Recent STAR Results from U+U and Au+Au Collisions

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Abstract.

Unlike Au or Pb nuclei which are more spherical, the uranium nuclei have a relatively large deformation on average. The prolate shape of uranium nuclei provides the feasibility to study how the initial geometry of the nuclei affects the azimuthal distributions of produced particles. It also provides a unique opportunity to understand the initial condition for particle production at mid-rapidity in heavy ion collisions as well as path length dependence of jet quenching and quarkonium in-medium effects.

In this proceedings, the two- and four- particle cumulant, $v_2\{2\}$ and $v_2\{4\}$, from U+U collisions at $\sqrt{s_{NN}} = 193$ GeV and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for inclusive charged hadrons at midrapidity will be presented. The STAR Zero Degree Calorimeter is used to subdivide the 0-1% centrality bin into even finer centralities. Differences were observed between the multiplicity dependence of $v_2\{2\}$ for most central Au+Au and U+U collisions. The observed $v_2\{2\}$ slope results were compared to Monte Carlo Glauber model predictions and it was seen that this model cannot explain the presented results on the multiplicity dependence of $v_2\{2\}$ in central collisions.

1. Introduction

Heavy nuclei are collided at the Relativistic Heavy Ion Collider (RHIC) in order to create matter that is hot and dense enough to create a Quark Gluon Plasma (QGP). One evidence of the formation of QGP is the strong v_2, which is defined as the second coefficient of the following Fourier expansion:

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \psi),$$

where ψ is a reference axis often identified with either the participant plane or reaction plane and ϕ is the azimuthal angle of the particles. In non-central heavy-ion collisions, the overlap area has an almond shape with a major axis and a minor axis. Model calculations indicate that different pressure gradients along the two axes will produce a large v_2.

The unique geometry shape of uranium nucleus provides opportunities to further test our understanding of the particle production mechanism and v_2. The larger size of uranium nucleus provides higher energy density in U+U collisions. On the other hand, the uranium nucleus is not spherical and have a prolate shape, which makes the collision geometry vary from body-on-body to tip-on-tip configurations, even in nearly fully overlapping collision. In the case of tip-on-tip collisions, the produced particle multiplicity should be higher due to the larger number of binary
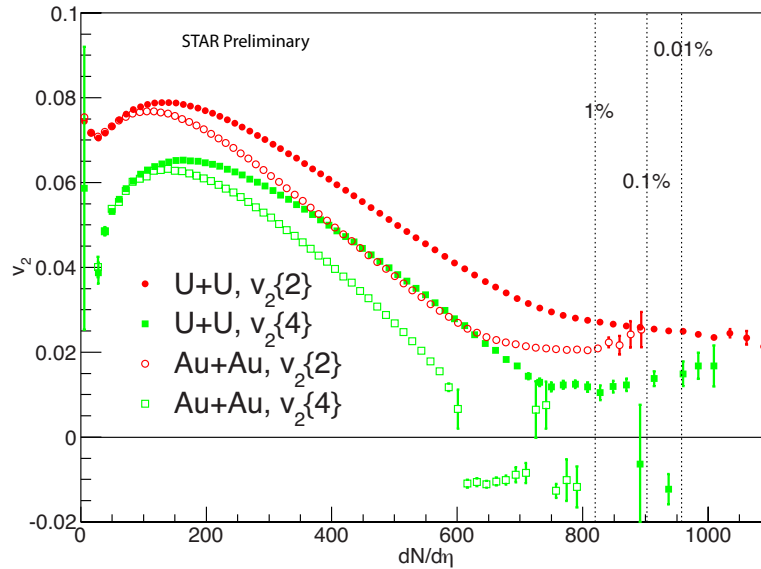
Figure 1. (Color online) The two- and four- particle cumulant $v_2\{2\}$ and $v_2\{4\}$ from 200 GeV Au+Au and 193 GeV U+U collisions as a function of $dN/d\eta$ at midrapidity for all charged particles. Dash lines represent multiplicity based centrality cuts for U+U collisions. Negative $v_2\{4\}^4$ are shown as negative $v_2\{4\}$.

collisions, and v_2 is smaller since the overlap region is symmetric, while in the case of body-on-body collisions, one should observe a smaller multiplicity associated with larger v_2. Thus if our understanding of particle production is correct, a strong correlation between multiplicity and v_2 should exist in U+U collisions compared with more symmetric systems like Au+Au.

2. Data and Analysis Method

The data sets for this analysis were collected by the STAR detector from Au+Au at $\sqrt{s_{NN}} = 200$ and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV in year 2011 and 2012, respectively. All charged particles within pseudo-rapidity $|\eta| < 1$ and transverse momentum $0.2 < p_T < 2.0$ GeV$/c$ were analyzed by the Time Projection Chamber (TPC). The Zero Degree Calorimeters (ZDCs) were used to select fully overlapping events based on spectator neutrons. Only events with primary vertices within 30 cm of the TPC center in the beam direction were analyzed. The reconstruction efficiency was obtained from GEANT based Monte Carlo simulation and the results presented here are corrected for reconstruction efficiency.

In this analysis, v_2 is calculated via the two- and four- particle cumulant methods ($v_2\{2\}$ and $v_2\{4\}$). The Q-cumulant method [4] allows us to calculate $v_2\{4\}$ without using generating functions or calculating an event plane thus it is simpler to perform. The two-particle cumulant is calculated from $v_2\{2\}^2 = \langle\cos[2(\varphi_1 - \varphi_2)]\rangle - \langle\cos(\varphi_1)\rangle\langle\cos(\varphi_2)\rangle - \langle\sin(\varphi_1)\rangle\langle\sin(\varphi_2)\rangle$. In order to remove correlations from HBT, Coulomb effects and track-merging, we reject pairs with $|\Delta\eta| < 0.1$. This is not practical for the four-particle cumulant but few particle correlations in $v_2\{4\}$ are largely suppressed by combinatorics.

3. Results

In this paper, the results are presented for both minimum-bias and central events. Figure 1 shows the two- and four- particle cumulant $v_2\{2\}$ and $v_2\{4\}$ from 200 GeV Au+Au and 193 GeV U+U collisions as a function of $dN/d\eta$ at midrapidity for all charged particles. The $v_2\{4\}$
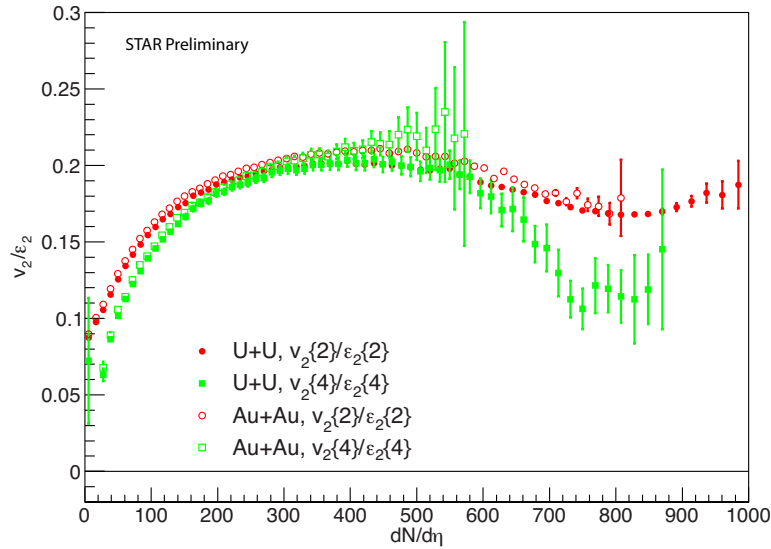
Figure 2. (Color online) v_2 scaled by participant eccentricity from 200 GeV Au+Au and 193 GeV U+U collisions as a function of $dN/d\eta$.

results are calculated from $v_2\{4\}^4$ and by taking the fourth root. For illustration purposes, we plot the imaginary $v_2\{4\}$ results as negative values. The Au+Au $v_2\{4\}$ results show a centrality dependence and turn negative (imaginary) at central collisions. This is allowed due to the fact that $v_2\{4\}$ results contains flow fluctuations and the flow signal from central collisions is small due to symmetrical collision system. Unlike $v_2\{4\}$ results in Au+Au, the $v_2\{4\}$ results in U+U are always positive at central collisions. The non-zero $v_2\{4\}$ in central U+U collision could result from the intrinsic prolate shape of the uranium nucleus: although the impact parameter is small in central U+U collisions, the prolate shape of uranium nucleus on average still provides an almond shaped overlap region which also produces this non-zero $v_2\{4\}$ result.

As discussed previously, high-multiplicity collisions would have predominantly tip-tip collisions, which also produces relatively smaller v_2. It has been predicted that a unique knee structure will be present in high multiplicity collisions if one plots v_2 vs. charged multiplicity [3]. However, the $v_2\{2\}$ results from U+U data show no indication of such a knee structure. The non-zero $v_2\{4\}$ and lack of knee structure in $v_2\{2\}$ together could indicate that although the prolate geometry shape of uranium nuclei do show up in the data, there might be additional fluctuation that washes out this knee structure in $v_2\{2\}$ results [5].

Another interesting topic is the v_2 divided by the initial anisotropy ε in coordinate space. It has been found previously that v_2/ε increases with $dN/d\eta$ and saturates at central collisions. This saturation is consistent with the picture that the system collectivity approaches the hydrodynamical limit. Figure 2 shows the v_2/ϵ from 200 GeV Au+Au and 193 GeV U+U collisions. Both U+U and Au+Au follow the same trend for v_2/ε, however, a turn-over is observed at central collisions where the initial geometry of the overlap region plays a dominant role. The turn-over may indicate an overestimation of ε in central collisions while other origins like hydro fluctuation are also possible.

In order to take advantage of the prolate shape of uranium nuclei, one needs to separate fully overlapped body-on-body and tip-on-tip collisions. Unfortunately, RHIC is not capable of providing polarized uranium beams so it relies on experimental observables to disentangle the body-on-body vs. tip-on-tip collisions. One strategy is to use spectator neutrons measured by the ZDC to select fully overlapping collision, then one could use charged particle multiplicity
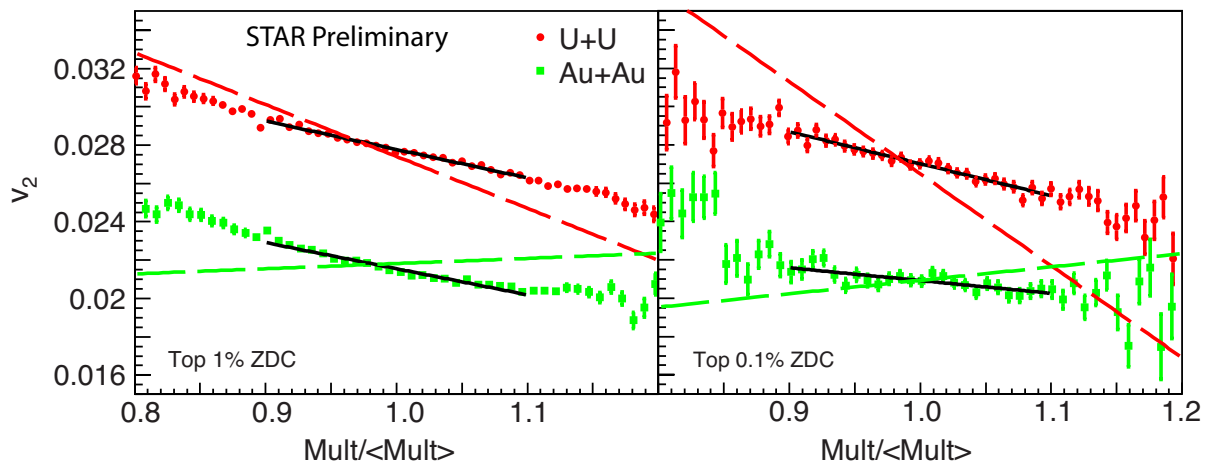
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Figure 3. (Color online) The v_2 of all charged particles as a function of the normalized multiplicity. The left panel shows the results for top 1% ZDC central events, while the right panel shows the results for top 0.1% ZDC central event. A linear fit between normalized multiplicity 0.9 to 1.1 is applied to extract the slope parameter. The dash lines represent Glauber-simulation slopes calculated via eccentricity.

to select body-on-body or tip-on-tip enhanced samples [1]. In case of body-on-body collision, the multiplicity will be lower due to smaller number of binary collisions, while the v_2 will be larger due to the almond overlapping region. For tip-on-tip collisions, there will be a higher multiplicity associated with small v_2. Thus a strong correlation between multiplicity and v_2 could serve as an evidence of selection of geometry orientations.

Figure 3 shows the v_2 of all charged particles as a function of the normalized multiplicity. The left panel shows the results for top 1% ZDC central events. Since the deformation of gold nuclei is small, in case of fully overlapping collisions, the multiplicity differences are mainly from fluctuations and there should be no correlations between multiplicity and v_2. However, a strong negative slope is observed in both Au+Au and U+U collisions, which indicates the impact parameter still dominates the observed correlation. A slightly off-center collision produces smaller multiplicity and stronger v_2 due to almond shaped overlapping region. In order to see the effects from initial geometry (body-on-body vs. tip-on-tip), one needs to reduce the effects from impact parameters and select further fully overlap collisions. The right panel of Fig. 3 shows the same results for top 0.1% ZDC central events. The slope magnitude in Au+Au collisions is smaller, indicating the effects from non-central collisions are reduced, and the multiplicity differences are mainly driven by fluctuations in Au+Au, while the slope for U+U becomes steeper. This comparison between Au+Au and U+U serves as evidence of selection of geometry orientation enhanced sample based on multiplicity. On the other hand, the Glauber model predicts a steeper slope for U+U collisions and a positive slope for Au+Au due to its oblate shape [6].

To further test the correlation between multiplicity and v_2, a linear fit is applied and the slope parameter is extracted. Figure 4 shows the slope parameter for 200 GeV Au+Au and 193 GeV U+U events as a function of ZDC centrality. With tighter ZDC cuts, the slope magnitude decreases in Au+Au, indicating that the effects from the impact parameter are reduced, while the U+U slope parameter increases (more negative). This stronger correlation between v_2 and multiplicity in U+U is due to the fact that with more central collisions selected by the ZDCs, the diffusion effects from impact parameter are reduced (at large impact parameter, central body-on-body and off-center tip-on-tip collisions produce the same multiplicity but different v_2). The
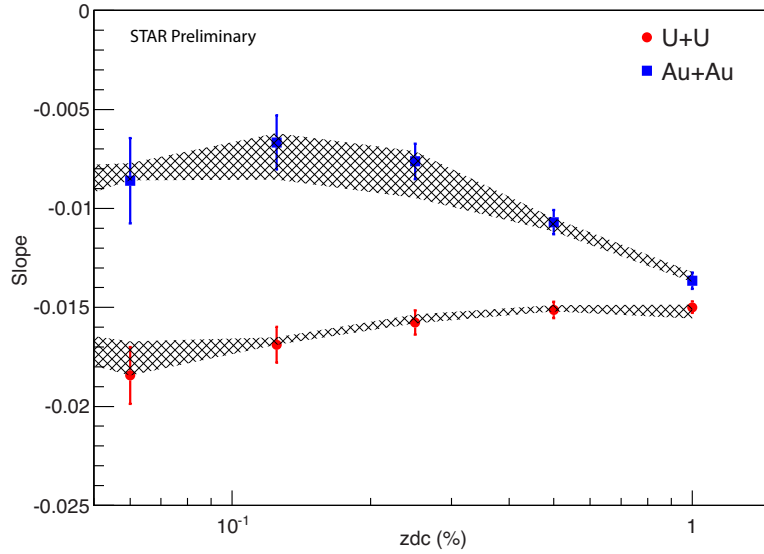
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Figure 4. (Color online) The slope parameter for 200 GeV Au+Au and 193 GeV U+U events as a function of ZDC centrality. Grey band represent systematical uncertainties.
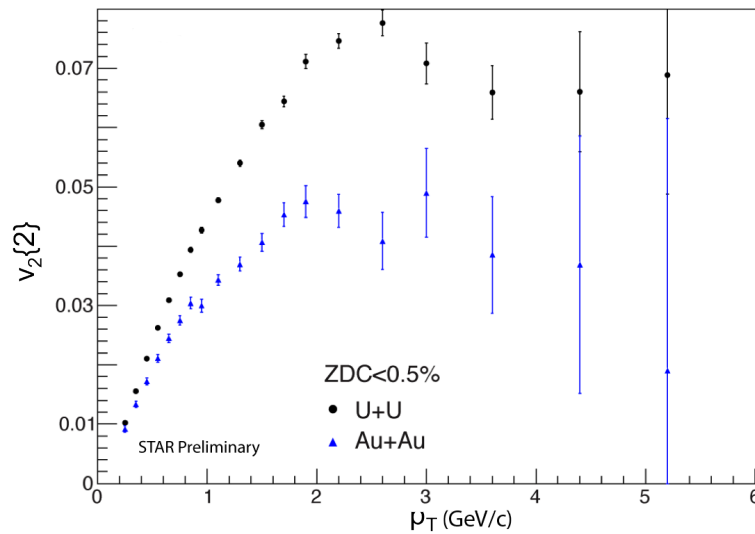

Figure 5. (Color online) p_T dependence of the two-particle cumulant $v_2\{2\}$.

comparison between Au+Au and U+U indicates that $dN/d\eta$ can help to select tip-on-tip vs. body-on-body enhanced samples.

Once selection of initial geometry (body-on-body vs. tip-on-tip) is possible, the central U+U collisions could serve as an ideal test ground for many observables like the path-length dependence of jet quenching or local parity violation [2, 3]. As the first step to study the path length dependence of jet quenching, Fig. 5 shows the p_T dependence of the two-particle cumulant $v_2\{2\}$. Both U+U and Au+Au show a maximum at p_t around 2.5 GeV/c and turn over at higher p_T. To take advantage of uranium nucleus's prolate shape, it is necessary in the future to divide the U+U data into body-on-body vs. tip-on-tip enhanced samples.

4. Conclusion

In summary, the two- and four- particle cumulant, $v_2\{2\}$ and $v_2\{4\}$, for inclusive charged hadrons have been presented from U+U collisions at $\sqrt{s_{NN}} = 193$ GeV and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV . The non-zero $v_2\{4\}$ results in U+U collisions suggest that we observe the prolate shape of uranium nuclei. However, no knee structure is visible in $v_2\{2\}$ results from central U+U collisions. We also observed an interesting turn over of v_2/ϵ_2 in central collisions for both Au+Au and U+U collisions. It has been demonstrated that by combining cuts on ZDC and charged particle multiplicity, one can select body-body or tip-tip enhanced samples of central U+U collisions. The capability of selecting initial geometry in U+U collisions provides new opportunities to study path-length dependent jet quenching and local parity violation in the future.

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