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Systematic dependences of the elliptic flow

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The transverse momentum (p_T) and centrality dependence of the azimuthal anisotropy (v_2) are measured for charged hadron species at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV in Cu + Cu and Au + Au collisions and at $\sqrt{s_{NN}}$ = 7.7 and 39 GeV in Au + Au collisions by the PHENIX experiment at RHIC. The results are consistent with eccentricity scaling and with quark number + KE_T scaling. Also, we found that v_2 divided by the participant eccentricity of the initial geometry proportionally increases with the number of participants to the 1/3 power except at small N_{part} in Cu + Cu at 62.4 GeV. Taking these scaling (quark number, KE_T, eccentricity and $N_{part}^{1/3}$) into account, there is a universal scaling for v_2 with different energies, collision sizes and particle species. We also report that this scaling works at the LHC energy comparing PHENIX results to ALICE results. The results indicate that v_2 is determined by more than just the geometrical eccentricity and also depends on the size of collisions.

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1. Introduction

Relativistic heavy ion collisions have been considered as a unique way to create the quark-gluon plasma (QGP), which is the phase of de-confined quarks and gluons. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was constructed to create and study the QGP. Azimuthal anisotropy of particles produced in relativistic heavy ion collisions is the one of the most powerful probes for investigating the characteristics of the QGP. Especially the strength of the elliptic anisotropy (v_2), which is defined by the second harmonics of Fourier expansion for the azimuthal distribution of produced particles with respect to the reaction plane, is expected to be sensitive to the early stage of heavy ion collisions. At non-central collision, the overlap region is geometrically anisotropic, like an almond shape. When the produced matter has small mean free path, interacting each other enough to reach local thermalization, it creates pressure gradient. The geometrical anisotropy transfers to the anisotropy in the momentum phase space as flow because of this pressure gradient, and v_2 indicates the strength of this elliptic flow. Thus, the measured v_2 reflects the equation of state of the dense matter such as QGP, produced in the collisions. The important thing here is since the produced particles randomly emit before thermalization, the geometrical eccentricity decrease with time. Therefore, to let the geometrical eccentricity make elliptic flow, the thermalization should be occurred very early stage before the geometrical eccentricity is totally gone.

2. Motivation

One of the most remarkable findings at RHIC is that the strength of v_2 can be described well by hydro-dynamical models in the low transverse momentum region ($\sim$ 1 GeV/c) [1]. In the intermediate transverse momentum region (1 $\sim$ 4 GeV/c), v_2 is consistent with n_q and KE_T (= m_T - m_0) scaling, and the result supports a quark-recombination model [2]. The matter produced in the high energy heavy ion collision is expected to undergo several stages from the initial hard scattering to the final hadron emission. When the matter reaches thermalization and QGP is created, we expect hydro-dynamical behavior at quark level. Since experimentally we cannot see the QGP directly, we need a comprehensive understanding from thermalization through hadronization to freeze-out. The elliptic flow is expected to be created at QGP stage by pressure gradient, but it is important to note whenever the matter interacts with each other, there is a possibility to change v_2. [3]

For a more comprehensive understanding of v_2 production mechanism, we have carried out systematic measurements of v_2, by measuring v_2 for identified charged hadrons in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ = 200 and 62.4 GeV and also for inclusive charged hadrons in Au+Au at $\sqrt{s_{NN}}$ = 7.7 and 39 GeV. We have studied the dependence on collision energy, size and species of the produced particles comparing the $\sqrt{s_{NN}}$ = 2.76 TeV data from LHC. [5]

3. Results

3.1 Collision Energy Dependence

In Au+Au collisions, the values of v_2 as a function of p_T agree well at $\sqrt{s_{NN}}$ = 39, 62.4 and

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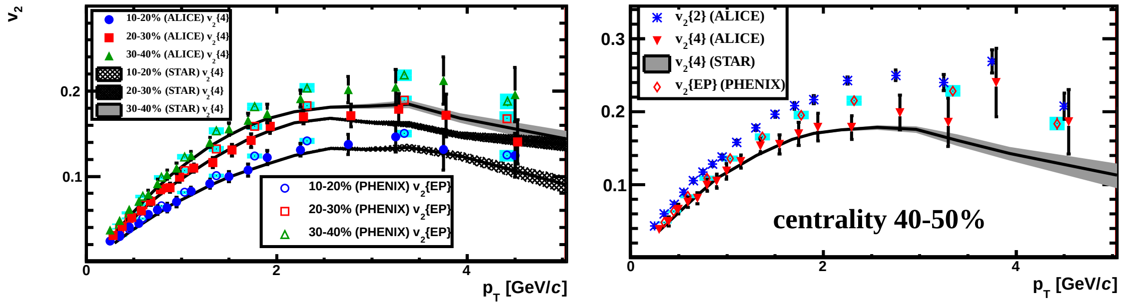

Figure 1: v_2 as a function of p_T at $\sqrt{s_{NN}}$ = 200 GeV and 2.76 TeV. Left panel is for 10-20, 20-30 and 30-40 % and right panel is for 40-50 %. PHENIX results are measured by event plan method. ALICE and STAR results are measured by cumulant method. The detail of measurement are in [5] [6] [7].

200 GeV for measured centralities, 10-20, 20-30, 30-40 and 40-50%. However, the v_2 at 7.7 GeV is much lower than these. This results may indicate the energy between 7.7 and 39 is the region which switch from partonic flow to hadronic flow.

Additionally, we compared the results of $\sqrt{s_{NN}}$ = 2.76 TeV data in Pb+Pb at LHC-ALICE, and it was found that v_2 at 2.76 TeV is very similar to the v_2 at 200 GeV especially at low p_T as shown in Figure 1. [5] [6] [7] While the differential v_2 is consistent between LHC and RHIC, integrated v_2 is increasing at higher collision energy. This is because the spectra shape is flatter so that the mean p_T is higher at LHC. This flatter spectra has been considered to be caused by larger radial flow. However, if this is due to the radial flow, the differential v_2 should also be shifted to higher p_T, so that the differential v_2 should be lower at low p_T at LHC and should not be matched to RHIC. Therefore, if we could subtract the effect from the radial flow, the v_2 values may not agree between LHC and RHIC.

3.2 Eccentricity and N$_{\rm part}$ Scaling

Next, we compared different system size of collisions. The left panel in Figure 2 shows the comparison of v_2 in Au+Au, Cu+Cu and Pb+Pb at $\sqrt{s_{NN}}$ = 200 GeV, 62.4 GeV and 2.76 TeV as a function of N$_{\rm part}$. The values of v_2 agree well at $\sqrt{s_{NN}}$ = 200 GeV, 62.4 GeV and 2.76 TeV in the errors, but have clear differences between the Cu+Cu and Au+Au (Pb+Pb). This is natural because the different nucleus collisions such as Au+Au, Cu+Cu and Pb+Pb, have different initial geometrical eccentricities at the same $N_{\rm part}$. Normalizing v_2 by eccentricity, ε, (eccentricity scaling), all results follow one curve as shown in the middle panel in Figure 2, therefore, v_2 is scaled by the eccentricity at the same N$_{\rm part}$. Here, we use the participant eccentricity, which includes the effect of participant fluctuations [4]. One can see that the values of v_2/ε are not a constant and it depends on $N_{\rm part}$. Therefore, v_2 can be normalized by ε at the same $N_{\rm part}$, but ε is not enough to determine v_2 . We found that v_2/ε is proportional to $N_{\rm part}^{1/3}$ as shown in the right panel of Figure 2. Including results of $\sqrt{s_{NN}}$ = 2.76 TeV, $v_2/(\varepsilon \cdot N_{\rm part}^{1/3})$ is independent of the collision systems except for small $N_{\rm part}$ in Cu+Cu at $\sqrt{s_{NN}}$ = 62.4 GeV. This exception might indicate that this is a region where the matter has not reached sufficient thermalization, although the errors are too large to discuss the difference. Therefore, a scan of collision energies and sizes would be very important for further study of this exception. Figure 2 is for p_T = 0.2 - 1.0 GeV/c. The results for p_T = 1.0 - 2.0 and 2.0 - 4.0 GeV/c

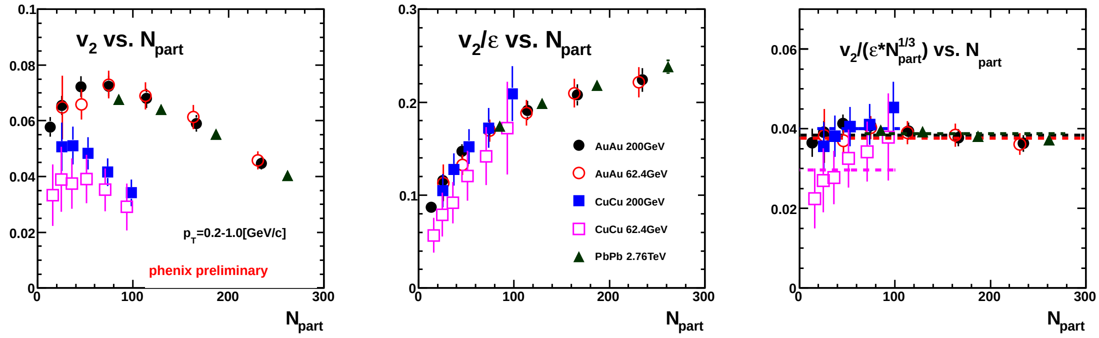

Figure 2: Comparison of integrated v_2 as a function of $N_{\rm part}$ for five different collision systems. Left panel shows v_2 vs. $N_{\rm part}$, middle panel is v_2/ε vs. $N_{\rm part}$ and right panel is $v_2/(\varepsilon \cdot N_{\rm part}^{1/3})$ vs. $N_{\rm part}$. Closed symbols indicate the results of $\sqrt{s_{\rm NN}}$ = 200 GeV and 2.76 TeV, and open symbols are for $\sqrt{s_{\rm NN}}$ = 62.4 GeV. Circles, squares and triangles indicate Au+Au, Cu+Cu and Pb+Pb collisions respectively. The statistical and systematic errors are included in the bars.

have the same tendency as well.

3.3 Quark number+ KE$_{\rm T}$ scaling and Universal v_2

One of the most famous results on RHIC v_2 measurement is that the v_2 for quark number($n_{\rm q}$) + KE$_{\rm T}$ scaling in Au+Au at at $\sqrt{s_{\rm NN}}$ = 200 GeV.[2] The $n_{\rm q}$ scaling is consistent to the recombination model which assumes the quark level flow at QGP phase, and the KE$_{\rm T}$ scaling has been considered to be able to subtract the difference of different particle v_2 at low $p_{\rm T}$ which is caused due to the radial flow effect. In Au+Au 200GeV collisions at recent PHENIX experiment, the large statistics and new detector allowed us to see that the both $n_{\rm q}$ and KE$_{\rm T}$ scaling works very well on various particle species including ϕ, Λ and deuteron, and even to see the break point of this scaling at KE$_{\rm T}$ = 1 GeV as shown in [9] . Above this $p_{\rm T}$ region, one can expect other mechanism is dominant to create v_2.

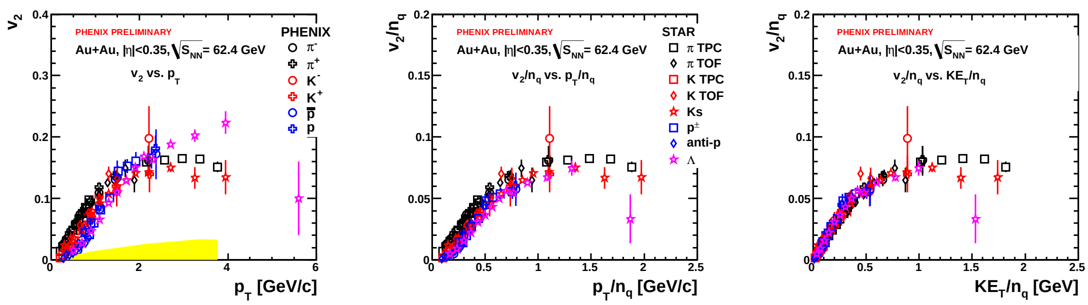

Figure 3: v_2 with the scaling. The left panel shows v_2 vs. $p_{\rm T}$, the middle shows v_2/n_q vs. $p_{\rm T}/n_q$ and the left shows v_2/n_q vs. KE$_{\rm T}/n_q$ for various charged hadron species in Au+Au at $\sqrt{s_{\rm NN}}$ = 62 GeV at 10-40 % centrality bin.

For the systematic study, we also measured particle identified v_2 in Au+Au at $\sqrt{s_{\rm NN}}$ = 62.4 GeV and in Cu+Cu at $\sqrt{s_{\rm NN}}$ = 200 GeV. The left panel of Figure 3 shows v_2 vs. $p_{\rm T}$, the middle shows v_2/n_q vs. $p_{\rm T}/n_q$ and the left shows v_2/n_q vs. KE$_{\rm T}/n_q$ for various charged hadron species in Au+Au at $\sqrt{s_{\rm NN}}$ = 62 GeV at 10-40 % centrality bin. It is found that v_2 in Au+Au at 62.4 GeV

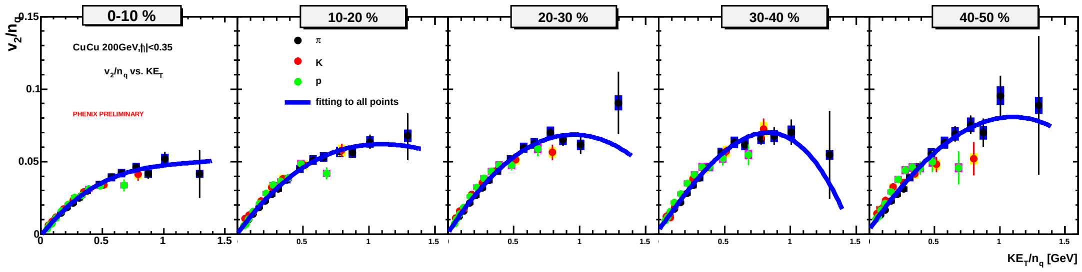

Figure 4: v_2/n_q vs. KE_T/n_q for charged π, K and p in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV for 0 - 50% centrality bins as 10% step. Blue lines are the fitting to these scaled v_2 together by one curve at each centrality bin.

is also consistent with n_q + KE_T scaling. Moreover, as shown in Figure 4 the n_q + KE_T scaling mostly works out in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV for central collisions. However, you can see the small discrepancy from the KE_T scaling at peripheral collisions at low p_T, 30-40, and 40-50%. For quantitative comparison, Figure 5 and 6 show the ratio of the π/K/p scaled v_2 to the fitting function which fit these scaled v2 by one curve at each centrality bin. The fitting curves in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV are shown as the blue lines in Figure 4. To compare Cu+Cu and Au+Au Collisions, the values of N_{part} at each centrality bin are written in each panel. It is clear that the discrepancy from the KE_T scaling depends on N_{part}. Comparing between π and proton, the results indicate the larger N_{part} produces more shift for proton to higher p_T based on π. This N_{part} dependence of KE_T scaling behavior for the v_2 is explained by the radial flow effect with blast wave model in [9].

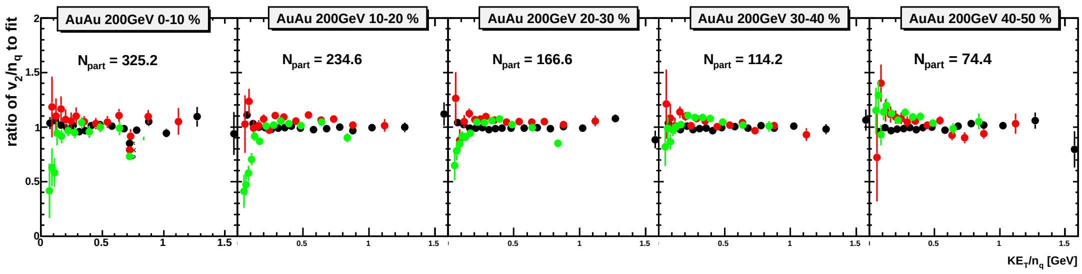

Figure 5: The ratio of the π/K/p scaled v_2 to the fitting function which fit these scaled v2 by one curve at each centrality bin in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.

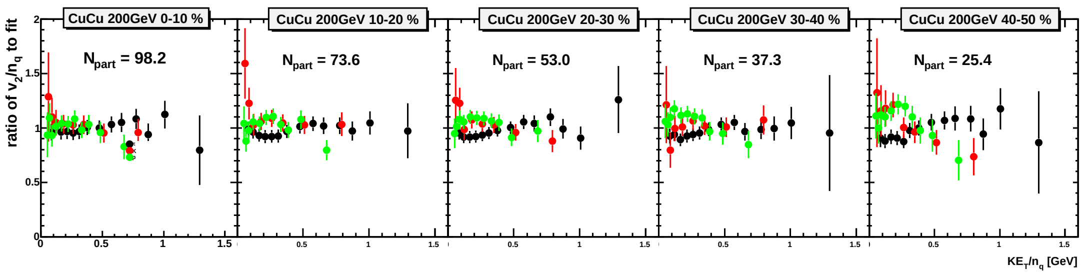

Figure 6: The ratio of the π/K/p scaled v_2 to the fitting function which fit these scaled v2 by one curve at each centrality bin in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV. The fitting curves are shown as the blue lines in Figure 4.

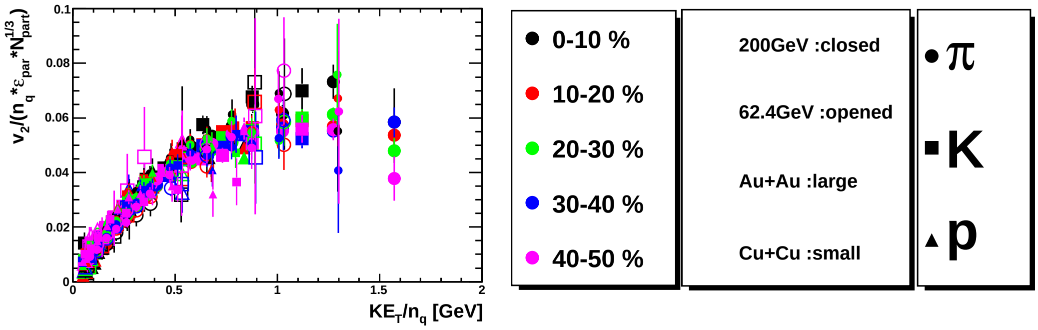

Figure 7: $v_2/(\varepsilon \cdot N_{\rm part}^{1/3} \cdot n_{\rm q})$ vs. $\mathrm{KE_T}/n_{\rm q}$ for π/K/p in Au+Au at $\sqrt{s_{\rm NN}}$ = 200 GeV, in Au+Au at $\sqrt{s_{\rm NN}}$ = 62.4 GeV and in Cu+Cu at $\sqrt{s_{\rm NN}}$ = 200 GeV at five centrality bins for 0-50 % as 10 % step for each system. There are 45 curves. Applying polynomial fitting, χ^2/NDF is 2.1.

In addition to the fact that $v_2(p_{\rm T})$ is consistent at $\sqrt{s_{\rm NN}}$ = 39 - 200 GeV, v_2 normalized by $n_{\rm q}$ + $\mathrm{KE_T}$, eccentricity, and $N_{\rm part}^{1/3}$ scaling follows a universal curve as shown in the right panel of Figure 7. This figure includes the 45 curves for π/K/p in Au+Au at $\sqrt{s_{\rm NN}}$ = 200 GeV, in Au+Au at $\sqrt{s_{\rm NN}}$ = 62.4 GeV and in Cu+Cu at $\sqrt{s_{\rm NN}}$ = 200 GeV for the five centrality bins from 0 - 50% in 10% steps. The χ^2/NDF of the polynomial fitting is 2.1. This is a universal scaling for v_2 with different energies, collision sizes and particle species, and it indicates that v_2 is determined not only by the geometrical eccentricity but also by the size of collision. This scaling assume that differential v_2 is consistent above 39 GeV while "v_2/ε vs. (1/S)(dN/dy)" scaling plotted in [8] assumes that the higher collision energy produces higher v_2. Therefore, this $N_{\rm part}^{1/3}$ scaling works better for the differential v_2 at PHENIX results. The size dependence of v_2 can be understood as thermal freeze-out nature of produced particles based on hydrodynamical behavior, which is different from that of chemical freeze-out. [9]

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