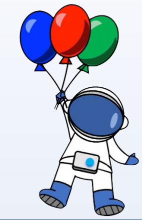

Imaging the shape of atomic nuclei in high energy nuclei collisions from STAR

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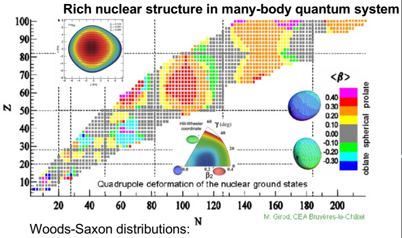
Motivations

Rich nuclear structure in many-body quantum system

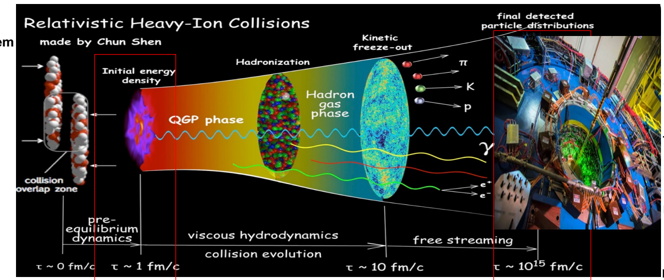


Woods-Saxon distributions:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0(1+\beta_2[\cos\gamma Y_{2,0}(\theta,\phi)+\sin\gamma Y_{2,2}(\theta,\phi)]+\beta_3 Y_{3,0}(\theta,\phi))$$

β_2 - Quadrupole deformation
β_3 - Octupole deformation
γ - Triaxiality
a_0 - Surface diffuseness
R_0 - Nuclear size



Initial shape $\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi}\rangle$

Initial size $R_\perp^2 \propto \langle r_\perp^2\rangle$

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

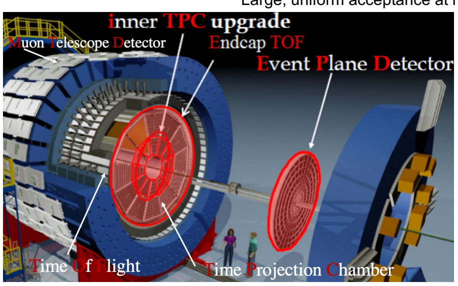
Approximate linear response in each event: $\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$ $\quad V_n \propto \mathcal{E}_n$

Motivations at the intersection of hot QCD and nuclear structure:

- High-energy collisions image nuclear shape at ultra short time scale of 10^{-25} s.
- The collective properties of the nuclear structure leave distinct signatures in the initial and final stages.
- Helps to constrain the initial conditions in heavy ion collisions.
- Reveal the novel properties of many-body nucleon correlation.

STAR detector

Large, uniform acceptance at mid-rapidity



Datasets: U+U @ 193GeV, Au+Au, Ru+Ru and Zr+Zr @ 200 GeV

Measurements are based on the TPC: $|\eta| < 1$, $0.2 < p_T < 2.0$ GeV/c

Centrality is defined by the number of charged particles: N_{ch} ($|\eta| < 0.5$)

Observables

Anisotropic flow v_n:

$$v_2\{2\} \equiv \sqrt{\left\langle e^{in(\phi_i-\phi_j)}\right\rangle}$$

STAR, PRL115, 222301(2015); G. Giacalone, PRL124, 202301(2020)
G. Giacalone, J. Jia and C. Zhang, PRL124, 242301(2021)
C. Zhang and J. Jia, PRL128, 022301(2022)
J. Jia, G. Giacalone and C. Zhang, PRL131, 242301(2023)

$[p_T]$ fluctuations:

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

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

J. Jia, PRC105, 014915(2022)
J. Jia, PRC105, 044905(2022)
S. Bhatta, J. Jia and C. Zhang, PRC105, 024904(2022)

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

Kurtosis: $\left\langle (\delta p_T)^4\right\rangle_c = \left\langle (\delta p_T)^4\right\rangle - 3\left\langle (\delta p_T)^2\right\rangle$

P. Bozek, PRC93, 044908(2016)
B. Schenke, C. Shen and P. Tribedy, PRC102, 044905 (2020)
J. Jia, S. Huang and C. Zhang, PRC105, 014906(2022)

$v_n - [p_T]$ correlations:

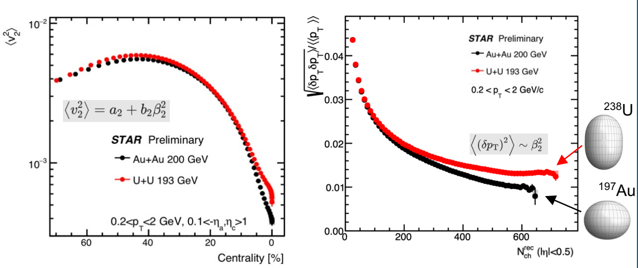
$$\rho(v_n^2,[p_T]) = \frac{\mathrm{cov}(v_n^2,[p_T])}{\sqrt{\mathrm{Var}(v_n^2)_{\mathrm{dyn}}}\sqrt{\langle\delta p_T \delta p_T\rangle}}$$

v_2 variance: $\mathrm{Var}(v_n^2)_{\mathrm{dyn}} = v_n\{2\}^4 - v_n\{4\}^4$

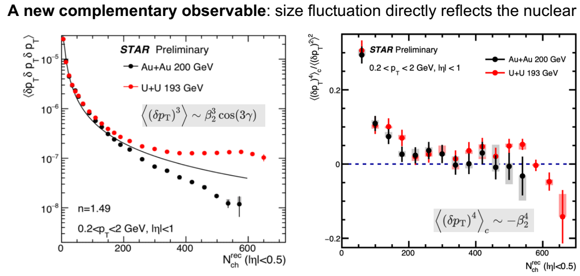
Covariance: $\mathrm{cov}(v_n^2,[p_T]) \equiv \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j}(p_{T,k}-\langle\langle p_T\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k}\right\rangle$

Nuclear deformation in ^{238}U

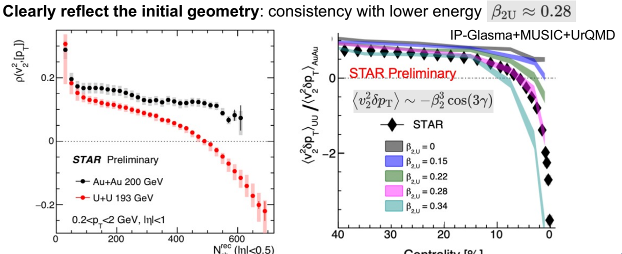
Enhancements from mid-central are due to nuclear deformation



A new complementary observable: size fluctuation directly reflects the nuclear shape

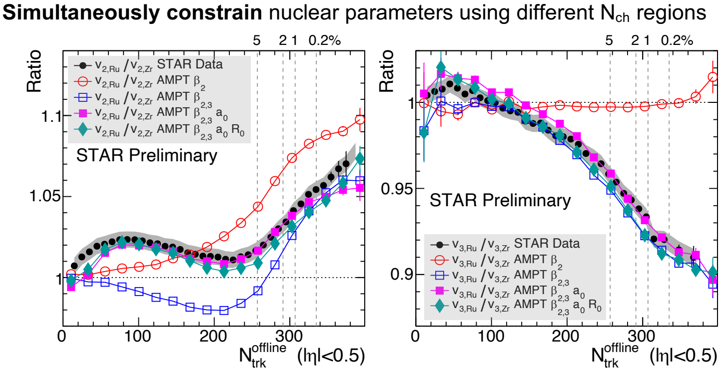


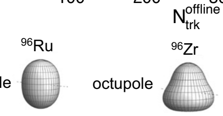
Clearly reflect the initial geometry: consistency with lower energy $\beta_{2U} \approx 0.28$



Nuclear structure in ^{96}Ru and ^{96}Zr

Simultaneously constrain nuclear parameters using different N_{ch} regions





STAR Preliminary

Species	β_2	β_3	a_0	R_0
Ru	0.162	0	0.46 fm	5.09 fm
Zr	0.06	0.20	0.52 fm	5.02 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

-- **Only probe structure differences**

$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a$$

-- **Isobar ratios cancel the final state effect.**

C. Zhang, S. Bhatta and J. Jia, PRC106, L031901(2022)

-- **Precisely constrain the initial conditions by testing different hydrodynamics models.** B. Bally et al., 2209.11042

-- **Nuclear structure affects multipole observables.**

Conclusions

- Collective flow assists imaging of the nuclear shape in high energy nuclei collisions: large particle multiplicity enables many-particle correlation event-by-event to probe many-body nucleon correlations in nuclei (difficult to measure in general in low energy).
  - The synergies have been tested in U+U, Au+Au, Ru+Ru and Zr+Zr collisions.
  - Quantitive extraction of the nuclear parameters via hydrodynamic and transport models.
- Manifestation of nuclear shape at high energy reveals many body nucleon correlations.
  - Constrain the heavy-ion initial conditions.
  - Helpful to understand the nuclear PDF and gluon saturation effect.

NSAC LRP White Paper, 2303.02579
D. Kharzeev et al., PLB523, 79(2001)
D. Kharzeev et al., PLB507, 121(2001)

Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science
Stony Brook University
BNL The STAR experiment at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

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