

# **Predictions of Elliptic flow and nuclear modification factor from 200 GeV U+U collisions at RHIC**

Hiroshi Masui, Bedangadas Mohanty,  
Nu Xu

September 9, 2009

*This work was supported by the Director, Office of  
Science, Office of Nuclear Science of the U.S.  
Department of Energy under Contract No. DE-AC02-  
05CH11231.*

# Predictions of Elliptic flow and nuclear modification factor from 200 GeV U + U collisions at RHIC

Hiroshi Masui<sup>\*,a</sup>, Bedangadas Mohanty<sup>b</sup>, Nu Xu<sup>a</sup>

<sup>a</sup>Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

<sup>b</sup>Variable Energy Cyclotron Centre, Kolkata 700064, India

---

## Abstract

Predictions of elliptic flow ( $v_2$ ) and nuclear modification factor ( $R_{AA}$ ) are provided as a function of centrality in U + U collisions at  $\sqrt{s_{NN}} = 200$  GeV. Since the  $^{238}\text{U}$  nucleus is naturally deformed, one could adjust the properties of the fireball, density and duration of the hot and dense system, for example, in high energy nuclear collisions by carefully selecting the colliding geometry. Within our Monte Carlo Glauber based approach, the  $v_2$  with respect to the reaction plane  $v_2^{\text{RP}}$  in U + U collisions is consistent with that in Au + Au collisions, while the  $v_2$  with respect to the participant plane  $v_2^{\text{PP}}$  increases  $\sim 30$ - $60\%$  at top 10% centrality which is attributed to the larger participant eccentricity at most central U + U collisions. The suppression of  $R_{AA}$  increases and reaches  $\sim 0.1$  at most central U + U collisions that is by a factor of 2 more suppression compared to the central Au + Au collisions due to large size and deformation of Uranium nucleus.

*Key words:* Glauber Model, Elliptic flow, Nuclear modification factor

*PACS:* 25.75.Bh, 25.75.Ld

---

## 1. Introduction

Most striking findings at RHIC are the large elliptic flow  $v_2$  [1] and the strong suppression of nuclear modification factor  $R_{AA}$  [2]. The  $v_2$  is defined by the second harmonic Fourier coefficient of azimuthal particle distribution with respect to the reaction plane, and the  $R_{AA}$  is defined by the ratio of invariant yield in A + A collisions to that in p + p collisions scaled by number of collisions. Recent systematic measurements of  $v_2$  [3] as well as developments of viscous hydrodynamical models [4, 5, 6, 7] provide a conservative upper limit of the viscosity  $\eta$  to the entropy  $s$  ratio  $\eta/s \leq 0.5$ . This corresponds to the 6 times larger value of an absolute lower bound  $\eta/s = 1/4\pi$  predicted by strongly coupled gauge field theories based on the AdS/CFT correspondence [8, 9]. It has been observed that the ratio  $v_2/\varepsilon$  in different systems from AGS to RHIC scale like  $1/SdN_{\text{ch}}/dy$  [10] as it was predicted by a low density limit of  $v_2$  [11, 12], where  $\varepsilon$  is the initial geometrical anisotropy (eccentricity),  $S$  is the transverse area and  $dN_{\text{ch}}/dy$  is the charged particle rapidity density. The saturation of  $v_2/\varepsilon$  would indicate that the system is approaching the hydrodynamical limit and the collectivity no longer increases when the system

---

\*Corresponding author

*Email addresses:* HMasui@lbl.gov (Hiroshi Masui), bedanga@rcf.bnl.gov (Bedangadas Mohanty), NXu@lbl.gov (Nu Xu)

size becomes larger. The measurements of transverse momentum spectra of charged hadrons showed that the yield at most central Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV is suppressed by a factor of  $\sim 5$  compared to the  $p + p$  reference scaled by number of binary collisions  $N_{\text{coll}}$  [13, 14] and the similar level of suppression persists for neutral pions up to  $p_T = 20$  GeV/c [15]. The integrated  $R_{AA}$  above  $p_T > 5$  GeV/c and  $> 10$  GeV/c decreased monotonically as a function  $N_{\text{part}}$  and there were no sign of saturation [15].

Assuming the underlying dynamics remains the same, we ask what would happen to  $v_2$  and  $R_{AA}$  for a larger colliding system  $^{238}\text{U} + ^{238}\text{U}$  collisions? Comparing to the  $^{197}\text{Au}$  nucleus, the  $^{238}\text{U}$  has a much larger mass and, more importantly, it is largely deformed. The planned U + U collisions at RHIC will be important for us to understand how those observables behave at higher particle density. Monte Carlo Glauber simulations showed that the transverse number density  $1/SdN_{\text{ch}}/dy$  increases  $\sim 35\%$  at most central events in ideal tip-tip collisions (head-on collisions along the longest axes) [16]. The U + U collisions will become possible when the Beam Ion Source becoming operational in 2012 [17].

In this letter, we will report a geometrical approach based on the Monte Carlo Glauber model to predict the elliptic flow  $v_2$  as well as the nuclear modification factor  $R_{AA}$  in U + U collisions at top RHIC energy. In the Section 2, we will discuss our parameterization of Glauber model and define geometrical quantities which are used in this study. In the Section 3, the results of  $v_2$  and  $R_{AA}$  in U + U collisions will be presented and compared to the data in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV.

## 2. Glauber Model

The nucleon density distribution is parameterized by a deformed Woods-Saxon profile [18]

$$\rho = \frac{\rho_0}{1 + \exp([r - R']/a)}, \quad (1)$$

$$R' = R [1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)], \quad (2)$$

where  $\rho_0$  is the normal nuclear density,  $R$  and  $a$  denote the radius of nucleus and the surface diffuseness parameter, respectively. We have used  $R = 6.38$  fm and  $a = 0.535$  fm for  $^{197}\text{Au}$  nucleus, and  $R = 6.81$  fm and  $a = 0.55$  fm for  $^{238}\text{U}$  nucleus. The  $Y_l^m(\theta)$  denotes the spherical harmonics and  $\theta$  is the polar angle with the symmetry axis of the nucleus. Deformation parameters are  $\beta_2 = 0.28$  [19] and  $\beta_4 = 0.093$  [20] for Uranium. The presence of  $\beta_4$  modifies the shape of Uranium compared to that only with  $\beta_2$ , which was implemented in several different models [16, 19]. The radius increases  $\sim 6\%$  ( $3\%$ ) at  $\theta = 0$  ( $\theta = \pi/2$ ), while it decreases  $\sim 3\%$  around  $\theta = \pi/4$ . We have assumed that Au nucleus is spherical ( $\beta_2 = \beta_4 = 0$ ), thus Eq. (1) reduces the spherical Woods-Saxon profile. Recent calculation [21] shows that the ground-state deformation of  $^{197}\text{Au}$  affects the eccentricity of initial geometry overlap only at most central collisions from both optical and Monte Carlo Glauber simulations. The positions of nucleons are sampled by  $4\pi r^2 \sin(\theta) \rho(r) d\theta d\phi$ , where the absolute normalization of  $\rho(r)$  is irrelevant.

Both projectile and target U nuclei are randomly rotated along the polar and azimuthal directions event-by-event with the probability distribution  $\sin \Theta$  and uniform distribution for  $\Theta$  and  $\Phi$ , respectively. The  $\sin \Theta$  weight needs to be implemented to simulate unpolarized nucleus-nucleus collisions. The results are averaged over all possible orientations unless otherwise specified.

A binary nucleon-nucleon collision take places if

$$d \leq \sqrt{\frac{\sigma_{NN}}{\pi}}, \quad (3)$$

where  $d$  is the distance between nucleons in the transverse direction orthogonal to the beam axis, and  $\sigma_{NN} = 42$  mb is the inelastic nucleon-nucleon cross section at  $\sqrt{s} = 200$  GeV. For each event, the total number of binary collisions  $N_{\text{coll}}$  is calculated by the sum of individual number of collision and the total number of participant nucleons  $N_{\text{part}}$  is the number of nucleons that interacts at least once.

Charged particle pseudorapidity density is obtained by a two component model [22]

$$\frac{dN_{ch}}{d\eta} = n_{pp} \left[ (1-x) \frac{N_{\text{part}}}{2} + x N_{\text{coll}} \right], \quad (4)$$

where  $n_{pp} = 2.29$  and  $x = 0.145$  are fixed to reproduce the PHOBOS results [23]. Event-by-event multiplicity fluctuations have been taken into account by convoluting Negative Binomial Distribution for a given  $N_{\text{part}}$  and  $N_{\text{coll}}$

$$P(\mu, k; n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \left(\frac{\mu}{k}\right)^n \left(1 + \frac{\mu}{k}\right)^{-(n+k)}, \quad (5)$$

where  $\mu = n_{pp}$  is the mean of the distribution and  $1/k = 0.5$  corresponds to deviation from a Poisson distribution. In this study, we have generated 1 million events for U + U collisions by randomly selecting an impact parameter  $b$  according to the  $d\sigma/db = 2\pi b$ .

Figure 1 shows the comparison of  $dN_{\text{ch}}/d\eta$  distributions in Au + Au and U + U collisions at  $\sqrt{s_{NN}} = 200$  GeV from our Monte Carlo Glauber model. The maximum  $dN_{\text{ch}}/d\eta$  in U + U collisions increases  $\sim 15\%$  compared to that in Au + Au collisions. We have defined the event centrality bins by the fraction of events in  $dN_{\text{ch}}/d\eta$ . The centrality bins are summarized in Table 1.

Table 1: Summary of centrality bins based on the  $dN_{\text{ch}}/d\eta$  and  $\langle N_{\text{part}} \rangle$ ,  $\langle N_{\text{coll}} \rangle$ ,  $\langle S_{\text{RP}} \rangle$ ,  $\langle S_{\text{PP}} \rangle$ ,  $\langle \varepsilon_{\text{RP}} \rangle$ ,  $\varepsilon_{\text{PP}}\{2\} \equiv \sqrt{\langle \varepsilon_{\text{PP}}^2 \rangle}$  and  $\langle L \rangle$  for each centrality bin in U + U collisions at  $\sqrt{s_{NN}} = 200$  GeV. Errors denote systematic uncertainties, see texts for more details of systematic error evaluations.

centrality	$dN_{\text{ch}}/d\eta$	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$	$\langle S_{\text{RP}} \rangle$	$\langle S_{\text{PP}} \rangle$	$\langle \varepsilon_{\text{RP}} \rangle$	$\varepsilon_{\text{PP}}\{2\}$	$\langle L \rangle$ (fm)
0-5%	$\geq 740$	$418 \pm 6$	$1341 \pm 105$	$30.9 \pm 1.7$	$29.7 \pm 1.7$	$0.021 \pm 0.007$	$0.156 \pm 0.004$	$4.4 \pm 0.1$
5-10%	$\geq 609$	$358 \pm 14$	$1058 \pm 52$	$27.1 \pm 1.9$	$26.9 \pm 1.9$	$0.08 \pm 0.02$	$0.18 \pm 0.01$	$4.2 \pm 0.2$
10-20%	$\geq 410$	$281 \pm 13$	$751 \pm 49$	$22.9 \pm 1.8$	$22.7 \pm 1.8$	$0.15 \pm 0.02$	$0.24 \pm 0.02$	$3.9 \pm 0.1$
20-30%	$\geq 269$	$199 \pm 14$	$462 \pm 45$	$18.4 \pm 1.6$	$18.2 \pm 1.6$	$0.23 \pm 0.03$	$0.31 \pm 0.03$	$3.5 \pm 0.1$
30-40%	$\geq 170$	$137 \pm 14$	$272 \pm 39$	$14.8 \pm 1.5$	$14.5 \pm 1.6$	$0.29 \pm 0.03$	$0.38 \pm 0.03$	$3.2 \pm 0.2$
40-50%	$\geq 101$	$89 \pm 13$	$149 \pm 31$	$11.8 \pm 1.5$	$11.4 \pm 1.5$	$0.34 \pm 0.04$	$0.45 \pm 0.04$	$2.9 \pm 0.2$
50-60%	$\geq 56$	$55 \pm 11$	$75 \pm 22$	$9.3 \pm 1.5$	$8.8 \pm 1.5$	$0.38 \pm 0.04$	$0.51 \pm 0.05$	$2.6 \pm 0.2$
60-70%	$\geq 29$	$31 \pm 9$	$35 \pm 13$	$7.1 \pm 1.5$	$6.5 \pm 1.6$	$0.39 \pm 0.05$	$0.59 \pm 0.07$	$2.3 \pm 0.2$
70-80%	$\geq 13$	$16 \pm 6$	$15 \pm 8$	$4.8 \pm 1.7$	$4.0 \pm 1.8$	$0.38 \pm 0.06$	$0.68 \pm 0.09$	$1.9 \pm 0.3$

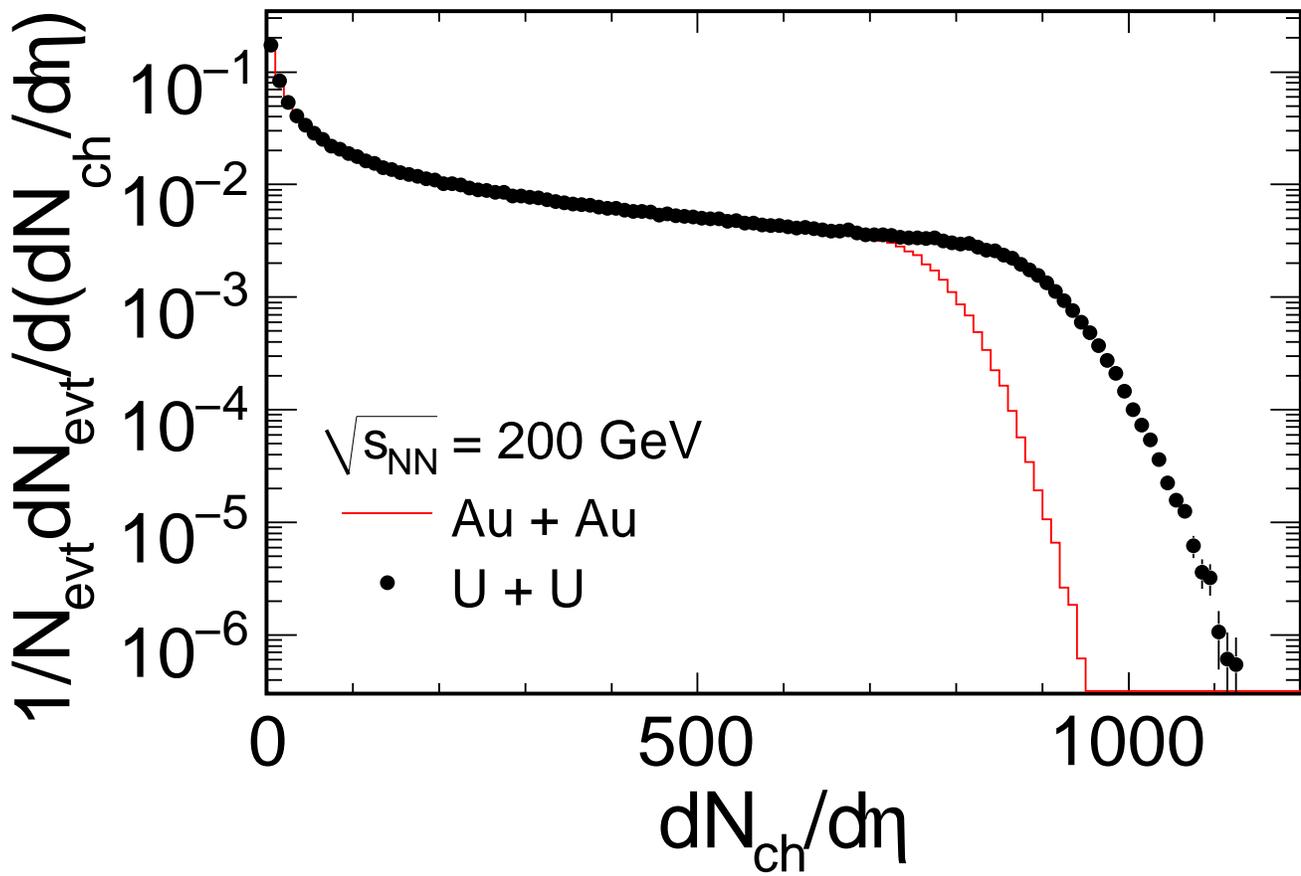


Figure 1: (Color online)  $dN_{\text{ch}}/d\eta$  distribution in Au + Au (solid line) and U + U collisions (filled circles) at  $\sqrt{s_{\text{NN}}} = 200$  GeV by averaging over all orientations.

Since the positions of nucleons fluctuate event-by-event, the principal axes of the participant nucleons in the transverse plane are tilted and rotated with respect to the original coordinate system. We define the participant plane (PP) which is the relevant plane to take into account the event-by-event position fluctuations of participant nucleons. The transverse area and eccentricity with respect to the reaction plane (RP) and participant plane are defined as

$$S_{\text{RP}} = \pi \sqrt{\sigma_x^2 \sigma_y^2}, \quad (6)$$

$$S_{\text{PP}} = \pi \sqrt{\sigma_x^2 \sigma_y^2 - \sigma_{xy}^2}, \quad (7)$$

$$\varepsilon_{\text{RP}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}, \quad (8)$$

$$\varepsilon_{\text{PP}} = \sqrt{\frac{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}{\sigma_y^2 + \sigma_x^2}}, \quad (9)$$

where  $\sigma_x^2 = \{x^2\} - \{x\}^2$ ,  $\sigma_y^2 = \{y^2\} - \{y\}^2$  and  $\sigma_{xy} = \{xy\} - \{x\}\{y\}$ . The curly brackets  $\{\dots\}$  denote the average over all participants for a given event. We have also calculated the averaged transverse path length  $L$  from the RMS width

$$L = \sqrt{\sigma_x^2 + \sigma_y^2}, \quad (10)$$

which could be a relevant geometrical quantity for the  $R_{AA}$ . The path length is very close to  $\rho L$  defined in [24], while Eq. (10) takes into account the event-by-event center of mass shift of the nuclei within the transverse plane. Average quantities,  $\langle N_{\text{part}} \rangle$ ,  $\langle N_{\text{coll}} \rangle$ ,  $\langle S \rangle$ ,  $\langle \varepsilon \rangle$  and  $\langle L \rangle$  have been calculated for each centrality bin where  $\langle \dots \rangle$  describe the average over all events.

Systematic uncertainties on the average quantities have been estimated (i) by varying input parameters  $R$ ,  $a$ ,  $n_{pp}$ ,  $x$  as well as the total cross section within  $\pm 5\%$  and (ii) by using different density profiles for nucleons in the Monte Carlo Glauber simulations. The dominant source of systematic uncertainty is the total cross section. Total systematic uncertainty has been evaluated by the quadratic sum of individual systematic uncertainty. Table 1 summarizes the centrality bins, average quantities and their systematic uncertainties obtained in the Monte Carlo Glauber simulation.

Figure 2 compares the  $N_{\text{coll}}$ , transverse number density  $1/\langle S_{\text{RP}} \rangle dN_{\text{ch}}/d\eta$ , reaction plane eccentricity  $\langle \varepsilon_{\text{RP}} \rangle$ , second order cumulant of participant eccentricity  $\varepsilon_{\text{PP}}\{2\} \equiv \sqrt{\langle \varepsilon_{\text{PP}}^2 \rangle}$ , and path length  $\langle L \rangle$  as a function of  $N_{\text{part}}$  together with their systematic uncertainties in Au + Au and U + U collisions at  $\sqrt{s_{NN}} = 200$  GeV. We found that the all geometrical quantities essentially scale with  $N_{\text{part}}$ . The  $N_{\text{coll}}$ ,  $\langle S \rangle$ ,  $\langle L \rangle$  increase and  $\langle \varepsilon_{\text{RP}} \rangle$  decreases at most central U + U collisions compared to those in Au + Au collisions because of the larger size of Uranium. One can see that the  $\varepsilon_{\text{PP}}\{2\}$  in U + U collisions starts deviating the  $N_{\text{part}}$  scaling around  $N_{\text{part}} = 200$ , and increases  $\sim 60\%$  at top 5% central U + U collisions. The higher values of  $\varepsilon_{\text{PP}}\{2\}$  in U + U collisions for large  $N_{\text{part}}$  is purely from the ground-state deformation of Uranium. We have confirmed that the  $\varepsilon_{\text{PP}}\{2\}$  becomes the same if we assume the Uranium is spherical. The relevance of the  $\varepsilon_{\text{PP}}\{2\}$  will be discussed in the next section.

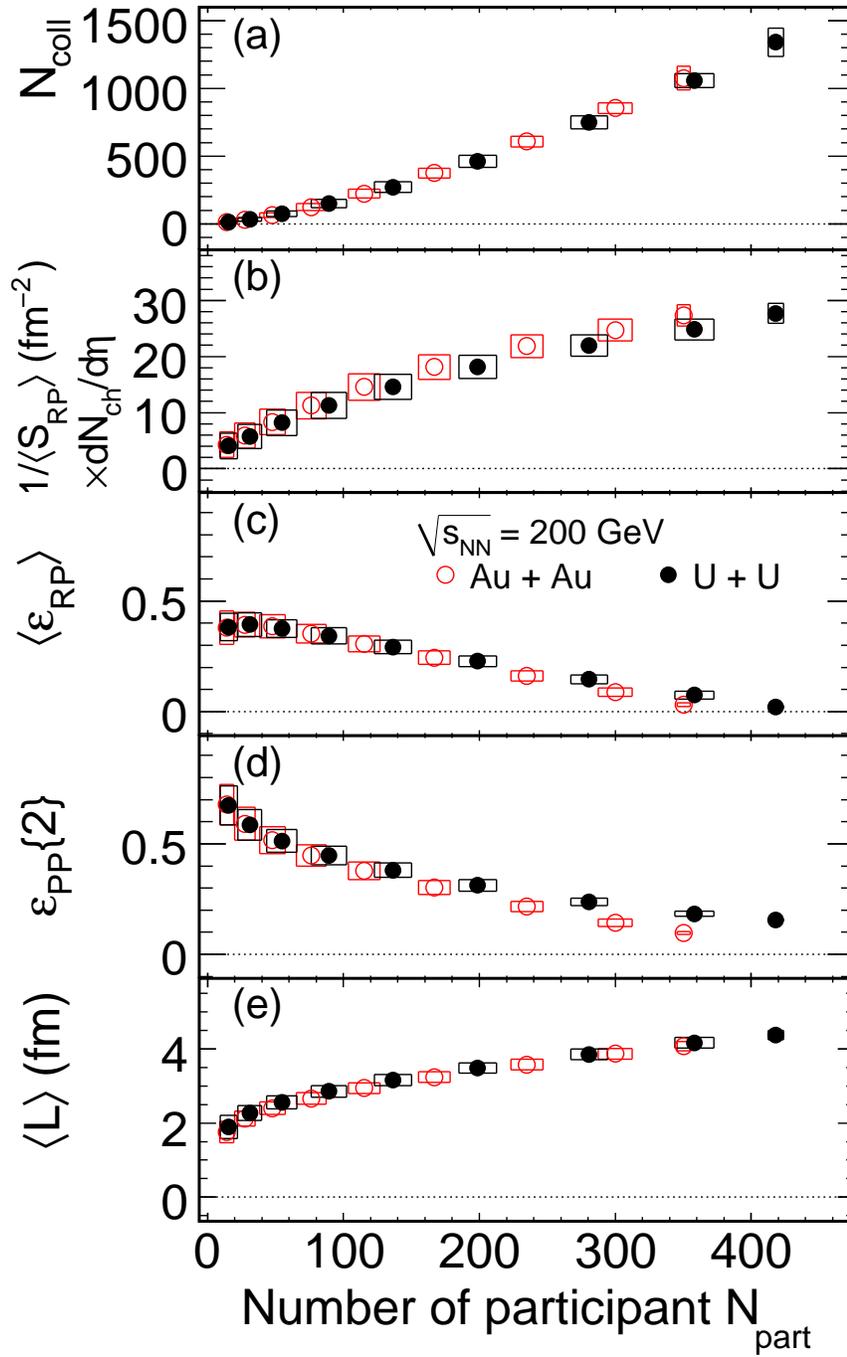


Figure 2: (Color online) Comparison of (a)  $N_{\text{coll}}$ , (b)  $1/\langle S_{\text{RP}} \rangle dN_{\text{ch}}/d\eta$ , (c)  $\langle \varepsilon_{\text{RP}} \rangle$ , (d)  $\varepsilon_{\text{PP}\{2\}}$  and (e)  $\langle L \rangle$  as a function of  $N_{\text{part}}$  in Au + Au (open circles) and U + U collisions (filled circles) at  $\sqrt{s_{NN}} = 200$  GeV. Open boxes show the systematic uncertainties in Monte Carlo Glauber simulations.

### 3. Results and Discussions

#### 3.1. Elliptic flow $v_2$

It has been found that the elliptic flow  $v_2$  divided by initial anisotropy  $\varepsilon$  in coordinate space scaled like  $1/SdN_{\text{ch}}/dy$  among different energies and collision systems from AGS to RHIC [10]. A simple formula that has been proposed in [25] describes very well the variation of  $v_2$  with  $1/SdN/dy$

$$\frac{v_2}{\varepsilon} = \frac{h}{1 + B (1/SdN/dy)^{-1}}, \quad (11)$$

where  $dN/dy$  is the rapidity density of total particles,  $h$  is the  $v_2/\varepsilon$  in the ideal hydrodynamical limit when  $1/S dN/dy \rightarrow \infty$ , and  $B$  contains informations about the equation of state and the partonic cross section [25]. The Eq. (11) reduces  $v_2/\varepsilon \sim (h/B)1/S dN/dy$  when  $1/S dN/dy \rightarrow 0$  for leading order in  $1/S dN/dy$ , thus the above equation satisfies both low density and ideal hydrodynamical limit of  $v_2$ . The integrated  $v_2$  for unidentified charged hadrons from the PHOBOS collaboration can be well described by the Eq. (11) [26]. Assuming no change in the collision dynamics, we will study the  $v_2/\varepsilon$  distributions versus the collision centrality in U + U collisions.

Figure 3 shows the  $v_2\{4\}/\langle\varepsilon_{\text{RP}}\rangle$  and  $v_2\{\text{EP}\}/\varepsilon_{\text{PP}}\{2\}$  as a function of  $1/\langle S \rangle dN/dy$  in Au + Au collisions at  $\sqrt{s_{\text{NN}}} = 200$  GeV, where  $v_2\{4\}$  and  $v_2\{\text{EP}\}$  denote the  $v_2$  from four particle cumulant method [27, 28] and that from standard event plane method [29], respectively. The  $dN/dy$  is obtained by multiplying 3/2 to the measured  $dN_{\text{ch}}/dy$  at STAR [30] to take into account the neutral particles. The simultaneous fit has been performed for (a) four particle cumulant  $v_2\{4\}$ , six particle cumulant and  $q$ -distribution method and for (b) standard event plane  $v_2\{\text{EP}\}$ , scalar product method,  $\eta$  subevent, random subevent, and two particle cumulant. The results of  $v_2$  are taken from [31]. The two different groups of  $v_2$  are categorized based on the multi-particle methods for (a) and two particle methods for (b). As long as the distribution of eccentricity is 2D gaussian in the transverse plane, the effect of fluctuation on the  $v_2\{4\}$  is negligible and thus the  $\varepsilon_{\text{RP}}$  can be used to scale the  $v_2\{4\}$  [32]. This assumption holds except for the peripheral 60-80% centrality, where the distribution of eccentricity becomes non-Gaussian. The  $v_2$  from two particle methods are expressed as  $(v_2^\alpha)^{1/\alpha}$  where  $v_2$  is the true  $v_2$  value and  $\alpha$  varies from 1 to 2 depending on the event plane resolution [33, 34]. In this study,  $\varepsilon_{\text{part}}\{2\} = \sqrt{\langle\varepsilon_{\text{part}}^2\rangle}$  was used by assuming  $\alpha = 2$ . We confirmed that the resulting  $v_2$  values unchanged by using  $\varepsilon_{\text{part}}$  (i.e.  $\alpha = 1$ ). Because the  $v_2$  values were extrapolated from  $(v_2/\varepsilon)$  multiplied by  $\varepsilon$ , most of the difference between  $\varepsilon_{\text{part}}\{2\}$  and  $\varepsilon_{\text{part}}$  is canceled out and thus the resulting  $v_2$  is the same regardless of the choice of eccentricity.

Figure 4 shows the extracted  $v_2$  in U + U collisions compared to those in Au + Au collisions as a function of centrality at  $\sqrt{s_{\text{NN}}} = 200$  GeV. The  $v_2^{\text{RP}}$  ( $v_2^{\text{PP}}$ ) denotes the  $v_2$  measured with respect to the reaction (participant) plane. The  $v_2^{\text{RP}}$  and  $v_2^{\text{PP}}$  have been calculated by multiplying the  $\langle\varepsilon_{\text{RP}}\rangle$  and  $\varepsilon_{\text{PP}}\{2\}$  to the fitting results of  $v_2/\varepsilon$  shown in Fig. 3 for each centrality bin. Since we have calculated the  $dN_{\text{ch}}/d\eta$  in the Monte Carlo Glauber simulation, it is necessary to convert the  $dN_{\text{ch}}/d\eta$  to  $dN/dy$  for calculating the  $v_2$  for each centrality bin. We assume that  $dN_{\text{ch}}/dy \approx 1.15dN_{\text{ch}}/d\eta$  to extrapolate the  $v_2/\varepsilon$  for each centrality [35]. The  $v_2^{\text{RP}}$  in U + U collisions is consistent with that in Au + Au collisions for centrality 0-80%. The  $v_2^{\text{PP}}$  is also consistent with each other in U + U and Au + Au collisions for centrality 20-80%, whereas the  $v_2$  in U + U collisions at top 0-10% centrality is 30-60% larger than that in Au + Au

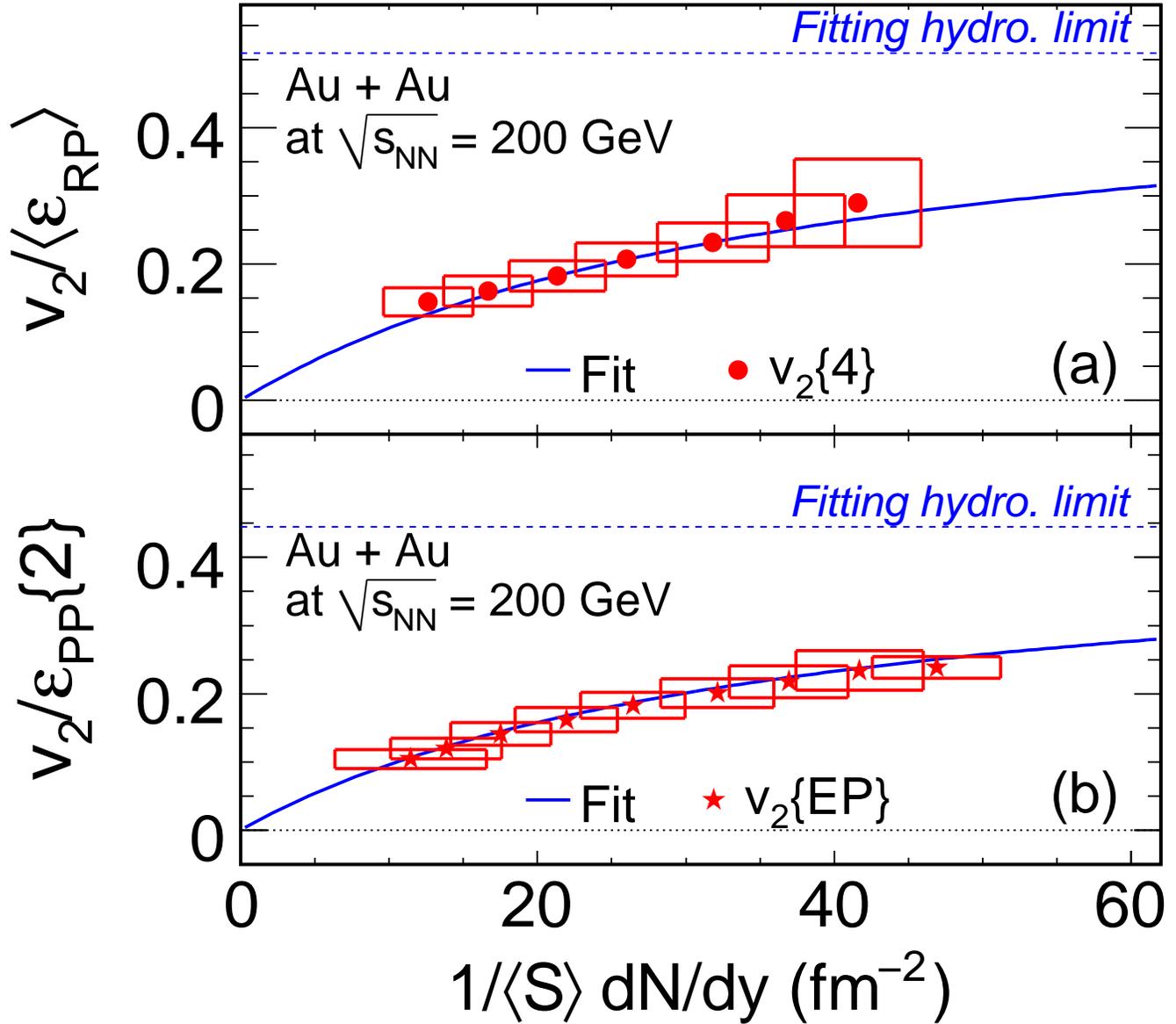


Figure 3: (Color online) (a) Four-particle cumulant  $v_2\{4\}/\langle \epsilon_{RP} \rangle$  as a function of  $1/\langle S_{RP} \rangle dN/dy$  for unidentified charged hadrons in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. (b) The same plot as (a) for the standard event plane  $v_2\{EP\}/\epsilon_{PP}\{2\}$  as a function of  $1/\langle S_{PP} \rangle dN/dy$ . Both the values of  $v_2\{4\}$  and  $v_2\{EP\}$  are taken from [31]. Only statistical errors on the  $v_2$  are shown and are smaller than symbols. Open boxes are systematic errors from the Monte Carlo Glauber simulation. Solid lines are fitting results by Eq. (11). See more details about fitting in the texts.

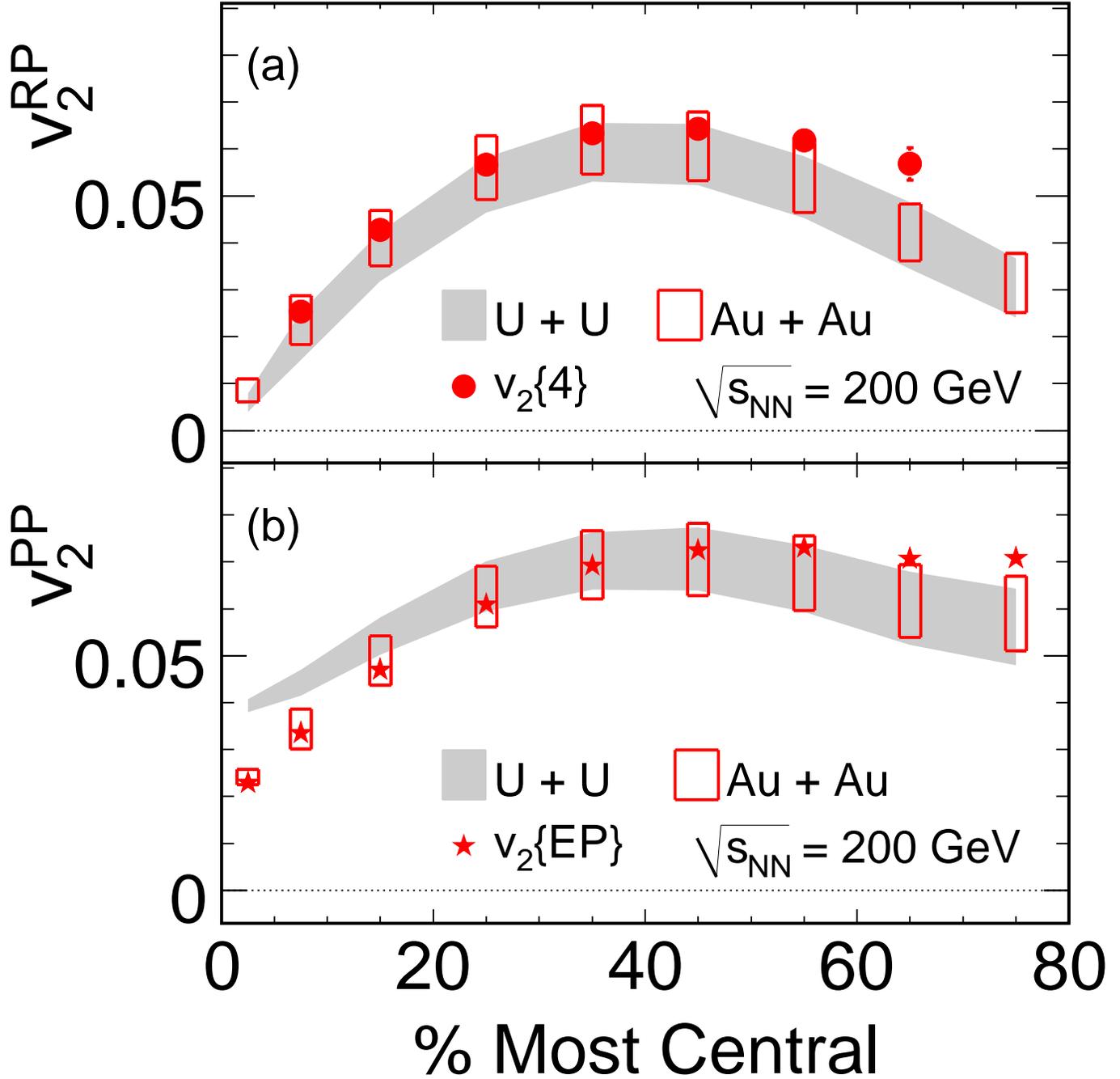


Figure 4: (Color online) (a) The  $v_2^{\text{RP}}$  as a function of centrality. Solid circles is the  $v_2\{4\}$ , open boxes and shaded band show the extracted  $v_2$  from the fitting of  $v_2/\langle\varepsilon_{\text{RP}}\rangle$  and  $\langle\varepsilon_{\text{RP}}\rangle$  in Monte Carlo Glauber simulation in Au + Au and U + U collisions, respectively. (b) The same comparison of  $v_2^{\text{PP}}$  with  $\varepsilon_{\text{PP}}\{2\}$  as (a), where solid stars are the  $v_2\{\text{EP}\}$ . The errors on the  $v_2$  include systematic errors from Monte Carlo Glauber simulation and errors from fitting of  $v_2/\varepsilon$ .

collisions. The larger  $v_2$  is attributed to the larger participant eccentricity due to the ground-state deformation in top 0-10% centrality in U + U collisions compared to that in Au + Au collisions. The extracted  $v_2$  in Au + Au collisions are slightly smaller than the data at peripheral collisions. Since the  $dN_{\text{ch}}/d\eta$  has been tuned to reproduce the PHOBOS results and is smaller than the STAR  $dN_{\text{ch}}/dy$  at peripheral 60-80%, the resulting  $v_2/\varepsilon$  (and hence the  $v_2$ ) become smaller than the STAR  $v_2$ .

### 3.2. Nuclear modification factor $R_{AA}$

The integrated  $R_{AA}$  over a certain  $p_T$  range in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV has been described by  $R_{AA} = (1 - S_0 N_{\text{part}}^a)^{n-2}$ , where  $n = 8.1$  is the power-law exponent of  $p_T$  distribution, and  $S_0 = (9.0 \pm 6.1) \times 10^{-3}$  and  $a = 0.57 \pm 0.14$  for  $N_{\text{part}} > 20$  and  $p_T > 5$  GeV/c [15]. We have assumed that the path length  $\langle L \rangle$  determines the  $R_{AA}$  in both Au + Au and U + U collisions. The  $R_{AA}$  in U + U collisions has been extrapolated by fitting the  $R_{AA}(L)$  in Au + Au collisions with an ansatz from above equation

$$R_{AA}(L) = (1 - S'_0 \langle L \rangle^b)^{n-2}, \quad (12)$$

where  $n = 8.1$ ,  $S'_0$  and  $b$  are free parameters that have been evaluated by fitting the data.

Figure 5 shows integrated  $R_{AA}$  for  $p_T > 5$  GeV/c from [15] as a function of  $\langle L \rangle$  in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. We have assumed that the definition of our centrality bins is the same as that of the PHENIX in order to plot the  $R_{AA}$  as a function of  $\langle L \rangle$  for each centrality. Result of the fit with Eq. (12) is shown by the solid line in Fig. 5 and holds quite well over entire range of  $\langle L \rangle$  since the  $\langle L \rangle$  scales like  $N_{\text{part}}^{1/3}$ .

Figure 6 shows integrated  $R_{AA}$  as a function of  $N_{\text{part}}$  extrapolated for U + U collisions at  $\sqrt{s_{NN}} = 200$  GeV. The  $R_{AA}$  in U + U collisions has been evaluated for a given  $\langle L \rangle$  in each centrality. The calculated  $R_{AA}$  in Au + Au collisions (open boxes) is consistent with the data within the systematic error as it should. We found that the  $R_{AA}$  reaches  $\sim 0.1$  at most central U + U collisions, which is by a factor of 2 more suppression compared to the central Au + Au collisions due to the larger size and the deformation of Uranium. Heinz and Kuhlman pointed out in [19] that the radiative energy loss  $\Delta E$  of a fast parton moving through the medium is almost independent of the orientations of nuclei for the out-of-plane direction in the full overlap U + U collisions. Whereas the  $\Delta E$  in the in-plane direction decreases by about 35% towards the ideal body-body collisions (head-on collisions along the shortest axes). For the body-body collisions, they found that the difference of  $\Delta E$  between out-of-plane and in-plane directions is more than twice in U + U collisions that achieved in Au + Au collisions. They also found that the total energy loss is larger by up to a factor of 2. More differential study, such as selecting the orientations of Uranium and directions with respect to the reaction plane, will be needed to see whether the  $R_{AA}$  would have such dependences or not. Since the  $\langle L \rangle$  in U + U collisions is slightly larger ( $\sim 3\%$  in central, and  $\sim 5\%$  in peripheral collisions) than that in Au + Au collisions, the  $R_{AA}$  in U + U collisions would be even more suppressed for a given  $N_{\text{part}}$ . Due to the large errors on the extrapolated  $R_{AA}$ , we have not observed any difference of the  $R_{AA}$  between Au + Au and U + U collisions for a given  $N_{\text{part}}$ .

## 4. Summary

In summary, we have predicted the  $v_2$  and  $R_{AA}$  in U + U collisions at  $\sqrt{s_{NN}} = 200$  GeV by a simple geometrical approach with the Monte Carlo Glauber simulation. We found that the  $v_2^{\text{RP}}$  is consistent

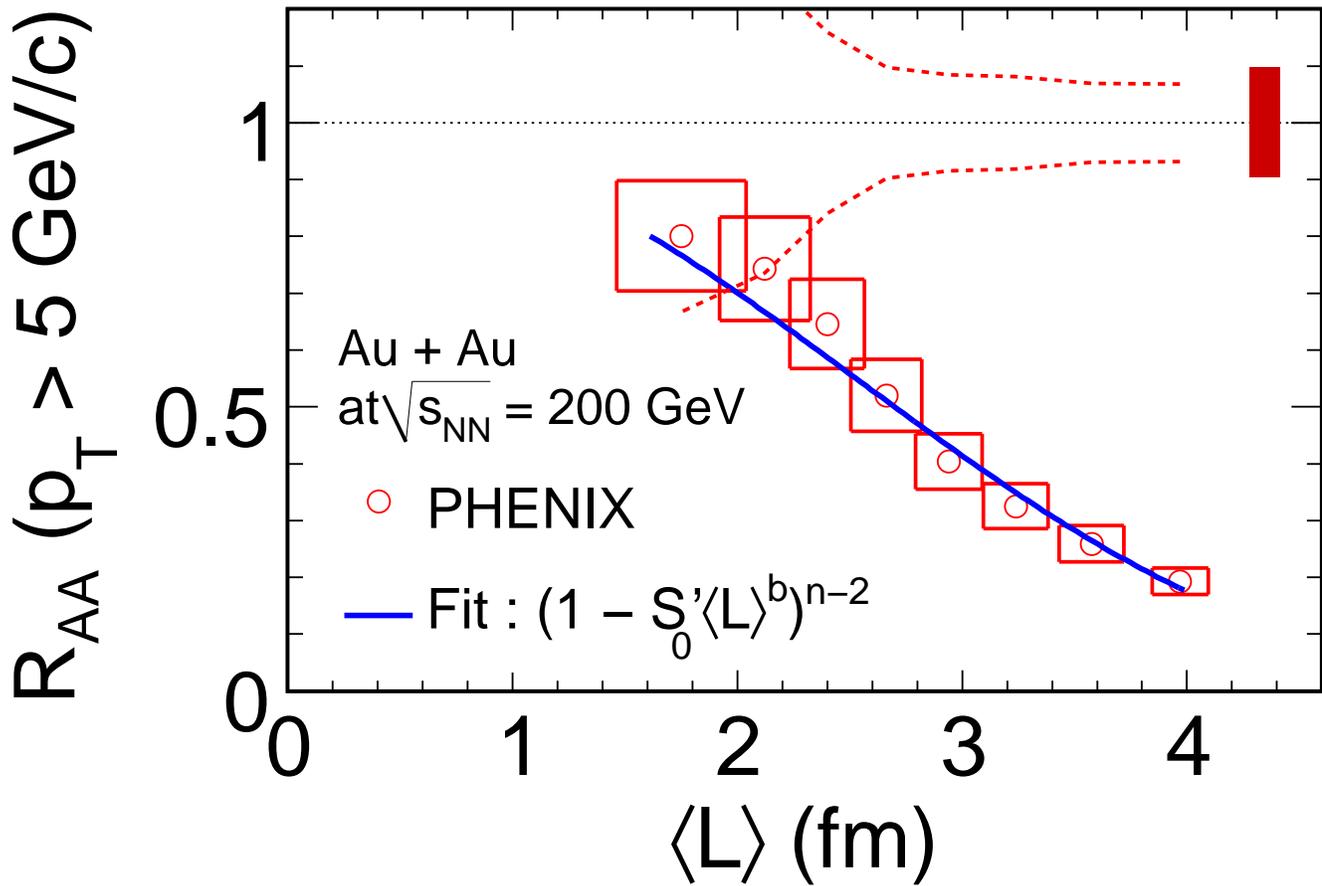


Figure 5: (Color online) Integrated  $R_{AA}$  above  $p_T > 5 \text{ GeV}/c$  [15] as a function of  $\langle L \rangle$  in Au + Au collisions at  $\sqrt{s_{NN}} = 200 \text{ GeV}$ . Most central bin denote 0-10% rather than 0-5%. Statistical and  $p_T$ -uncorrelated errors are smaller than symbols. Open boxes are the errors on  $\langle L \rangle$  in x axis and  $p_T$ -correlated systematic errors on the  $R_{AA}$  in y axis. The dashed lines and the single box on right at unity show the errors on  $N_{\text{coll}}$  and normalization of the  $p + p$  reference, respectively [15]. Solid line is the fitting result by Eq. (12).

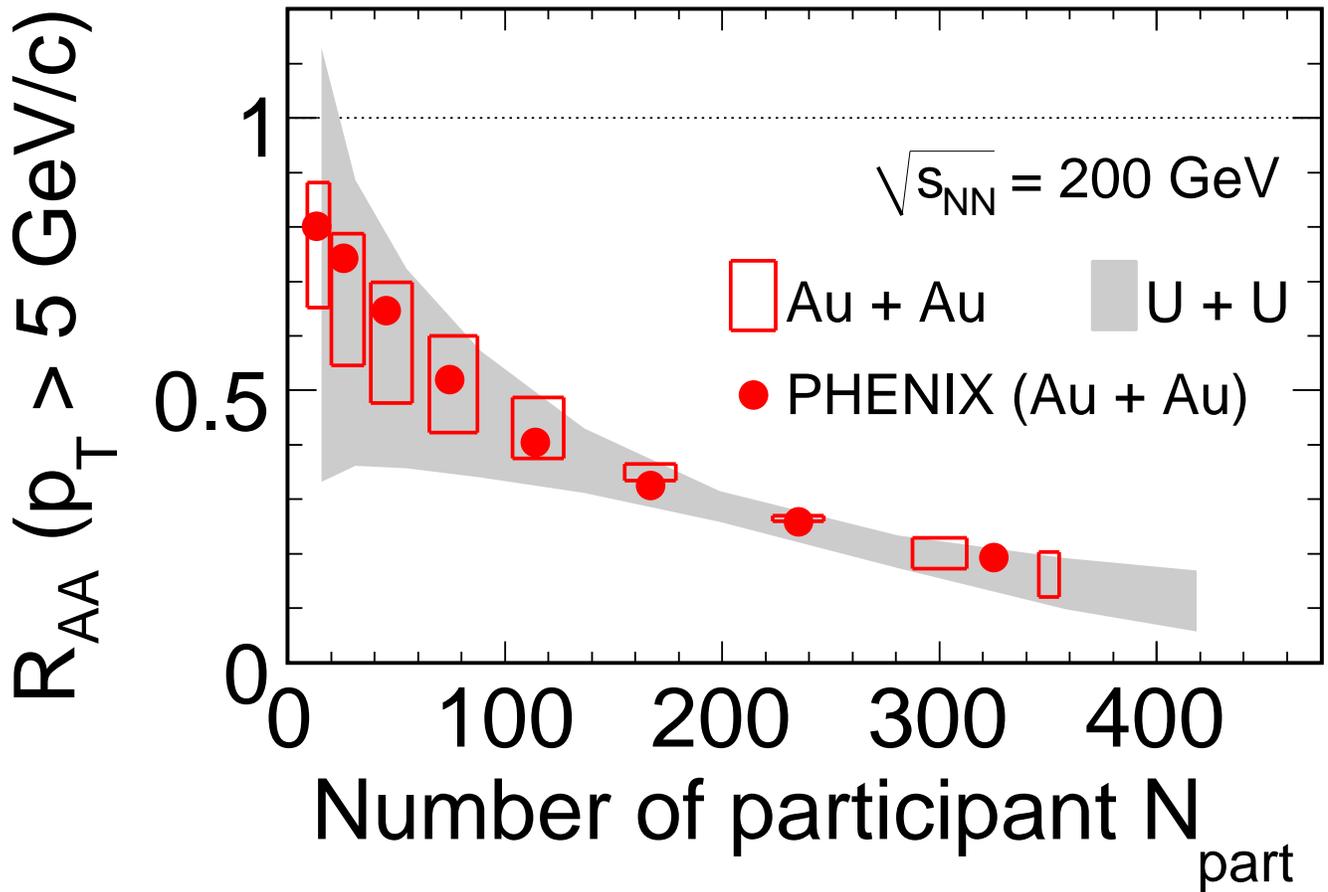


Figure 6: (Color online) Integrated  $R_{AA}$  as a function of  $N_{part}$  at  $\sqrt{s_{NN}} = 200 \text{ GeV}$ , where open boxes and shaded bands show the  $R_{AA}$  extrapolated by Monte Carlo Glauber simulation in Au + Au and U + U collisions, respectively. Fitting error and systematic errors from Monte Carlo Glauber simulation have been included. Additional error from  $N_{coll}$  has also been included in U + U collisions. The result in Au + Au at  $\sqrt{s_{NN}} = 200 \text{ GeV}$  from PHENIX experiment (solid circles) [15] are plotted for comparison.

with that in Au + Au collisions over all centrality range, whereas the  $v_2^{\text{PP}}$  increase by 30-60% at most central 0-10% collisions due to the larger  $\varepsilon_{\text{PP}}\{2\}$  in U + U collisions. The  $R_{AA}$  at top 5% central U + U collisions further suppressed and reaches  $\sim 0.1$ , which is by a factor of 2 more suppression compared to the most central Au + Au collisions. It is clear that the larger mass and deformation form the U nucleus will allow us to study the matter at higher density. By selecting the relative orientation of the colliding Uranium nuclei, the discussed effects may be further enhanced. We will report the method in a separate paper.

## Acknowledgements

We thank Peter Filip and Art Poskanzer for discussions. The work is supported in part by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

## References

- [1] K. H. Ackermann *et al.* [STAR Collaboration], Phys. Rev. Lett. **86**, 402 (2001)
- [2] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 022301 (2002)
- [3] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **77**, 054901 (2008)
- [4] K. Dusling and D. Teaney, Phys. Rev. C **77**, 034905 (2008)
- [5] H. Song and U. W. Heinz, Phys. Rev. C **77**, 064901 (2008)
- [6] M. Luzum and P. Romatschke, Phys. Rev. C **78**, 034915 (2008) [Erratum-ibid. C **79**, 039903 (2009)]
- [7] P. Huovinen and D. Molnar, Phys. Rev. C **79**, 014906 (2009)
- [8] G. Policastro, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **87**, 081601 (2001)
- [9] P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005)
- [10] S. A. Voloshin [STAR Collaboration], J. Phys. G **34**, S883 (2007)
- [11] H. Heiselberg and A. M. Levy, Phys. Rev. C **59**, 2716 (1999)
- [12] S. A. Voloshin and A. M. Poskanzer, Phys. Lett. B **474**, 27 (2000)
- [13] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **97**, 152301 (2006)
- [14] B. I. Abelev *et al.* [STAR Collaboration], Phys. Lett. B **655**, 104 (2007)
- [15] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **101**, 232301 (2008)
- [16] C. Nepali, G. Fai and D. Keane, Phys. Rev. C **73**, 034911 (2006).
- [17] J. G. Alessi *et al.*, *In the Proceedings of Particle Accelerator Conference (PAC 05), Knoxville, Tennessee, 16-20 May 2005, pp 363.*

- [18] K. Hagino, N. W. Lwin and M. Yamagami, Phys. Rev. C **74**, 017310 (2006)
- [19] U. W. Heinz and A. Kuhlman, Phys. Rev. Lett. **94**, 132301 (2005)
- [20] P. Moller, J. R. Nix, W. D. Myers and W. J. Swiatecki, Atom. Data Nucl. Data Tabl. **59**, 185 (1995)
- [21] P. Filip, N. Xu, R. Lednicky and H. Masui, *in preparation*. (2009)
- [22] D. Kharzeev and M. Nardi, Phys. Lett. B **507**, 121 (2001)
- [23] B. B. Back *et al.* [PHOBOS Collaboration], Phys. Rev. C **70**, 021902 (2004)
- [24] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **76**, 034904 (2007)
- [25] R. S. Bhalerao, J. P. Blaizot, N. Borghini and J. Y. Ollitrault, Phys. Lett. B **627**, 49 (2005)
- [26] H. J. Drescher, A. Dumitru, C. Gombeaud and J. Y. Ollitrault, Phys. Rev. C **76**, 024905 (2007)
- [27] N. Borghini, P. M. Dinh and J. Y. Ollitrault, Phys. Rev. C **63**, 054906 (2001)
- [28] N. Borghini, P. M. Dinh and J. Y. Ollitrault, Phys. Rev. C **64**, 054901 (2001)
- [29] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998)
- [30] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **79**, 034909 (2009)
- [31] J. Adams *et al.* [STAR Collaboration], Phys. Rev. C **72**, 014904 (2005)
- [32] S. A. Voloshin, A. M. Poskanzer, A. Tang and G. Wang, Phys. Lett. B **659**, 537 (2008)
- [33] B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. C **77**, 014906 (2008)
- [34] J. Y. Ollitrault, A. M. Poskanzer and S. A. Voloshin, arXiv:0904.2315 [nucl-ex].
- [35] C. Adler *et al.* [STAR Collaboration], Phys. Rev. C **66**, 034904 (2002)