U+U and Cu+Au results from PHENIX

Aneta Iordanova, for the PHENIX Collaboration

University of California, Riverside

E-mail: anetai@ucr.edu

Abstract. The flexibility of RHIC to collide different nuclei provides experiments with a rich set of data to systematically test models and scaling behaviors in various collision systems. The latest RHIC run collided U+U and Cu+Au nuclei. These collisions promise an array of unique initial geometrical configurations. For example, in U+U collisions the slightly elongated nuclei overlap in a variety of different ways such that, even at zero impact parameter, distinct configurations exist. In central Cu+Au collisions the Cu nucleus is completely embedded within the Au. Such geometries present an opportunity to measure the wide range of initial energy densities of these systems. They also allow the study of some unique features arising from these configurations. In particular, the odd harmonics from the Cu+Au system offer sensitivity to v_3 generated from the collision geometry as opposed to fluctuations in a symmetric system.

In these proceedings the analysis status of the recently taken U+U and Cu+Au data in PHENIX is presented. The results from the global particle production and the challenges in analyzing these asymmetric systems is discussed.

1. Introduction

The versatility of RHIC to provide heavy ion collisions at different center of mass energies and for different ion species has been further demonstrated during run 12. The latest improvements in the ion source and the stochastic beam cooling lead to two new unique collision environments: first U+U collisions at $193\,\text{GeV}$ and Cu+Au at $200\,\text{GeV}$. Both systems serve as an important test of the initial geometry.

As the U nucleus is deformed, the initial collision geometry will change event-by-event. The $tip - tip$ orientation, where the two oval-like nuclei collide along their semi-major (long) axis, is of a special interest. Early theoretical works [1] predicted a much higher energy density (up to 55%) for this configuration in central collisions than for the $body - body$ U+U or Au+Au collisions at the same centrality. Thus it was suggested that U+U collisions would provide an excellent opportunity to further study the initial geometry in heavy ion collisions and its relation to the resulting elliptical flow, parton energy loss, and potentially other observables. The key point for such promising measurements is to be able to experimentally separate such distinct initial configurations.

Cu+Au collisions stirred interest due to the initial asymmetry of the colliding system. The $core - corona$ description of the initial collision overlap [2], shows this asymmetric density profile in the core, and also in the corona, where the corona is larger on the Au-side of the collision area, see Fig. 1. Such a substantial initial asymmetry could lead to naturally arising odd harmonics, from both the core and/or the corona. The case where the Cu nucleus is completely swallowed by the Au, for central collisions, could also be potentially very interesting.
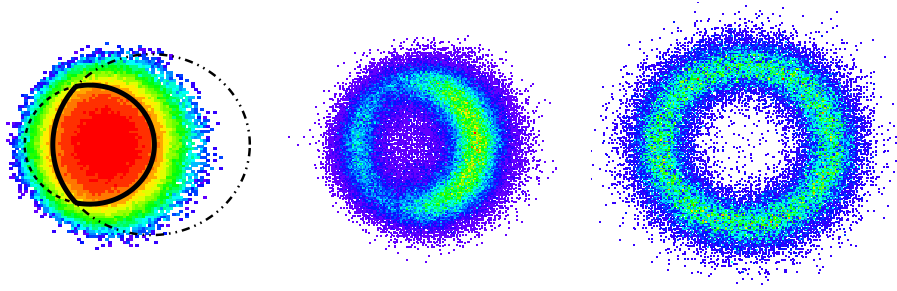
Figure 1. Illustration of the initial geometry of Cu+Au collisions, from a Glauber model simulation [3]. The left panel shows the *core*, or the participant density, for mid-central collisions. The middle panel shows the singly-interacting nucleons, *corona*, at the same centrality. The right panel shows the spectator nucleons for the special case of very central collisions, where the Cu nucleus is completely swallowed by the Au.

2. Global particle production

The charged particle multiplicity, $dN/d\eta$, was measured in U+U collisions and compared to other symmetric systems measured by PHENIX (Fig. 2). $dN/d\eta$ increases with increasing collision energy, and an increase for more central collisions compared to peripheral for all energies is observed. U+U and Au+Au collisions are similar and there is no significant excess of particle production in very central U+U collisions compared to Au+Au at the same energy. This is contrary to the expectation that $tip-tip$ U+U collisions should yield a much higher multiplicity. Note that the currently employed centrality selection cannot separate this configuration from the rest of the events and instead the most central 1% class is shown (the rightmost point), which is believed to contain an enhanced number of this type of collisions.
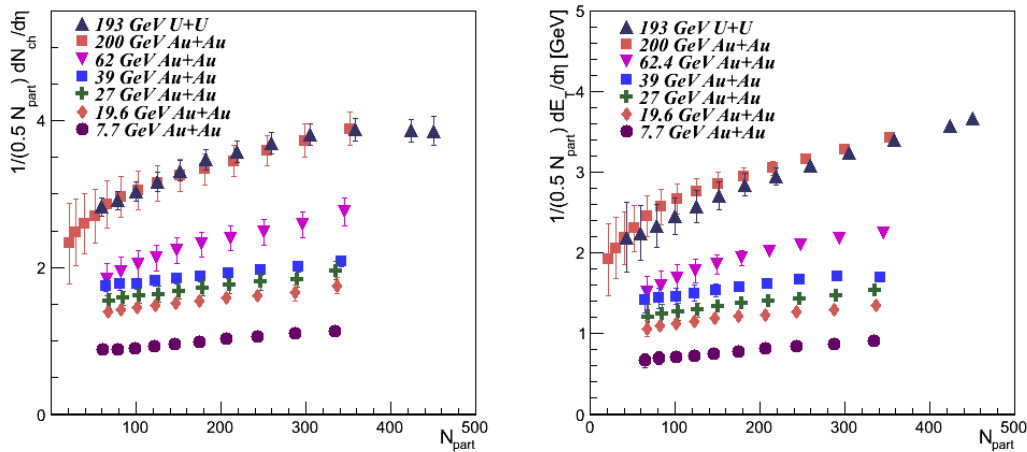

Figure 2. $dN/d\eta$ (left) and $dE_T/d\eta$ (right panel) as a function of centrality in U+U collisions at 193 GeV compared to various collision energies in Au+Au. Centrality selection for the U+U system is defined in 5% bins. The rightmost point shows the 1% most central data.

The measured transverse energy density in U+U, $dE_T/d\eta$, is also very similar to that in Au+Au at 200 GeV (see the centrality distribution in Fig. 2, right panel). A small increase is observed for the most central U+U data, which translates to a new record of energy density

measured at RHIC. The value of the Bjorken energy density, ϵ_B, in most central U+U collisions is $6.15\,\mathrm{GeV/fm^2}/c$. Although the increase from the most central Au+Au collisions to the most central U+U is only moderate, 20%, this represents an increase in energy density by a factor of 3.8 compared to the lowest collision energy of $7.7\,\mathrm{GeV}$.

From this new U+U data, the centrality dependence of the transverse energy production is seen to be independent of the collision system. This was also observed in the comparison of Au+Au and Cu+Cu at 200 and 62.4 GeV, shown in Fig. 3. Surprisingly, the new Cu+Au results at 200 GeV exhibit a similar centrality trend, but an overall higher E_T. This was not expected, and may reflect the larger core in the Cu+Au system at the same N_{part} value compared to the symmetric systems.
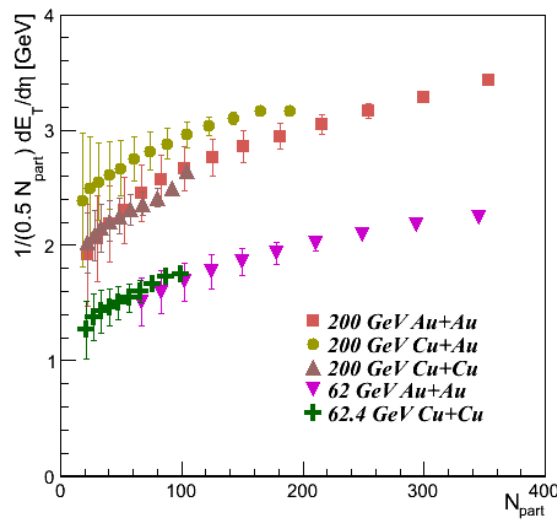

Figure 3. $dE_T/d\eta$ as a function of centrality in Cu+Au collisions at $200\,\mathrm{GeV}$ compared to Au+Au and Cu+Cu at 200 and $62.4\,\mathrm{GeV}$.

3. Mid-rapidity identified flow

Measuring the elliptic flow, v_2, is one of the main initial geometry tests for the U+U collision system. Comparison of v_2 of pions and protons in Au+Au and U+U shows mass ordering at low-p_T, with similar shapes across systems and centrality, see Fig. 4. There is a slight difference in the slope of the proton v_2 in the 0-10% central U+U collisions. This effect of flattening at low-p_T was further examined by splitting the central data into smaller percentile bins; it was observed that this flattening is most pronounced in the very central 0-2% class and goes away for the 6-10% class. More studies are needed to examine if this is caused only by the moderate increase (20%) in the energy density from central Au+Au to most central U+U, or if the proton radial flow plays a major role.

Previous PHENIX measurements [4] have shown that the identified charged hadron v_2 obeys number of the valance quark scaling rule. For identified hadrons in Au+Au at $200\,\mathrm{GeV}$ this scaling holds for the most central data (0-10%) and starts to break in the next (10-20%) centrality class. For the U+U system the number of valence quark scaling is studied for pions and protons (Fig. 5). Here, the scaling holds for all centrality bins. Note that future measurements, utilizing the full statistics of the run, will further extend the measured range in p_T.

The expectations for the v_n measurements in Cu+Au take into consideration the asymmetric nature of the colliding system. The initial asymmetric density profile (Fig. 6 left) will lead to
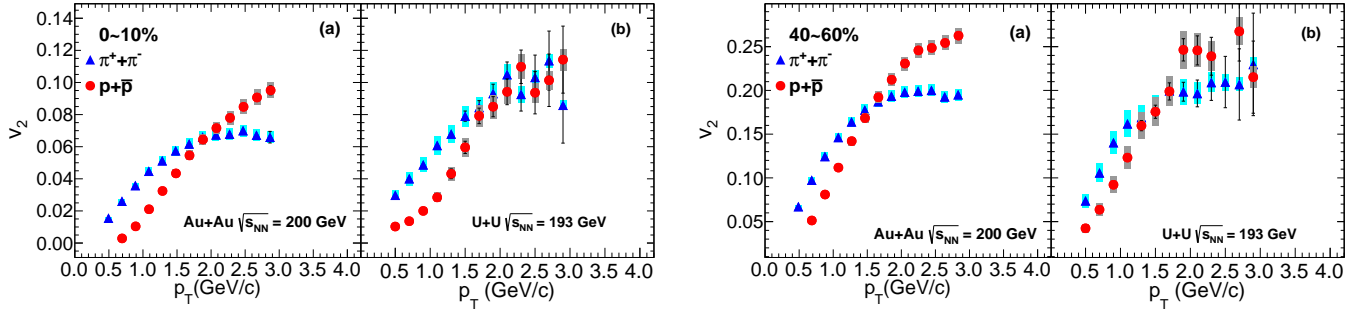
Figure 4. Comparison of elliptic flow for identified hadrons in Au+Au and U+U for 0-10% central data (left pair) and 40-60% mid central data (right pair).
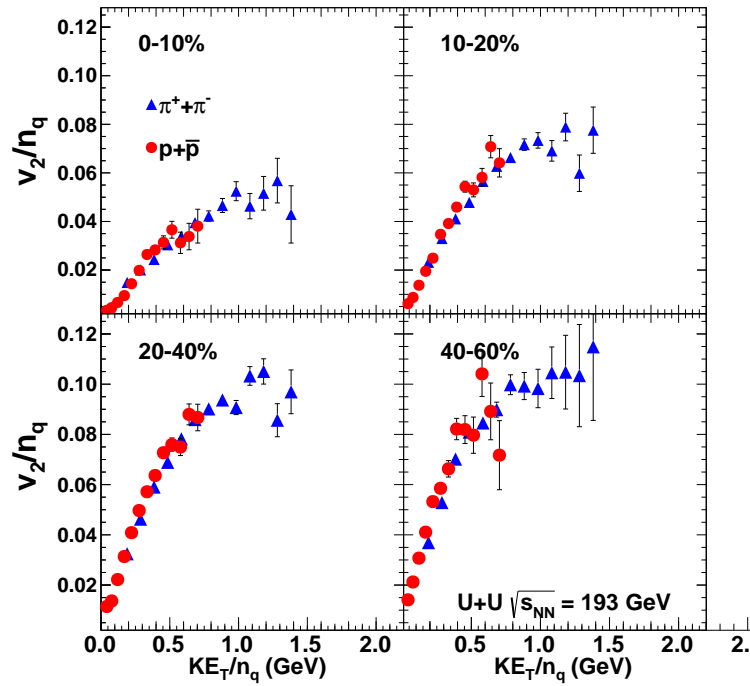

Figure 5. Number of valence quark scaling for v_2 of identified charged hadrons in U+U collisions.

an asymmetric pressure gradient, possibly resulting in an odd harmonic flow. The direction of the true (spectator) plane is defined by the Au spectators, which produce more yield, as shown by simulations (Fig. 6, right). The corresponding spectator reaction plane in data, $\psi_1 smd$, is measured by the shower max detector in the ZDCs (neutrons).

As expected, and asymmetric $dN/d\Delta\phi$ is observed at mid-rapidity, $|\eta|<0.35$ (Fig. 7 left), with a maximum along the reaction plane direction; more particles are emitted from the Au-side than from the Cu-side of the colliding system. This angular particle distribution is fitted with a Fourier function and the v_1, v_2 and v_3 coefficients are extracted. Hadrons at mid-rapidity have large v_1 component in Cu+Au, which is not observed in the Au+Au collision system. This could be naively explained by the asymmetric *corona*. There is also a large v_2 component but

surprisingly, the extracted v_3 is consistent with 0. (Note that this measurement of v_3 – with respect to the v_1-reaction plane – does not exclude the possibility of a significant v_3 signal with respect to the v_3-reaction plane, arising from participant nucleons.) The results are compared with model predictions (Fig. 7 right). The trend of v_2 as observed in data is expected by the models. The predicted v_1 has wrong sign compared to that in data.
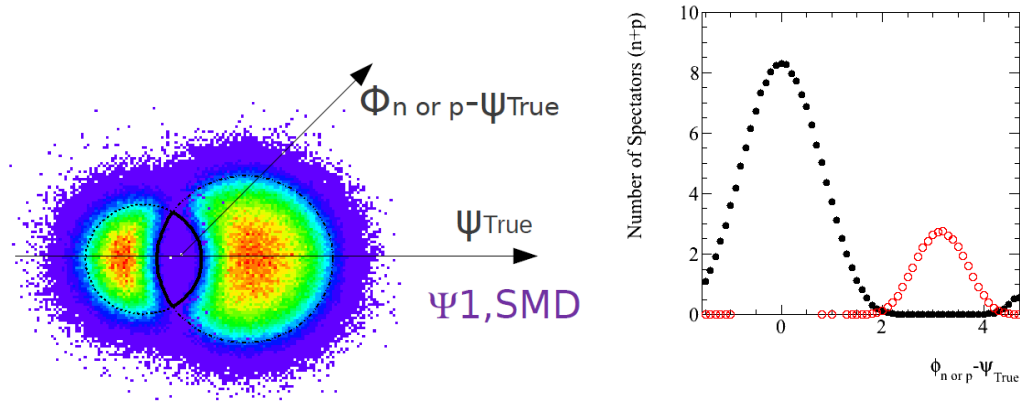

Figure 6. Glauber simulation of the Cu+Au spectator collision profile in 200 GeV (left panel). The true reaction plane, ψ_{True}, is oriented along the Au-side of the collision. Simulation of the angular distribution of the number of spectators from the Au nucleus (black) and from the Cu nucleus (red) (right panel).
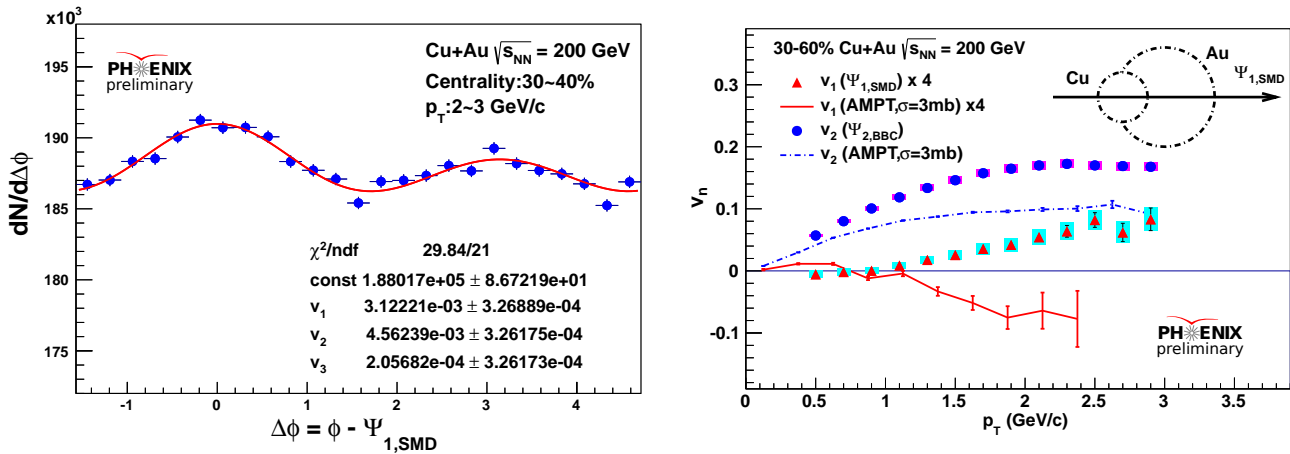
Figure 7. The measured angular distribution of the charged particles at mid rapidity with respect to the $\psi_1 smd$ in Cu+Au at 200 GeV (left). The line represents a fit with Fourier components v_1, v_2, v_3. AMPT model predictions [5] (lines) for the measured v_1 and v_2 in Cu+Au data (points), (right panel).

Fig. 8 shows the measured mid-rapidity pion v_1 in Cu+Au at 200 GeV for a few centrality bins. Sizable positive v_1 is observed for $p_T > 1$ GeV/c at mid-rapidity. The signal increases with p_T in all centrality bins shown. This signal may be due to the initial asymmetric density profile of the system. The results for protons require the use of full data statistics and are not shown. The v_2 for pions and protons (Fig. 9) are measured as a function of p_T and centrality.

The v_2 mass ordering is observed at low p_T for all centrality bins. The number of valence quark scaling also holds in Cu+Au collisions over the measured p_T range and centrality. For the data presented here, the v_2 signal was measured with respect to the second order reaction plane from the BBCs, $\psi_2 bbc$. As a cross check, $\psi_1 smd$ was also used and the measure v_2 for hadrons was found to be consistent with that from $\psi_2 bbc$.
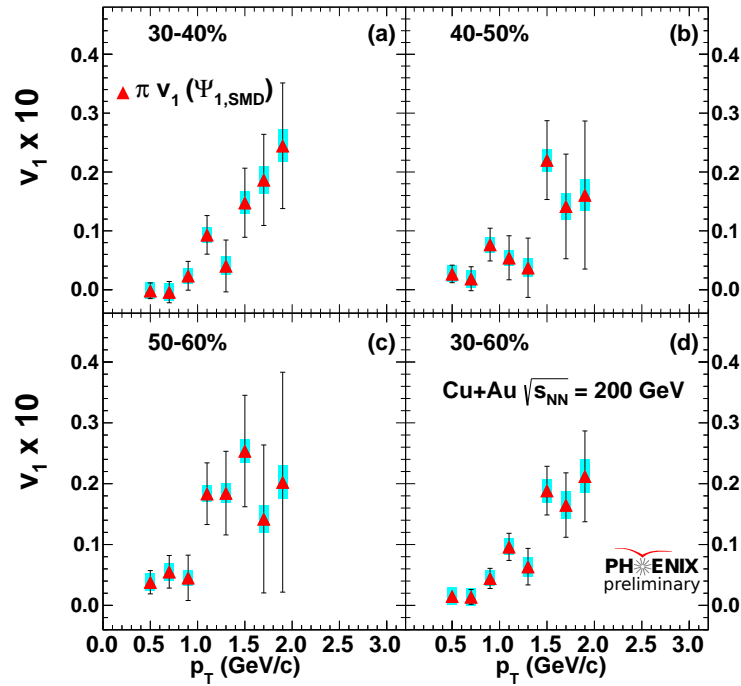

Figure 8. Pion v_1 at mid-rapidity measured in Cu+Au collisions at 200 GeV for a few centrality bins.

4. Identified charged particle spectra

The identified charged particle spectra at mid-rapidity in Cu+Au collisions at 200 GeV were measured for pions and protons. The pion nuclear modification factors, R_{AB}, were formed and then compared to the ones observed in Au+Au collisions at the same center of mass energy, and for an equivalent N_{coll} number, see Fig. 10. The pion nuclear modification factors are very similar in both asymmetric (Cu+Au) and symmetric (Au+Au) systems. Then the baryon-to-meson ratio is examined by forming the spectra ratios between pions and protons, separately for the positive and negative particles, see Fig. 11. Significant baryon enhancement is observed in central collisions, with similar magnitude for the positive and negative ratios. This is quite different than the previous observations in Au+Au and Cu+Cu at the same collision energy, [6]. The pbar/p ratio at mid-rapidity in symmetric systems depends on the collision energy only, with a small centrality and p_T dependence. It is approximately 0.8 in 200 GeV collisions and 0.5 in 62.4 GeV [7]. In Cu+Au collisions the pbar/p ratio is ≈ 0.9. There seems to be less protons produced and the question is why? We have measured a higher ϵ_B for an equivalent N_{part} in this asymmetric system than in the symmetric Cu+Cu and Au+Au systems, possibly due to a larger *core*. Further measurements are needed to find the answer.
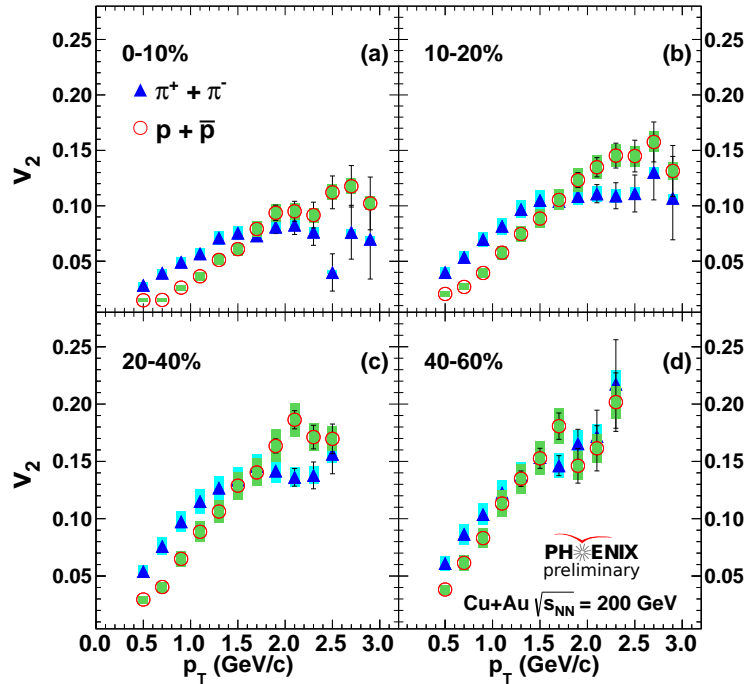
Figure 9. Pion and proton v_2 at mid-rapidity measured in Cu+Au collisions at 200 GeV for a few centrality bins.
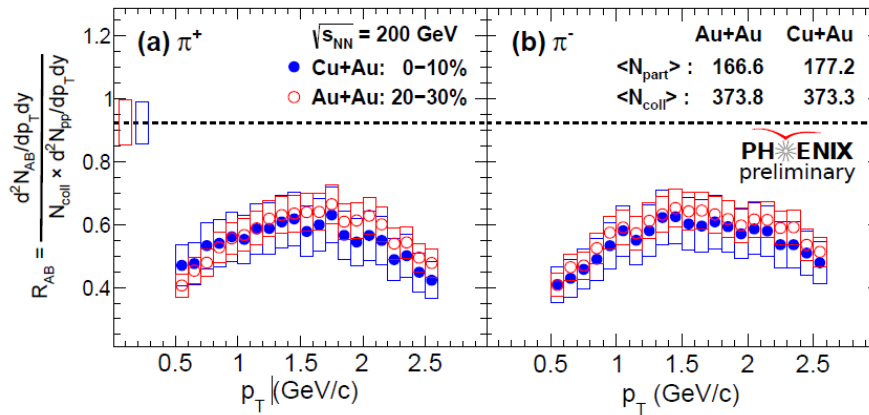
Figure 10. Pion nuclear modification factor, R_{AB}, in Cu+Au collisions at 200 GeV (closed circles) compared to that from Au+Au (open circles) at an equivalent N_{coll}. The results for π^+ are in panel a), for π^- in panel b).

5. Summary

PHENIX has shown first measurements at RHIC from two very unique systems: U+U at 193 GeV and Cu+Au at 200 GeV. Data from both systems are attempting to shed more light on the role of the initial collision configuration and the final data observables. The U+U system holds the highest energy density so far measured at RHIC. The initial results on global particle production in these collisions follow the observed trends in other systems, but more experimental
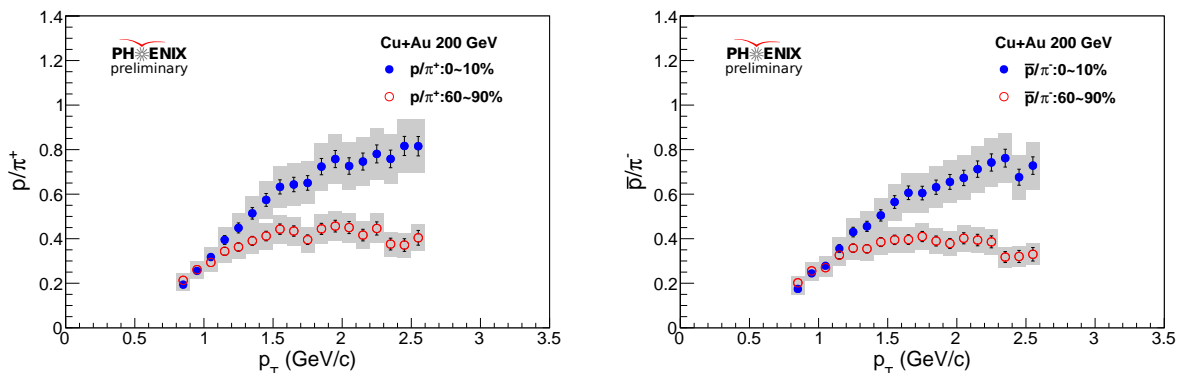
Figure 11. Ratios of proton to pion spectra for two centrality bins measured in Cu+Au collisions at 200 GeV. Ratios from positive particles are shown in the left panel, and for the negative particles in the right panel.

work is needed to further explore the initial collision configurations and to separate $tip - tip$ from $body - body$ collisions.

The asymmetric Cu+Au system has shown surprising results for the measured v_n harmonics at mid-rapidity. Non zero v_1 is observed, possibly due to the nature of this system's initial asymmetry. On the other hand, no v_3 component was observed. The higher energy density in Cu+Au compared to that in other symmetric systems at the same energy and N_{part} is also an interesting observation. We have also seen a different pbar/p ratio compared to that in symmetric systems at the same center of mass energy. PHENIX plans in future to provide further systematic measurements from both U+U and Cu+Au collisions.

References

[1] U. Heinz and A. Kuhlman, Phys. Rev. Lett. **94** (2005) 132301.
[2] R.S. Hollis, Nucl. Phys **A904** (2013) 507c
[3] B. Alver *et al.*, arXiv:0805.4411v1.
[4] A. Adare *at al.* Phys. Rev. C **85** (2012) 064914
[5] H. Ruiz and J. Nagle, AMPT (V1.21) calculation with string melting cross-section σ=3 mb, arXiv:1011.4534
[6] A. Adler *et al.* Phys. Rev. **C74** (2006) 024904
[7] M. Aggarwal *et al.*, Phys. Rev. **C83** (2011) 034910