Beam Energy Dependence of Azimuthal Anisotropy at RHIC-PHENIX

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Recent PHENIX measurements of the elliptic (v_2) and hexadecapole (v_4) Fourier flow coefficients for charged hadrons as a function of transverse momentum (p_T), collision centrality and particle species are presented and compared with results from the PHOBOS and STAR collaborations respectively. The status of extensions to future PHENIX measurements at lower beam energies is also discussed.

1. INTRODUCTION

The discovery of large elliptic flow (v_2) for all particle species studied at the Relativistic Heavy Ion Collider (RHIC) is a key piece of evidence for the creation of hot and dense partonic matter in ultra relativistic nucleus-nucleus collisions [1, 2]. This is well supported by the observed agreement between differential flow measurements and calculations that model an essentially locally equilibrated quark gluon plasma (QGP) having a small value for the specific shear viscosity (η/s) [3–6]. After ten years of experiments at RHIC, the most extensive set of flow measurements for various hadrons with different masses, charges, quark content and hadronic cross-sections became available for the first time in the history of heavy-ion collisions. They show that, for a given centrality, elliptic flow for all observed hadrons (at RHIC) scale to a single curve when plotted as v_2/n_q versus KE_T/n_q, where n_q is the number of constituent quarks in a given hadron species and KE_T is the transverse kinetic energy for these hadrons [7, 8]. Such scaling is illustrated in Fig. 1 where a compilation of elliptic flow results for identified hadrons, measured by STAR [9–12] and PHENIX [7, 13–15] for minimum-bias AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV (Fig. 1*a*), 10–40% midcentral AuAu collisions at $\sqrt{s_{NN}} = 62.4$ GeV (Fig. 1*b*) and 0–50% central CuCu collisions at $\sqrt{s_{NN}} = 200$ GeV (Fig. 1*c*). The observation that all of these data show scaling indicates that the

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agreement between the STAR and PHENIX v_2 data is better than $\sim 15\%$, otherwise, the scaling would be broken. More importantly, the observed scaling suggests that the bulk of the elliptic flow at RHIC energies is partonic, rather than hadronic [7, 8, 18].

Lowering the collision energy and studying the energy dependence of anisotropic flow allows a search for the onset of the transition to a phase with partonic degrees of freedom at an early stage of the collision [6, 17]. In the present work, we review the most recent flow measurements performed by the PHENIX collaboration at top RHIC energies, and give the most comprehensive comparison of these results with measurements from both PHOBOS and STAR collaborations. We also discuss the progress of our ongoing flow analysis at lower collision energies at RHIC.

2. RESULTS

Future progress in the extraction of the transport properties of hot and dense partonic matter from flow measurements at RHIC, depends strongly on further developments of theoretical models, as well as a better understanding of the systematic errors associated with flow measurements. First comparisons of differential elliptic flow data from the top RHIC energy ($\sqrt{s_{NN}} = 200$ GeV) with viscous relativistic hydrodynamic simulations, demonstrate that a 20% uncertainty in the measured v_2 leads to $\simeq$ 60–70% uncertainty in the extracted value of specific shear viscosity (η/s) [3, 4, 16]. The role of fluctuations and so-called "non-flow" correlations can be important for such measurements [20]. The next lesson is that the simultaneous measurement of v_2 and higher harmonics such as hexadecapole flow (v_4) and triangular flow (v_3), can help to better constrain η/s [21–23].

PHENIX has addressed many of these issues via a new set of measurements of charged hadron v_2 and v_4 [19]. These measurements were performed in the two PHENIX central arms ($|\eta| \leq 0.35$) relative to event planes obtained from four separate reaction-plane detectors in the range $1.0 < |\eta| < 3.9$, see Fig. 2*a*. Multiple event planes allow a search for possible $\Delta\eta$-dependent non-flow contributions that would influence the magnitude of $v_{2,4}$, which is crucial for reliable extraction of transport coefficients. Fig. 2*b* compares the double differential flow coefficients $v_{2,4}(p_T, N_{\mathrm{part}})$ for event-plane detectors spanning the range $1.0 < |\eta| < 3.9$. Within systematic errors, they agree to better than $\sim 5\%$ (10%) for v_2 (v_4) in mid-central collisions and approximately 10% (20%) in central and peripheral events.

This agreement indicates that the present measurements of v_2 and v_4 are not affected by $\Delta\eta$- and p_T-dependent non-flow contributions for $p_T \lesssim 3$ GeV/c and centrality $\leq 60\%$ [19].

The recently installed time-of-flight detector (TOFw) with intrinsic timing resolution of $\simeq$ 75 ps significantly improved the particle identification capabilities, as well as the acceptance of PHENIX for flow measurements of identified hadrons. Time-of-flight measurements in conjunction with measured momentum and flight-path length allow proton/kaon separation up to $\mathrm{p}_T \simeq 4.5$ GeV/c via mass-squared calculations. With the combined measurements of mass-squared and photon yield from the Aerogel Cherenkov counter (ACC), one can extend the v_2 measurements of charged pions and protons up to $p_T \simeq 6$ GeV/c [24]. This is shown in Fig. 3a where measured v_2 values for charged pions , kaons and protons are plotted in the scaled variables v_2/n_q versus KE_T/n_q. These scaled data indicate that the universal KE_T/n_q scaling, evident at low KE_T, is broken after $KE_T/n_q \gtrsim 1$ GeV/c^2, indicating a possible change in the physics. Statistically significant measurements of v_4 for identified hadrons also enable a study of a related scaling relation between v_4 for different particle species, as well as the ratio v_4/v_2^2. Fig. 3b shows the result of such a study in which both v_2 and v_4 are plotted using the generalized scaling variables, $v_n/n_q^{n/2}$ vs. KE_T/n_q. Further detailed studies of this generalized scaling for different flow harmonics, as well as the KE_T/n_q range where scaling breaks down, should help to better understand the transition from soft to hard physics [16] and the process of hadronization at RHIC. An important step toward reducing the systematic uncertainty associated with flow measurements at RHIC, is a detailed comparison of differential flow results obtained by different collaborations – PHOBOS, PHENIX, and STAR. One way to show such comparisons is to plot the respective ratios of these measurements as a function of p_T and centrality, while ensuring that both centrality and mean p_T are the same. For reference, we have used PHENIX flow measurements of charged hadrons with respect to the MPC ($3.1 < |\eta| < 3.7$) and RXN combined ($1.0 < |\eta| < 2.8$) event planes [19] from recent data obtained in 2007. The ratios v_2(PHOBOS)/v_2(PHENIX) are plotted in Fig. 4 as a function of p_T for several bins in collision centrality as indicated. The values for PHOBOS $v_2(p_T)$ were obtained for charged hadrons with $0 < \eta < 1.5$ with respect to the second order event plane measured at $2.05 < \eta < 3.2$ [25]. The ratio plots indicate that the difference between PHENIX/PHOBOS v_2 results are $\leq 5\%$ and do not show a significant p_T dependence. The STAR v_2 for charged hadrons from AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV measured with respect to the event plane from the FTPC detector ($2.5 < |\eta| < 4.0$)

are not available. Therefore our comparison was made with STAR results obtained via the standard event plane method using the central TPC ($0 < |\eta| < 1$) $v_2\{\mathrm{EP}\}$, and a modified event plane method where particles within $|\Delta\eta| < 0.5$ around the highest p_T particle were excluded for the determination of the modified event plane $v_2\{EP_2\}$; this procedure reduces some of the non-flow effects at high p_T [9, 11]. The ratios $v_2(\mathrm{STAR\ EP})/v_2(\mathrm{PHENIX})$ are plotted in the top panel of Fig. 5 for 30–40% and 40–60% midcentral AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV. The difference between STAR/PHENIX v_2 values is less than 2–5% below $p_T \simeq 2.5$ GeV/c. At higher transverse momentum, STAR v_2 is systematically larger than the PHENIX v_2 and the ratio tends to grow with p_T reaching the value of 20% at $p_T \simeq 5.5$ GeV/c. The difference in v_2 values at higher p_T can be attributed to non-flow effects due to di-jets which are mostly suppressed by the rapidity gaps in the case of the PHENIX measurements. The lower panels of Fig. 5 show the same ratios but in this case the STAR v_2 data were obtained by the modified event plane method $v_2\{\mathrm{EP}_2\}$. Here, the difference between STAR/PHENIX ratios at high p_T, are much smaller, but still persist on the level of 5–10% at $\mathrm{p}_T \simeq 5.5$ GeV/c for mid-central collisions. The comparison for other centralities can be found elsewhere [26]. Fig. 6 show the comparison of the same PHENIX v_2 data set with STAR v_2 results obtained using multi-particle methods. That is, the four particle cumulant method (Fig. 6a) and the Lee-Yang Zero method (Fig. 6b). The ratio plots indicate that STAR v_2 results obtained using multi-particle methods are smaller than PHENIX $v_2\{\mathrm{EP}\}$ event plane results by 10–12%. Note however that this difference does not show a p_T dependence and can be attributed to the expected difference in the eccentricity fluctuations for the two- and multi-particle measurements.

3. COLLISION ENERGY DEPENDENCE OF AZIMUTHAL ANISOTROPY

A large number of elliptic flow measurements have been performed by many experimental groups at SIS, AGS, SPS, and RHIC energies over the last twenty years. However, the fact that these data were not obtained under the same experimental conditions, do not allow a detailed and meaningful comparison in most cases – the situation at RHIC is of course somewhat better. Experimental differences include: (a) different centrality selection, (b) different transverse momentum acceptance, (c) different particle species, (d) different rapidity coverage, and (e) different methods for flow analysis. The results from PHENIX and STAR indicate that the magnitudes and trends of the differential elliptic flow, v_2 (p_T, centrality), change very little over the collision energy range $\sqrt{s_{NN}}$ = 62–200 GeV, indicating saturation of the excitation function for v_2 at these energies [10, 27], see Fig. 7*b*. The figure also shows that the differential elliptic flow for charged hadrons increase by almost 50% from the top SPS energy of 17.3 GeV to $\sqrt{s_{NN}} = 62$ GeV at RHIC. This conclusion is based on the comparison of PHENIX results with published results from CERES collaboration [28]. However, the comparison of STAR results for $v_2(p_T)$ for charged pions and protons at $\sqrt{s_{NN}} = 62$ GeV with results from NA49 Collaboration at 17.3 GeV [29], leads to the conclusion that the differential v_2 change only by 10–15% from top SPS energy to RHIC [10]. This may indicate that the existing flow results at the SPS are prone to large systematic uncertainties which are not yet well understood. Given the fact that the energy density increases by approximately 30% over the range $\sqrt{s_{NN}}$ = 62.4–200 GeV, the apparent saturation of differential v_2 at RHIC could be an indication of a softening of the equation of state due to the crossover transition.

In Run 2010 the PHENIX Collaboration collected $\sim 5 \times 10^8$ minimum-bias AuAu events at $\sqrt{s_{NN}} = 62.4$ GeV and $\sim 2 \times 10^8$ minimum-bias AuAu events at $\sqrt{s_{NN}} = 39$ GeV. The analysis of these data is progressing very well. Fig. 7*b* shows the centrality dependence of the event plane resolution factors for v_2 and v_4 measurements obtained for the second order event planes from the RXN detector for the collision energies 39, 62.4, and 200 GeV. They indicate that reliable extraction of the flow harmonics should be straightforward. Note that this large data set in conjunction with an improved event plane resolution, gives an equivalent of $\simeq$ 30-fold increase in statistics over the previous measurement of v_2 at 62 GeV [27]. We expect that they will allow detailed measurements of the differential v_2 and v_4 as a function of p_T and centrality for several particle species at both energies.

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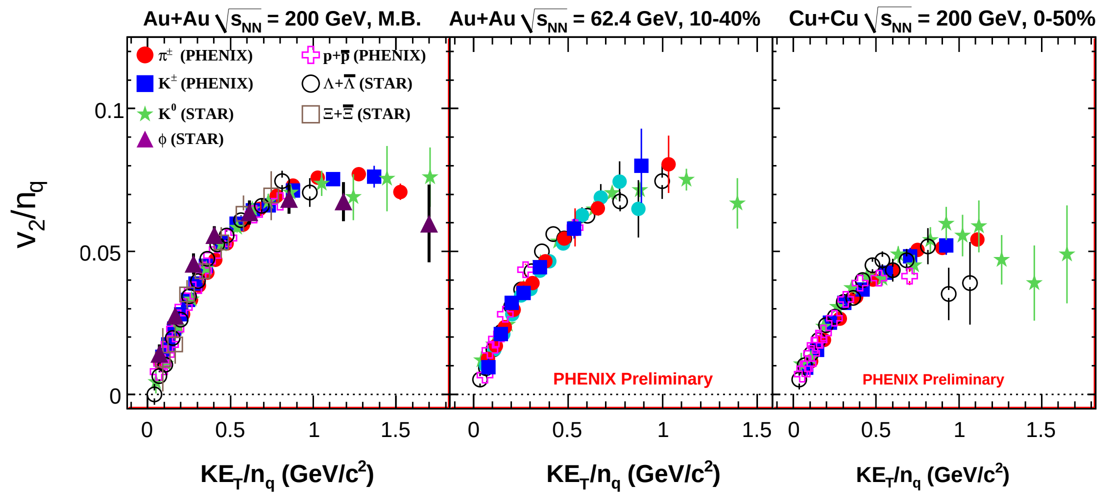

Figure 1. v_2/n_q as a function of KE_T/n_q for identified particle species obtained in minimum-bias AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV (a), in 10–40% midcentral AuAu collisions at $\sqrt{s_{NN}} = 62.4$ GeV (b) and in 0–50% central CuCu collisions at $\sqrt{s_{NN}} = 200$ GeV (c).

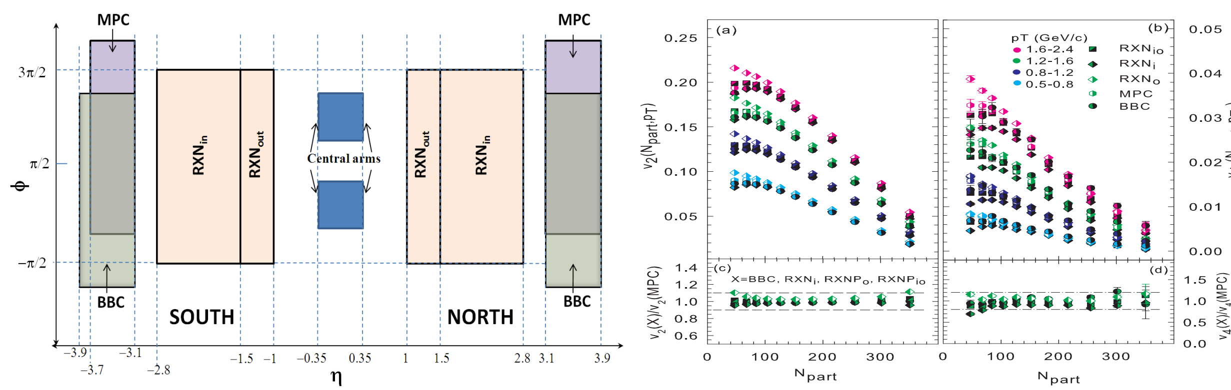

Figure 2. a): The azimuthal angle ϕ and pseudo-rapidity η acceptance of PHENIX detectors used for event plane reconstruction, together with the central arm acceptances for charged hadron measurements. b): comparison of v_2 vs. $N_{\rm part}$ and v_4 vs. $N_{\rm part}$ for charged hadrons obtained with several reaction plane detectors for the p_T selections indicated [19]. Ratios for the p_T range 1.2–1.6 GeV/c are shown in (c) and (d).

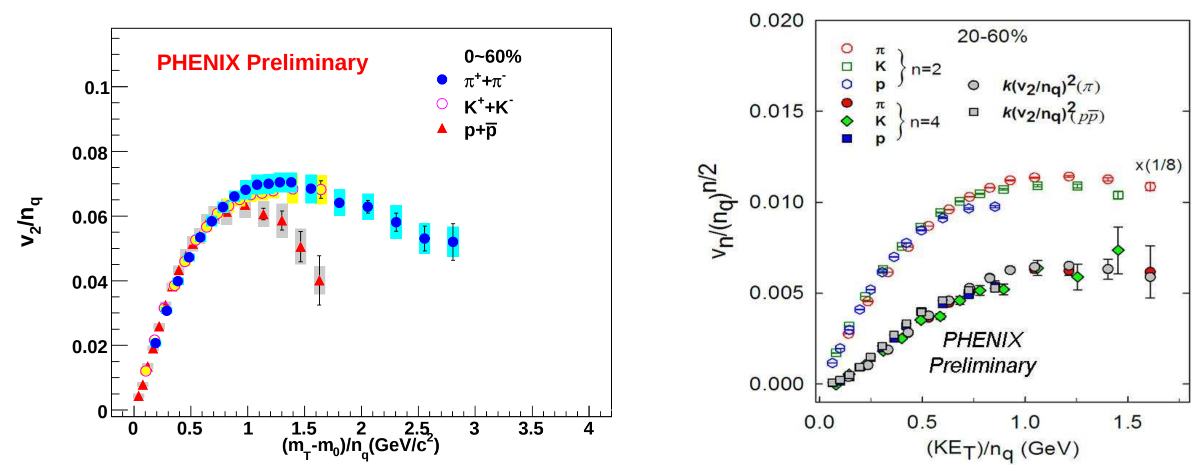

Figure 3. v_2/n_q as a function of KE_T/n_q for identified charged hadrons obtianed in 0–60% central AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV (a) and $v_n/n_q^{n/2}$ as a function of KE_T/n_q for the same particle species (b).

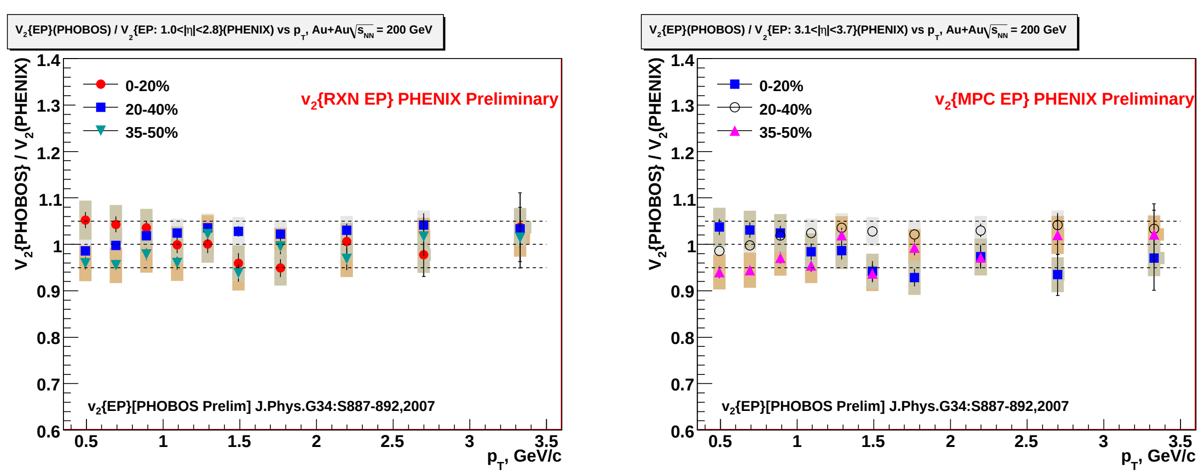

Figure 4. p_T dependence of the ratio of PHOBOS v_2 values [25] obtained by event plane method $v_2\{\mathrm{EP}\}$ $(2.05 < |\eta| < 3.2)$ to the PHENIX v_2 measured using RXN $(1.0 < |\eta| < 2.8)$ (a) and MPC $(3.1 < |\eta| < 3.7)$ (b).

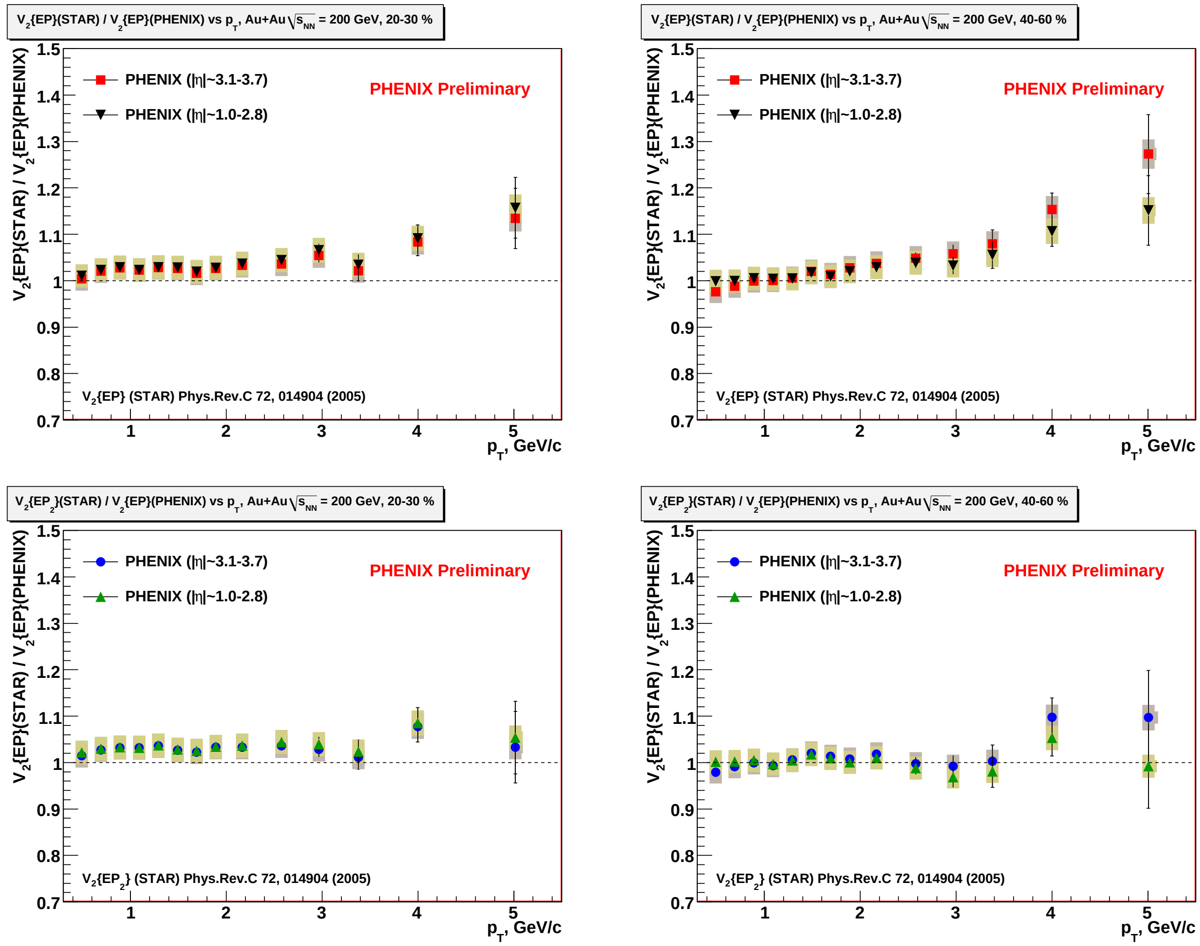

Figure 5. p_T dependence of the ratio of STAR v_2 values for charged hadrons obtained by standard (upper panel) and modified (lower panel) event plane method $v_2\{\mathrm{EP}\}$ using central TPC ($|\eta| < 1.0$) to the PHENIX v_2 values obtained by event plane method using MPC/RXN event planes for 30–40% and 40–60% midcentral AuAu collisions.

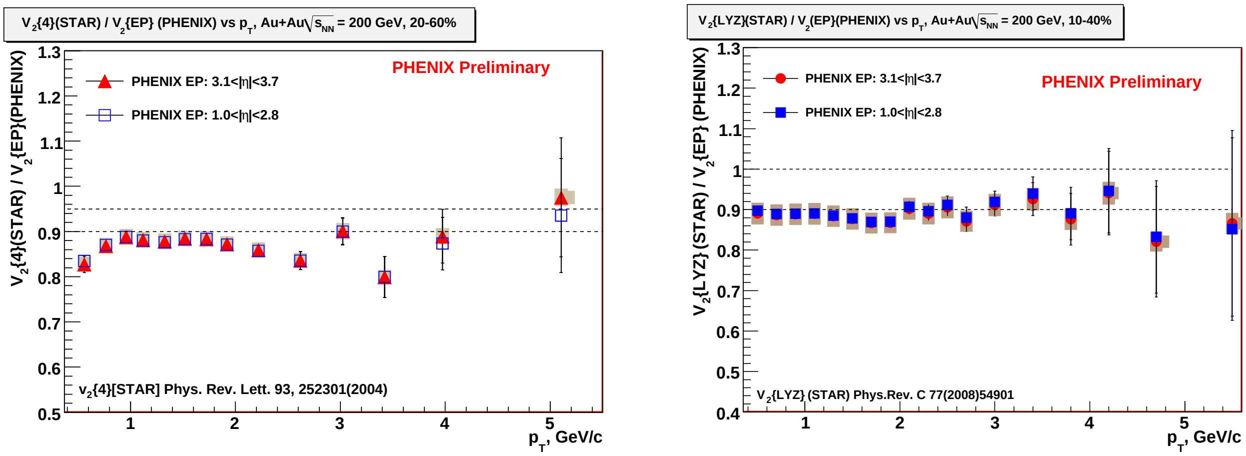

Figure 6. p_T dependence of the ratio of STAR v_2 values for charged hadrons obtained by four-particle cumulant method $v_2\{4\}$ (a) and Lee-Yang Zero method (b) using charged tracks from central TPC ($|\eta| < 1.0$) to the PHENIX v_2 values obtained by event plane method using MPC/RXN event planes.

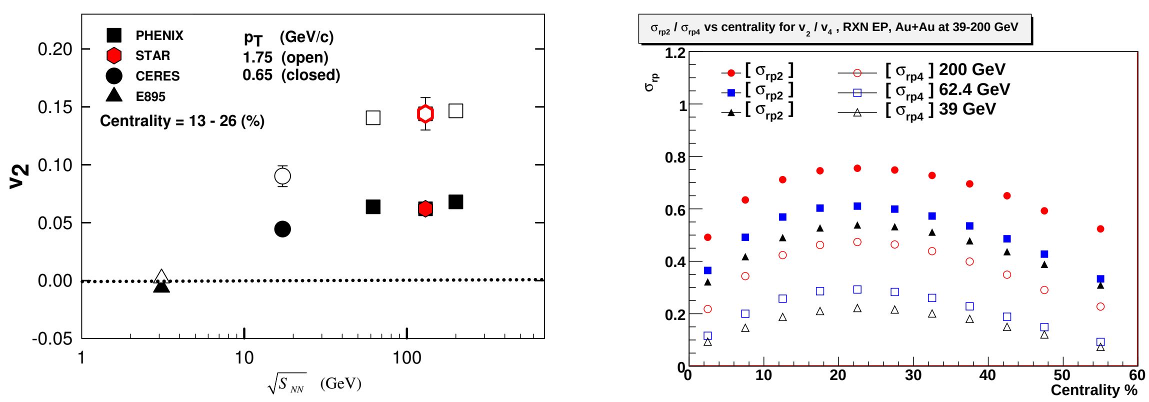

Figure 7. a): differential v_2 vs. $\sqrt{s_{NN}}$ for charged hadrons in nucleus-nucleus collisions for centrality cut of 13–26% and two different mean p_T values. From [27]. b): centrality dependence of event plane resolution factors for v_2 (closed symbols) and v_4 (closed symbols) measurements using PHENIX RXN detector for AuAu collisions at $\sqrt{s_{NN}}$ = 39–200 GeV.

FIGURE CAPTIONS

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