DNP2022

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Hyatt Regency Hotel, New Orleans, LA

APS physics

Measurement of nuclear deformation in high-energy isobaric ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr collisions at STAR

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For the STAR Collaboration

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Stony Brook University

STAR

On the way to understand the nuclear structure

1911 — Rutherford model

1932 — Femi-gas model

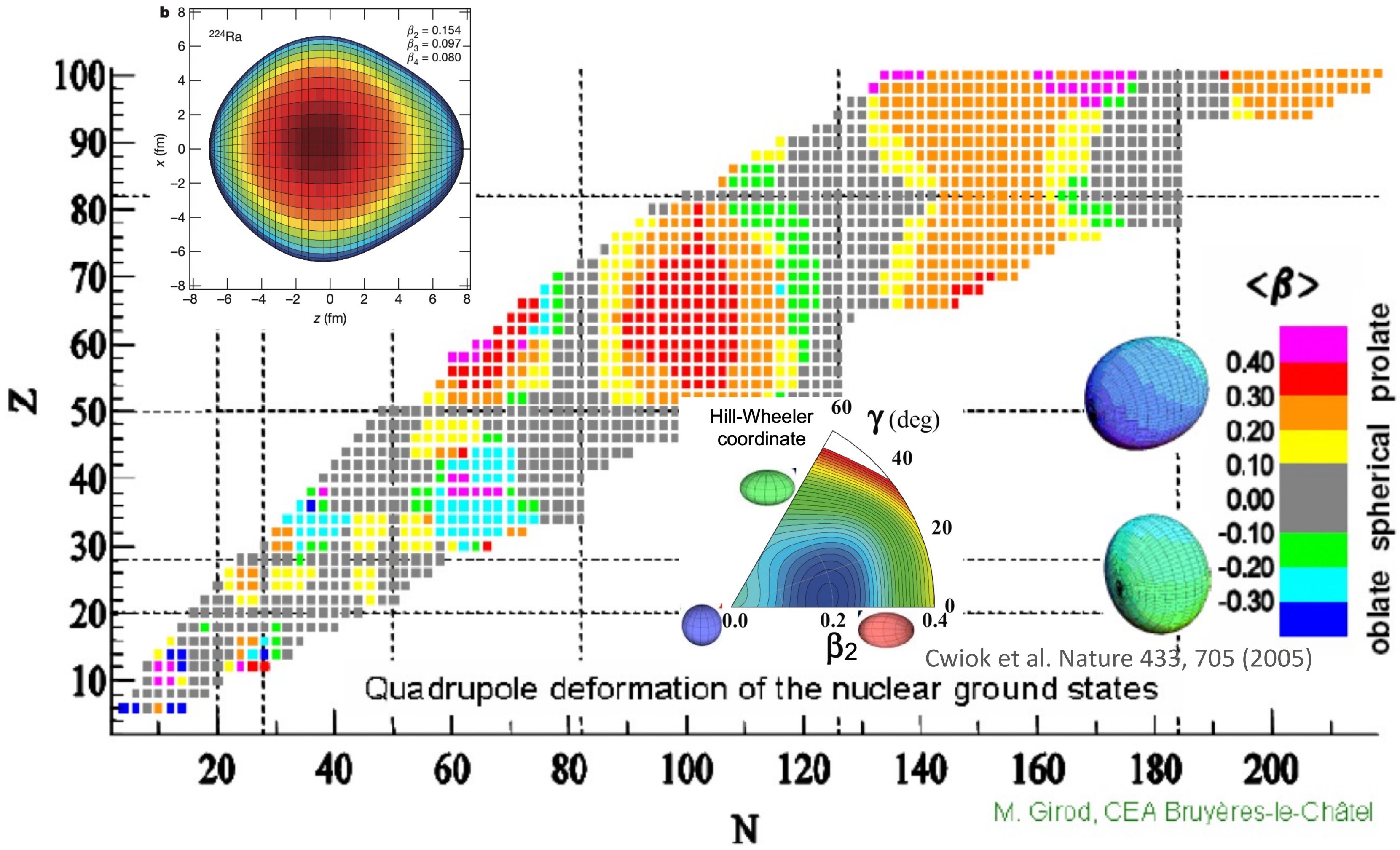
1936 — Liquid drop model

1949 — Shell model 

1953 — Collective model 

Gaffney et al. Nature 497, 199 (2013)

The nuclear landscape

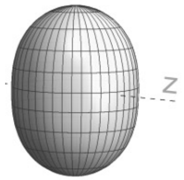


Cwiok et al. Nature 433, 705 (2005)

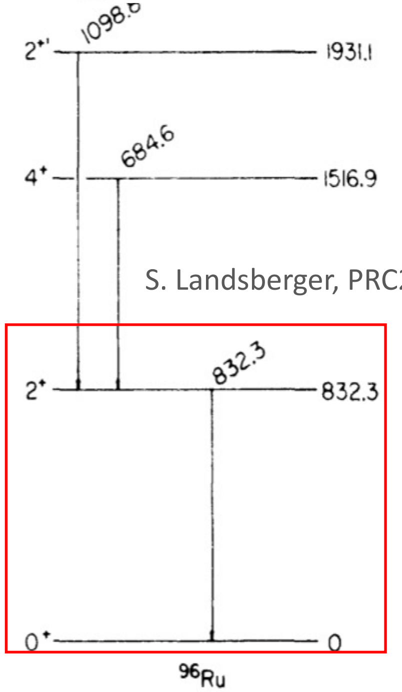
Rich nuclear structure in quantum many-body system

Measurement from lower energy literature and $0\upsilon\beta\beta$ search

^{96}Ru

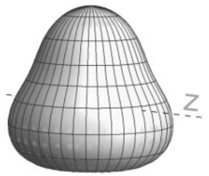


$$\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}}$$

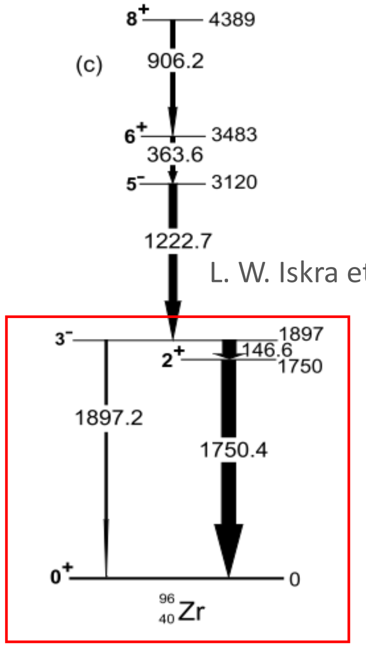


S. Landsberger, PRC21, 2 (1980)

^{96}Zr



$$\beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$$



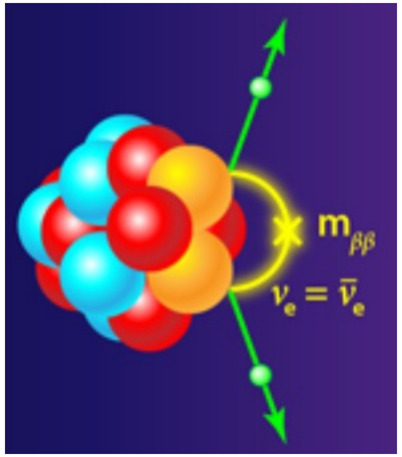
L. W. Iskra et al., PLB 788, 396 (2019)

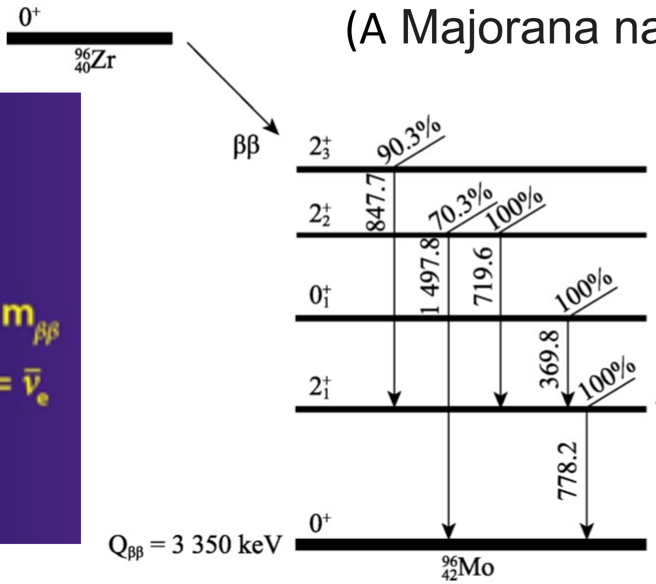
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

^{96}Zr is a good candidate for the $0\nu\beta\beta$ search

$$\left[T_{1/2}^{0v}\right]^{-1} = G^{0v}\left|M^{0v}\right|^2\langle m_{\beta\beta}\rangle^2$$

(A Majorana nature?)





https://physics.aps.org/articles/v11/30

M. Alanssari et al., PRL116, 072501 (2016)

Lower energy experiment data show large $\beta_{2,\mathrm{Ru}}$ and $\beta_{3,\mathrm{Zr}}$

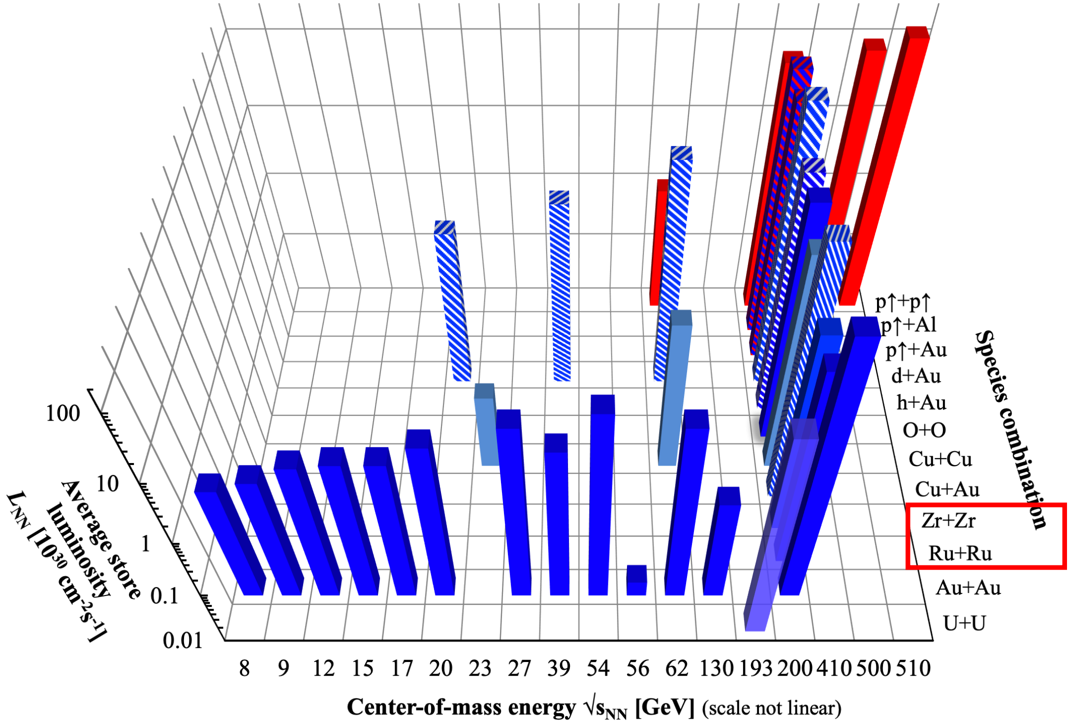
	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90

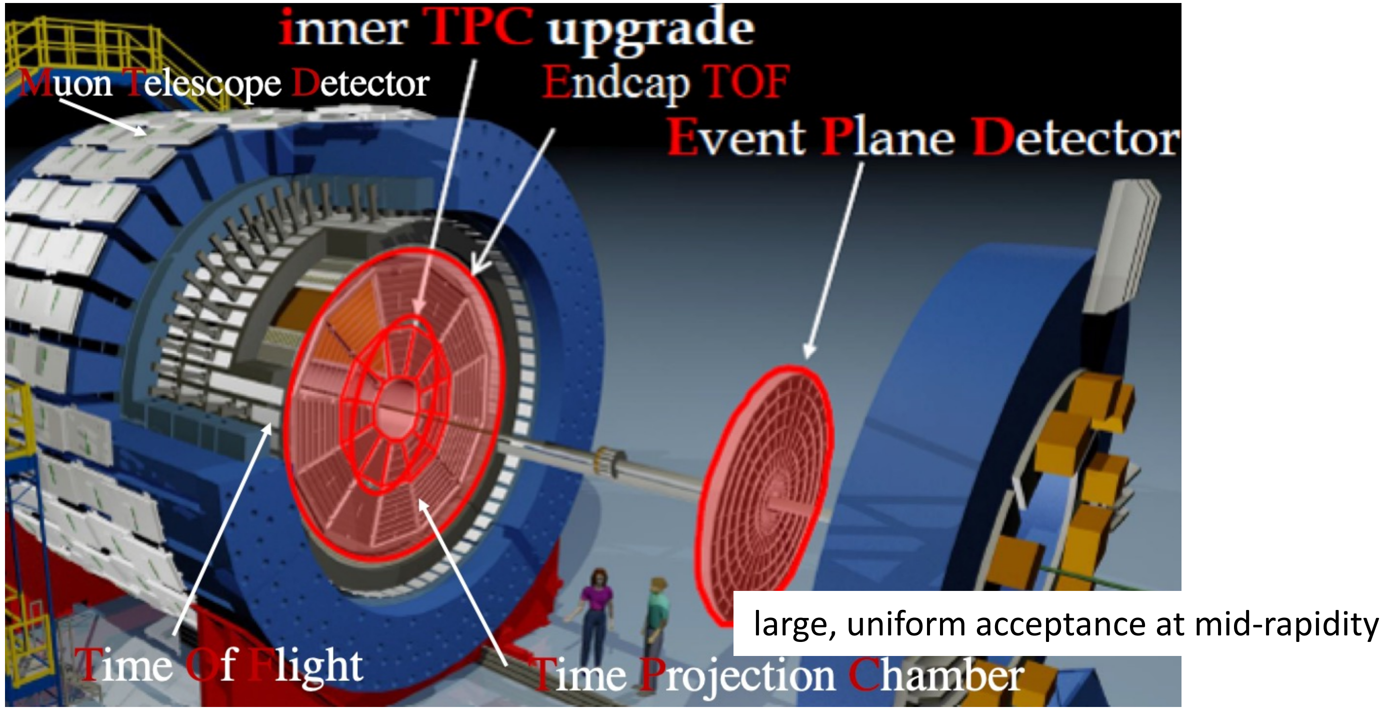
1) **Rarely explored in experiments** and **model dependences**

2) Nuclear structure can affect the β decay and radioactive half-time

Unique isobar runs and the STAR detector

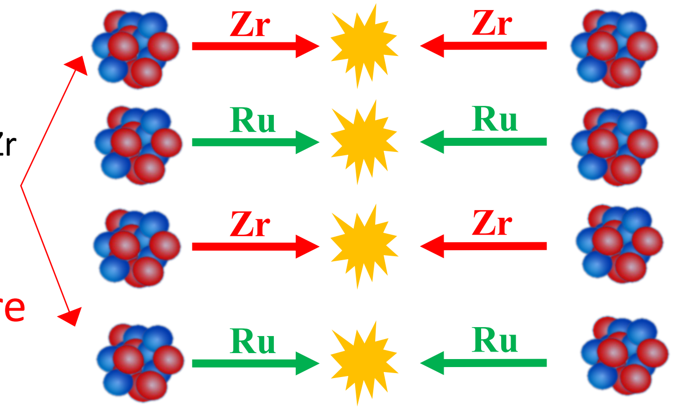
RHIC energies, species combinations and luminosities (Run-1 to 22)





Special operation mode:

- Fill-by-fill switching between Ru+Ru and Zr+Zr
- Similar run conditions at STAR (minimize the systematics)



Ideal systems to study nuclear structure and initial stage: $\frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \stackrel{?}{=} 1$

- Datasets:

  Ru+Ru @200 GeV, Zr+Zr @200 GeV

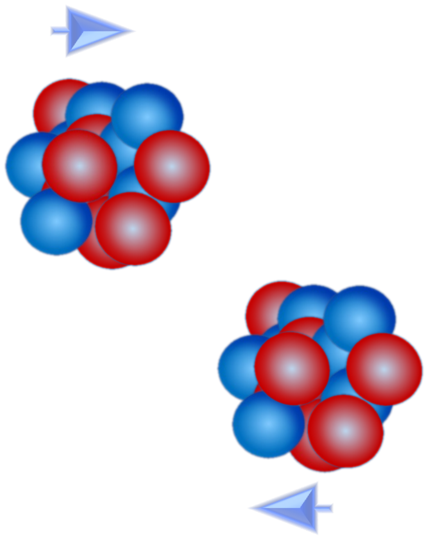
- Measurement based on TPC:

  $|\eta| < 1.0,\ 0.2 < p_T < 2\ \mathrm{GeV}/c$

- Centrality based on uncorrected tracks $N_{ch}^{offline}$ in $|\eta|$< 0.5

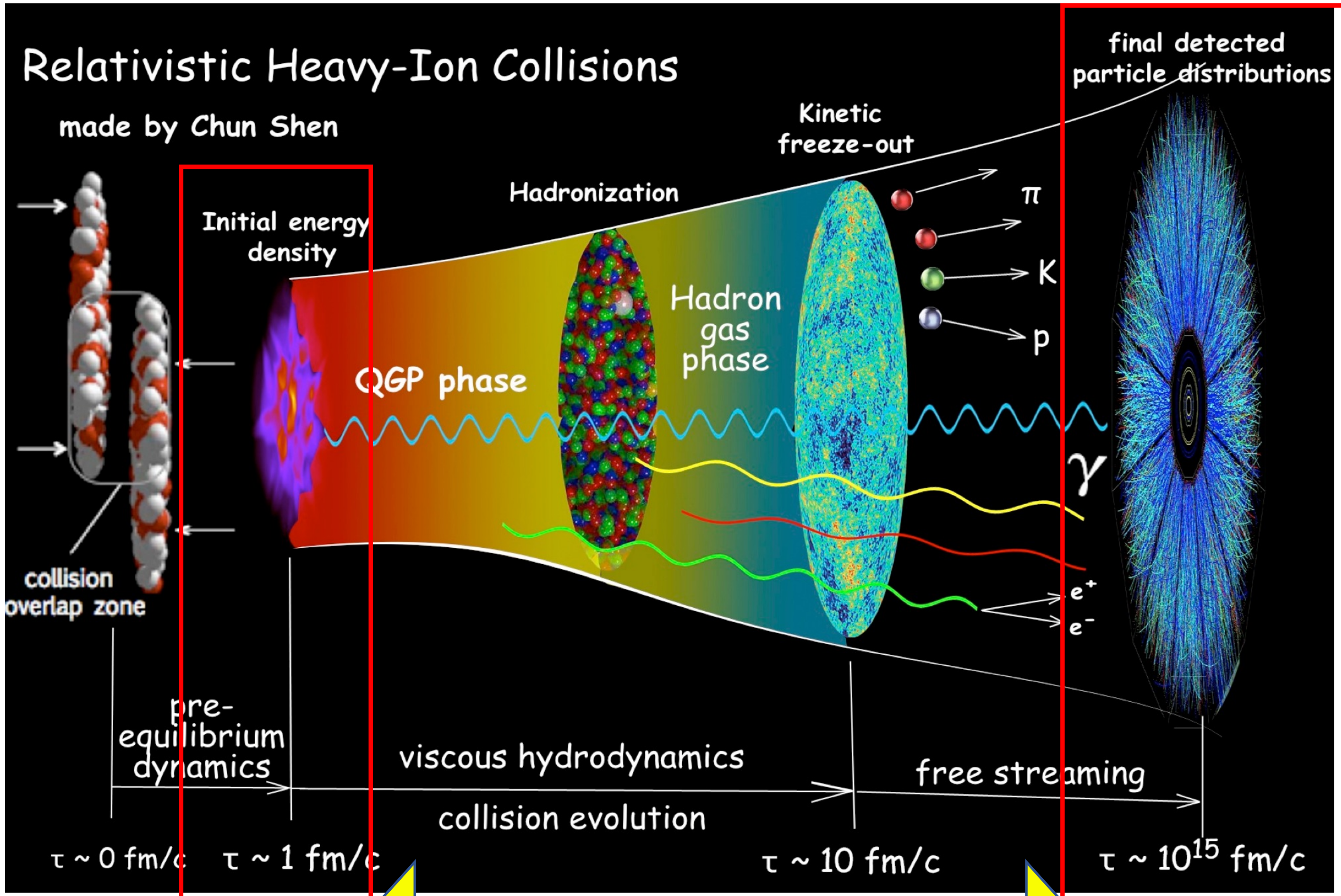
Relativistic heavy-ion collisions and nuclear structure

Nuclear Structure



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

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



Anisotropic flow

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

radial flow

Initial Size: $R_\perp^2 \propto \langle r_\perp^2 \rangle$

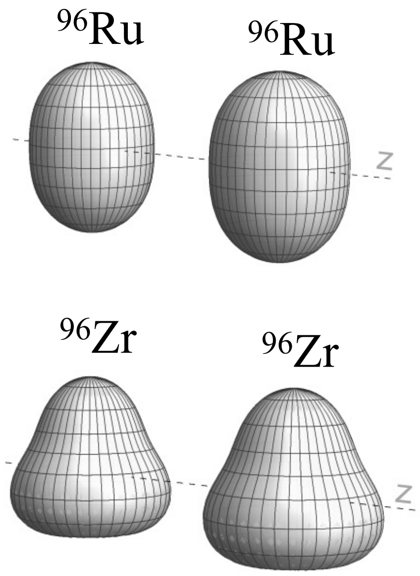
Initial Shape: $\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

?

R_0 a_0 β_n

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

Study nuclear structure via collectivity



$R = 5.09$ fm
$a_0 = 0.46$ fm
$\beta_2 = 0.162$
$\beta_3 \sim 0$

$R = 5.02$ fm
$a_0 = 0.52$ fm
$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

Jia, PRC105, 014905(2022)

Heavy-ion expectation:

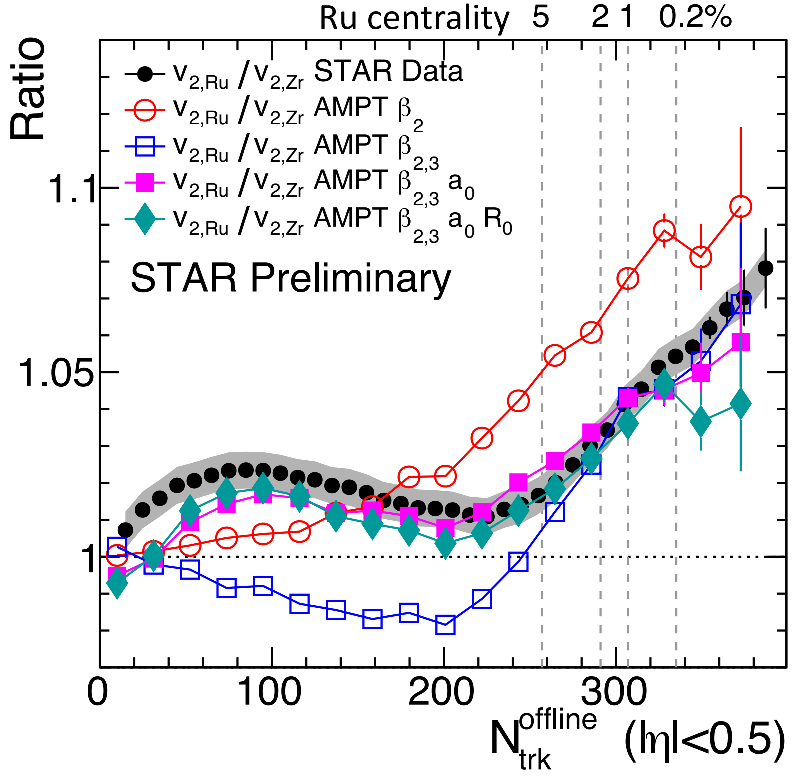
$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

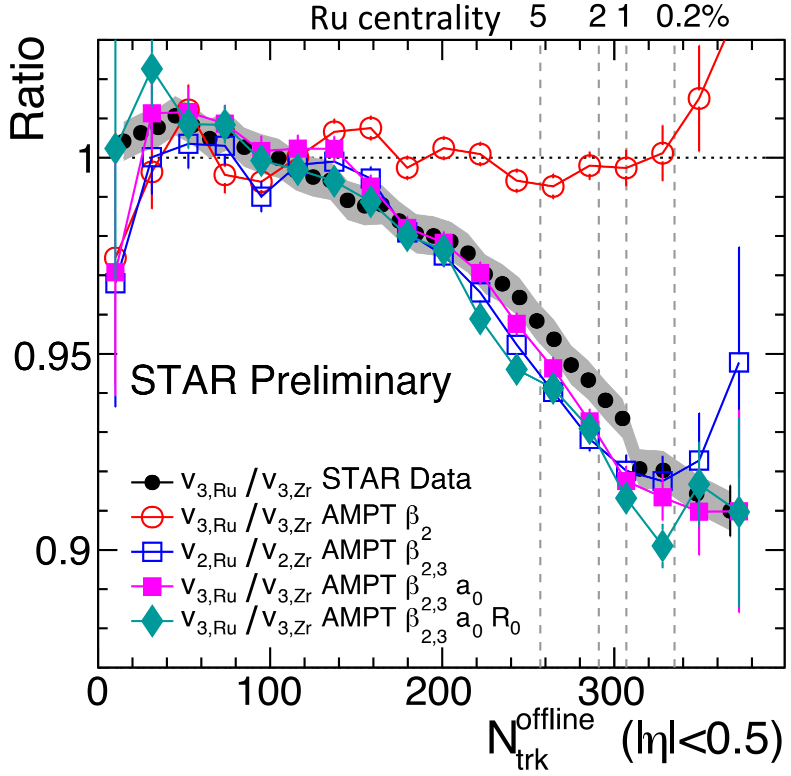
$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2) - \frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2$$

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

Approximate cancellation expected in noncentral collisions

Shou et al., PLB749, 215(2015)
Li et al., PRC98, 054907(2018)
Xu et al., PLB819, 1136453(2021)
Giuliano et al., PRC104, L041903(2021)
Zhang and Jia, PRL128, 022301(2022)





1) v_2 ratio: large $\beta_{2,\mathrm{Ru}}$, negative contribution from $\beta_{3,\mathrm{Zr}}$ ⇒ Sharper increase in central

2) v_3 ratio: strong decrease from $\beta_{3,\mathrm{Zr}}$ with negligible $\beta_{2,\mathrm{Ru}}$ distortion

3) Residual effect due to radial structure, e.g., neutron skin in Zr

4) No significant effect due to nuclear size R_0

✓ The large differences of v_2 and v_3 suggest $\boldsymbol{\beta_{2,Ru} \gg \beta_{2,Zr}}$ **and** $\boldsymbol{\beta_{3,Ru} \ll \beta_{3,Zr}}$.

Direct measurement of octupole deformation in heavy ion collider

Study of nuclear structure via event-by-event fluctuations

Heavy-ion expectation:

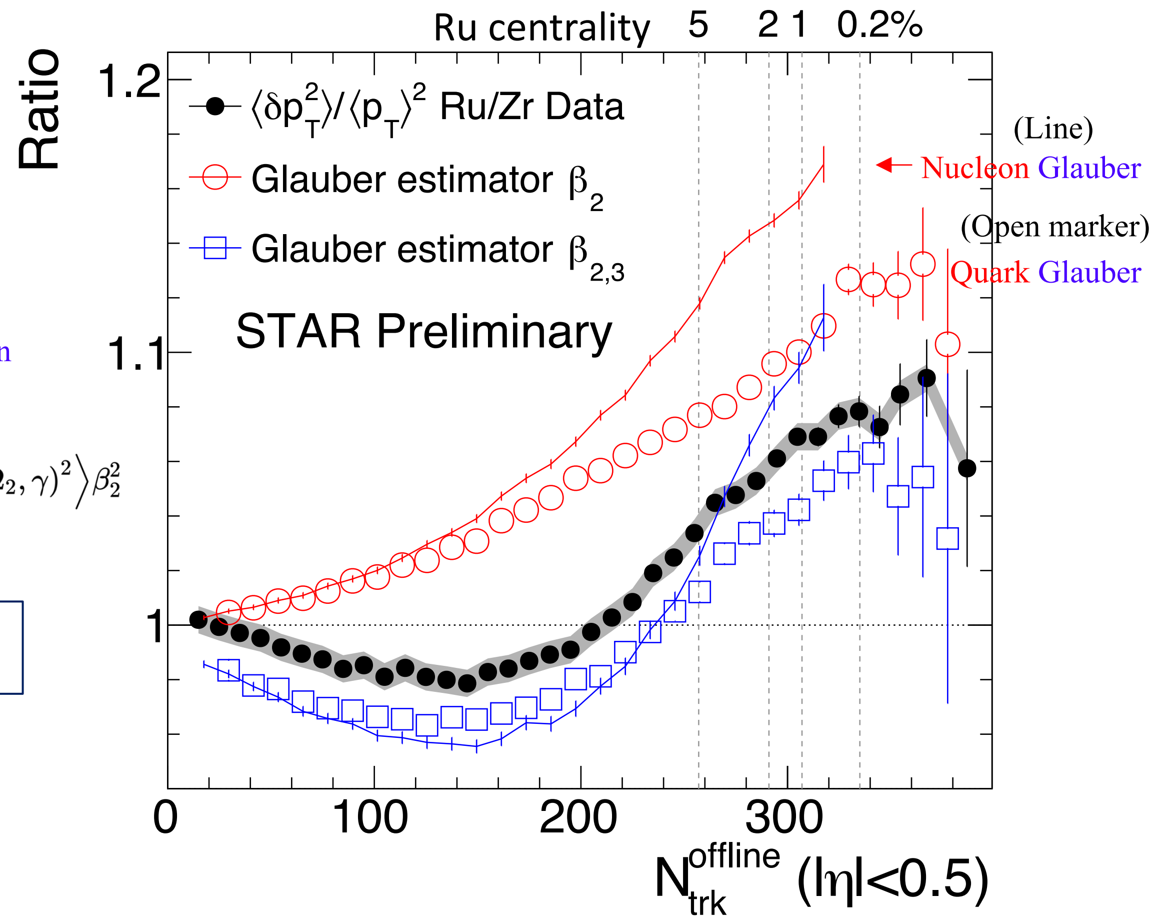
$$\left\langle \left(\delta[p_\mathrm{T}]/[p_\mathrm{T}]\right)^2 \right\rangle = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

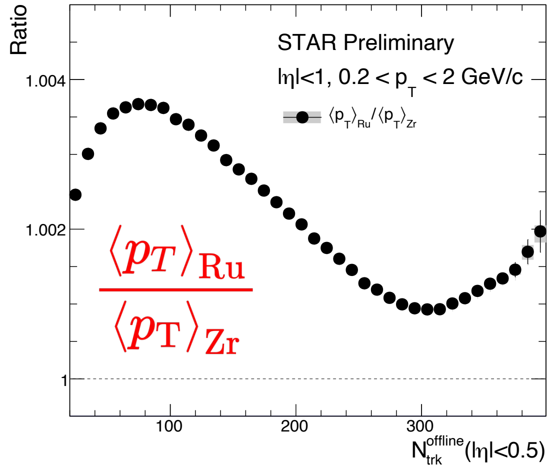
$$\frac{\langle \delta p_T^2 \rangle_{\mathrm{Ru}}}{\langle \delta p_T^2 \rangle_{\mathrm{Zr}}} \approx 1 + \frac{b_0}{a_0}\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right) - \frac{b_{0,3}}{a_0}\beta_{3,\mathrm{Zr}}^2$$

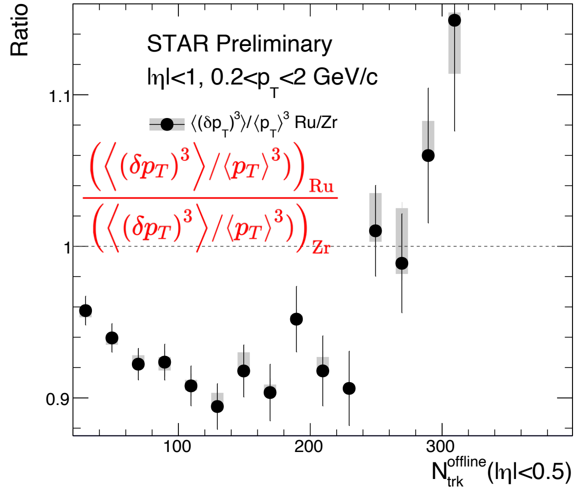
Cancelation expected in non-central collisions

$$\left\langle \left(\delta[p_\mathrm{T}]/[p_\mathrm{T}]\right)^2 \right\rangle \propto \left\langle \left(\delta d_\perp/d_\perp\right)^2 \right\rangle = \langle \delta_d^2 \rangle + \left\langle p_0(\Omega_1,\Omega_2,\gamma)^2 \right\rangle \beta_2^2$$

✓ $\beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}}$ and $\beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}$.







1) Nonmonotonic trend: large suppression in mid-central and increase in central collisions

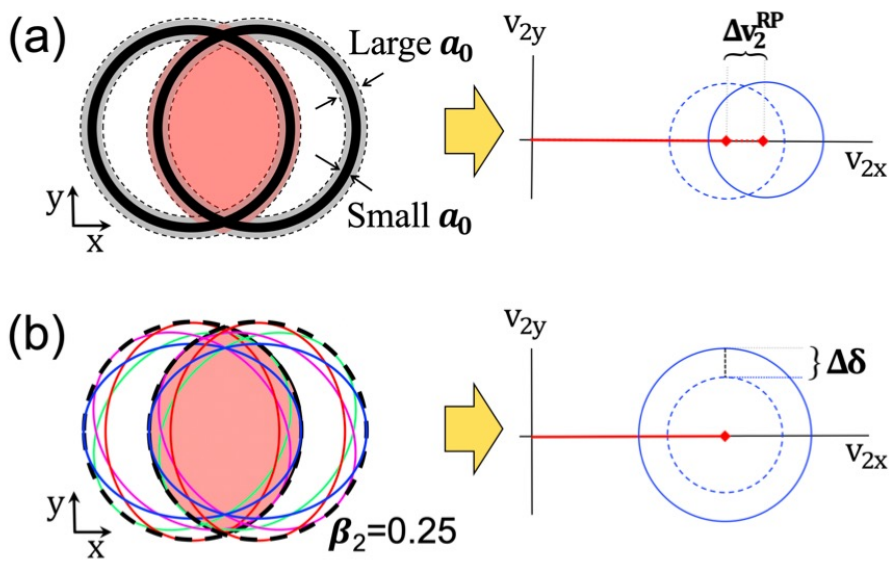
2) Enhancement from mid-central ⇒ larger $\beta_{2,\mathrm{Ru}}$

3) Large suppression in mid-central ⇒ stronger octupole $\beta_{3,\mathrm{Zr}}$

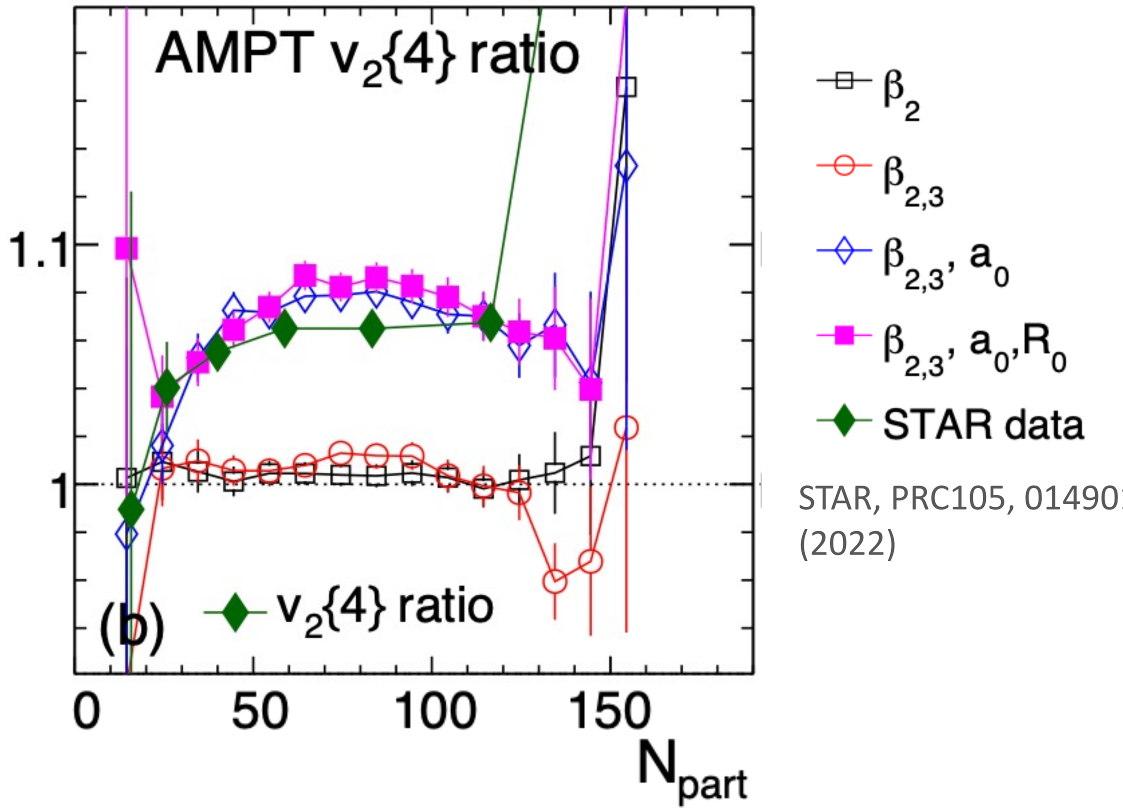
[p_T] fluctuations can also be used to constrain the nuclear deformation.

Separate the impact of neutron skin and nuclear deformation

$v_2\{4\} = v_2\{6\} = \ldots = v_2\{\infty\} = v_2^{\mathrm{rp}}$ $\delta^2 = v_2\{2\}^2 - v_2\{4\}^2$



Jia, Giuliano and Zhang, 2206. 10449



STAR, PRC105, 014901 (2022)

1) Difference in skin thickness between Ru and Zr impacts the intrinsic ellipticity of the collision systems, or elliptic flow relative to reaction-plane, v_2^{rp}.

2) Differences in nuclear deformations impact only the fluctuations of v_2 around v_2^{rp}.

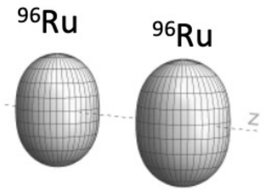
3) This idea is confirmed by the STAR-published data from PRC105, 014901(2022).

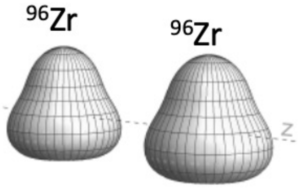
(More investigations using STAR are on the way!)

Conclusions and outlooks

- v_n ratios as **a new probe to constrain** nuclear structure parameters:

AMPT estimation: $\beta_2^{\mathrm{Ru}} = 0.16 \pm 0.02$ $\beta_3^{\mathrm{Zr}} = 0.20 \pm 0.02$ $\Delta a_{0,\mathrm{Ru-Zr}} = -0.06\ \mathrm{fm}$





- Mean p_T fluctuations also serve as a **complementary** probe to decipher nuclear structure:

The nonmonotonic trend with N_{ch} in mean, enhancement in normalized variance and normalized skewness ratios

- **A significant step**: separating the impact of nuclear skin and nuclear deformation on elliptic flow and its fluctuations (more studies on the way!)

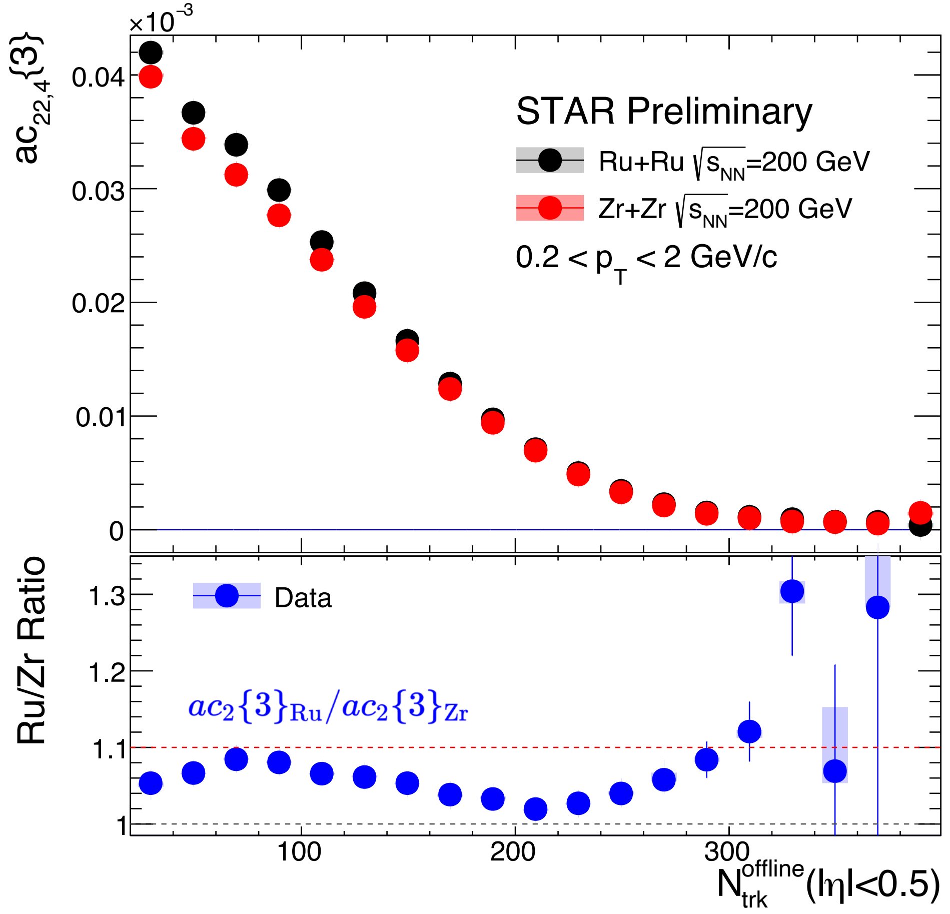
Thank you for your attention and thanks to APS physics

Backup

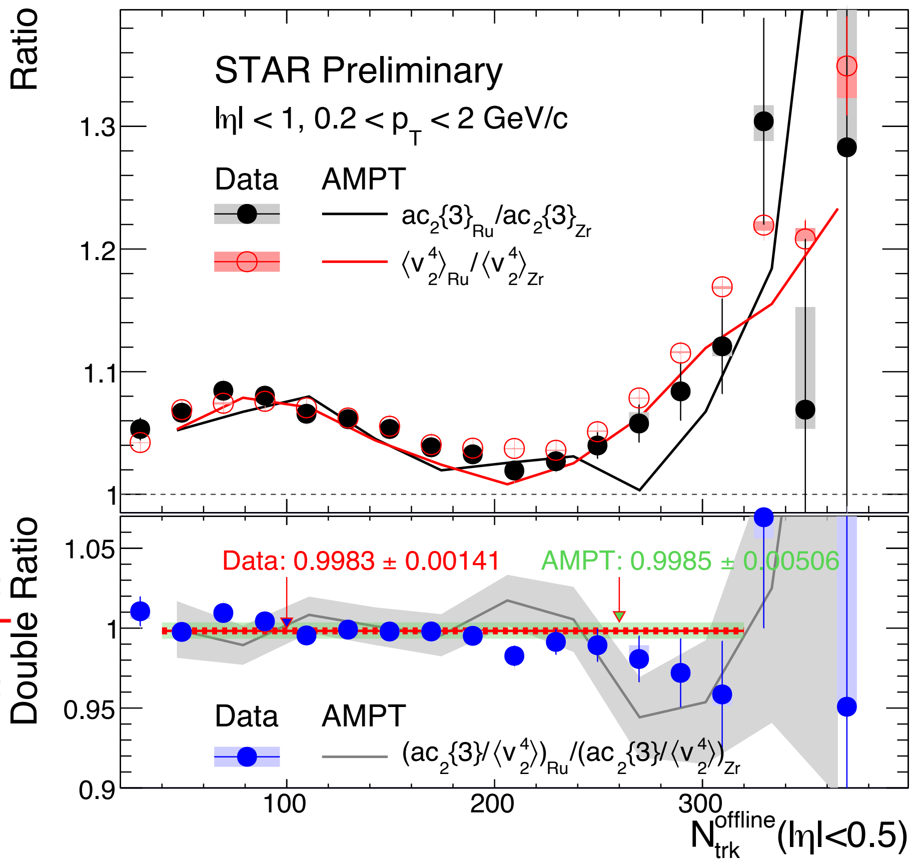
Nonlinear coupling coefficient

Asymmetric cumulant: $\mathrm{ac}_2\{3\} = \langle V_2^2 V_4^* \rangle = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle$

Nonlinear coupling coefficient: $\chi_{4,22} = \dfrac{\langle V_2^2 V_4^* \rangle}{\langle v_2^4 \rangle}$ $\quad V_4 = U_4 + \chi_{4,22} V_2^2$



$$\frac{\chi_{4,22}^{\mathrm{Ru}}}{\chi_{4,22}^{\mathrm{Zr}}}$$



$$\frac{\mathrm{ac}_2\{3\}_{\mathrm{Ru+Ru}}}{\mathrm{ac}_2\{3\}_{\mathrm{Zr+Zr}}} \overset{?}{\approx} \frac{\langle v_2^4 \rangle_{\mathrm{Ru+Ru}}}{\langle v_2^4 \rangle_{\mathrm{Zr+Zr}}}$$

1) AMPT well reproduces data.

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

2) $\chi_{4,22}$: nearly independent of initial state; expected to be identical in final state

(Fitting from 40 to 320)

Nonmonotonic trend: reflect difference in nuclear structure

$$\text{Data}: \frac{\chi_{4,22}^{\mathrm{Ru+Ru}}}{\chi_{4,22}^{\mathrm{Zr+Zr}}} = 0.9983 \pm 0.00141 \qquad \text{AMPT}: \frac{\chi_{4,22}^{\mathrm{Ru+Ru}}}{\chi_{4,22}^{\mathrm{Zr+Zr}}} = 0.9985 \pm 0.00506$$

Nonlinear coupling is comparable between Ru and Zr

Li and Ollitrault, PLB744, 82(2015); Giuliano et al., PRC97, 054905 (2018); Zhao, Xu et al., 2204.02387; Jia et al., 2206.07184