normalization and \( N_{1/3}^{part} \) scaling for each colliding system. Because we have observed that \( v_2 \) saturates with beam energy between 62-200 GeV, we do not apply any scaling with beam energy. The \( v_2 \) data with the four factors applied (quark number scaling, \( K_{ET} \) scaling, eccentricity normalization and \( N_{1/3}^{part} \) scaling) are shown as a function of \( K_{ET}/n_q \) in Fig. 22, which includes data from Au+Au at 200 GeV, Au+Au at 62.4 GeV and Cu+Cu at 200 GeV at five centrality bins over 0%-50% in 10% steps for each system. There are 45 \( v_2 \) data sets in total. The combined data is fit with a single 3rd-order-polynomial, producing a \( \chi^2/NDF = 1034/490 = 2.11 \) (including both statistical and systematic uncertainties). Note there is no Cu+Cu 62.4 GeV data in Fig. 22 because there were insufficient statistics to determine \( v_2 \) for identified particles.

If we apply the \( N_{1/3}^{coll} \) scaling to the same data sets instead of \( N_{1/3}^{part} \) scaling, we obtain \( \chi^2/NDF = 2643/490 = 5.39 \). Therefore, \( N_{1/3}^{part} \) is a better scaling factor than \( N_{1/3}^{coll} \). As we mentioned Section IV, there are some deviations from the quark number and \( K_{ET} \) scalings, therefore this \( N_{1/3}^{part} \) normalized curve is not perfectly a single line. Further investigation of these deviations would require higher precision measurements.

VI. SUMMARY AND CONCLUSION

We have measured the strength of the elliptic anisotropy, \( v_2 \), for inclusive charged hadrons and identified charged hadrons (\( \pi/K/p \)) in Au+Au and Cu+Cu.
 collisions at √sNN = 200 and 62.4 GeV to study the dependence of v2 on collision energy, species and centrality. Results of this systematic study reveal the following features. Comparisons between 200 and 62.4 GeV collisions demonstrate that v2 as a function of pT does not depend on beam energy in Au+Au. In Cu+Cu, the v2 at 62.4 GeV is slightly lower than that at 200 GeV.

One possibility for the lower v2 values 62.4 GeV in Cu+Cu is less complete thermalization in small systems at lower beam energies. At least two types of theoretical models have been used to investigate the question of incomplete thermalization for systems formed at RHIC. Borghini argues that because v2/ε depends on dN/dy [41], the systems formed at RHIC are not fully thermalized during the time when v2 develops. Borghini argues that this dN/dy dependence can be interpreted as dependence on a Knudsen number representing incomplete thermalization. Recent hydrodynamical models that include shear viscosity and initial fluctuations [11–13] effectively include nonequilibrium effects through the finite viscosity. Using a different non-equilibrium approach, microscopic transport models [42] solve the relativistic Boltzmann equation. Both the viscous hydrodynamical and the Boltzmann transport models can be tested with our two observation that the v2 at Cu+Cu at 62.4 GeV is slightly lower than that at 200 GeV, and that the measured universal scaling breakdowns in peripheral Cu+Cu.

For various hadron species the measured v2 results as a function of pT are well scaled by quark number. Interestingly, it appears that this scaling holds also for higher orders in azimuthal anisotropy [43]. The KE_T scaling performs better than p_T scaling, particularly in the intermediate transverse momentum region (p_T = 1–4 GeV/c). This scaling property suggests that the matter flows with quark-like degrees of freedom, and therefore is consistent with the formation of QGP matter [7]. A small deviation from KE_T scaling can be seen for both Au+Au and Cu+Cu collisions, and this deviation depends on the number of participants N_part. This deviation might indicate a restricted region where KE_T scaling works well, possibly dependent on the strength of the radial flow.

For both Au+Au to Cu+Cu collisions, we confirm that v2 can be normalized by participant eccentricity (ε) [30]. This indicates that the effect of initial geometrical anisotropy can be partially removed by eccentric-
ity normalization. However, $v_2$ normalized by $\varepsilon$ still depends on $N_{\text{part}}$. $v_2$ is not fully determined by $\varepsilon$ alone and we have empirically found that $v_2/\varepsilon$ is proportional to $N_{\text{part}}^{1/3}$. The initial participant size $N_{\text{part}}^{1/3}$, is related to a length scale or an expansion time scale. Taking account all scalings and normalization, the data $v_2/n_q/\varepsilon/N_{\text{part}}^{1/3}$ vs. $KE_T/n_q$ lie on a universal curve for $0.1 < KE_T/n_q < 1$ GeV.

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