EXPLORATION OF THE NUCLEAR STRUCTURE VIA RELATIVISTIC HEAVY ION COLLISION

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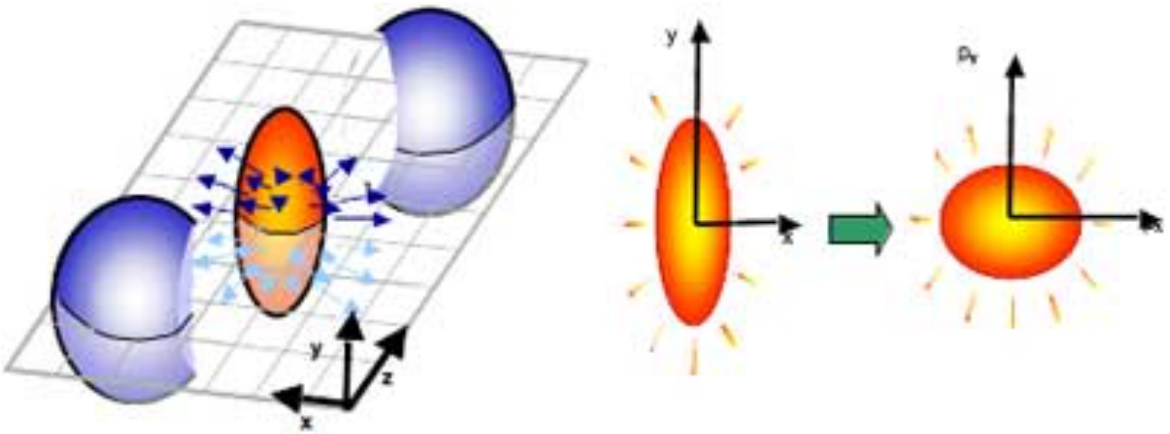
The 2nd Workshop on Ultra-Peripheral Collision Physics: Strong Electromagnetic fields, UPC and EIC/EicC，2024.4.12-16，Hefei

Relativistic Heavy ion collisions and nuclear structure

Woods-Saxon distributions

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

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

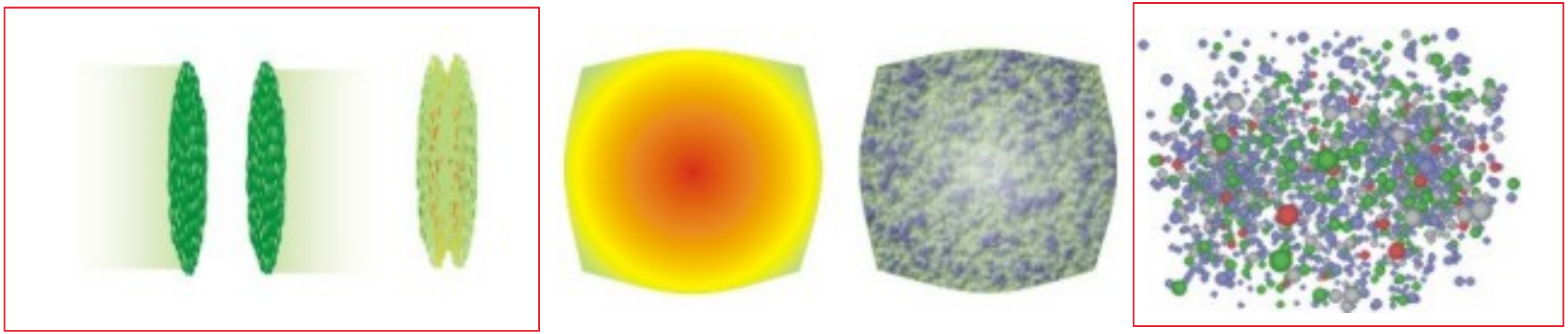


Anisotropic flow,
Flow fluctuations
HBT,
....

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

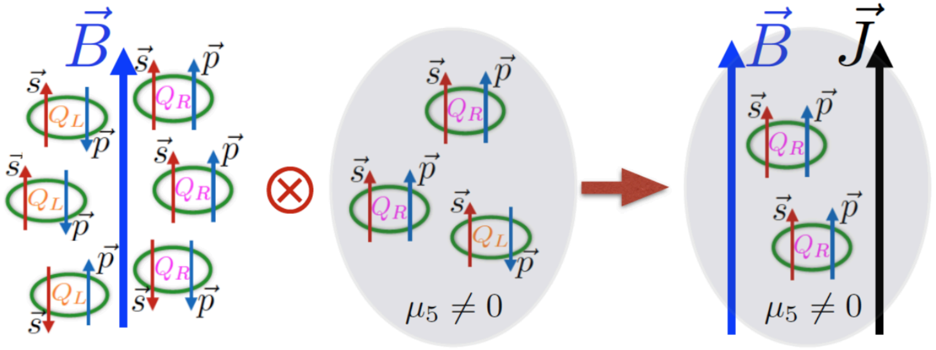
Initial geometry

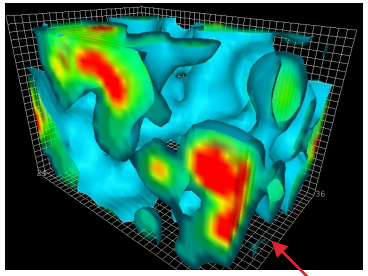
Final observables

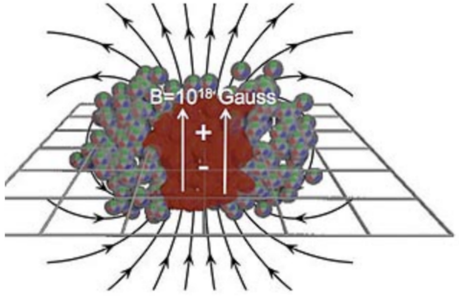


Relativistic isobaric collisions and chiral magnetic effect

Chiral magnetic effect (CME)





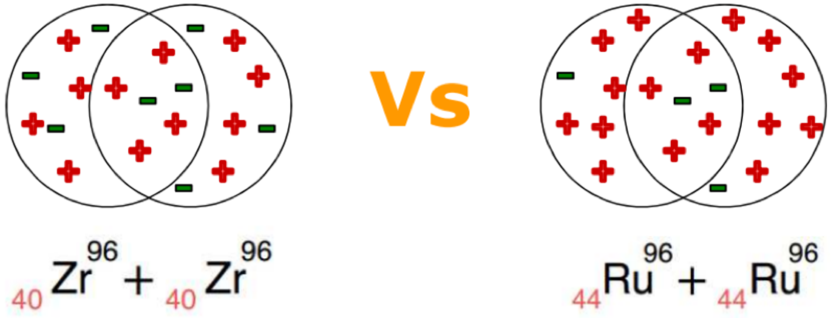


$$\mathbf{J_{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B},$$

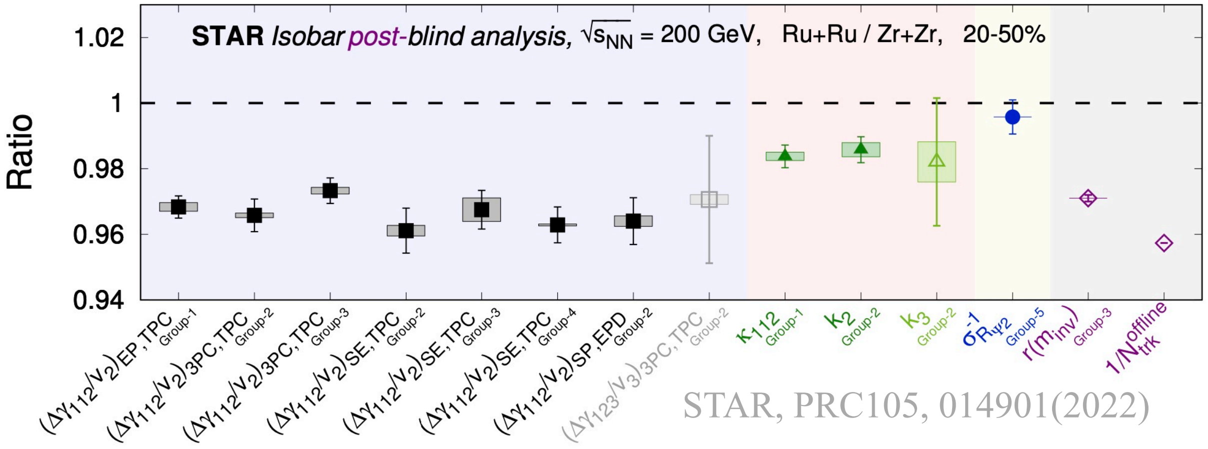
D. Kharzeev,et.al., PPNP88, 1(2016)

The isobar collisions was 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!!!

1. The neutron distribution differ from proton distribution: neutron skin

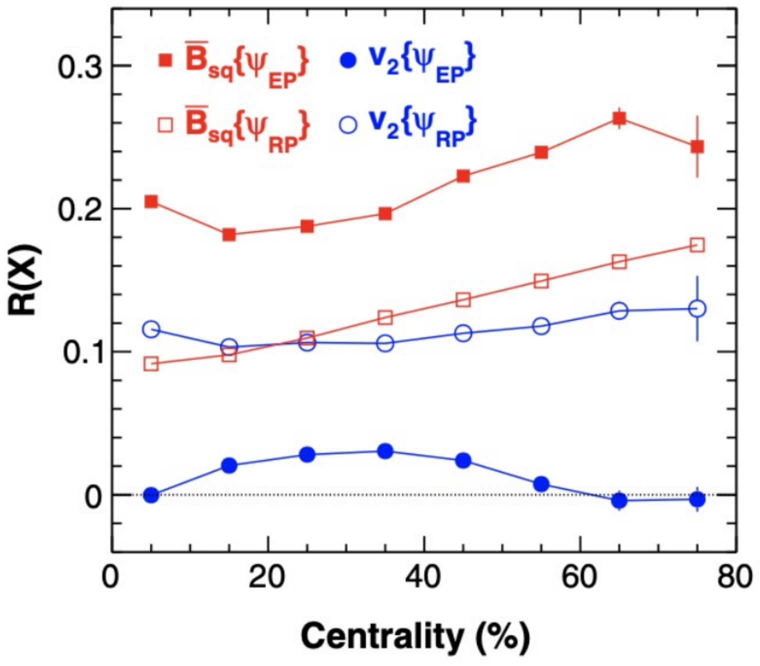
Nuclear densities for HIC models

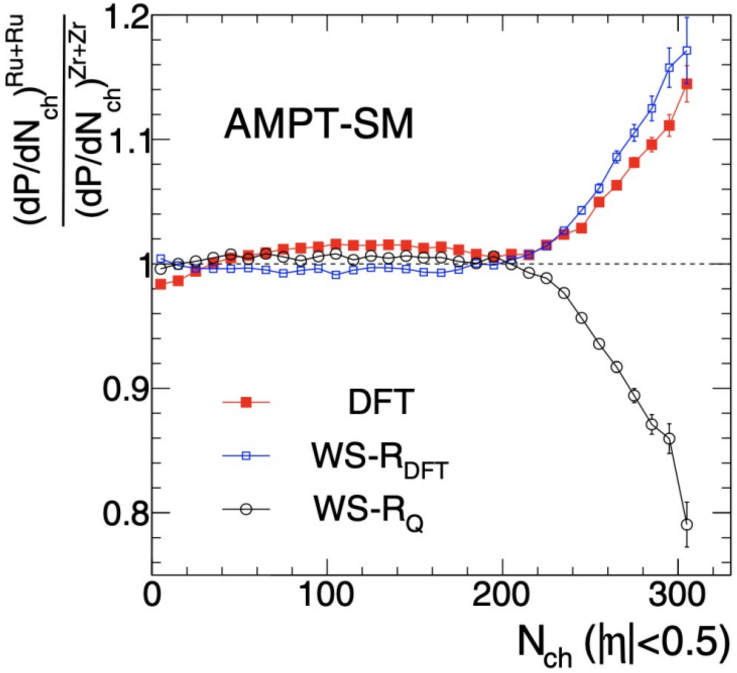
PHYSICAL REVIEW LETTERS **121,** 022301 (2018)

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

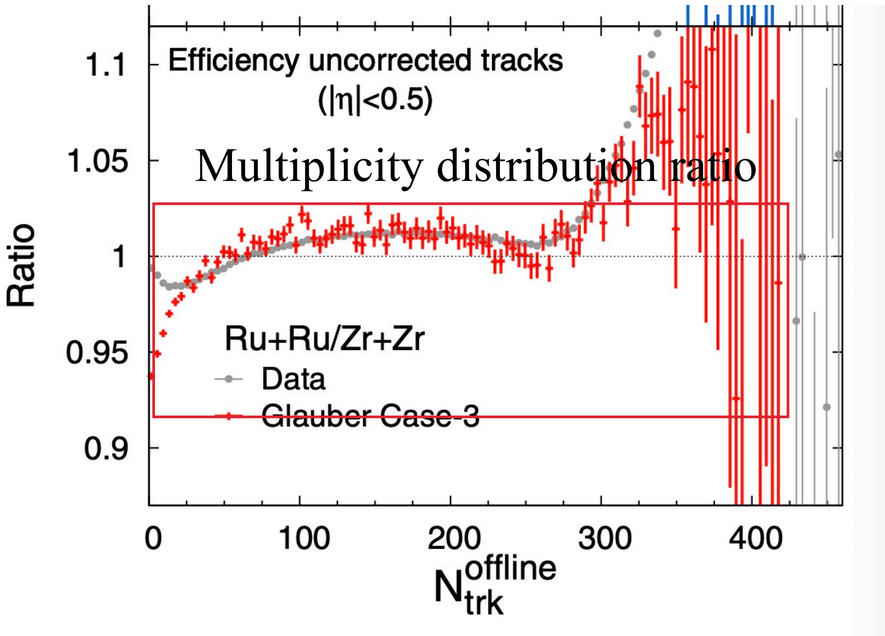
Importance of Isobar Density Distributions on the Chiral Magnetic Effect Search

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,*]

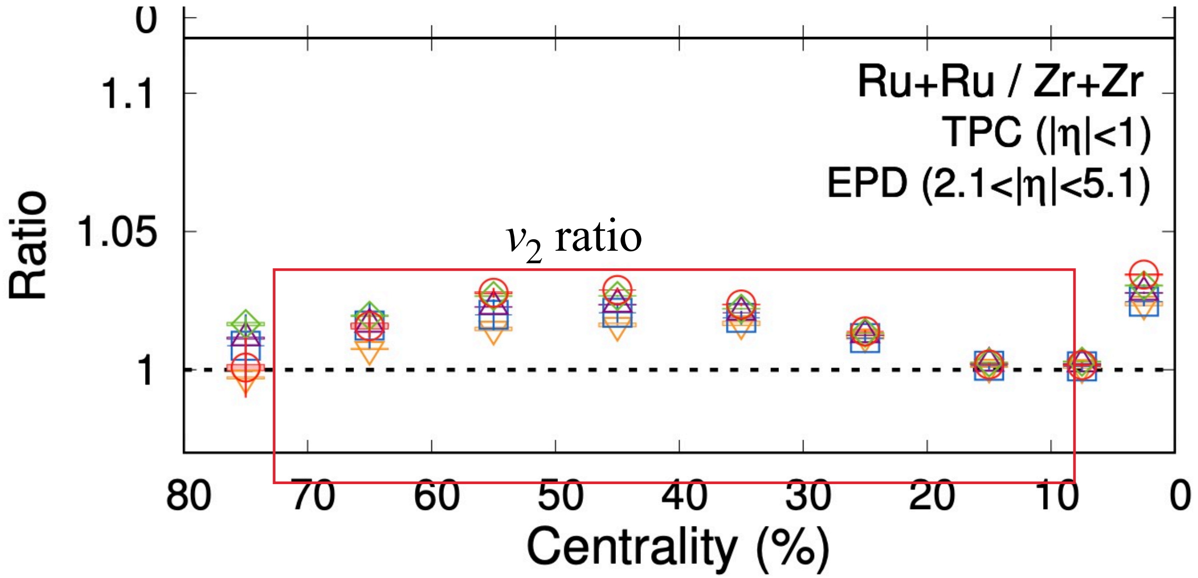


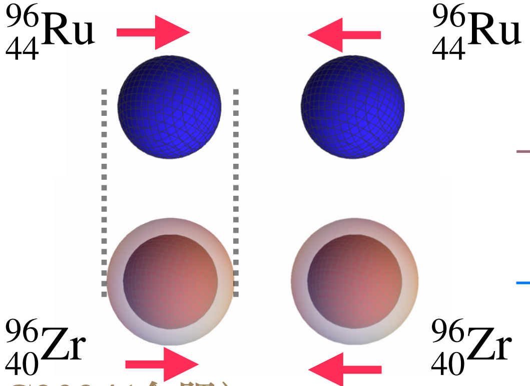


DFT predictions are verified by STAR data



STAR, PRC105, 014901(2022)





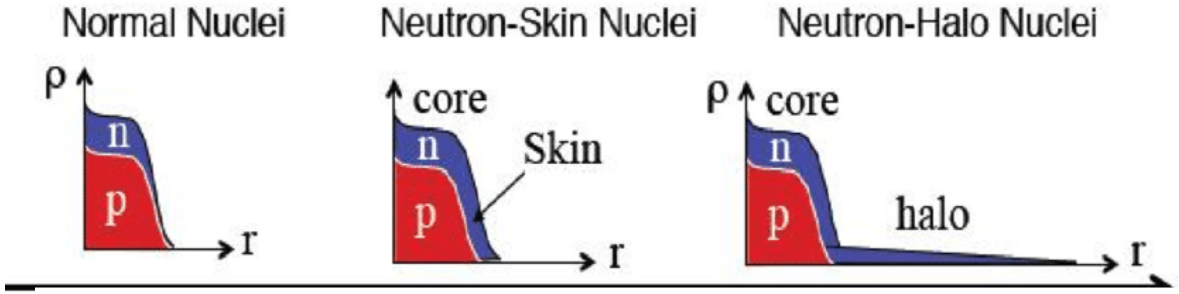
Neutron skin thickness $\Delta r_{np} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$

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

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

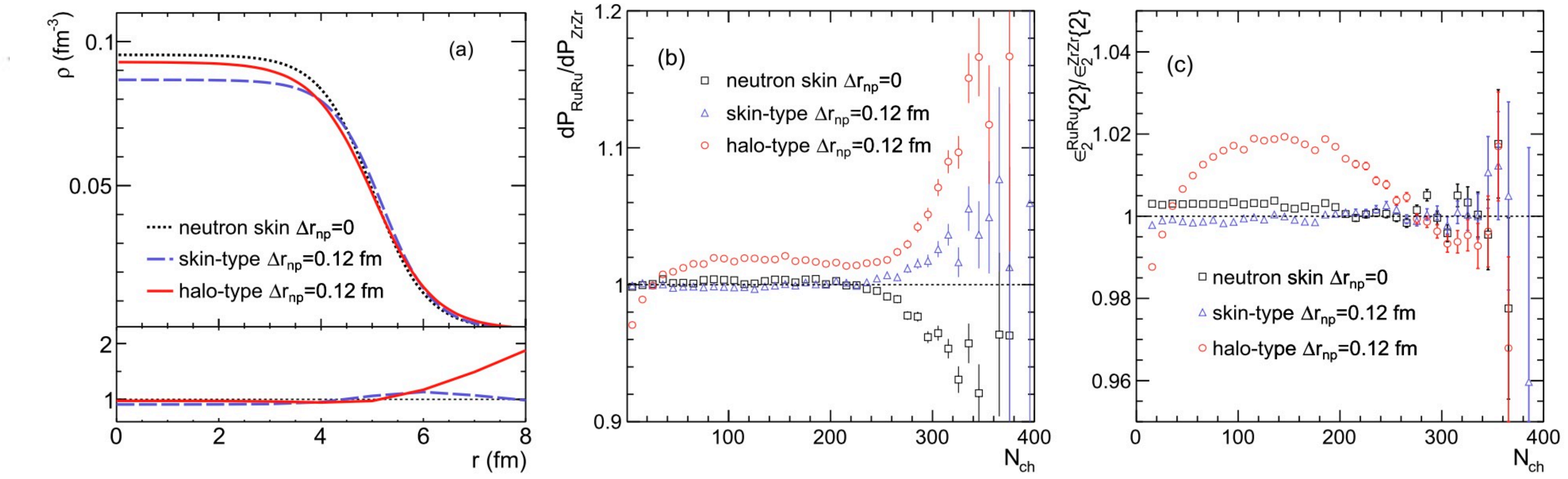
Determine the neutron skin type by STAR data

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



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

	^{96}Ru		^{96}Zr	
	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



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

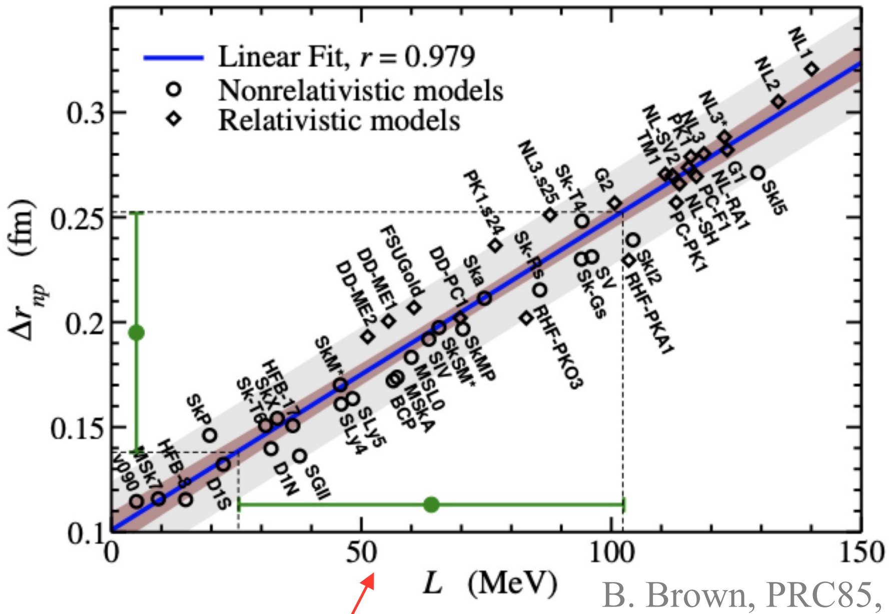
$^{96}_{40}\mathrm{Zr}: (N-Z)/A = 0.167$

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

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

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.

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,‡]

More references:

- HJX, H. Li, X. Wang, C. Shen, F. Wang, PLB819, 136453 (2021), arXiv:2103.05595
- HJX, H. Li, Y. Zhou, X. Wang, J. Zhao, L. Chen, F. Wang, PRC105, L014901 (2022), arXiv:2105.04052
- HJX, W. Zhao, H. Li, Y. Zhou, L. Chen, F. Wang, PRC108, L011902 (2023), arXiv:2111.14812
- S. Zhao, HJX, Y. Liu, H. Song, PLB840, 137838 (2023), arXiv:2204.02387
- S. Li, R. Wang, J. Wang, H. Xu, S. Pu, Q. Wang, PRD107, 054004 (2023), arXiv:2210.05106
- J. Wang, HJX, F. Wang, arXiv:2305.17114
- Q. Liu, S. Zhao, HJX, H. Song, PRC108, 034912 (2024), arXiv:2311. 01747 (Semi-isobar)

Photoproduction of di-electrons in peripheral isobar collisions

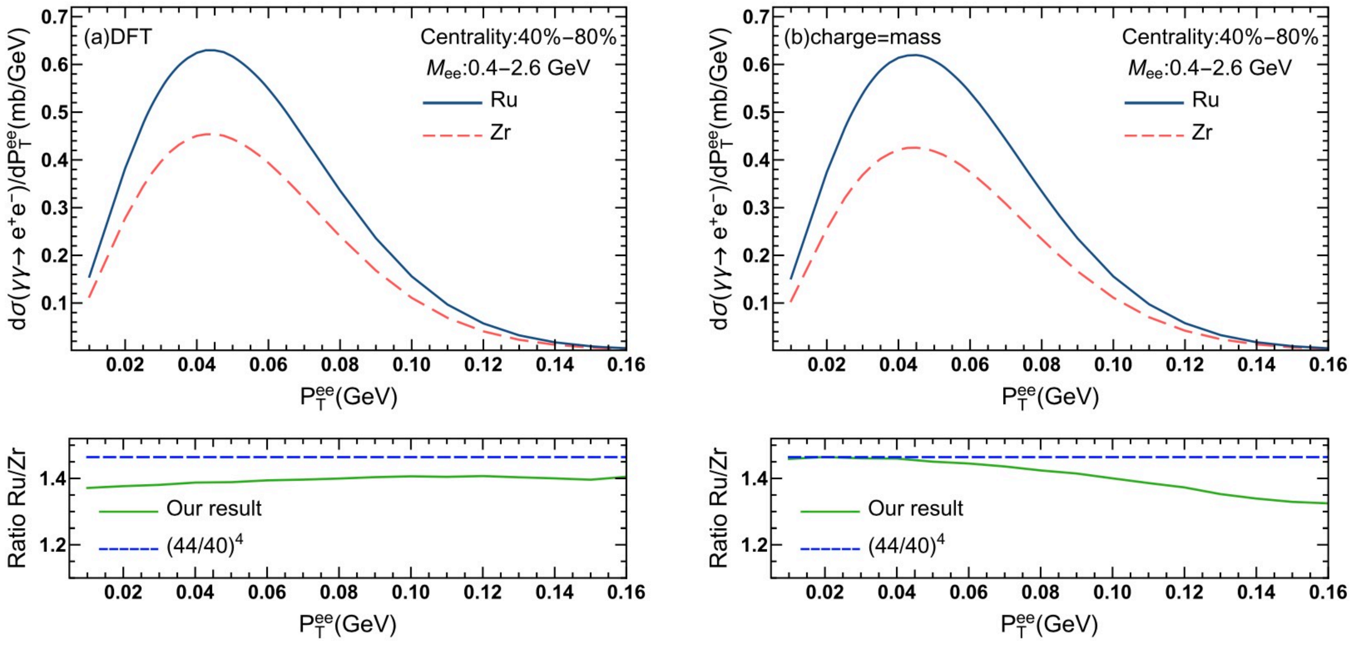
PHYSICAL REVIEW D **107**, 054004 (2023)

Centrality: 40-80%

Photoproduction of e^+e^- in peripheral isobar collisions

Shuo Lin,[1,*] Ren-Jie Wang,[1,†] Jian-Fei Wang,[1,‡] Hao-Jie Xu,[2,§] Shi Pu,[1,∥] and Qun Wang[1,¶]

of China, Anhui 230026, China
g 313000, China



The centrality determination vary with isobar densities, important for the differential cross section differences in isobar collisions

More observables

Probing neutron-skin thickness with free spectator neutrons in ultracentral high-energy isobaric collisions

Lu-Meng Liu (Beijing, GUCAS), Chun-Jian Zhang (Stony Brook U.), Jia Zhou (Beijing, GUCAS and SINAP, Shanghai), Jun Xu (SINAP, Shanghai and CAS, SARI, Shanghai), Jiangyong Jia (Stony Brook U. and Brookhaven) et al. (Mar 18, 2022)

Published in: *Phys.Lett.B* 834 (2022) 137441 • e-Print: 2203.09924 [nucl-th]

Detecting nuclear mass distribution in isobar collisions via charmonium

Jiaxing Zhao (SUBATECH, Nantes and Tsinghua U., Beijing), Shuzhe Shi (Stony Brook U.) (Nov 3, 2022)

Published in: *Eur.Phys.J.C* 83 (2023) 6, 511 • e-Print: 2211.01971 [hep-ph]

Hard probes in isobar collisions as a probe of the neutron skin #

Wilke van der Schee (CERN and Utrecht U.), Yen-Jie Lee (MIT, LNS), Govert Nijs (MIT, Cambridge, CTP), Yi Chen (MIT, LNS) (Jul 21, 2023)

e-Print: 2307.11836 [nucl-th]

Examination of nucleon distribution with Bayesian imaging for isobar collisions

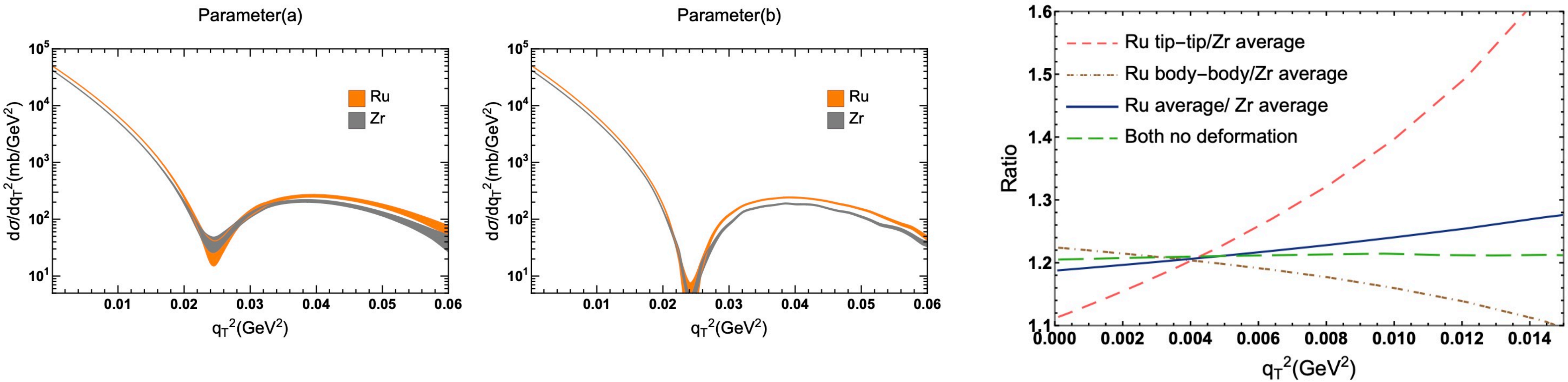
Yi-Lin Cheng (Frankfurt U., FIAS and Fudan U., Shanghai and SINAP, Shanghai and Fudan U. and Beijing, GUCAS), Shuzhe Shi (Tsinghua U., Beijing and Stony Brook U. and SUNY, Stony Brook), Yu-Gang Ma (Fudan U., Shanghai and Fudan U.), Horst Stöcker (Frankfurt U., FIAS and Darmstadt, GSI and Frankfurt U.), Kai Zhou (Frankfurt U., FIAS) (Jan 10, 2023)

Published in: *Phys.Rev.C* 107 (2023) 6, 064909 • e-Print: 2301.03910 [nucl-th]

Photoproduction of ρ^0 in ultraperipheral isobar collisions

S. Lin, et.al, in prepare

UPC

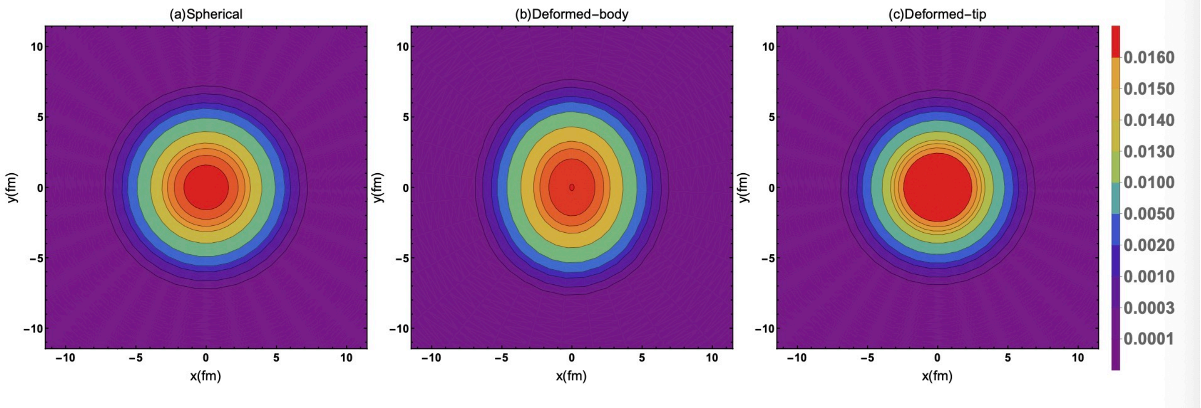


The effect of nuclear deformation are important for the differential cross section differences in isobar collisions

Photoproduction of ρ^0 in ultraperipheral isobar collisions

S. Lin, et.al, in prepare

UPC



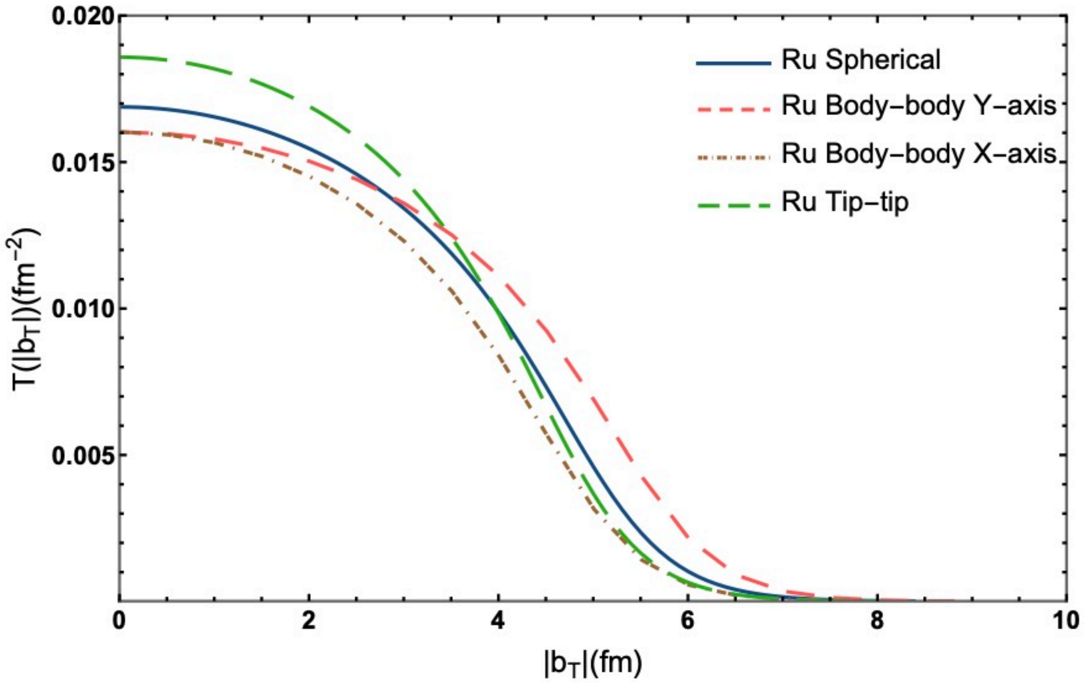
$$\mathcal{A}(q_T^2) \propto e^{-\frac{1}{4}q_T^2 w_T^2}, \quad (17)$$

Therefore, the ratio of differential cross section for two types of nucleus is

$$\frac{d\sigma_{\rm Ru}/dq_T^2}{d\sigma_{\rm Zr}/dq_T^2} \propto e^{\delta w_T q_T^2}, \quad (18)$$

with

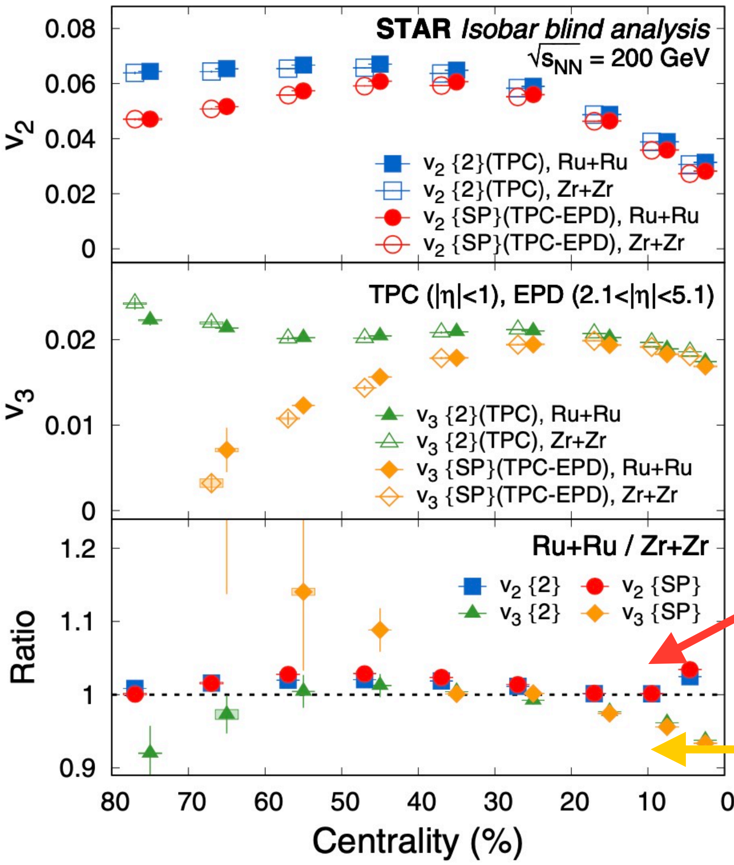
$$\delta w_T \equiv -\frac{1}{2}\left[(w_T^{\rm Ru})^2 - (w_T^{\rm Zr})^2\right]. \quad (19)$$

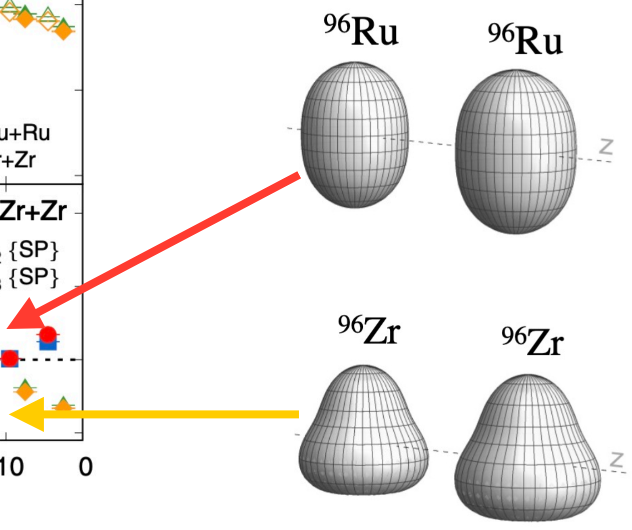


We offer a simple explanation by introducing the effective width of the nuclei in the thickness function.

Nuclear deformation

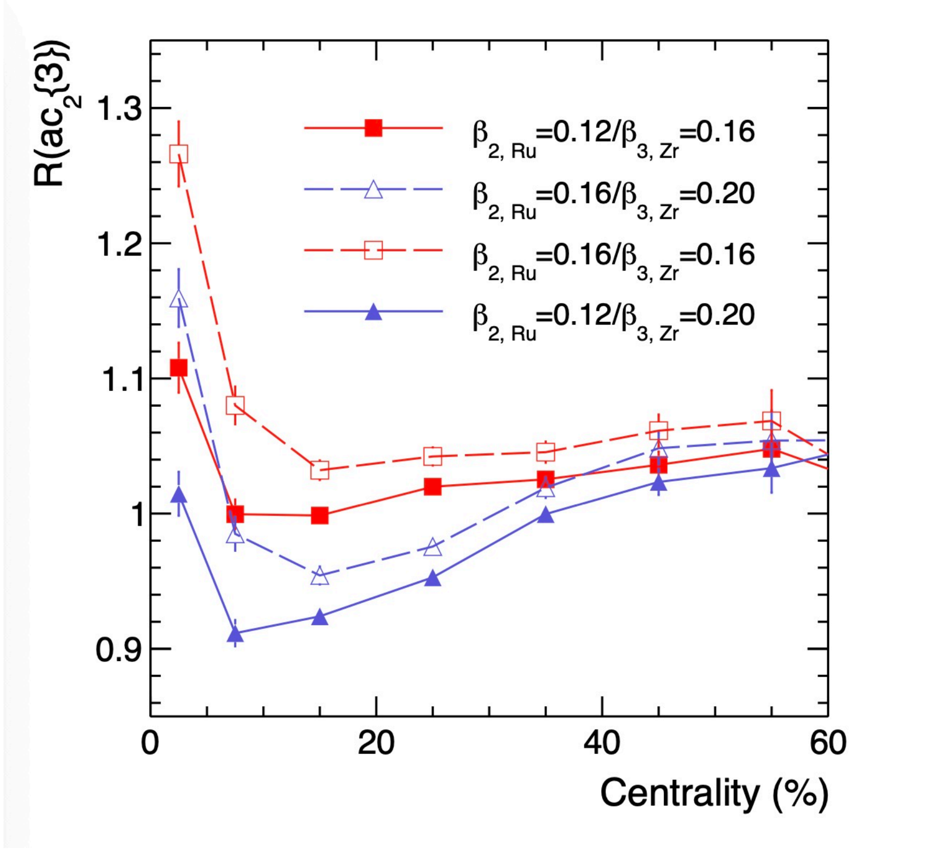
STAR, PRC105, 014901 (2022)
C. Zhang, J. Jia, PRL128, 022301(2022)





S. Zhao, HJX, et.al, PLB840, 137838 (2023)

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

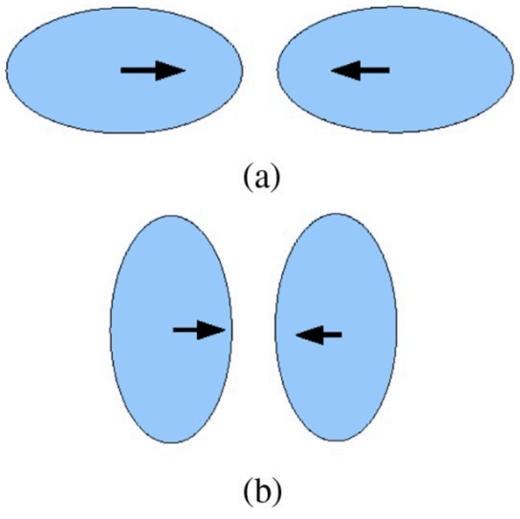


Sizable v_2 and v_3 ratios in central collisions indicate
shape difference between isobars

2. The quadrupole deformation and hexadecapole deformation are correlated

Nuclear deformation

S. Voloshin, PRL95, 122301 (2010)



PHYSICAL REVIEW C, VOLUME 61, 021903(R)

Uranium on uranium collisions at relativistic energies

Bao-An Li*
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)

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)
H. Mantysaari, et.al, PRL131, 062301(2023)
……..

Hexdecapole deformation

PHYSICAL REVIEW LETTERS **130,** 212302 (2023)

$\beta_2^{WS} \neq \beta_2$

Evidence of Hexadecapole Deformation in Uranium-238 at the Relativistic Heavy Ion Collider

Wouter Ryssens,[1,*] Giuliano Giacalone,[2] Björn Schenke,[3] and Chun Shen[4,5]

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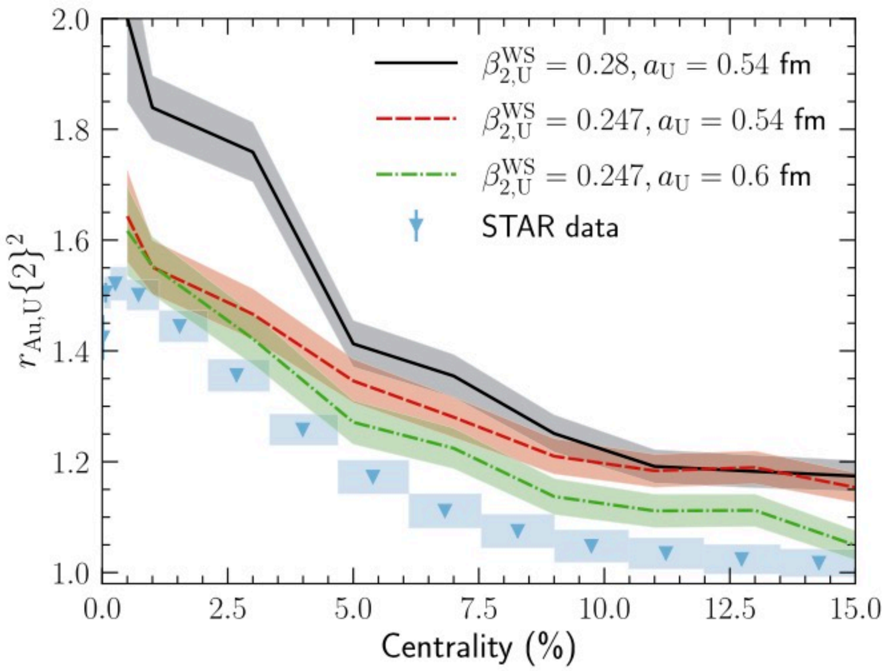
[2]*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg,*
[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[4]*Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201,*
[5]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973,*

$$\beta_\ell = \frac{4\pi}{(2\ell+1)ZR_0^\ell}\sqrt{\frac{B(E\ell)}{e^2}}.$$

$$\beta_{20} = \frac{R_d^2}{R_0^2}\left[\beta_{20}^{\mathrm{WS}} + \frac{2}{7}\sqrt{\frac{5}{\pi}}(\beta_{20}^{\mathrm{WS}})^2 + \frac{12}{7\sqrt{\pi}}\beta_{20}^{\mathrm{WS}}\beta_{40}^{\mathrm{WS}}\right],$$



Determine the hexadecapole deformation

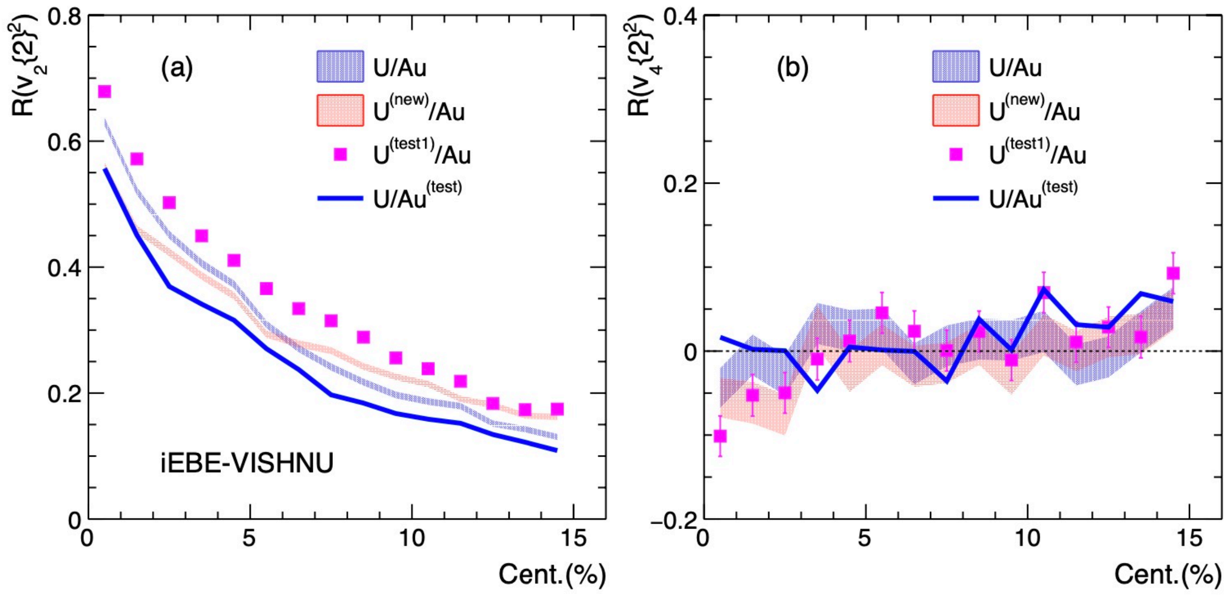
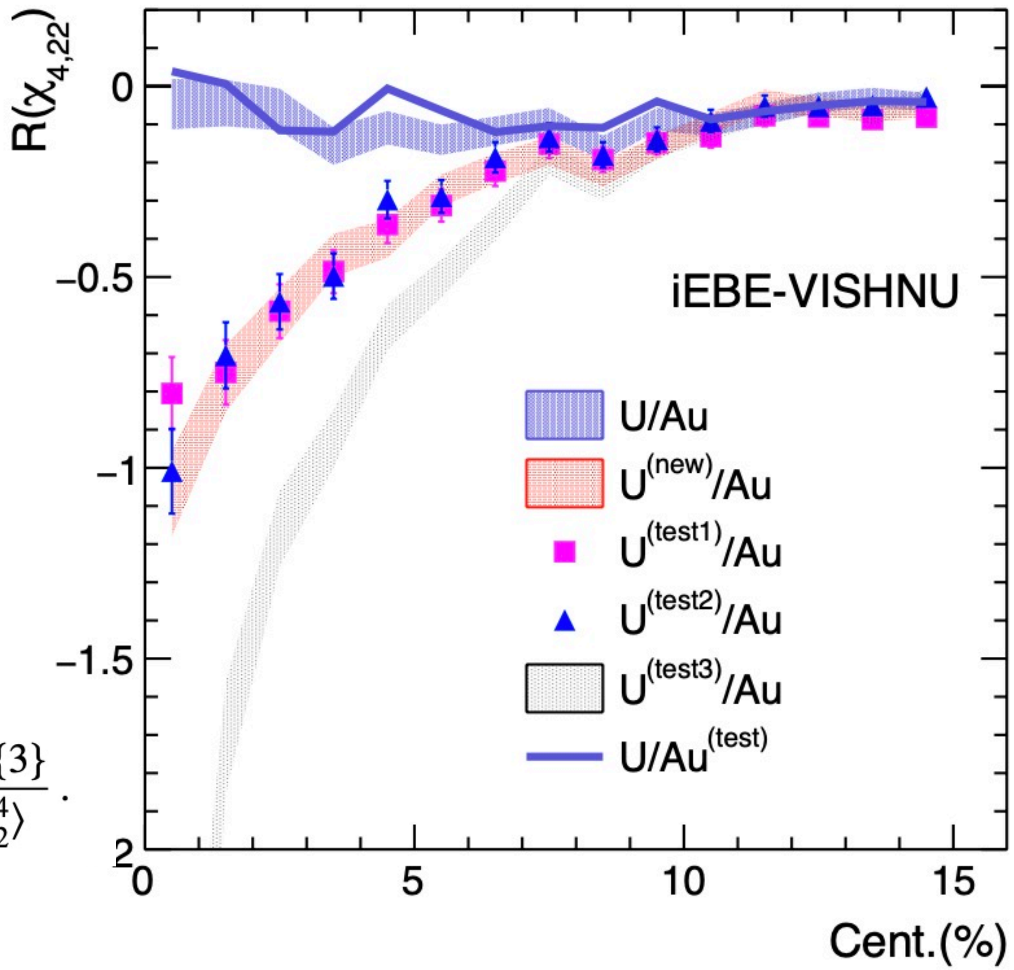


TABLE I. WS parameters for ^{238}U and ^{197}Au used in this work.

	R_0 (fm)	a (fm)	β_2	β_4
U	6.87	0.556	0.286	0.000
$U^{(new)}$	6.90	0.538	0.259	0.100
$U^{(test1)}$	6.87	0.556	0.286	0.100
$U^{(test2)}$	"	"	0.232	0.100
$U^{(test3)}$	"	"	0.286	0.200
Au	6.38	0.535	−0.131	−0.031
$Au^{(test)}$	"	"	−0.160	"

$$\chi_{4,22} \equiv \frac{v_4\{\Phi_2\}}{\langle v_2^4\rangle^{1/2}} = \frac{ac_2\{3\}}{\langle v_2^4\rangle}.$$



HJX, J. Zhao, F. Wang, arXiv:2402.16550

Summary

$$\text{I. } \sqrt{\langle r_n^2 \rangle} \neq \sqrt{\langle r_p^2 \rangle}$$

$$\text{II. } \beta_2^{\mathrm{WS}} \neq \beta_2$$

Exploring the compactness of α cluster in the ^{16}O nuclei with relativistic ^{16}O+^{16}O collisions

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[2]*School of Science, Huzhou University, Huzhou, Zhejiang 313000, China*
[3]*Strong-Coupling Physics International Research Laboratory (SPiRL), Huzhou University, Huzhou, Zhejiang 313000, China.*
[4]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[5]*Center for High Energy Physics, Peking University, Beijing 100871, China*
(Dated: March 18, 2024)

Probing the α cluster of ^{16}O with the relativistic ^{16}O+^{16}O collisions has raised great interest in the heavy ion community. However, the effects of the α cluster on the soft hadron observables are largely different for these previous studies. In this paper, we explain the differences by the compactness of the α cluster in oxygen, using `iEBE-VISHNU` hydrodynamic simulations with different initial state α cluster configurations. We also find several observables, such as the intensive skewness of the $[p_\mathrm{T}]$ correlator Γ_{p_T}, the harmonic flows $v_2\{2\}$, $v_2\{4\}$, $v_3\{2\}$, and the $v_n^2-\delta[p_\mathrm{T}]$ correlations $\rho(v_2^2,[p_\mathrm{T}])$, $\rho(v_3^2,[p_\mathrm{T}])$ in ^{16}O+^{16}O collisions are sensitive to the compactness of the α cluster in the colliding nuclei, which can be used to constrain the configurations of ^{16}O in the future. Our study serves as an important step toward the quantitative exploration of the α cluster configuration in the light nuclei with relativistic heavy ion collisions.

arXiv:2401.15723 α cluster

Exploring the Nuclear Shape Phase Transition in Ultra-Relativistic ^{129}Xe+^{129}Xe Collisions at the LHC

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[1]*School of Physics, Peking University, Beijing 100871, China*
[2]*School of Science, Huzhou University, Huzhou, Zhejiang 313000, China*
[3]*Strong-Coupling Physics International Research Laboratory (SPiRL), Huzhou University, Huzhou, Zhejiang 313000, China.*
[4]*Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[5]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[6]*Center for High Energy Physics, Peking University, Beijing 100871, China*
(Dated: March 13, 2024)

The shape phase transition for certain isotope or isotone chains, associated with the quantum phase transition of finite nuclei, is an intriguing phenomenon in nuclear physics. A notable case is the Xe isotope chain, where the structure transits from a γ-soft rotor to a spherical vibrator, with the second-order shape phase transition occurring in the vicinity of $^{128-130}$Xe. In this letter, we focus on investigating the γ-soft deformation of ^{129}Xe associated with the second-order shape phase transition by constructing novel correlators for ultra-relativistic ^{129}Xe+^{129}Xe collisions. In particular, our iEBE-VISHNU model calculations show that the $v_2^2-[p_T]$ correlation ρ_2 and the mean transverse momentum fluctuation Γ_{p_T}, which were previously interpreted as the evidence for the rigid triaxial deformation of ^{129}Xe, can also be well explained by the γ-soft deformation of ^{129}Xe. We also propose two novel correlators $\rho_{4,2}$ and $\rho_{2,4}$, which carry non-trivial higher-order correlations and show unique capabilities to distinguish between the γ-soft and the rigid triaxial deformation of ^{129}Xe in ^{129}Xe+^{129}Xe collisions at the LHC. The present study also provides a novel way to explore the second-order shape phase transition of finite nuclei with ultra-relativistic heavy ion collisions.

γ-soft arXiv:2403.07441

Thank you for your attention!

Haojie Xu(徐浩洁)

Huzhou University(湖州师范学院)