通过相对论重离子碰撞研究原子核形变

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STAR区域研讨会

2024.10.10-15, 重庆大学

Outline

I 相对论重离子碰撞中核结构的重要性

II 通过相对论重离子碰撞研究原子核形变

III 总结与展望

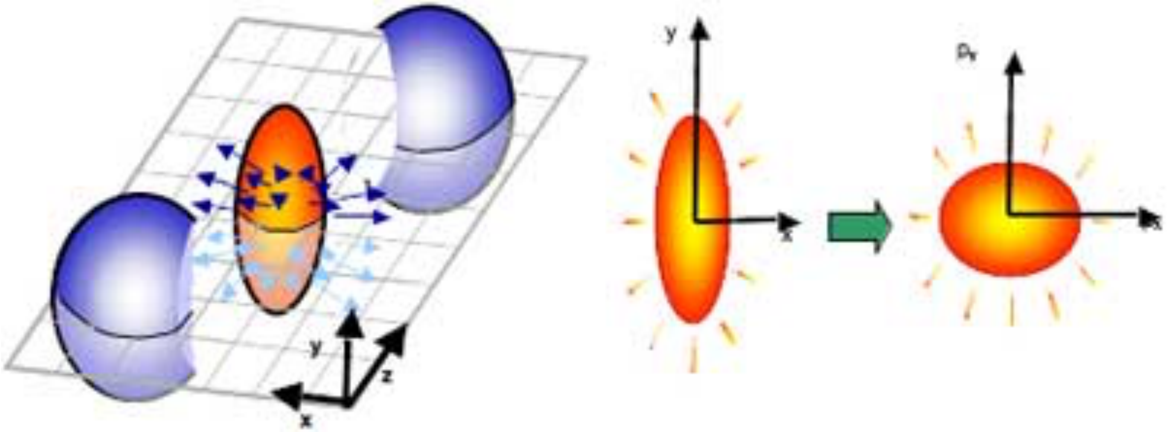
Based on:

- **HJX**, J. Zhao, F. Wang, "**Hexadecapole Deformation** of 238U from Relativistic Heavy-Ion Collisions Using a Nonlinear Response Coefficient", Phys.Rev.Lett., 132, 262301 (2024)
- Z. Wang, J. Chen, **HJX**, J. Zhao, "Systematic investigation of the **nuclear multipole deformations** in U+U collisions with a multi-phase transport model", Phys.Rev., C110, 034907(2024)
- S. Zhao, **HJX**, Y. Liu, H. Song, "Probing the **nuclear deformation** with three-particle asymmetric cumulant in RHIC isobar runs", Phys.Lett., B840, 137838 (2023)
- S. Zhao, **HJX**, Y. Zhou, Y. Liu, H. Song, "Exploring the **Nuclear Shape Phase Transition** in Ultra-Relativistic 129Xe+129Xe Collisions at the LHC", Phys.Rev.Lett., in production (2024)

Relativistic Heavy ion collisions and nuclear structure

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

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

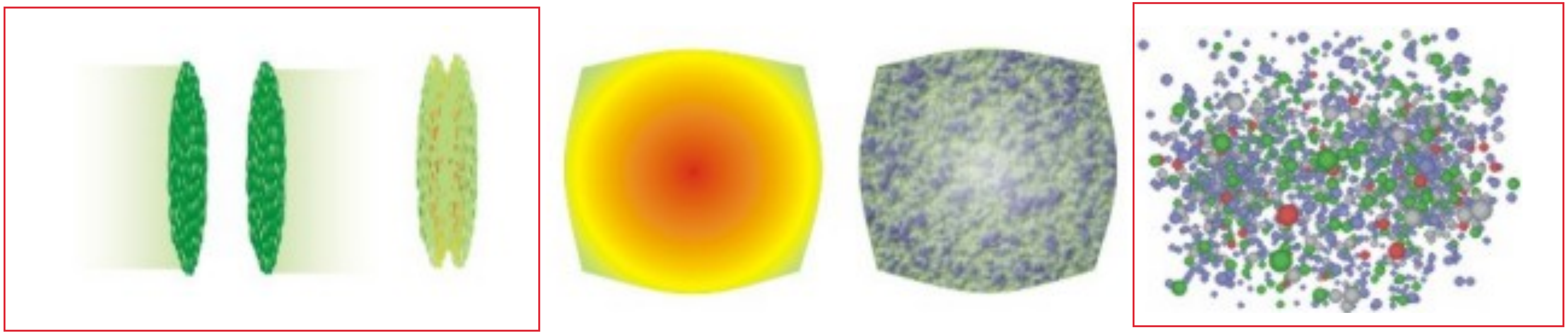


Anisotropic flow,
Flow fluctuations
HBT,
....

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

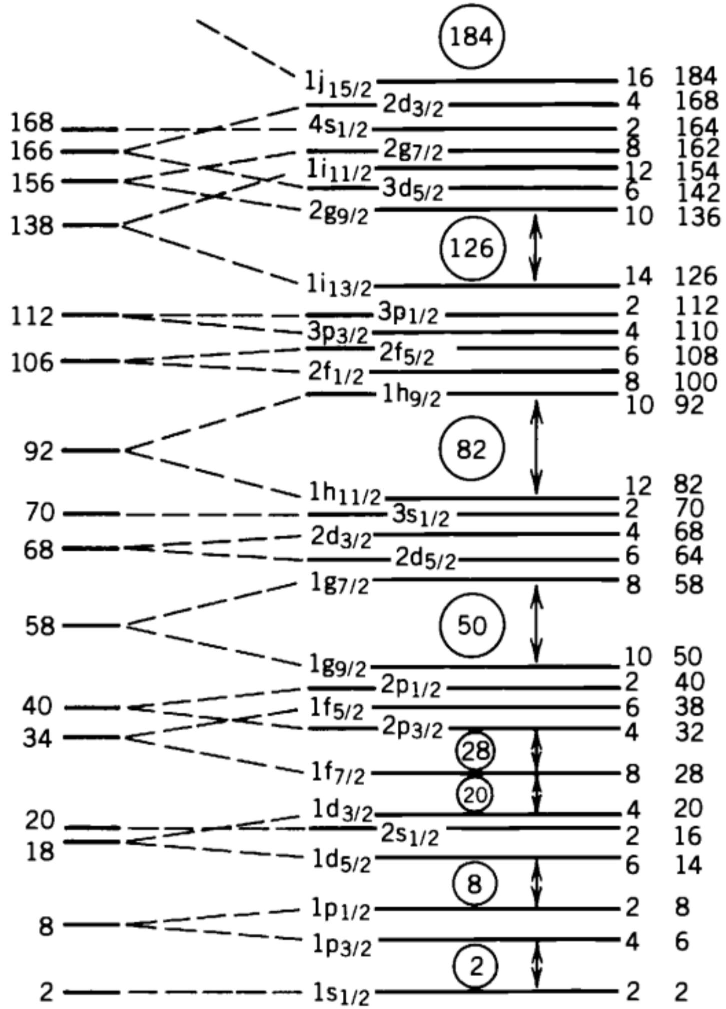
Initial geometry

Final observables

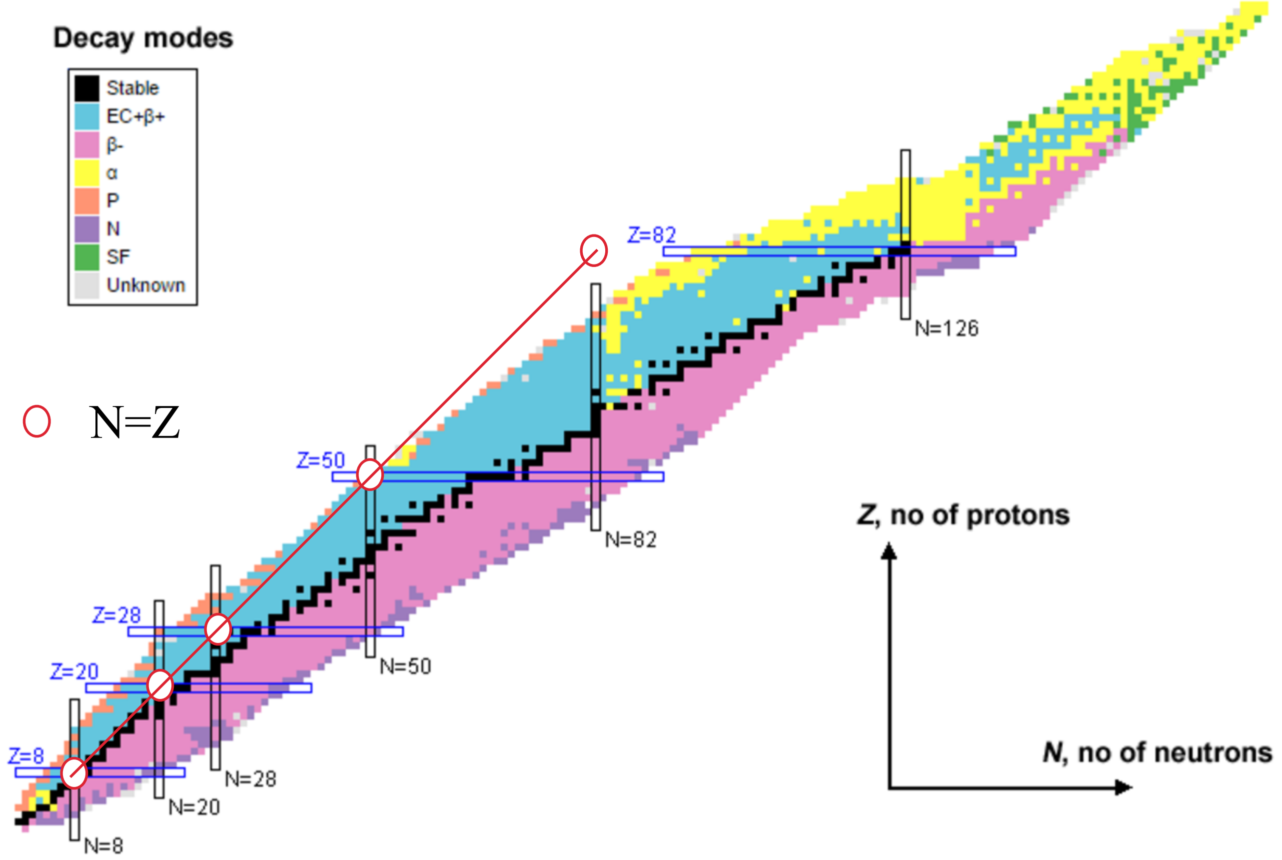


Fine nuclear structure

Nuclear deformation

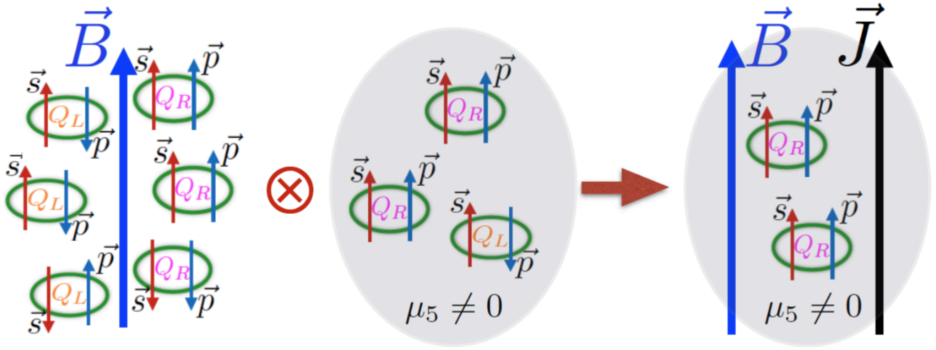


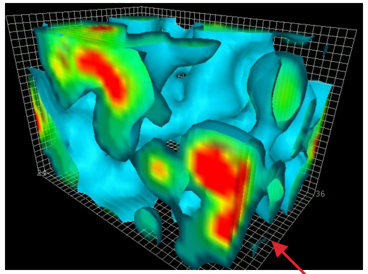
Neutron skin thickness

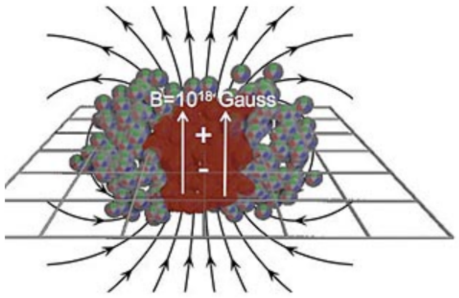


Relativistic isobaric collisions and chiral magnetic effect

Chiral magnetic effect (CME)





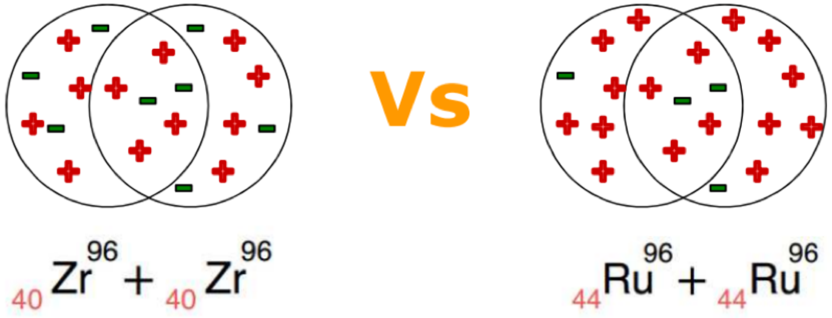


$$\mathbf{J_{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B},$$

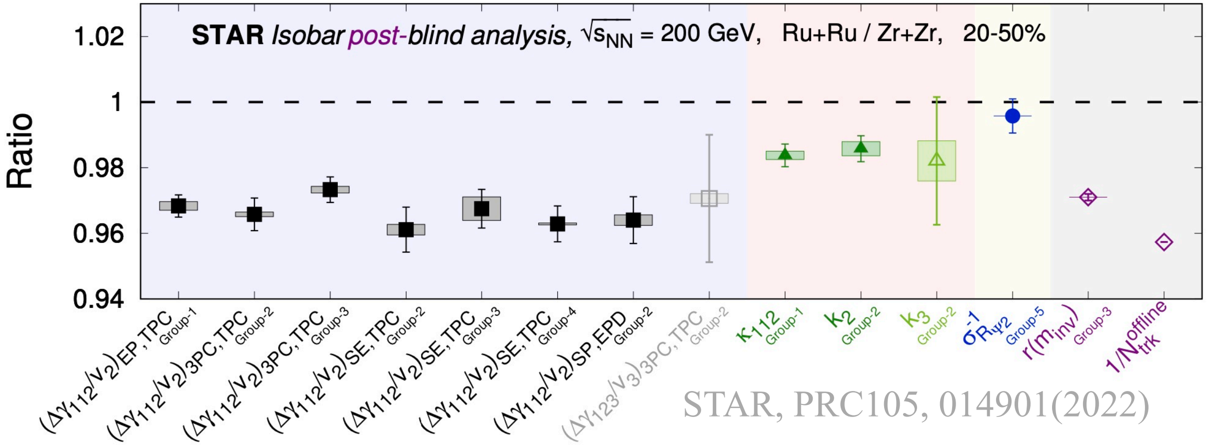
D. Kharzeev,et.al., PPNP88, 1(2016)

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!!!

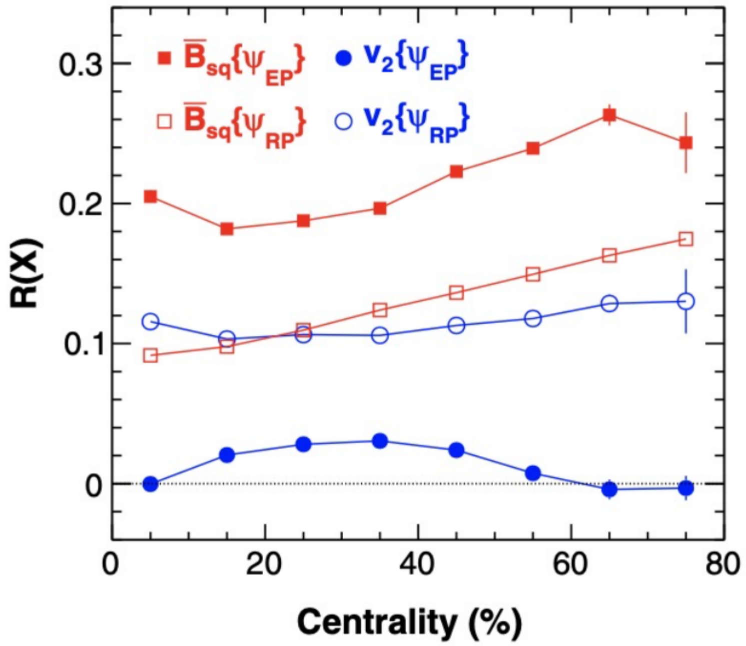
Nuclear densities for HIC models

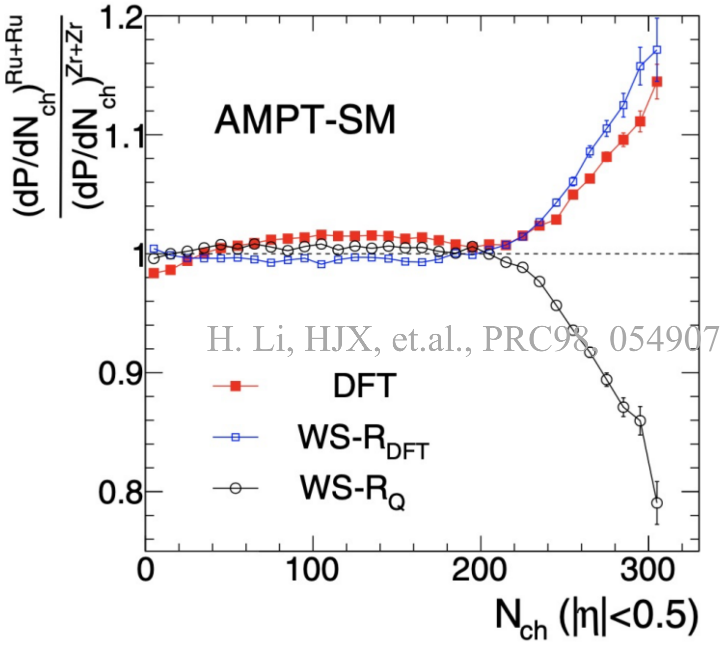
PHYSICAL REVIEW LETTERS 121, 022301 (2018)

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,*]



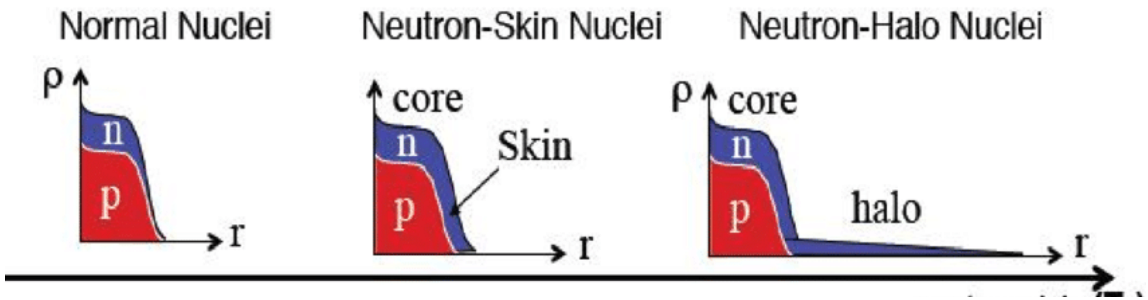


H. Li, HJX, et.al., PRC98, 054907 (2018)

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

Determine the neutron skin type by STAR data

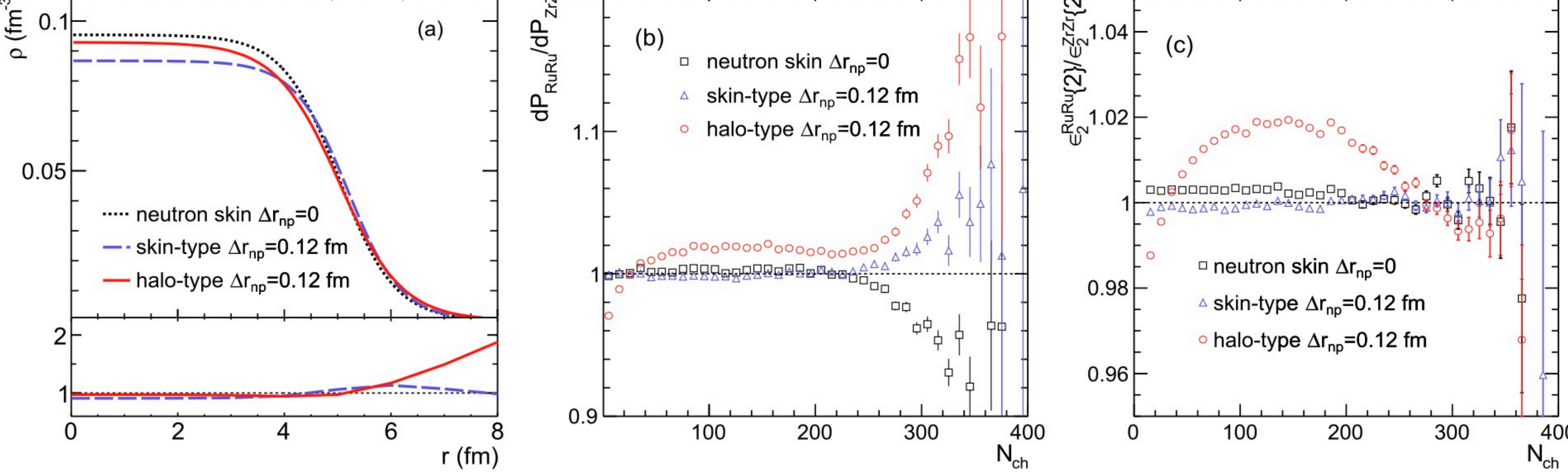
$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}$$



- 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)

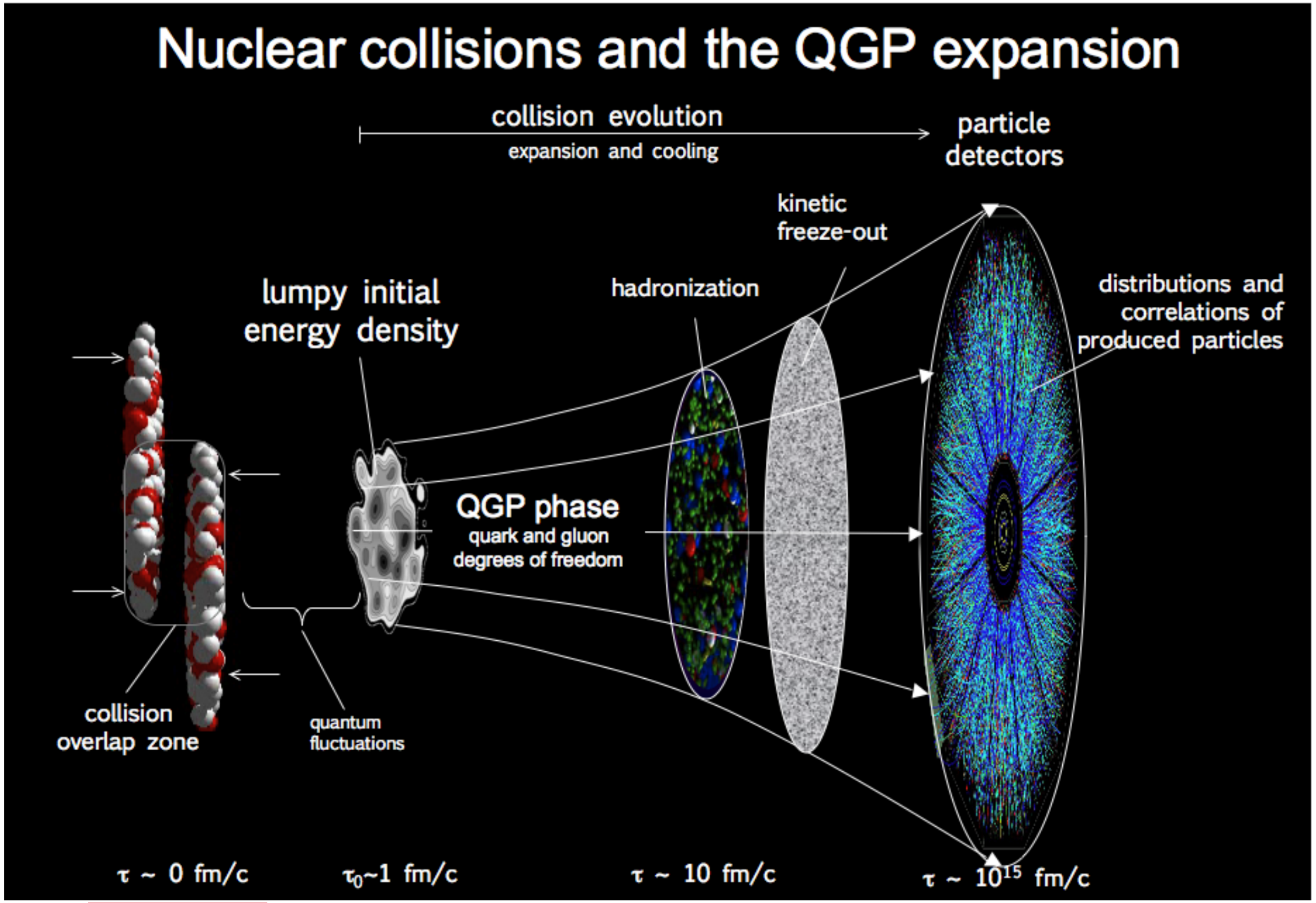


The shapes of the Ru+Ru/Zr+Zr ratios of the multiplicity and eccentricity in mid-central collisions can further distinguish between skin-type and halo-type neutron densities.

Relativistic heavy ion collisions

The "Little Bang"

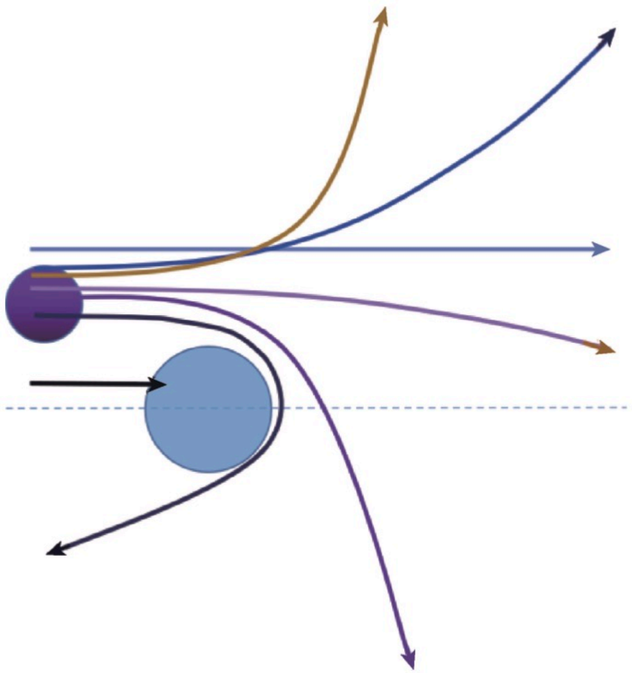
$\sqrt{s} = 100\text{GeV} \sim \text{TeV}$



Yoctosecond (10^{-24} s) 幺秒

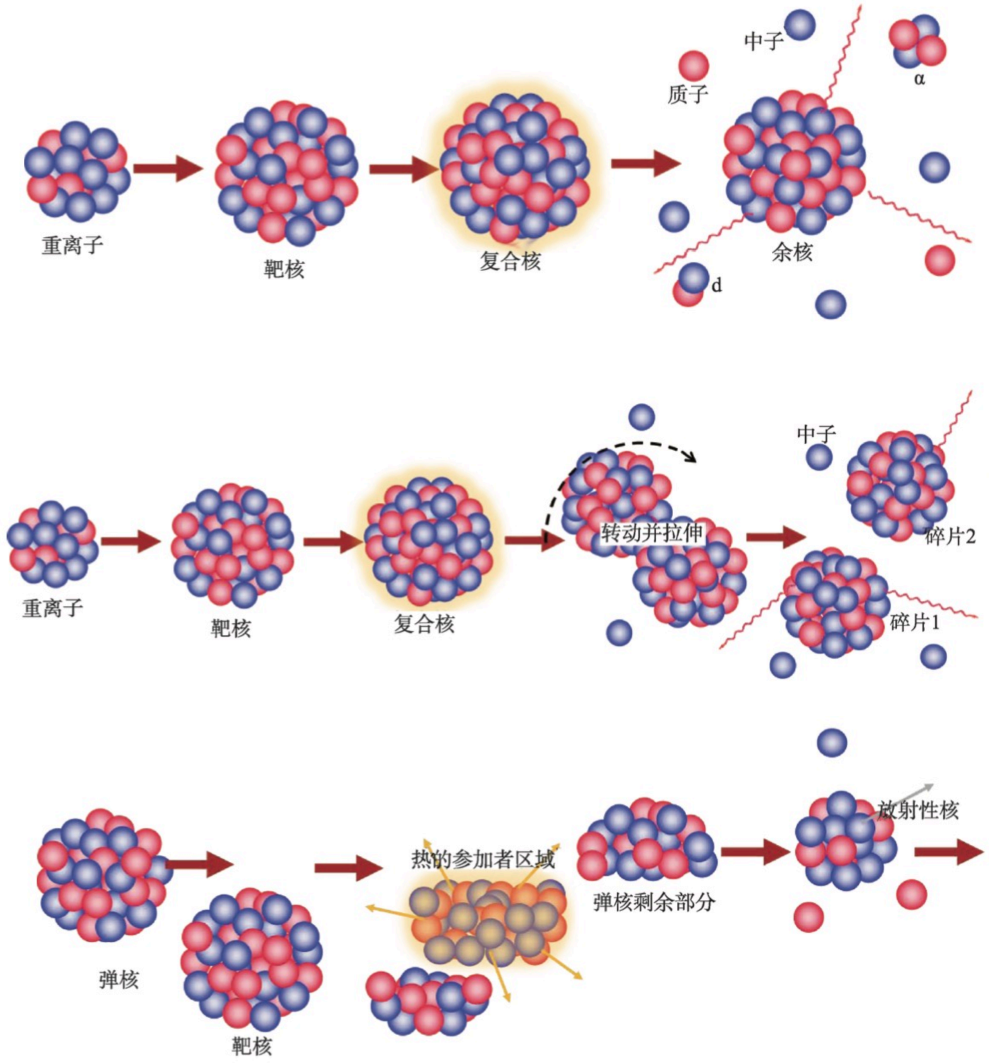
Nucleus-Nucleus Reactions (Collisions)

G. Jin, Modern Physics



Hard scattering

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



nuclear evaporation

fragmentation

projectile fragmentation

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,‡]

- **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. Lin, R. Wang, J. Wang, **HJX**, S. Pu, Q. Wang, PRD107, 054004 (2023), arXiv:2210.05106
- J. Wang, **HJX**, F. Wang, Nucl. Sci. Tech. 35, 108(2024), arXiv:2305.17114
- S. Lin, J. Hu, **HJX**, S. Pu, Q. Wang, arXiv:2405.16491
- ……

More studies

中国科学: 物理学 力学 天文学 2024 年 第 54 卷 第 9 期: 292006
SCIENTIA SINICA Physica, Mechanica & Astronomica physcn.scichina.com

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

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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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收稿日期: 2024-01-22; 接受日期: 2024-04-28; 网络出版日期: 2024-08-14
国家自然科学基金(编号: 12275082, 12035006, 12075085)资助项目

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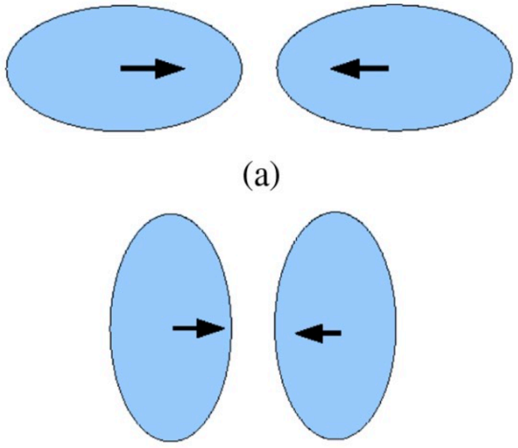
发布时间: 2024年08月13日

Nuclear deformation

S. Voloshin, PRL95, 122301 (2010)



(a) (b)

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

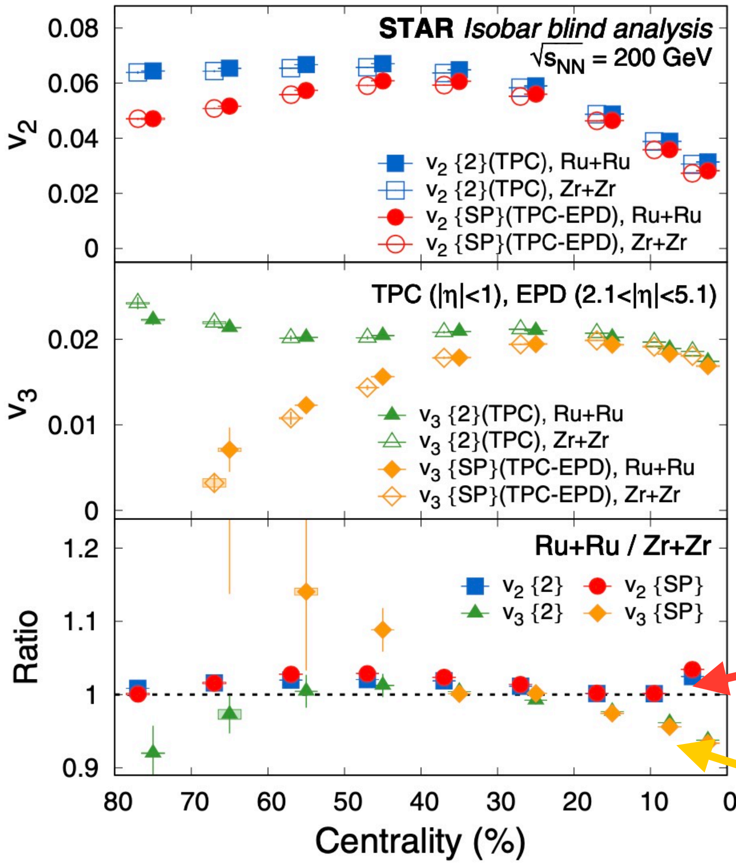
Anisotropic Flow and Jet Quenching in Ultrarelativistic U+U Collisions

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)
C. Zhang, J. Jia, PRL128,022301(2022)
H. Mantysaari, et.al, PRL131, 062301(2023)
……..

Nuclear deformation

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

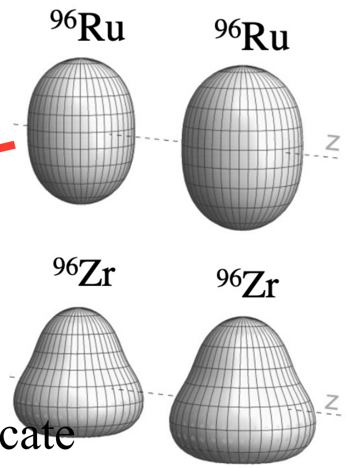


Background for CME:

Neutron skin!

Non flow!

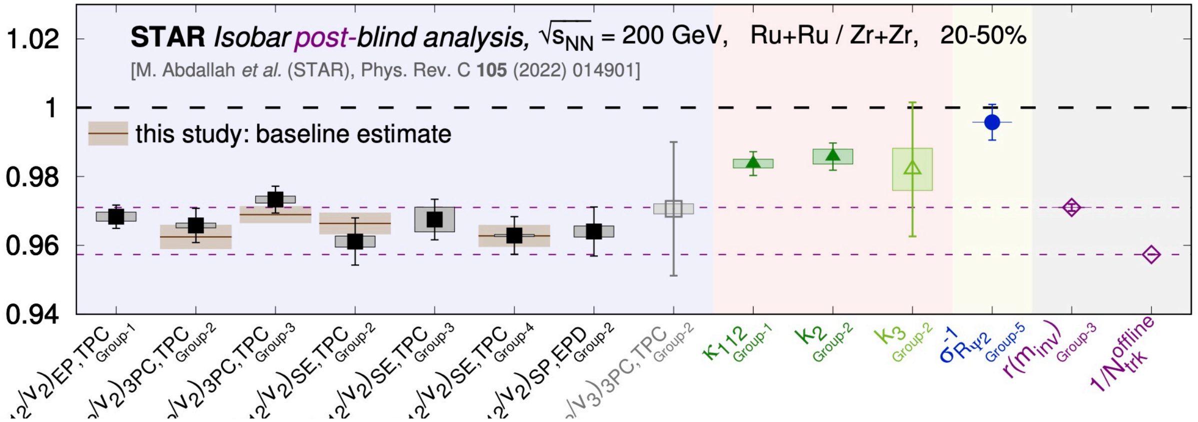
Deformation



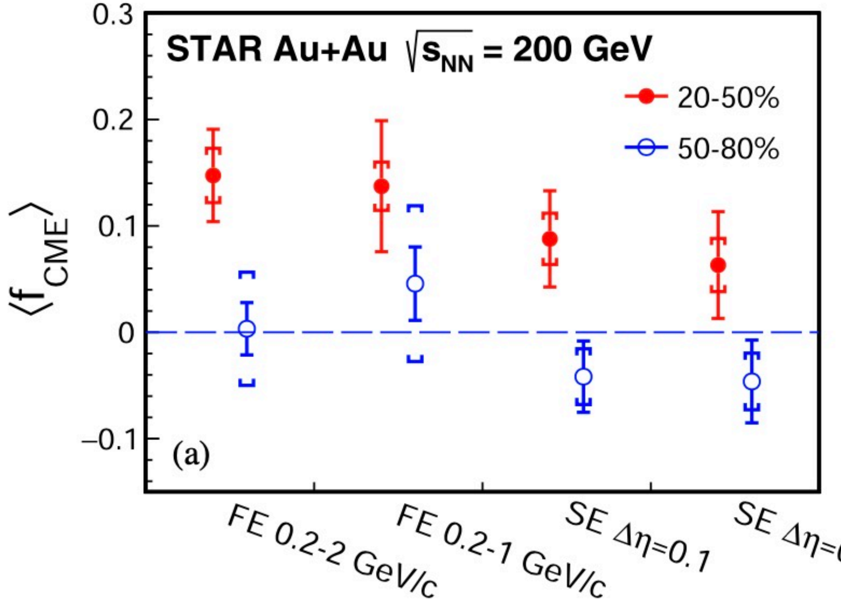
Sizable v_2 and v_3 ratios in central collisions indicate

shape difference between isobars

STAR Collaboration, arXiv:2308.16846



STAR Collaboration, PRL128, 092301 (2022)



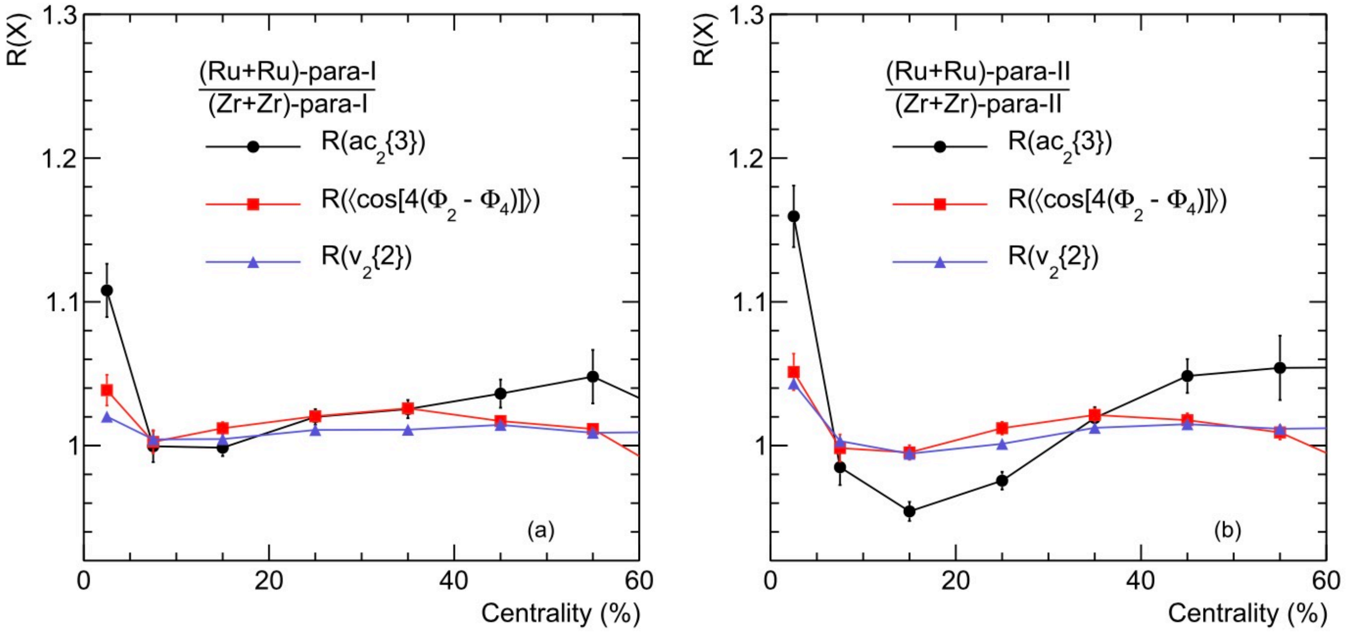
More Au+Au data is ongoing!!!

Neutron hexadecapole deformation

$$R = R_0 \left[1 + \beta_2 Y_{20}\right] \longrightarrow R = R_0 \left[1 + \beta_2 Y_{20} + \beta_3 Y_{30} + \beta_4 Y_{40}\right]$$

3-particle asymmetry cumulants

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



$$\mathrm{ac}_2\{3\} \equiv \langle\langle 3\rangle_{2,2,-4}\rangle = \langle\langle e^{i(2\varphi_1+2\varphi_2-4\varphi_3)}\rangle\rangle$$

$$\mathrm{ac}_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle,$$

$$\mathrm{ac}_2\{3\} \equiv \langle\langle 3\rangle_{2,2,-4}\rangle = \langle v_2^4\rangle^{1/2} v_4\{\Phi_2\},$$

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

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

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

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

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

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

$\mathrm{ac}_2\{3\}$ and $\langle\cos 4(\Phi_4 - \Phi_2)\rangle$ are sensitive to β_2 and β_3.

Hexadecapole deformation

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

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

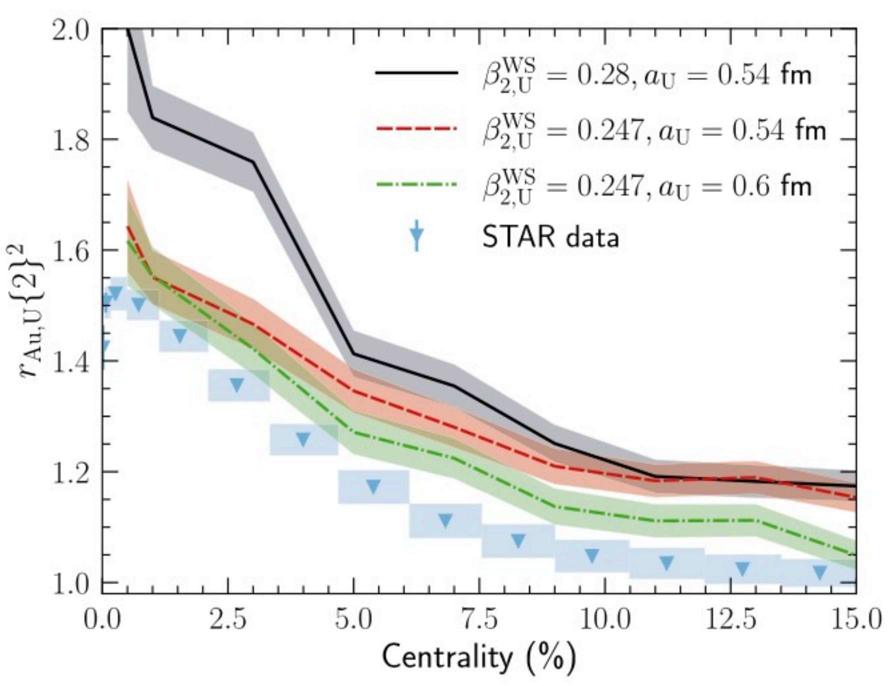
Evidence of Hexadecapole Deformation in Uranium-238 at the Relativistic Heavy Ion Collider

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,*

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

$$\beta_l^* = \frac{4\pi}{(2l+1)ZR_0^l}\sqrt{\frac{B(El)}{e^2}}$$

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



Liquid drop limit

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

Deformation of Au

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

$\beta_2^{\mathrm{Au}} = 0.17$

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

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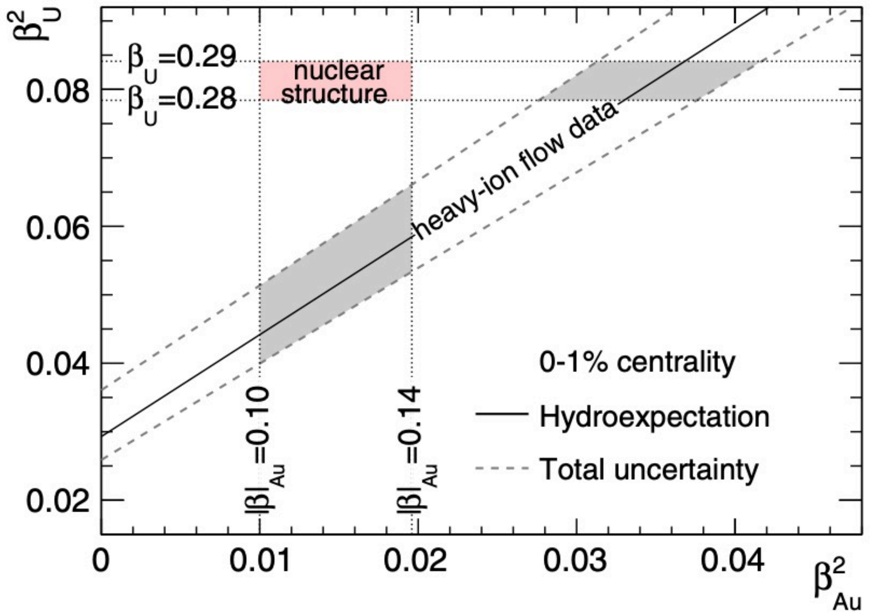
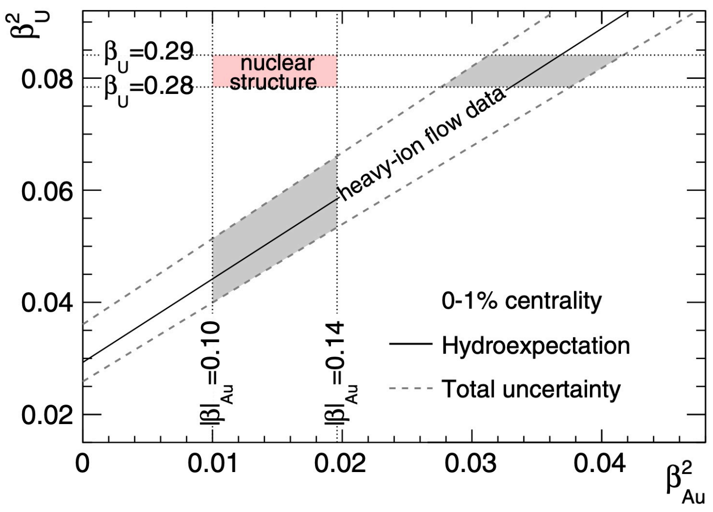
[1]*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, German*
[2]*Department of Chemistry, Stony Brook University, Stony Brook, New York 11794, USA*
[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11976, USA*

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

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.

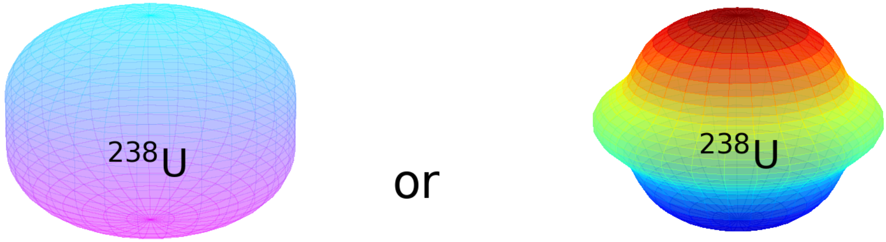


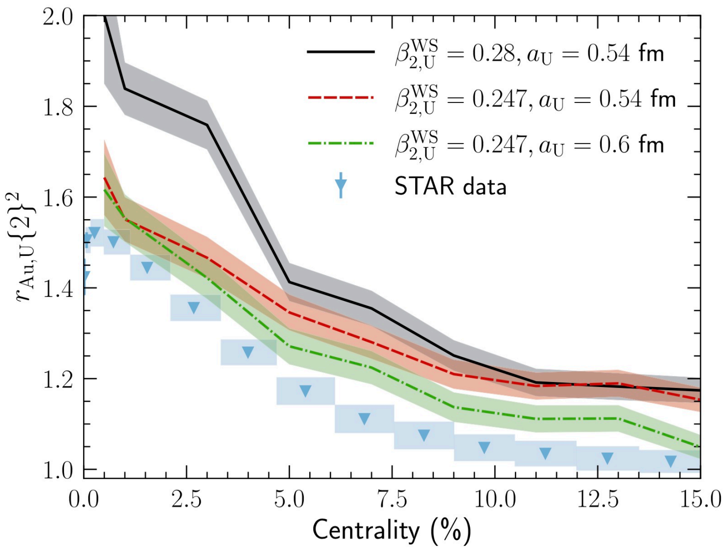
Hexadecapole deformation



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

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





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

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

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

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

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

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

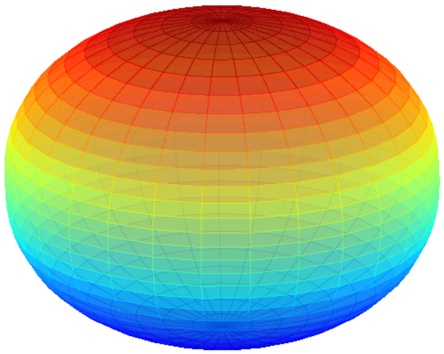
$\beta_{4,U}$ is poorly known from low-energy nuclear experiment, can it be measured in relativistic heavy ion collisions? **YES!**

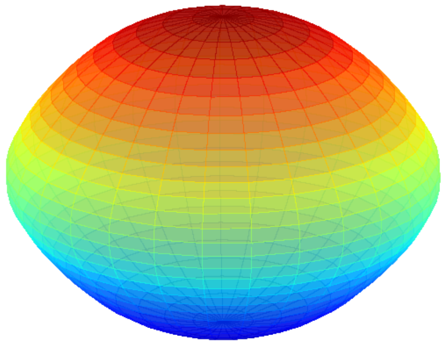
Nuclear deformation for Uranium-238

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

$\beta_{2,\mathrm{U}} = 0.28$

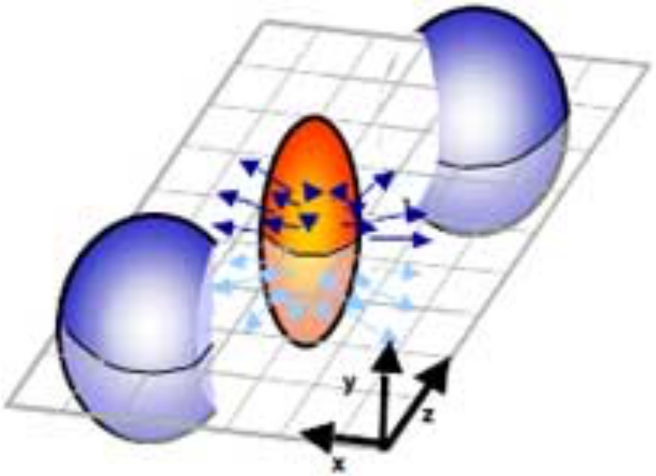
$\beta_{4,\mathrm{U}} = 0.0$

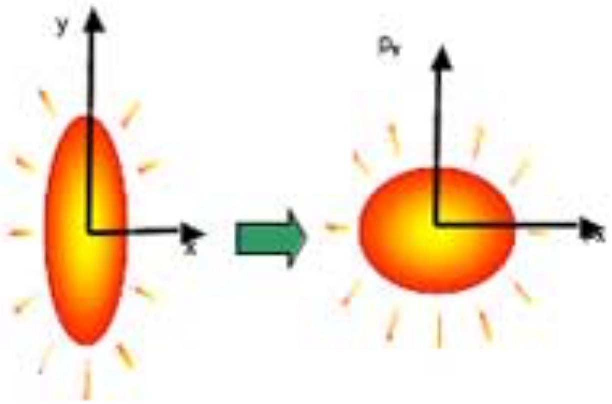




$\beta_{2,\mathrm{U}} = 0.25$

$\beta_{4,\mathrm{U}} = 0.1$





$$\frac{dN}{d\phi} \propto [1 + \underline{v_2}\cos 2(\phi - \Psi_2)$$ probe β_2 ✓

$$+\underline{v_3}\cos 3(\phi - \Psi_3)$$ probe β_3 ✓

$$+\underline{v_4}\cos 4(\phi - \Psi_3)$$ probe β_4 ?

$$+\ldots]$$

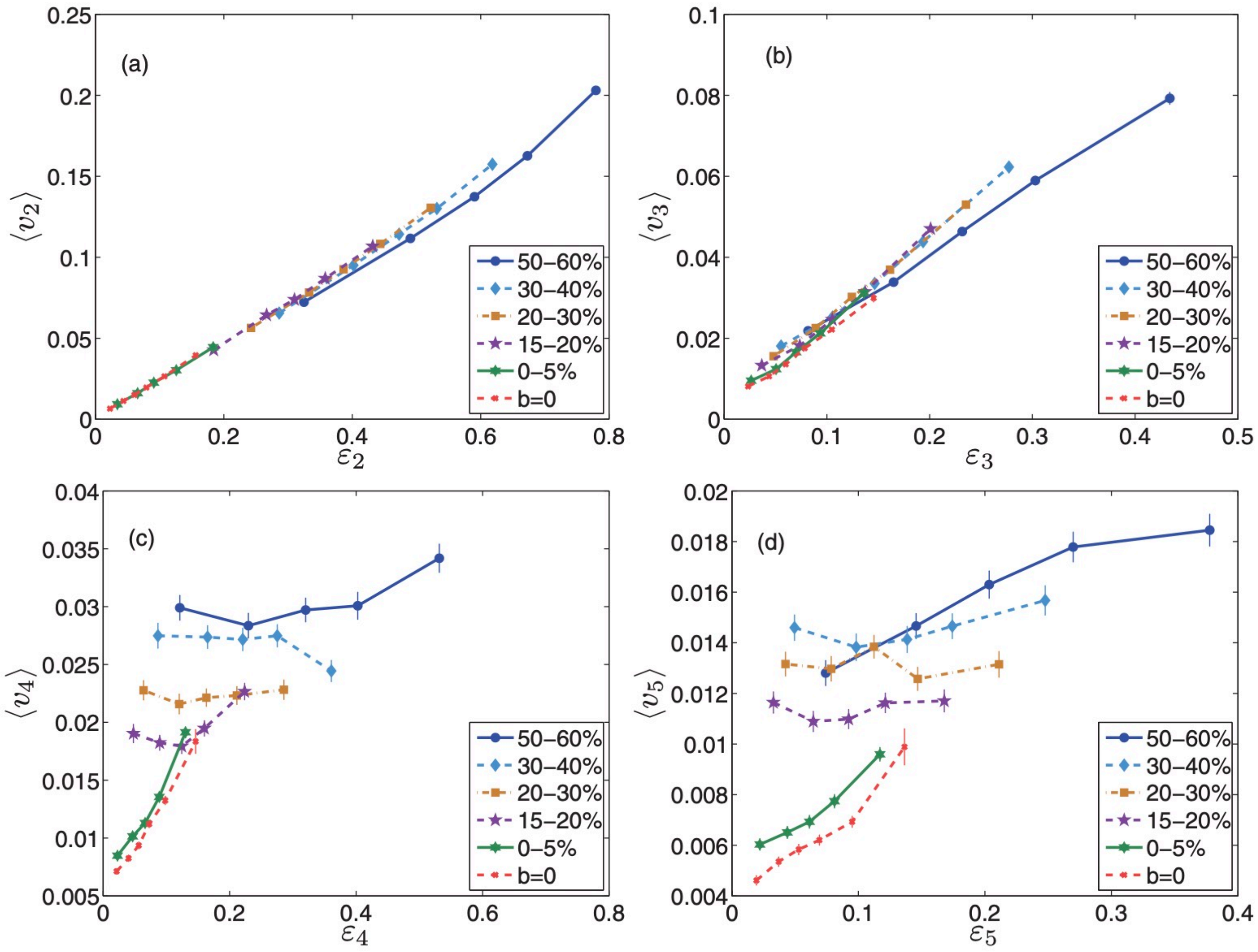
Hexadecapole flow

$\epsilon_4^2 \propto \beta_4^2$ ✓

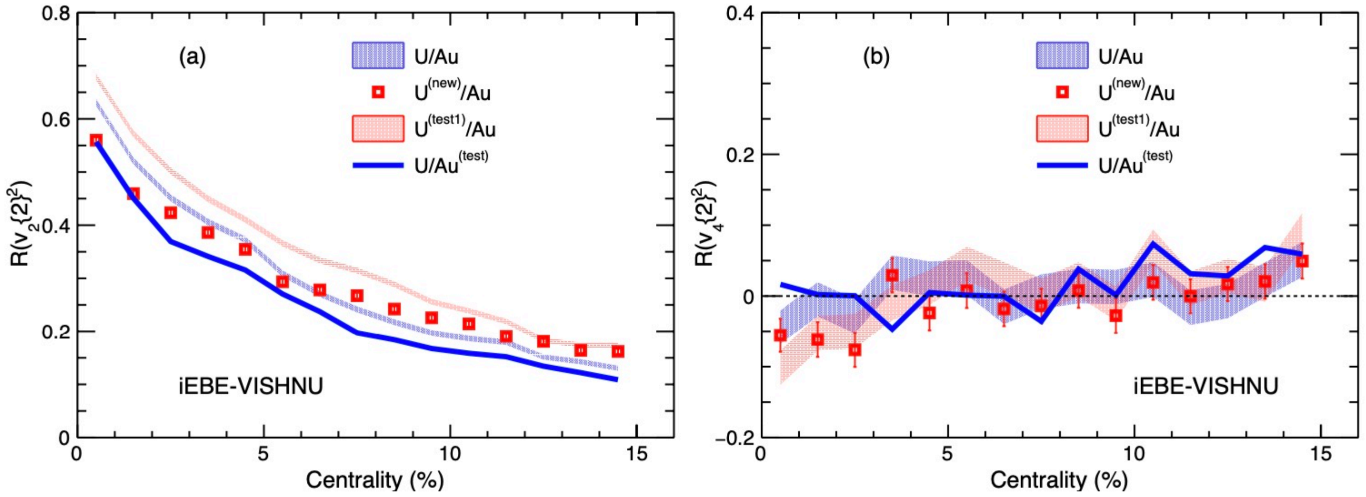
$v_4^2 \propto \epsilon_4^2$ ✗

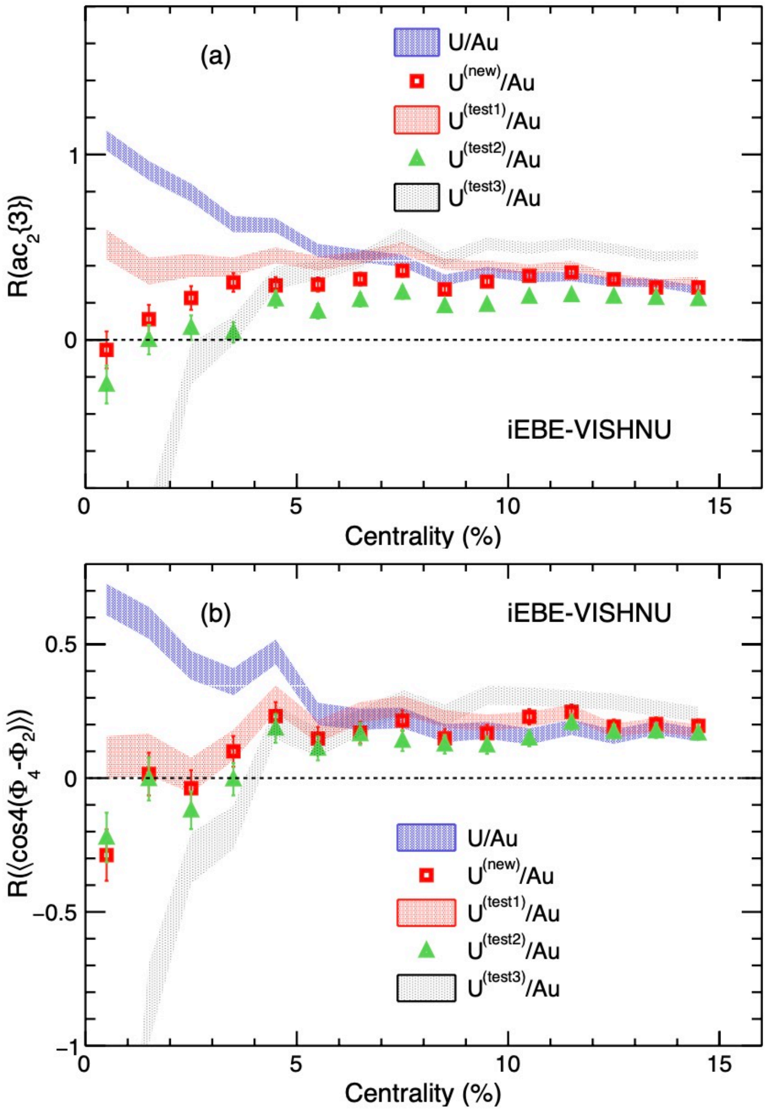
The hydrodynamic response for v_n $(n \geq 4)$ with event-by-event fluctuations is not only non-diagonal but also nonlinear.

Z. Qiu and U. Heinz, PRC84, 024911(2011)



Determine the hexadecapole deformation



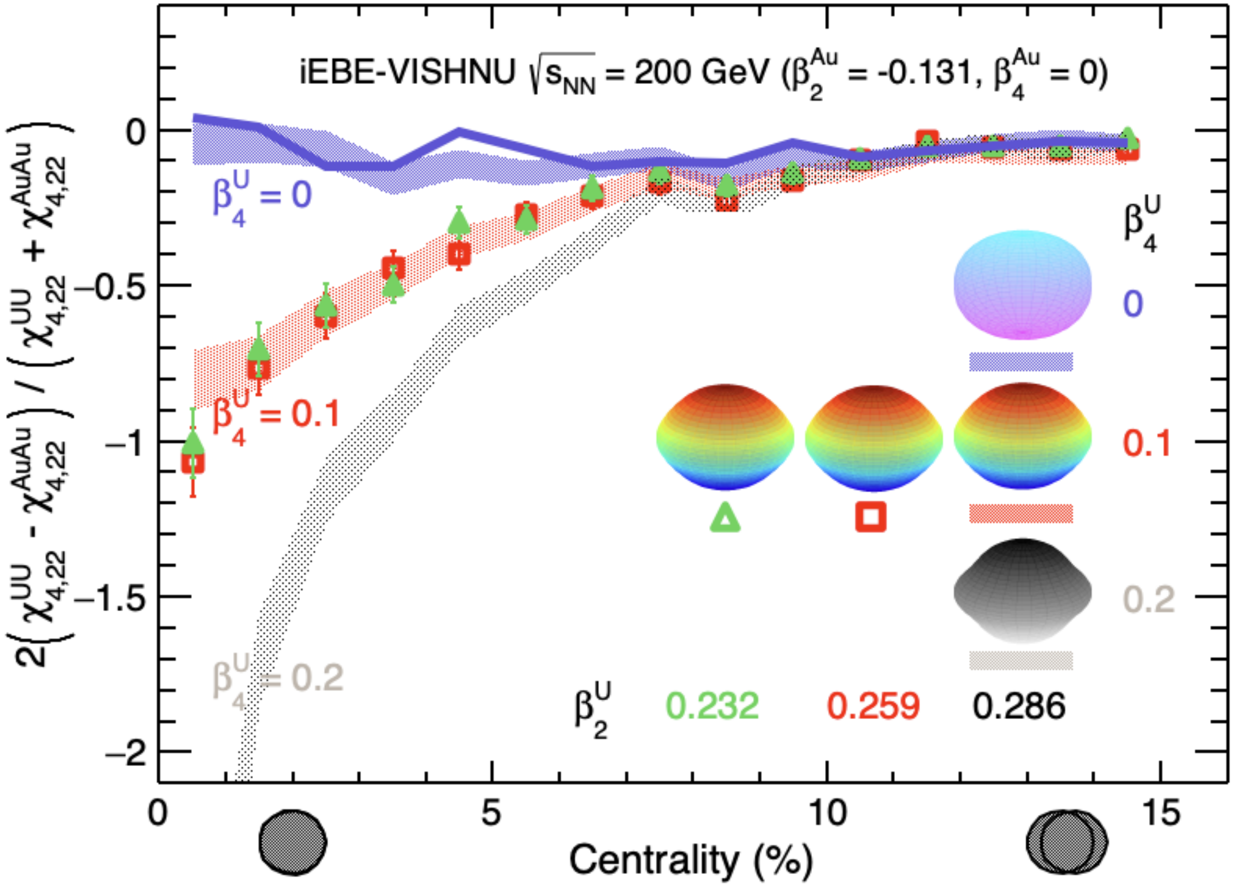


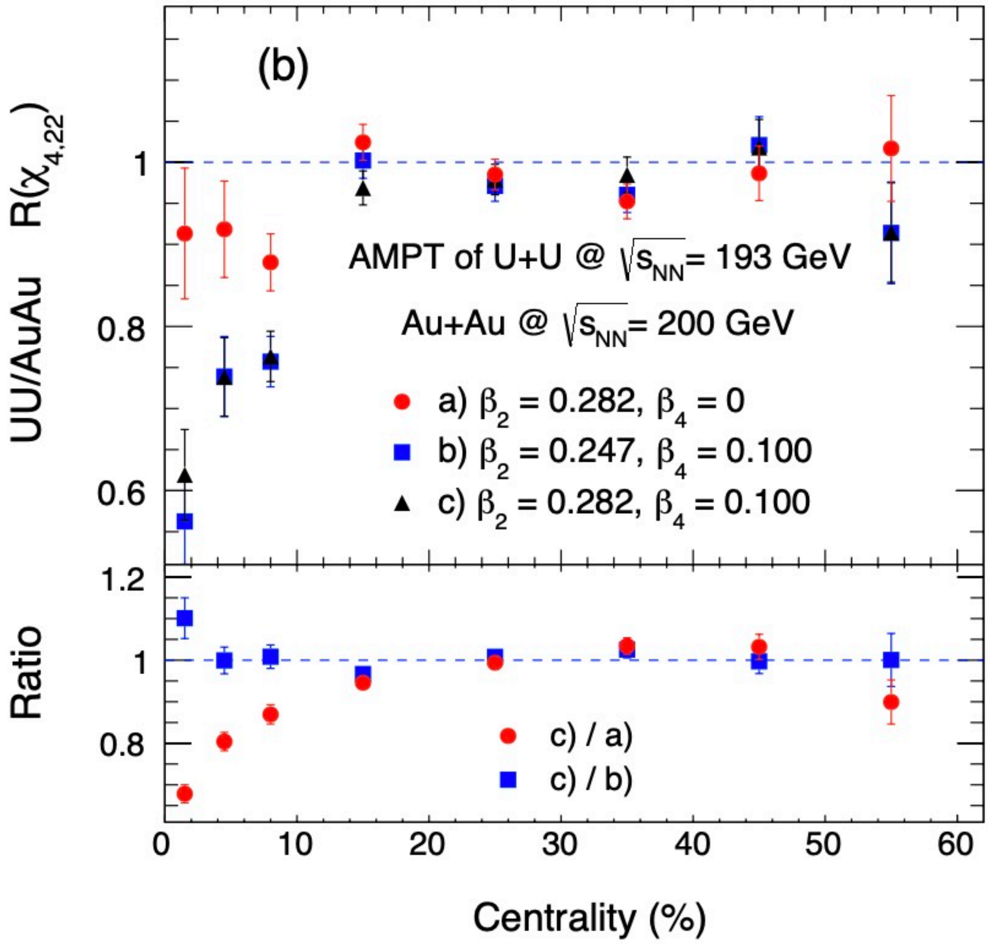
HJX, J. Zhao, F. Wang, PRL132, 262301 (2024)

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	"

Determine the hexadecapole deformation





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

HJX, J. Zhao, F. Wang, PRL132, 262301 (2024)
Z. Wang, J. Chen, **HJX**, J. Zhao, PRC,110, 034907(2024)

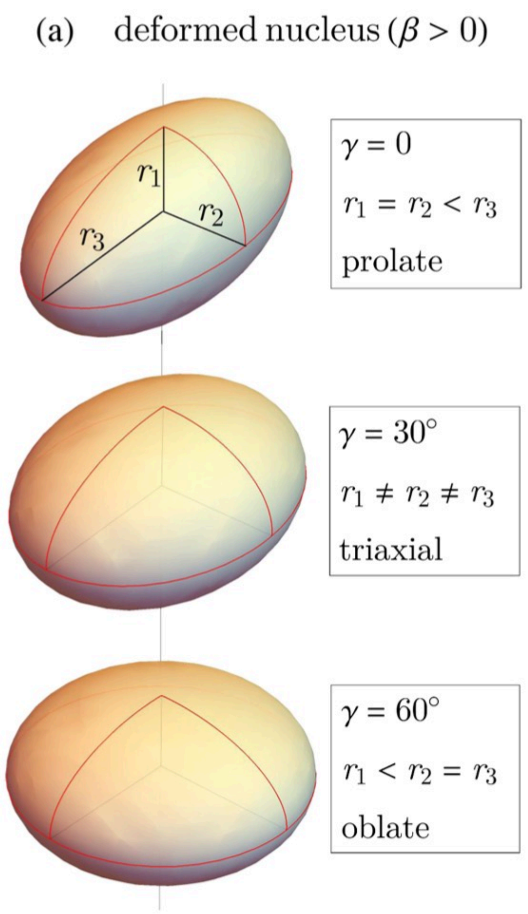
Nuclear shape phase transition

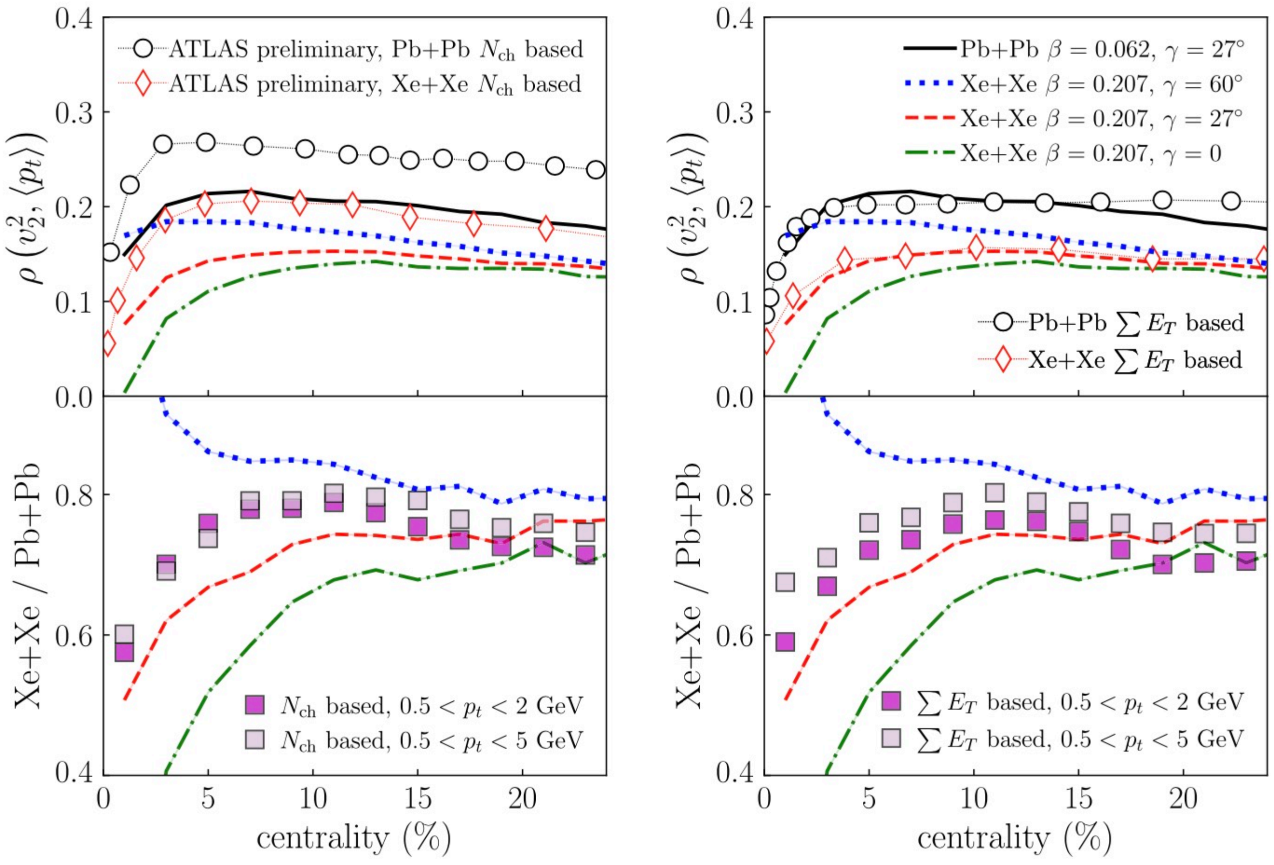
$$R = R_0 \left[1 + \beta_2 Y_{20}\right] \longrightarrow R = R_0 \left[1 + \beta_2 \left(Y_{20} \cos\gamma + Y_{22} \sin\gamma\right)\right]$$

γ-independent? ✗

Triaxial deformation

$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}.$$



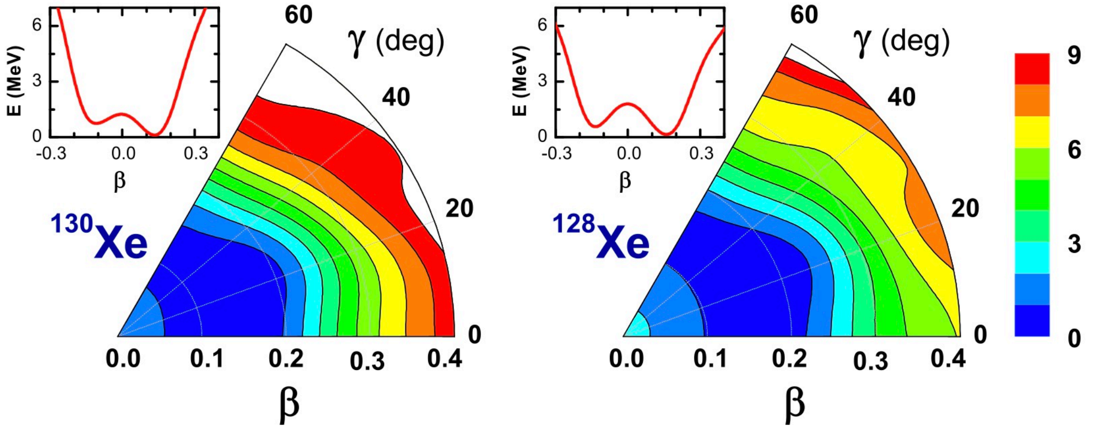


The LHC data indicate $\gamma \simeq 30°$

B. Bally, M. Bender, G. Giacalone, V. Soma, PRL128, 082301 (2022)
ALICE, PLB834, 137393 (2022)

γ fluctuation

S. Zhao, **HJX**, Y. Zhou, Y. Liu, H. Song, PRL, in production (2024)



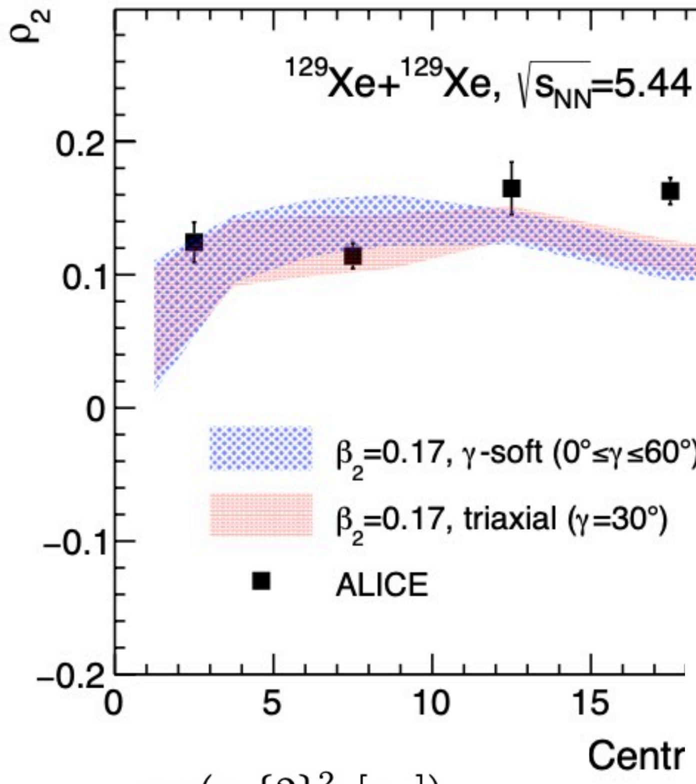
Z. Li, T. Niksic, D. Vretenar, J. Meng, PRC81, 034316(2010)

S. Zhao, **HJX**, Y. Zhou, Y. Liu, H. Song, PRL, in production (2024)

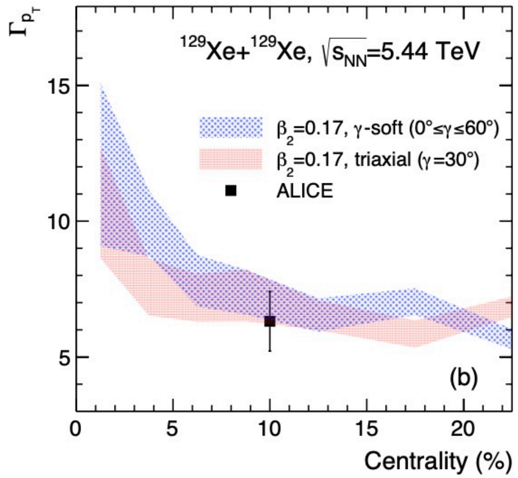
Two scenarios:

- Rigid trivial deformation: $\gamma = 30°$
- γ-soft: flat distribution in $\gamma \in [0°, 60°]$

Our results indicate $\langle\gamma\rangle \simeq 30°$,
fluctuations can not be determined



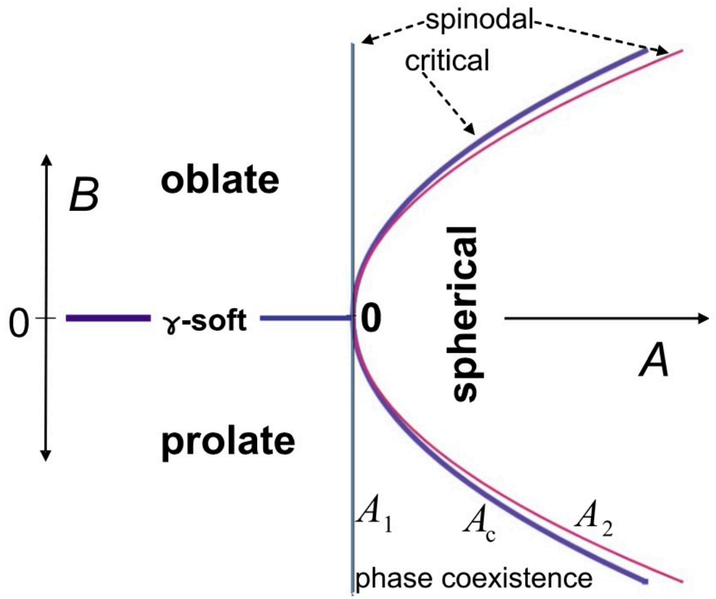
$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}.$$



$$\Gamma_{p_T} = \frac{\langle \delta p_{T,i}\delta p_{T,j}\delta p_{T,k}\rangle\langle[p_T]\rangle}{\langle\delta p_{T,i}\delta p_{T,j}\rangle^2},$$

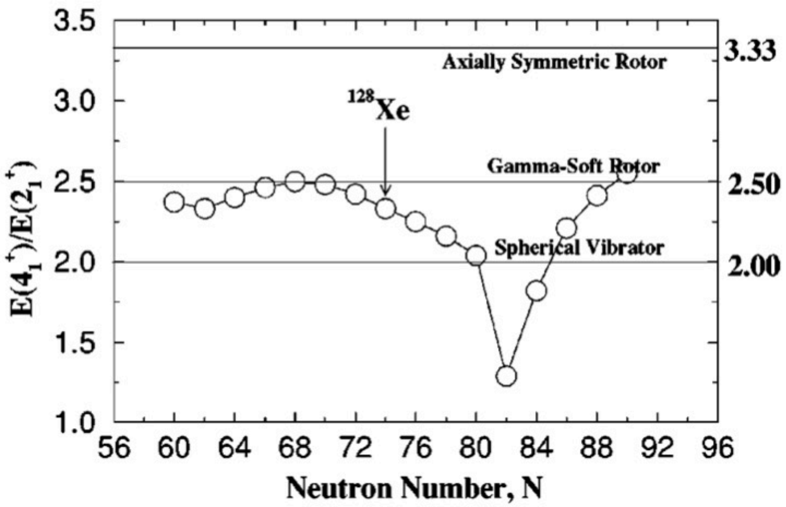
Shape phase transition

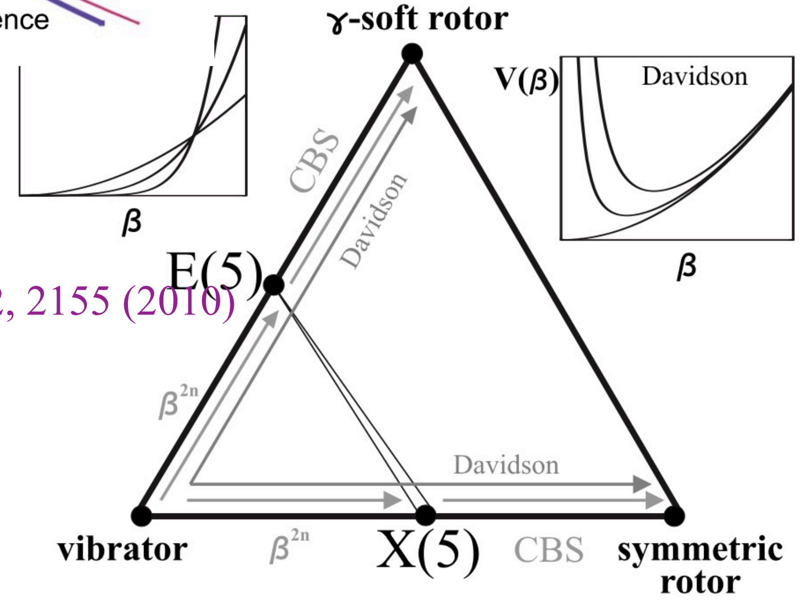
R. Clark, et.al, PRC69, 064322 (2004)



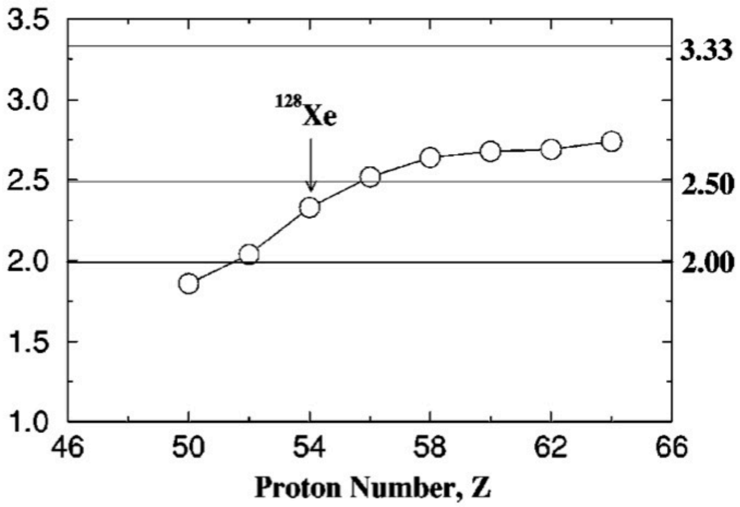
^{128}Xe — ^{130}Xe

^{129}Xe





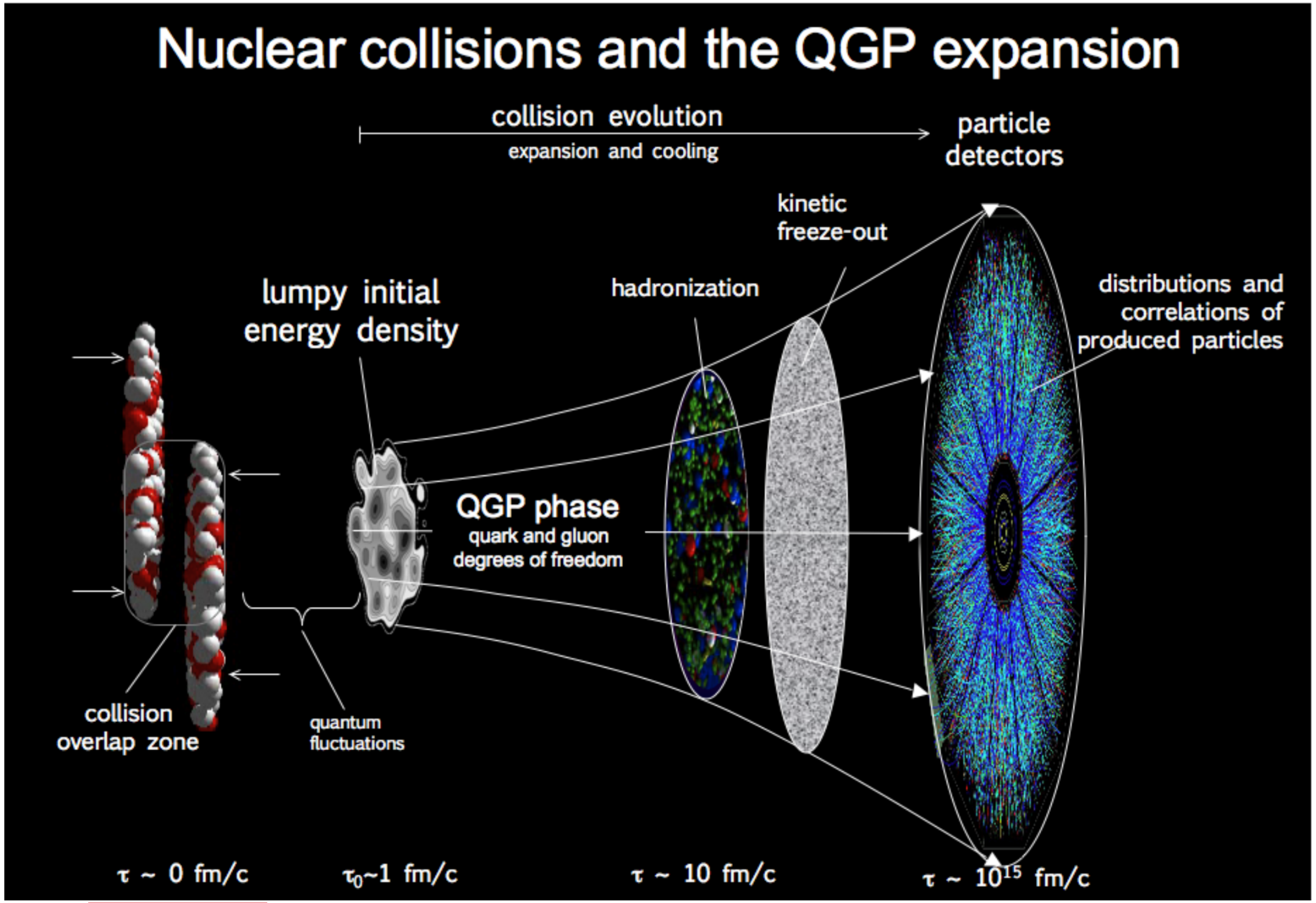
P. Cejnar, J. Jolie, R. Casten, RMP82, 2155 (2010)



Yoctosecond snapshots

The “Little Bang”

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

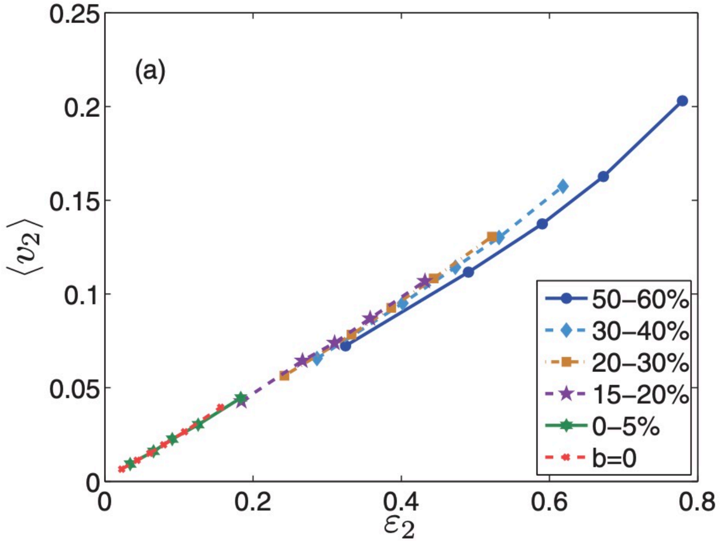


Yoctosecond (10^{-24} s) 幺秒

徐浩洁 (湖州师范学院)

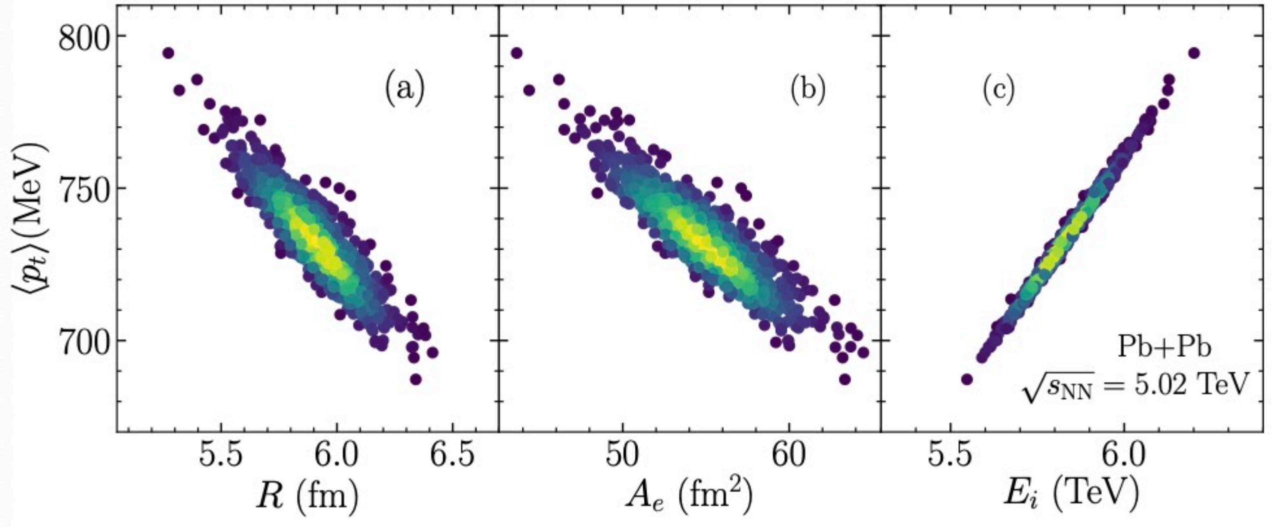
Final to initial mapping

Z. Qiu and U. Heinz, PRC84, 024911(2011)



$v_2 \propto \epsilon_2$

G. Giacalone, F. Gradim, J. Noronha-Hostler, J. Ollitrault, PRC103, 024909 (2021)



$p_T \propto E_i$

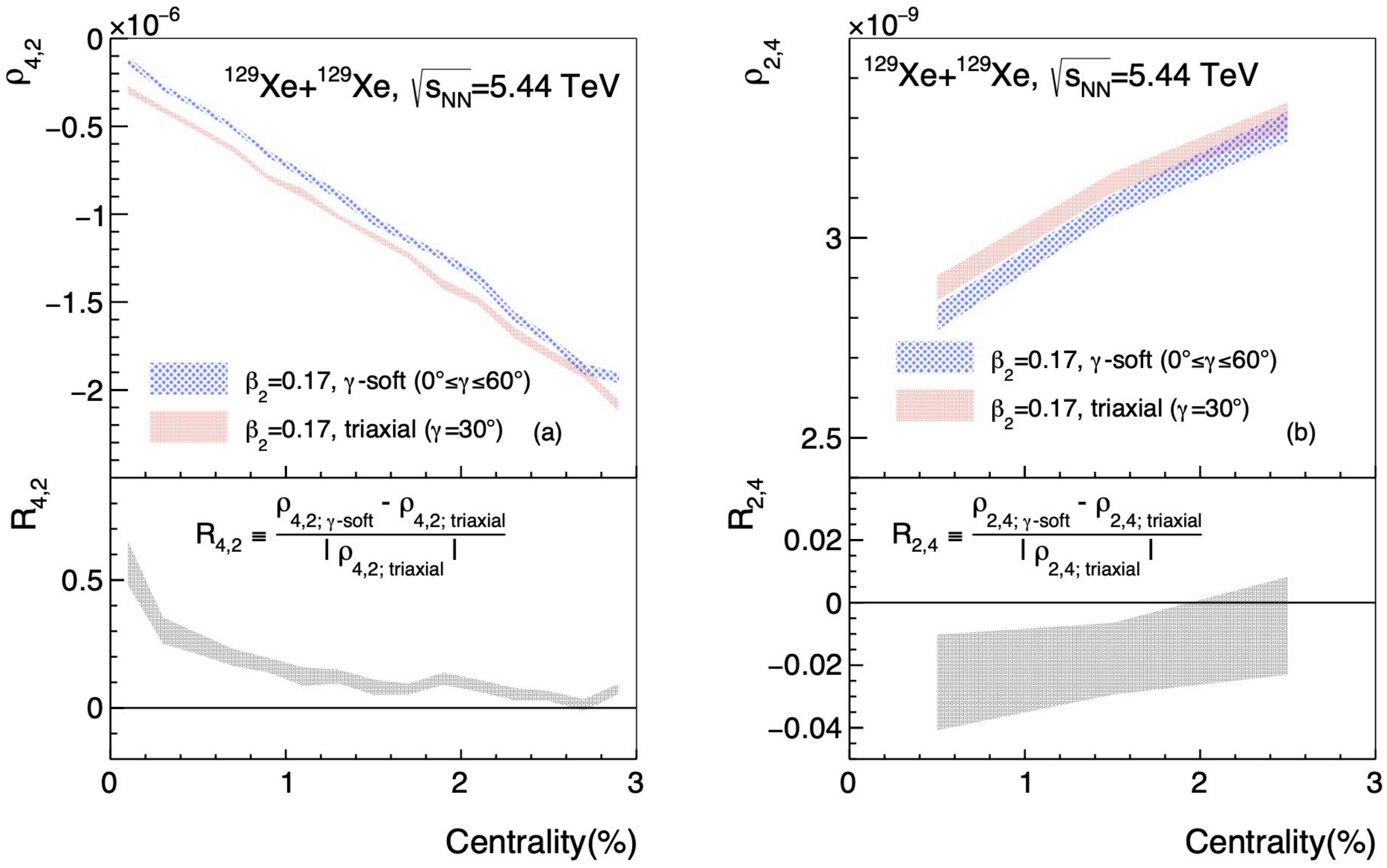
6-particle correlators: S. Zhao, **HJX**, Y. Zhou, Y. Liu, H. Song, PRL, in production (2024)

$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \right)_c \equiv \frac{1}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \left[\langle \varepsilon_2^4 \delta d_\perp^2 \rangle + 4 \langle \varepsilon_2^2 \rangle^2 \langle \delta d_\perp^2 \rangle - \langle \varepsilon_2^4 \rangle \langle \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \rangle \langle \varepsilon_2^2 \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \delta d_\perp \rangle^2 \right]$$

$$\rho_{2,4} \equiv \left(\frac{\langle \varepsilon_2^2 \delta d_\perp^4 \rangle}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \right)_c \equiv \frac{1}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \left[\langle \varepsilon_2^2 \delta d_\perp^4 \rangle - 6 \langle \varepsilon_2^2 \delta d_\perp^2 \rangle \langle \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \delta d_\perp \rangle \langle \delta d_\perp^3 \rangle - \langle \varepsilon_2^2 \rangle \langle \delta d_\perp^4 \rangle + 6 \langle \varepsilon_2^2 \rangle \left(\langle \delta d_\perp^2 \rangle \right) \right] .$$

Observable for shape fluctuation

S. Zhao, **HJX**, Y. Zhou, Y. Liu, H. Song, PRL, in production (2024)



A first step towards exploring the second-order shape phase transition of finite nuclei in ultra-relativistic heavy-ion collisions.

More studies:

- Full hydrodynamic simulations
- β fluctuations
- Shape coaxstence
- ….

Summary and outlook

Relativistic heavy ion collisions can tell us:

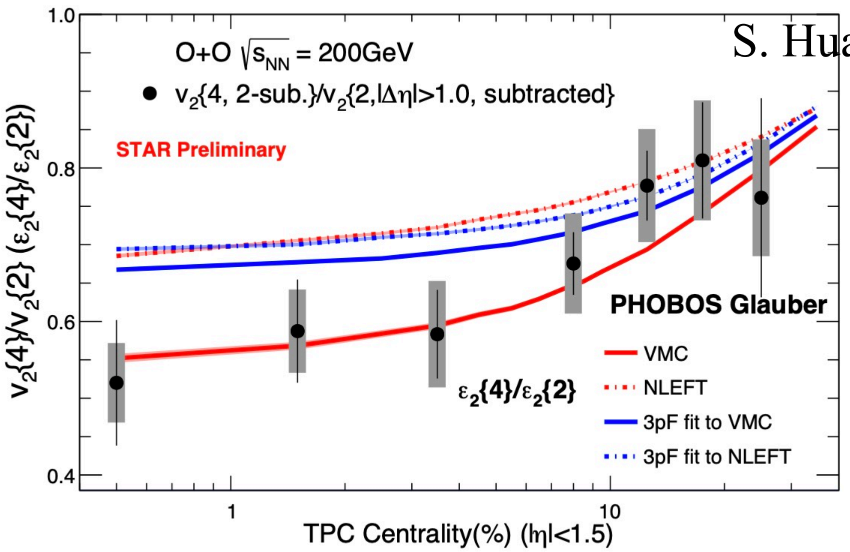
I. Nuclear hexadecapole deformation in ^{238}U.
II. Nuclear shape phase transition in ^{129}Xe

One body distribution measurements :

I. Neutron skin: mean multiplicity, mean transverse momentum in isobar collisions,
II. Nuclear hexadecapole deformation: nonlinear response coefficient in U+U collisions,

Beyond one body distributions:

Multi-body correlations
alpha cluster in ^{12}C, ^{16}O ?



S. Huang, arXiv:2312.12167

Thank you for your attention!

Haojie Xu(徐浩洁)

Huzhou University(湖州师范学院)

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,‡]

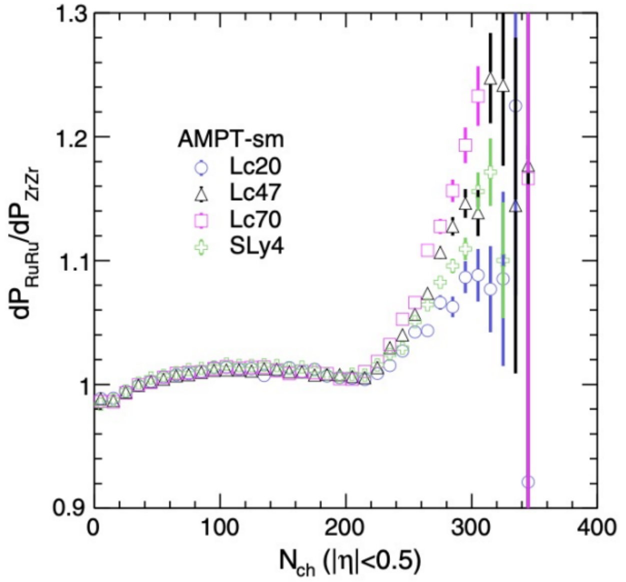
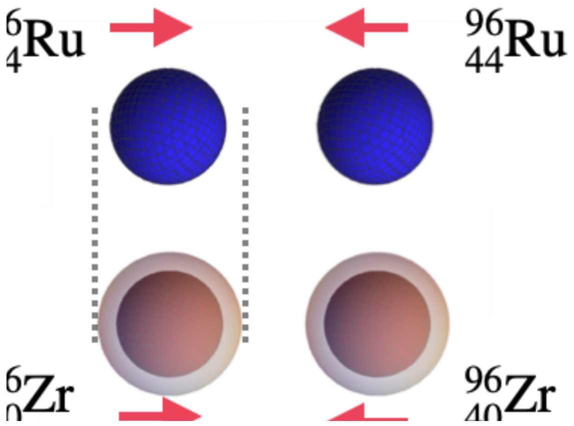
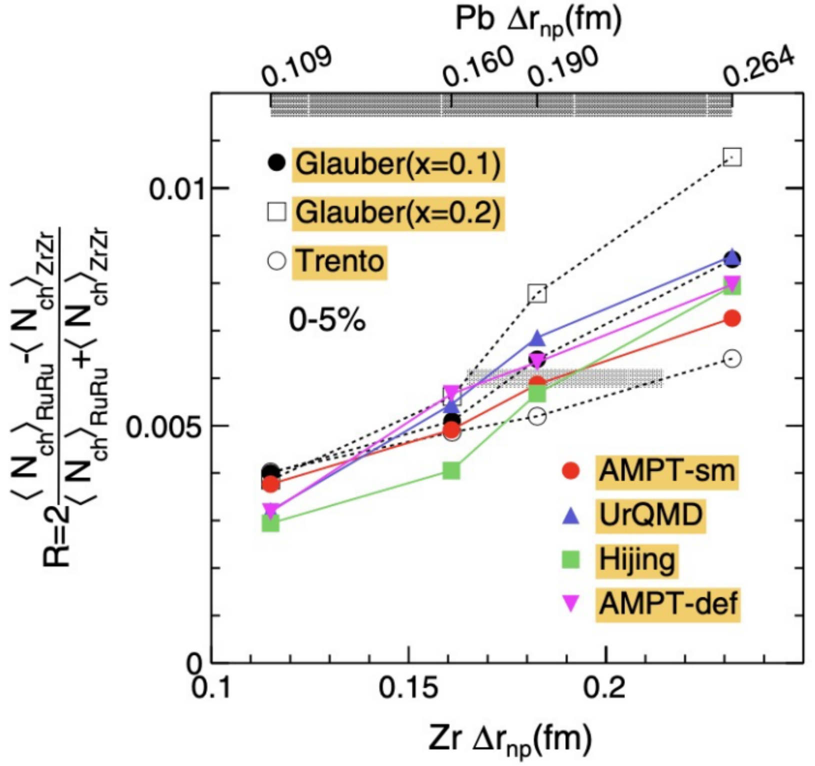


FIG. 3. Ratio of the N_{ch} distribution in Ru + Ru to that in Zr + Zr for various densities in AMPT-sm. The other models are similar.





Neutron skin: sensitive probe of symmetry energy

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

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

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

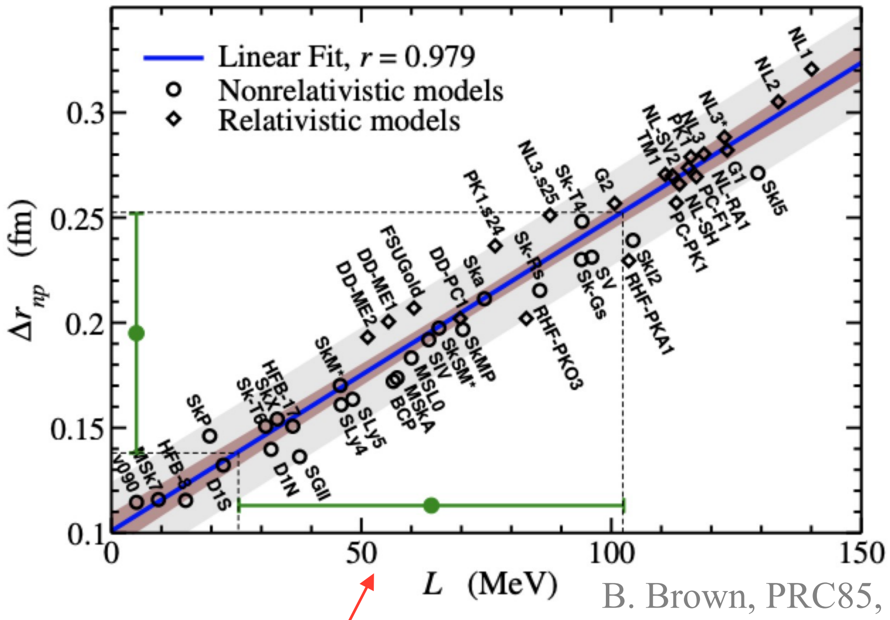
DFT(eSHF): State-of-the-art DFT calculation using extended Skyrme-Hartree-Fock (eSHF) model.

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

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

Slope parameter :

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



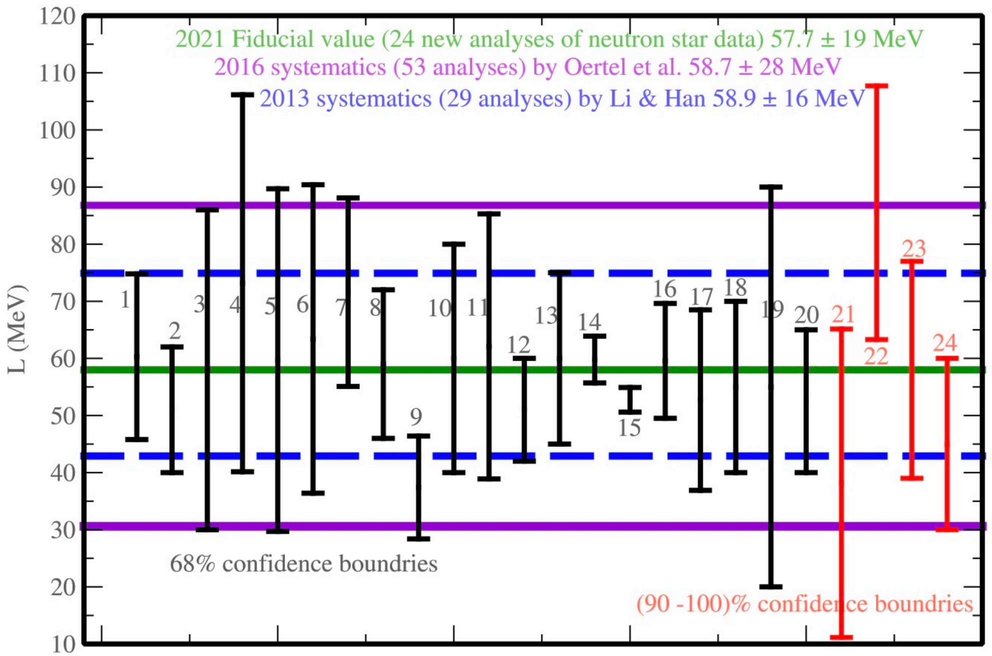
B. Brown, PRC85, 5296 (2000)
R. Furnstahl, NPA, 706, 85 (2002)
X. Roca-Maza, et.al. PRL106, 252501 (2011)

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

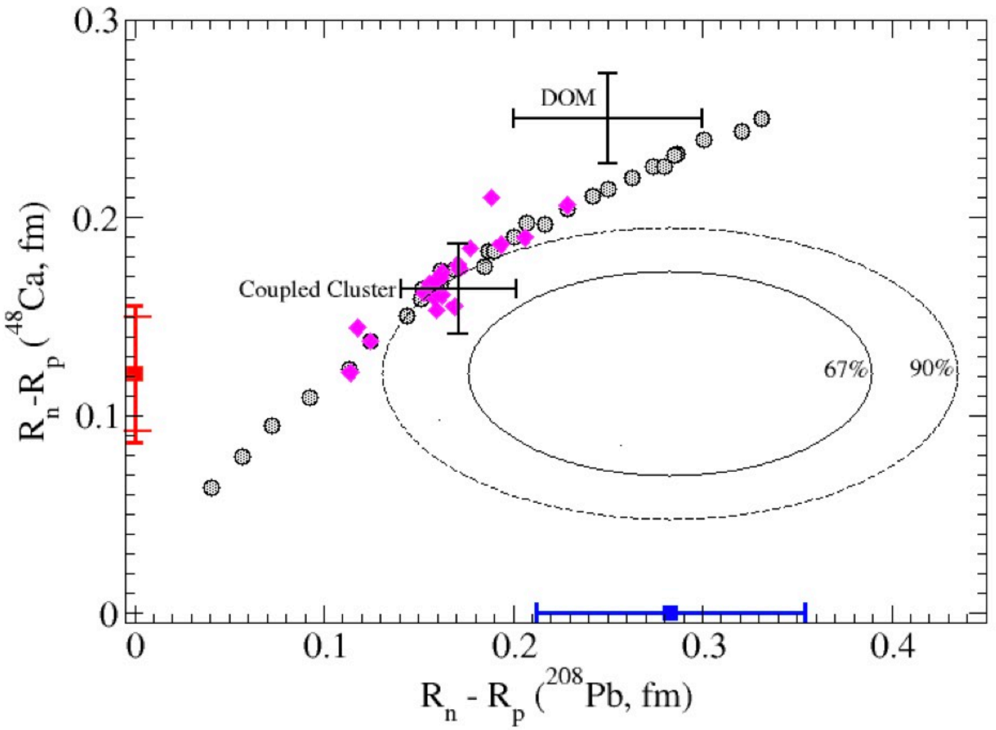
The symmetry energy is crucial to our understanding of the masses and drip lines of neutron-rich nuclei and the equation of state (EOS) of nuclear and neutron star matter.

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.

Mean transverse momentum

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

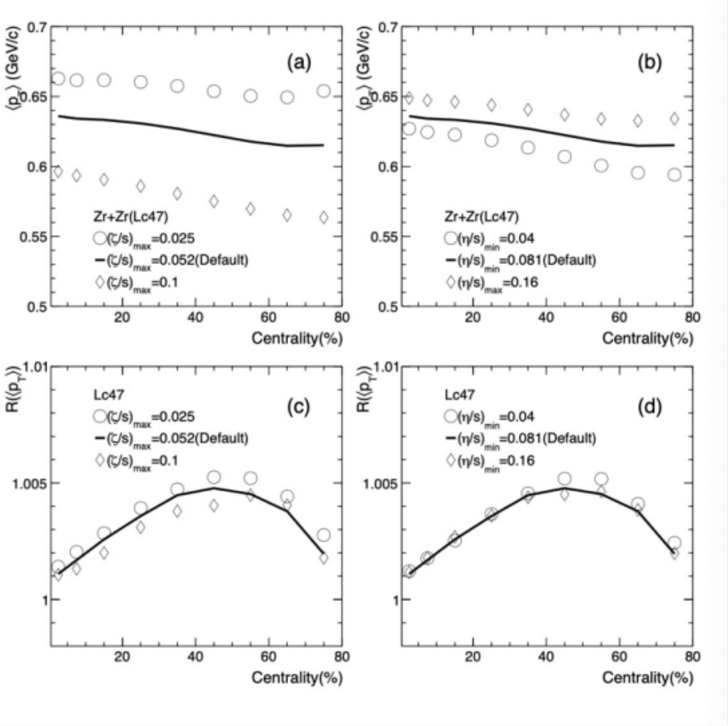
Letter

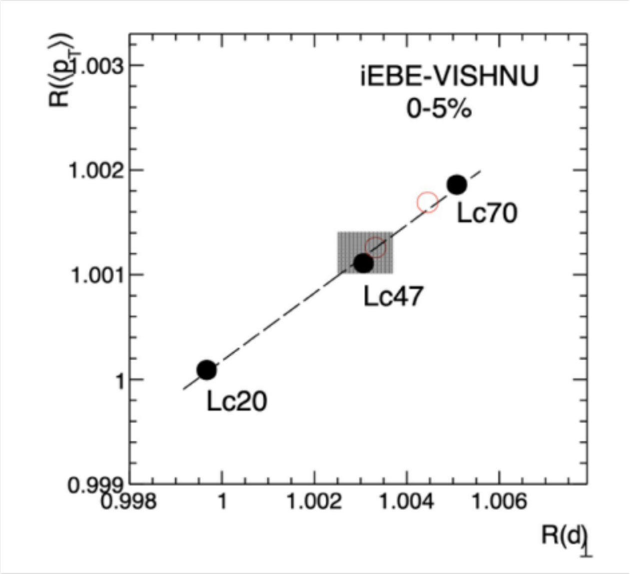
首次证明演化带来的系统不确定性很小

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]

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





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

STAR Preliminary results

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:

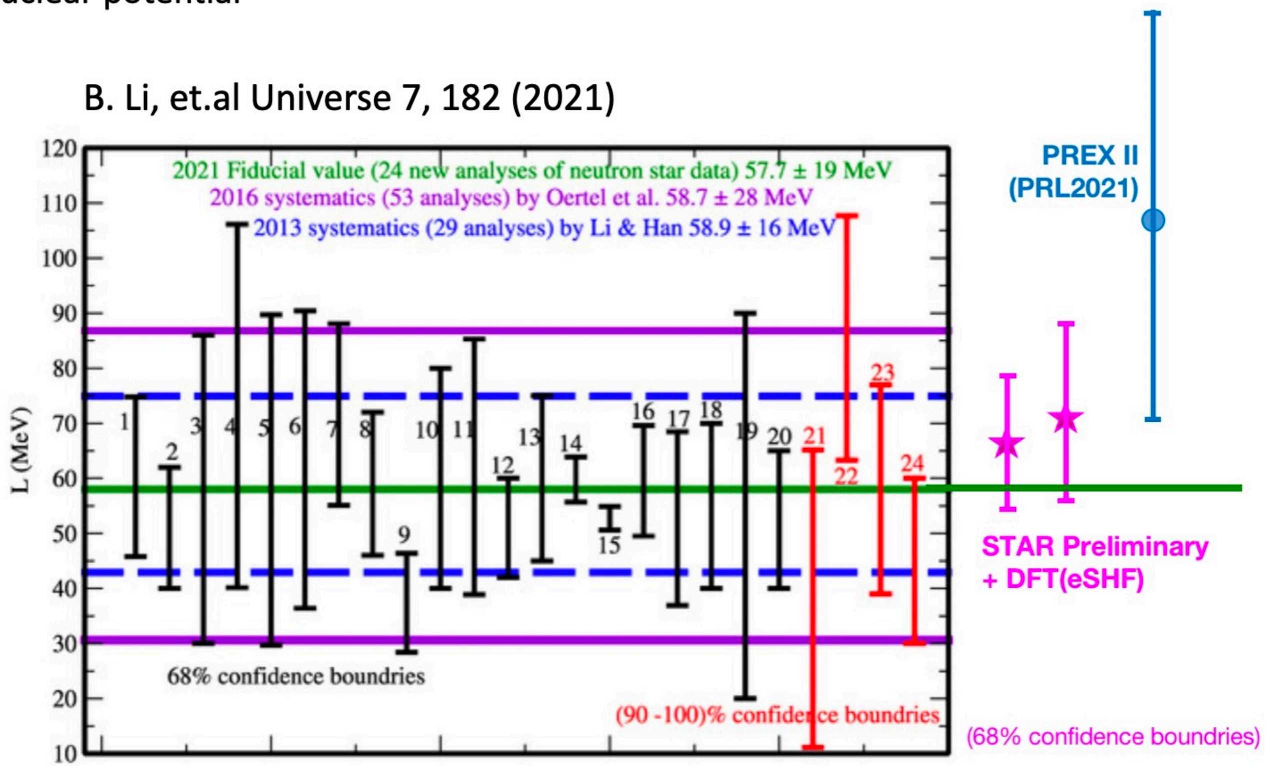
  $L(\rho_c) = 56.8 \pm 0.4 \pm 10.4$ MeV

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

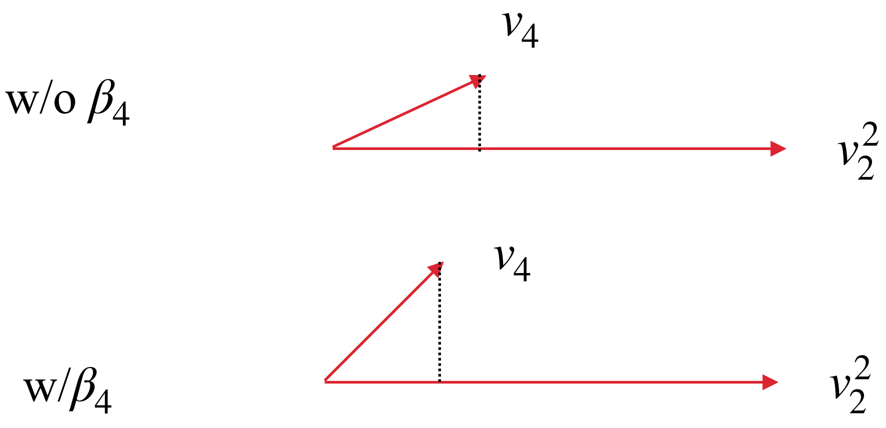
Haojie Xu

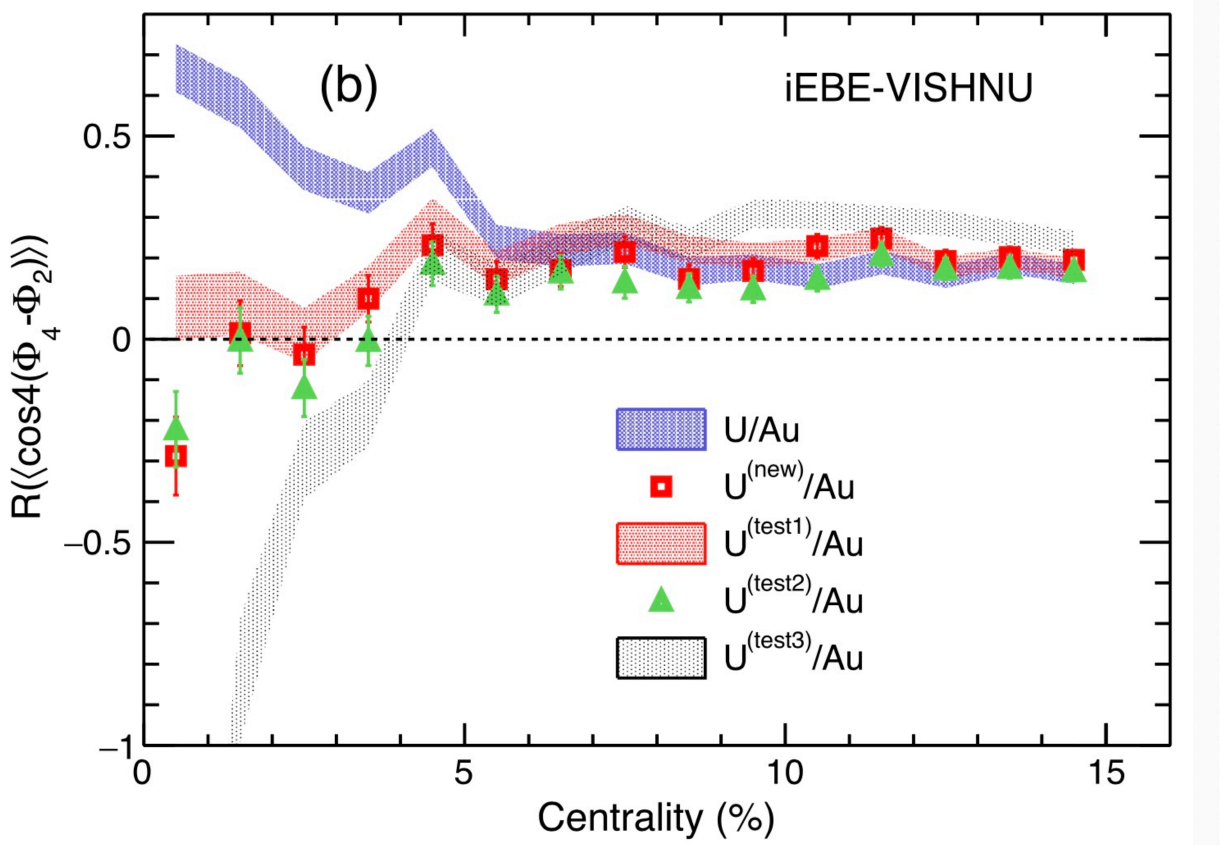
QM QUARK MATTER KRAKOW 2022

Backup

v_2 and v_4 are almost insensitive to β_4, $v_4 = v_{4L} + v_{4NL} = v_{4L} + \chi_{4,22} v_2^2$, the dominated contribution for v_4 is v_{4L}, then why $\chi_{4,22}$ is very sensitive to β_4?

Almost due to flow angle correlations!





Flow angle Φ_4: fluctuation driven -> geometry driven