U+U and Cu+Au results from PHENIX

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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 GeV and Cu+Au at 200 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 \textit{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 \textit{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 \textit{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, $\epsilon_B$, in most central U+U collisions is 6.15 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 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 $N_{\text{part}}$ value compared to the symmetric systems.

![Figure 3. $dE_T/d\eta$ as a function of centrality in Cu+Au collisions at 200 GeV compared to Au+Au and Cu+Cu at 200 and 62.4 GeV.](image)

### 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 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
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, $\psi_{1smd}$, is measured by the shower max detector in the ZDCs (neutrons).

As expected, an 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, $\psi_{\text{True}}$, 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 $\psi_{1\text{,SMD}}$ 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, $\psi_{2\text{bbc}}$. As a cross check, $\psi_{1\text{smd}}$ was also used and the measure $v_2$ for hadrons was found to be consistent with that from $\psi_{2\text{bbc}}$.

![Figure 8. Pion $v_1$ at mid-rapidity measured in Cu+Au collisions at 200 GeV for a few centrality bins.](image)

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 $N_{\text{coll}}$ 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 $p_{\text{bar}}/p$ 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 $p_{\text{bar}}/p$ ratio is $\approx 0.9$. There seems to be less protons produced and the question is why? We have measured a higher $\epsilon_B$ for an equivalent $N_{\text{part}}$ 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, $R_{AA}$, 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 $\pi^+$ are in panel a), for $\pi^-$ 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
work is needed to further explore the initial collision configurations and to separate \( t\text{ip} \) – \( t\text{ip} \) from \( b\text{ody} \) – \( b\text{ody} \) 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 \( N_{\text{part}} \) 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
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