Study of nuclear deformation in high energy nuclear collisions

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Supported in part by U.S. DEPARTMENT OF ENERGY | Office of Science

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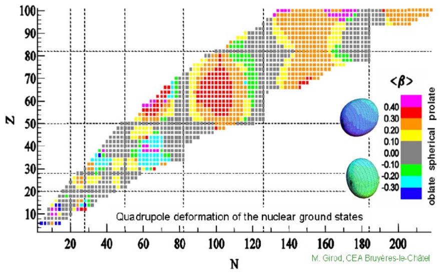
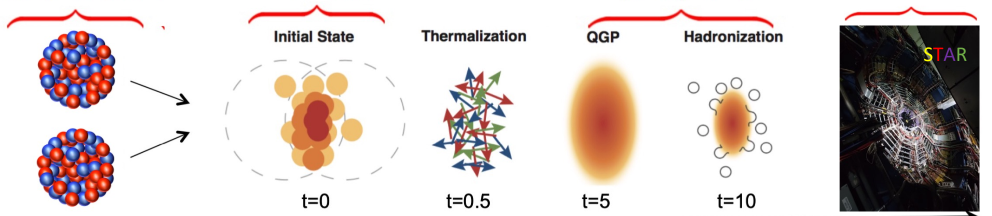
STAR

Heavy-ion collisions and nuclear structure



A. gorgen, Tech. Rep.051, 019(2015); BNL Nuclear Data Center

Nuclear structure | **Initial state** | **Hydrodynamics** | **Collider**



$$\rho(r,\theta,\phi)=\frac{\rho_0}{1+e^{(r-R_0(1+\sum_n \beta_n Y_n^0(\theta,\phi)))/a_0}}$$

- β_2 ▶ Quadrupole deformation
- β_3 ▶ Octupole deformation
- R_0 ▶ Half-density nuclear radius
- a_0 ▶ Surface diffuseness

Initial Size: $R_\perp^2 \propto \langle r_\perp^2\rangle$ Initial Shape: $\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi}\rangle$?

R_0 a_0 β_n

linear hydrodynamic response

$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

Radial flow | Anisotropic flow

$$\frac{d^2N}{d\phi dp_T}=N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$$

Observables

Anisotropic flow

$$v_n\{2\}=\sqrt{c_n\{2\}}=\sqrt{\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle}$$

Pearson correlation coefficient

$$\mathrm{cov}(v_n^2,[p_T])\equiv\left\langle\frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i}e^{-in\phi_j}(p_{T,k}-\langle\langle p_T\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k}\right\rangle_{\mathrm{evt}}$$

$$\rho(v_n^2,[p_T])=\frac{\mathrm{cov}(v_n^2,[p_T])}{\sqrt{\mathrm{Var}(v_n^2)_{\mathrm{dyn}}\langle\delta p_T\delta p_T\rangle}}$$

$$\mathrm{Var}(v_n^2)_{\mathrm{dyn}}=v_n\{2\}^4-v_n\{4\}^4$$

$$\langle\delta p_T\delta p_T\rangle=\left\langle\frac{\sum_{i\neq j} w_i w_j (p_{T,i}-\langle\langle p_T\rangle\rangle)(p_{T,j}-\langle\langle p_T\rangle\rangle)}{\sum_{i\neq j} w_i w_j}\right\rangle_{\mathrm{evt}}$$

Mean transverse momentum fluctuations

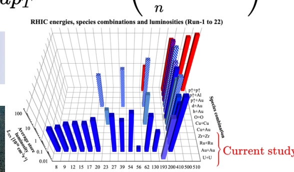
Mean : $[p_T]\equiv\frac{\sum_i w_i p_{T,i}}{\sum_i w_i}, \langle\langle p_T\rangle\rangle\equiv\langle[p_T]\rangle_{\mathrm{evt}}$

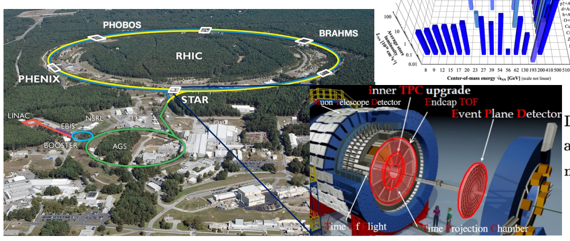
Variance : $\langle\delta p_T\delta p_T\rangle=\left\langle\frac{\sum_{i\neq j} w_i w_j (p_{T,i}-\langle\langle p_T\rangle\rangle)(p_{T,j}-\langle\langle p_T\rangle\rangle)}{\sum_{i\neq j} w_i w_j}\right\rangle_{\mathrm{evt}}$

Skewness : $\langle\delta p_T\delta p_T\delta p_T\rangle=\left\langle\frac{\sum_{i\neq j\neq k} w_i w_j w_k (p_{T,i}-\langle\langle p_T\rangle\rangle)(p_{T,j}-\langle\langle p_T\rangle\rangle)(p_{T,k}-\langle\langle p_T\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k}\right\rangle_{\mathrm{evt}}$

Kurtosis : $\langle\delta p_T\delta p_T\delta p_T\delta p_T\rangle_c=\langle\delta p_T\delta p_T\delta p_T\delta p_T\rangle-3\langle\delta p_T\delta p_T\rangle^2$

STAR Detector

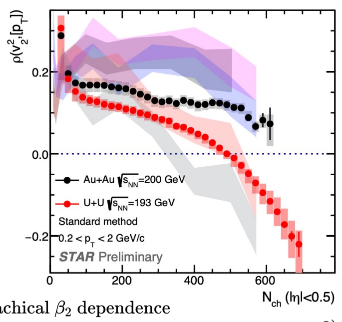


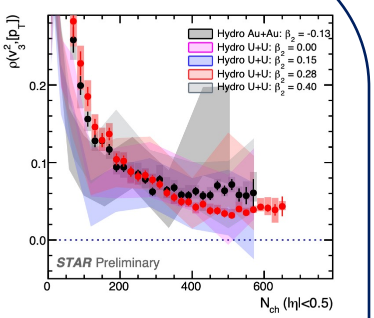


Large uniform acceptance at mid-rapidity

Nuclear deformation in U+U and Au+Au

Highly deformed ^{238}U nuclei





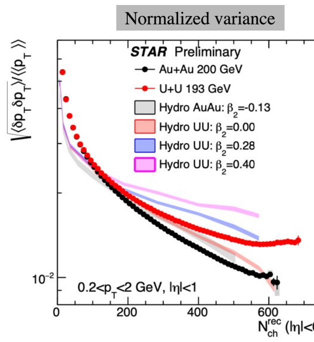
1) Hierachical β_2 dependence

2) Sign-change in central U+U collisions

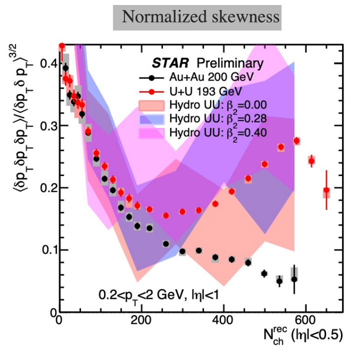
3) Fluctuation-driven $\rho(v_3^2,[p_T])$ are roughly same

Constraint from central data based on hydrodynamics : $\beta_2^{\mathrm{U}}=0.28\pm0.03$

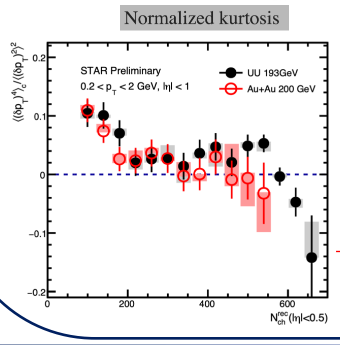
Normalized variance



Normalized skewness



Normalized kurtosis



1) Clear size $-$ $[p_T]$ transmutation : $\frac{1}{R}\rightarrow[p_T]$

enhancement in normalized variance and normalized skewness

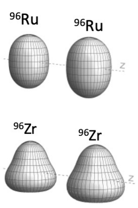
sign-change in normalized kurtosis

2) More dramatic influence in central collisions, but impacts the full centrality range

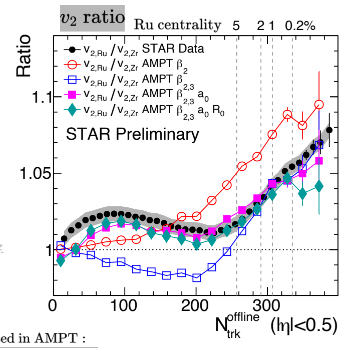
→ Nuclear deformation influences collisions over a wide centrality range

Nuclear structure in Ru+Ru and Zr+Zr

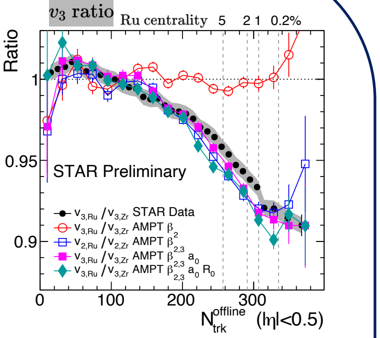
Large quadrupole in ^{96}Ru, large octupole and neutron skin in ^{96}Zr



v_2 ratio



v_3 ratio



Nuclear parameters used in AMPT :

Species	β_2	β_3	a_0(fm)	R_0(fm)
Ru	0.162	0	0.46	5.09
Zr	0.06	0.20	0.52	5.02

Heavy-ion expectation : $v_2^2=a_2+b_2\beta_2^2+b_{2,3}\beta_3^2$, $\quad v_3^2=a_3+b_3\beta_3^2$

$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2}\approx 1+\frac{b_2}{a_2}(\beta_{2,\mathrm{Ru}}^2-\beta_{2,\mathrm{Zr}}^2)-\frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2$$

Cancelation expected in non-central collisions

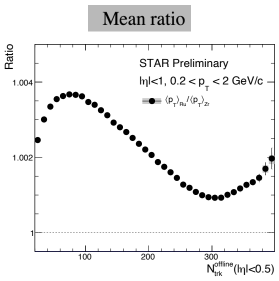
$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2}\approx 1-\frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2<1$$

AMPT extractions:

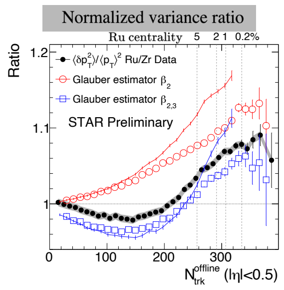
$\beta_2^{\mathrm{Ru}}=0.16\pm0.02$ $\quad\beta_3^{\mathrm{Zr}}=0.20\pm0.02$ $\quad\Delta a_{0,\mathrm{Ru-Zr}}=-0.06$ fm

Direct indication and well constraint on the nuclear deformation

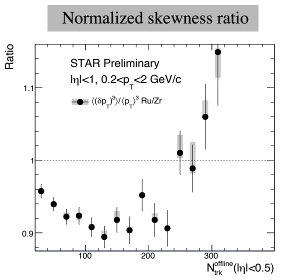
Mean ratio



Normalized variance ratio



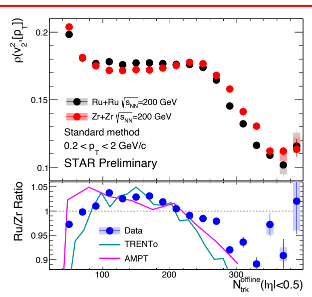
Normalized skewness ratio

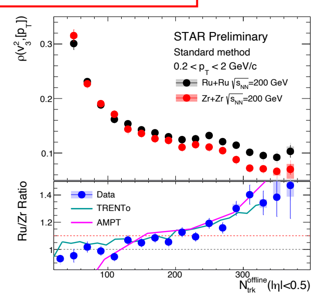


1) Mean : nonmonotonic trend reflects neutron skin and nuclear deformation

2) Normalized variance and skewness : enhancement in mid-central due to $\beta_{2,\mathrm{Ru}}$ and large suppression due to $\beta_{3,\mathrm{Zr}}$

A complementary probe to decipher the Ru and Zr structure





TRENTo assumptions : $v_n\propto\epsilon_n$ $\quad[p_T]\propto\frac{E}{S}$

1) $\rho(v_n^2,[p_T])$ Ru/Zr ratio could also reflect nuclear structure

2) TRENTo and AMPT can reproduce data

Summary and outlook

1) v_n, $[p_T]$ fluctuations, and $\rho(v_n^2,[p_T])$ are sensitive to the nuclear deformation parameters β_n

$$\rho(r,\theta,\phi)=\frac{\rho_0}{1+e^{(r-R_0(1+\sum_n \beta_n Y_n^0(\theta,\phi)))/a_0}}$$

2) Data is qualitatively described by hydrodynamics models

$\beta_2^{\mathrm{U}}=0.28\pm0.03$ $\quad\beta_2^{\mathrm{Ru}}=0.16\pm0.02$ $\quad\beta_3^{\mathrm{Zr}}=0.20\pm0.02$ $\quad\Delta a_{0,\mathrm{Ru-Zr}}=-0.06$ fm

3) Nuclear structure influences collisions over a wide centrality range

β_n : mid-central to central; $\quad a_0$: peripheral to mid-central

4) Data can improve model tuning and provide new ways to probe nuclear structure

References

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