



PROBING NEUTRON SKIN AND SYMMETRY ENERGY WITH ISOBAR COLLISIONS

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Outline

I. Nuclear structure of isobars

II. How to probe nuclear structure using isobar collisions

III. Summary

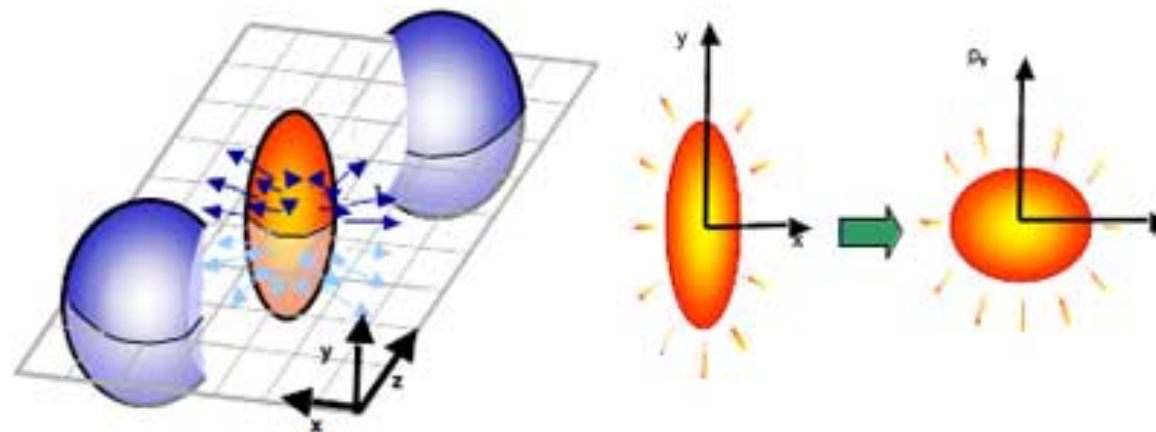


Relativistic Heavy ion collisions

Woods-Saxon
distributions

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}$$

$$R = R_0 [1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

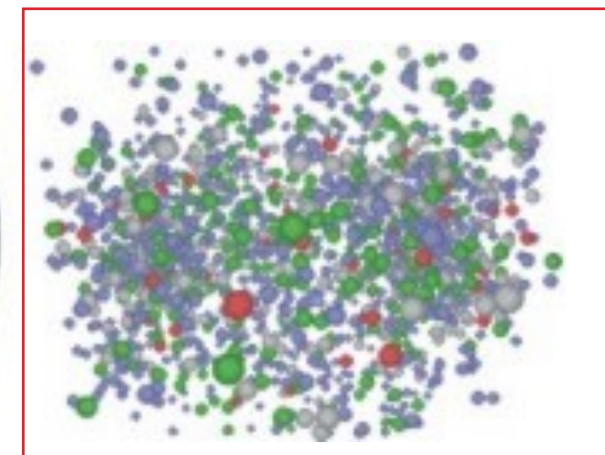
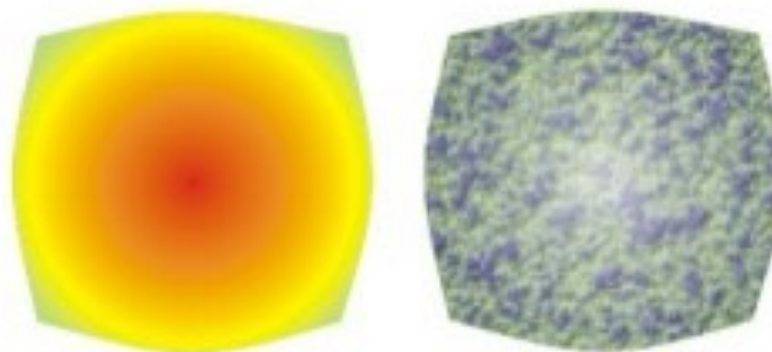
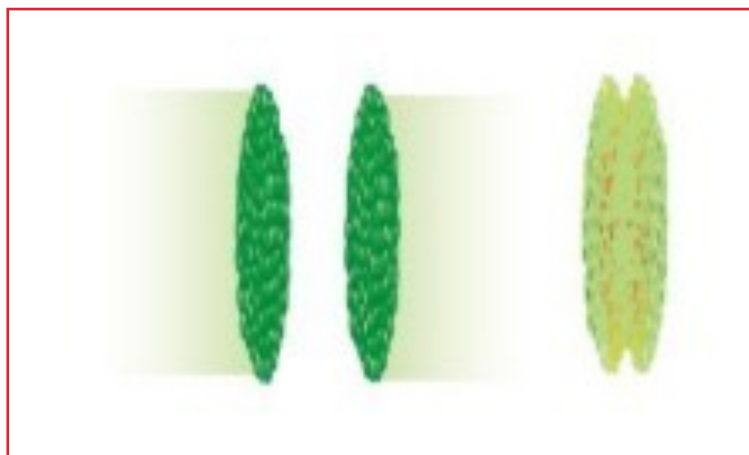


Bulk properties of QGP medium: $\eta/s, \zeta/s, \dots$

Anisotropic flow,
Flow fluctuations
HBT,
....

Initial geometry

Final observables

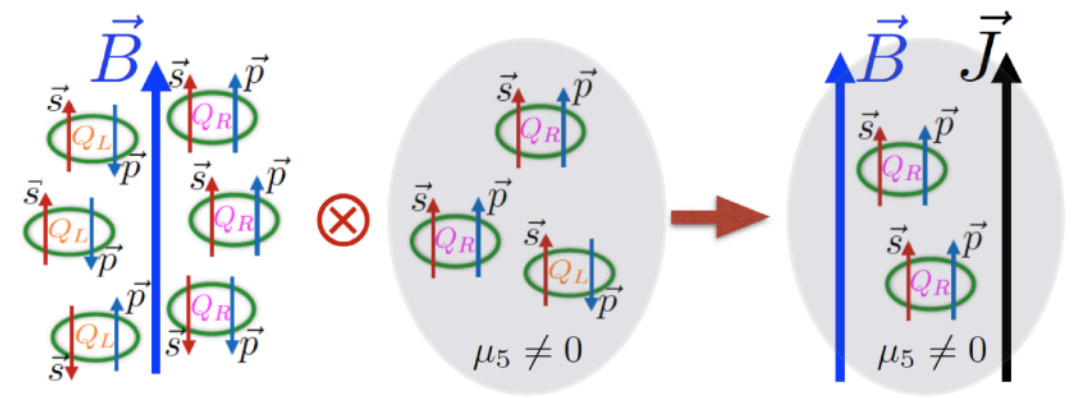




Relativistic isobaric collisions and chiral magnetic effect

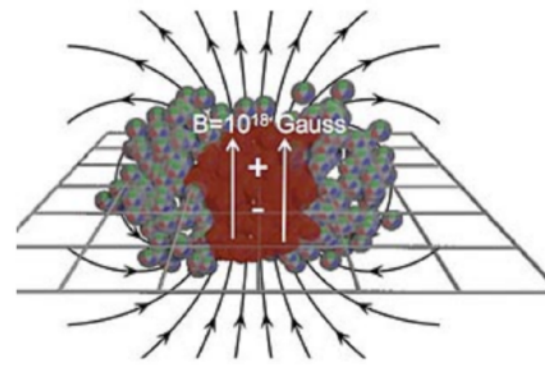
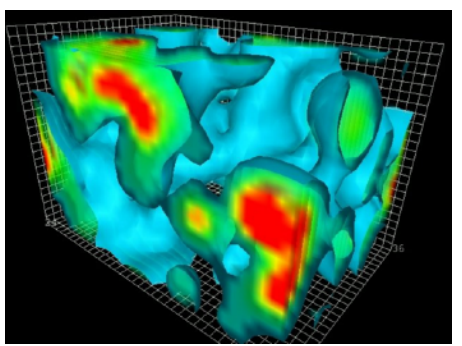
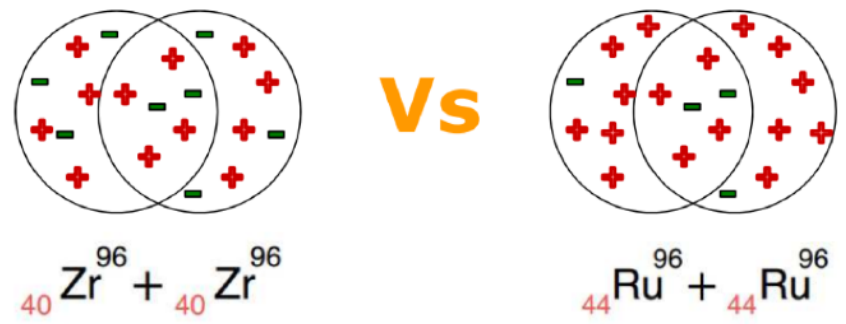
Evan Finch, SQM talk

Chiral magnetic effect (CME)



The isobar collisions was proposed to measure the chiral magnetic effect.

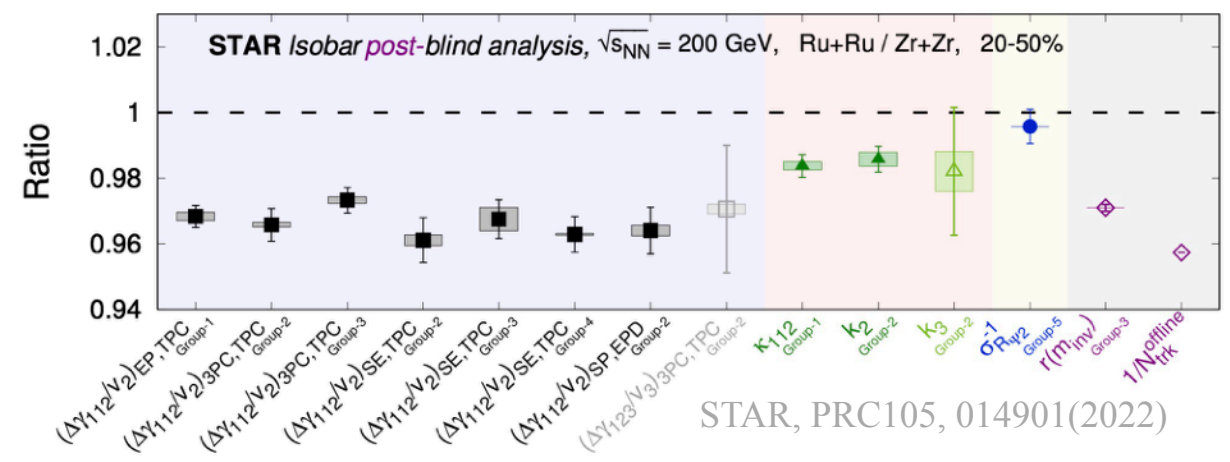
S. Voloshin, PRL105, 172301 (2010)



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

D. Kharzeev, et.al., PPNP88, 1(2016)

- Same background
- Different magnetic field => different CME signals



STAR, PRC105, 014901(2022)

Backgrounds are not identical!!!

Haojie Xu



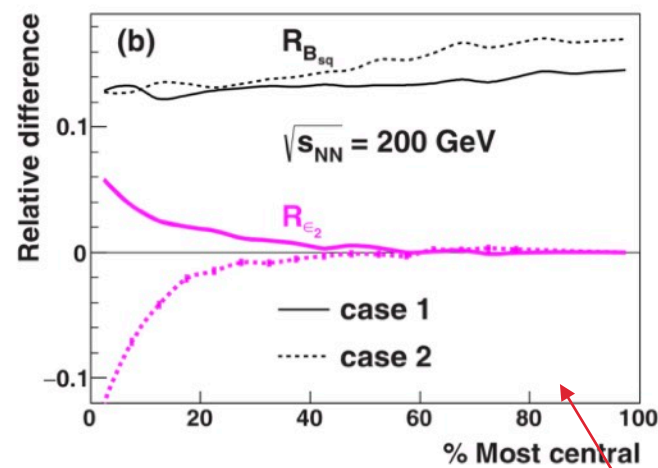
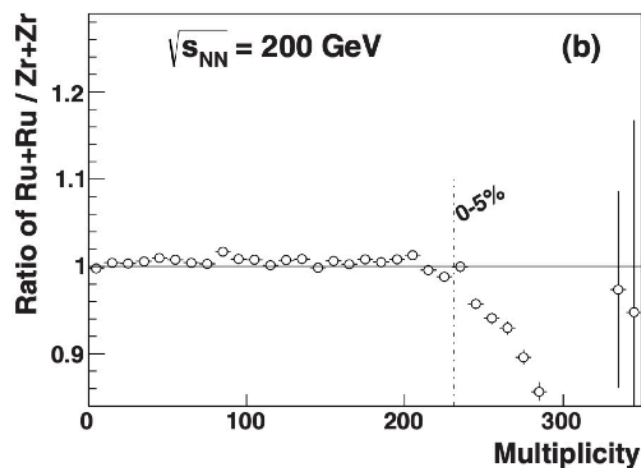
Predictions from charge density distributions

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

	R	a	beta2
Zr	5.02	0.46	0.08/0.217
Ru	5.085	0.46	0.158/0.053

WS parameters extracted from **charge** density distributions

W. Deng, X. Huang, et.al., PRC94,041901(2016)

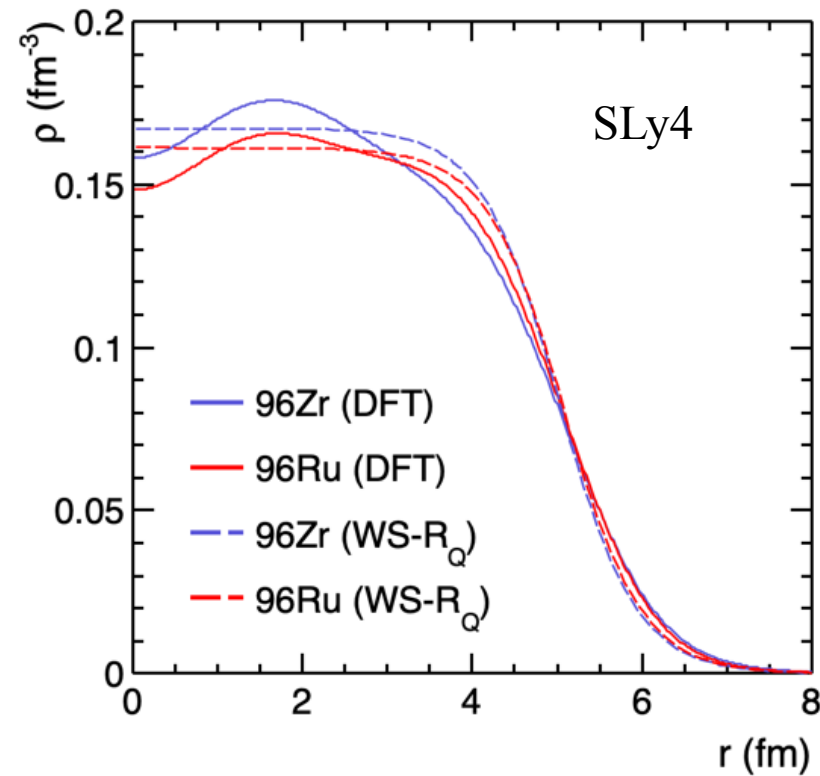


$$\Delta\gamma_{\text{bkg}} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle = \frac{N_{\text{cluster}}}{N_\alpha N_\beta} \times \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\text{cluster}}) \rangle \times v_{2,\text{cluster}}$$



Nuclear structure calculation by DFT

- **Charge density \neq nuclear density.**
- The proton and neutron densities obtained from the **energy density functional theory (DFT)**



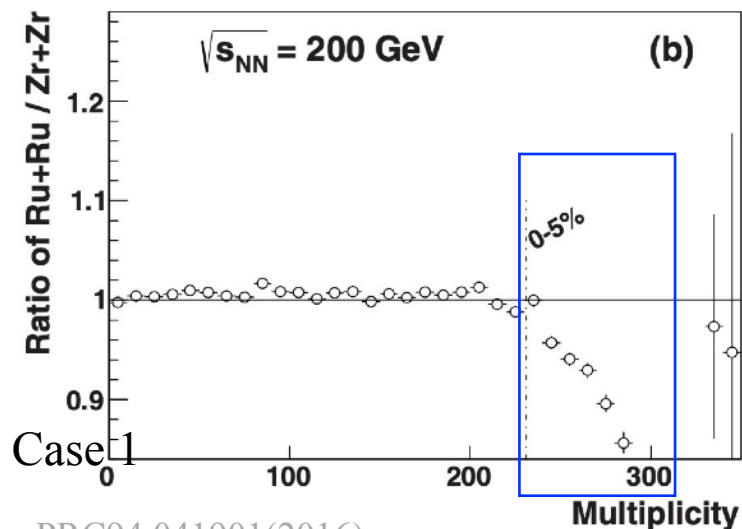
HJX, et.al., PRL121, 022301 (2018)

H. Li, HJX, et.al., PRC98, 054907(2018)

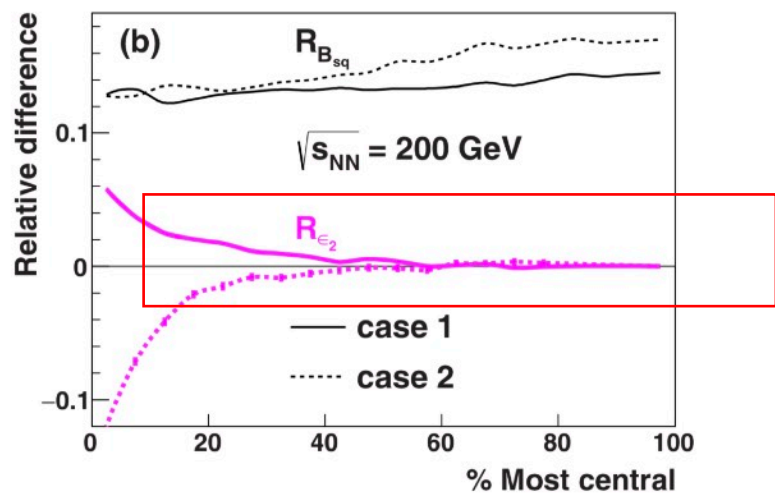


Predictions on isobar differences

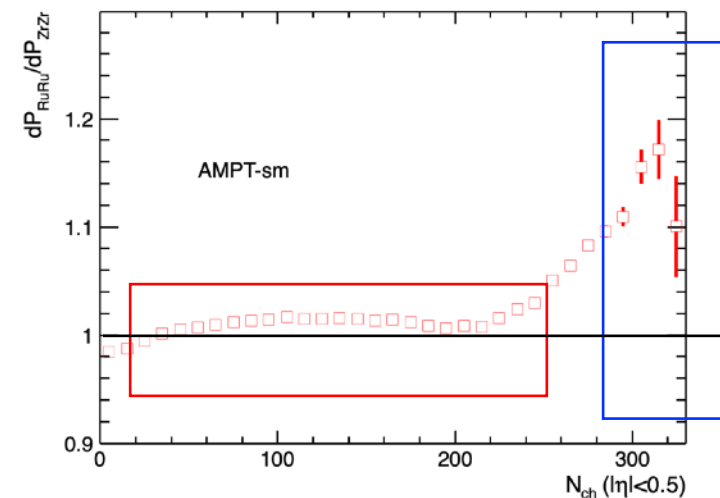
Predictions with charge densities



W. Deng, et.al., PRC94,041901(2016)

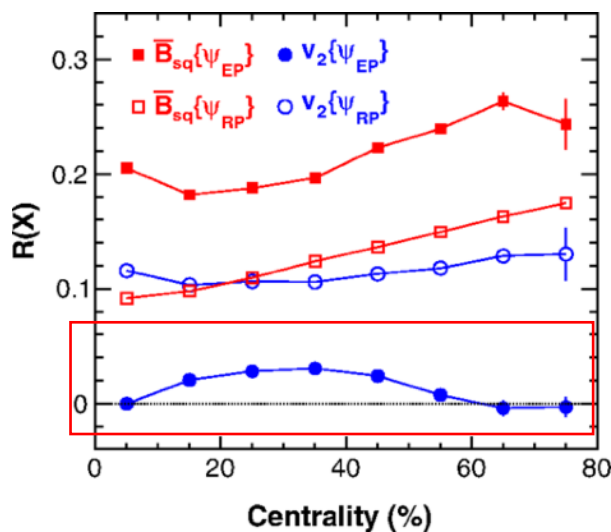


Predictions with DFT densities



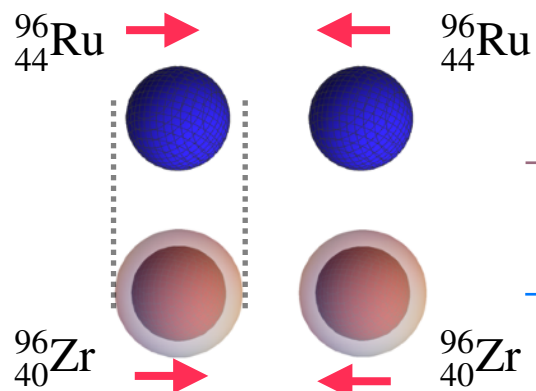
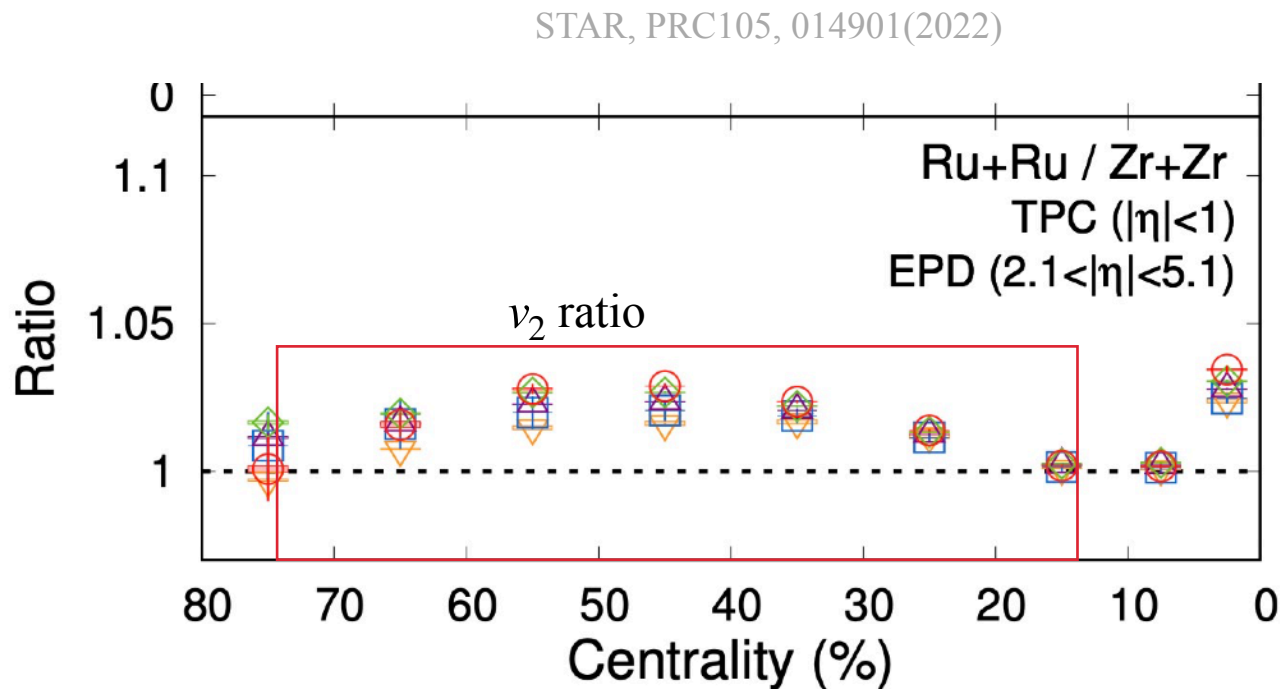
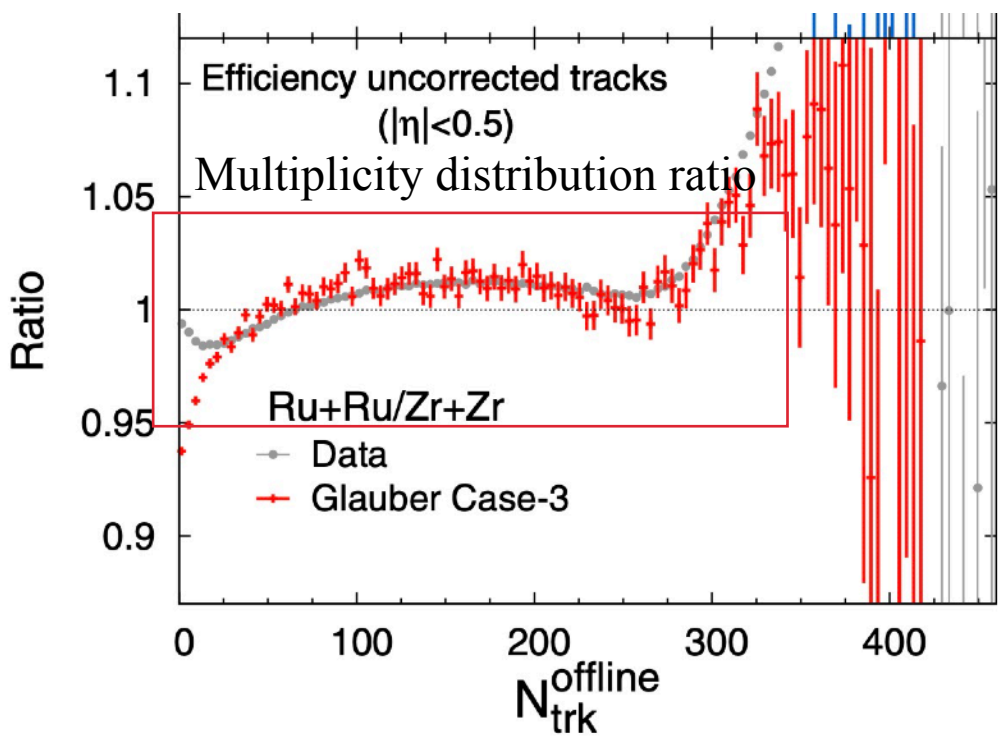
HJX, et.al, PRL121, 022301(2018)

H. Li, HJX, et.al., PRC98, 054907(2018)





DFT predictions are verified by STAR data



\rightarrow Smaller r , larger density

\rightarrow Larger r , smaller density

Neutron skin thickness

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

\rightarrow Larger N_{ch} and $\langle p_T \rangle$

\rightarrow 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)

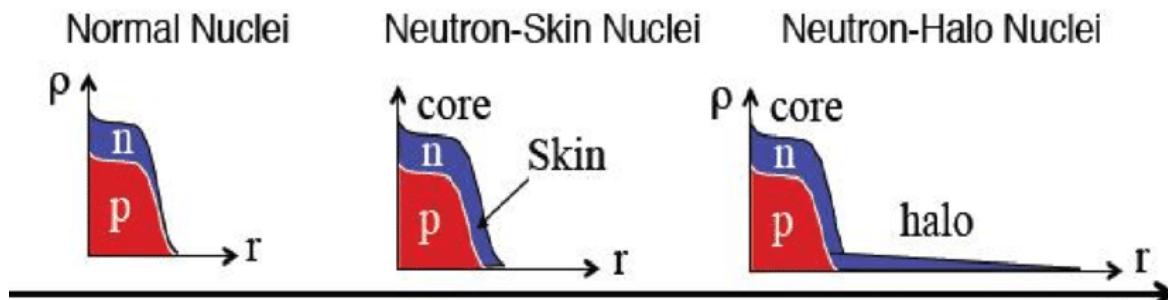
Haojie Xu



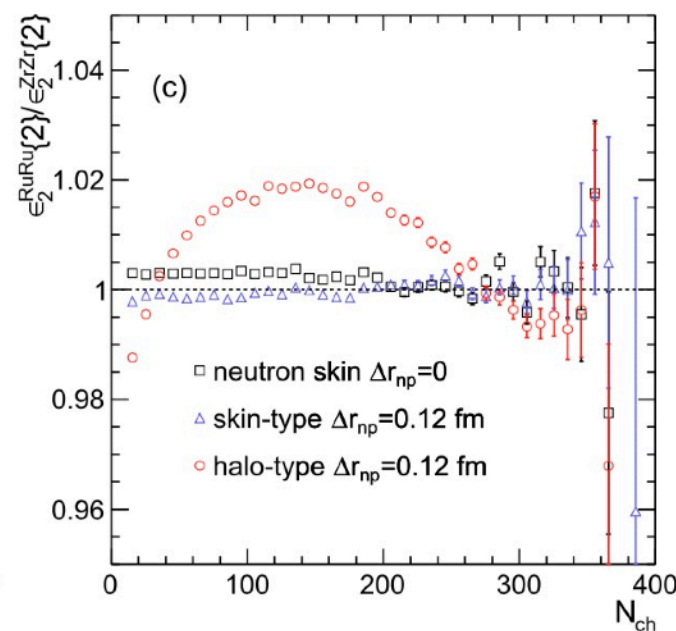
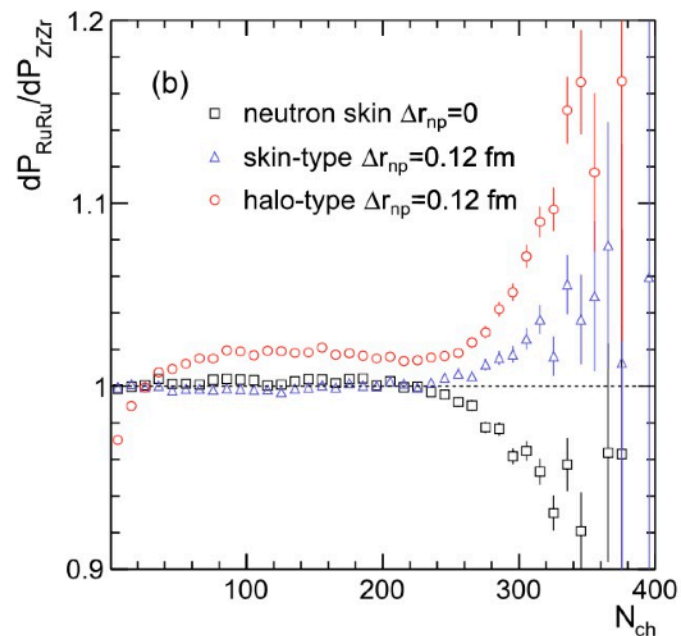
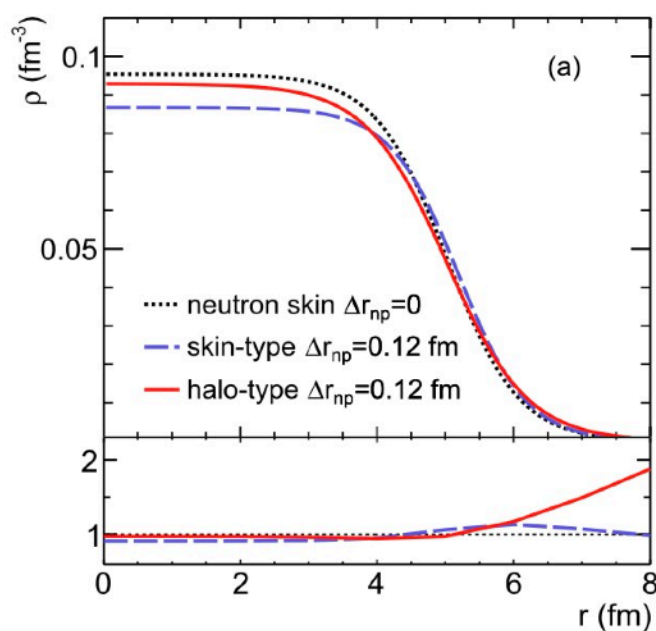
Determine the neutron skin type by STAR data

HJX, et.al., PLB819, 136453 (2021)

● Neutron-skin nuclei and neutron-halo nuclei for Zr



	⁹⁶ Ru		⁹⁶ Zr	
	<i>R</i>	<i>a</i>	<i>R</i>	<i>a</i>
p	5.085	0.523	5.021	0.523
skin-type n	5.085	0.523	5.194	0.523
halo-type n	5.085	0.523	5.021	0.592



The shapes of the Ru+Ru/Zr+Zr ratios of the multiplicity and eccentricity in mid-central collisions can further distinguish between skin-type and halo-type neutron densities.



Neutron skin: sensitive probe of symmetry energy

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

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

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

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

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

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

Slope parameter :

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

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

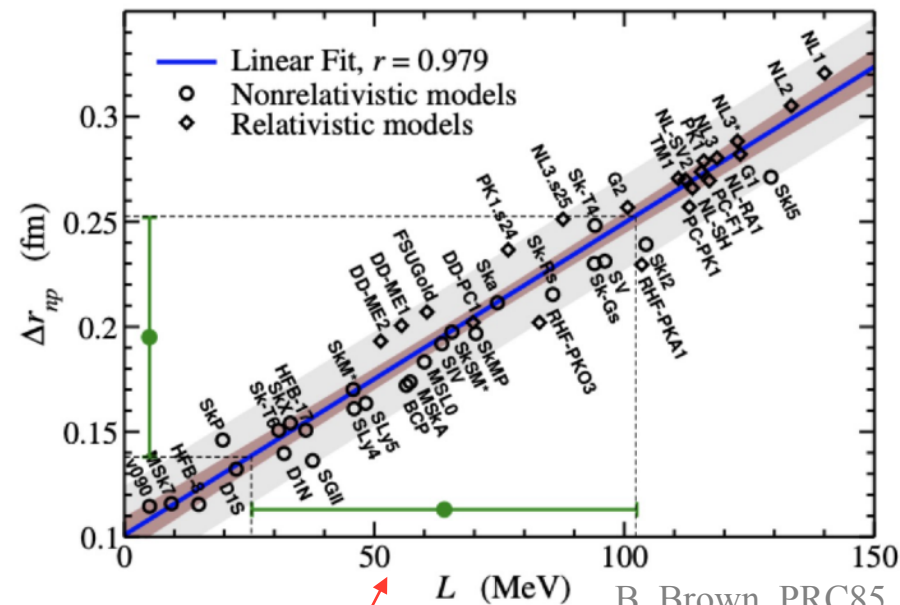
Larger L
Harder EOS



Need small δ to lower E



Smaller ρ_n , larger Δr



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

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.

Current status of neutron skin measurements

PREX-2 Collaboration, PRL126, 172502(2021); B. Reed, et.al., PRL126, 172503(2021)

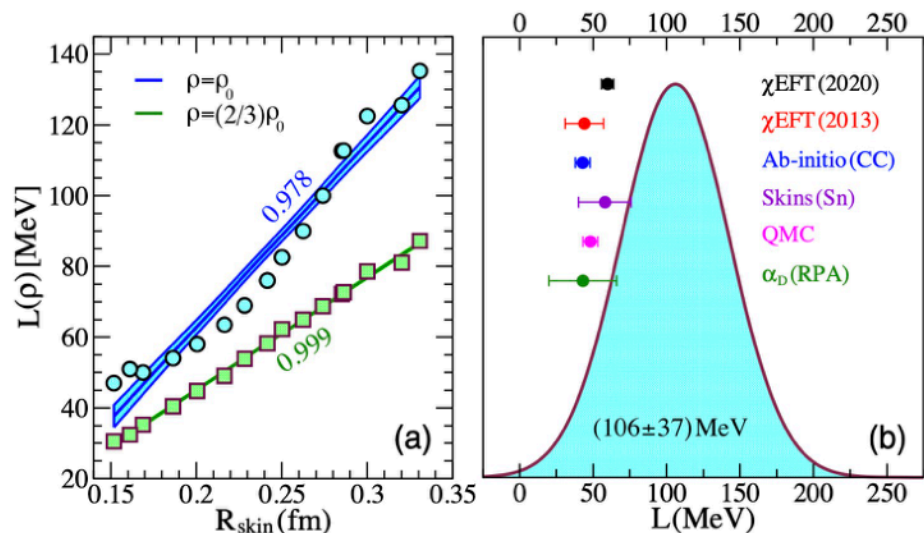
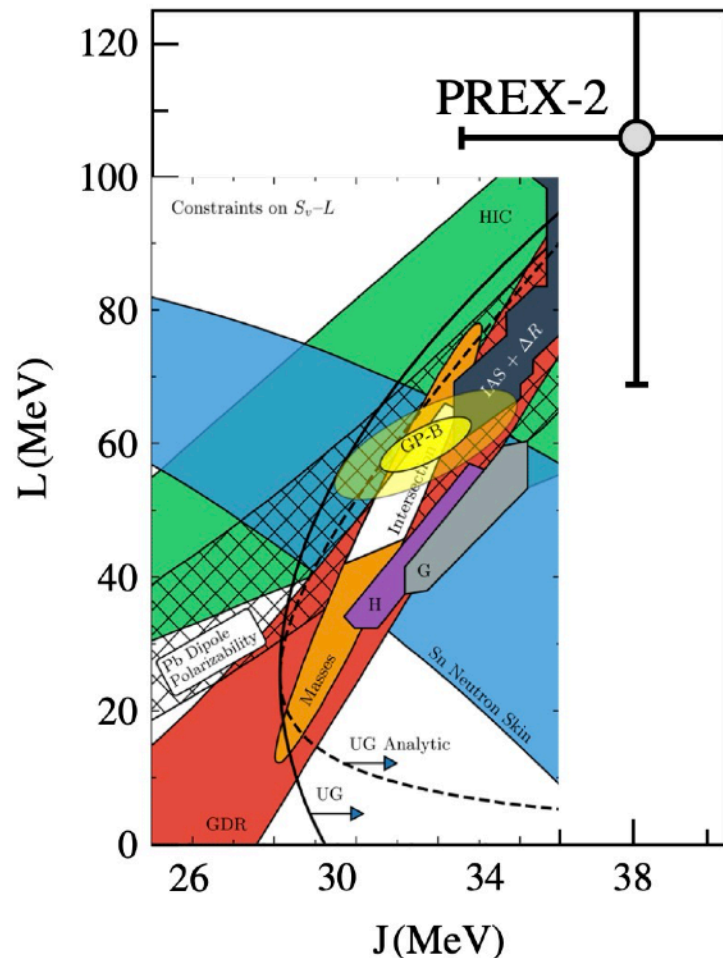


FIG. 1. Left: slope of the symmetry energy at nuclear saturation density ρ_0 (blue upper line) and at $(2/3)\rho_0$ (green lower line) as a function of R_{skin}^{208} . The numbers next to the lines denote values for the correlation coefficients. Right: Gaussian probability distribution for the slope of the symmetry energy $L = L(\rho_0)$ inferred by combining the linear correlation in the left figure with the recently reported PREX-2 limit. The six error bars are constraints on L obtained by using different theoretical approaches [14,19–25].



$$\Delta r_{\text{np}}^{\text{Pb}} = (0.284 \pm 0.071) \text{ fm}$$

$$L(\rho_0) = (106 \pm 37) \text{ MeV}$$

$$L(\rho_c) = (71.5 \pm 22.6) \text{ MeV}$$

This PREX-2 result favors a large neutron skin thickness and symmetry energy slope parameter, at tension with existing experimental data and theoretical analyses.



Neutron skin and nuclear symmetry energy

Z. Zhang, PRC94, 064326(2016)

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

SHF: Standard Skyrme-Hartree-Fock (SHF) model

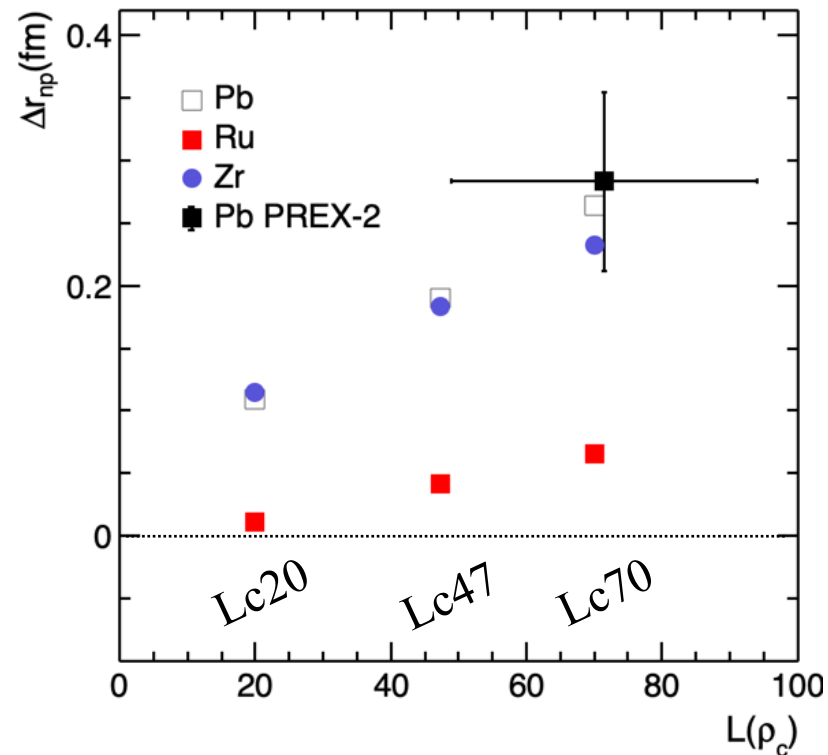
eSHF: Extended SHF model

$$\begin{aligned}
 v_{i,j} = & t_0(1 + x_0 P_\sigma) \delta(\mathbf{r}) + \frac{1}{6} t_3(1 + x_3 P_\sigma) \rho^\alpha(\mathbf{R}) \delta(\mathbf{r}) \\
 & + \frac{1}{2} t_1(1 + x_1 P_\sigma) [K'^2 \delta(\mathbf{r}) + \delta(\mathbf{r}) K^2] \\
 & + t_2(1 + x_2 P_\sigma) \mathbf{K}' \cdot \delta(\mathbf{r}) \mathbf{K} \\
 & + \frac{1}{2} t_4(1 + x_4 P_\sigma) [K'^2 \delta(\mathbf{r}) \rho(\mathbf{R}) + \rho(\mathbf{R}) \delta(\mathbf{r}) K^2] \\
 & + t_5(1 + x_5 P_\sigma) \mathbf{K}' \cdot \rho(\mathbf{R}) \delta(\mathbf{r}) \mathbf{K} \quad \text{Extended} \\
 & + iW_0(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) \cdot [\mathbf{K}' \times \delta(\mathbf{r}) \mathbf{K}], \quad (4)
 \end{aligned}$$

$$E(\rho, \delta) = E_0(\rho) + E_{\text{sym}}(\rho) \delta^2 + O(\delta^4)$$

$$\rho = \rho_n + \rho_p; \quad \delta = \frac{\rho_n - \rho_p}{\rho}$$

$$L(\rho_c) = 3\rho_c \left[\frac{dE_{\text{sym}}(\rho)}{d\rho} \right]_{\rho=\rho_c}; \quad \rho_c \simeq 0.11 \text{fm}^{-3}$$

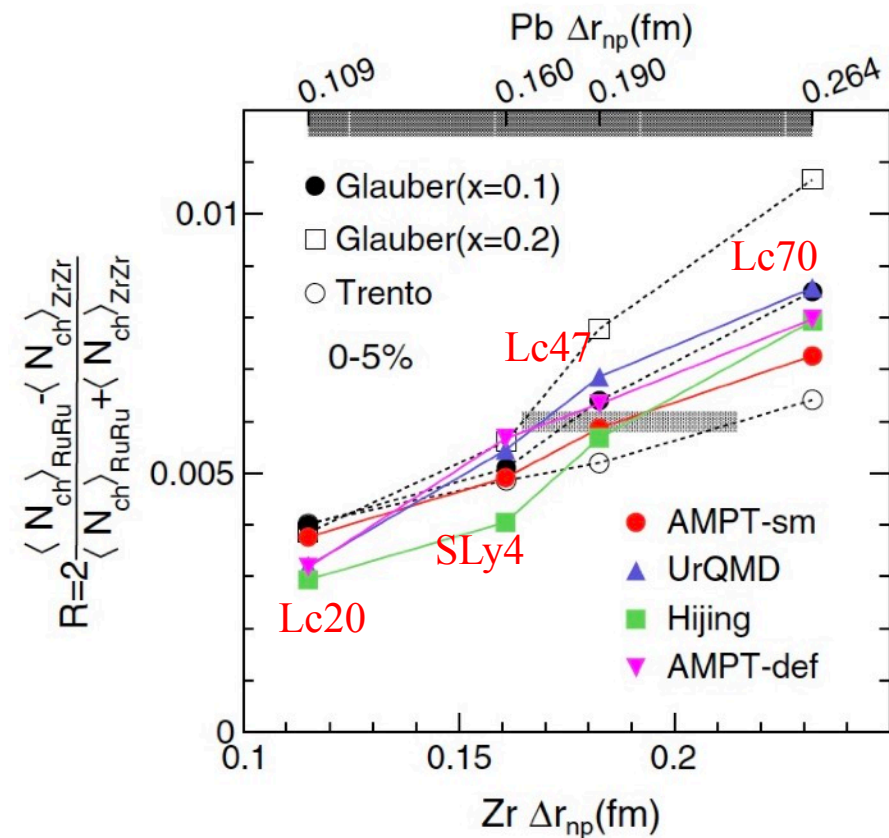
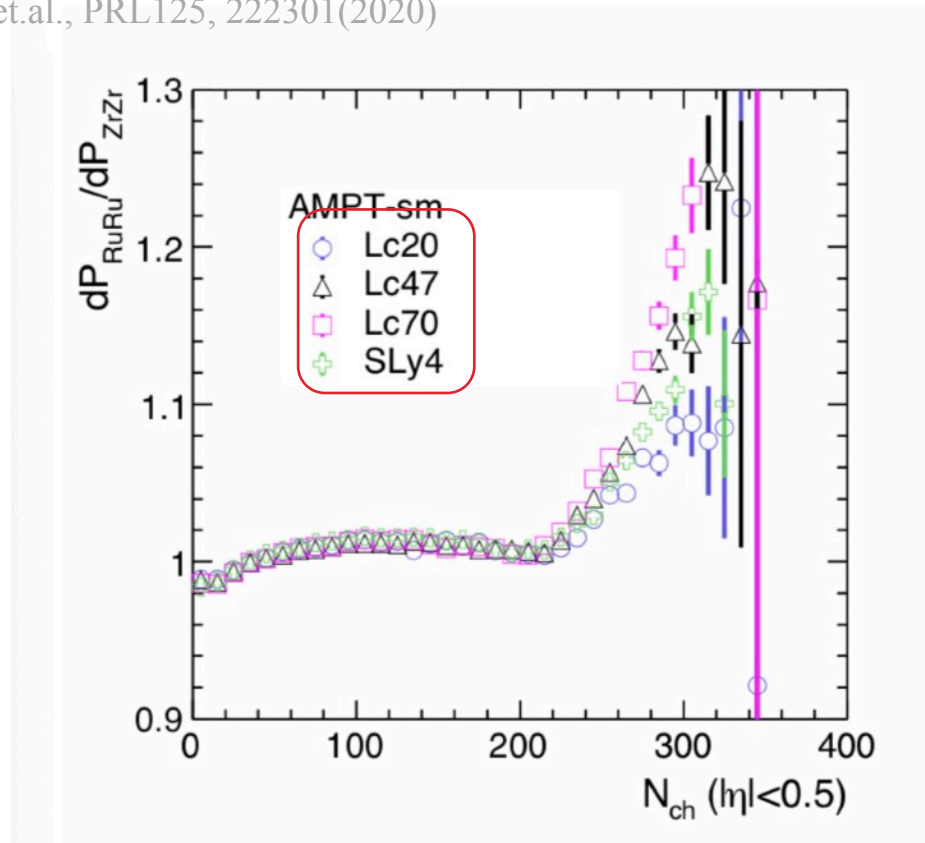


			⁹⁶ Zr			⁹⁶ Ru			²⁰⁸ Pb
	$L(\rho_c)$	$L(\rho_0)$	r_n	r_p	Δr_{np}	r_n	r_p	Δr_{np}	Δr_{np}
Lc20	20	13.1	4.386	4.27	0.115	4.327	4.316	0.011	0.109
Lc47	47.3	55.7	4.449	4.267	0.183	4.360	4.319	0.042	0.190
Lc70	70	90.0	4.494	4.262	0.232	4.385	4.32	0.066	0.264
SLy4	42.7	46.0	4.432	4.271	0.161	4.356	4.327	0.030	0.160



Method I: multiplicity distribution ratio

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

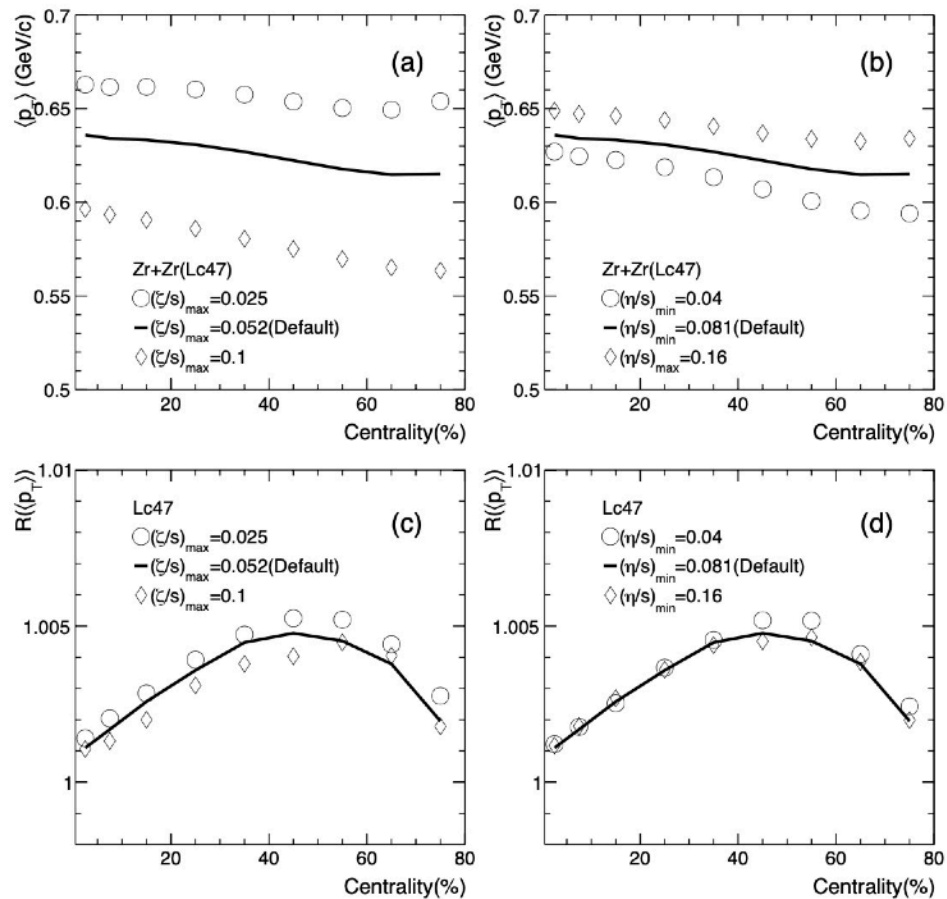


- The ratio of N_{ch} distributions **highlight the differences**
- To **quantify the differences**, we use the **R observable** of N_{ch} at top 5% centrality.
- R is a relative measure, **much of experimental effects cancel**

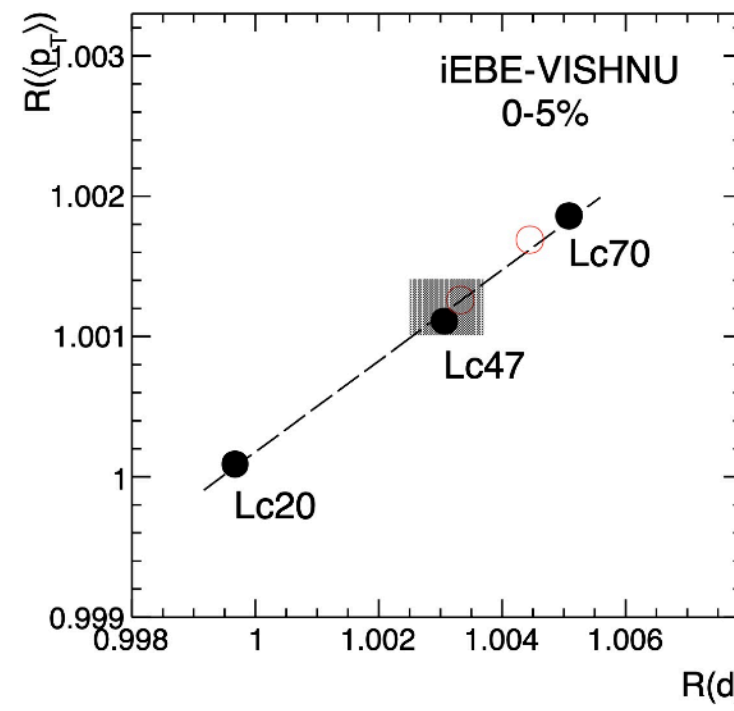


Method II: mean p_T ratio

HJX, et.al, arXiv:2111.14812



$$R(\langle p_T \rangle) \propto R(d_{\perp}) \propto 1/R(\langle \sqrt{r^2} \rangle)$$



The $R(\langle p_T \rangle)$ is **inversely proportional** to nuclear size ratio in most central collisions.



STAR measurements



Compare to world wide data

HJX(STAR)¹⁸, QM2022

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

Zhang, Chen, PRC94, 064326 (2016)

- Multiplicity ratio:

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

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

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

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

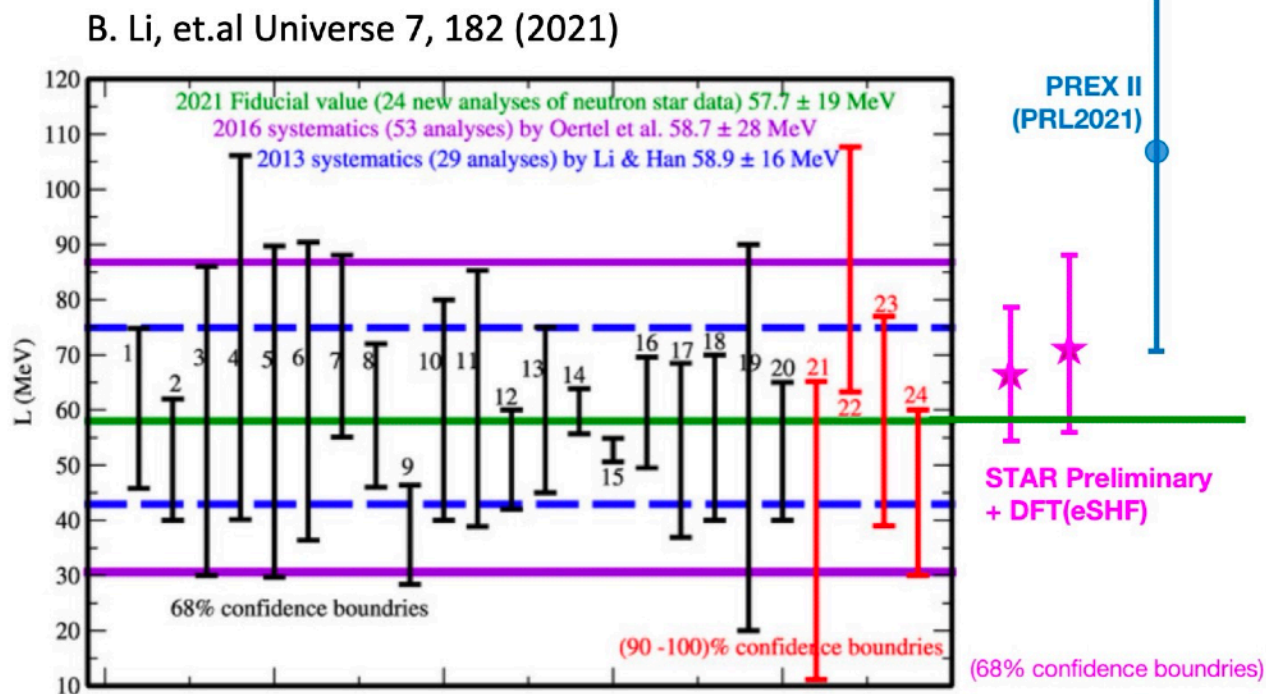
- $\langle p_T \rangle$ ratio:

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

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

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

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



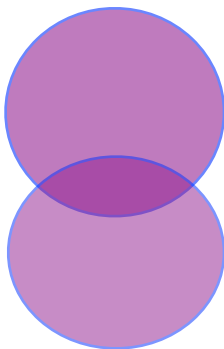
Consistent with world wide data with good precision



Method III: net-charge ratio in very peripheral collisions

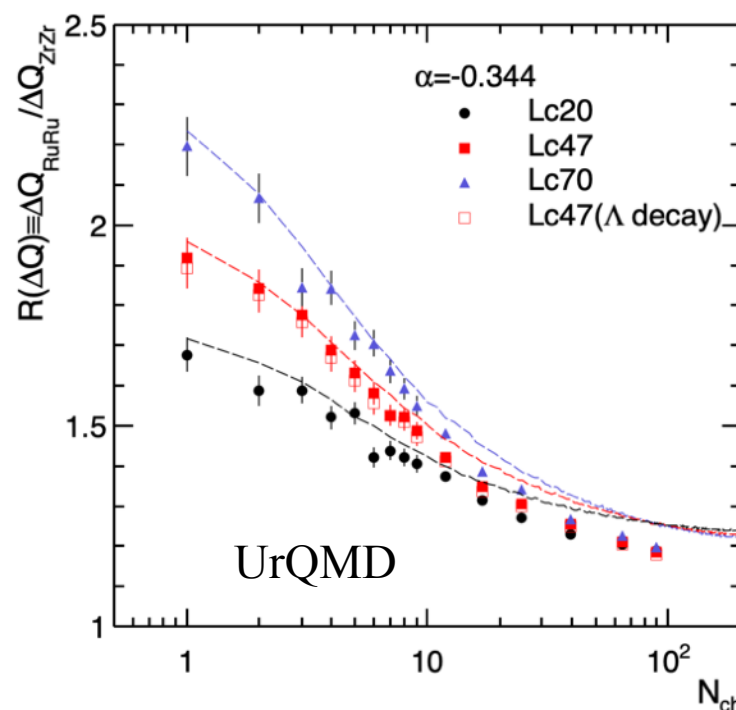
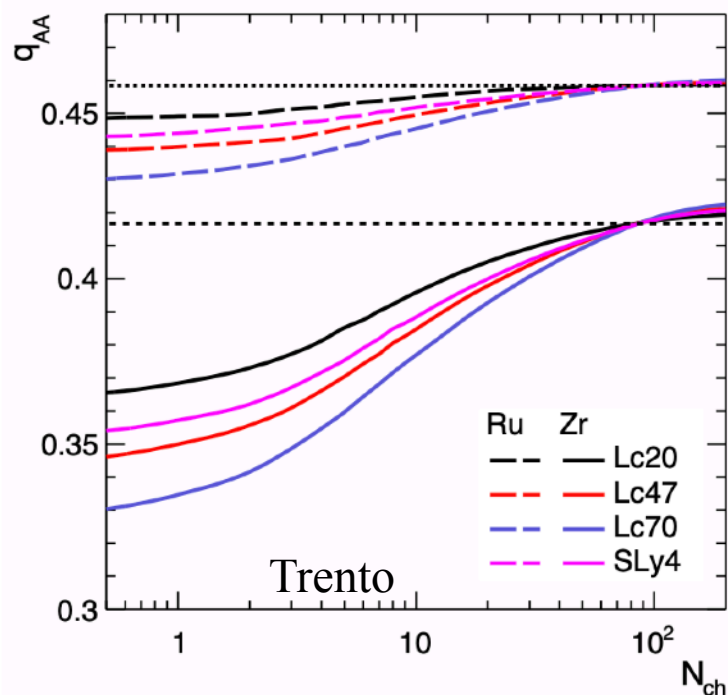
HJX, et.al., PRC105, L011901 (2022)

For the colliding nuclei with large neutron skin thickness



more n+n collisions at most peripheral collisions

Less participant charges, thus less final net-charges



The curves are calculated by superimposition assumption

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

where $q_{RuRu/ZrZr}$ are the fraction of protons among the participant nucleons, obtained by the Trento model.

α is the ΔQ ratio in nn to pp interaction:

Pytha: $\alpha = -0.352$

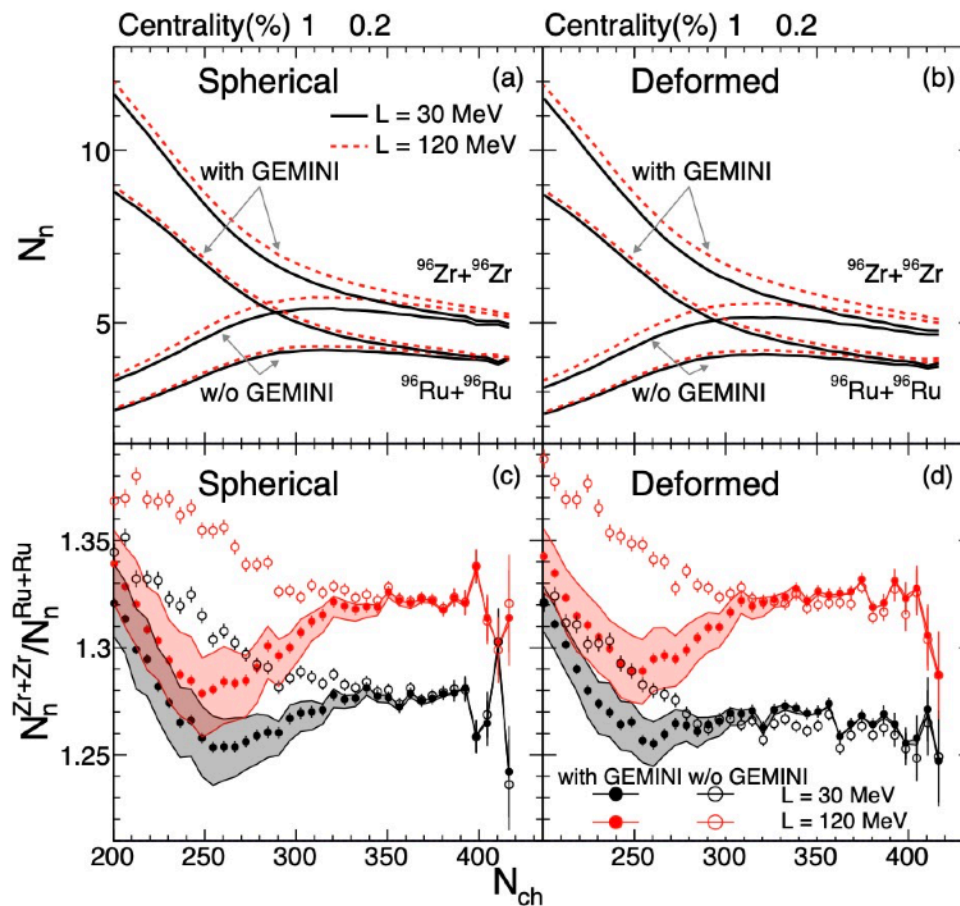
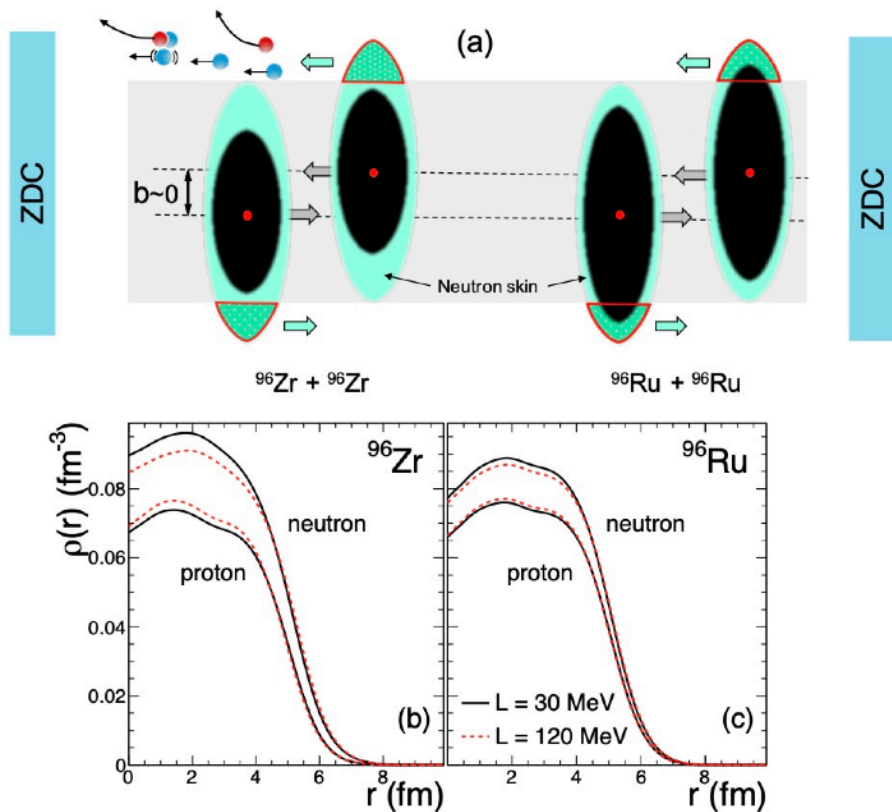
Hijing: $\alpha = -0.389$

UrQMD: $\alpha = -0.344$



Method IV: spectator neutrons in ultracentral collisions

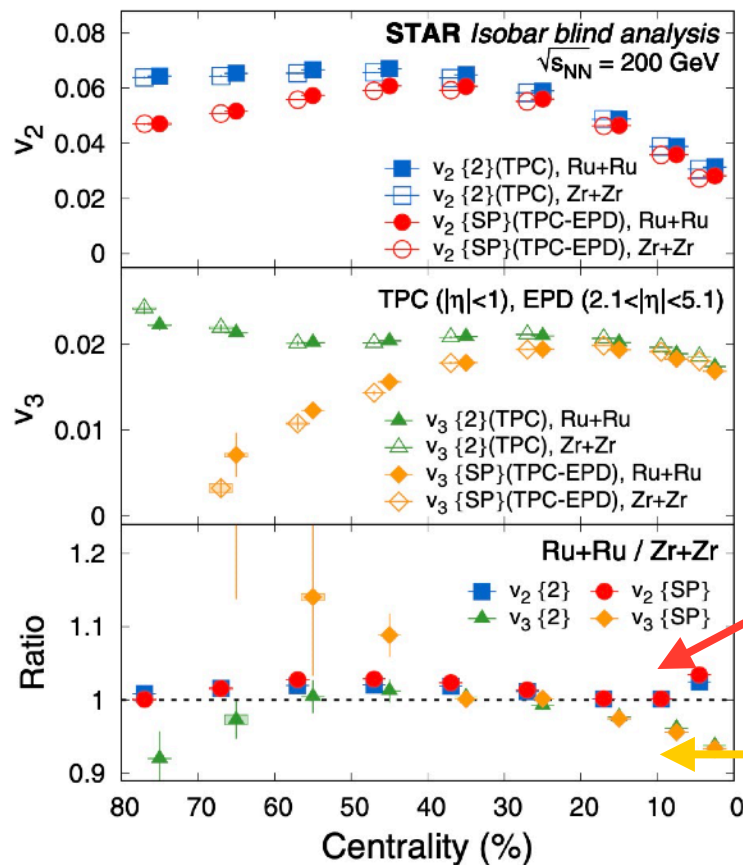
L. Liu, et.al, arXiv:2203.09924(2022)



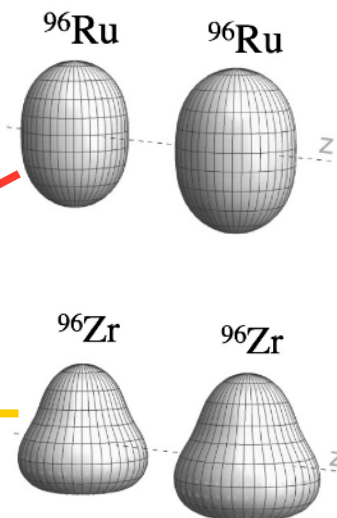
The yield ratio of free spectator neutrons is a clean probe of the neutron-skin thickness



Nuclear deformation



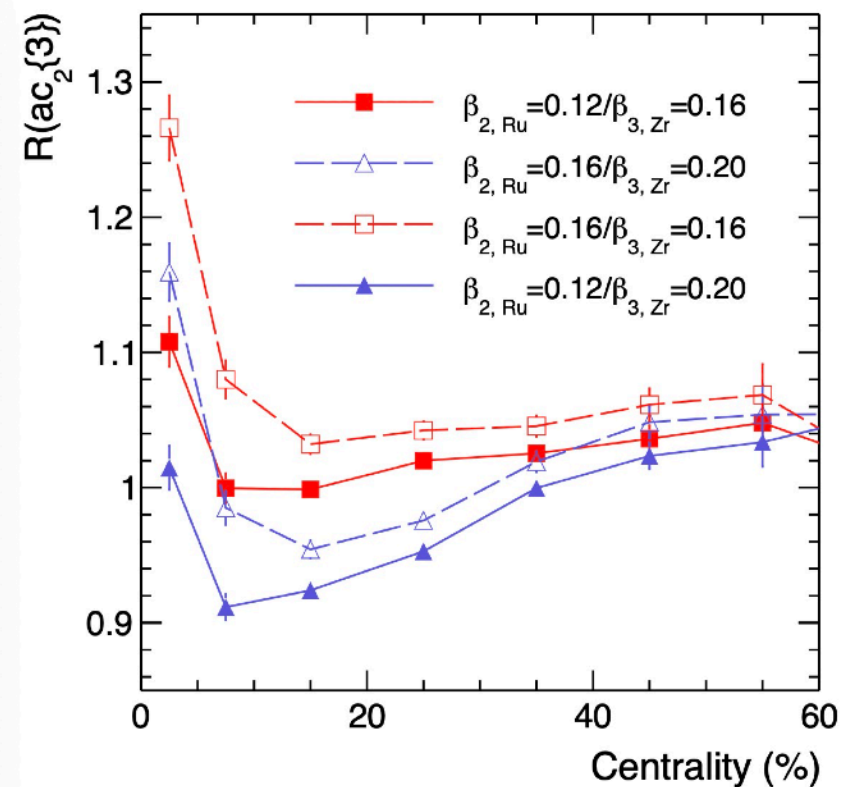
STAR, PRC105, 014901 (2022)
 C. Zhang, J. Jia, PRL128, 022301(2022)



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

S. Zhao, HJX, et.al, arXiv:2204.02387

$$ac_2\{3\} \equiv \langle\langle e^{i(2\varphi_1+2\varphi_2-4\varphi_3)} \rangle\rangle = \langle v_2^2 v_4 \cos 4(\Psi_2 - \Psi_4) \rangle$$





SUMMARY

- The STAR isobar data indicate **thick halo-type neutron skin in Zr**, consistent with **DFT** calculations
 - Nuclear structure causes isobar multiplicity and v_2 differences, important for the CME search
- Precision isobar data can be used to **probe the neutron skin and symmetry energy**
 - Multiplicity distribution ratio; Mean p_T ratio; Net charge ratio; Spectator proton ratio,...

**Thank you for
your attention!**

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