Constraints on Neutron Skin Thickness and Nuclear Deformations Using Relativistic Heavy-ion Collisions from STAR

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Outline

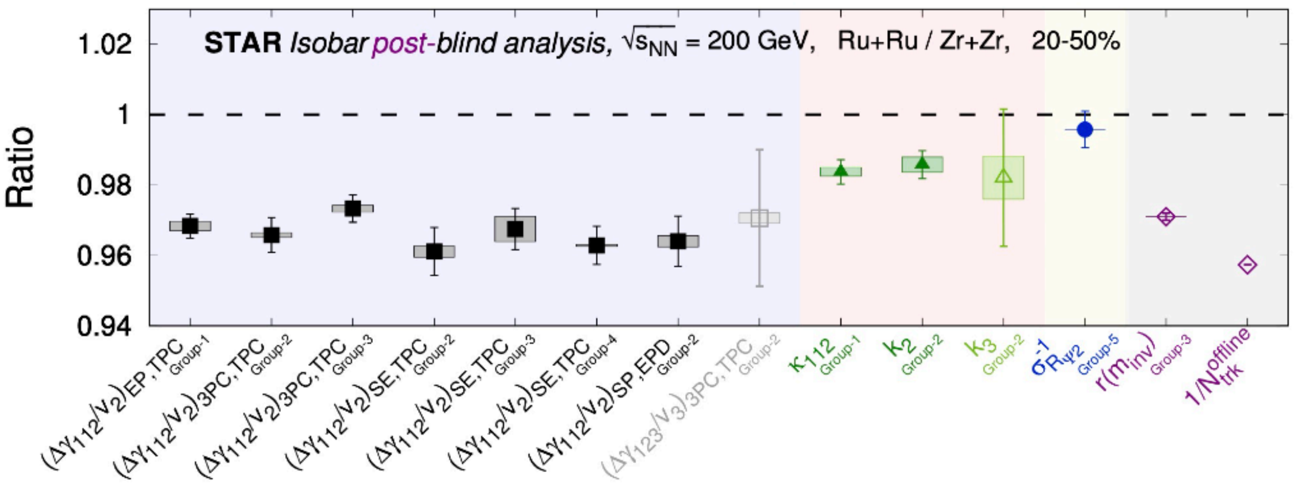
- Introduction
- Probing nuclear deformation in heavy-ion collisions
- Probing neutron skin and symmetry energy in isobar collisions
- Summary

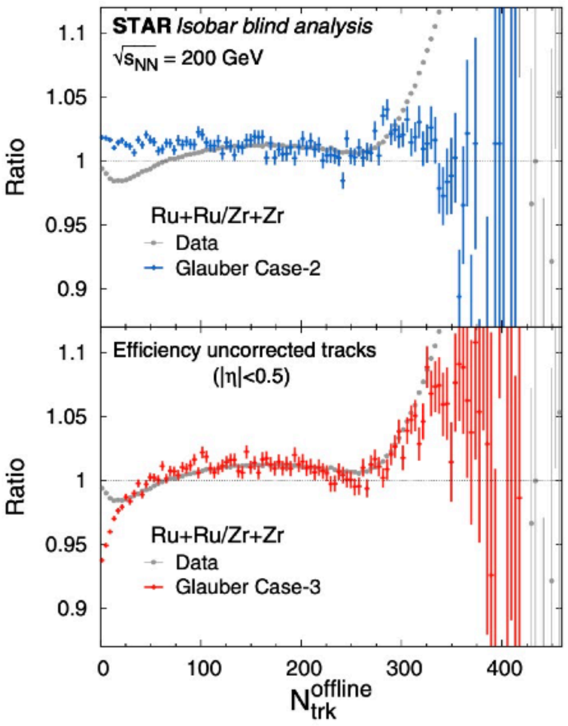
CME search and isobar structures

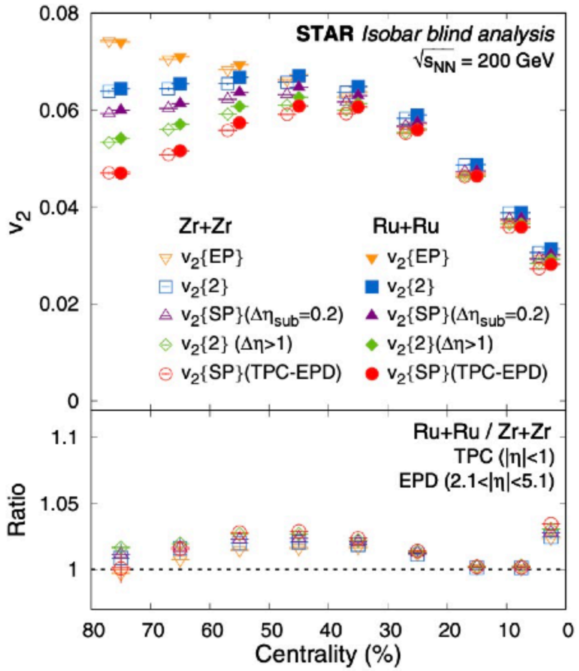
Chiral magnetic effect (CME)

D. Kharzeev, PPNP88, 1 (2016)
STAR, PRC105, 014901 (2022)

$$\mathbf{J_{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B},$$





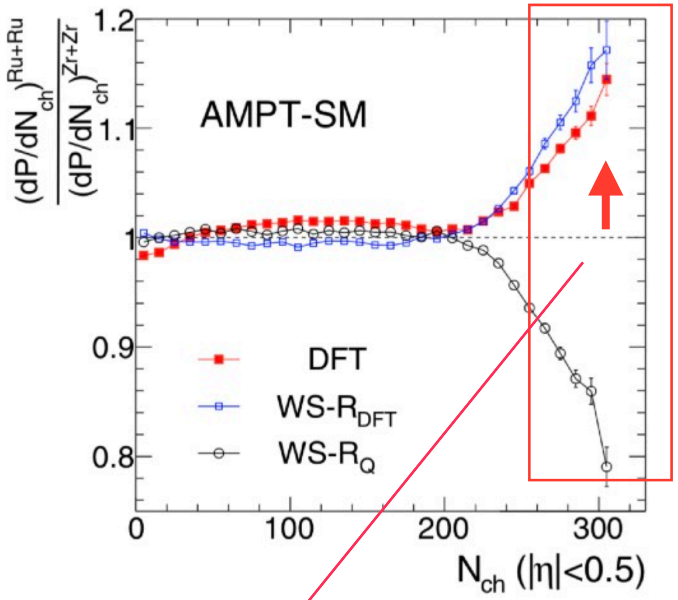


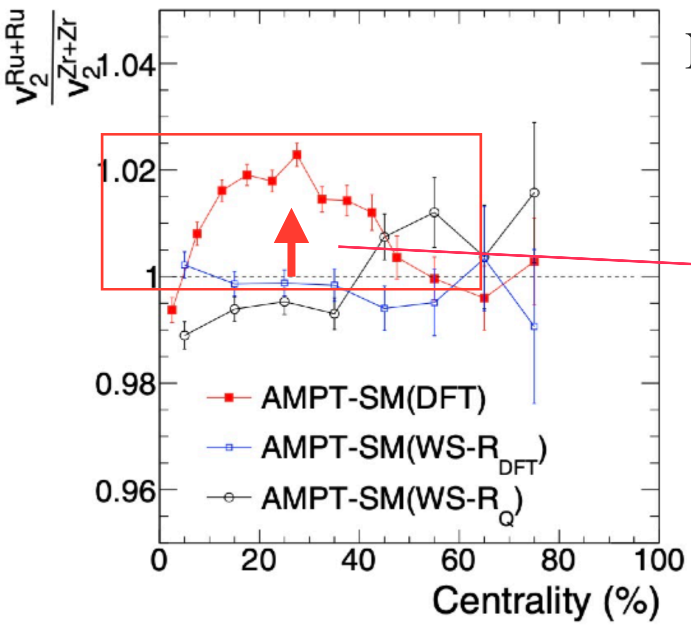
Yu Hu : Session T02, Apr 7
Yicheng Feng : Poster Session 1 T02

The multiplicity and v_2 differences are crucial for the CME search in isobar collisions

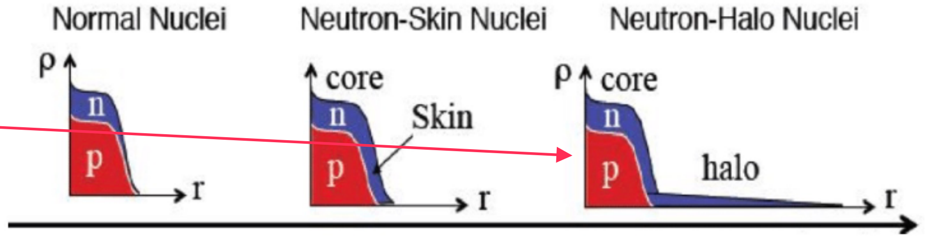
Clear differences in multiplicity and elliptic flow, indicating isobar structure difference

Isobar structure difference is predicted by DFT



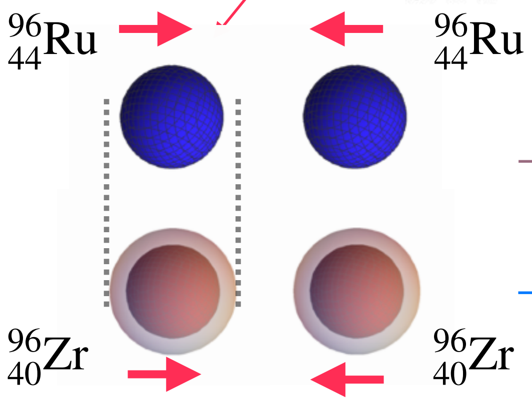


Neutron skin thickness $\Delta r_{np} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$



Normal Nuclei	Neutron-Skin Nuclei	Neutron-Halo Nuclei
$R_n = R_p$	$R_n > R_p$	$R_n = R_p$
$a_n = a_p$	$a_n = a_p$	$a_n > a_p$

$$\rho = \frac{\rho_0}{1 + \exp\left[\frac{r - R}{a}\right]}$$



→ Smaller r, larger density → Larger N_{ch} and $\langle p_T \rangle$

→ Larger r, smaller density → Smaller N_{ch} and $\langle p_T \rangle$

HJX, et.al., PRL121, 022301 (2018)
H. Li, HJX, et.al., PRC98, 054907 (2018)
HJX, et.al., PLB819, 136453 (2021)

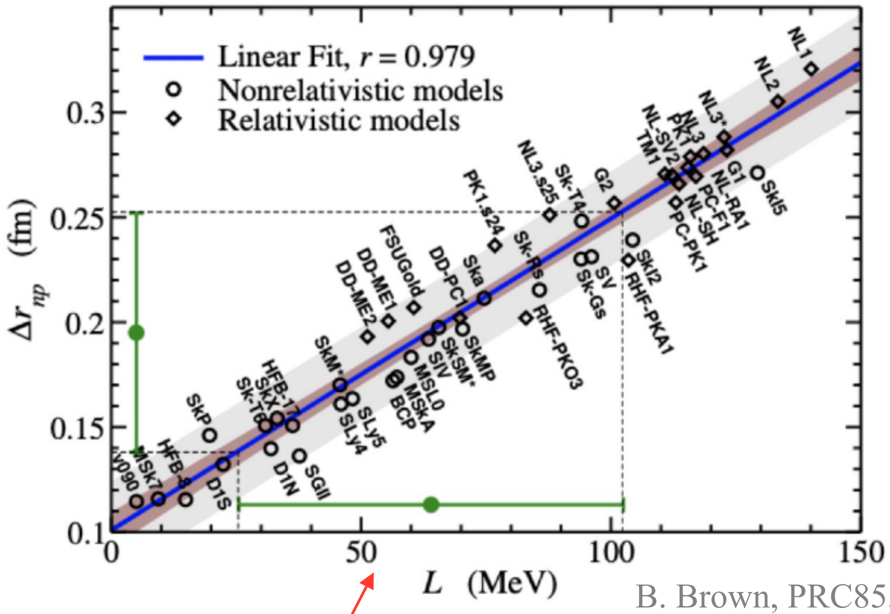
The STAR isobar data demonstrate **thick halo-type neutron skin in Zr,** consistent with **DFT** (energy density functional theory) calculations

Neutron skin: sensitive probe of symmetry energy

$^{96}_{40}\mathrm{Zr}: (N-Z)/A = 0.167$

$^{96}_{44}\mathrm{Ru}: (N-Z)/A = 0.083$

$\Delta r_{\mathrm{np}}^{\mathrm{Zr}} \gg \Delta r_{\mathrm{np}}^{\mathrm{Ru}}$



DFT(eSHF): State-of-the-art DFT calculation using extended Skyrme-Hartree-Fock (eSHF) model.

Z. Zhang, L. Chen, PRC94, 064326(2016)

B. Brown, PRC85, 5296 (2000)
R. Furnstahl, NPA, 706, 85 (2002)
X. Roca-Maza, et.al. PRL106, 252501 (2011)

$$E(\rho,\delta) = E_0(\rho) + E_{\mathrm{sym}}(\rho)\delta^2 + O(\delta^4); \quad \rho = \rho_n + \rho_p; \quad \delta = \frac{\rho_n - \rho_p}{\rho};$$

Slope parameter :

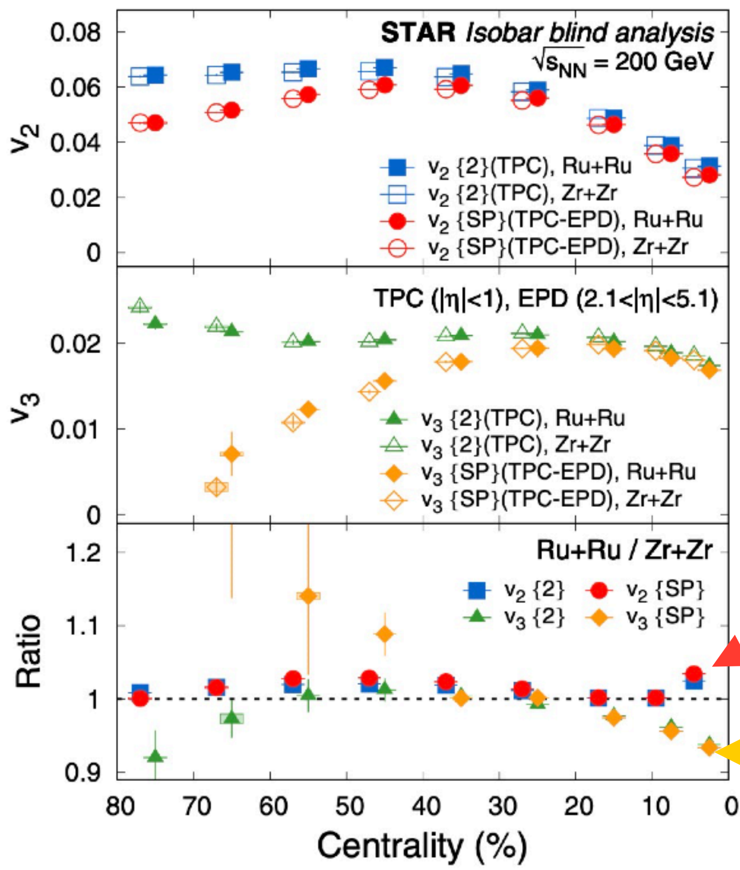
$$L \equiv L(\rho) = 3\rho \left[\frac{dE_{\mathrm{sym}}(\rho)}{d\rho}\right]_{\rho=\rho_0} \text{ saturation density} \qquad L(\rho_c) = 3\rho_c \left[\frac{dE_{\mathrm{sym}}(\rho)}{d\rho}\right]_{\rho=\rho_c=0.11\rho_0/0.16}$$

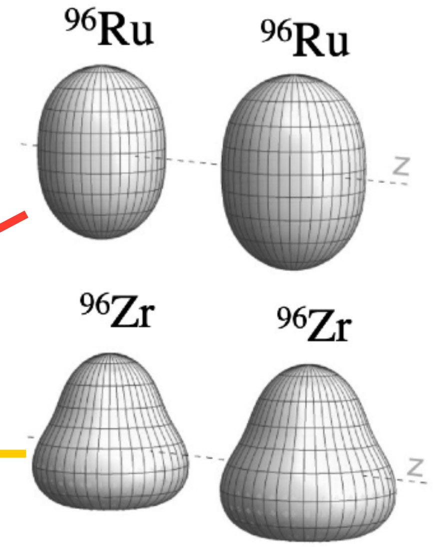
Larger L
Harder EOS ⟷ Need small δ to lower E ⟷ Smaller ρ_n, larger Δr

The symmetry energy is crucial to our understanding of the masses and drip lines of neutron-rich nuclei and the equation of state (EOS) of nuclear and neutron star matter

Central isobar data indicate nuclear deformation

STAR, PRC105, 014901 (2022)





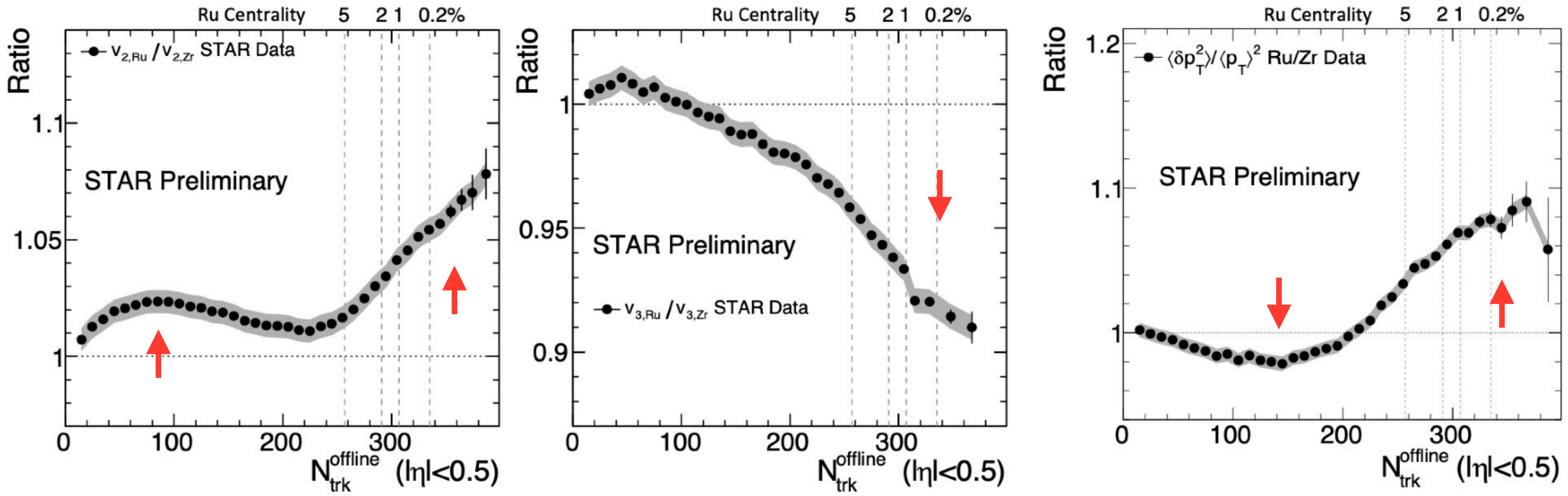
Sizable v_2 and v_3 ratios in central collisions indicate **shape difference between isobars**

Part I

Probing nuclear deformation in heavy-ion collisions

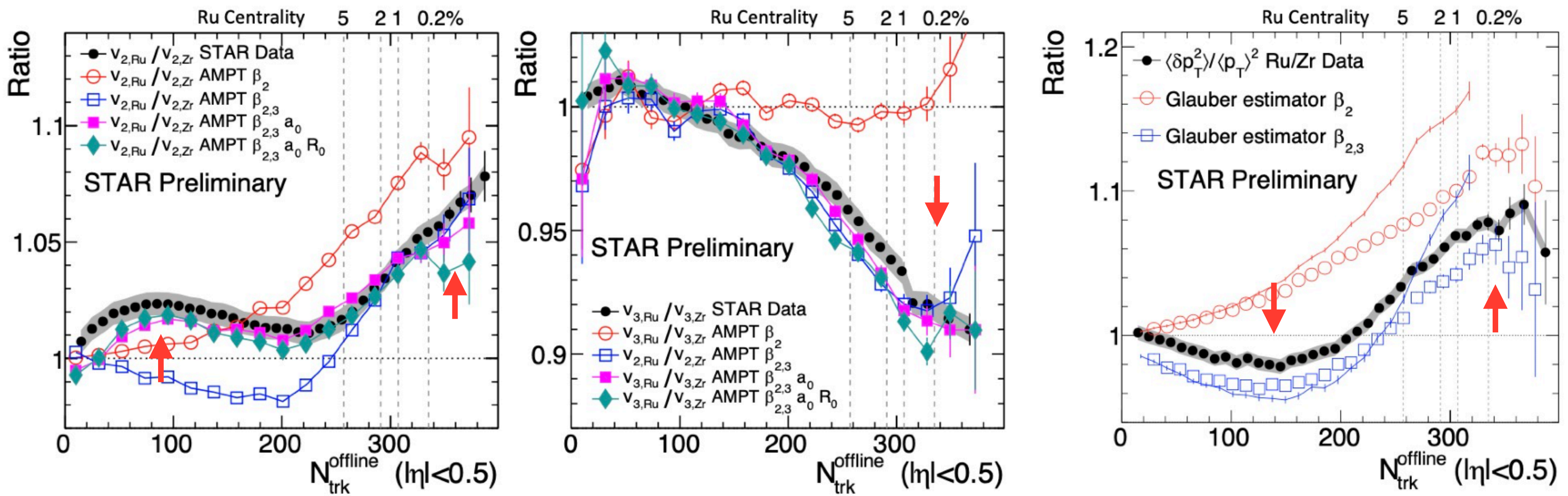
Chunjian Zhang : Poster Session 2 T01
Jiangyong Jia : Poster Session 2 T01

v_2, v_3, $\langle p_T \rangle$ variance ratios in isobar



- Mapping on same $N_{trk}^{offline}$ instead of centrality
- The ratios show non-monotonic trends

v_2, v_3, $\langle p_T \rangle$ variance ratios in isobar



- Mapping on same $N_{\text{trk}}^{\text{offline}}$ instead of centrality
- The ratios show non-monotonic trends
- The ratios well constrain the nuclear structure parameters

$$\beta_{2,\text{Ru}} = 0.16 \pm 0.02$$

$$\beta_{3,\text{Zr}} = 0.20 \pm 0.02$$

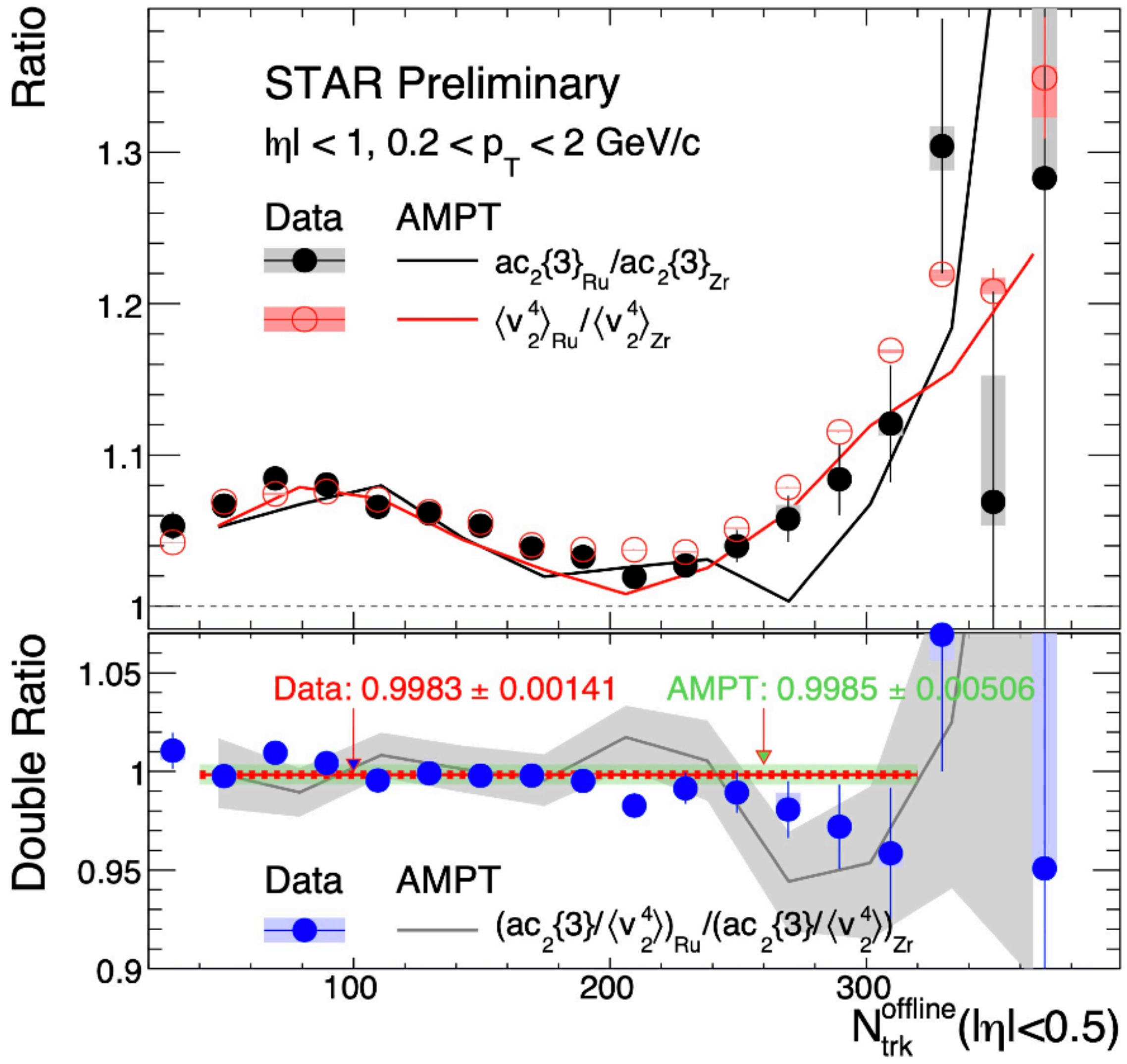
Estimate based on AMPT

C. Zhang, J. Jia, PRL128, 022301 (2022)
J.Jia and C. Zhang, arXiv:2111.15559
B. Pritychenko, et.al. At.Data Nucl.Data Tables 107, 1 (2016)
T. Kebedi, et.al. At.Data Nucl.Data Tables 80, 35 (2002)

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

Isobar ratios as new probe to nuclear deformation

Asymmetric cumulant $ac_2\{3\}$



$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Psi_2 - \Psi_4)\rangle$$

Non-linear coefficient: $\langle \chi_{4,22} \rangle = \dfrac{ac_2\{3\}}{\langle v_2^4 \rangle}$

Expectation: $\dfrac{ac_2\{3\}_{RuRu}}{ac_2\{3\}_{ZrZr}} = \dfrac{\chi_{4,22}^{RuRu}}{\chi_{4,22}^{ZrZr}} \dfrac{\langle v_2^4 \rangle_{RuRu}}{\langle v_2^4 \rangle_{ZrZr}}$

- Non-monotonic trend driven by v_2, with large sensitivity
- AMPT model can reproduce the trend
- Non-linear coefficient is identical in the final-state

$$\frac{\chi_{4,22}^{RuRu}}{\chi_{4,22}^{ZrZr}} = 0.998 \pm 0.001$$

S. Zhao, HJX, Y. Liu, H. Song, arXiv:2204.02387
L Yan, J. Ollitrault, PLB744, 82 (2015)
G. Giacalone, L. Yan, J. Ollitrault, PRC97, 054905 (2018)

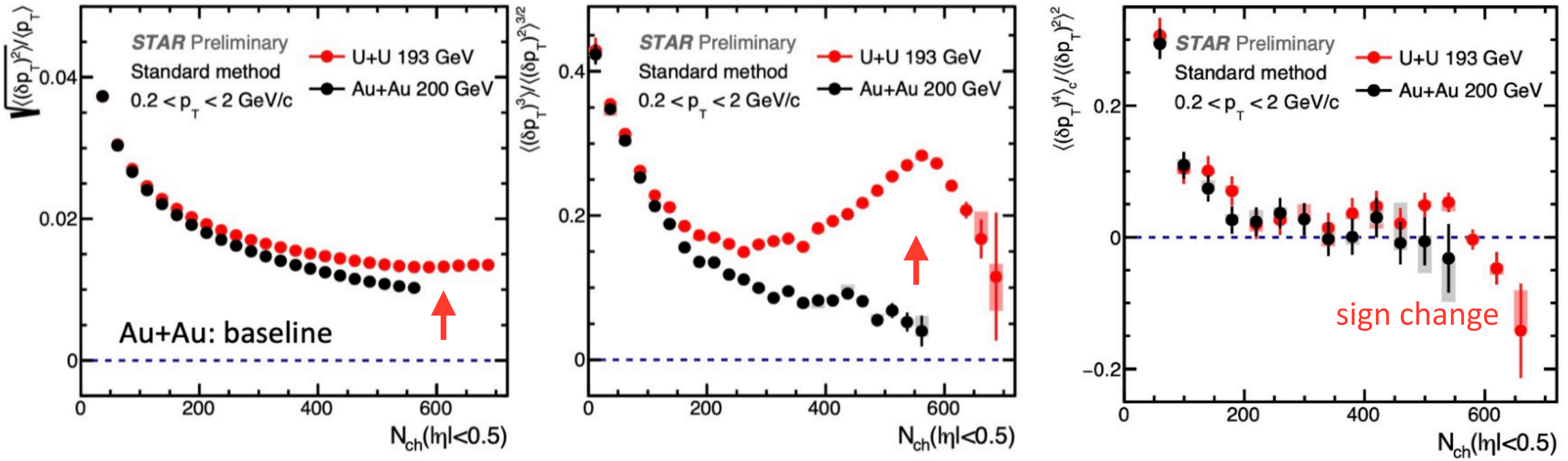
Independent test on nuclear structure

Event-by-event $[p_T]$ fluctuation in U+U and Au+Au

$$c_n = \frac{\sum_{i_2 \neq \ldots \neq i_n} w_{i_1} \ldots w_{i_n} (p_{T,i_1} - \langle p_T \rangle) \ldots (p_{T,i_n} - \langle p_T \rangle)}{\sum_{i_2 \neq \ldots \neq i_n} w_{i_1} \ldots w_{i_n}}$$

G.Giacalone et al., PRC103, 024910 (2021)
J. Jia, arXiv:2109.00604
S. Bhatta, C. Zhang and J. Jia, PRC105, 024904 (2022)

$\sqrt{c_2}/\langle p_T \rangle$ Scaled variance | $c_3/c_2^{3/2}$ Scaled skewness | $(c_4 - 3c_2^2)/c_2^2$ Scaled kurtosis



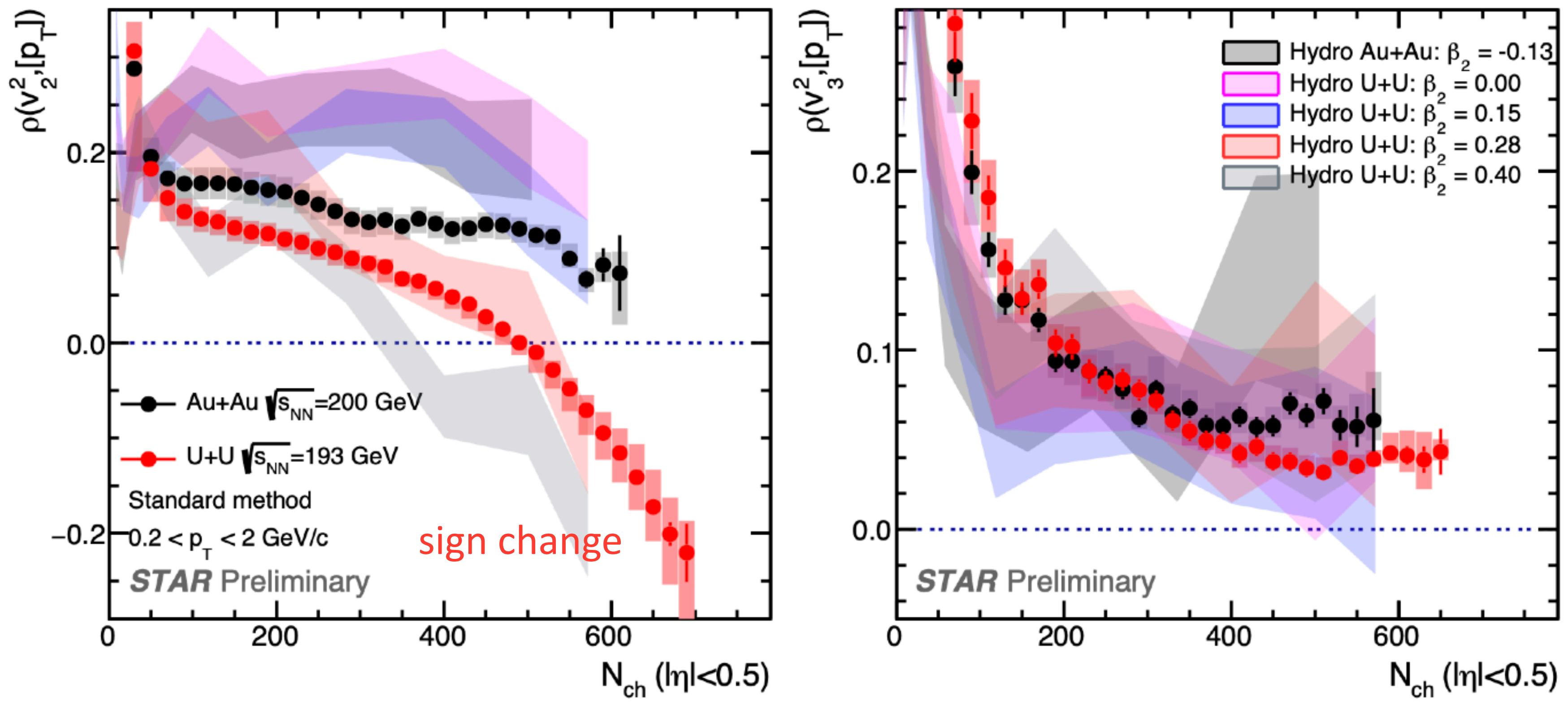
- Clear enhancements of U+U related to Au+Au due to prolate U deformation
- Sign change of the kurtosis in central U+U collisions

Uranium deformation has clear influence on $[p_T]$ fluctuation

Pearson correlation coefficient in U+U and Au+Au

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

IPGlasma+Hydro: private calculation provided by Bjoern Schenke (PRC102, 044905 (2020))

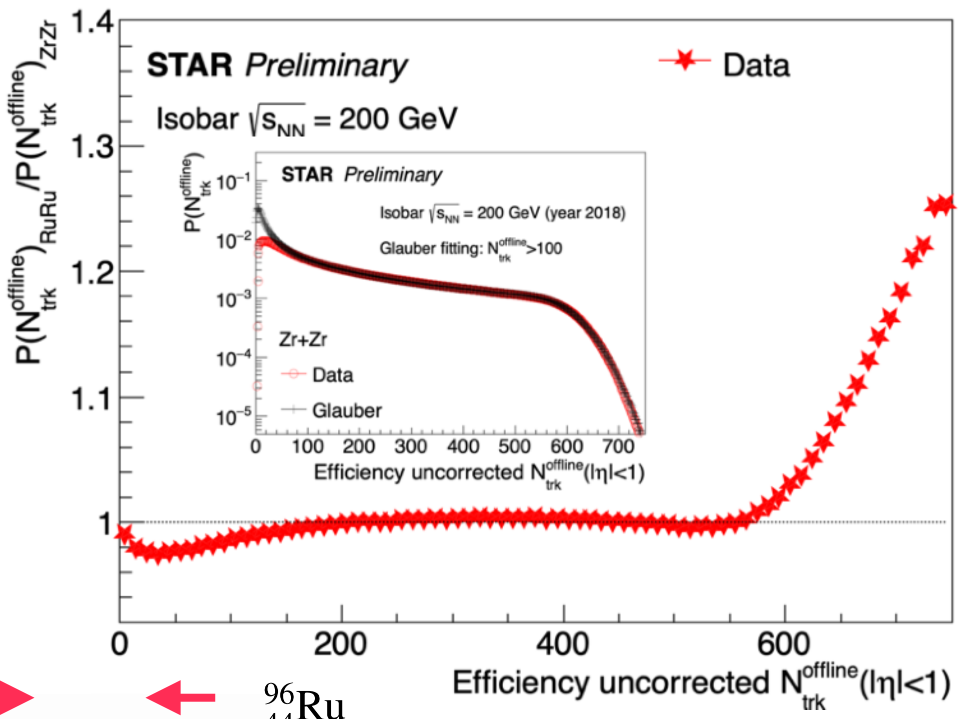


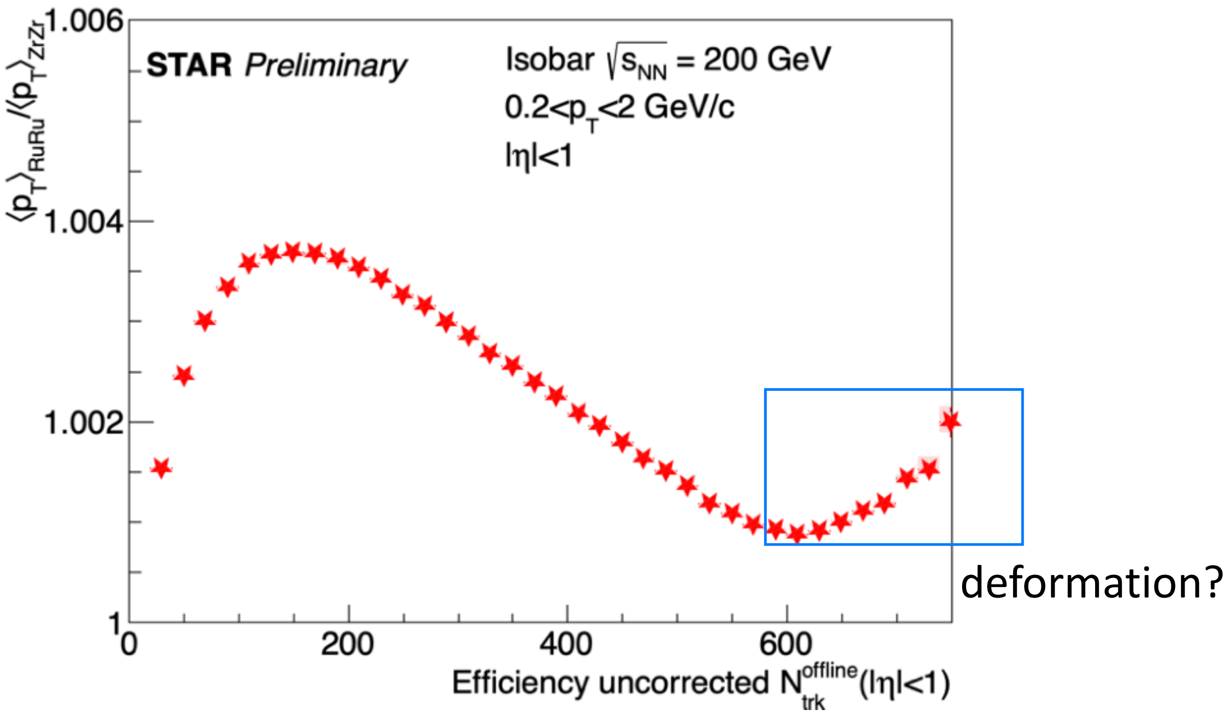
Sign change of $\rho(v_2^2,[p_\mathrm{T}])$ confirms that U is prolate and $\beta_{2,\mathrm{U}} = 0.28 \pm 0.03$ (IPGlasma + Hydro)

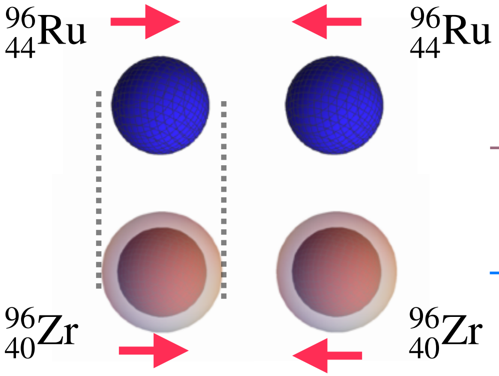
Part II

Probing neutron skin thickness and symmetry energy in isobar collisions

Multiplicity distribution and $\langle p_T \rangle$ ratios in isobar collisions







Smaller r, larger density → Larger N_{ch} and $\langle p_T \rangle$

Larger r, smaller density → Smaller N_{ch} and $\langle p_T \rangle$

→ $R(\langle N_{ch} \rangle)$, $R(\langle p_T \rangle)$ → $\Delta r_{np}, L(\rho)$

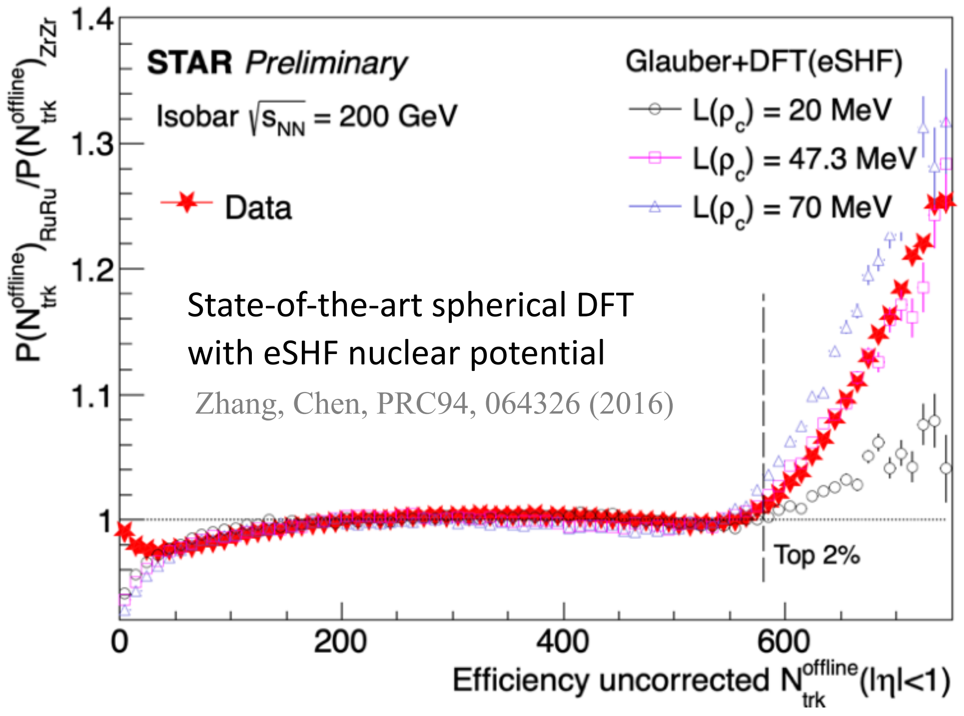
H. Li, HJX, et.al, PRL125, 222301 (2020)
HJX, et.al arXiv:2111.14812

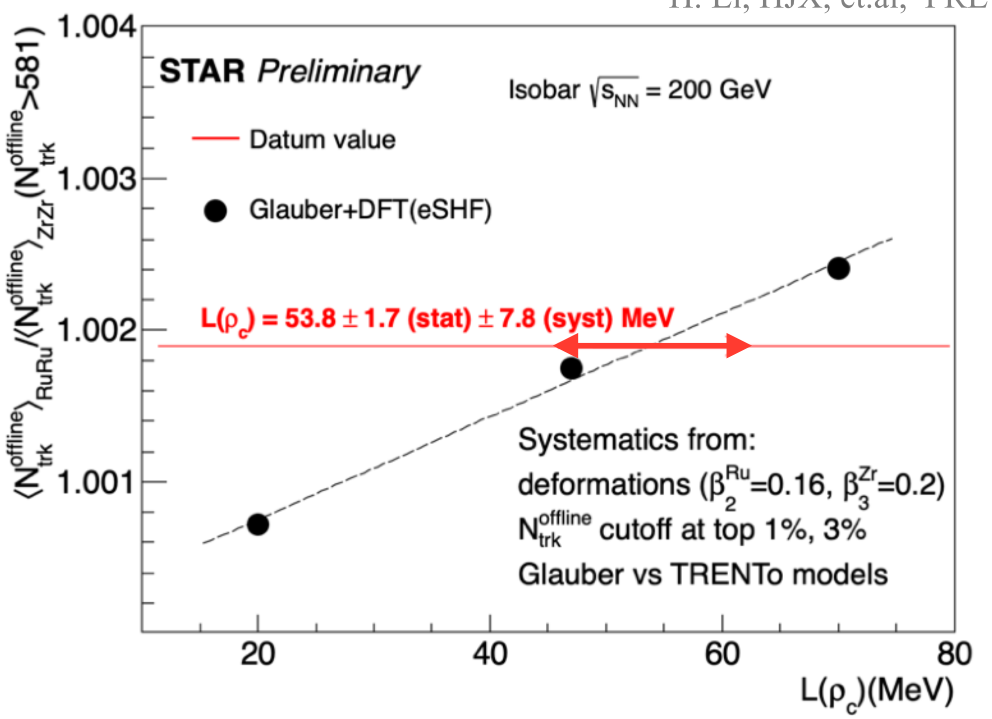
Haojie Xu

The multiplicity and $\langle p_T \rangle$ differences can probe neutron skin and symmetry energy

Multiplicity ratio to probe symmetry energy

H. Li, HJX, et.al, PRL125, 222301 (2020)





- Mean multiplicity ratio in central collisions to extract neutron skin thickness and symmetry energy
- Uncertainties can be improved with deformed (more difficult) DFT calculations

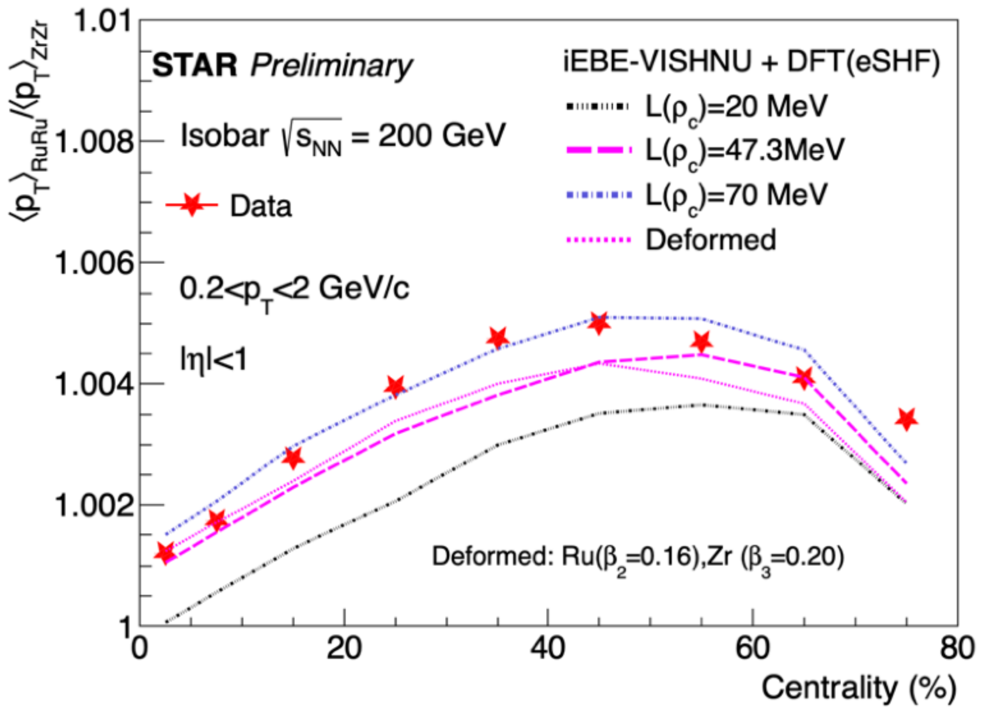
$$L(\rho_c) = 53.8 \pm 1.7 \pm 7.8 \text{ MeV}$$

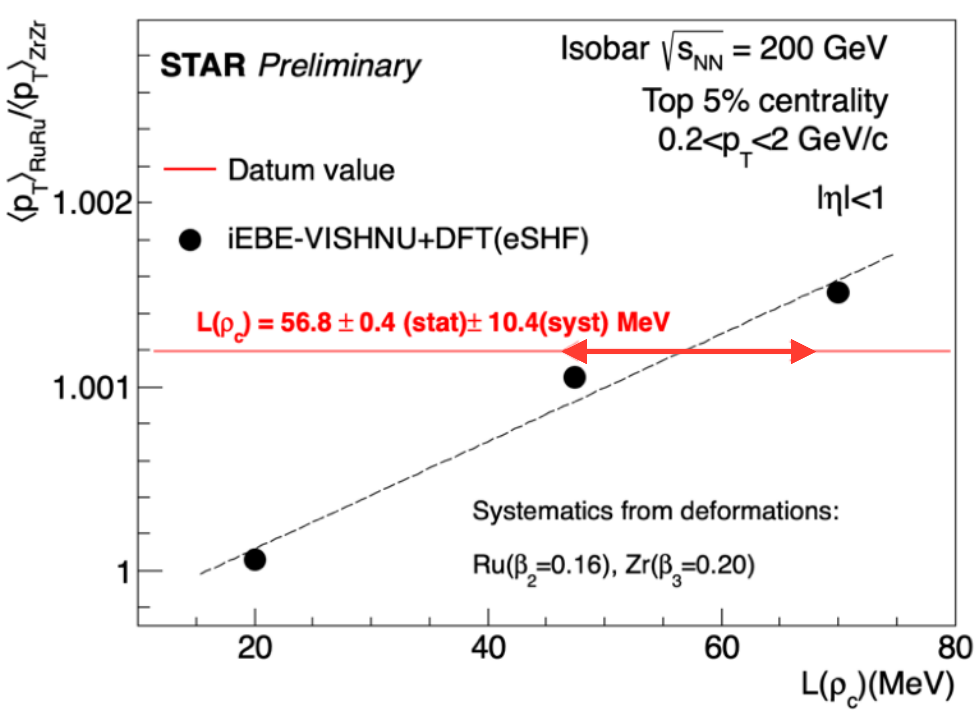
$$L(\rho) = 65.4 \pm 2.1 \pm 12.1 \text{ MeV}$$

$$\Delta r_{np,Zr} = 0.195 \pm 0.019 \text{ fm}$$

$$\Delta r_{np,Ru} = 0.051 \pm 0.009 \text{ fm}$$

$\langle p_T \rangle$ ratio to probe symmetry energy





- The values at top 5% are used to extract neutron skin
- The centrality dependence needs further investigation (nuclei size vs collision geometry)

$$L(\rho_c) = 56.8 \pm 0.4 \pm 10.4 \text{ MeV}$$

$$L(\rho) = 69.8 \pm 0.7 \pm 16.0 \text{ MeV}$$

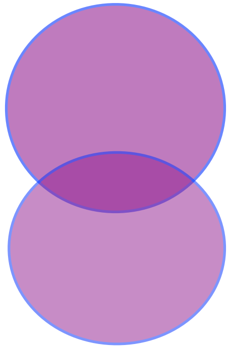
$$\Delta r_{\mathrm{np,Zr}} = 0.202 \pm 0.024 \text{ fm}$$

$$\Delta r_{\mathrm{np,Ru}} = 0.052 \pm 0.012 \text{ fm}$$

HJX, et.al arXiv:2111.14812

Consistent with the measurement from multiplicity ratio

Net-charge (ΔQ) ratio in most peripheral isobar collisions

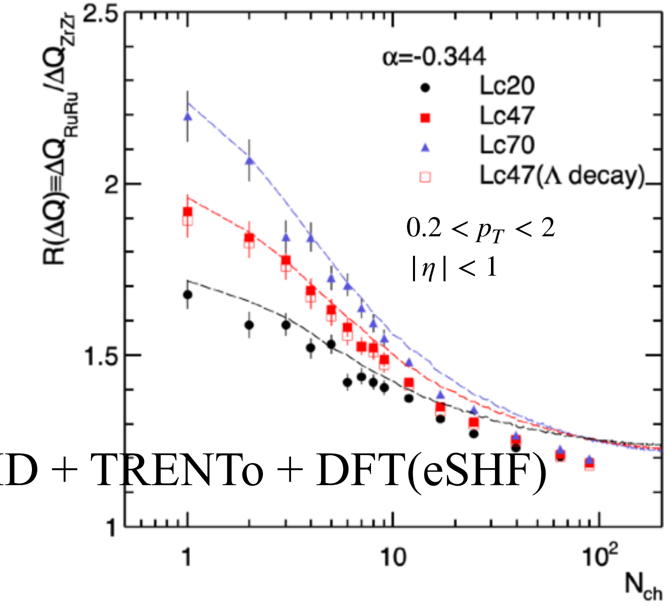


more n+n in most peripheral collisions → Fewer participant protons, thus smaller net-charge

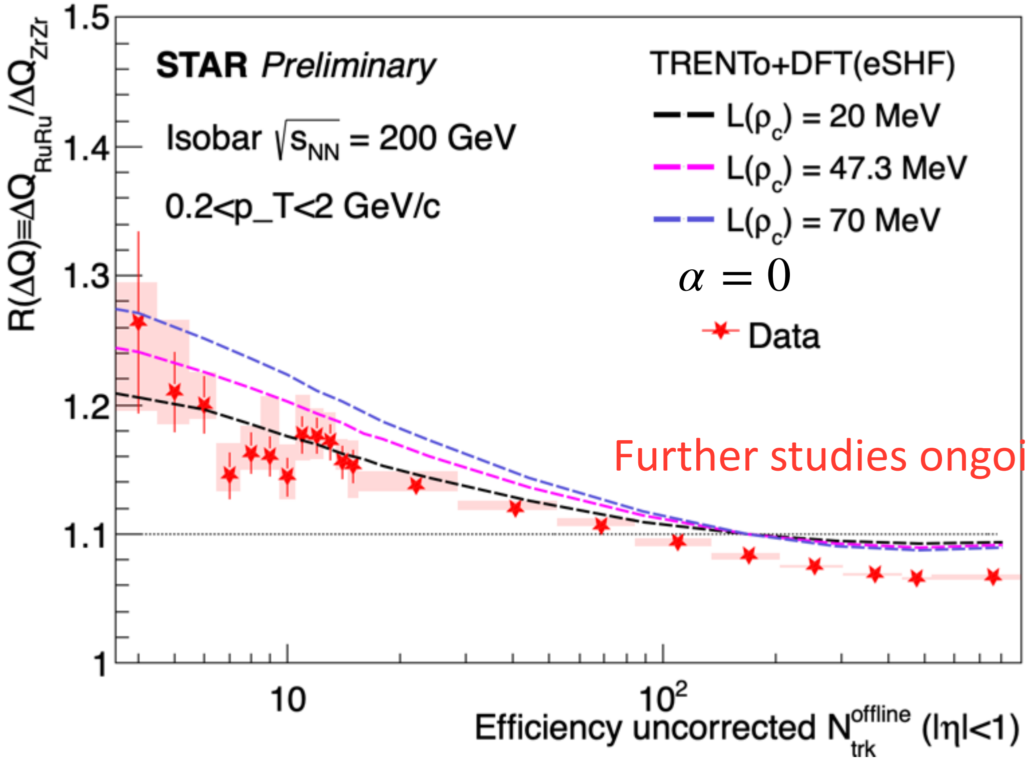
HJX, et.al., PRC105, L011901 (2022)

$$R(\Delta Q) = \frac{q_{\mathrm{RuRu}} + \alpha/(1+\alpha)}{q_{\mathrm{ZrZr}} + \alpha/(1+\alpha)}$$

- q_{AA}: participant p/(p+n)
- $\alpha = \Delta Q_{nn}/\Delta Q_{pp}$



UrQMD + TRENTo + DFT(eSHF)



Further studies ongoing

- $R(\Delta Q)$ in very peripheral collisions is directly related to neutron skin thickness
- Data imply $\alpha \sim 0$, contrast to model studies

Compare to world wide data

State-of-the-art **spherical** DFT with eSHF nuclear potential

Zhang, Chen, PRC94, 064326 (2016)

- Multiplicity ratio:

$$L(\rho_c) = 53.8 \pm 1.7 \pm 7.8 \text{ MeV}$$

$$L(\rho) = 65.4 \pm 2.1 \pm 12.1 \text{ MeV}$$

$$\Delta r_{\text{np,Zr}} = 0.195 \pm 0.019 \text{ fm}$$

$$\Delta r_{\text{np,Ru}} = 0.051 \pm 0.009 \text{ fm}$$

- $\langle p_T \rangle$ ratio:

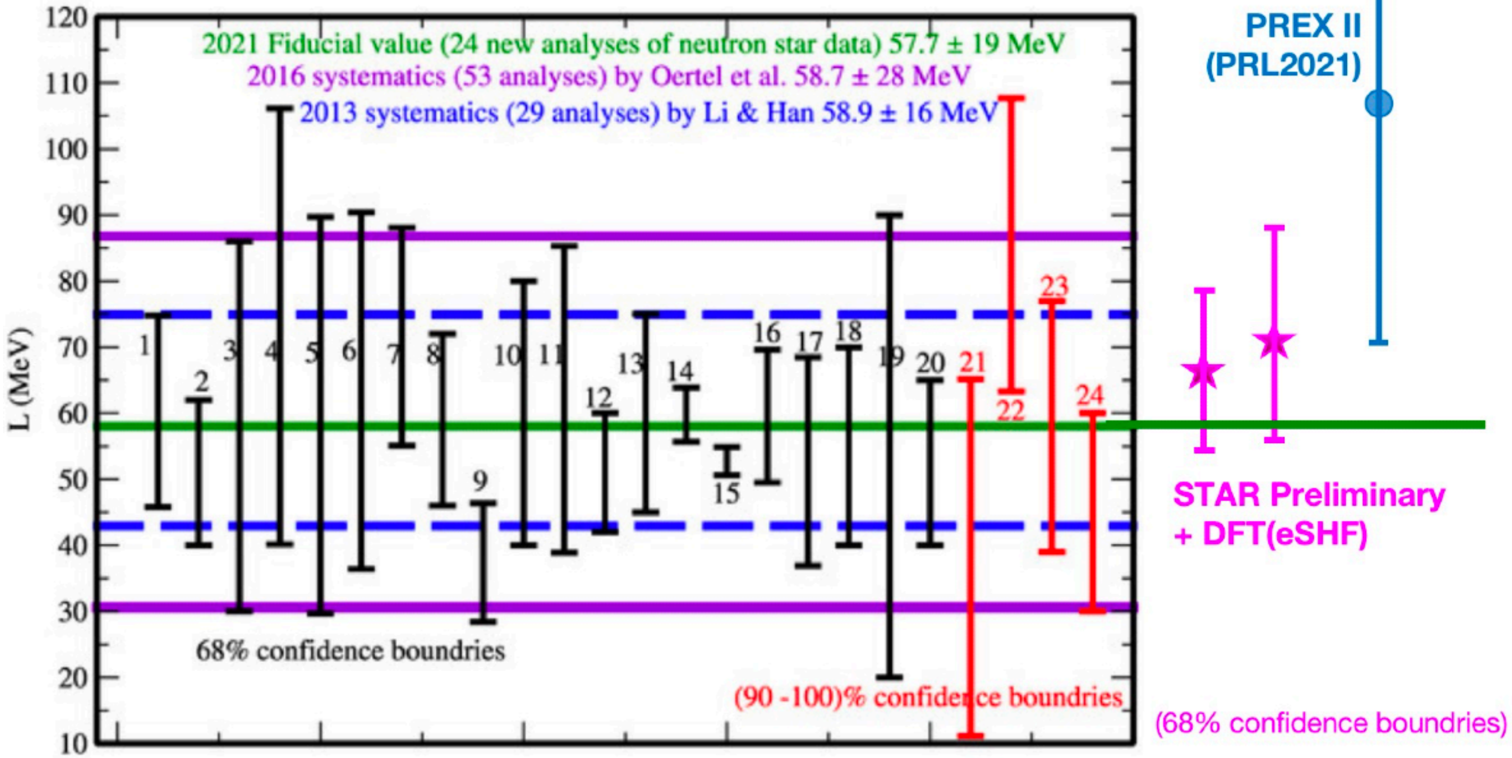
$$L(\rho_c) = 56.8 \pm 0.4 \pm 10.4 \text{ MeV}$$

$$L(\rho) = 69.8 \pm 0.7 \pm 16.0 \text{ MeV}$$

$$\Delta r_{\text{np,Zr}} = 0.202 \pm 0.024 \text{ fm}$$

$$\Delta r_{\text{np,Ru}} = 0.052 \pm 0.012 \text{ fm}$$

B. Li, et.al Universe 7, 182 (2021)



Consistent with world wide data with good precision

Summary

1. v_2, v_3, $\langle p_T \rangle$ variance ratios, v_n^2-$\langle p_T \rangle$ correlations to probe **nuclear deformation**
   - Estimated from AMPT: $\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$ and $\beta_{3,\mathrm{Zr}} = 0.2 \pm 0.02$
   - Estimated from IPGlasma+Hydro: $\beta_{2,\mathrm{U}} = 0.28 \pm 0.03$

2. Multiplicity and $\langle p_T \rangle$ ratios in isobar to probe **neutron skin and symmetry energy**
   - $L(\rho_c) = 53.8 \pm 1.7 \pm 7.8$ MeV from multiplicity ratio
   - $L(\rho_c) = 56.8 \pm 0.4 \pm 10.4$ MeV from $\langle p_T \rangle$ ratio
   - Systematic uncertainties due to deformation can be improved

Relativistic heavy-ion collisions can constrain
nuclear deformation, neutron skin and symmetry energy

Thank you for your attention!

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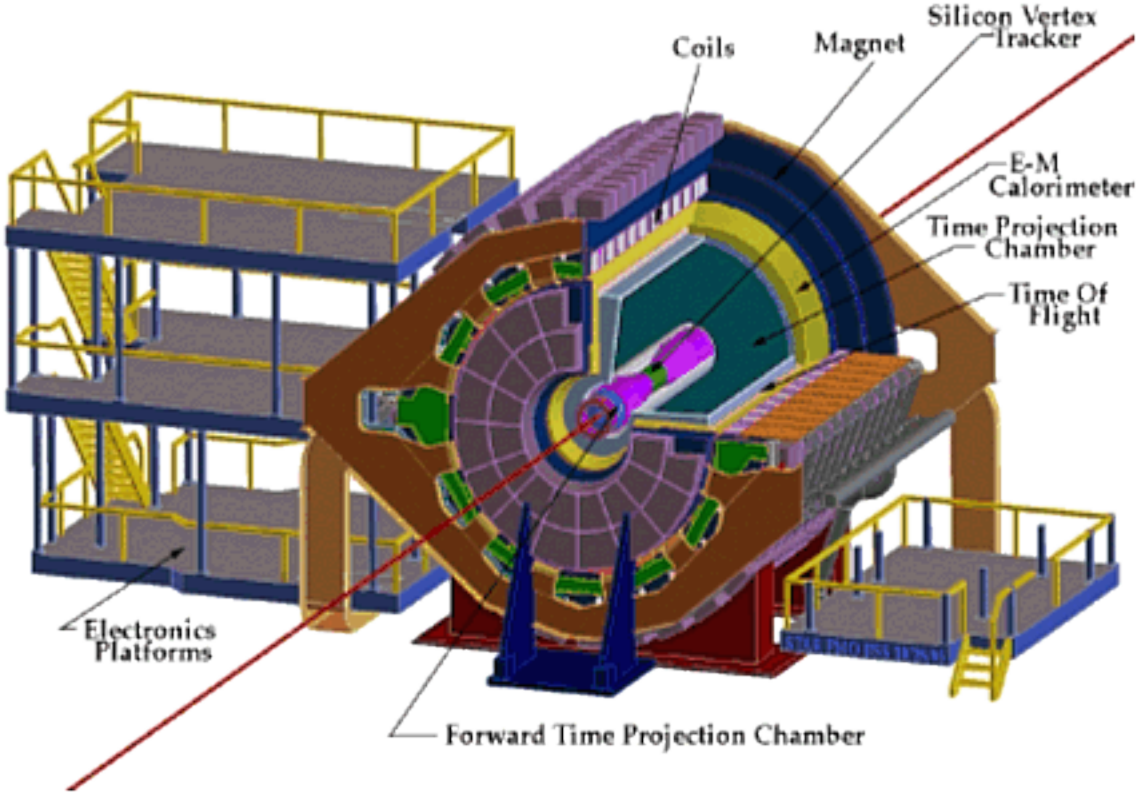
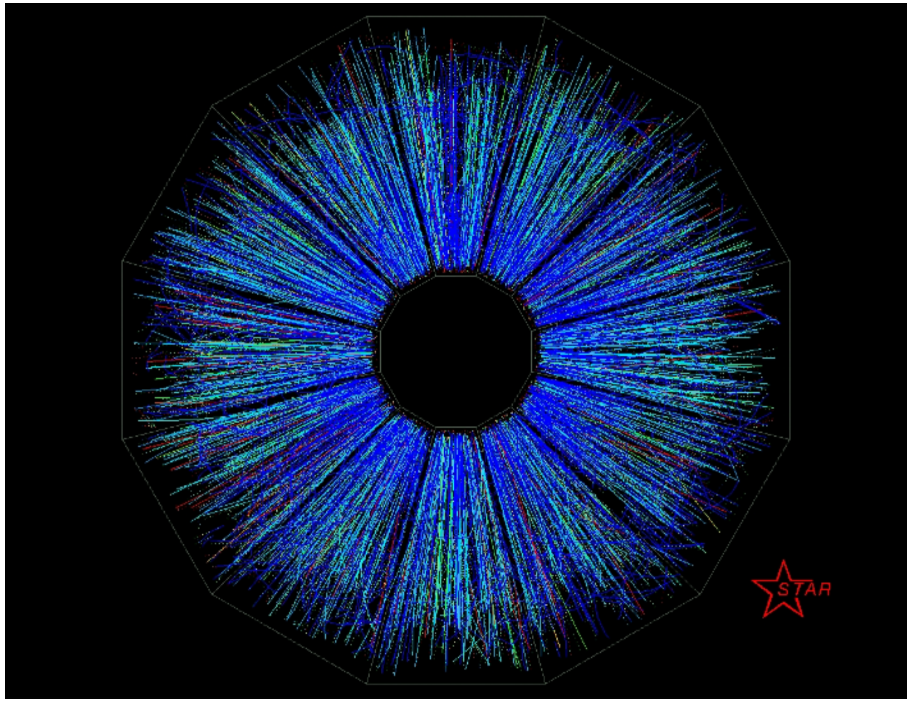
The STAR Detector



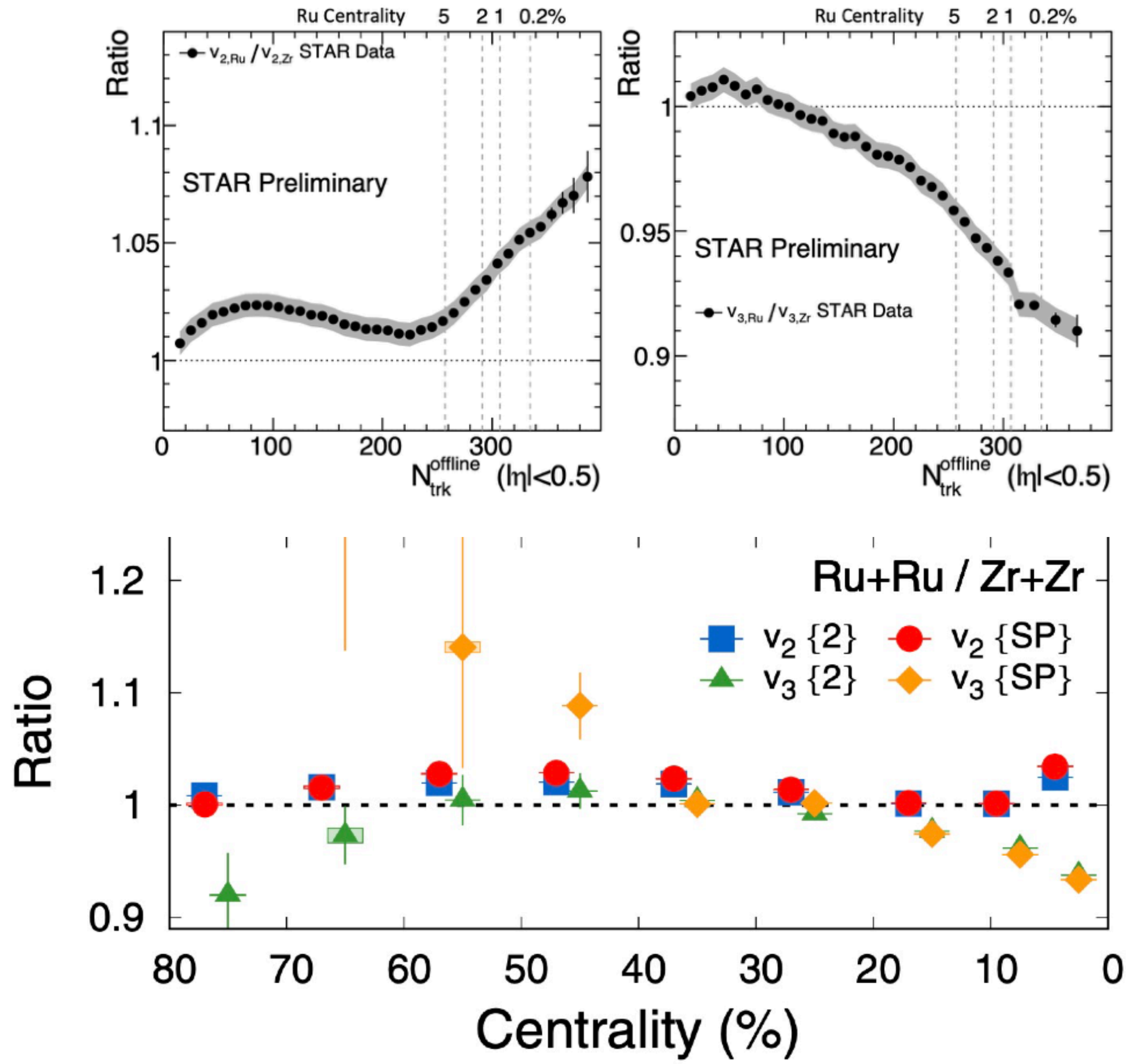


Dataset:
Zr+Zr and Ru+Ru 200 GeV
U+U 193 GeV
Au+Au 200 GeV

Acceptance:
$|\eta| < 1$
$0.2 < p_T < 2$ GeV/c
$0 < \phi < 2\pi$

Centrality vs Multiplicity

STAR, PRC105, 014901 (2022)
J. Jia, G. Wang, C. Zhang, arXiv:2203.12654 (2022)



- Due to bin shift, mapping on the same $N_{trk}^{offline}$ and mapping on the same centrality have some different