Flavor Scaling of Azimuthal Anisotropy: unveiling the fine structure of v_2

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Transverse rapidity flavor scaling y_T^{fs}, of the azimuthal anisotropy (v_2) for identified particles produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (Run 2) is investigated. Exquisite flavor scaling is observed over a broad range in centrality and transverse rapidity y_T. This scaling suggests that hadronic re-scattering effects are unimportant, and supports the picture of a suddenly hadronizing (recombining) fluid of quarks. An apparent breaking of flavor scaling at relatively large y_T^{fs} points to an important change in the mechanism for kaon emission. The scaling parameters can provide important constraints for the freeze-out temperature and the EOS.

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I. INTRODUCTION

In an earlier note [1] we presented detailed results for the azimuthal anisotropy v_2, for charged mesons (π, K) and baryons (p, $\bar{p}$) produced in Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV. In addition, unequivocal evidence for eccentricity scaling of baryons and mesons (respectively) was presented.

In this addendum, we extend our earlier analysis to investigate the possibility of a simple flavor-scaling relationship between the v_2 values for baryons and mesons. Such information could be crucial to the resolution of a number of outstanding issues related to reaction dynamics at RHIC. A particularly important ongoing debate is concerned with the question of whether or not flow is developed at the partonic level, and whether or not the coalescence mechanism plays an important role for (i) the observed magnitude of v_2 and (ii) an apparent "enhanced baryon yield" in Au+Au collisions.

This note focuses on the question of whether or not the v_2 data for several particle flavors show transverse rapidity scaling as would be expected from a suddenly hadronizing (recombining) fluid of quarks. The origin of an "enhanced baryon yield" (relative to that for pions) is also transparent in the ensuing analysis. A full analysis with collateral quantitative details is deferred to a future note.

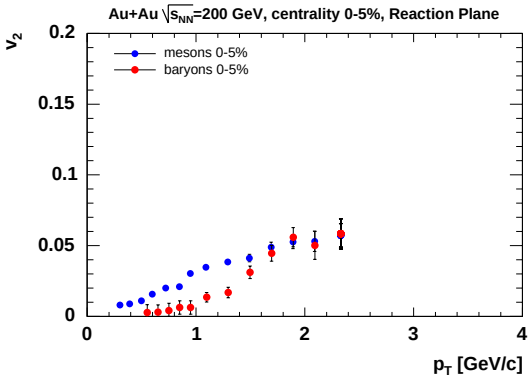


FIG. 1: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 0-5%.

II. RESULTS

Analysis details for the data presented in this note have been discussed in Ref. [1]. They are not repeated here.

Figures 1 - 10 compares the differential anisotropy $v_2(p_T)$, for baryons and mesons over a broad range of centrality selections. For relatively central events, the baryons show a much stronger quadratic dependence at low p_T than the mesons. This dependence, dubbed the fine structure of v_2, can be associated with strong radial flow. Figs. 1 - 10 also shows that there is an apparent weakening of this quadratic dependence as the collisions become less central. Such a dependence quite possibly results from simultaneous changes in the freeze-out temperature and the radial flow velocity as the collisions become more peripheral. The differential anisotropies $[v_2(p_T)]$ for mesons, shown in Figs. 1 - 10, contrasts those for baryons. That is, they indicate much less shape variation as the centrality changes. On the other hand, the magnitude of $v_2(p_T)$ for both baryons and mesons increase with decreasing centrality (more peripheral) in accordance with eccentricity scaling [1].

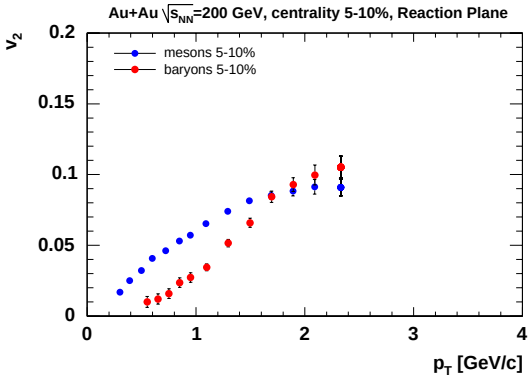


FIG. 2: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 5-10%.

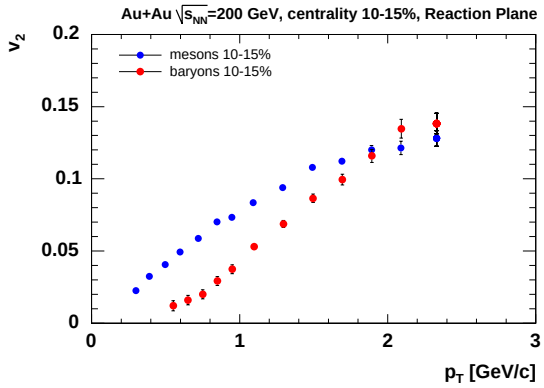


FIG. 3: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 10-15%.

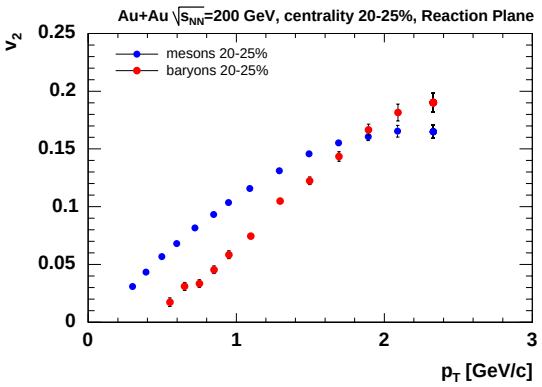


FIG. 5: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 20-25%.

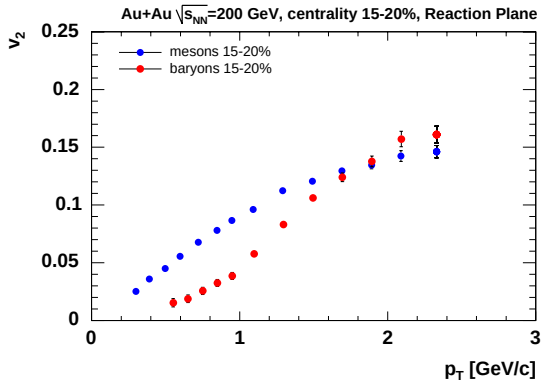


FIG. 4: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 15-20%.

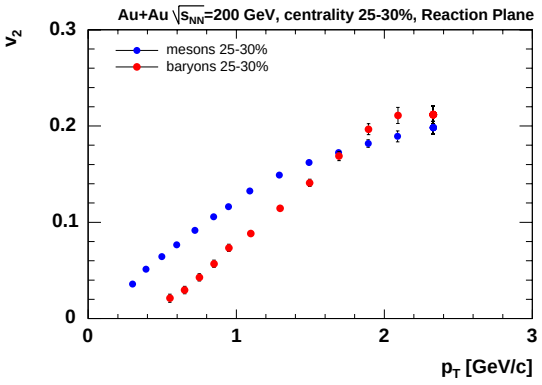


FIG. 6: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 25-30%.

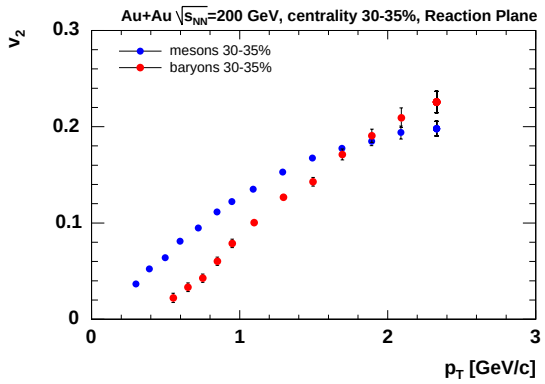


FIG. 7: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 30-35%.

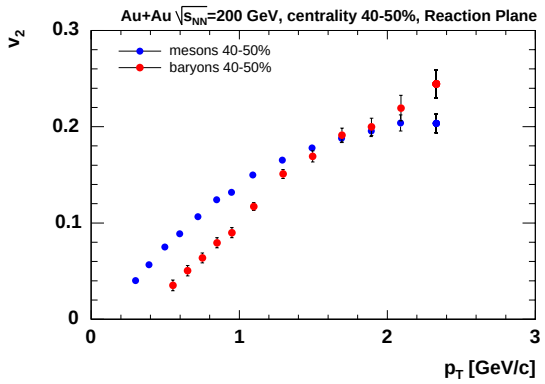


FIG. 9: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 40-50%.

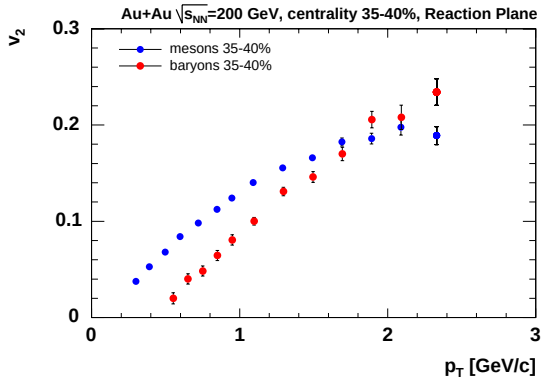


FIG. 8: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 35-40%.

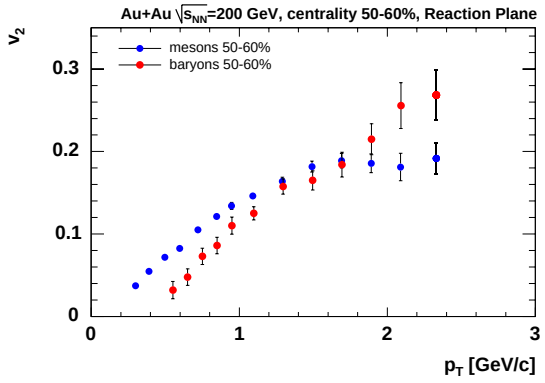


FIG. 10: Comparison of v_2 for charged mesons (dominantly pions) and baryons (p, $\bar{p}$) as a function of p_T. Results are shown for a centrality selection of 50-60%.

III. FLAVOR SCALING OF v_2

Blast wave inspired fits to the m_T spectra of baryons and mesons are commonly exploited for the extraction of the radial expansion velocity β, and the temperature T at kinetic freeze-out. Fig. 11 shows the resulting β and T values obtained from a recent radial flow analysis of PHENIX data by Kiyomichi et. al [2]. The results indicate rather substantial radial flow velocities and freeze-out temperatures with the expected trends, for central and mid-central collisions; albeit with some anti-correlation between β and T. More important is the

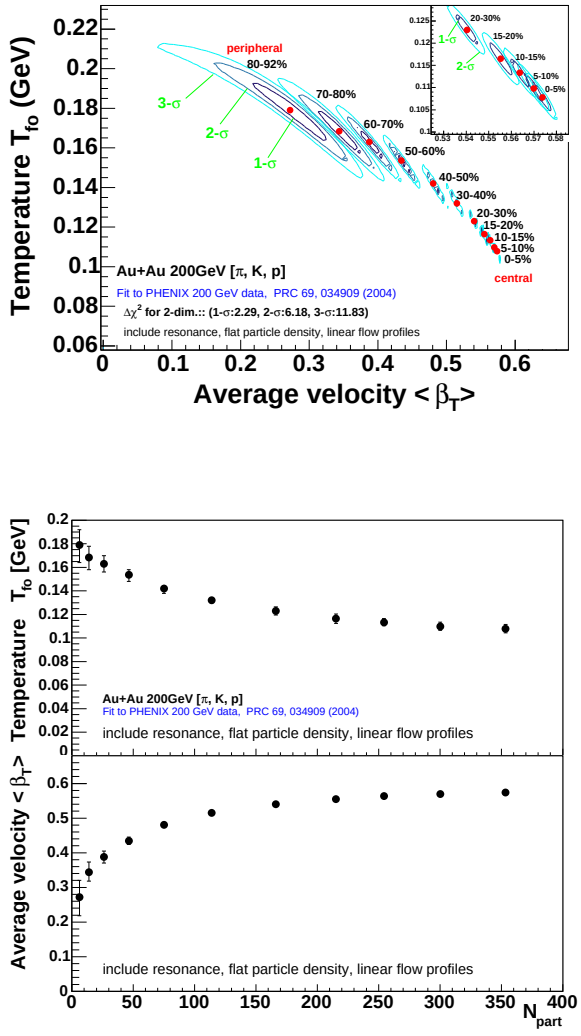


FIG. 11: Radial flow velocity β, and freeze-out temperature obtained in recent blast wave inspired fit to the m_T spectra of pions, kaons and protons by Kiyomichi et. al. The Figure is reproduced from Ref. [2].

fact that these results indicate that the m_T spectra for pions, kaons and protons are compatible with emission from a single expanding source at a common freeze-out temperature.

A much less appreciated [and sometimes misunderstood] fact is that the thermal contributions to the transverse momentum p_T, of very light hadrons are substantial. This is very clearly illustrated in Fig. 12 which shows the $< v_T >$ for various particle species for two different freeze-out scenarios. The figure indicates that the thermal contributions can be as much as a factor of three times that obtained from collective expansion (depending of course on details). An equally important observation that can be made is that the thermal contribution is quadratic. This is of course not surprising since thermal velocities should be $\sim \sqrt{(T_{fo}/\gamma m)}$. T_{fo} is the freeze-out temperature and m is the mass of the particle. It is also evident from Fig. 12 that with increasing mass the $< v_T >$ reflects the hydrodynamical flow velocity.

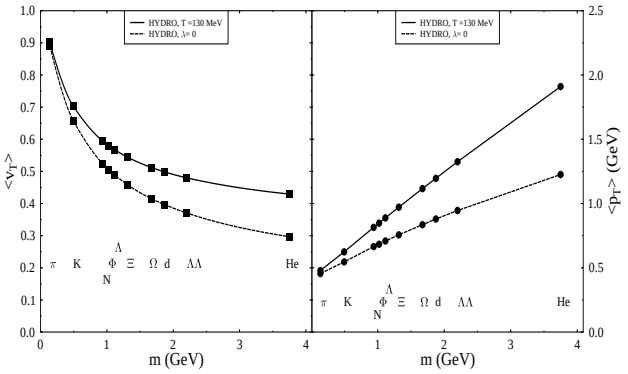


FIG. 12: Mean transverse velocity ($< v_T >$) vs. particle mass (left panel) for two different freeze-out conditions. The right panel shows the $< p_T >$ for the same particle species. The Figure is reproduced from Ref. [3].

The actual flow velocity of all particles can be obtained via a simple scaling rule as illustrated in Figs. 13 and 14. The red circles and green diamonds in Figs. 13 and 14 show the result of the scaling of the $< v_T >$ values shown in 12 by

$$k_m\sqrt{m}$$

to obtain the hydrodynamical flow velocity. k_m is a mass ordering (or mass dependent) constant referenced to the heaviest particle (ie. $k_{He} = 1$).

Given the above finding one might expect a straight forward scaling rule which connects the elliptic flow of different particle flavors as a function of the transverse rapidity, y_T. In what follows, we investigate a possible scaling of v_2 in this space, and explore an even more universal scaling behavior which shows that v_2 for different particle types, obtained for different centrality classes, follow a universal scaling function.

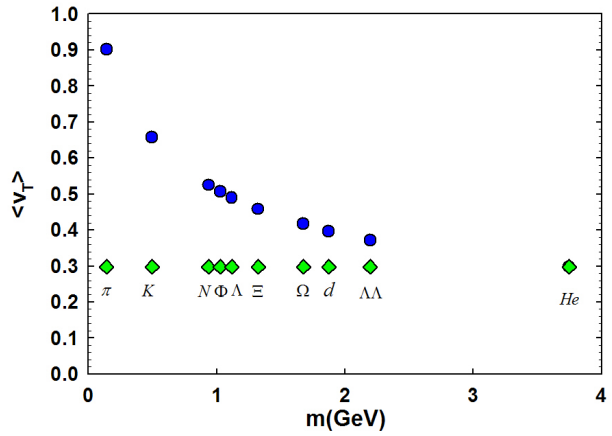


FIG. 13: Mean transverse velocity ($< v_T >$) vs. particle mass (same as the bottom curve in the left panel of Fig. [**?**]). The diamonds show the result of $\sqrt{(}m)$ scaling of $< v_T >$. The scaling is referenced to the heaviest particle.

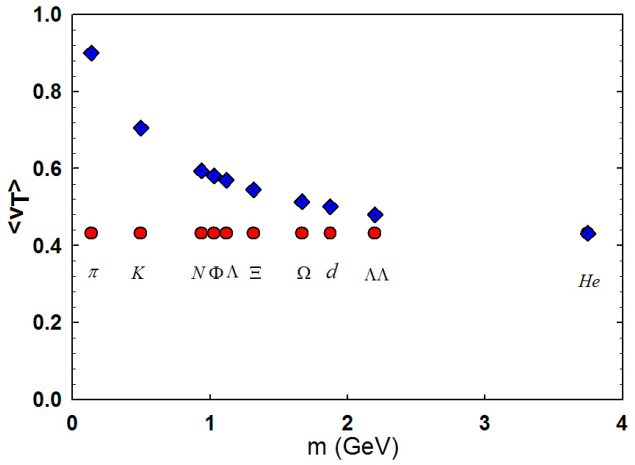


FIG. 14: Mean transverse velocity ($< v_T >$) vs. particle mass (same as the top curve in the left panel of Fig. [**?**]). The diamonds show the result of $\sqrt{(}m)$ scaling of $< v_T >$. The scaling is referenced to the heaviest particle.

A. y_T^{fs} Scaling within the Hydrodynamical Model

Extensive comparisons have been made between RHIC v_2 data and hydrodynamical model calculations. Although this model [and its various incarnations] do NOT fully account for all of the measured doubly differential anisotropy $v_2(p_T, centrality)$, in all cases, it can still serve as a good benchmark to address the question of whether or not flavor scaling of elliptic flow is to be expected.

In the Buda-Lund hydro model for ellipsodially symmetric fireballs [4], it has been shown that

$$v_2 = \frac{I_1(w)}{I_0(w)},\ w = \frac{p_T^2}{\overline{m_T}}\left(\frac{1}{T_y} - \frac{1}{T_x}\right).$$

Here, $I_{0,1}$ are Bessel functions, T_x and T_y are direction and transverse mass dependent slope parameters [4] and $\overline{m_T}$ is an average, rapidity dependent transverse mass. At midrapidity, [where this analysis is performed] $\overline{m_T}$ is equal to the transverse mass m_T.

Substitution for y_T in the above expression followed by an expansion gives the the following terms [5]

$$v_2 \propto y_T^2(k1\frac{m}{T_0} + k_2 + k_3\frac{T_0}{m} + ...)$$

where T_0 is the freeze-out temperature and $k_{1,2,3}$ are constants. For $m >> T_0$, as in the case of relatively heavy particles, the leading term indicates a $\sqrt{m}$ transverse rapidity scaling. That is, v_2 vs. y_T for different particle species should scale approximately with $\sqrt{m}$. Thus, one might expect the following scaling variable for v_2:

$$y_T^{fs} \sim k_m\sqrt{m} \times y_T$$

where k_m is a mass dependent scale factor which should be ~ 1 for relatively heavy particles.

This scaling procedure can be tested via the analysis of v_2 results obtained from a hydrodynamical calculation. Figure 15 shows the flavor dependence of the differential anisotropy $v_2(p_T)$ obtained from a hydrodynamical calculation for a fixed centrality selection [6]. The very well known mass ordering of v_2 for the different particle flavors is evident in the figure. Figure 16 shows the same data plotted vs. y_T^{fs}.

$$y_T^{fs} = k_m\sqrt{m} \times y_T,$$

where k_Ω was set to unity and $k_{\pi,K,p,\Lambda}$ were empirically determined. The figure indicates excellent y_T^{fs} scaling for the different particle flavors over a relatively broad y_T range. For large y_T^{fs} (corresponding to large p_T) we have observed a break down of flavor scaling in the hydro model, especially for the lightest hadrons. Either the hydro model from which these results were obtained does not evaluate v_2 correctly at hight p_T or other production mechanisms become dominant. In any case it is generally agreed on that at some transverse momenta and hence y_T, hydro models are expected to break down.

B. Tests for y_T^{fs} Scaling in PHENIX v_2 data

Prior to any discussion of scaling, it is important to demonstrate the reliability and consistency of the data to be scaled. Figure 17 compares the the v_2 for baryons ($p, \bar{p}$ measured in the TOF only and baryons measured in TOF + EMC. It should be noted that the statistics for baryon detection in the EMC is much larger than that for the TOF. The figure shows good agreement between both sets of measurements as is to be expected. Figure 18 compares the the v_2 for mesons ($\pi, K^{+,-}$) measured in the TOF only and mesons measured in TOF + EMC. The comparison shows the expected invariance of v_2 with

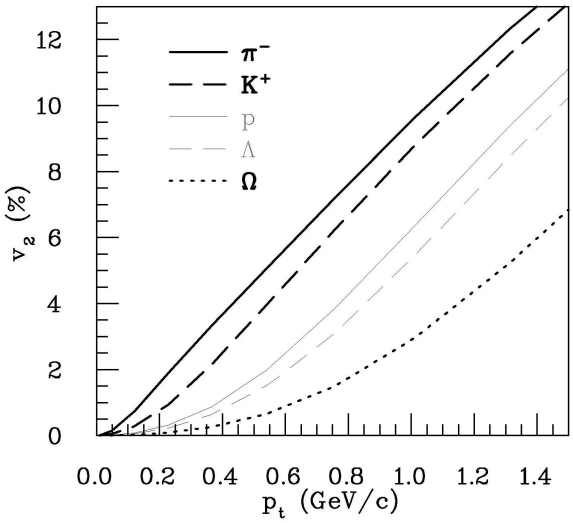


FIG. 15: v_2 vs. p_T for Ω, Λs, p, Ks and πs as indicated. A distinct mass ordering of v_2 for the different particle flavors is evident. The figure has been reproduced form Ref. [6].

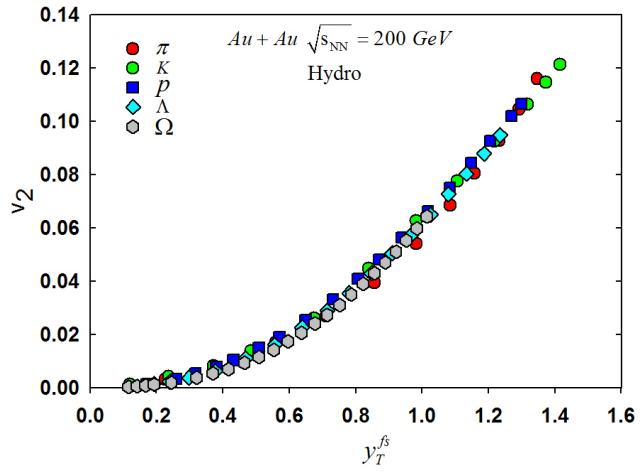


FIG. 16: v_2 vs. y_T^{fs} for Ω, Λs, p, Ks and πs as indicated. The unscaled values are shown as a function of p_T in Fig. 15.

the subsystem used for the measurement. Figure 18 also compares the v_2 of mesons with the v_2 of pions measured in the TOF with very clean PID. The comparison clearly indicates that the meson v_2 measurements are dominated by pions. This fact is made even more clear in Fig. 19 where a comparison of $v_2(p_T)$ for pions and kaons indicate smaller v_2 values for kaons over the entire p_T range. In short, $v_2(mesons) \approx v_2(pions)$ only if the meson yield is dominated by pions.

Figure 20 shows a comparison of the differential anisotropy $v_2(p_T)$ for protons, kaons and pions detected in the TOF. The well known and rather characteristic flavor dependence is exhibited in this figure. In what follows, we investigate possible flavor scaling of these measurements and the results presented in Figs. 1 - 10.

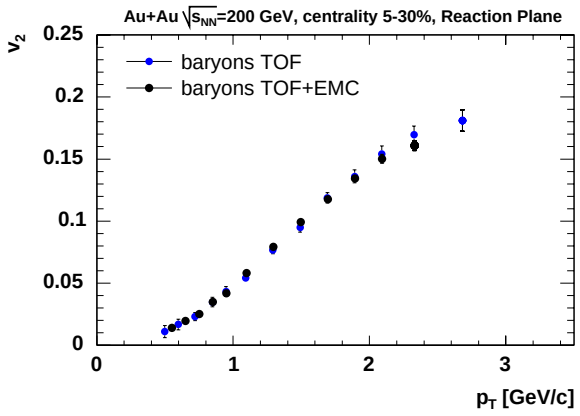


FIG. 17: Comparison of of v_2 measurements for baryons (p, $\bar{p}$) made with the TOF and the EMC + TOF respectively. Results are shown for the centrality selection of 5-30%.

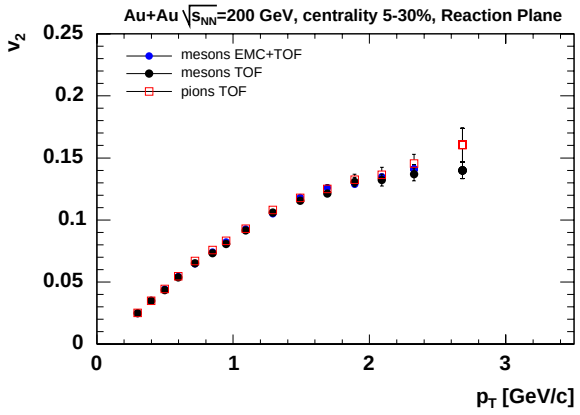


FIG. 18: Comparison of of v_2 measurements for mesons ($\pi, K^{+,-}$) made with the TOF and the EMC + TOF respectively. Results obtained for pions only with the TOF are also compared. All results are shown for the centrality selection of 5-30%.

Figures 21 - 30 give illustrative examples of the result of flavor scaling (y_T^{fs}) to the v_2 data presented for baryons and mesons in Figs. 1 - 10. For mesons, we scale by the mass of the pion (note that pions dominate the meson yield). These figures show that scaling is observed for mesons and baryons for each centrality selections and persists for y_T^{fs} values corresponding to relatively large p_T selections.

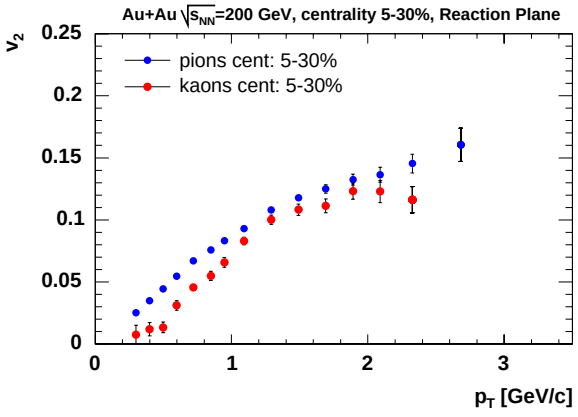


FIG. 19: Comparison of of v_2 measurements for pions and kaons. All results are shown for the centrality selection of 5-30%.

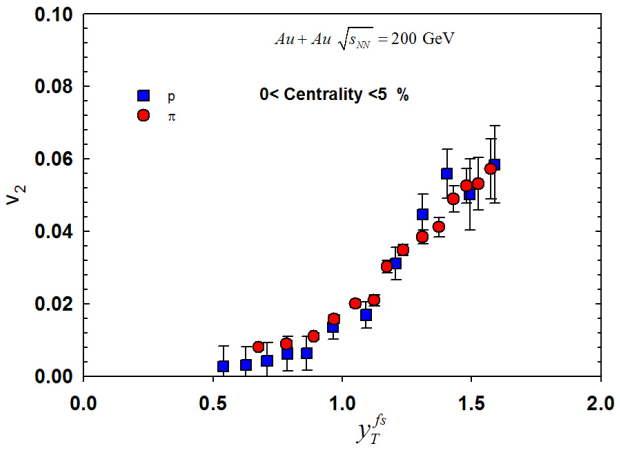


FIG. 21: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 0-5%.

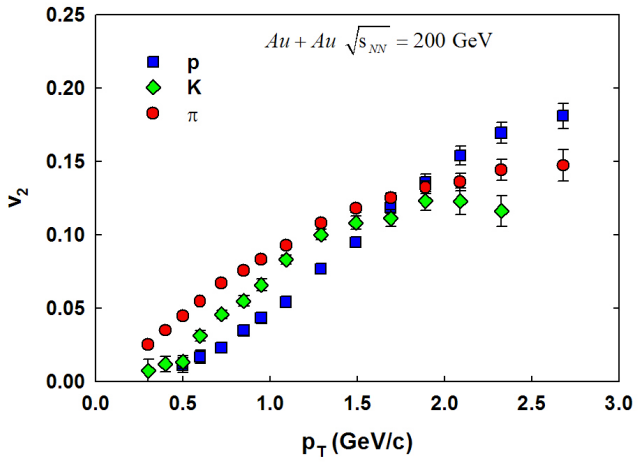


FIG. 20: Comparison of of v_2 measurements for pions, kaons and protons. All results are shown for the centrality selection of 5-30%.

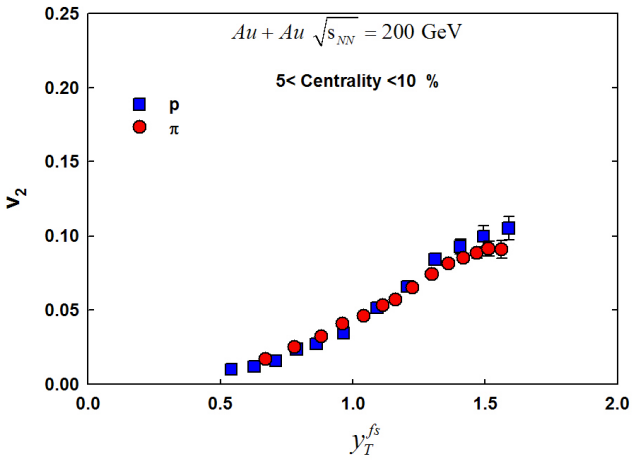


FIG. 22: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 5-10%.

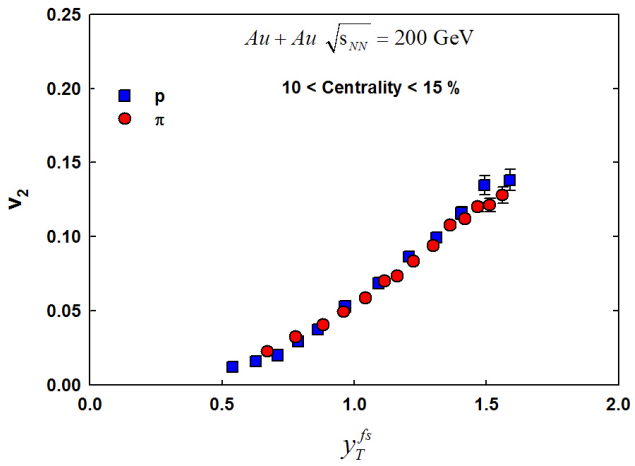


FIG. 23: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 10-15%.

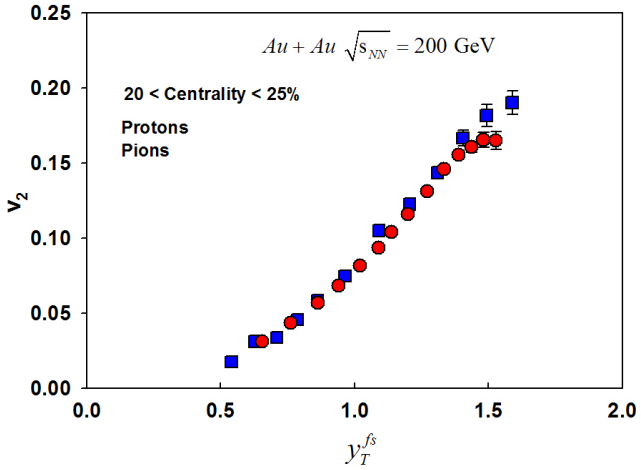


FIG. 25: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 20-25%.

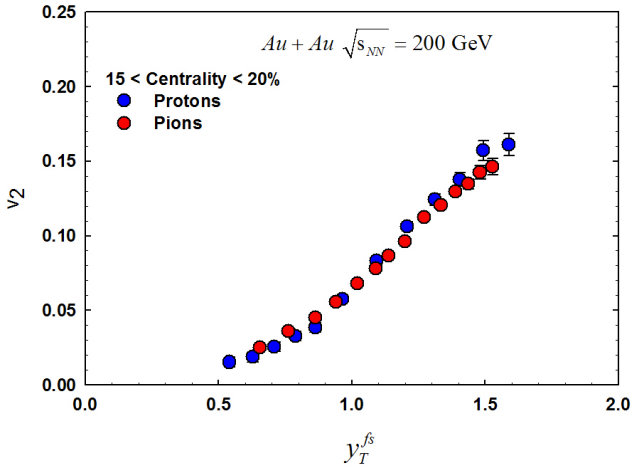


FIG. 24: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 15-20%.

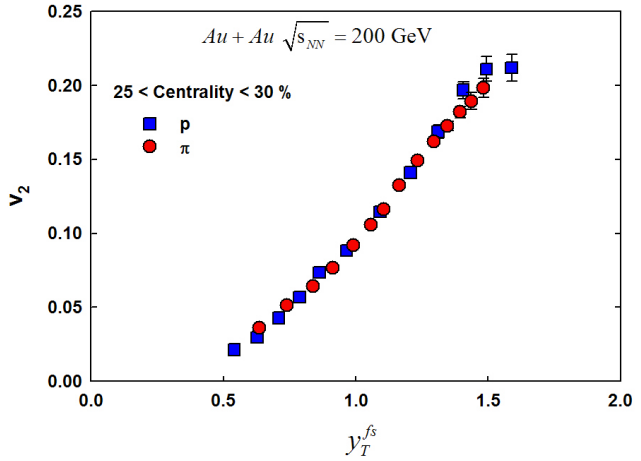


FIG. 26: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 25-30%.

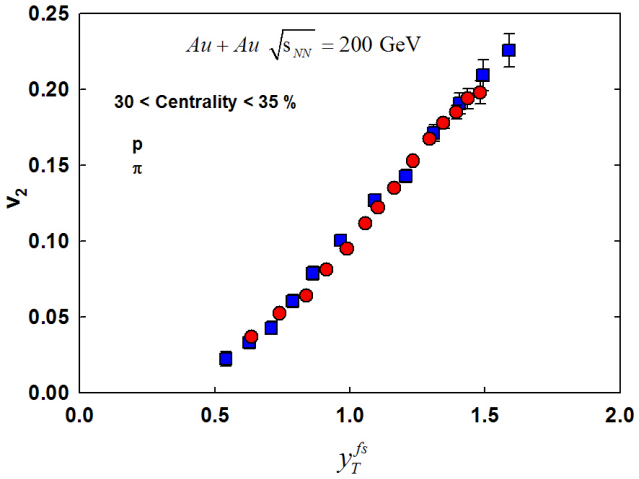


FIG. 27: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 30-35%.

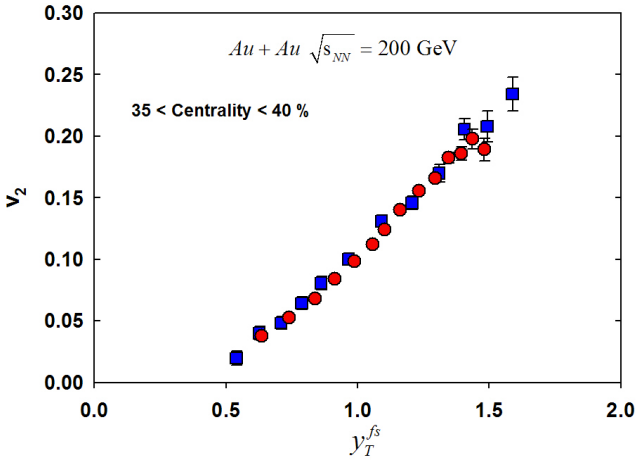


FIG. 28: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 35-40%.

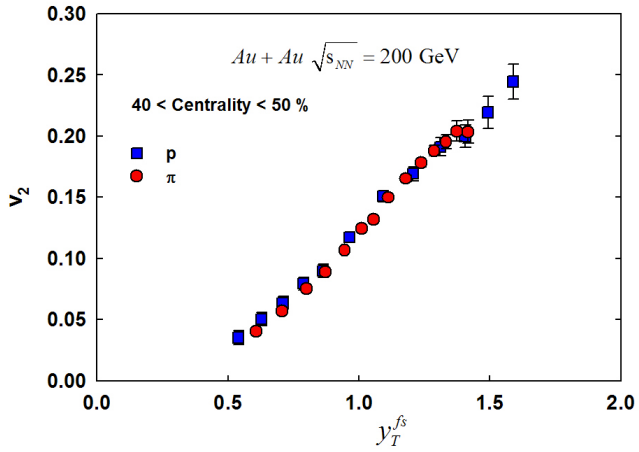


FIG. 29: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 40-50%.

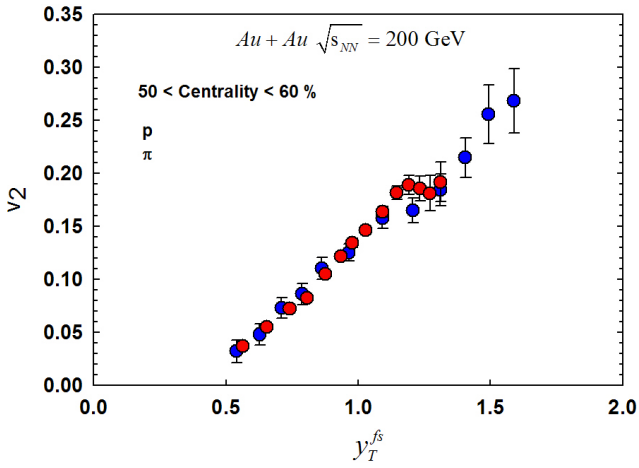


FIG. 30: Flavor scaled v_2 for charged mesons and baryons (p, $\bar{p}$). Mesons are dominated by the charged pions. Results are shown for the centrality selection of 50-60%.

C. Test for y_T^{fs} Scaling in PHENIX and STAR v_2 data

A wealth of recent discussions have focused on the possibility that flow develops at the partonic level and the coalescence mechanism may be responsible for much of the v_2 developed at intermediate p_Ts. Fig. 31 shows a popular quark scaling demonstration between Λs and K^0s reproduced from Ref. [7]. This scaling result is very often used to argue for coalescence. It should be noted however that quark-number scaling is not obtained for pions. The same coalescence mechanism has been invoked to account for an apparent baryon yield enhancement (relative to that for pions) even for p_T of 2-3 GeV/c. The presence or absence of y_T^{fs} scaling can serve as a more revealing tool to test the importance of the coalescence mechanism for the relevant p_T or y_T ranges.

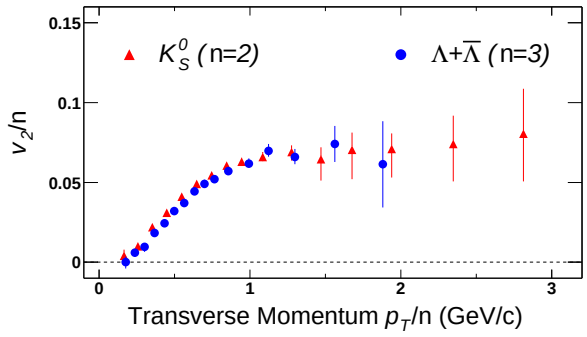


FIG. 31: The v2 parameter for K^0_S and Λ scaled by the number of constituent quarks (n) and plotted versus pT /n. The error bars shown include statistical and point-to-point systematic uncertainties from the background. The additional non-flow systematic uncertainties are approximately 20%. The figure is reproduced from Ref. [7]

Figure 32 gives an illustration of y_T^{fs} flavor scaling of the v_2 data obtained in Au+Au collisions by PHENIX and STAR for charged pions, neutral kaons, charged kaons, protons and lambda particles for the centrality selection presented. New results for deuterons and ϕ-mesons are currently being worked-up and will be included in this data set as soon as the results from an ongoing analysis is finalized. The data shown in Fig. 32 indicate very good flavor scaling over a broad range of scaled transverse rapidity. It is interesting to note however that y_T^{fs} scaling appears to breakdown for kaons at the highest values. This breakdown, could be signaling a a significant change in the particle emission mechanism for kaons. Further investigations of this issue are underway.

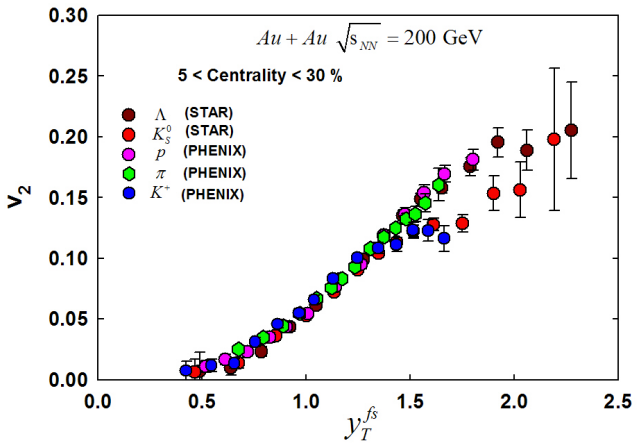


FIG. 32: Comparison of v_2 for charged pions, neutral kaons, (anti)protons and lambdas as a function of y_T^{fs}. Results are shown for the centrality selection of 5-30%.

D. Centrality evolution of flavor scaling

Figures 21 - 30 show a clear evolution of the centrality dependence of the flavor-scaled v_2 for baryons and mesons (mesons are dominated by pions). That is, v_2 evolves from an essentially quadratic-like dependence on y_T^{fs} to an essentially linear dependence on y_T^{fs}. This evolution is undoubtedly related to the transverse expansion velocity, the freeze-out temperature and the EOS. We pursue this line in the next section.

E. Scale Factors (k_m) and all that

The k_m scale factors necessary to achieve v_2 flavor scaling and the shape evolution of $v_2(y_T^{fs})$ are related to the freeze-out temperature, and the EOS. This being the case, these factors can serve as important constraints ..... to be updated shortly.

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