EXPLORING NEUTRON SKIN WITH RELATIVISTIC HEAVY ION COLLISIONS

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Exploring nuclear physics across energy scales 2024
2024.4.20-4.24, Beijing

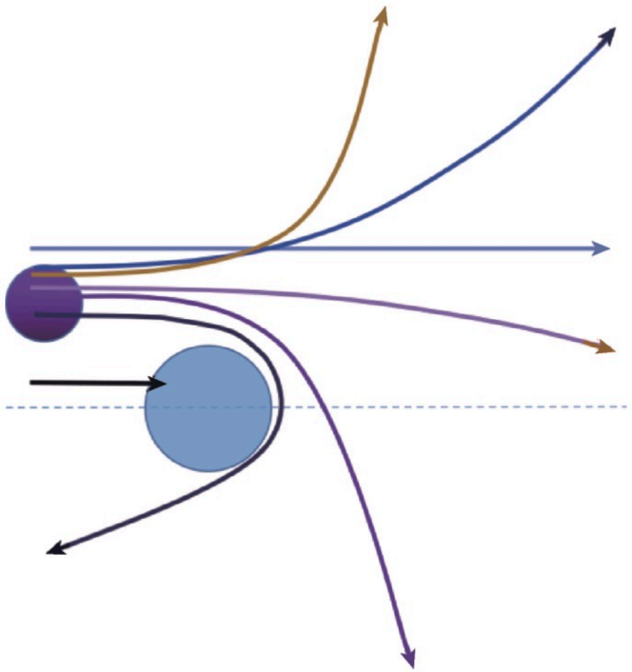
Outlines

Introduction
1. Neutron skin effect
2. Nuclear deformation effect
Summary

What we have learn from nuclear structure?
What information we can provide to nuclear structure community?

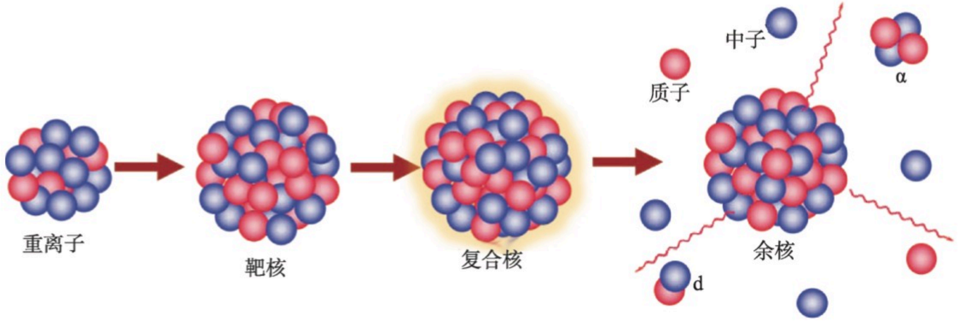
Nucleus-Nucleus Reactions (Collisions)

G. Jin, Modern Physics

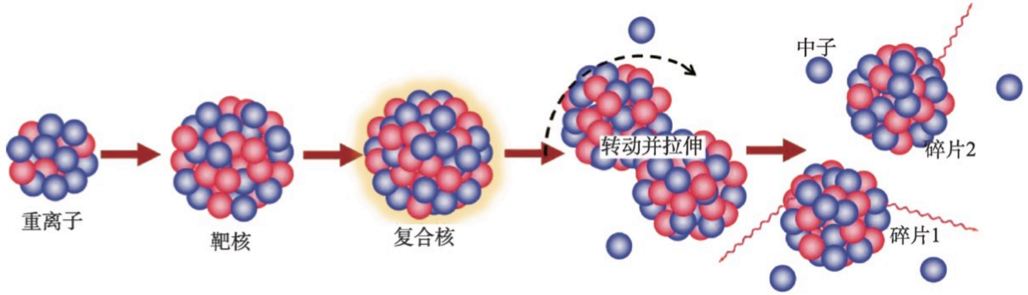


Hard scattering

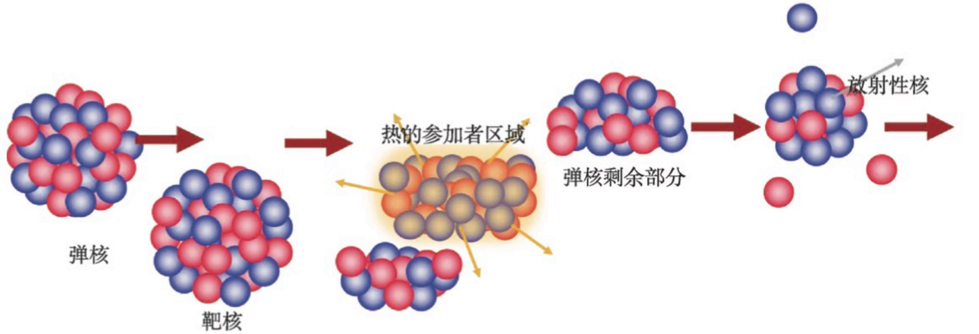
$\sqrt{s} < \mathrm{GeV}$



nuclear evaporation



fragmentation

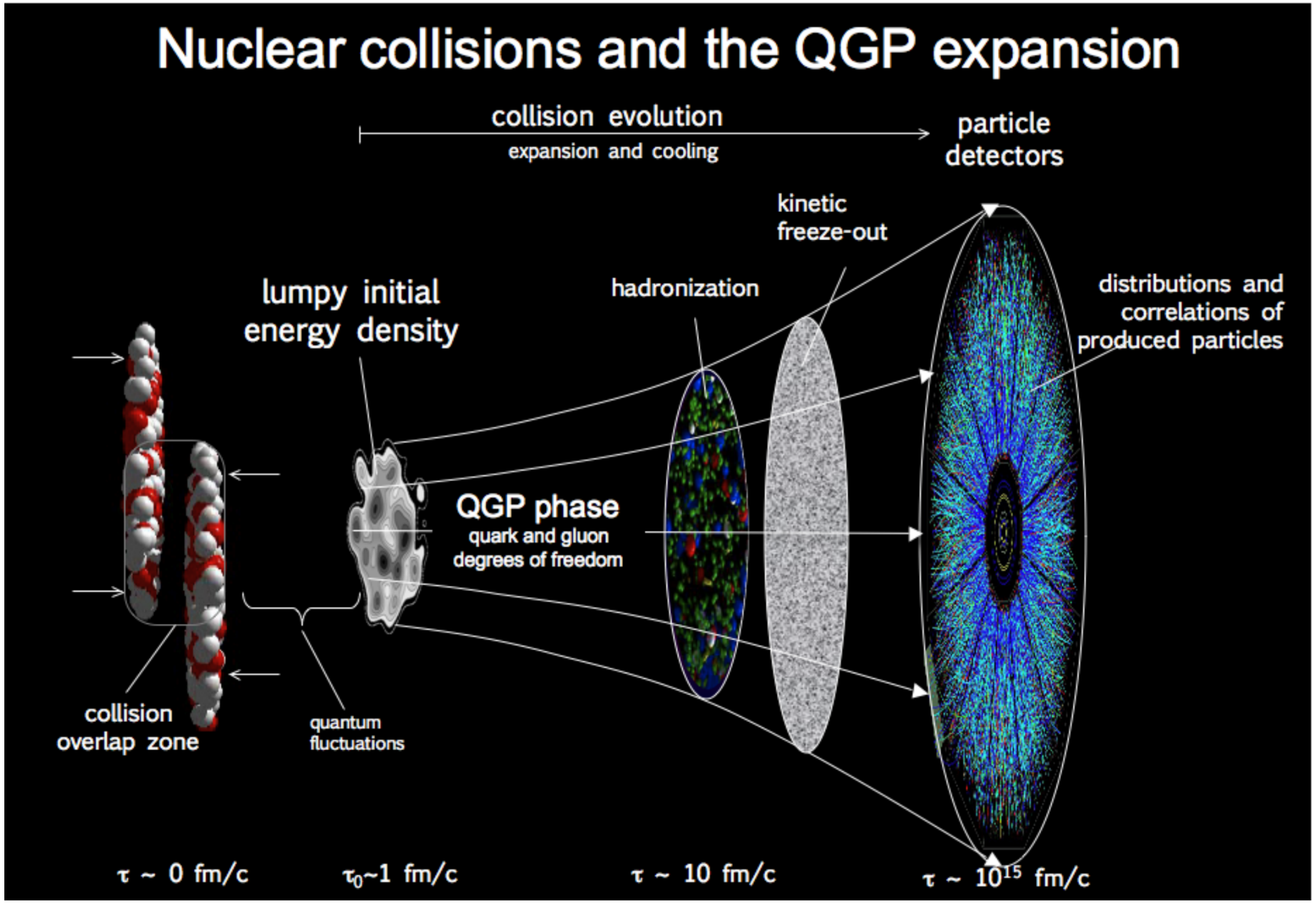


projectile fragmentation

Relativistic heavy ion collisions

The “Little Bang”

$$\sqrt{s} = 100\text{GeV} \sim \text{TeV}$$

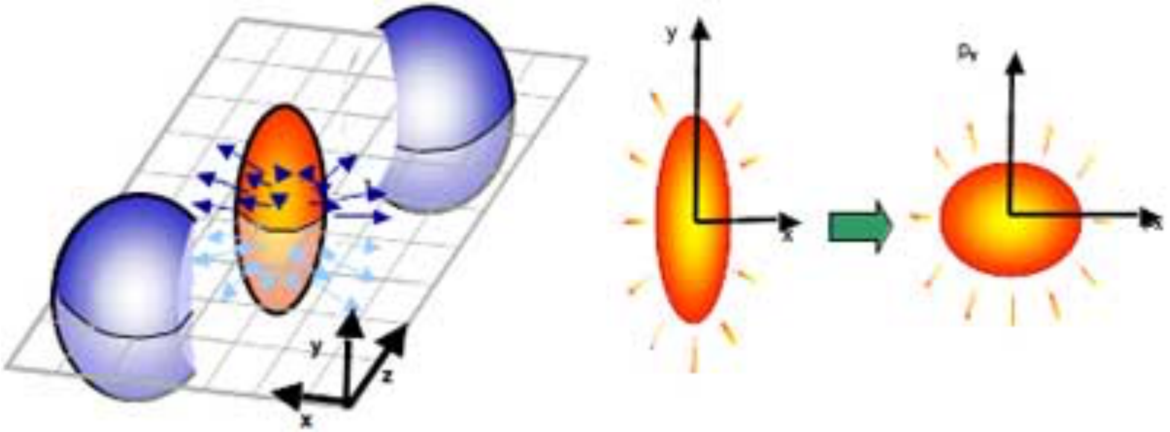


Relativistic Heavy ion collisions and nuclear structure

Woods-Saxon distributions

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

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

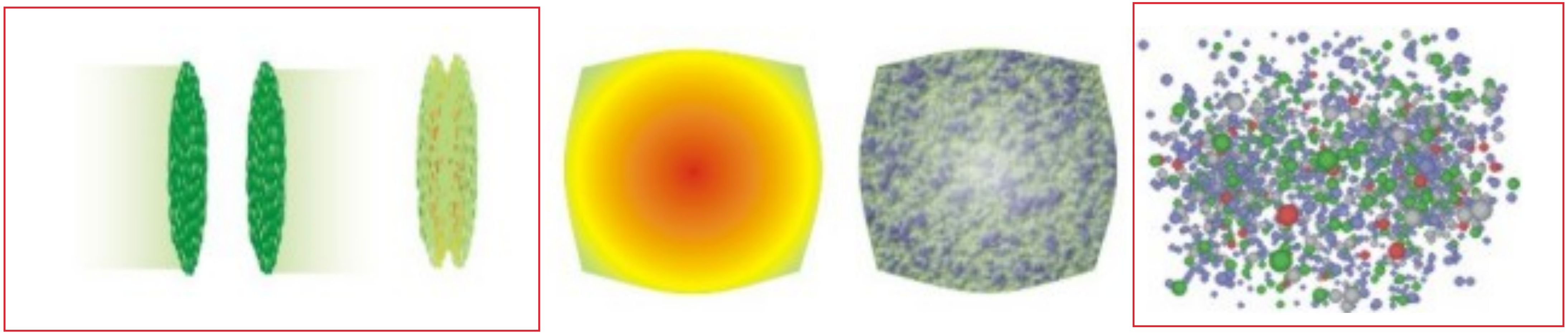


Anisotropic flow,
Flow fluctuations
HBT,
....

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

Initial geometry

Final observables

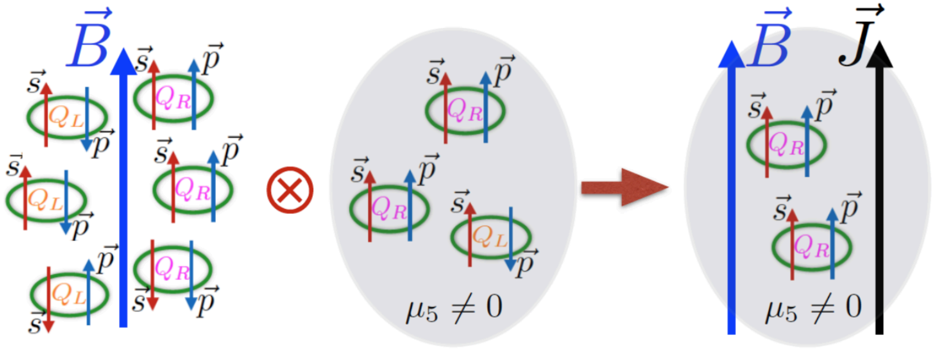


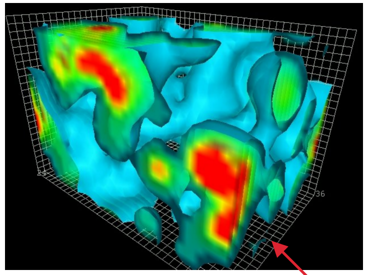
1. The neutron distribution differ from proton distribution: neutron skin

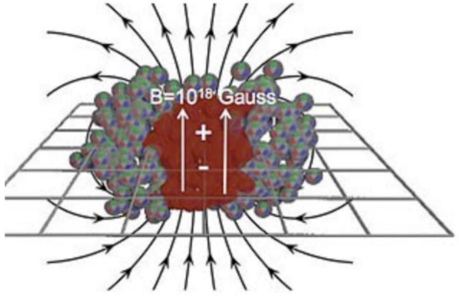
HJX, Xiaobao Wang, Hanlin Li, Jie Zhao, Zi-wei Lin, Caiwan Shen, Fuqiang Wang, PRL121, 022301 (2018)
Hanlin Li, **HJX**, Ying Zhou, Xiaobao Wang, Jie Zhao, Lie-wen Chen, Fuqiang Wang, PRL125, 222301 (2020)
HJX (for the STAR Collaboration), Acta Phys.Polon.Supp. 16, 1-A30 (2023), Quark Matter 2022

Relativistic isobaric collisions and chiral magnetic effect

Chiral magnetic effect (CME)





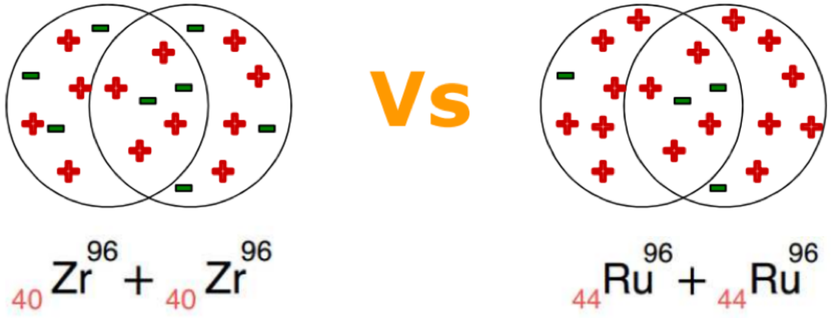


$$\mathbf{J_{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B},$$

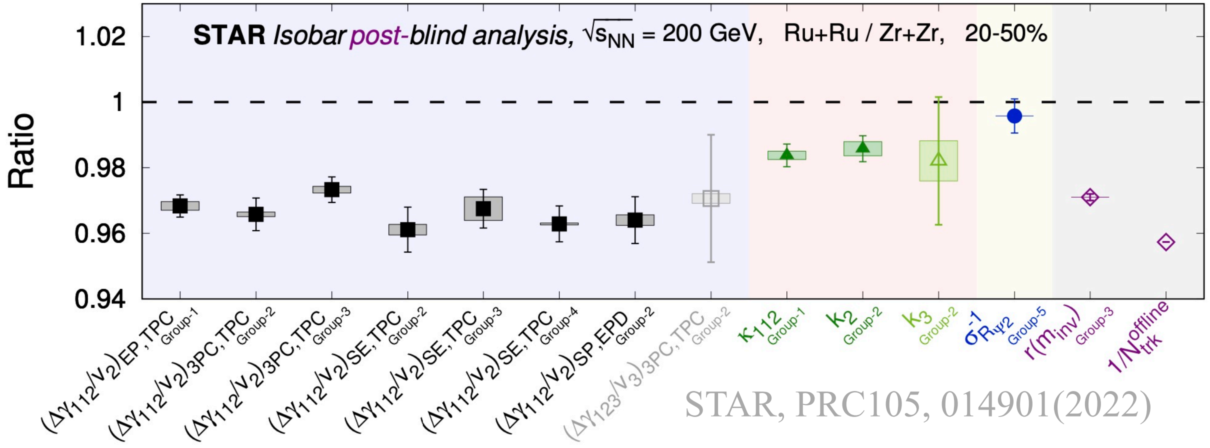
D. Kharzeev,et.al., PPNP88, 1(2016)

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!!!

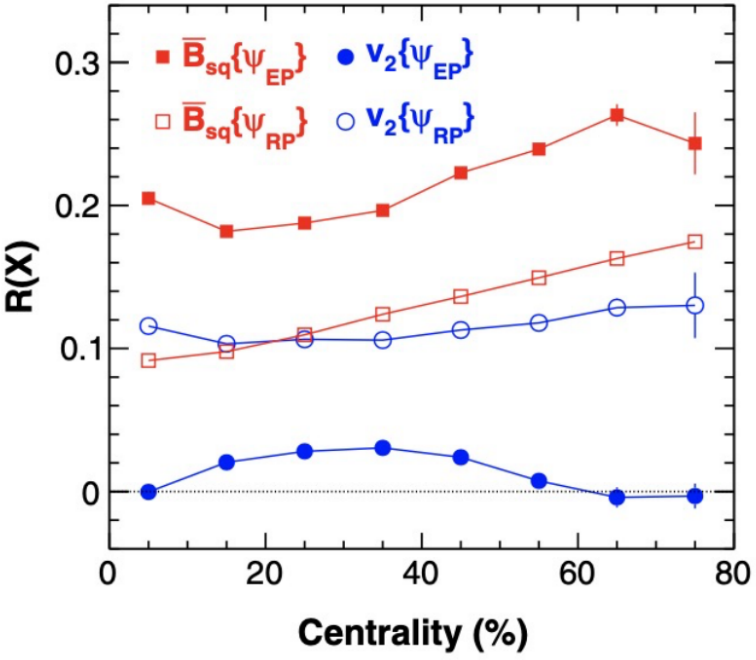
Nuclear densities for HIC models

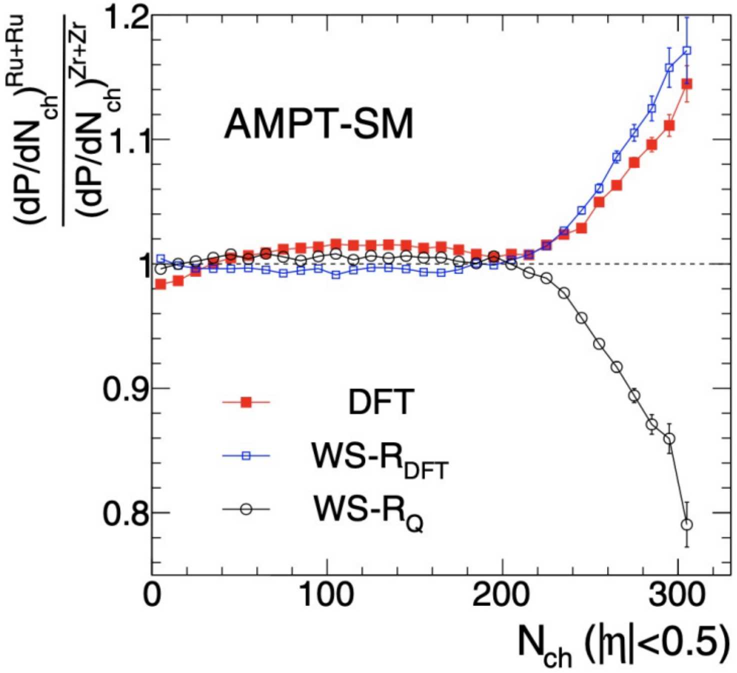
PHYSICAL REVIEW LETTERS **121,** 022301 (2018)

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

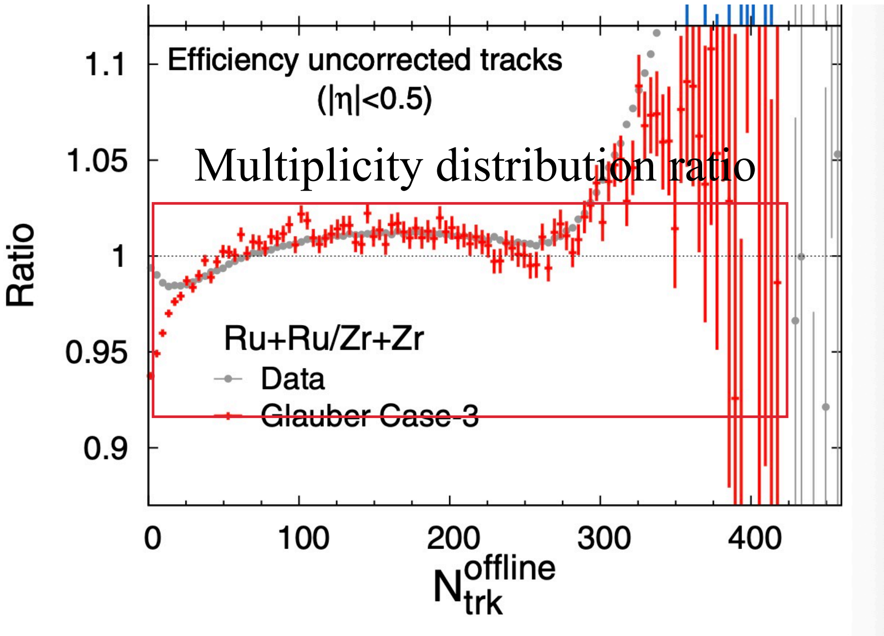
Importance of Isobar Density Distributions on the Chiral Magnetic Effect Search

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,*]



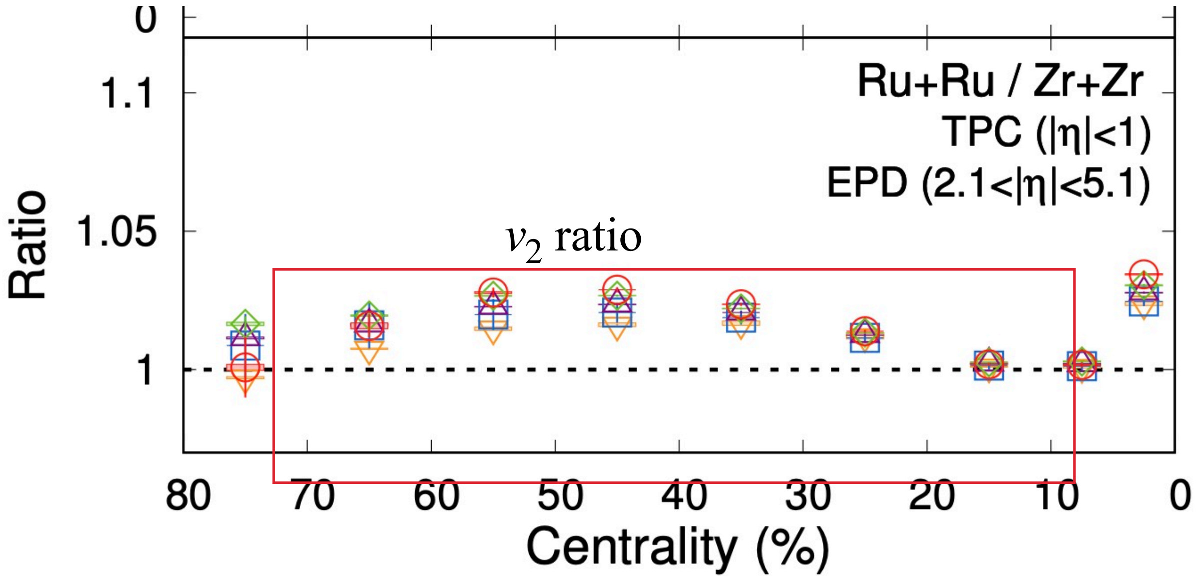


DFT predictions are verified by STAR data

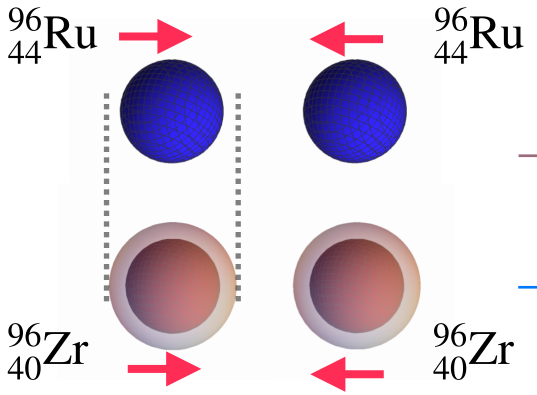


Multiplicity distribution ratio

STAR, PRC105, 014901(2022)



v_2 ratio



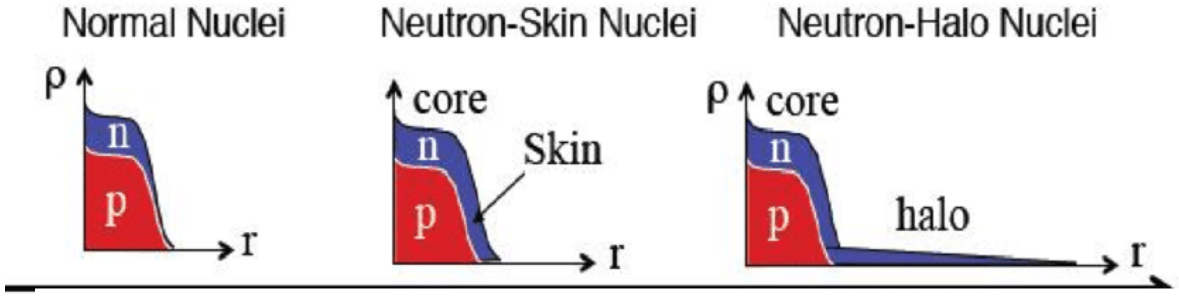
Neutron skin thickness $\Delta r_{np} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$

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

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

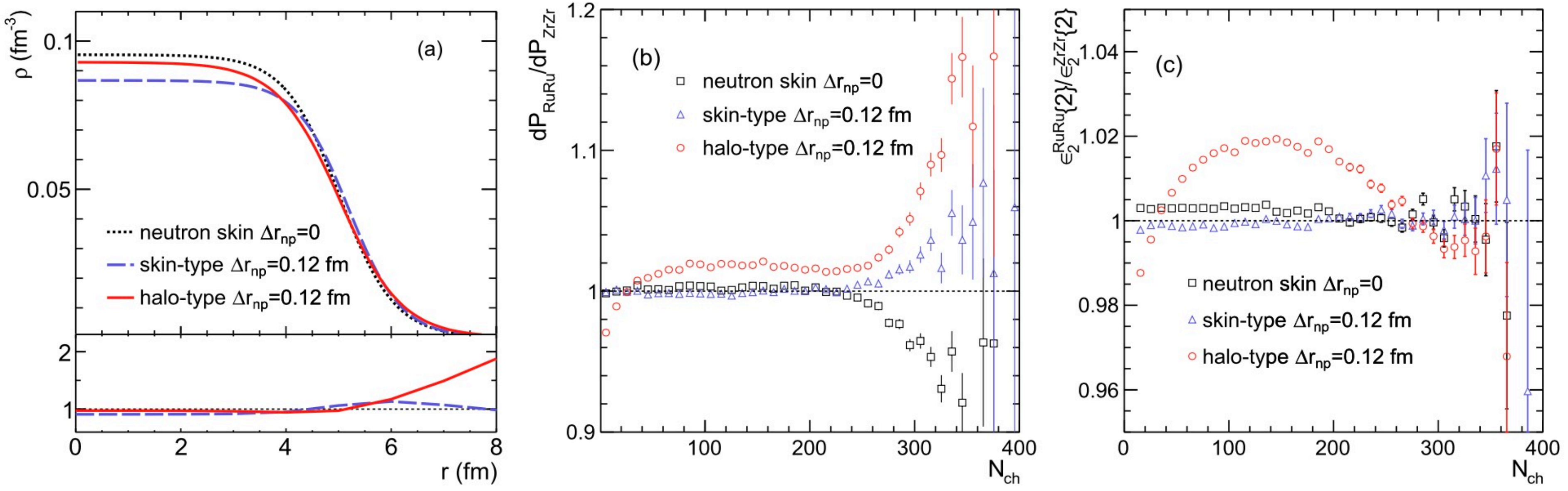
Determine the neutron skin type by STAR data

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



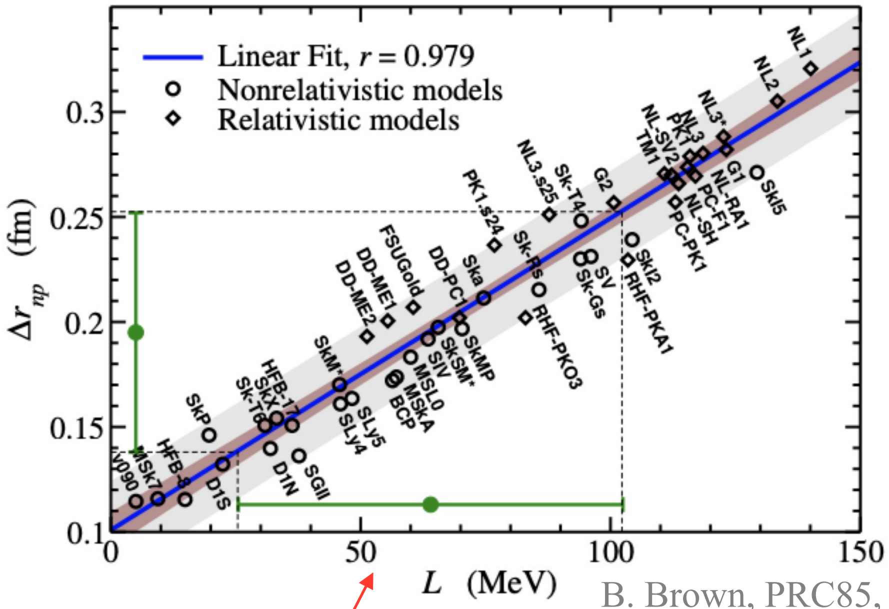
The shapes of the Ru+Ru/Zr+Zr ratios of the multiplicity and eccentricity in mid-central collisions can further distinguish between skin-type and halo-type neutron densities.

Neutron skin: sensitive probe of symmetry energy

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

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

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



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

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

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

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

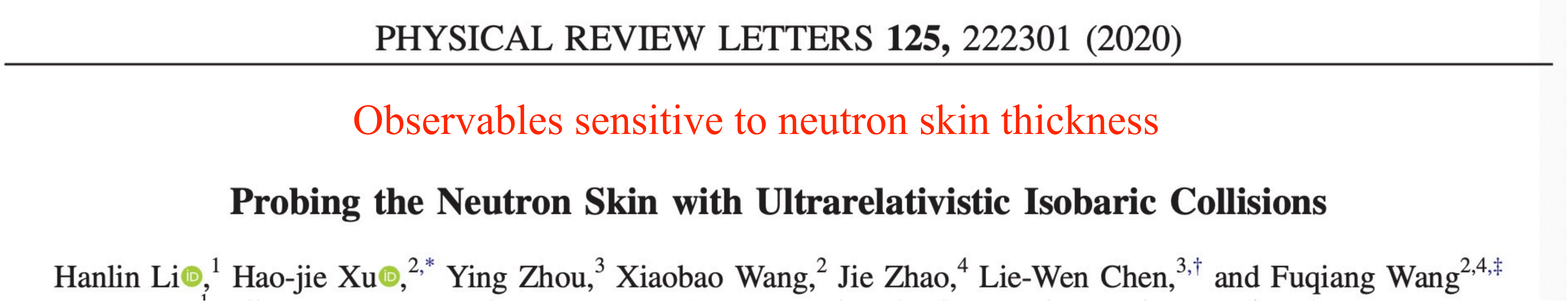
Slope parameter :

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

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, PRC109, 034912 (2024), arXiv:2311.01747

More observables

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

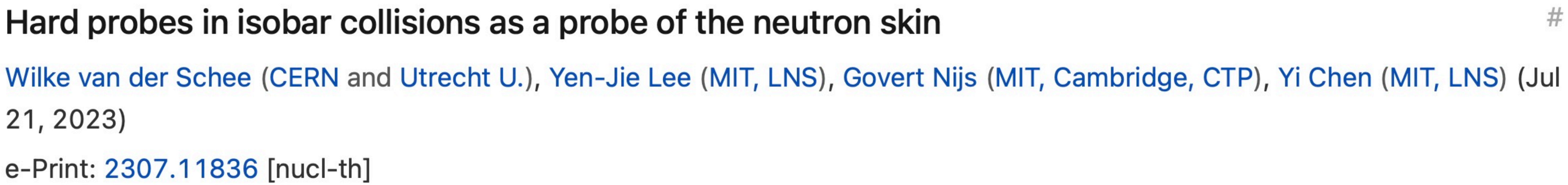
Lu-Meng Liu (Beijing, GUCAS), Chun-Jian Zhang (Stony Brook U.), Jia Zhou (Beijing, GUCAS and SINAP, Shanghai), Jun Xu (SINAP, Shanghai and CAS, SARI, Shanghai), Jiangyong Jia (Stony Brook U. and Brookhaven) et al. (Mar 18, 2022)

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]

STAR Preliminary results

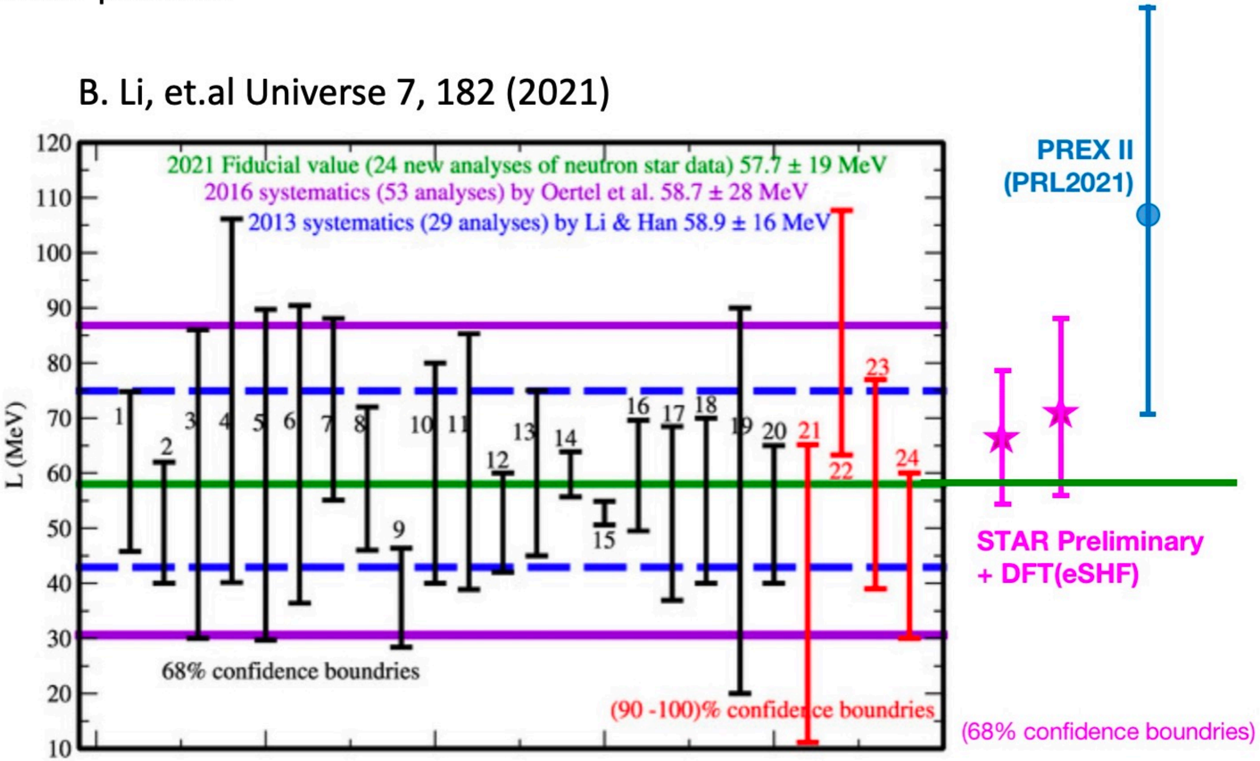
Compare to world wide data

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
  - $\Delta r_{\mathrm{np,Zr}} = 0.195 \pm 0.019$ fm
  - $\Delta r_{\mathrm{np,Ru}} = 0.051 \pm 0.009$ 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
  - $\Delta r_{\mathrm{np,Zr}} = 0.202 \pm 0.024$ fm
  - $\Delta r_{\mathrm{np,Ru}} = 0.052 \pm 0.012$ fm

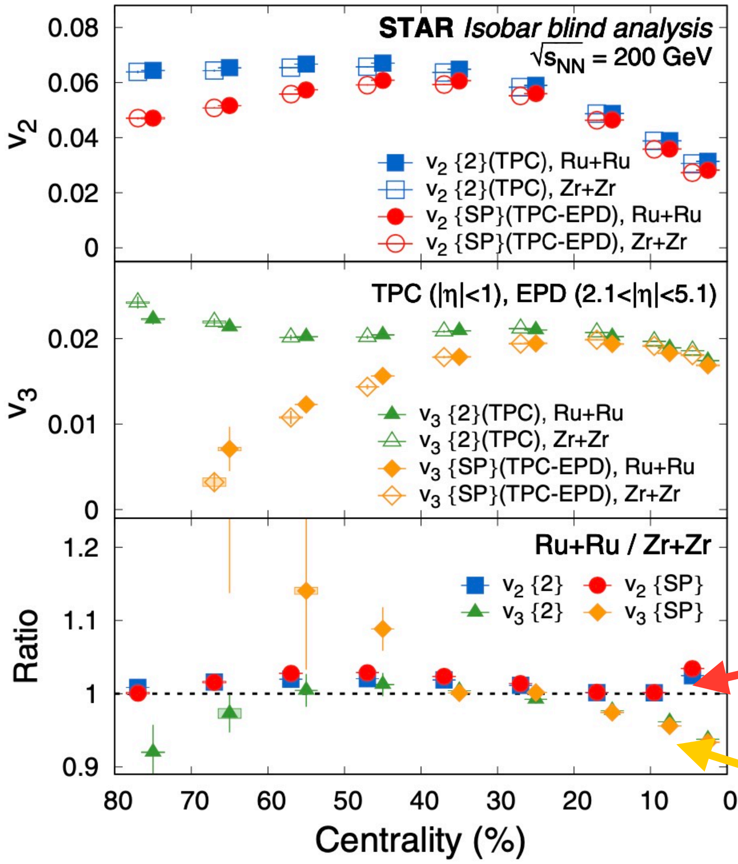
B. Li, et.al Universe 7, 182 (2021)



Consistent with world wide data with good precision

Nuclear deformation

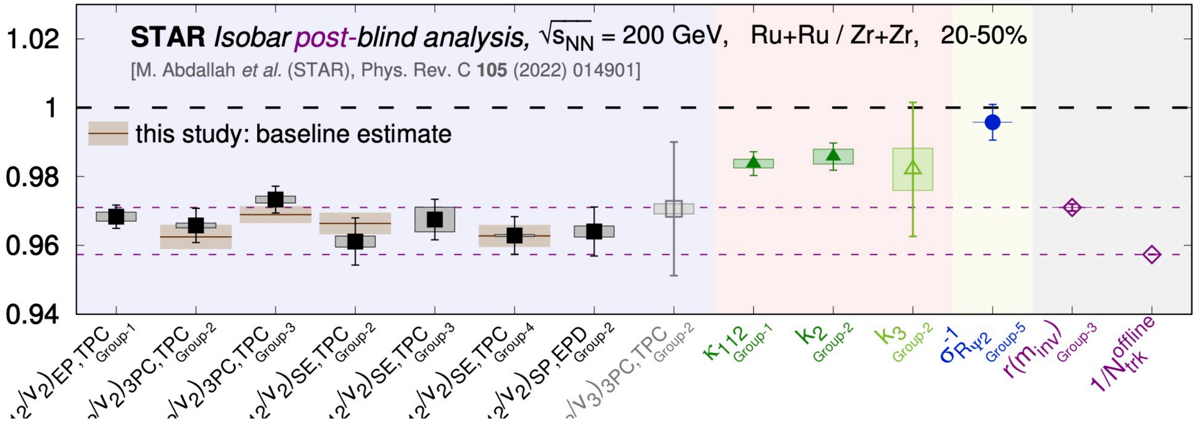
STAR, PRC105, 014901 (2022)
C. Zhang, J. Jia, PRL128, 022301(2022)



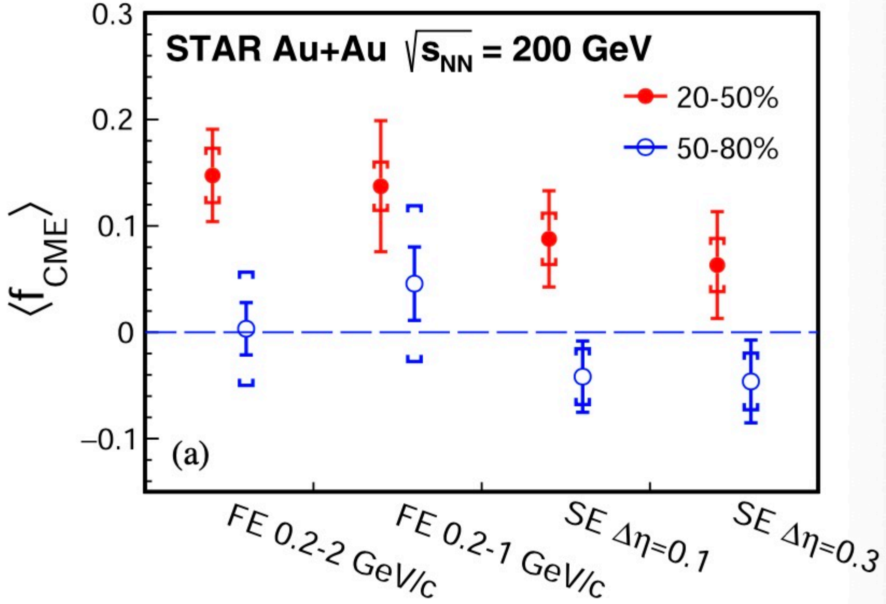
Background for CME:

- Neutron skin! ✓
- Non flow! ✓
- Deformation ✗

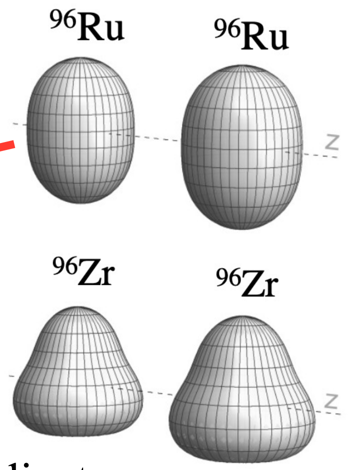
STAR Collaboration, arXiv:2308.16846



STAR Collaboration, PRL128, 092301 (2022)



More Au+Au data is ongoing!!!



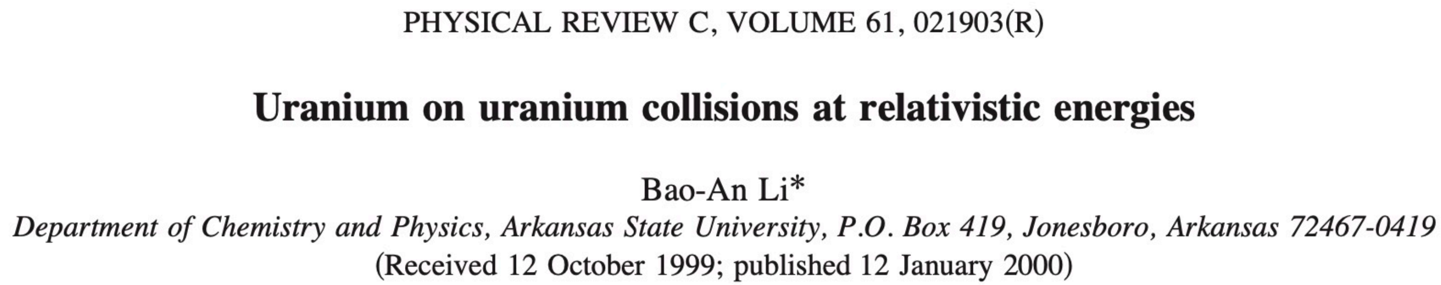
Sizable v_2 and v_3 ratios in central collisions indicate **shape difference between isobars**

C. Zhang's talk

2. The quadrupole deformation and hexadecapole deformation are correlated

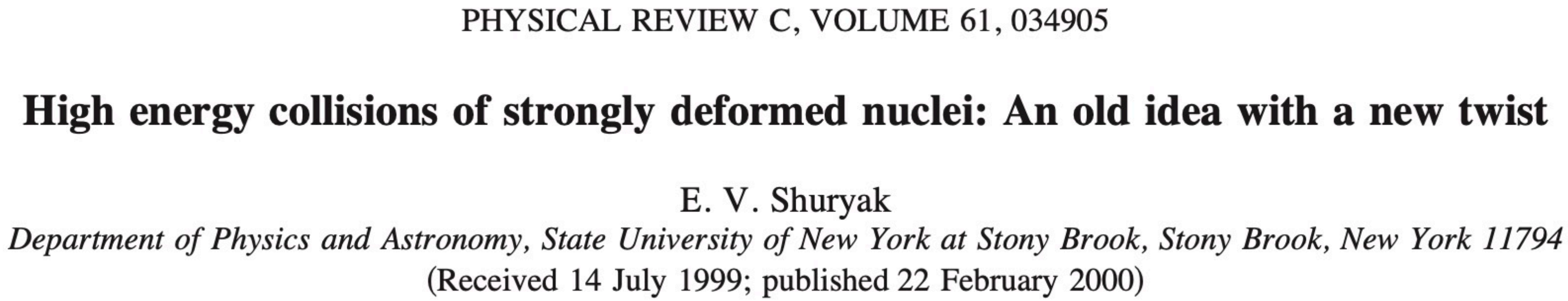
HJX, Jie Zhao, Fuqiang Wang, arXiv:2402.16550

Nuclear deformation


PHYSICAL REVIEW C, VOLUME 61, 021903(R)

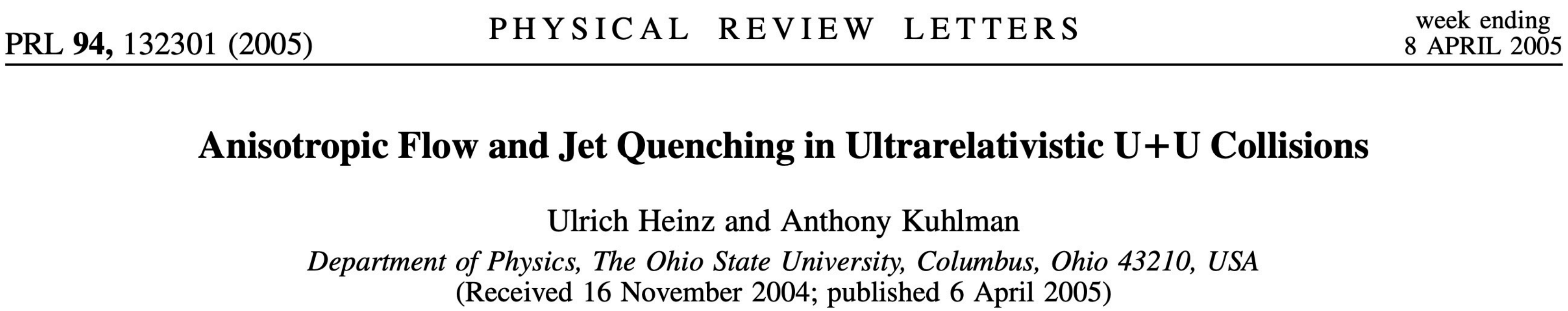
Uranium on uranium collisions at relativistic energies

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

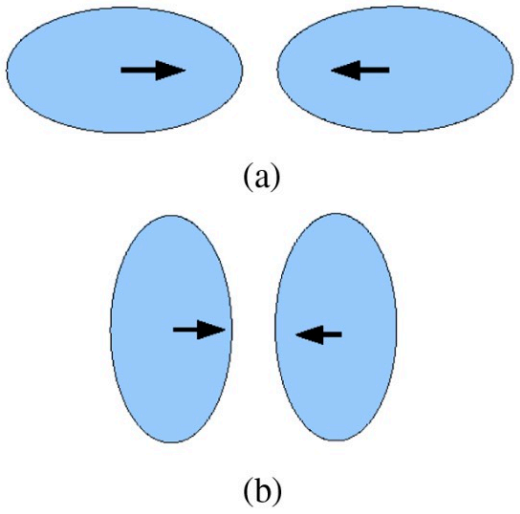
E. V. Shuryak
Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 14 July 1999; published 22 February 2000)


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)

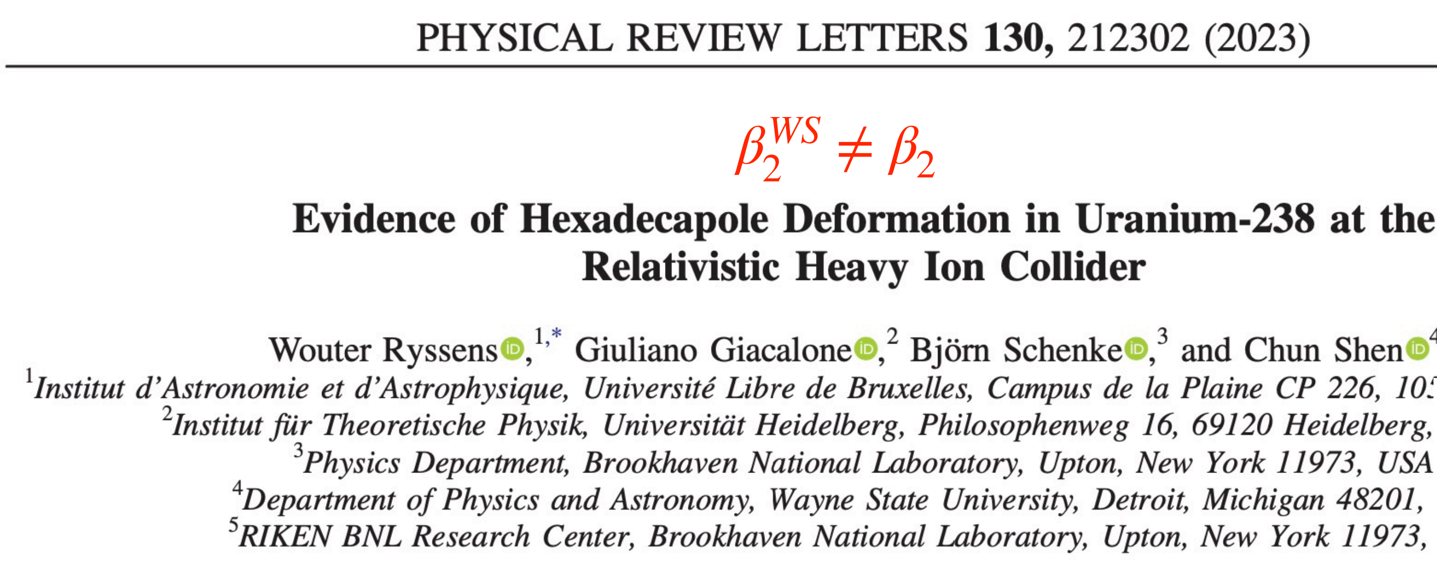
S. Voloshin, PRL95, 122301 (2010)


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

Hexadecapole deformation



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

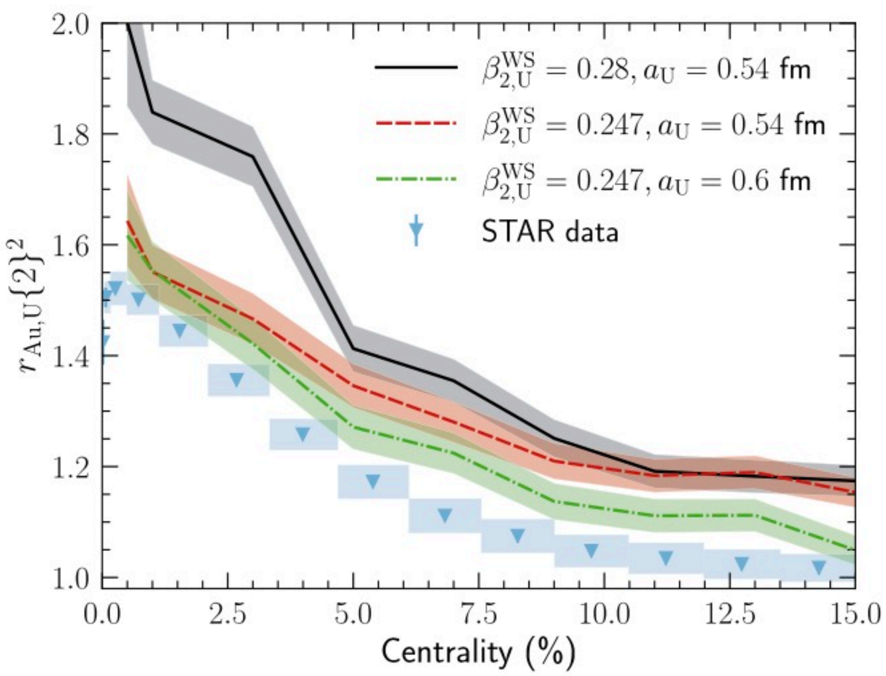
$\beta_2^{WS} \neq \beta_2$

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]
[1] *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine CP 226, 10*
[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,*

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

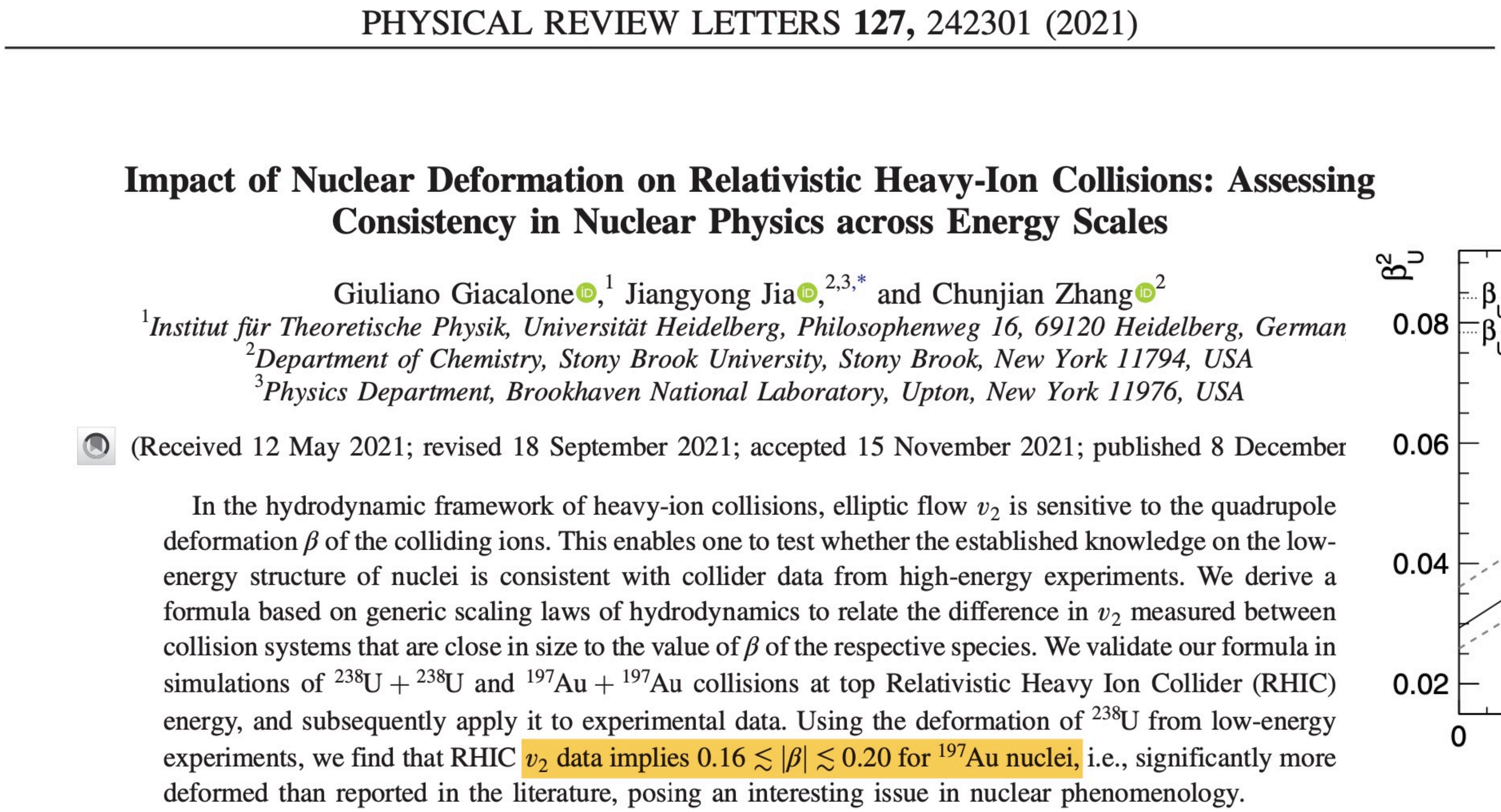
$B(E2,U^{238}) = 12.09 \pm 0.2\ e^2b^2$



Liquid drop limit

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

Deformation of Au



PHYSICAL REVIEW LETTERS **127,** 242301 (2021)

Impact of Nuclear Deformation on Relativistic Heavy-Ion Collisions: Assessing Consistency in Nuclear Physics across Energy Scales

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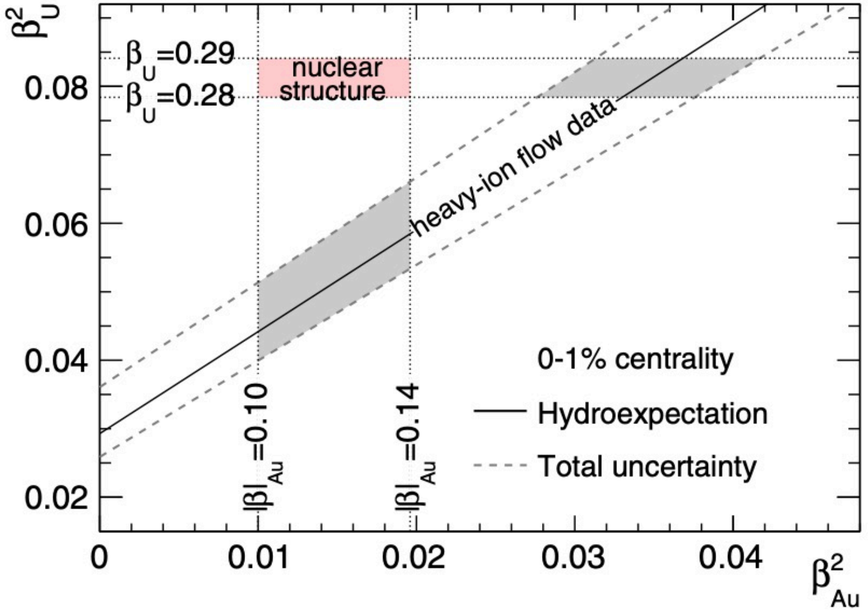
[2]*Department of Chemistry, Stony Brook University, Stony Brook, New York 11794, USA*
[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11976, USA*

(Received 12 May 2021; revised 18 September 2021; accepted 15 November 2021; published 8 December

In the hydrodynamic framework of heavy-ion collisions, elliptic flow v_2 is sensitive to the quadrupole deformation β of the colliding ions. This enables one to test whether the established knowledge on the low-energy structure of nuclei is consistent with collider data from high-energy experiments. We derive a formula based on generic scaling laws of hydrodynamics to relate the difference in v_2 measured between collision systems that are close in size to the value of β of the respective species. We validate our formula in simulations of ^{238}U + ^{238}U and ^{197}Au + ^{197}Au collisions at top Relativistic Heavy Ion Collider (RHIC) energy, and subsequently apply it to experimental data. Using the deformation of ^{238}U from low-energy experiments, we find that RHIC v_2 data implies $0.16 \lesssim |\beta| \lesssim 0.20$ for ^{197}Au nuclei, i.e., significantly more deformed than reported in the literature, posing an interesting issue in nuclear phenomenology.

$\beta_2^{\mathrm{Au}} = ???$



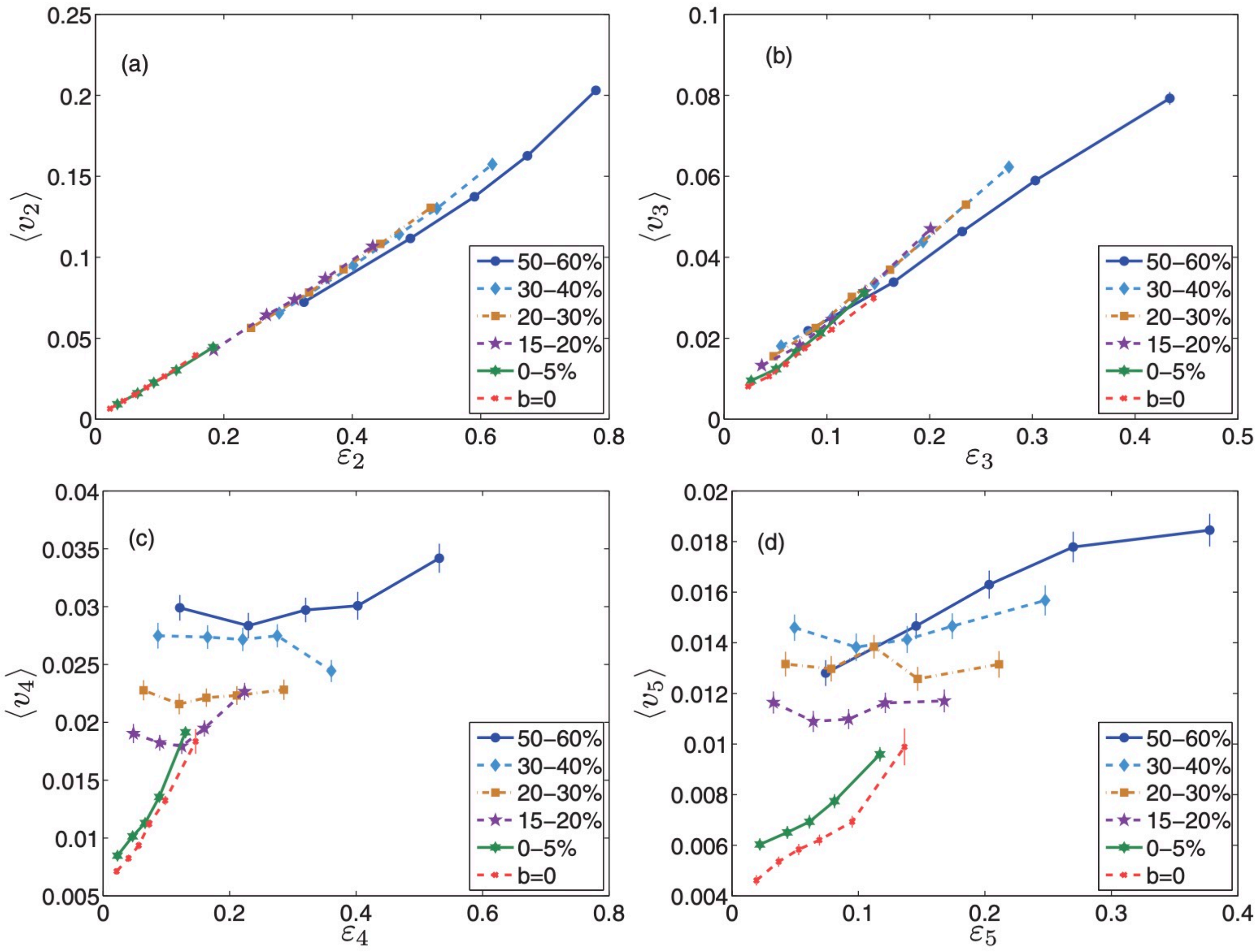
Hexadecapole flow

$\epsilon_4^2 \propto \beta_4^2$ ✓

$v4^2 \propto \epsilon_4^2$ ✗

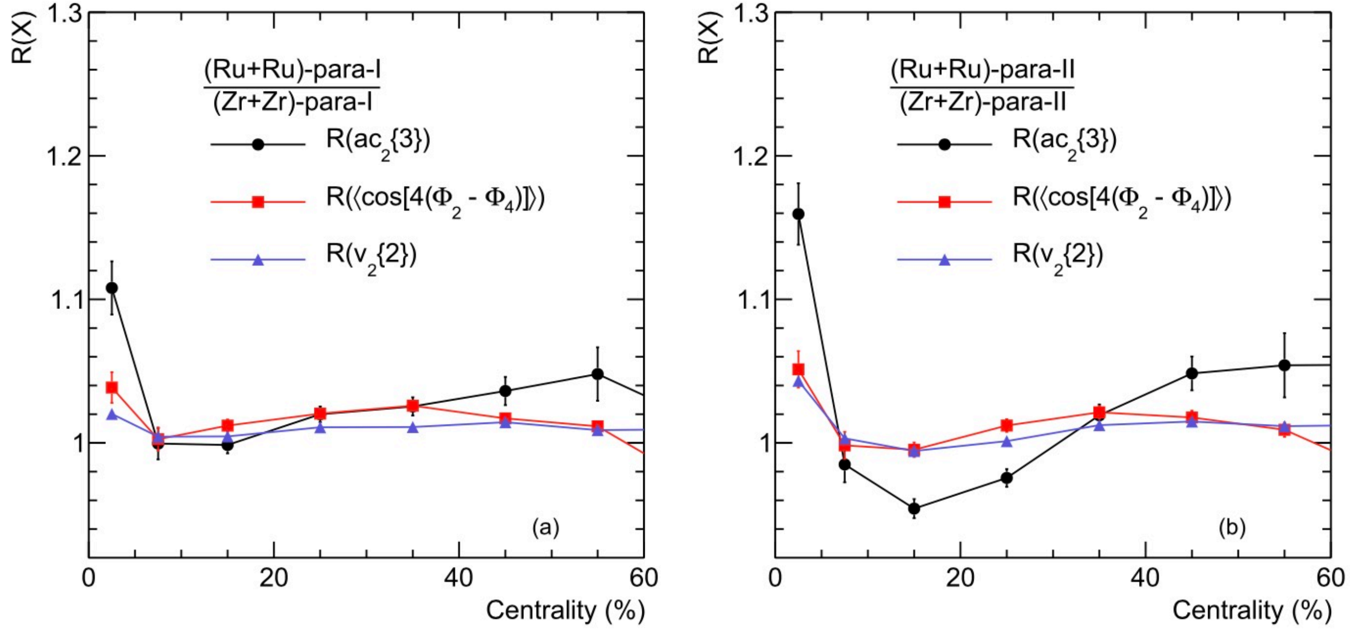
The hydrodynamic response for v_n $(n \geq 4)$ with event-by-event fluctuations is not only non-diagonal but also nonlinear.

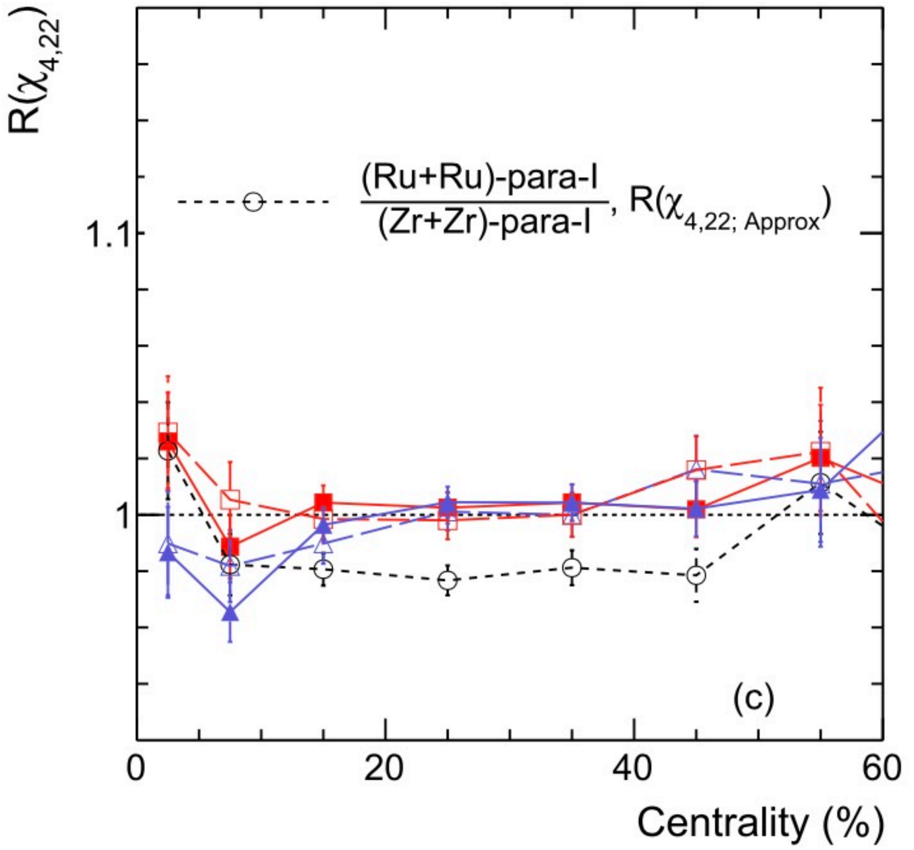
Zhi Qiu and Ulrich Heinz, PRC84, 024911(2011)



Nonlinear response coefficient

S. Zhao, HJX, Y. Liu, H. Song, PLB839, 137838 (2023)





$$v_4\{\Psi_2\} \equiv \frac{\mathrm{Re}\langle V_4 (V_2^*)^2\rangle}{\sqrt{\langle |V_2|^4\rangle}}$$

$$v_6\{\Psi_2\} \equiv \frac{\mathrm{Re}\langle V_6 (V_2^*)^3\rangle}{\sqrt{\langle |V_2|^6\rangle}}$$

$$v_6\{\Psi_3\} \equiv \frac{\mathrm{Re}\langle V_6 (V_3^*)^2\rangle}{\sqrt{\langle |V_3|^4\rangle}}.$$

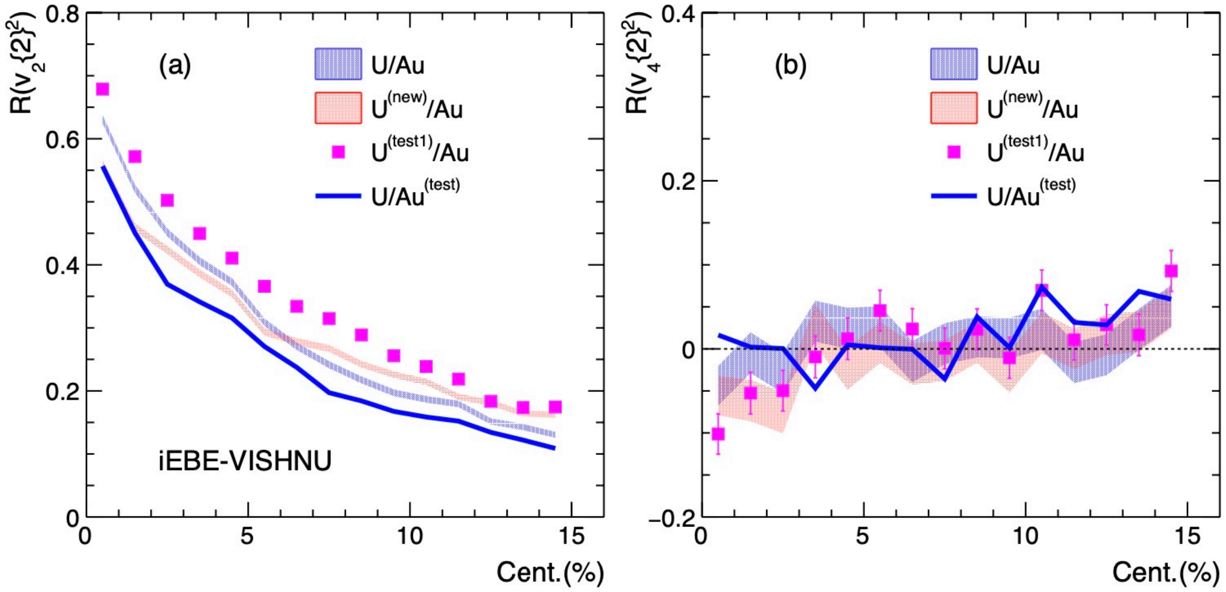
$$\chi_4 = \frac{\langle V_4 (V_2^*)^2\rangle}{\langle |V_2|^4\rangle} = \frac{v_4\{\Psi_2\}}{\sqrt{\langle |V_2|^4\rangle}}$$

$$\chi_5 = \frac{\langle V_5 V_2^* V_3^*\rangle}{\langle |V_2|^2 |V_3^2|\rangle} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle |V_2|^2 |V_3^2|\rangle}}$$

L. Yan, J. Ollitrault, PLB744, 82-87 (2015)

$ac_2\{3\}$ and $\langle\cos 4(\Phi_4 - \Phi_2)\rangle$ are sensitive to β_2 and β_3, while $\chi_{4,22}$ is sensitive to neither!!

Determine the hexadecapole deformation



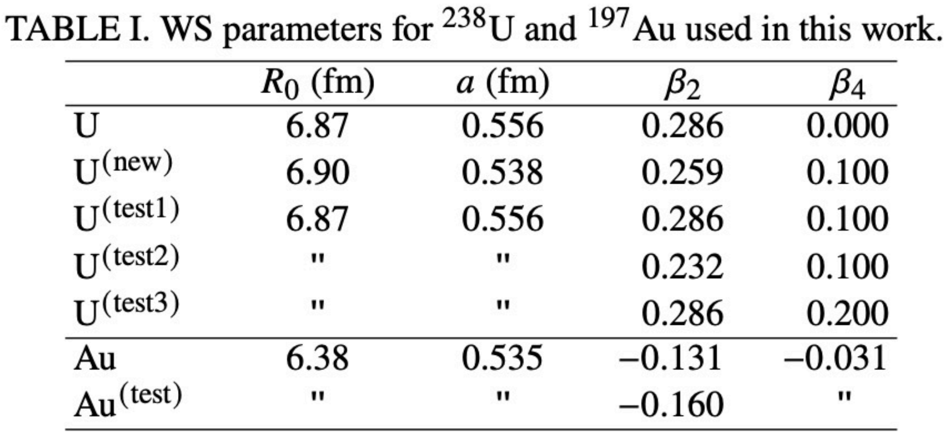
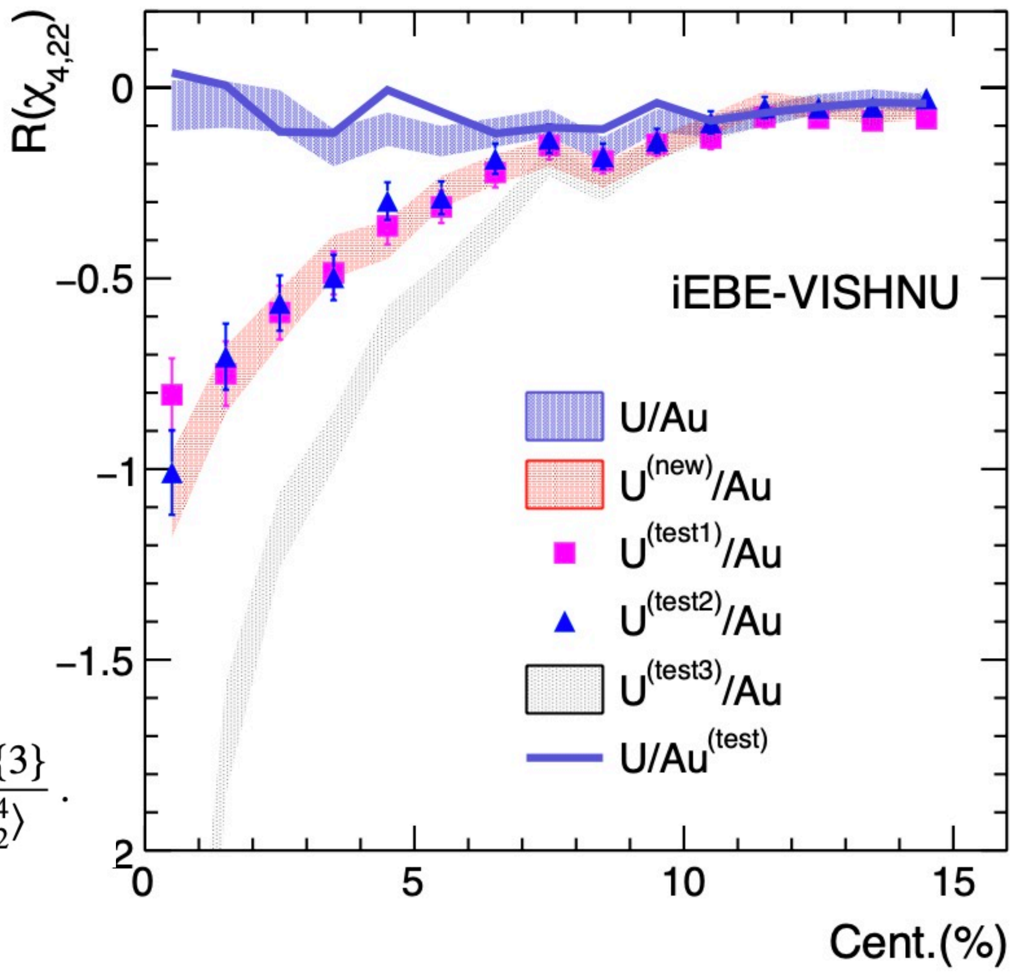


TABLE I. WS parameters for ^{238}U and ^{197}Au used in this work.

	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	"

$$\chi_{4,22} \equiv \frac{v_4\{\Phi_2\}}{\langle v_2^4\rangle^{1/2}} = \frac{\mathrm{ac}_2\{3\}}{\langle v_2^4\rangle}\,.$$



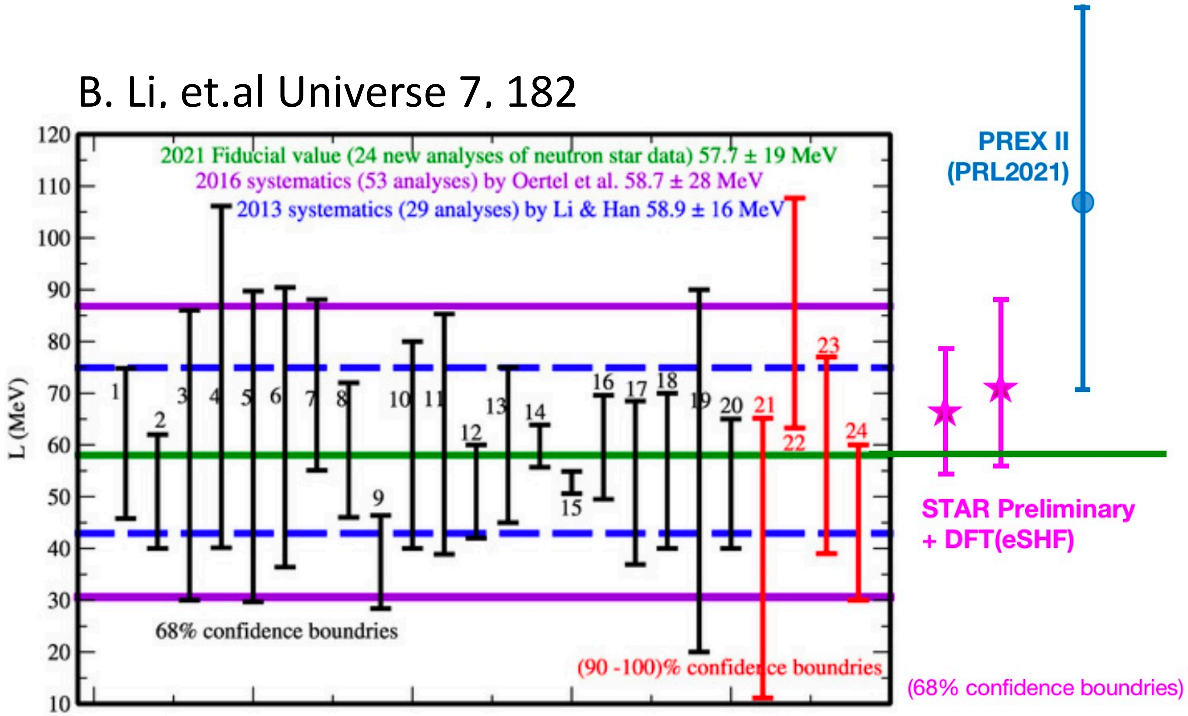
HJX, J. Zhao, F. Wang, arXiv:2402.16550

Summary

I. $\sqrt{\langle r_n^2 \rangle} \neq \sqrt{\langle r_p^2 \rangle}$, important for isobar collisions

II. $\beta_2^{\mathrm{WS}} \neq \beta_2$, important for U+U collisions

B. Li. et.al Universe 7. 182



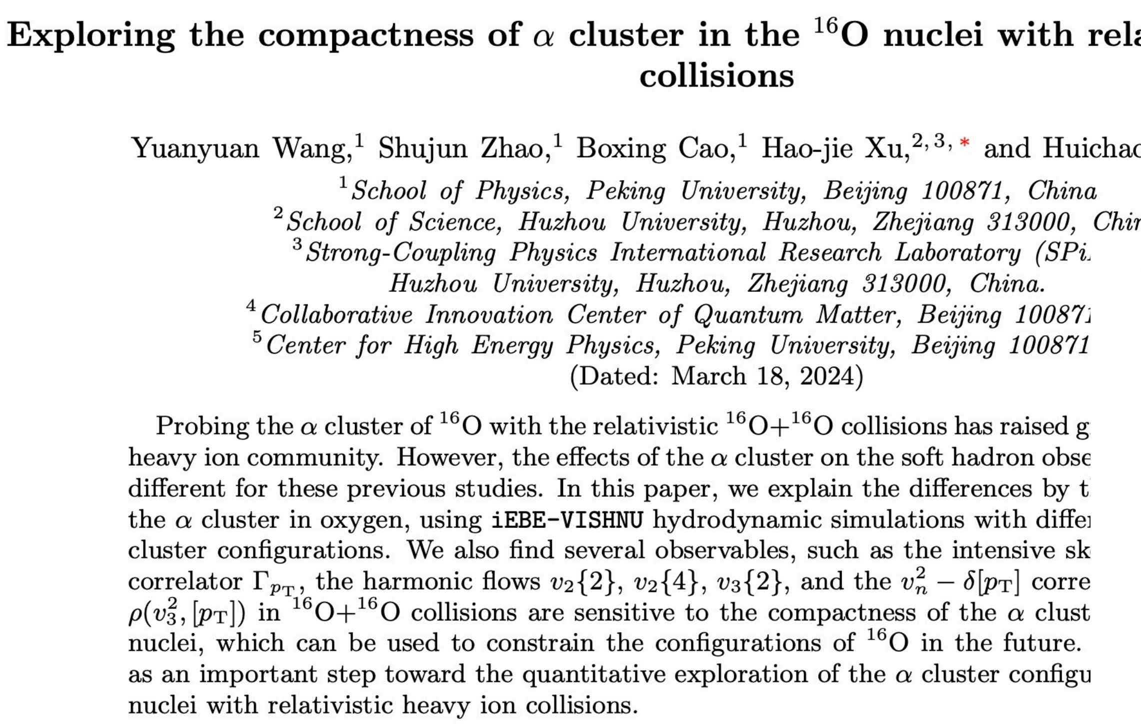
$\beta_4^{\mathrm{U}} = ???$

$\beta_2^{\mathrm{Au}} = ???$

More nuclear structure effect

H. Song's talk

γ-soft arXiv:2403.07441



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

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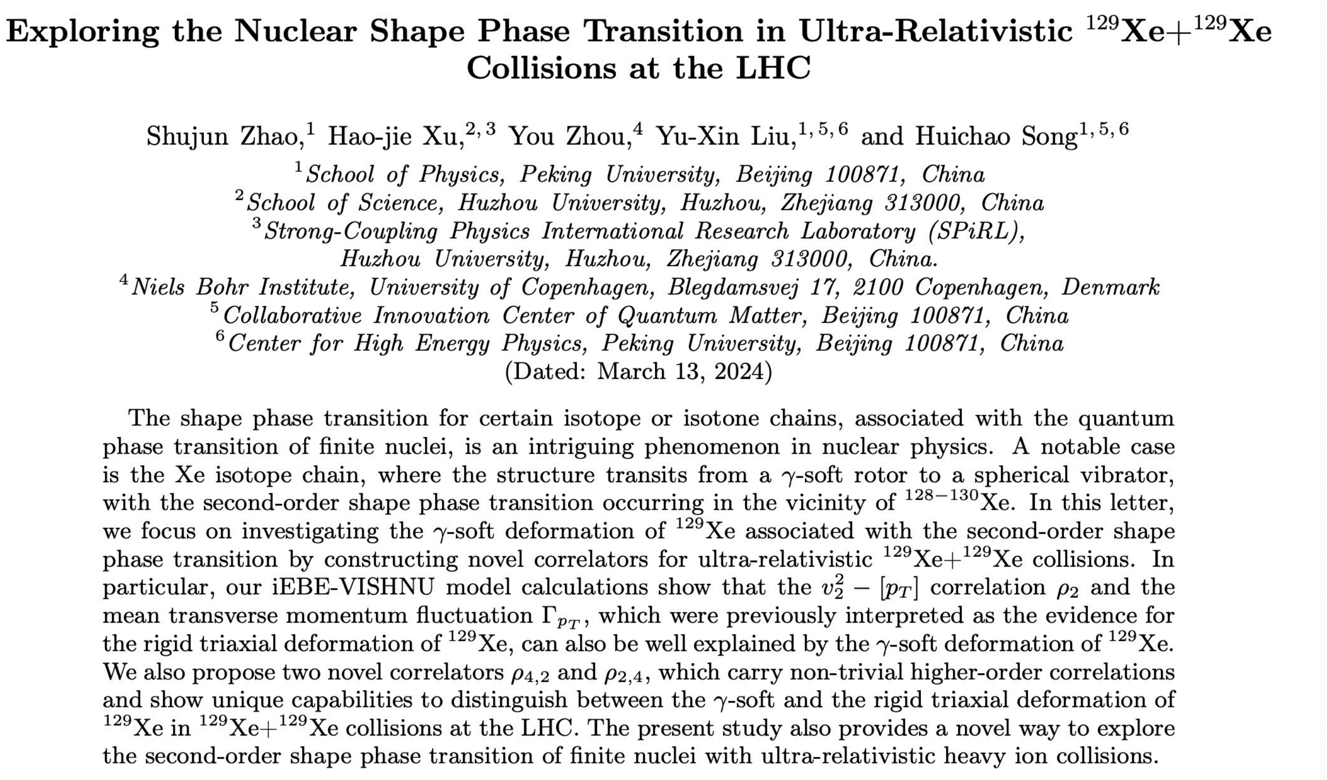
(Dated: March 18, 2024)

Probing the α cluster of ^{16}O with the relativistic ^{16}O+^{16}O collisions has raised g
heavy ion community. However, the effects of the α cluster on the soft hadron obse
different for these previous studies. In this paper, we explain the differences by t
the α cluster in oxygen, using `iEBE-VISHNU` hydrodynamic simulations with diffe
cluster configurations. We also find several observables, such as the intensive sk
correlator $\Gamma_{p_{\mathrm{T}}}$, the harmonic flows $v_2\{2\}$, $v_2\{4\}$, $v_3\{2\}$, and the $v_n^2 - \delta[p_{\mathrm{T}}]$ corre
$\rho(v_3^2, [p_{\mathrm{T}}])$ in ^{16}O+^{16}O collisions are sensitive to the compactness of the α clust
nuclei, which can be used to constrain the configurations of ^{16}O in the future.
as an important step toward the quantitative exploration of the α cluster configu
nuclei with relativistic heavy ion collisions.

arXiv:2401.15723, PRC Letter, accepted

α cluster



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

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(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.

Thank you for your attention!

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