PHYSICS OPPORTUNITIES FROM RELATIVISTIC ISOBAR COLLISIONS

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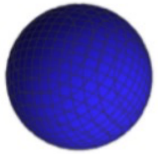
第20届全国中高能核物理大会暨第十四届全国中高能核物理专题研讨会

2025.04.24-28, 上海

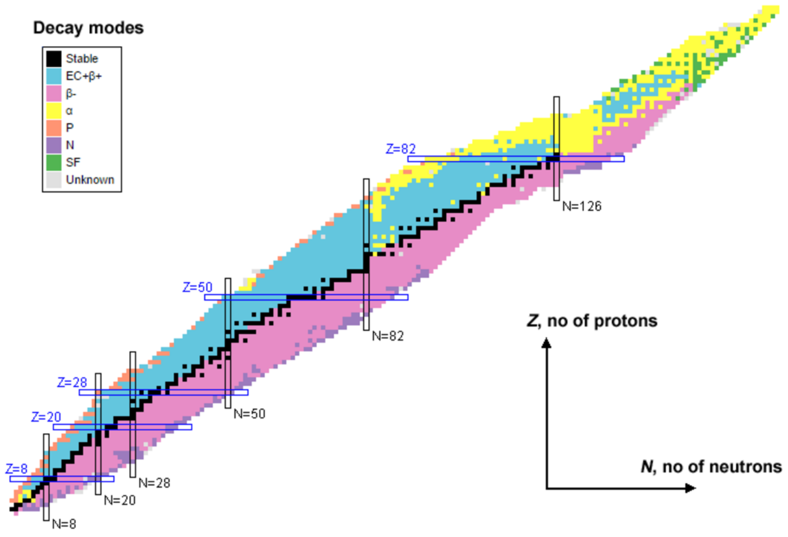
Outline

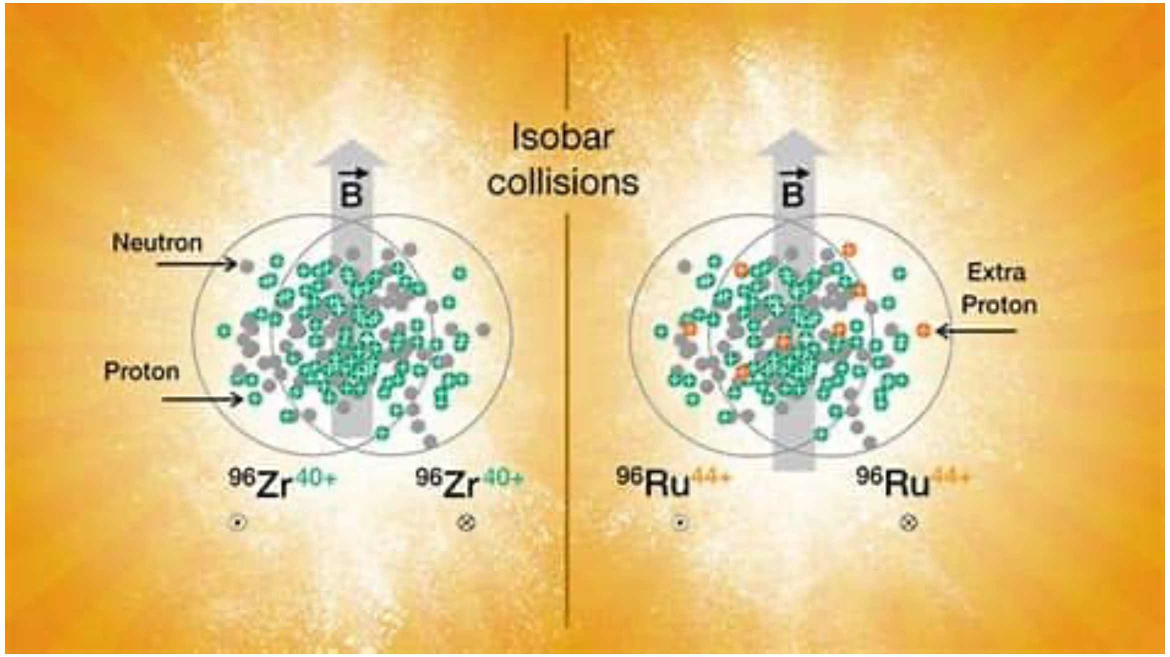
I Introduction
II Nuclear structure measurements
III Solve the flow puzzle with nuclear structure
IV Summary

$^{96}_{40}Zr$ Zirconium 锆



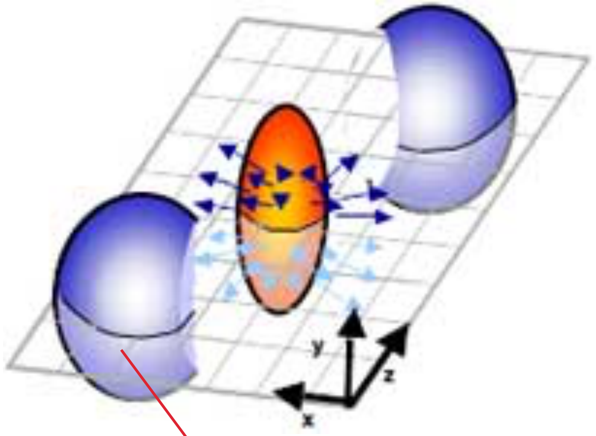
$^{96}_{44}Ru$ Ruthenium 钌

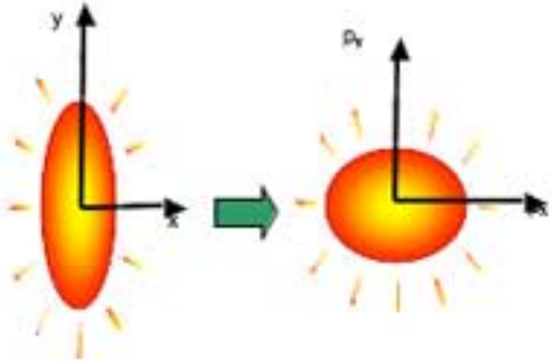


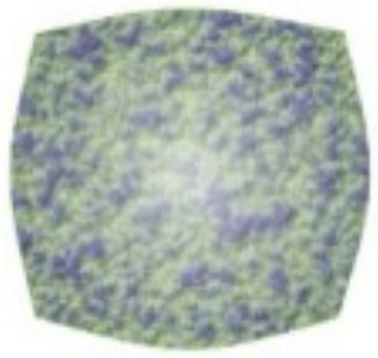


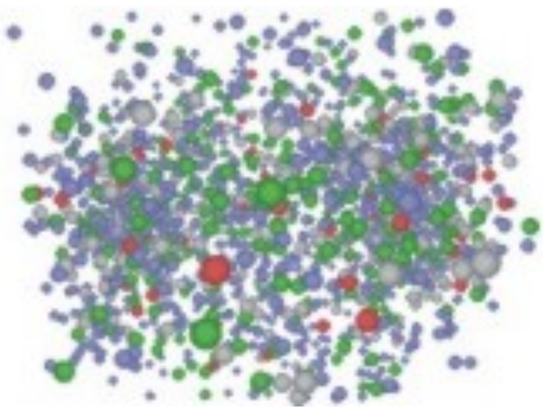
Relativistic heavy ion collisions

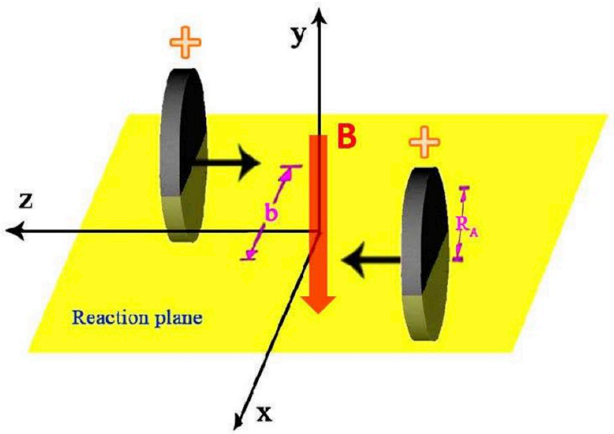
Participants

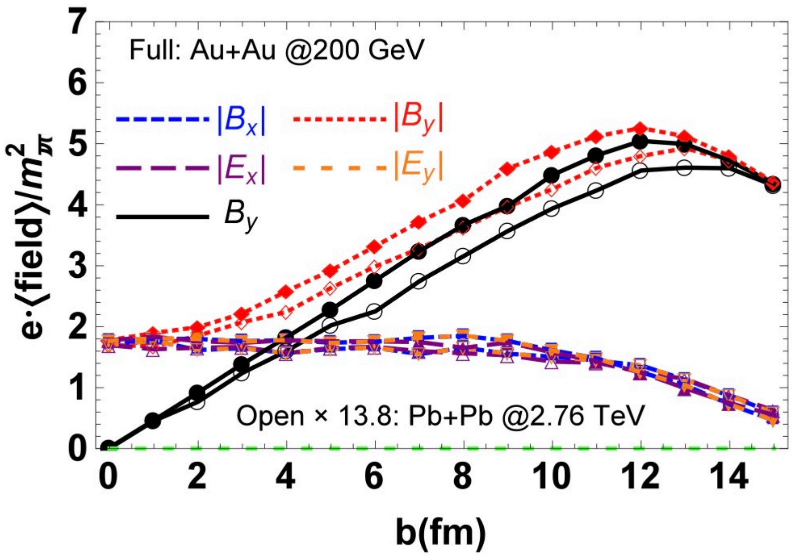










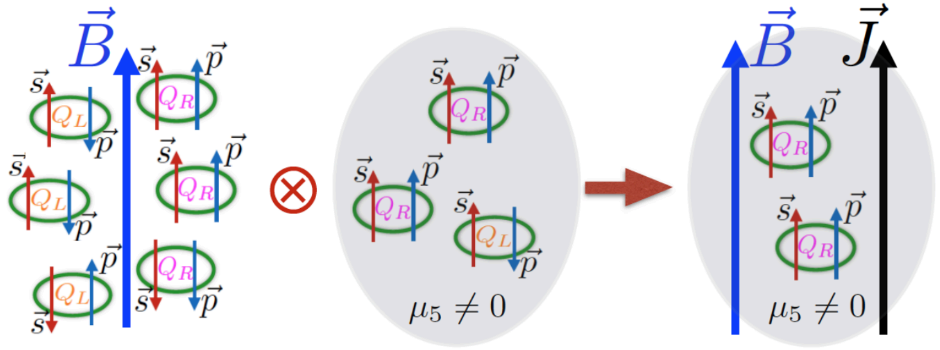


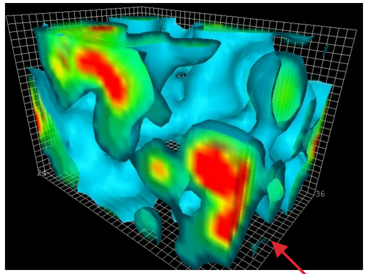
Spectators

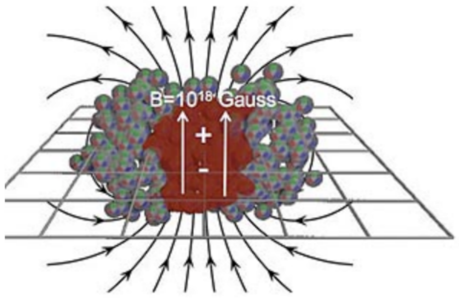
徐浩洁 (湖州师范学院)

Chiral magnetic effect

Chiral magnetic effect (CME)





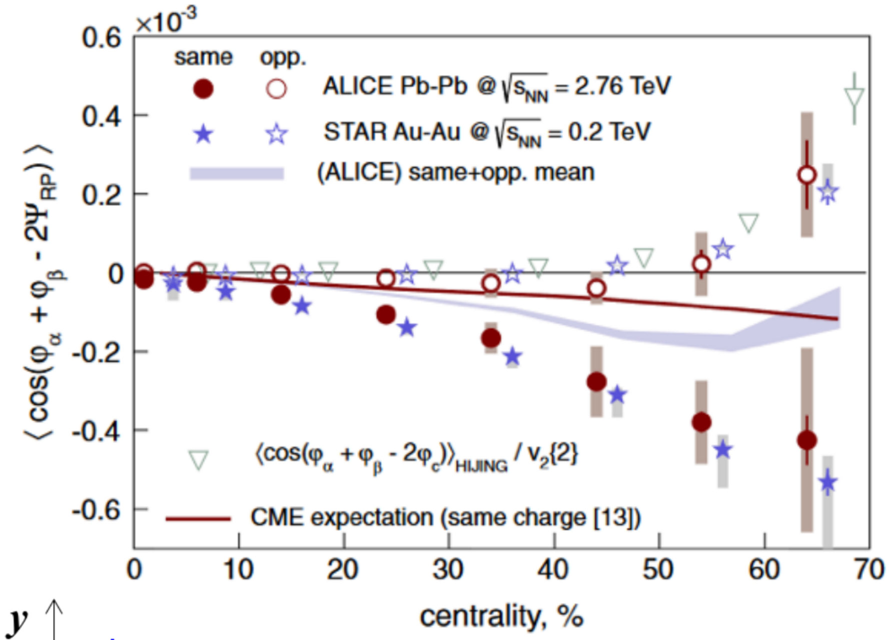


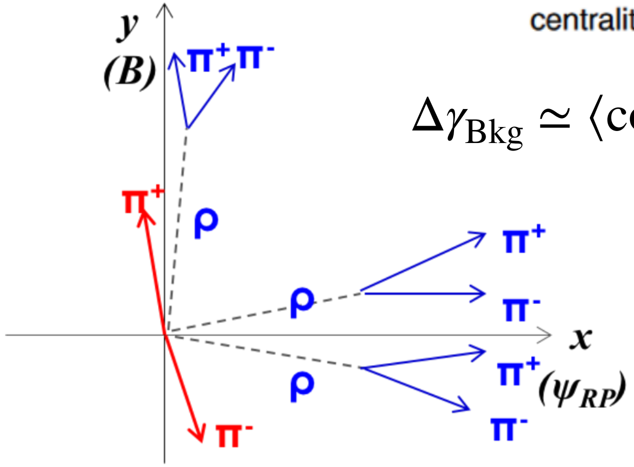
$$\mathbf{J_{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2}\mu_5\right)\mathbf{B},$$

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

CME signal vs background

STAR, PRL103, 251601 (2009)
ALICE, PRL110, 012301 (2013)



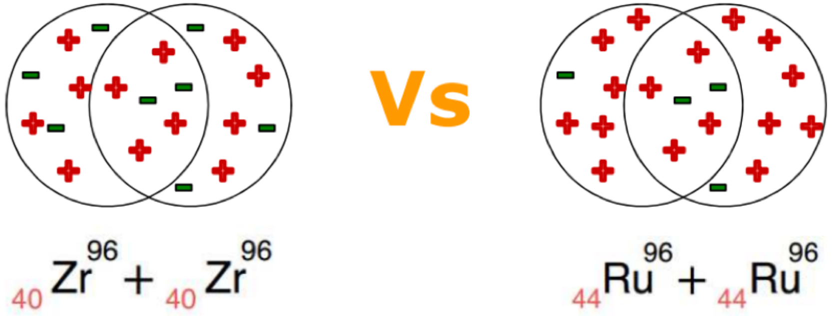


$$\Delta\gamma_{\mathrm{Bkg}} \simeq \langle\cos(\phi_a + \phi_b - 2\Psi_{\mathrm{RP}})\rangle v_{2,\mathrm{clust}}$$

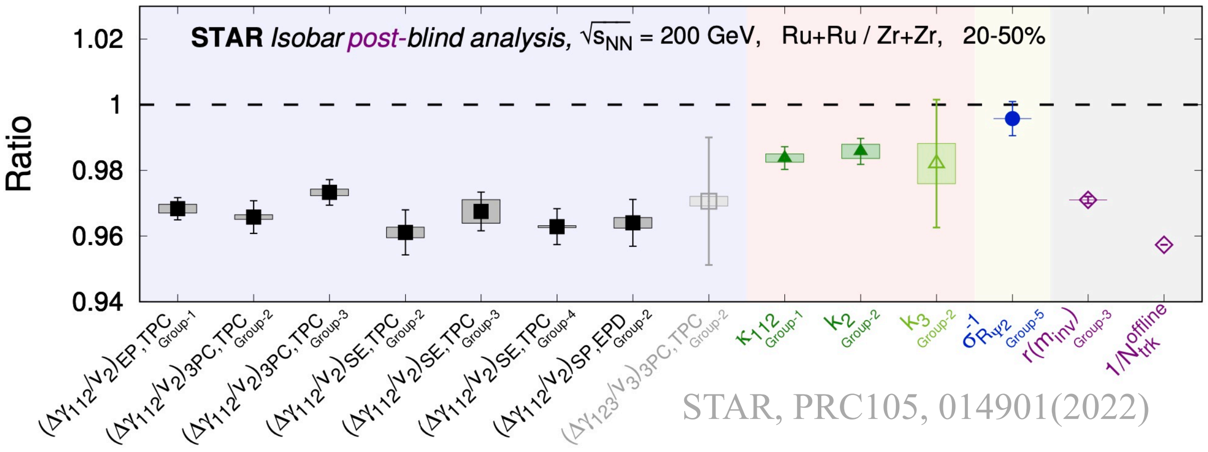
Schlichting, PRC83(2011)
Bzdak, PRC81(2010)
Wang, PRC81(2010)

Relativistic isobaric collisions

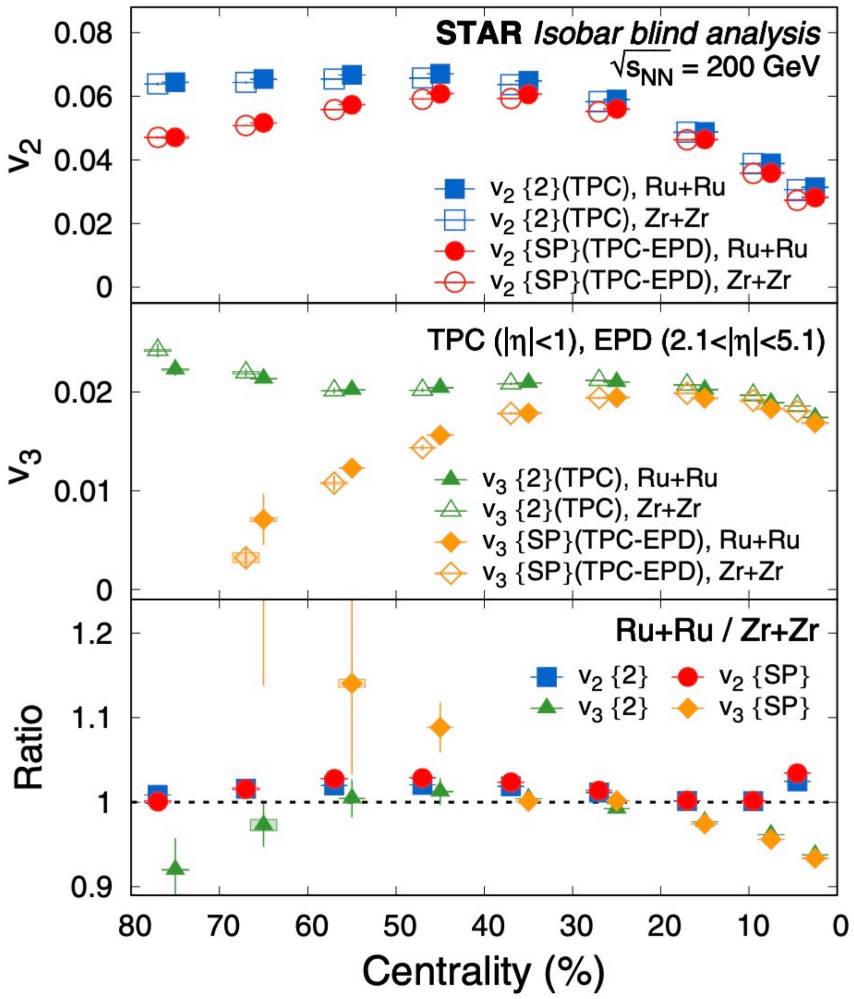
The isobar collisions were proposed to measure the chiral magnetic effect. S. Voloshin, PRL105, 172301 (2010)



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



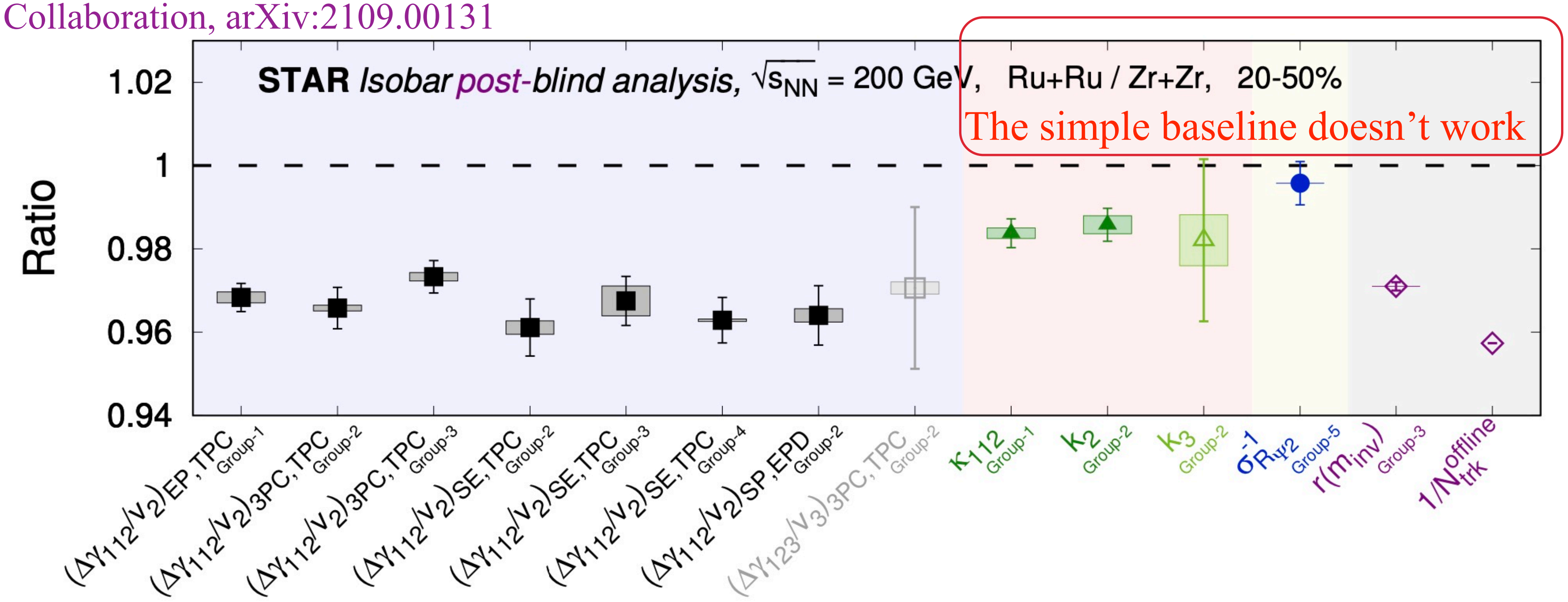
STAR, PRC105, 014901(2022)



Backgrounds are not identical!!!

Isobar structures are important for the CME search

STAR Collaboration, arXiv:2109.00131



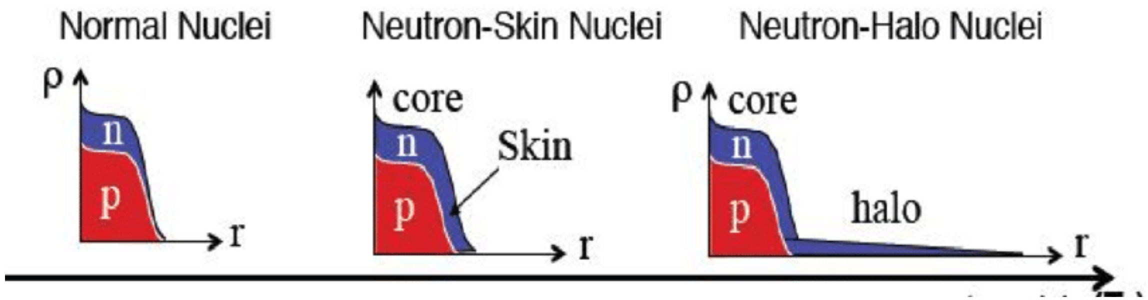
$$\Delta\gamma_{\rm bkg} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle = \frac{N_{\rm cluster}}{N_\alpha N_\beta} \times \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm cluster}) \times v_{2,{\rm cluster}}\rangle$$

Multiplicity differences

Flow differences

The multiplicity and v2 differences from isobar structure are crucial for the CME search in the isobar collisions at RHIC

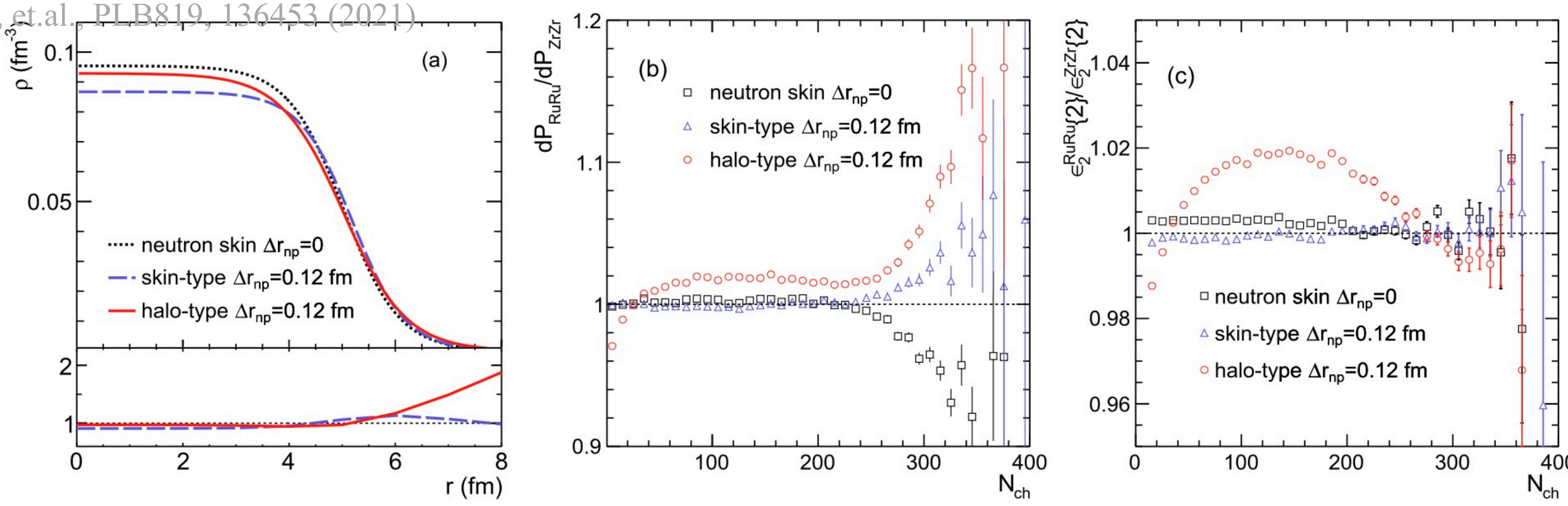
Neutron skin



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

	^{96}Ru		^{96}Zr	
	R	*a*	*R*	*a*
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

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



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

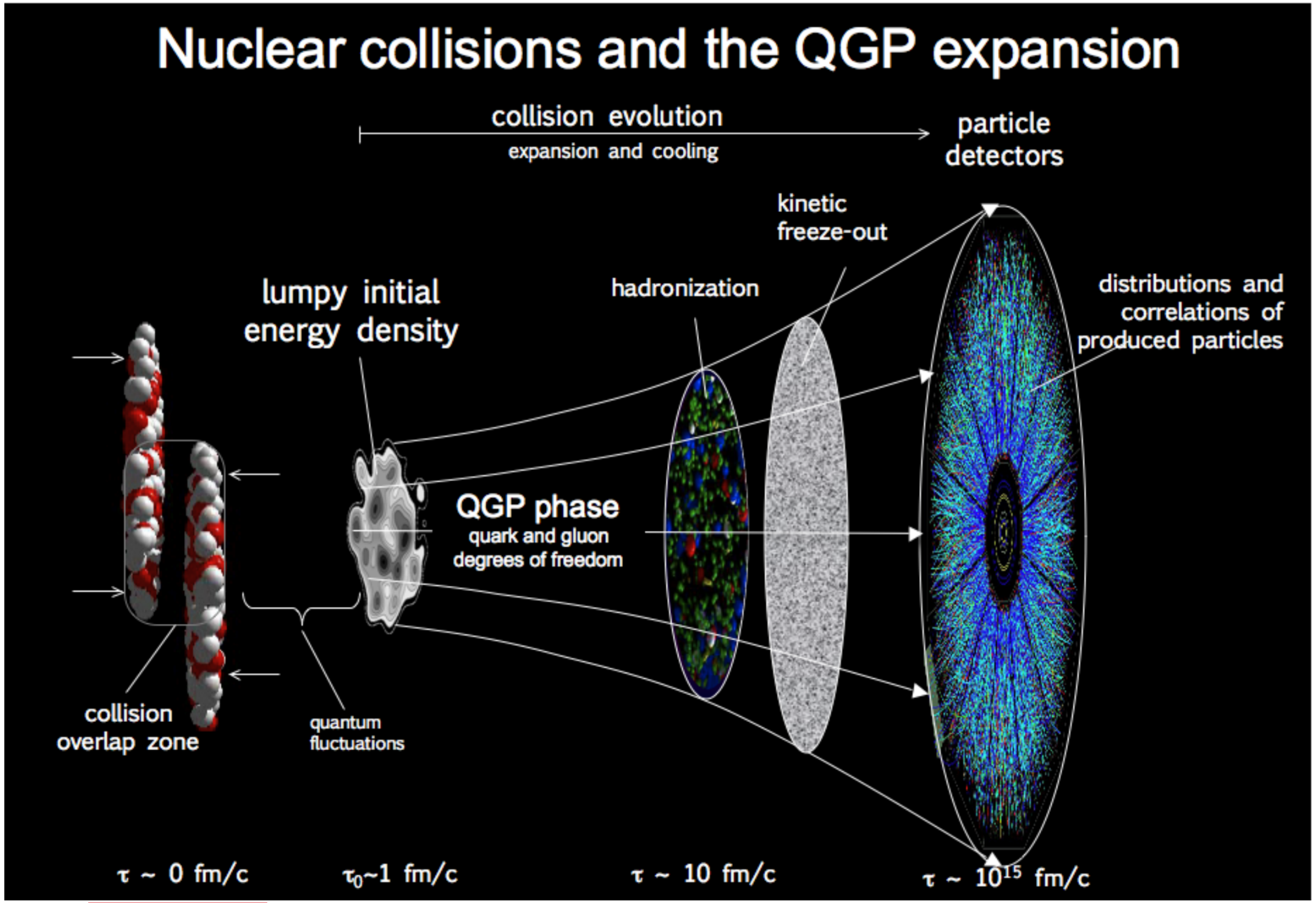
The shapes of the Ru+Ru/Zr+Zr ratios of the multiplicity and eccentricity in mid-central collisions can distinguish between skin-type and halo-type neutron densities.

Nuclear structure measurements

Relativistic heavy ion collisions

The "Little Bang"

$\sqrt{s}$ = 100GeV ~ TeV

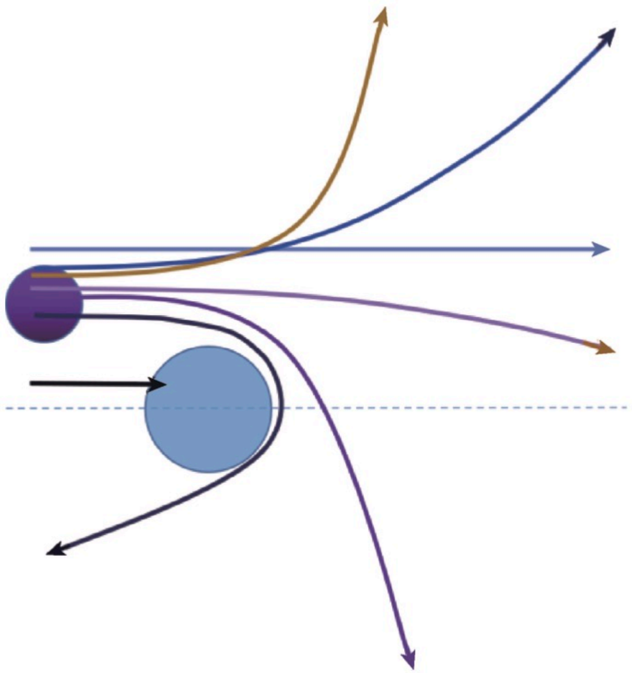


Yoctosecond (10^{-24} s) 幺秒

徐浩洁 (湖州师范学院)

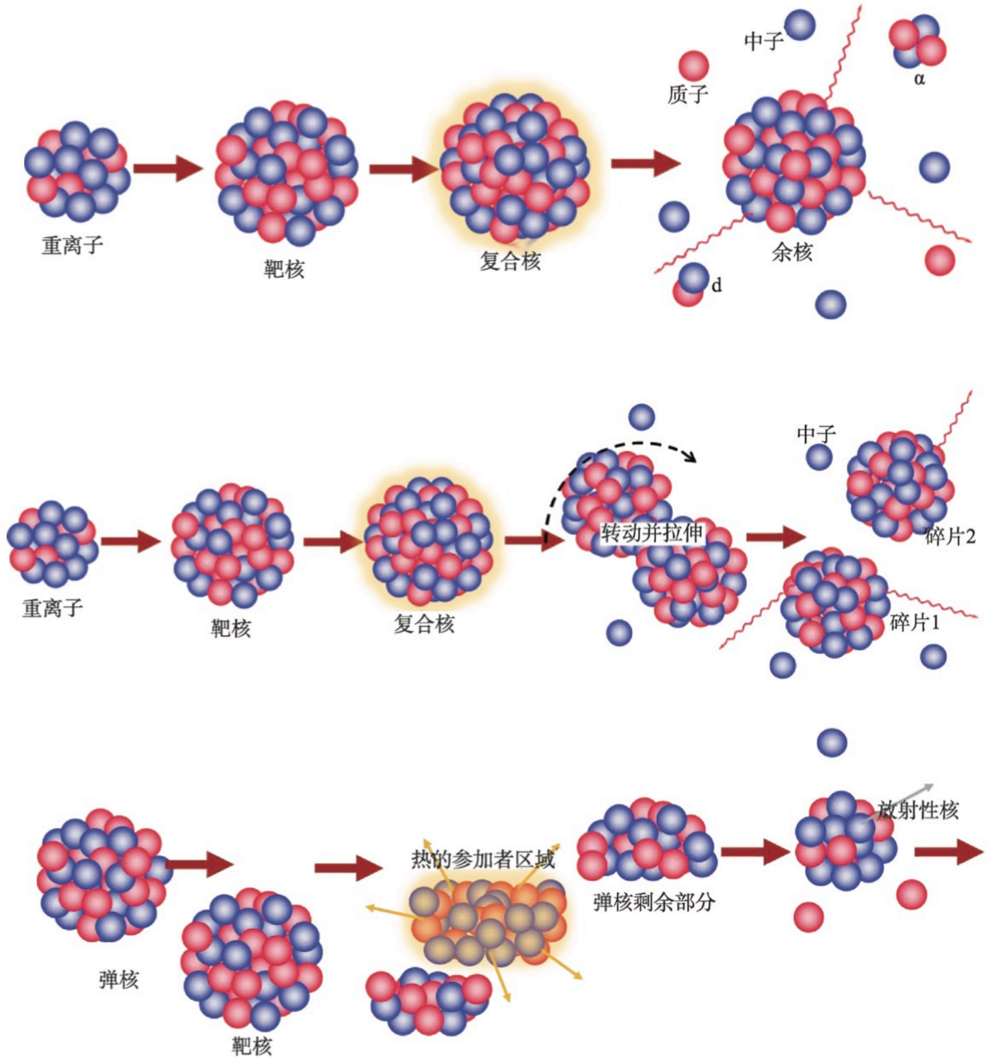
Nucleus-Nucleus Reactions (Collisions)

G. Jin, Modern Physics



Hard scattering

$\sqrt{s} < \text{GeV}$



nuclear evaporation

fragmentation

projectile fragmentation

Nuclear deformation

PHYSICAL REVIEW C, VOLUME 61, 021903(R)

Uranium on uranium collisions at relativistic energies

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Department of Chemistry and Physics, Arkansas State University, P.O. Box 419, Jonesboro, Arkansas 72467-0419
(Received 12 October 1999; published 12 January 2000)

PHYSICAL REVIEW C, VOLUME 61, 034905

High energy collisions of strongly deformed nuclei: An old idea with a new twist

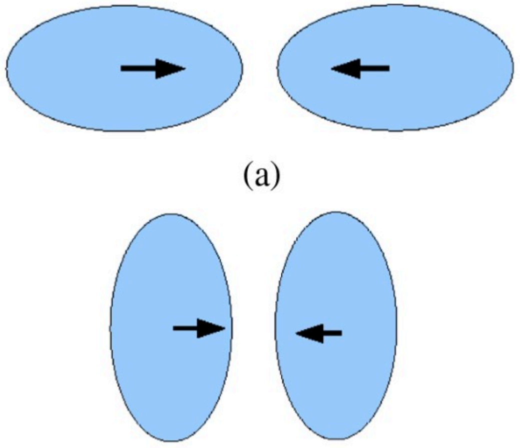
E. V. Shuryak
Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 14 July 1999; published 22 February 2000)

PRL **94,** 132301 (2005) PHYSICAL REVIEW LETTERS week ending 8 APRIL 2005

Anisotropic Flow and Jet Quenching in Ultrarelativistic U+U Collisions

Ulrich Heinz and Anthony Kuhlman
Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA
(Received 16 November 2004; published 6 April 2005)

S. Voloshin, PRL95, 122301 (2010)



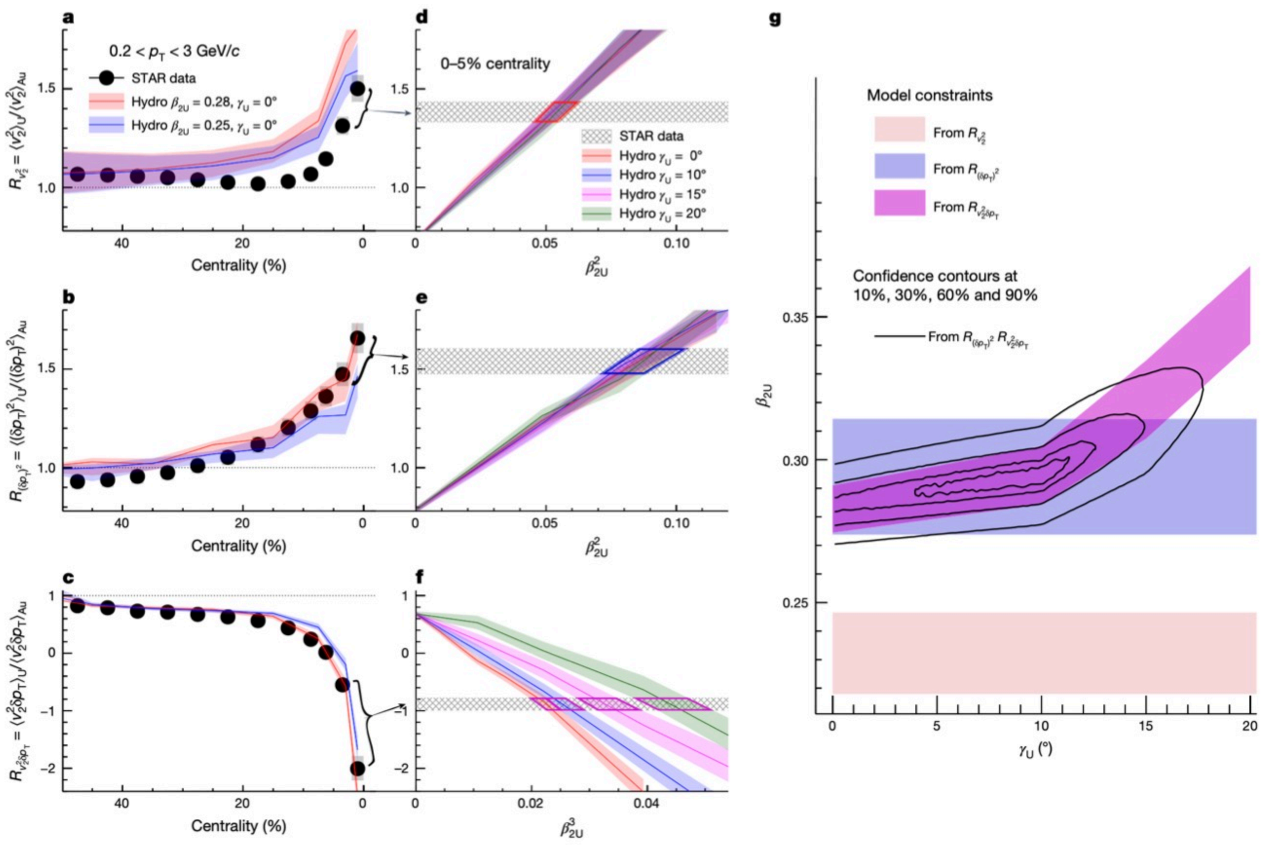
(a)

(b)

H. Masui, B. Mohanty, N. Xu, PLB679, 440(2009)
G. Giacalone, PRC99, 024910 (2019)
G. Giacalone, J. Jia, C. Zhang, PRL127, 242301(2021)
J. Jia, PRC105, 014905 (2022)
B. Bally, et.al, PRL128, 082301(2022)
C. Zhang, J. Jia, PRL128,022301(2022)
H. Mantysaari, et.al, PRL131, 062301(2023)
……..

Semi-isobar collisions

Imaging shape of the ground-state ^{238}U: β_2 and γ



Sufficient precision is achieved from ratios in ultra-central collisions

Relation confirmed from hydro

$$\langle v_2^2 \rangle = a_1 + b_1\beta_2^2$$
$$\left\langle (\delta p_{\mathrm{T}})^2 \right\rangle = a_2 + b_2\beta_2^2$$
$$\langle v_2^2 \delta p_{\mathrm{T}} \rangle = a_3 - b_3\beta_2^3\cos(3\gamma)$$

Constraints on β_2 and γ of ^{238}U simultaneously with data-hydro -comparison

$$\beta_{2U} = 0.297 \pm 0.015$$
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

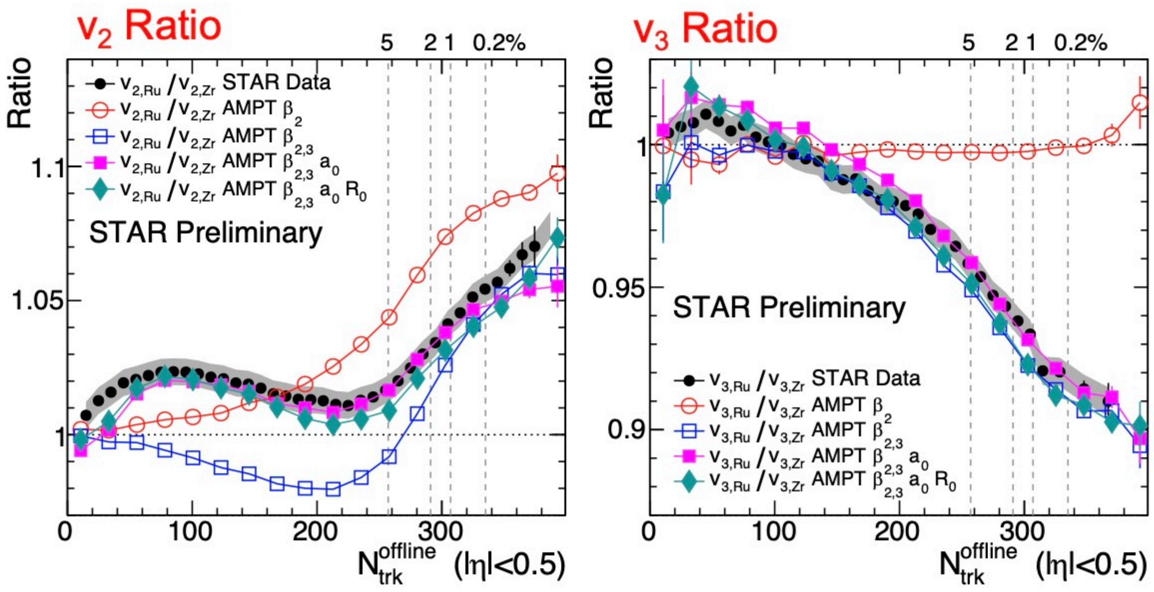
STAR, Nature 635, 67-72 (2024)
https://www.nature.com/articles/s41586-024-08097-2

C. Zhang
QM25

A large deformation with a slight deviation from axial symmetry in the nuclear ground-state

Isobar collisions

Nuclear structure via collectivity v_n ratio $\frac{\mathcal{O}_{^{96}\mathrm{Ru}}+\mathcal{O}_{^{96}\mathrm{Ru}}}{\mathcal{O}_{^{96}\mathrm{Zr}}+\mathcal{O}_{^{96}\mathrm{Zr}}} \stackrel{?}{=} 1$

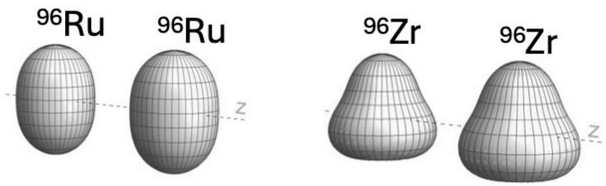


β_{2Ru} ~ 0.16 increase v_2, no influence on v_3 ratio

β_{3Zr} ~ 0.2 decrease v_2 in mid-central, decrease v_3 ratio

Δa_0 = -0.06 fm increase v_2 mid-central, small impact on v_3

Radius ΔR_0 = 0.07 fm only slightly affects v_2 and v_3 ratio.



- Direct observation of octupole deformation in ^{96}Zr nucleus
- Imply the neutron skin difference between ^{96}Ru and ^{96}Zr
- Simultaneously constrain parameters using Bayesian analysis

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

$\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$ $\beta_{3,\mathrm{Zr}} = 0.20 \pm 0.02$

	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
difference	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, C. Zhang, PRC 107, L012901(2023)

C. Zhang QM25

Neutron skin: sensitive probe of symmetry energy

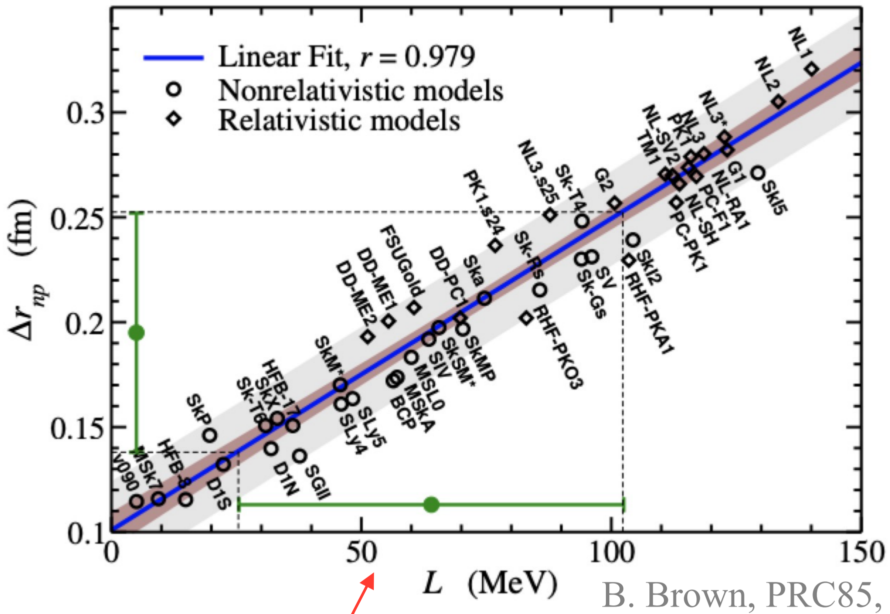
$^{96}_{40}\mathrm{Zr} : (N-Z)/A = 0.167$

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

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

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 :

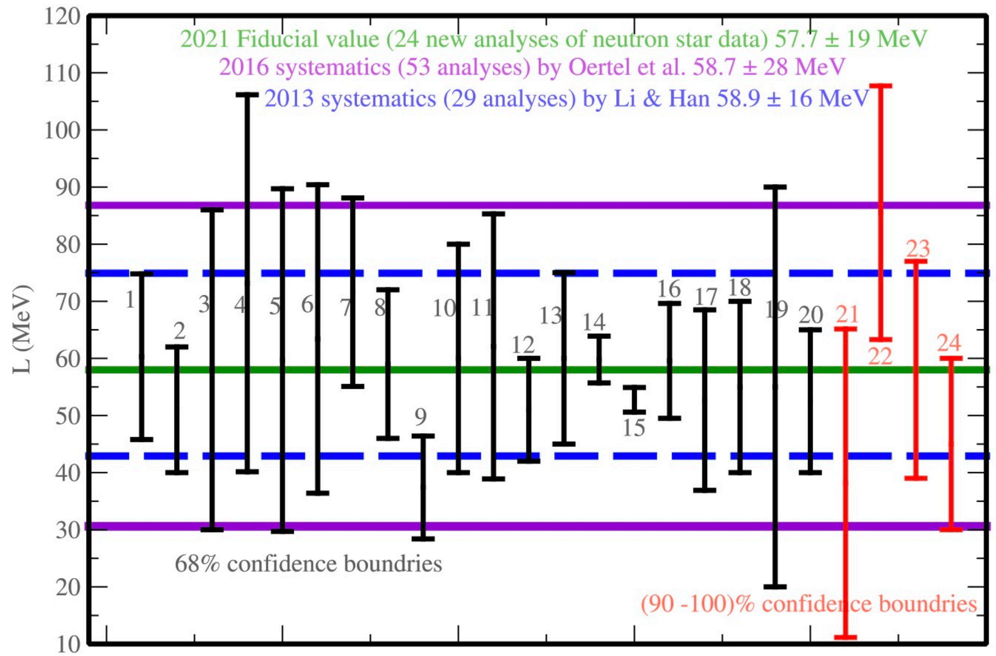
$$L \equiv L(\rho) = 3\rho \left[\frac{dE_{\mathrm{sym}}(\rho)}{d\rho}\right]_{\rho=\rho_0 \text{ saturation density}} \qquad L(\rho_c) = 3\rho_c \left[\frac{dE_{\mathrm{sym}}(\rho)}{d\rho}\right]_{\rho=\rho_c=0.11\rho_0/0.16}$$

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

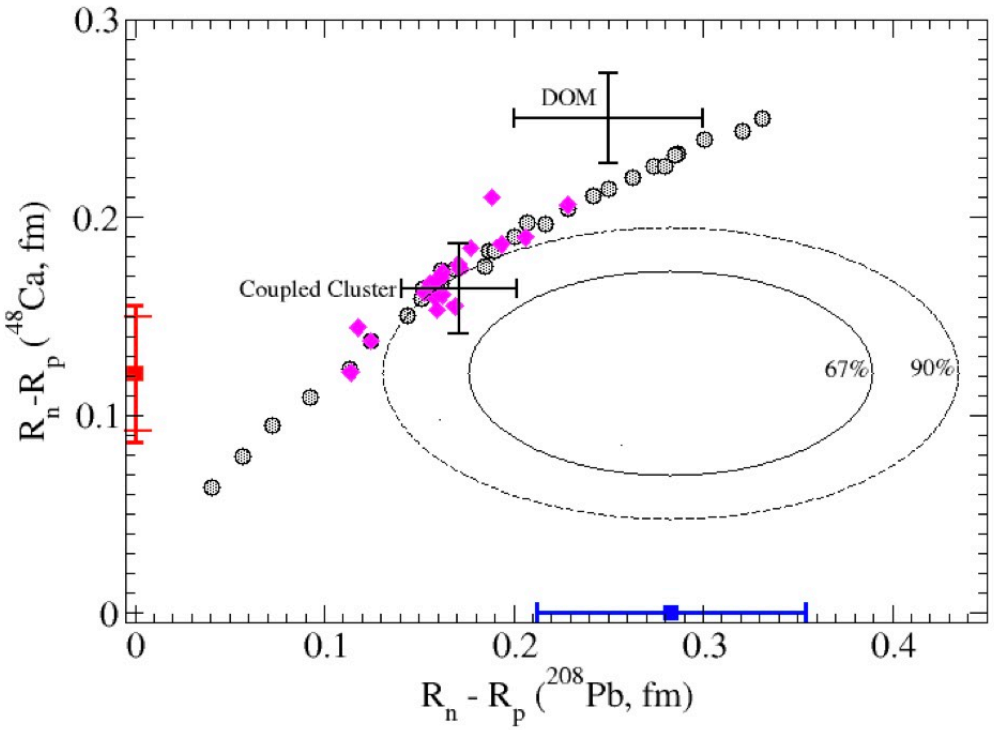
The symmetry energy is crucial to our understanding of the masses and drip lines of neutron-rich nuclei and the equation of state (EOS) of nuclear and neutron star matter.

Nuclear symmetry energy

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



CREX Collaboration, PRL129, 042501 (2022)



Symmetry energy is transitionally measured by low energy nuclear experiment. Over many decades, the issue is still not fully settled; e.g. world average L parameter is about 50 MeV, PREX electroweak measurement favors 100 MeV whereas CREX favors 30 MeV.

Probing the neutron skin thickness

PHYSICAL REVIEW LETTERS **125,** 222301 (2020)

Observables sensitive to neutron skin thickness

Probing the Neutron Skin with Ultrarelativistic Isobaric Collisions

Hanlin Li,[1] Hao-jie Xu,[2,*] Ying Zhou,[3] Xiaobao Wang,[2] Jie Zhao,[4] Lie-Wen Chen,[3,†] and Fuqiang Wang[2,4,‡]

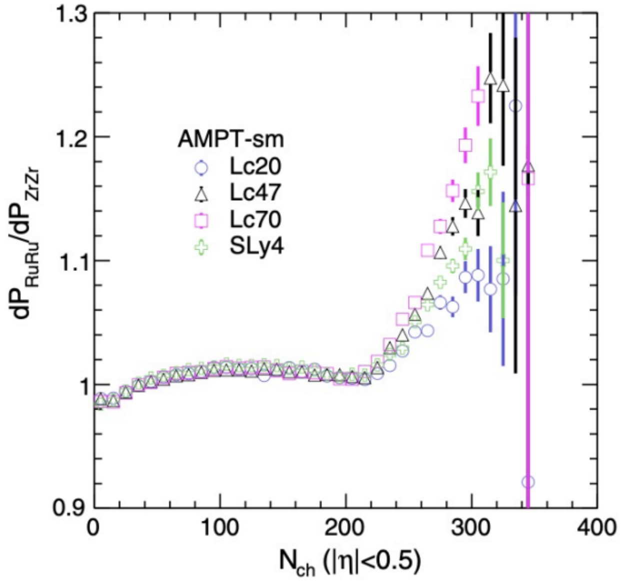
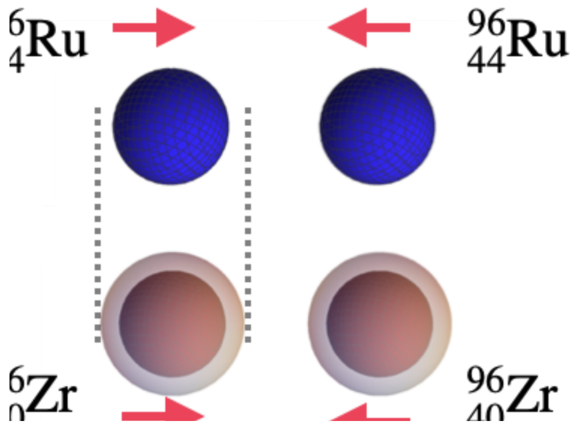
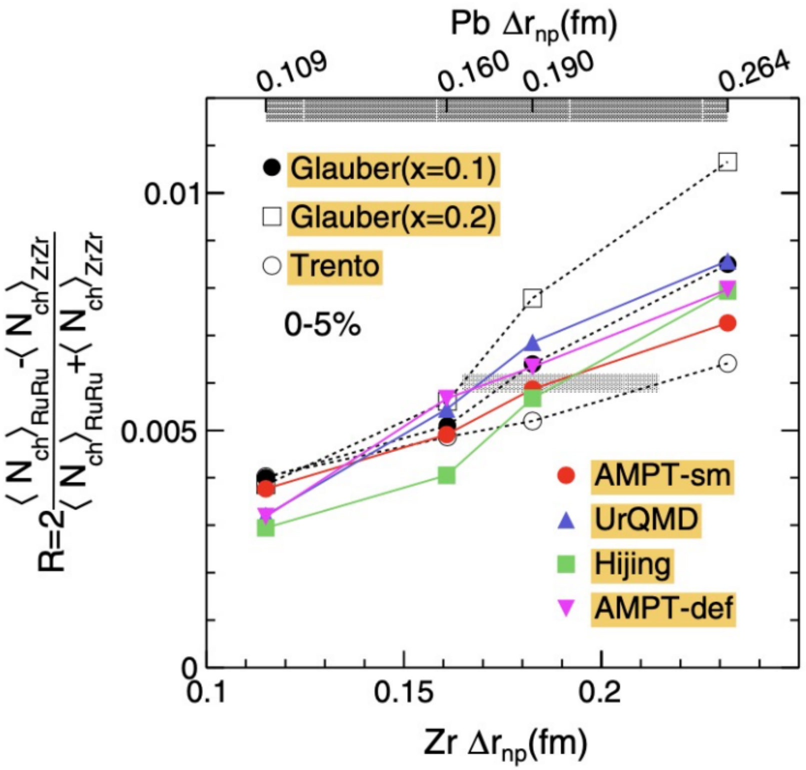


FIG. 3. Ratio of the N_{ch} distribution in Ru + Ru to that in Zr + Zr for various densities in AMPT-sm. The other models are similar.





Mean transverse momentum

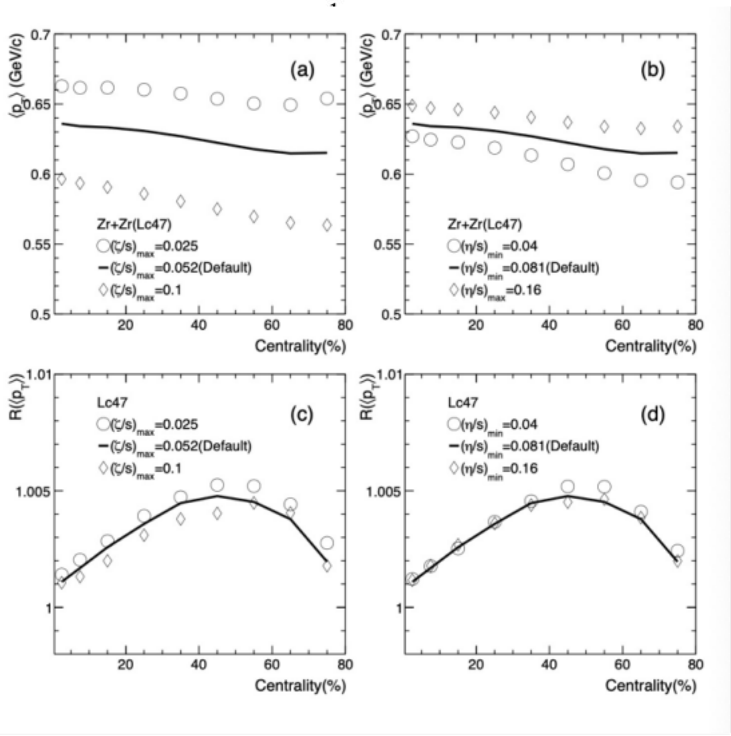
PHYSICAL REVIEW C **108**, L011902 (2023)

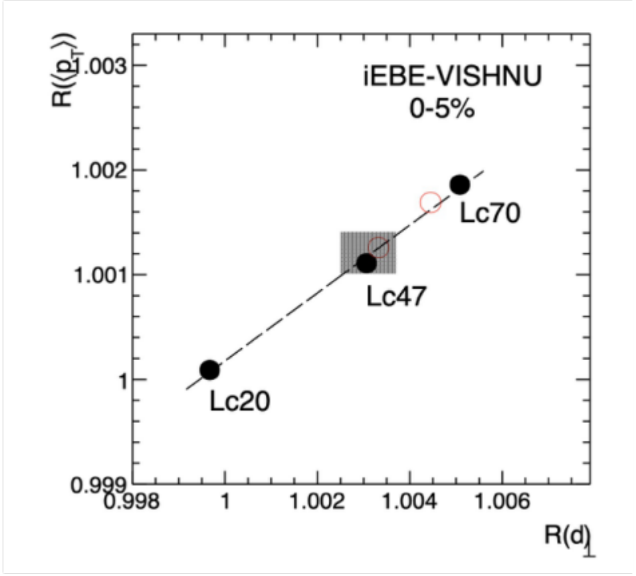
Letter

Probing nuclear structure with mean transverse momentum in relativistic isobar collisions

Hao-jie Xu[1,2] Wenbin Zhao[3] Hanlin Li,[4] Ying Zhou,[5] Lie-Wen Chen[5] and Fuqiang Wang[1,2,6]

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





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

STAR Preliminary results

18

Compare to world wide data

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

Zhang, Chen, PRC94, 064326 (2016)

- Multiplicity ratio:

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

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

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

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

- $\langle p_T \rangle$ ratio:

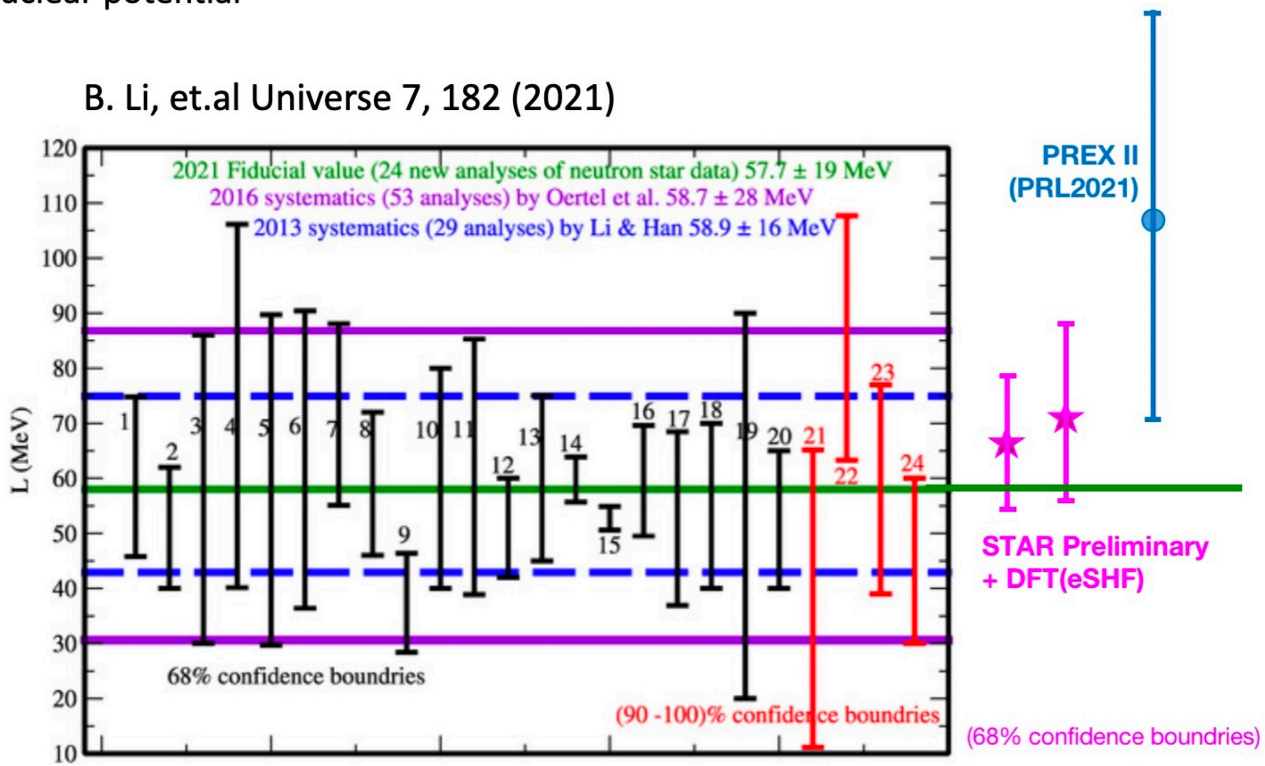
  $L(\rho_c) = 56.8 \pm 0.4 \pm 10.4$ MeV

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

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

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

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



Consistent with world wide data with good precision

More studies

中国科学 : 物理学 力学 天文学 2024 年 第 54 卷 第 9 期 : 292006
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评 述 高能核-核碰撞和原子核结构专题

通过相对论重离子碰撞研究中子皮和核对称能

徐浩洁[1,2*], 王福强[1,2,3]

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2. 湖州师范学院强耦合物理国际实验室, 湖州 313000;
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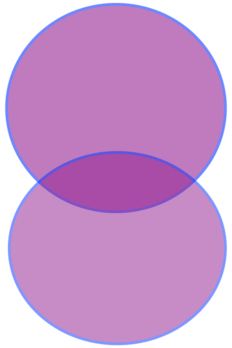
发布时间: 2024年08月13日

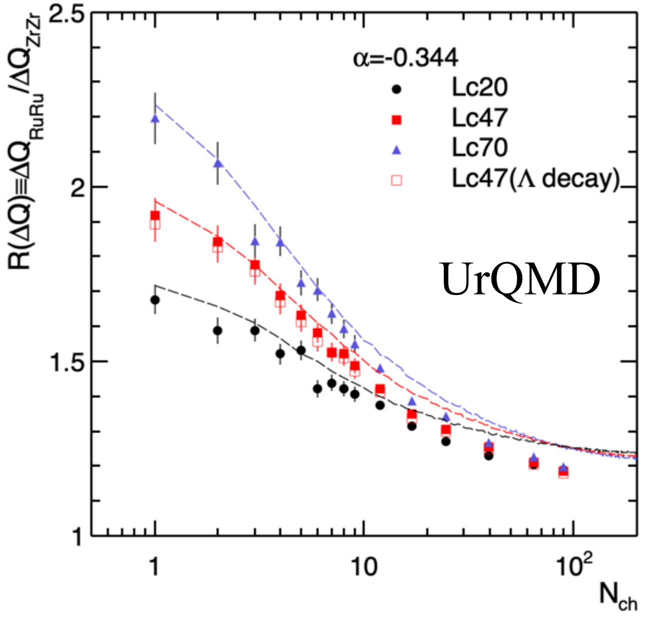
Net charges

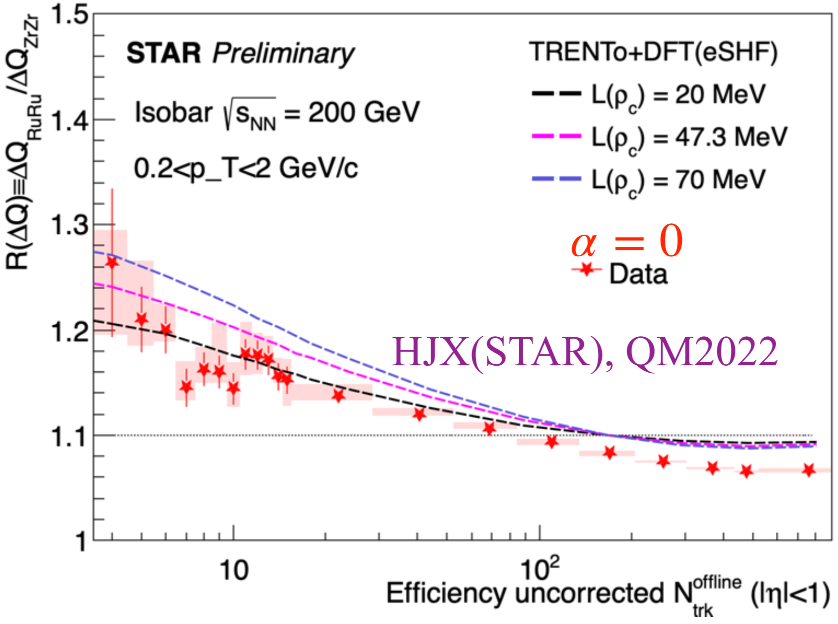
HJX, et.al., PRC105, L011901 (2022)

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: $\alpha = -0.344$

STAR data: $\alpha \simeq 0$

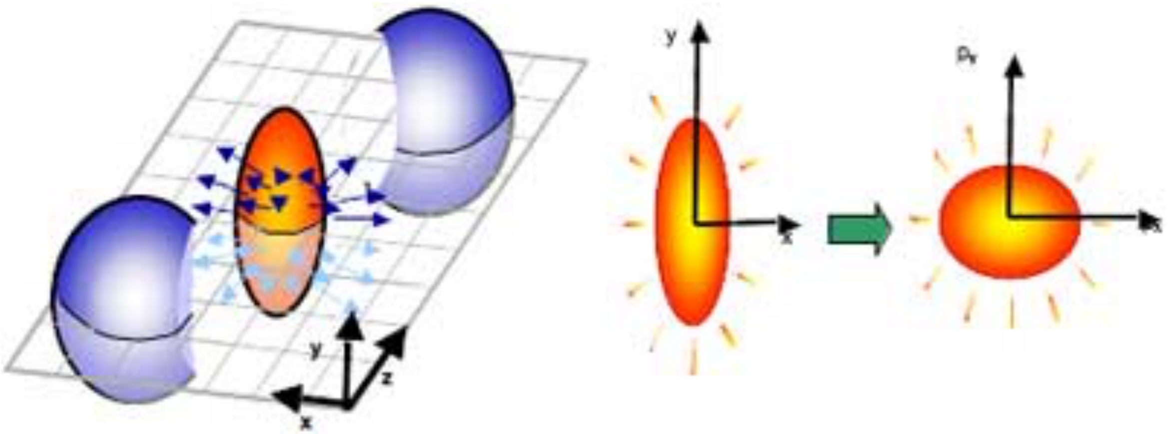
Baryon junction? Zebo Tang's talk

Solve the flow puzzle with nuclear structure

Solve the flow puzzle with nuclear structure

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

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

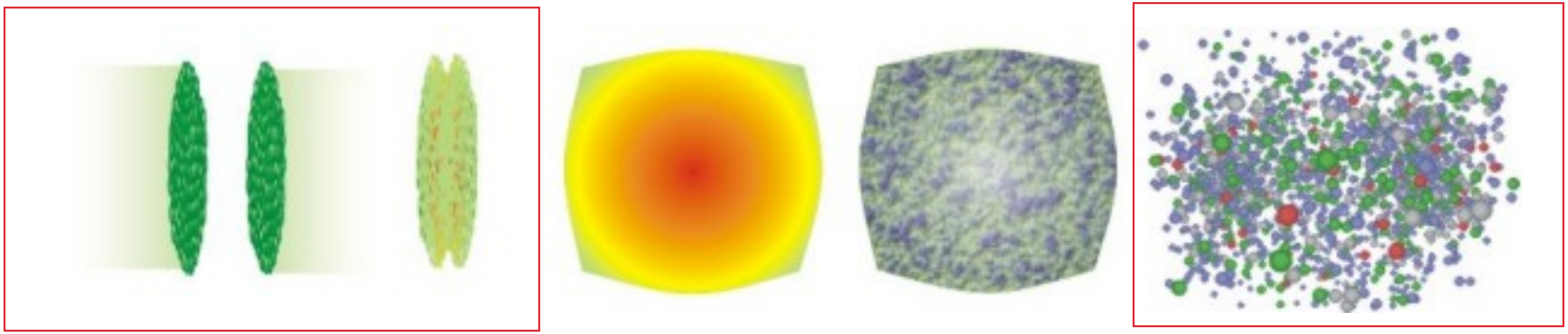


Anisotropic flow,
Flow fluctuations
HBT,
....

Initial geometry

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

Final observables

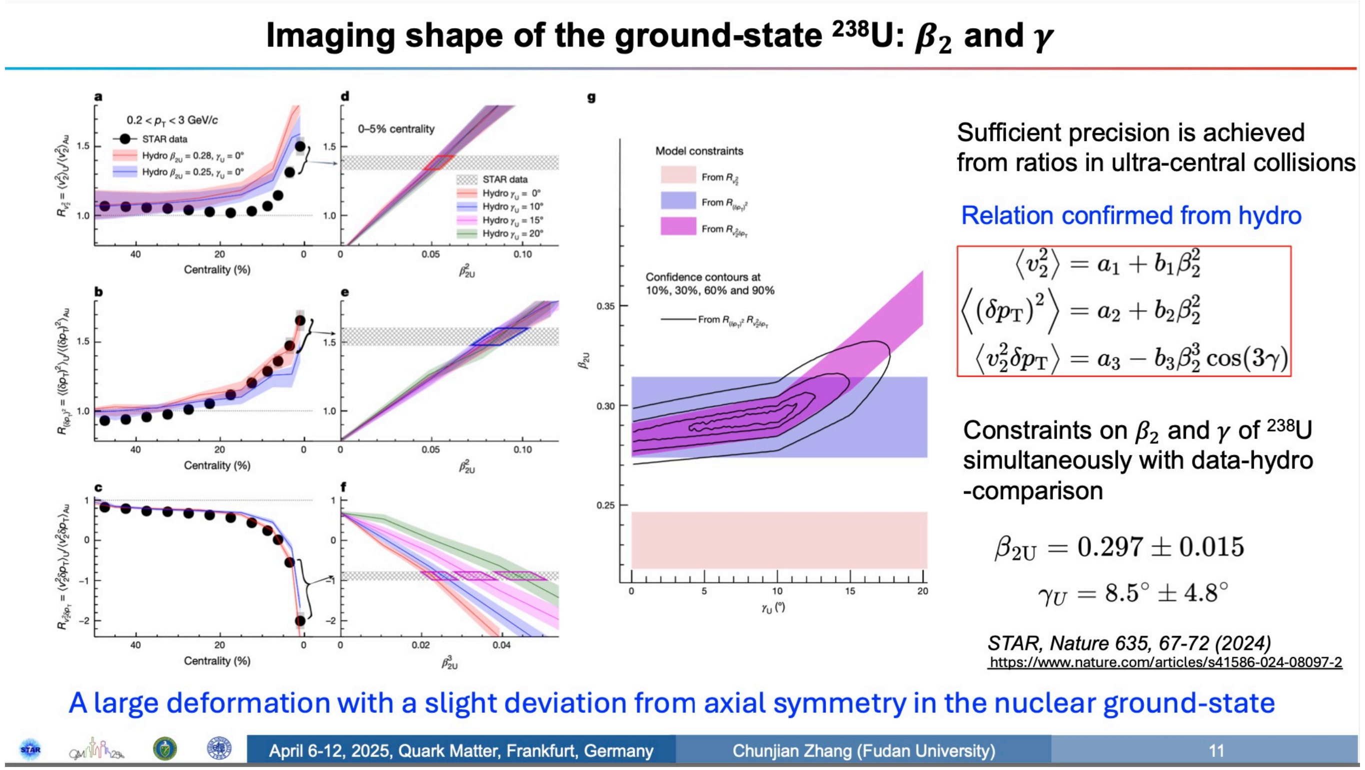


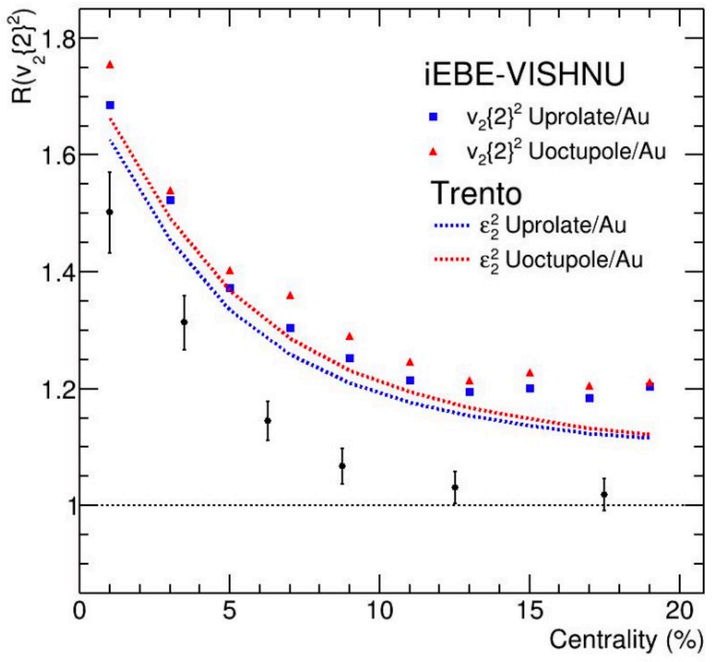
Semi-isobar collisions

Yuan Li Poster 184

Probing octupole deformation in U-238 via relativistic heavy-ion collisions

C. Zhang QM25





$\beta_2 = 0.29$

$R(v_2^2)$ is not used for the above β_2 extractions

$R(v_2^2)$ —- $\beta_2 = 0.234 \pm 0.014$

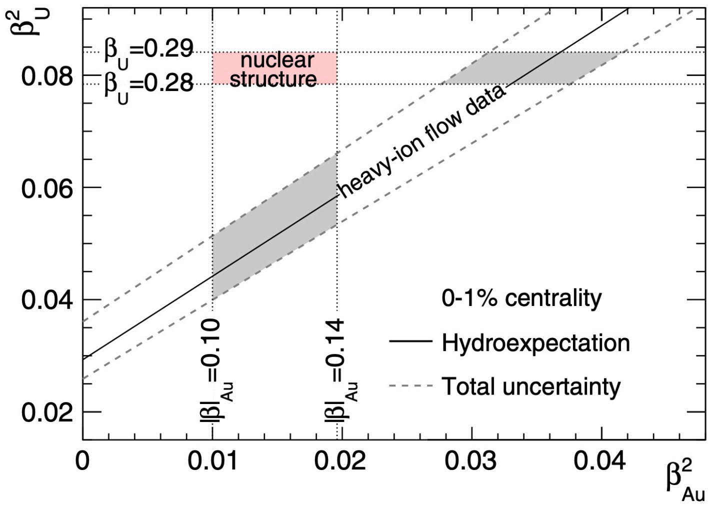
CDFT density instead of Woods-Saxon density

$R(v_2^2)$ is consistent with data

Hexadecapole deformation

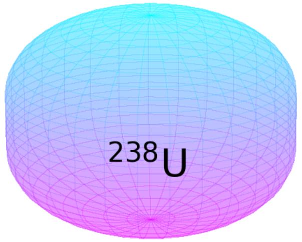
G. Giacalone, et.al, PRL127, 242301 (2021)

W. Ryssens, et.al, PRL130, 212302 (2023)

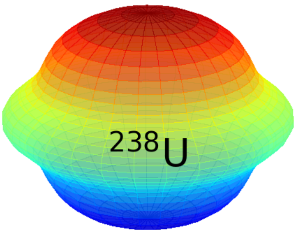


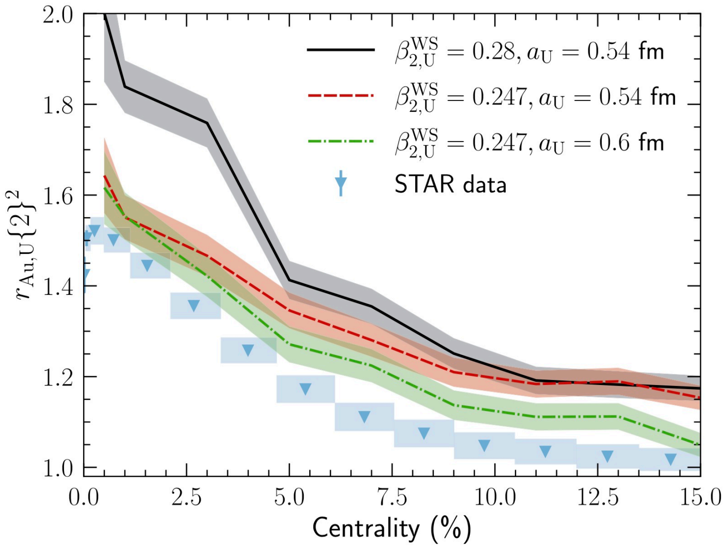
$$\beta_2^* \propto \mathrm{BE(2)}$$

$$\mathrm{BE(2,U)} = 12.09 \pm 0.02 \quad \mathrm{e^2b^2}$$



or





$$\beta_{2,\mathrm{U}} \sim 0.28, \quad \beta_{4,\mathrm{U}} \sim 0$$

$$\beta_{2,\mathrm{Au}} \sim 0.17$$

$$\beta_2^* \propto \left(\beta_2 + \frac{2}{7}\sqrt{\frac{5}{\pi}}\beta_2^2 + \frac{12}{7\sqrt{\pi}}\beta_2\beta_4 + \ldots\right)$$

$$R = R_0\left[1 + \beta_2 Y_{20} + \beta_4 Y_{40}\right]$$

$$\beta_{2,\mathrm{U}} \sim 0.25, \quad \beta_{4,\mathrm{U}} \sim 0.1$$

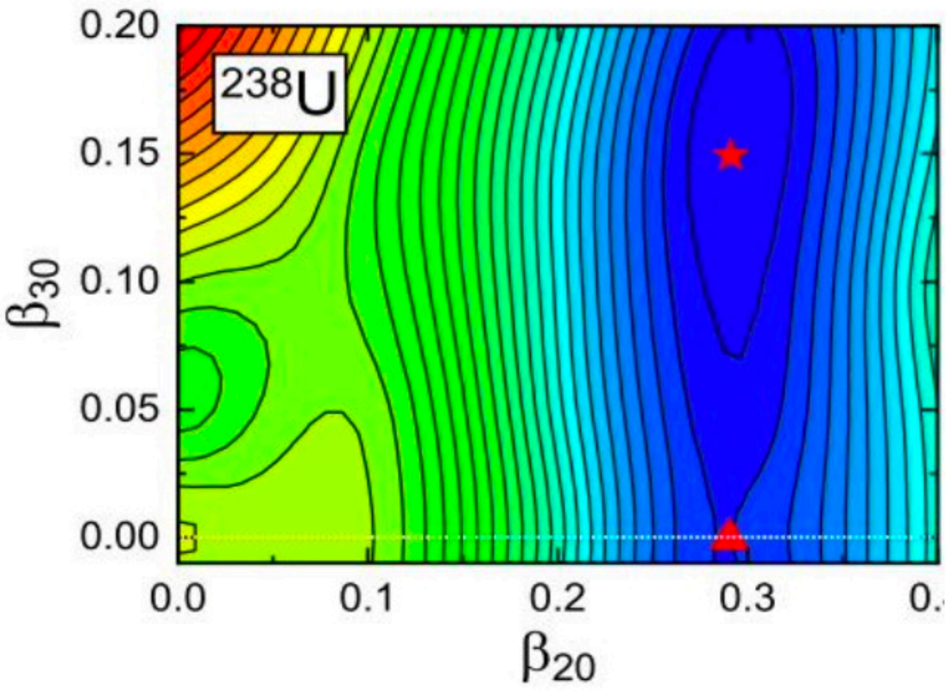
$$\beta_{2,\mathrm{Au}} \sim 0.14$$

$\beta_{4,\mathrm{U}}$ is poorly known from low-energy nuclear experiments, can it be measured in relativistic heavy ion collisions? **YES!**

Zhi-jie Yang Poster 140 Systematic study of nonlinear response coefficients for the fourth-to-second flow harmonics in relativistic U+U collisions

Octupole deformation

D. Zhang, et.al, Phys.Rev., C109, 024609(2024)



Covariant density functional theory:

$\beta_{20} = 0.29$

$\beta_{30} = 0.15$

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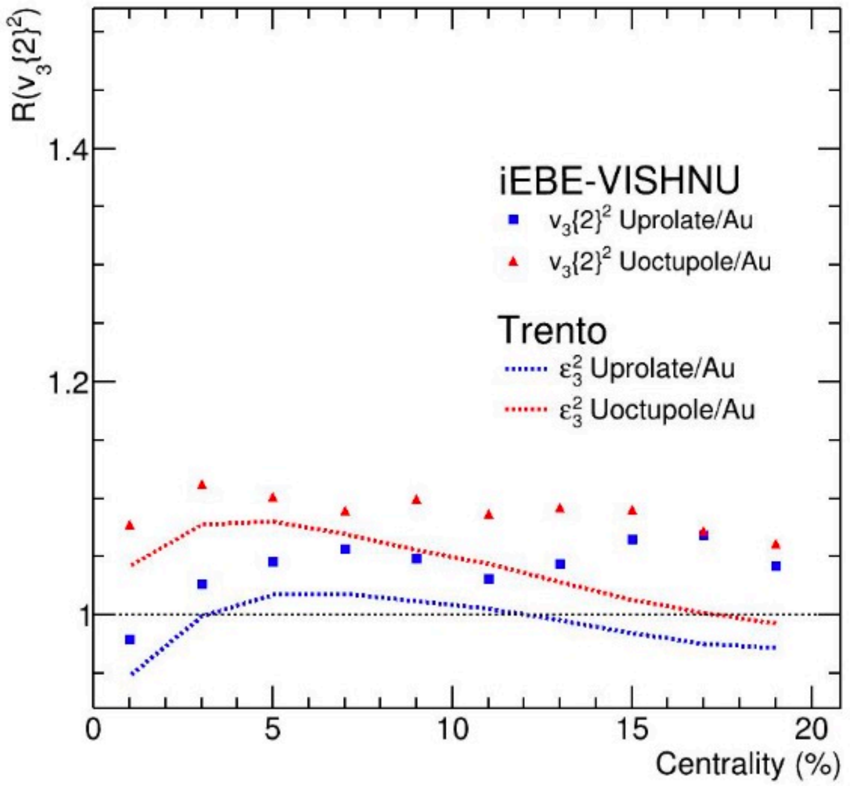
Probing octupole deformation in U-238 via relativistic heavy-ion collisions



CDFT density instead of Woods-Saxon density

$R(v_2^3)$ can be used to determine the octupole deformation.

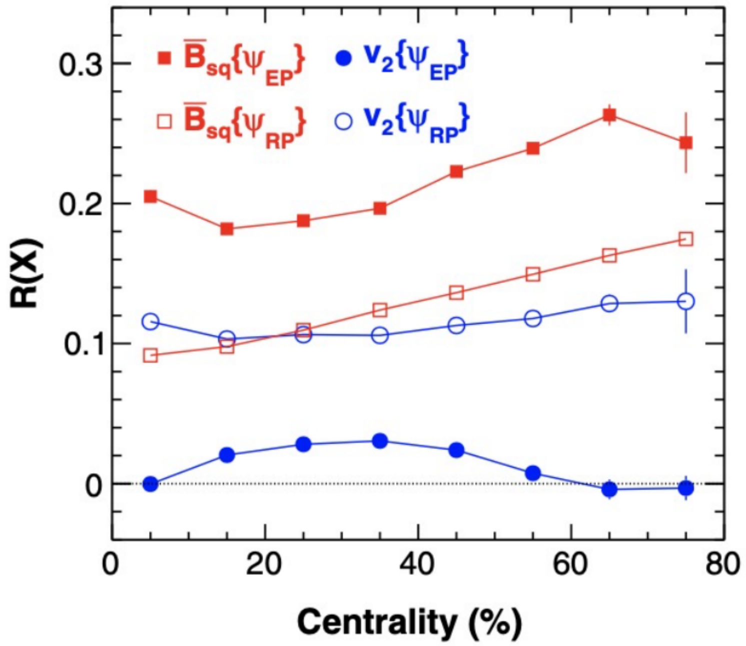
Solve the flow puzzle with nuclear structure

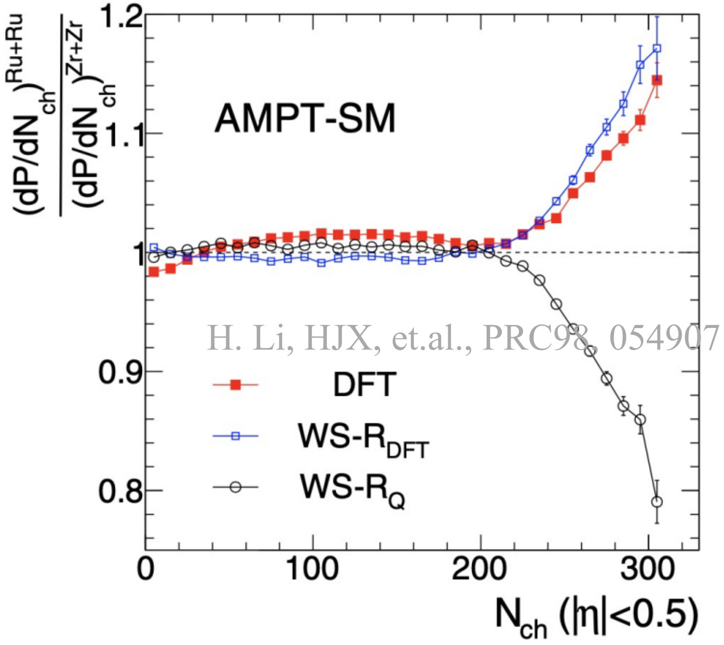
PHYSICAL REVIEW LETTERS **121,** 022301 (2018)

Instead of WS densities, we use the nuclear densities obtained from density functional theory calculations

Importance of Isobar Density Distributions on the Chiral Magnetic Effect Search

Hao-jie Xu,[1] Xiaobao Wang,[1] Hanlin Li,[2] Jie Zhao,[3] Zi-Wei Lin,[4,5] Caiwan Shen,[1] and Fuqiang Wang[1,3,*]





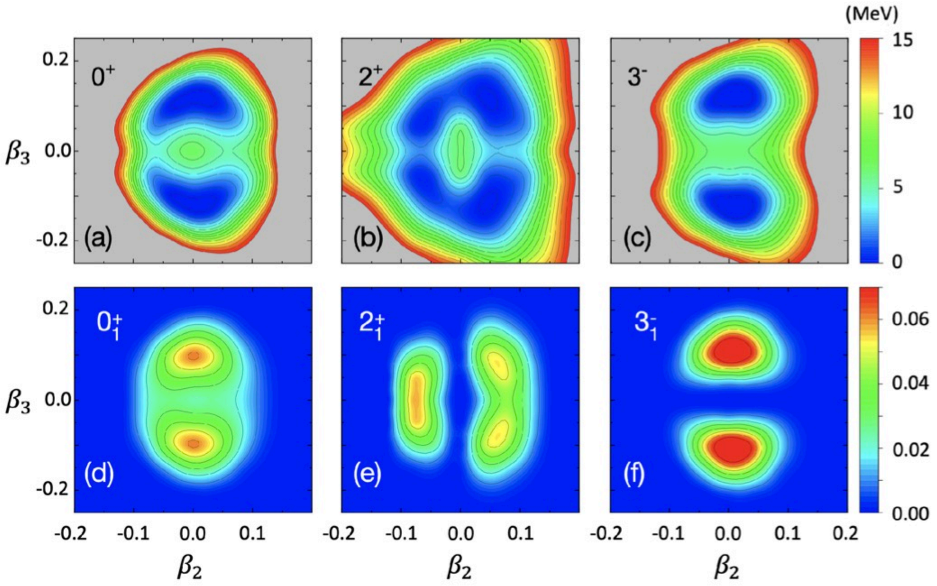
H. Li, HJX, et.al., PRC98, 054907 (2018)

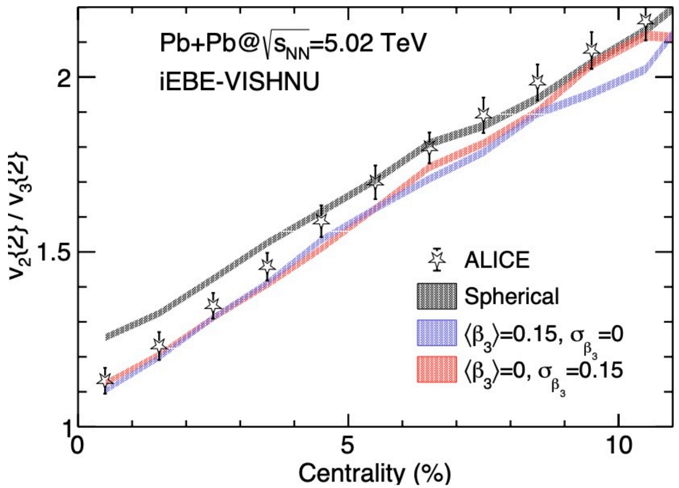
Neutron skin thickness $\Delta r_{np} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$

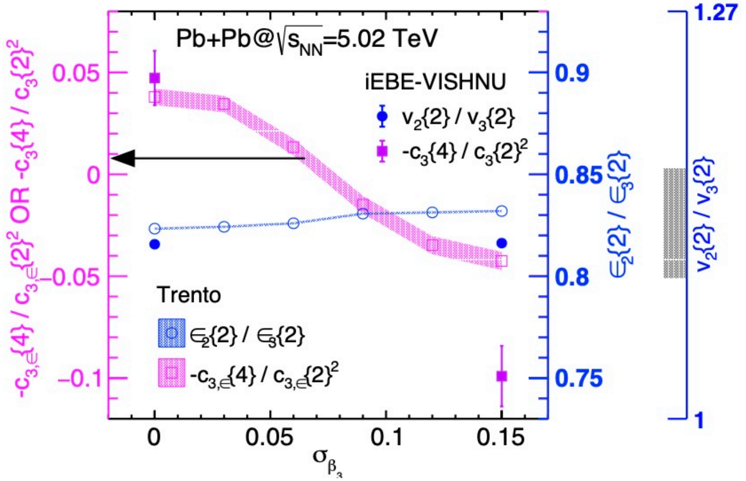
Solve the flow puzzle with nuclear structure

J. Henderson, PRL134, 062502 (2025)

$$P(\beta_3) \propto \exp\left[-\frac{(\beta_3 - \langle\beta_3\rangle)^2}{2\sigma_{\beta_3}^2}\right].$$







A "breathing" octupole ^{208}Pb nucleus: resolving the elliptical-to-triangular azimuthal anisotropy puzzle in ultracentral relativistic heavy ion collisions

Summary

Thank you for your attention!

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Huzhou University(湖州师范学院)