Study of the nuclear deformation at RHIC

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For the STAR Collaboration

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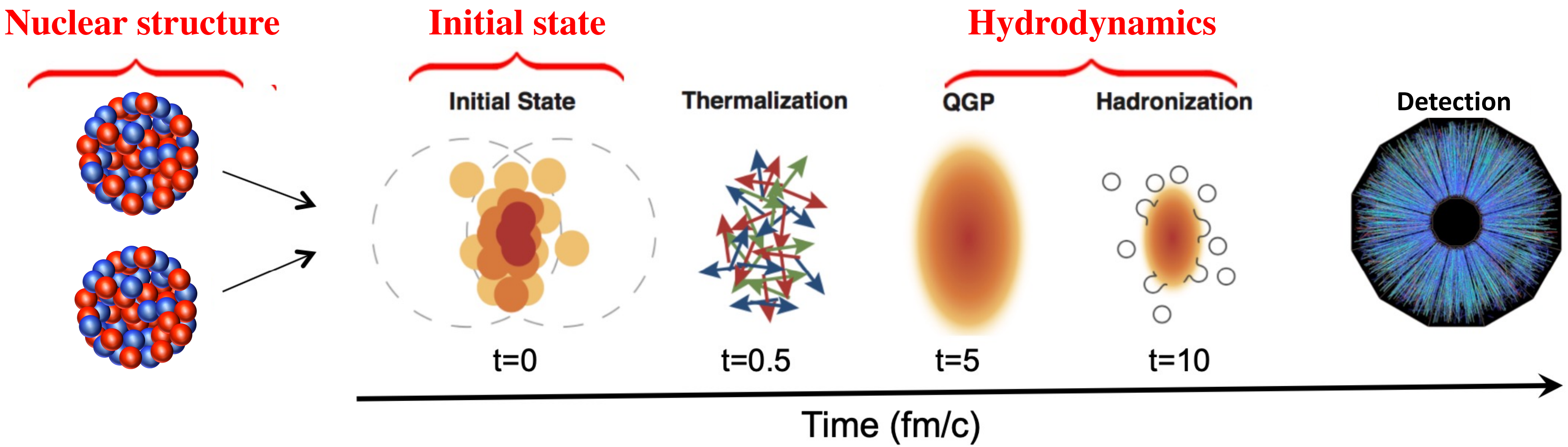
STAR

Heavy-ion collisions and nuclear structure

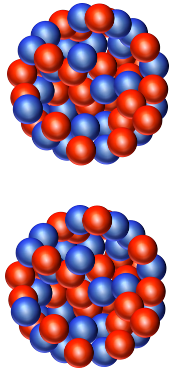


Space-time evolution of heavy-ion collisions can be considered as a hydrodynamic response to the nucleon density distribution in the initial overlap region in the transverse plane, driven by pressure gradient.

The shape and the size of the overlap are controlled by the shape and radial profile of the colliding nuclei.

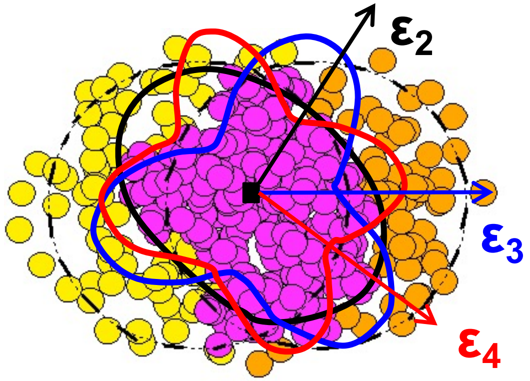
Hydrodynamic response to initial state

Nuclear Structure



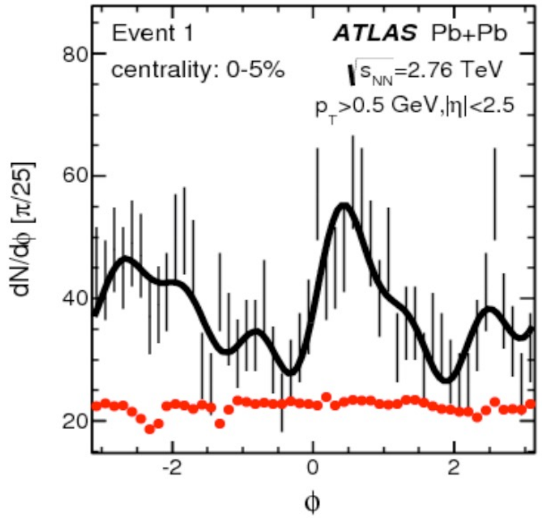
Imaging?

Initial State



hydrodynamic response

Produced Particle Flow



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

$\beta_2 \rightarrow$ Quadrupole

$\beta_3 \rightarrow$ Octupole

Initial Size

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

Initial Shape

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

?

$R_0 \quad a_0 \quad \beta_n$

Radial Flow

Anisotropic Flow

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

D. Teaney et al., arXiv:1206.1905

Approximate linear response in each event:

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

Connecting shape ε_n and size R to β_n

- ε_n **is related to the shape of the Y_n^n projected to the transverse plane**

$$\mathcal{E}_n = -\frac{\langle r_\perp^n e^{in\phi}\rangle}{\langle r_\perp^n\rangle} \propto \langle Y_n^n\rangle = \underbrace{\boldsymbol{\epsilon}_{n;0}}_{\text{Undeformed}} + \underbrace{\boldsymbol{p}_n(\Omega_1,\Omega_2)}_{\text{Phase factor}}\beta_n + \mathcal{O}(\beta_n^2)$$

J. Jia, arXiv:2109.00604

Y_n^n: spherical harmonics

$$\text{Flow variance } \langle v_n^2\rangle \propto \langle \varepsilon_n^2\rangle = \langle \varepsilon_0^2\rangle + \langle \boldsymbol{p}_2(\Omega_1,\Omega_2)\boldsymbol{p}_2^*(\Omega_1,\Omega_2)\rangle\beta_n^2$$

- $R_\perp$ **is related to Y_2^0 projected to the transverse plane**

$$R_\perp^2 = \langle x^2\rangle + \langle y^2\rangle \propto \left\langle 1 - 2\sqrt{\frac{\pi}{5}}Y_2^0\right\rangle$$

$$d_\perp \equiv 1/R_\perp$$

$$\frac{\delta d_\perp}{d_\perp} = \delta_d + p_0(\Omega_1,\Omega_2)\beta_2 + \mathcal{O}(\beta_2^2)$$

fluctuation of δ_d (ϵ_0) is uncorrelated with p_0 ($\boldsymbol{p}_2$)

$$\text{Variance } \left\langle (\delta[p_T]/[p_T])^2\right\rangle \propto \left\langle (\delta d_\perp/d_\perp)^2\right\rangle = \langle \delta_d^2\rangle + \left\langle p_0(\Omega_1,\Omega_2)^2\right\rangle\beta_2^2$$

The STAR detector and unique isobar run

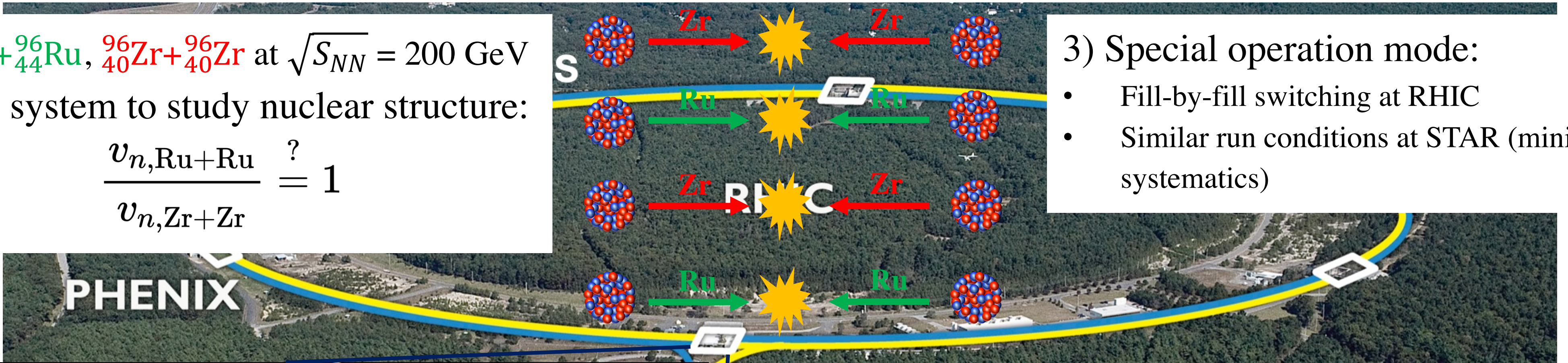
1) ${}^{96}_{44}$Ru+${}^{96}_{44}$Ru, ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr at $\sqrt{S_{NN}}$ = 200 GeV

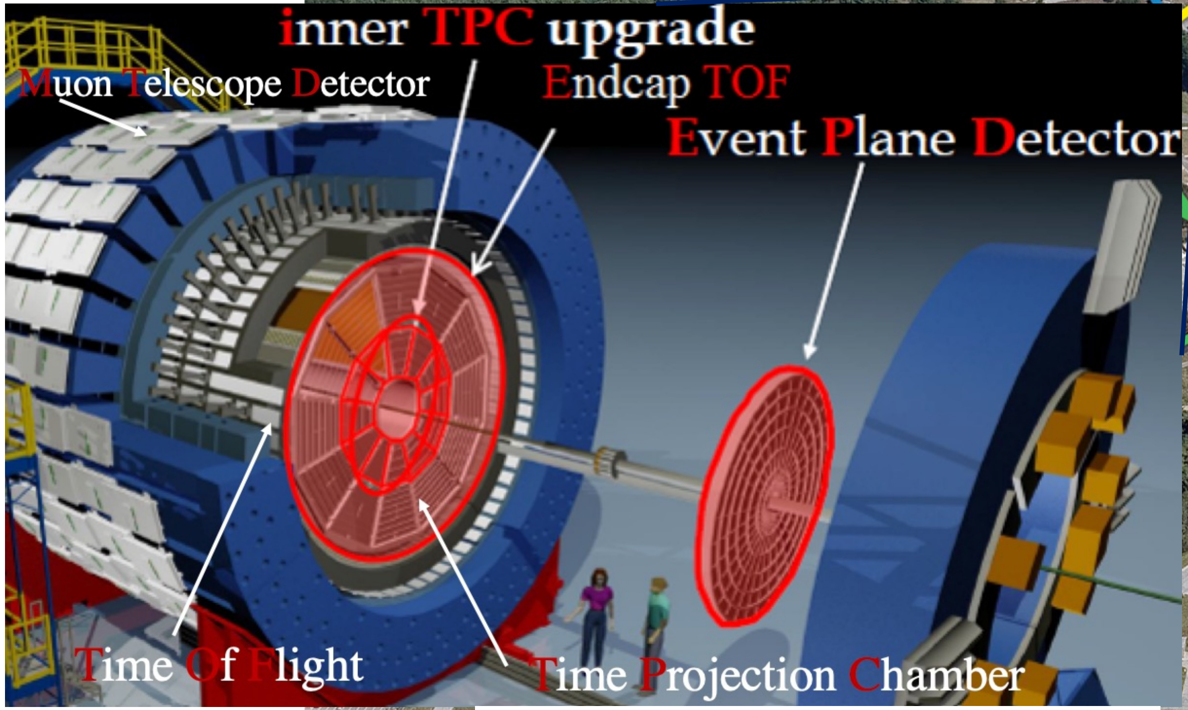
2) Ideal system to study nuclear structure:

$$\frac{v_{n,\mathrm{Ru+Ru}}}{v_{n,\mathrm{Zr+Zr}}} \stackrel{?}{=} 1$$

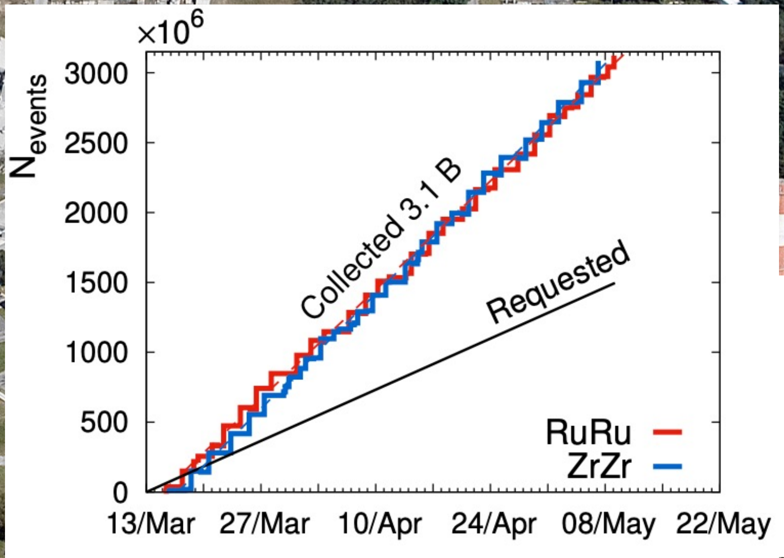
3) Special operation mode:

- Fill-by-fill switching at RHIC
- Similar run conditions at STAR (minimize the systematics)





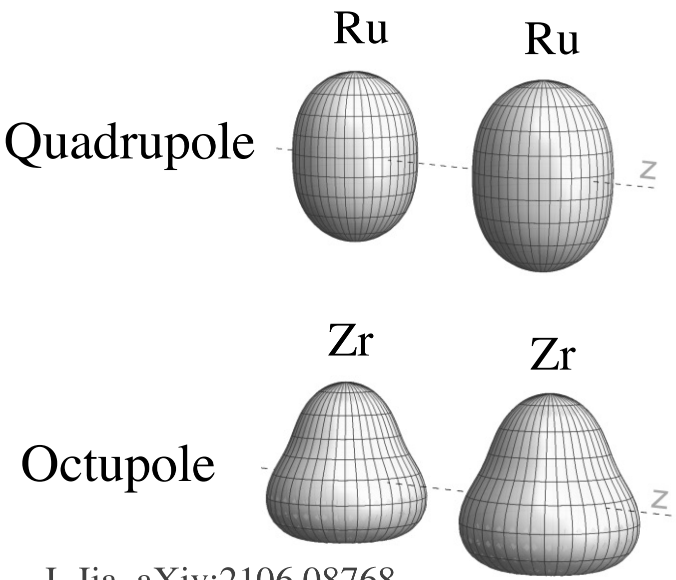
Large, uniform acceptance at mid-rapidity



Isobar run originally dedicated to CME search

CME search at RHIC
Session CA(Oct. 11)
(Sergei A Voloshin)

Nuclear deformation in isobar collisions

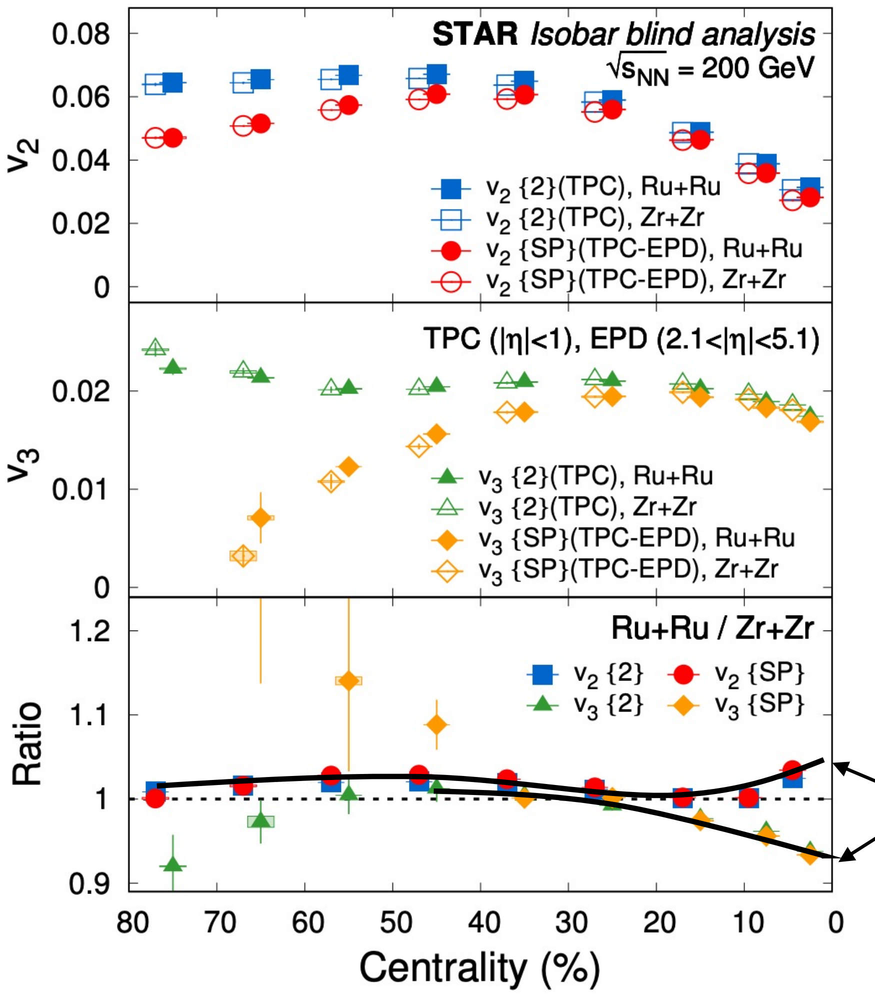


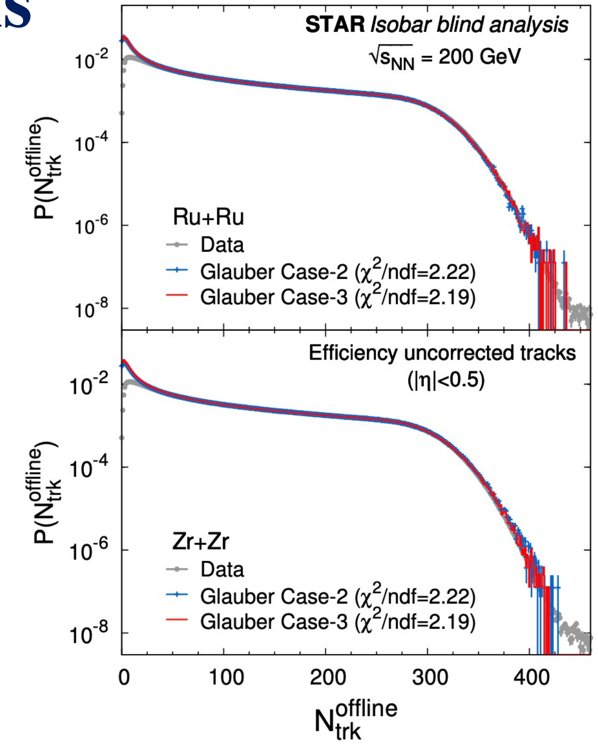
$\beta_2 = 0.15$
$\beta_3 \sim 0$

$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

J. Jia, aXiv:2106.08768

STAR, arXiv:2109.00131





Nuclear structure data on Ru/Zr deformation:

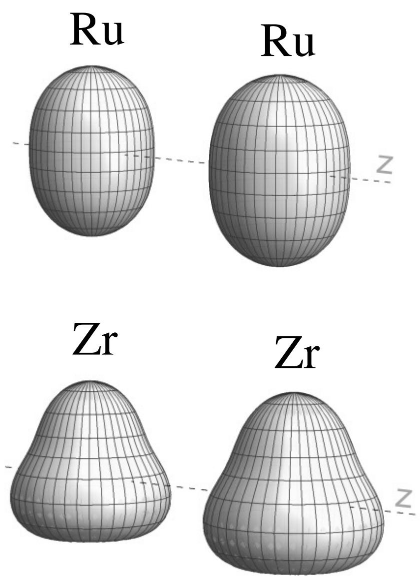
	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90

$$\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}} \qquad \beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$$

C. Zhang et al., arXiv:2109.01631
G. Giacalone et al., arXiv:2102.08158

Goal: explore effect of β_n in finer bins of multiplicity

v_2 and v_3 ratio



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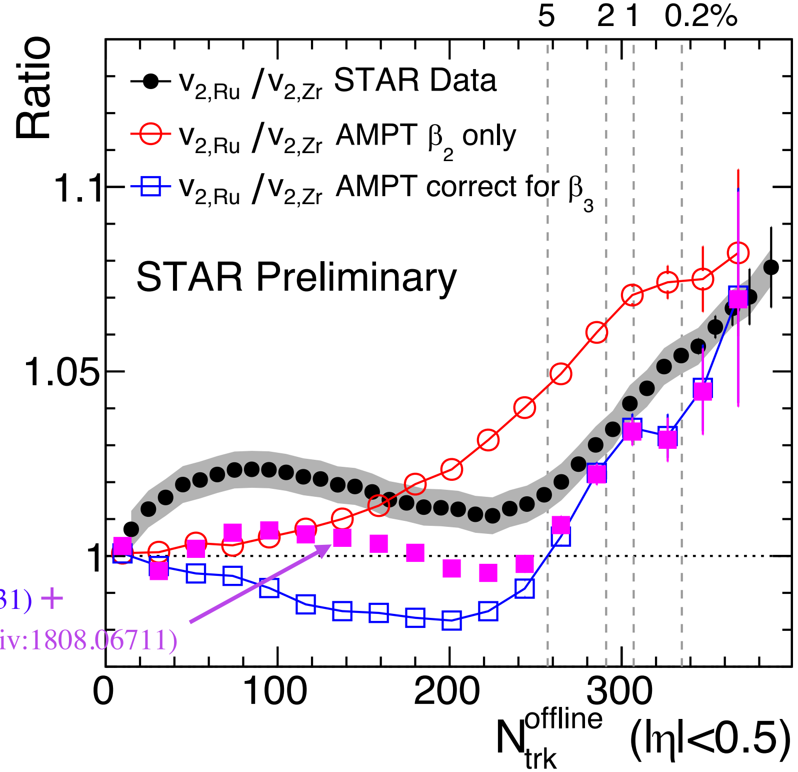
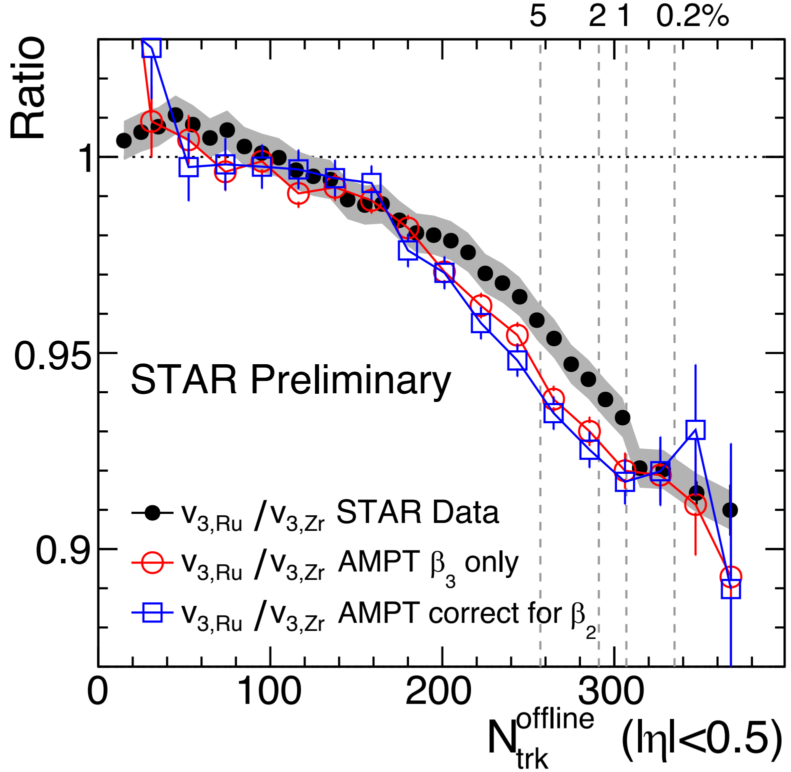




Heavy-ion expectation:

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

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

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

Cancelation expected in non-central collisions

C. Zhang et al., arXiv:2109.01631

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

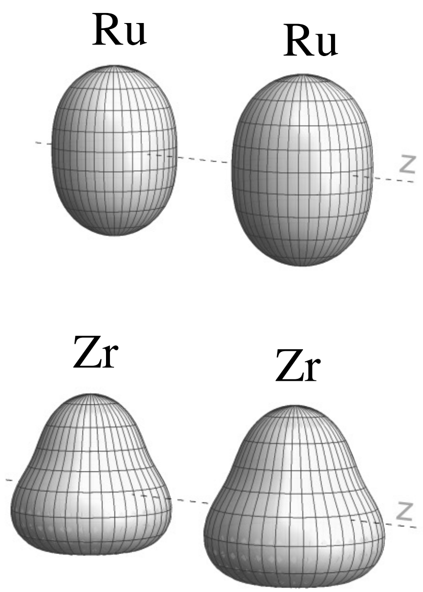
3) Residual effect due to radial structure of Zr?

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

This is the first, direct indication of octupole deformation using heavy-ion collisions.

$[p_T]$-variance ratio

J. Jia, aXiv:2106.08768



$\beta_2 = 0.15$
$\beta_3 \sim 0$

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Heavy-ion expectation:

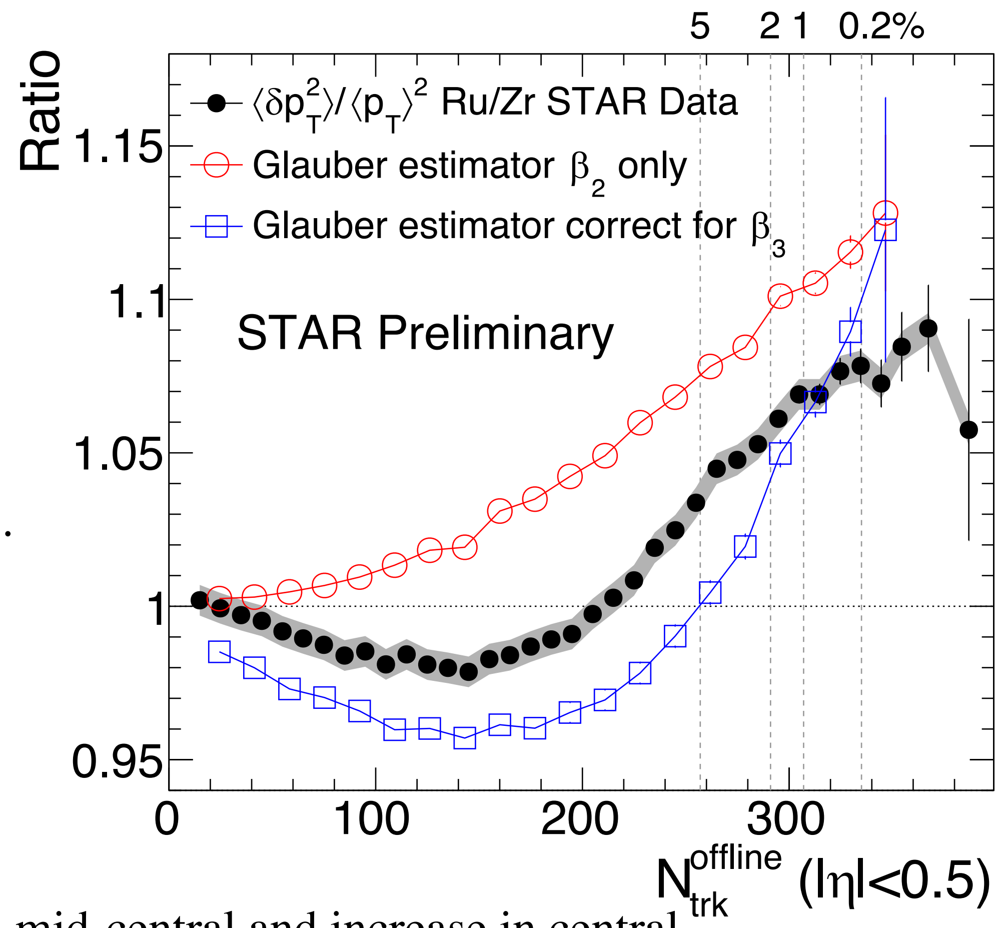
$$\left\langle (\delta[p_\mathrm{T}]/[p_\mathrm{T}])^2 \right\rangle = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

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

Cancelation expected in non-central collisions

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

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



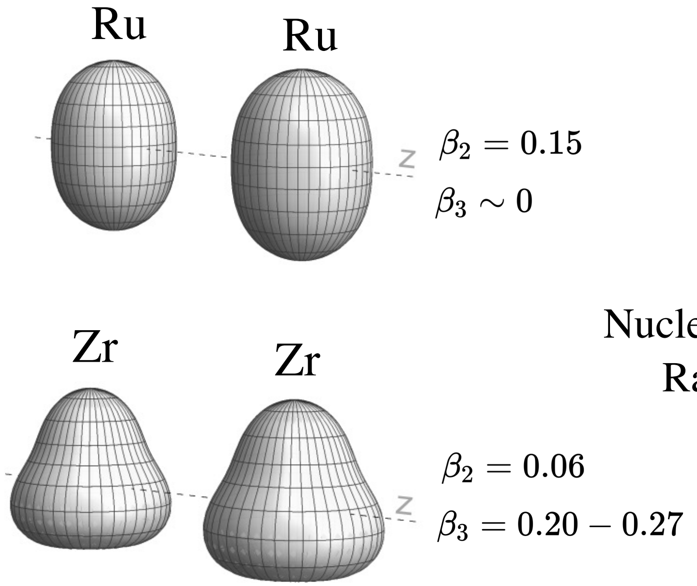
1) Nonmonotonic trend: large suppression in mid-central and increase in central

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

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

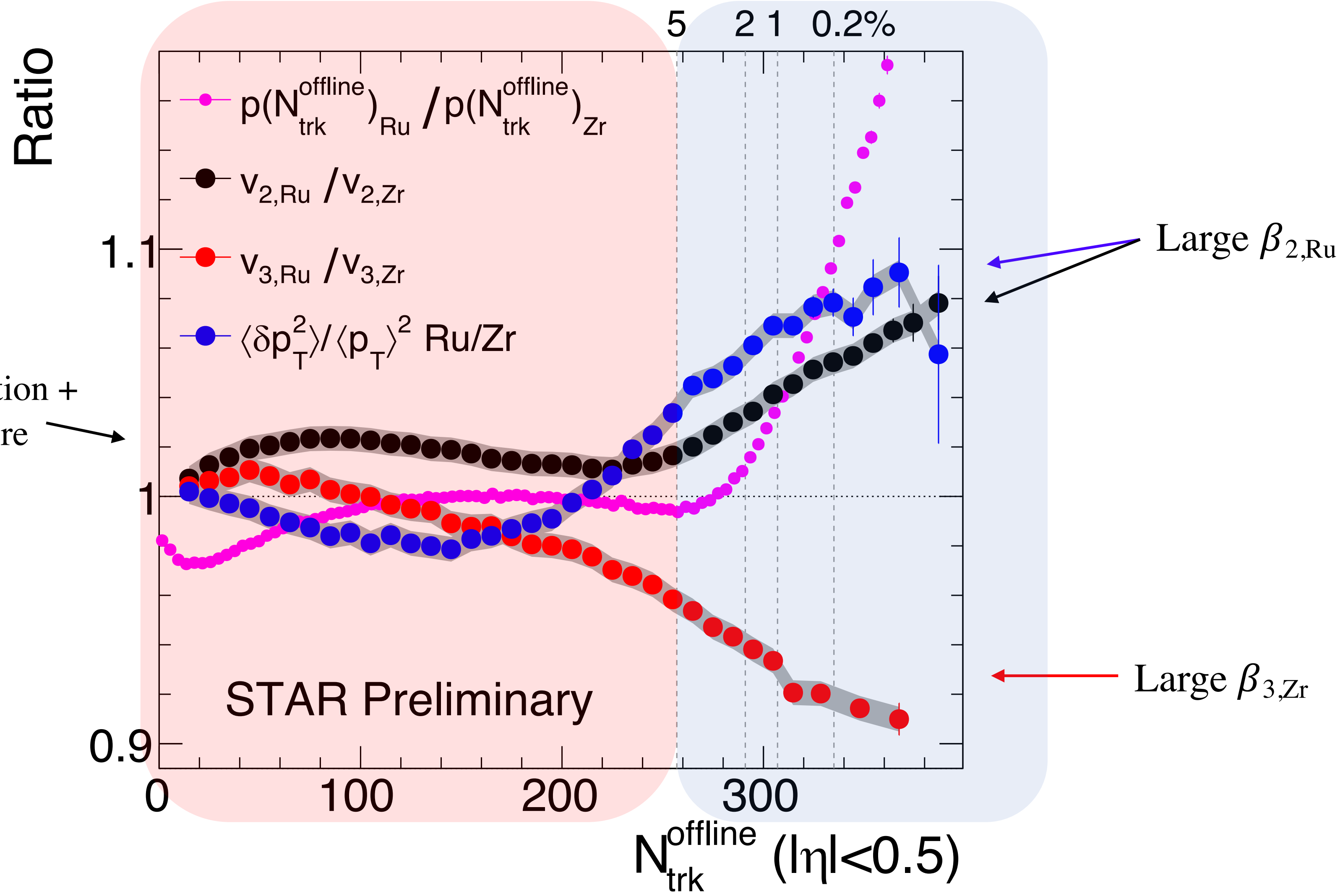
Variance of $[p_T]$ fluctuations can also be used to constrain the nuclear deformation.

flow, [p_T]-variance and multiplicity ratio



J. Jia, aXiv:2106.08768

Nuclear deformation +
Radial structure



Ratio of any bulk observables can image the shape of the nuclei.

Conclusions and outlooks

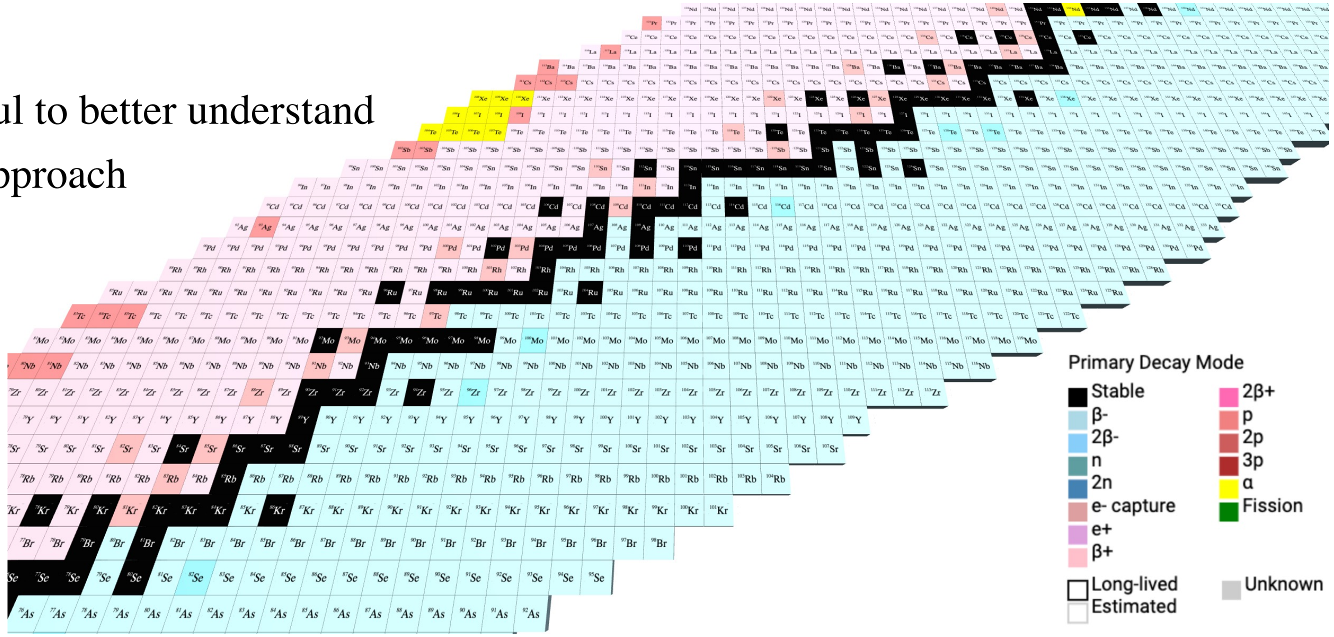
✓ **Isobar collision is a new tool to study the nuclear structure using heavy-ion collision.**

✓ **We show the large difference of v_{2}, v_3 and $[p_T]$ fluctuations ratio imply: $\beta_{2,Ru} \gg \beta_{2,Zr}$ and $\beta_{3,Ru} \ll \beta_{3,Zr}$**

✓ **This is the first, direct observation of ^{96}Zr octupole deformation using heavy-ion collisions.**

✓ **Isobar collision opens up new opportunity to study nuclear structure at a very short time scale ($\sim 10^{-24}$s) through heavy-ion collisions**

- By doing future deformed-system scan
- Species with well known deformation will be useful to better understand the systematics and establish the efficacy of this approach



Many thanks to APS DNP and also thank you for listening.