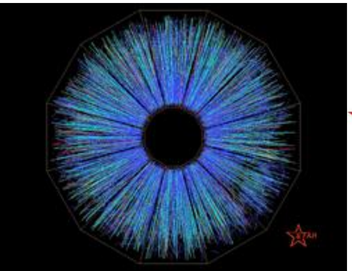
Nuclear symmetry energy from isobar collisions at RHIC

Fuqiang Wang

Purdue University



OUTLINE

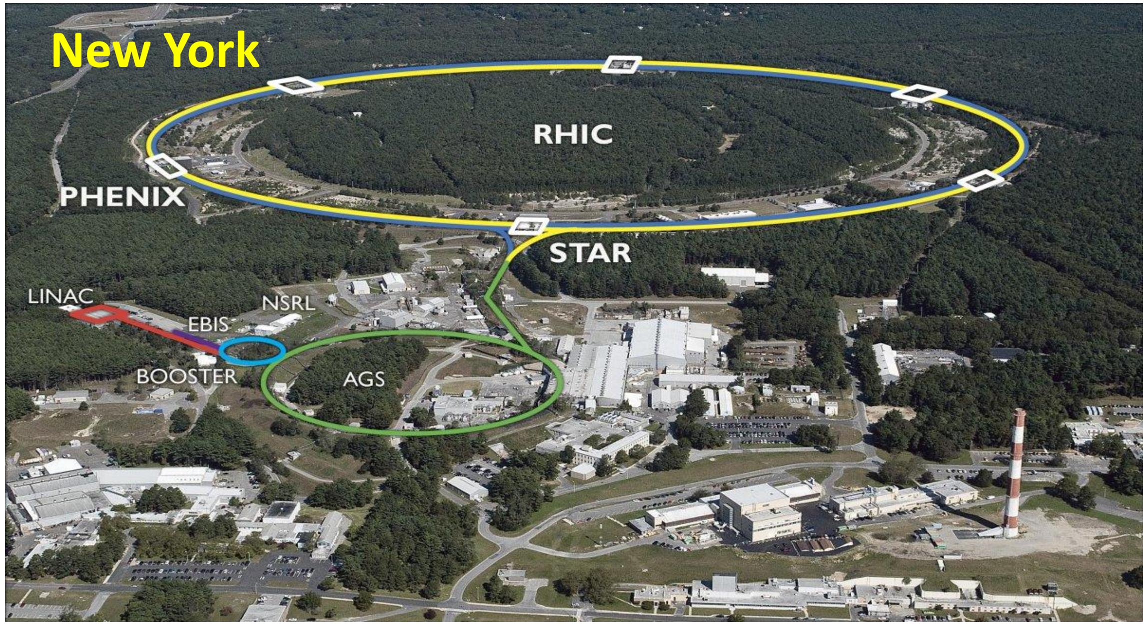
- Brief introduction
  - Relativistic heavy ion collisions
  - The RHIC isobar program and its physics motivation (i.e. CME)

- Byproduct of the isobar program

  - ➢ Symmetry energy slope parameter
  - ➢ Nuclear shapes / deformation

- Summary

RELATIVISTIC HEAVY ION COLLIDER (AND THE LHC)



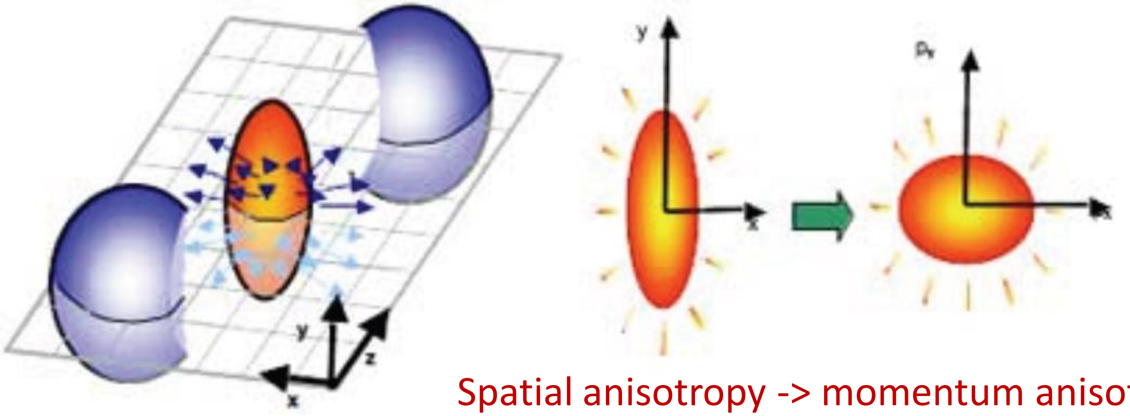
- RHIC: versatile, many nuclear species, lower beam-energy scan
- LHC: not as versatile, but a few species already; possible low energies

RELATIVISTIC HEAVY ION COLLISIONS

Woods-Saxon distributions

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

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



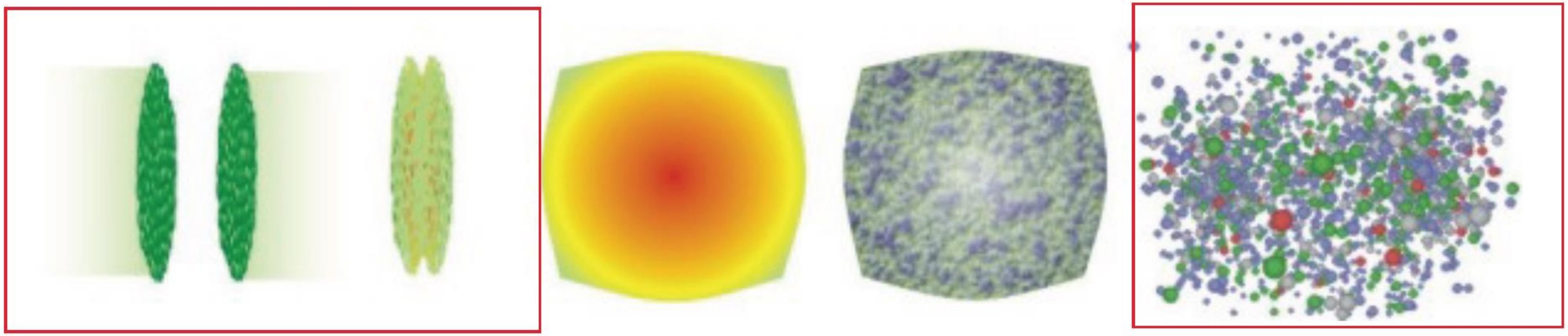
Spatial anisotropy -> momentum anisotropy

Anisotropic flow,
Flow fluctuations
HBT,
....

Initial geometry

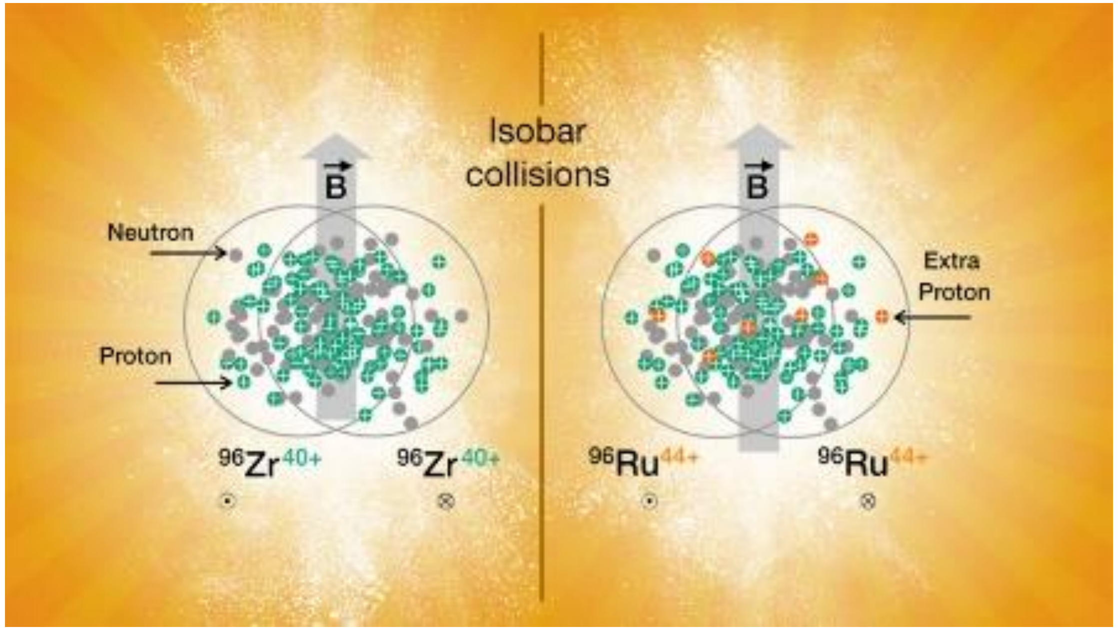
Bulk properties of QGP medium: $\eta/s, \zeta/s, \ldots$

Final observables



THE ISOBAR PROGRAM

Kharzeev,Pisarski,Tytgat,PRL81(1998)512
Kharzeev, et al. NPA 803 (2008) 227
Voloshin, PRL 105 (2010) 172301



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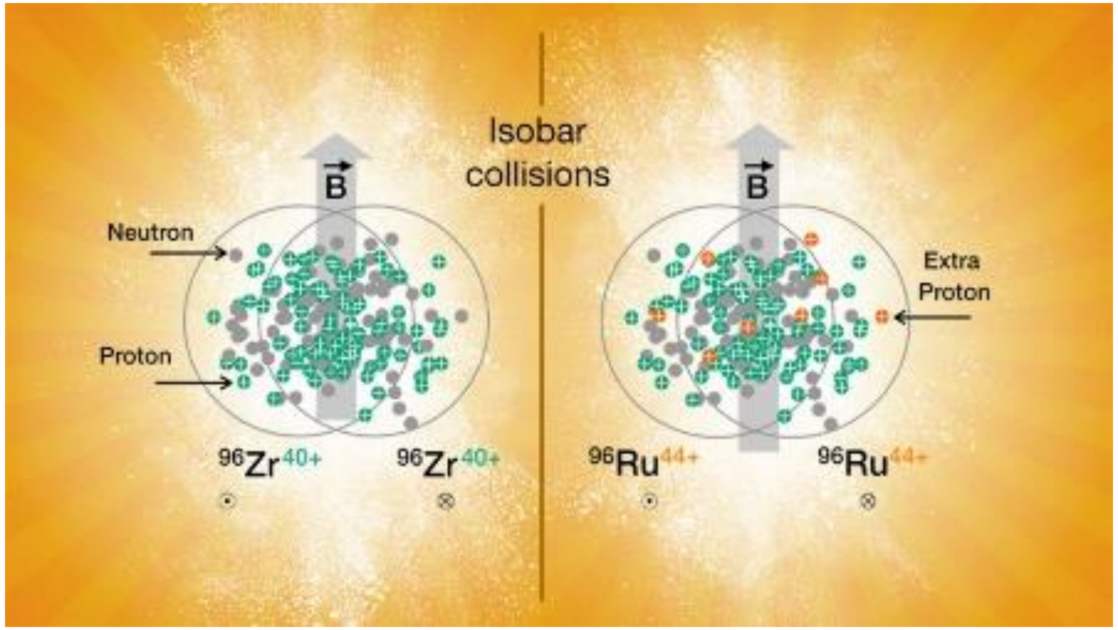

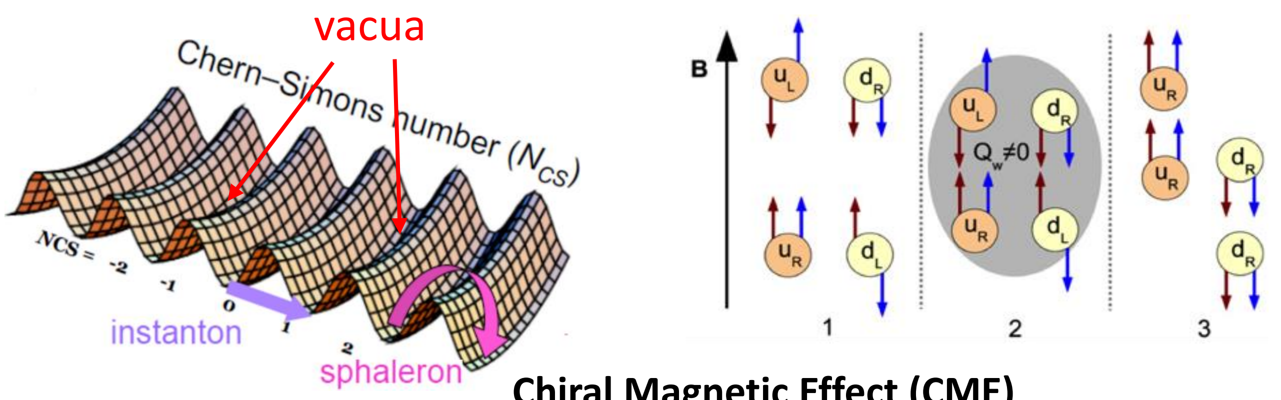

Chiral Magnetic Effect (CME)

THE ISOBAR PROGRAM

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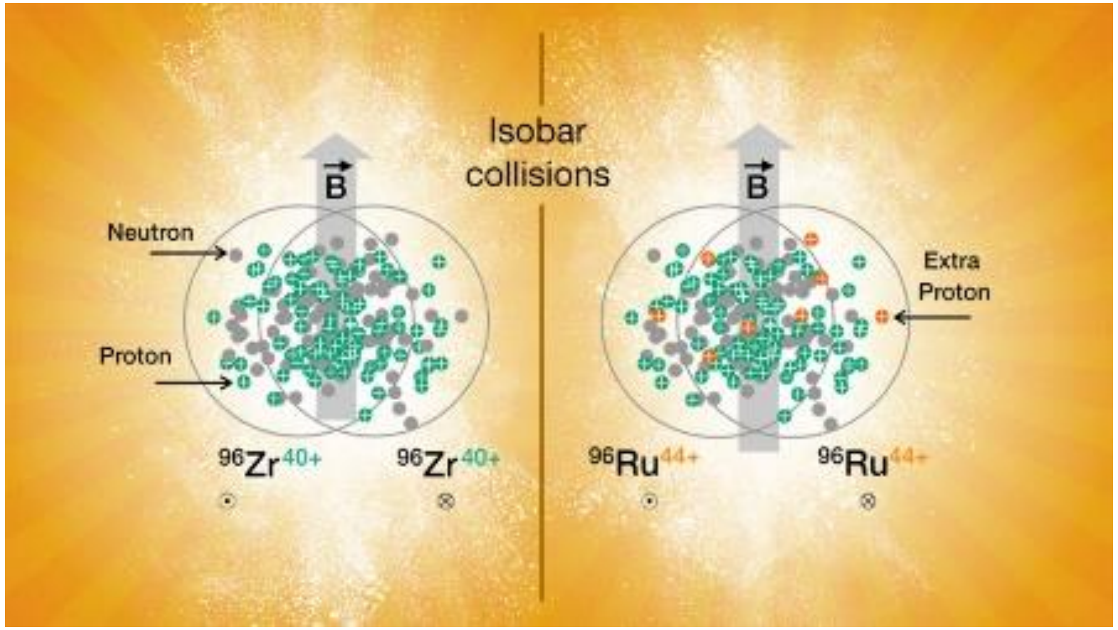
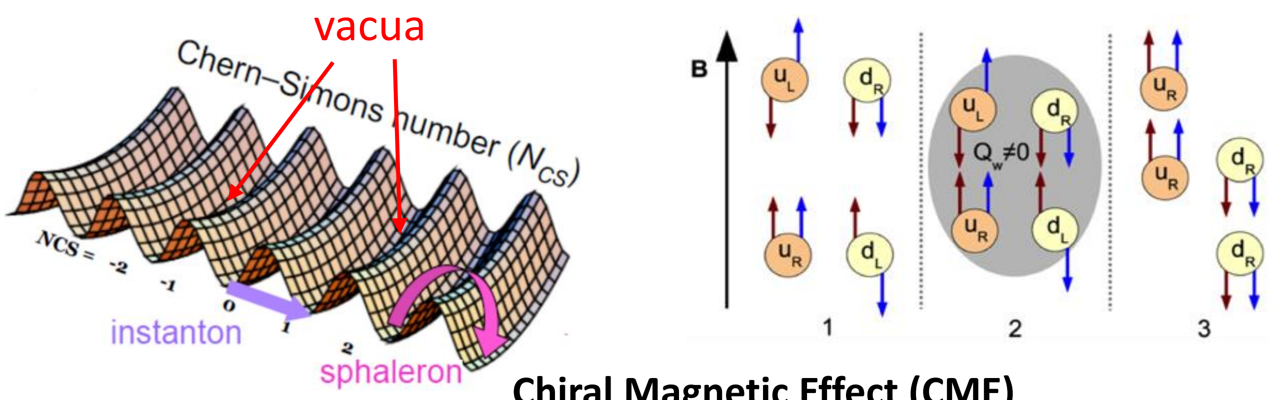
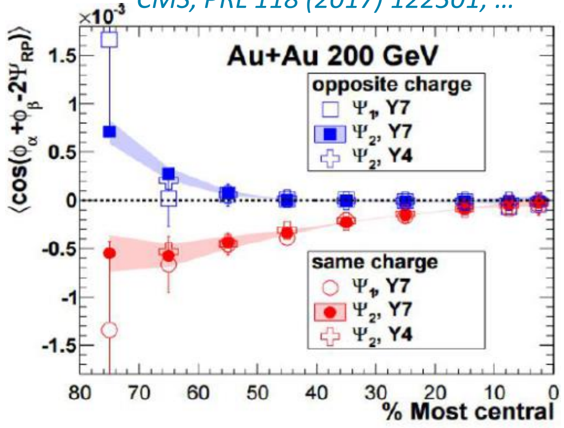
Kharzeev, et al. NPA 803 (2008) 227
Voloshin, PRL 105 (2010) 172301



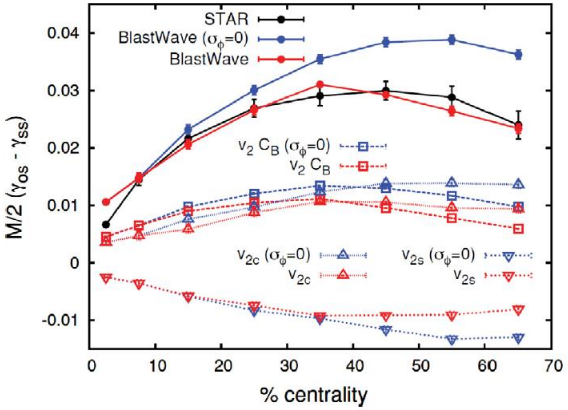


Chiral Magnetic Effect (CME)

STAR, PRL 103 (2009) 251601; PRC 81 (2010) 054908; …
ALICE, PRL 110 (2013) 012301; …
CMS, PRL 118 (2017) 122301; …



FW, PRC 81 (2010) 064902;
Bzdak, Koch, Liao, PRC 81 (2010) 031901(R);
Schlichting, Pratt, PRC 83 (2011) 014913; ……

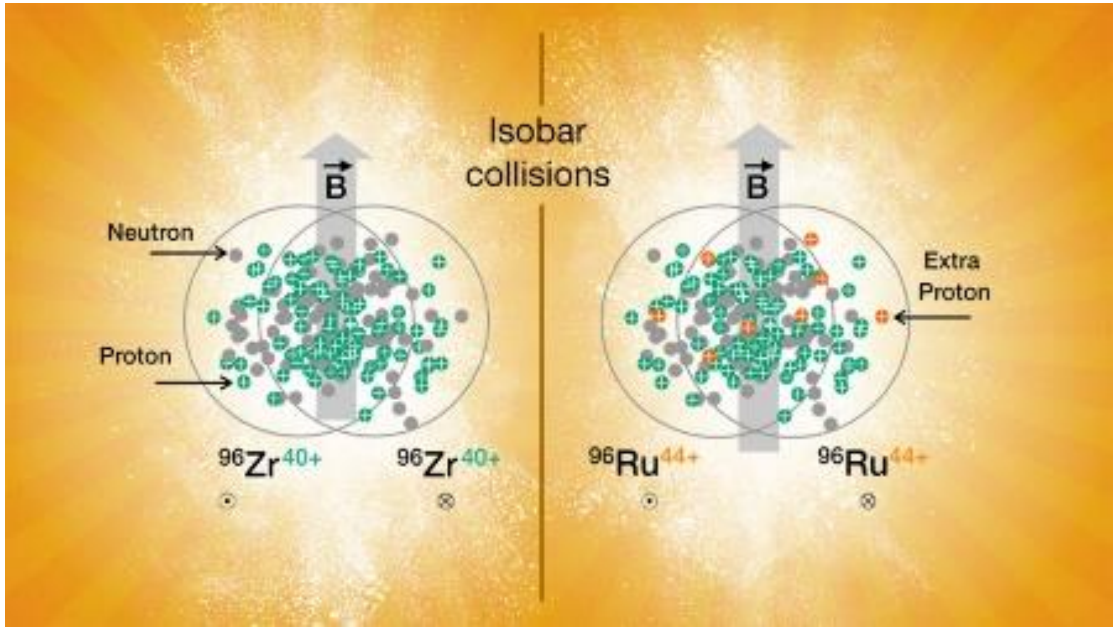


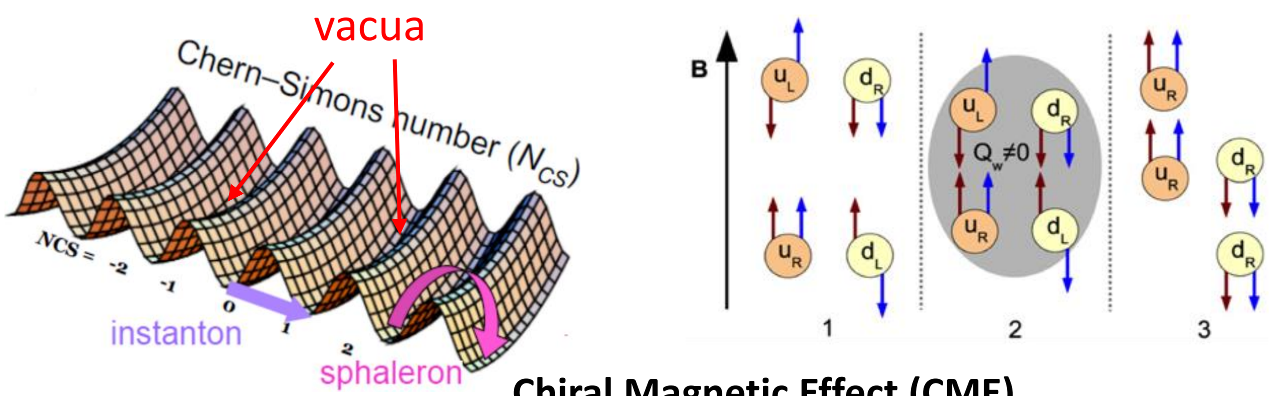
$$\Delta\gamma_{\mathrm{bkgd}} = \frac{N_\rho}{N_\alpha N_\beta}\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \right\rangle v_{2,\rho} \propto v_2 / N$$

Background dominates!

THE ISOBAR PROGRAM

Kharzeev,Pisarski,Tytgat,PRL81(1998)512
Kharzeev, et al. NPA 803 (2008) 227
Voloshin, PRL 105 (2010) 172301





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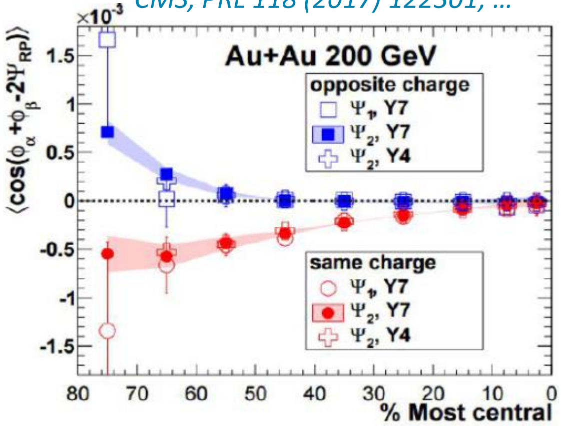

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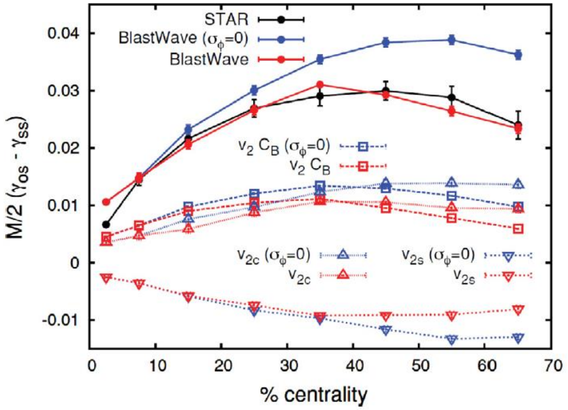


Same A: same strong interaction physics
→ equal background

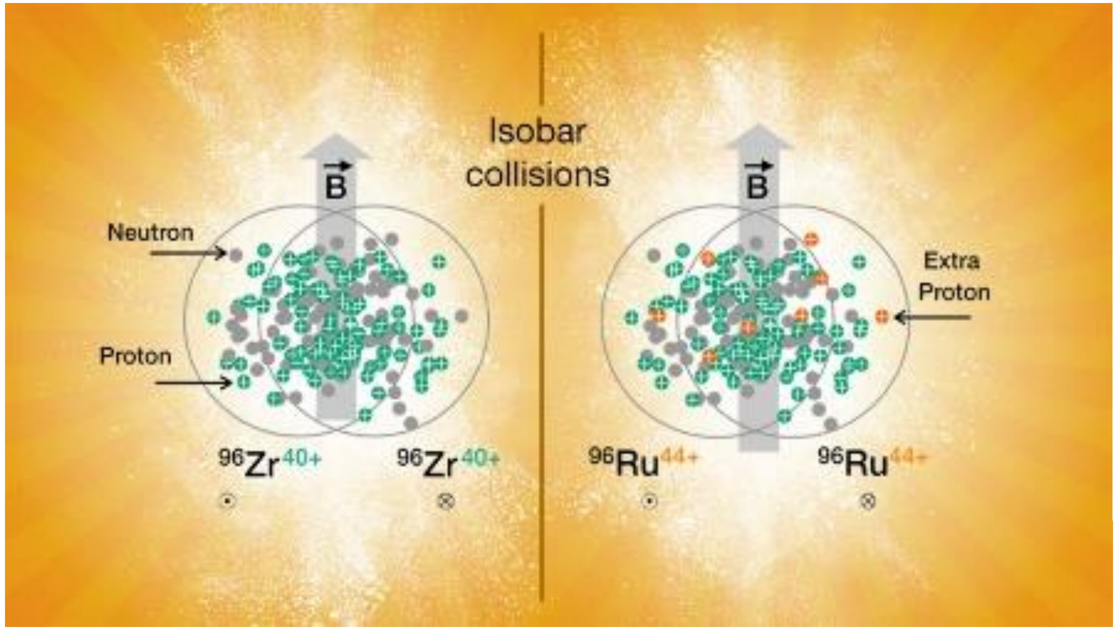
Different Z: number of protons differ 10%
→ different magnetic fields
→ different CME signal
→ $\Delta\gamma$ observable differ by 20%

$$\Delta\gamma_{\text{bkgd}} = \frac{N_\rho}{N_\alpha N_\beta}\left\langle\cos(\varphi_\alpha+\varphi_\beta-2\varphi_\rho)\right\rangle v_{2,\rho} \propto v_2 / N$$

Background dominates!

THE ISOBAR PROGRAM

Voloshin, PRL 105 (2010) 172301
Haojie Xu et al. PRL 121 (2018) 022301
Hanlin Li et al. PRC 98 (2018) 054907



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

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,*]
[1]*School of Science, Huzhou University, Huzhou, Zhejiang 313000, China*
[2]*College of Science, Wuhan University of Science and Technology, Wuhan, Hubei 430065, China*
[3]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*
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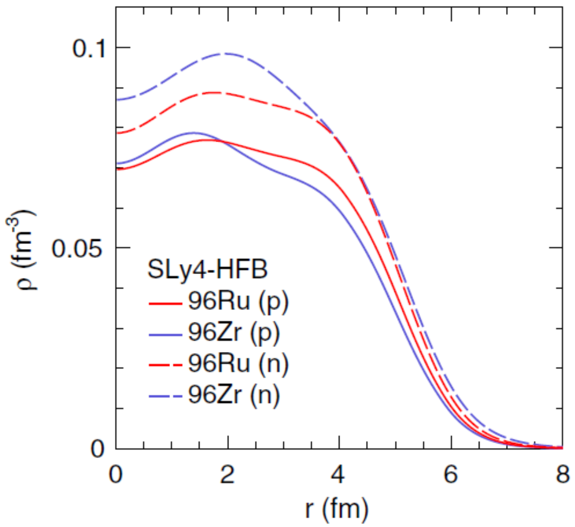
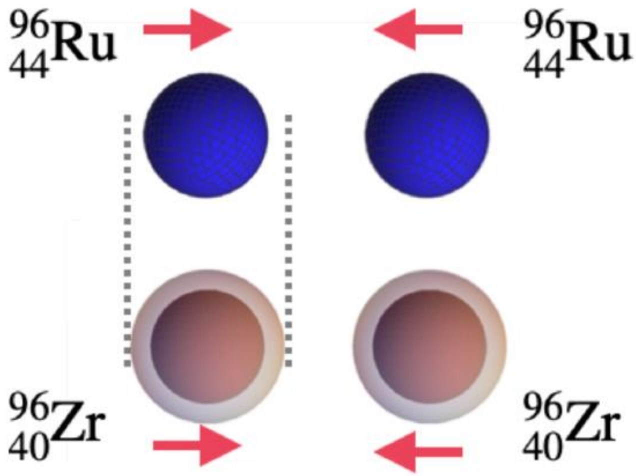




Same A: same strong interaction physics

→ equal background

Different Z: number of protons differ 10%

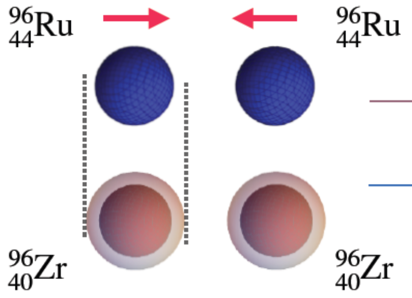
→ different magnetic fields

→ different CME signal

→ $\Delta\gamma$ observable differ by 20%

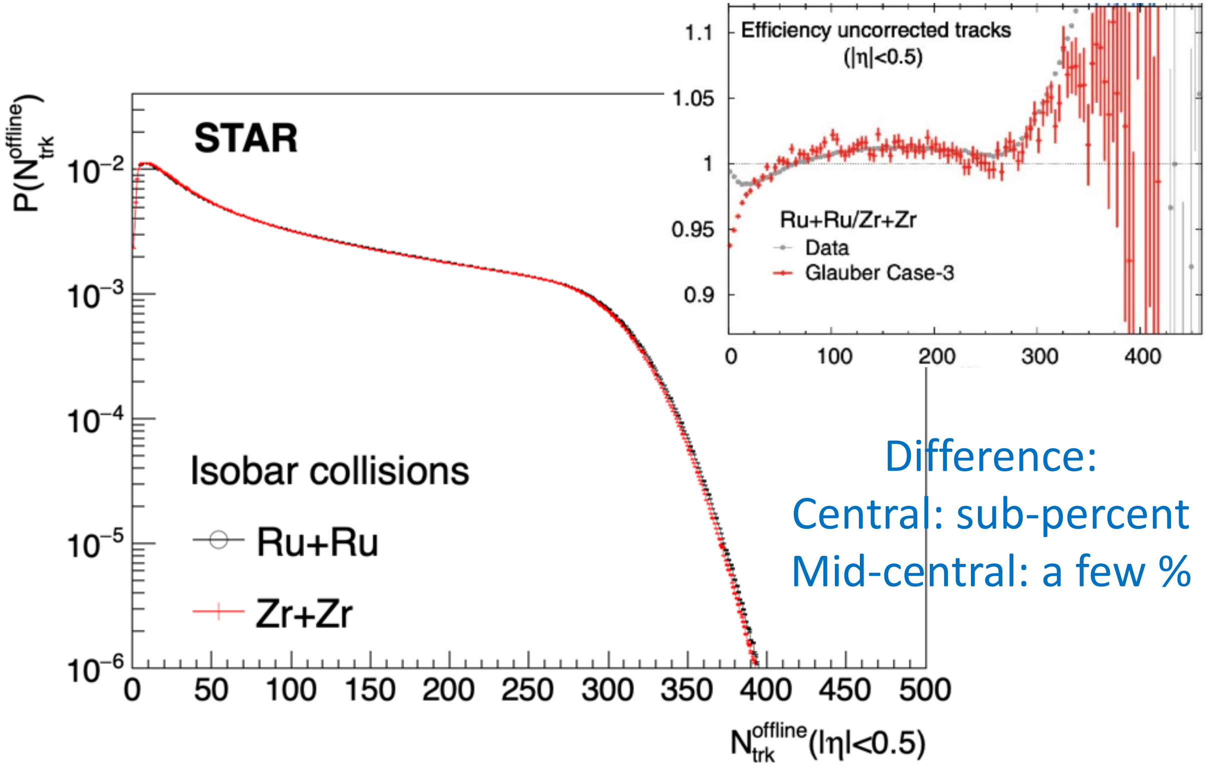
ISOBAR COLLISIONS ARE DIFFERENT

STAR, PRC 105 (2022) 014901

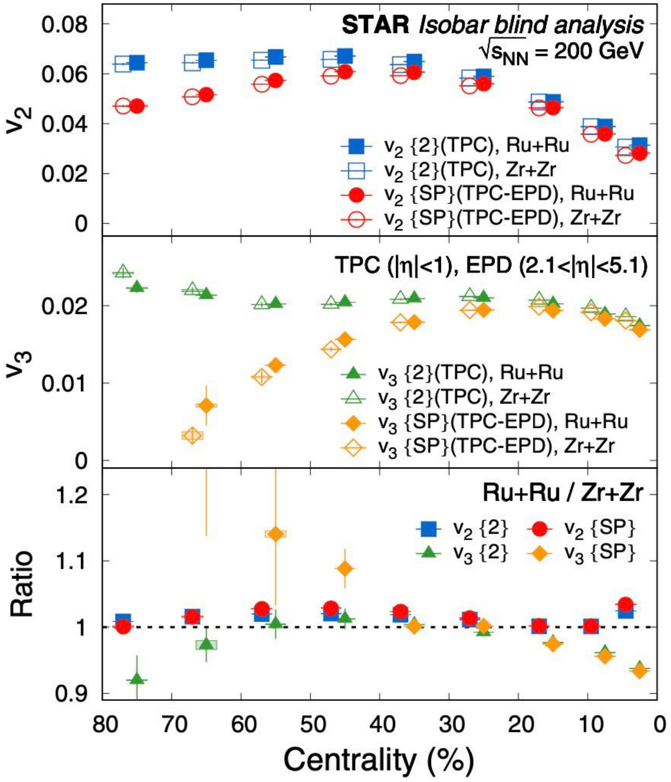


Smaller r, larger density → Larger N_{ch} and $\langle p_{\mathrm{T}} \rangle$

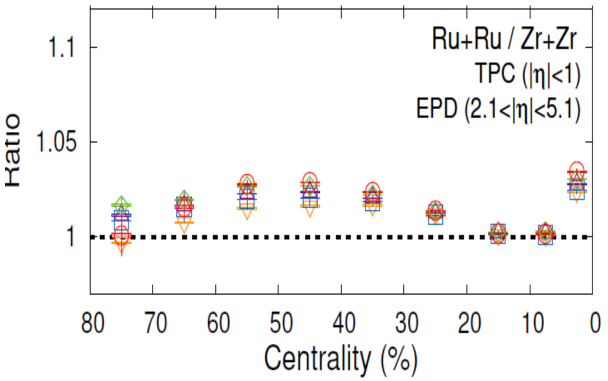
Larger r, smaller density → Smaller N_{ch} and $\langle p_{\mathrm{T}} \rangle$



Difference:
Central: sub-percent
Mid-central: a few %

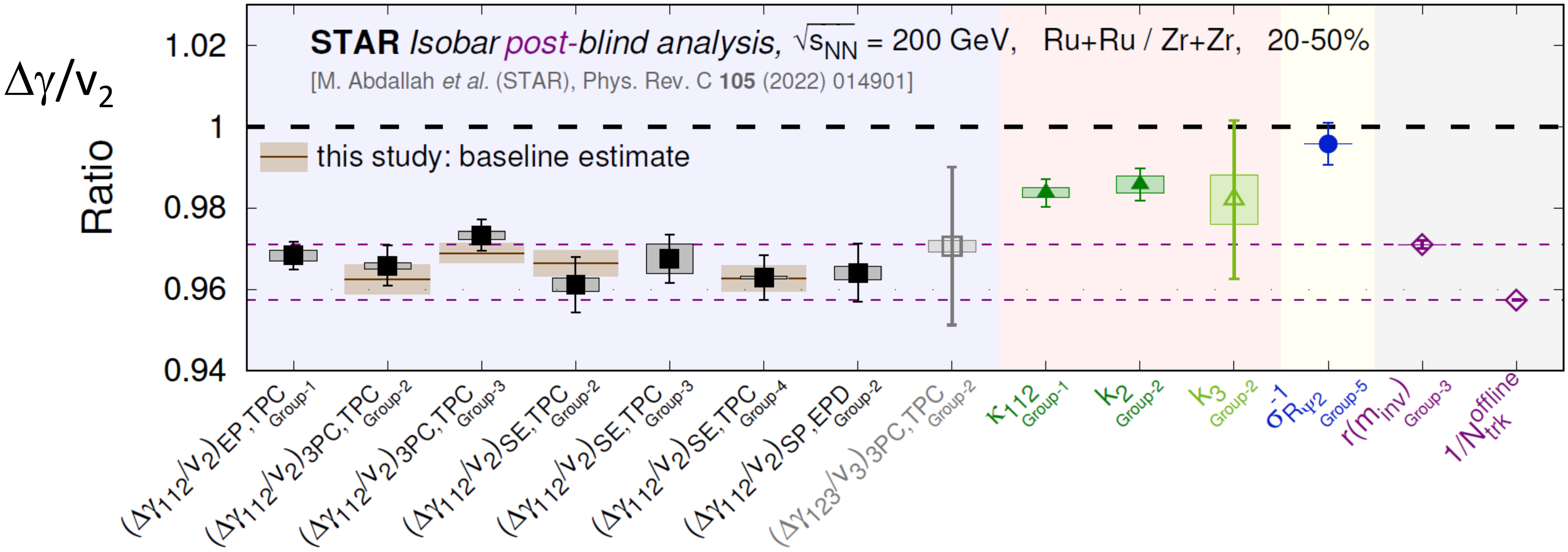


Eccentricities and elliptic flows are also different



CME OBSERVABLE ISOBAR RATIO

STAR, PRC 105 (2022) 014901
Feng et al., PRC 105 (2022) 024913
STAR, 2308.16846



- 0.4% precision is achieved!
- But isobar ratio is below unity; primary reason is multiplicity difference due to nuclear structure.
  - CME Upper Limit 10% (of inclusive $\Delta\gamma$ measurement), at 95% Confidence Level.

TURN THE QUESTION AROUND

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

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,‡]

- Large data samples, high statistical precision (2 billions MB events each)
- Exquisite care in controlling systematics: run conditions, run alteration, data blinding, online monitoring… offline calibration, blind data analysis → Large degree of cancellation of systematics
- Sensitive only to matter densities, but proton densities are well measured
- Unique means to probe neutron skin and symmetry energy slope parameter

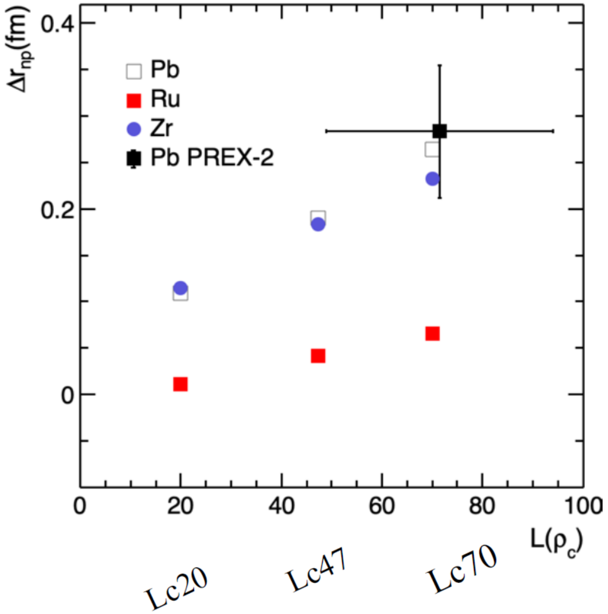
A FEW DETAILS ON DFT CALC

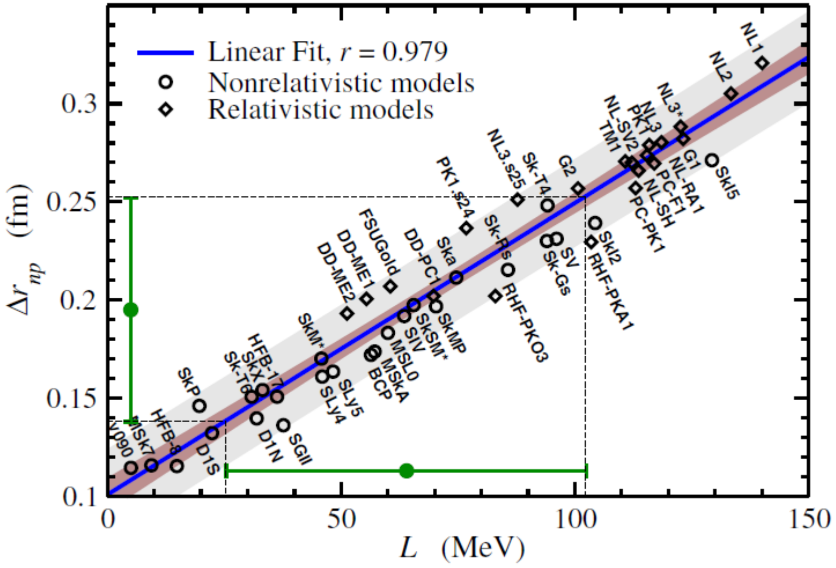
Z. Zhang & L-W Chen, PRC 94 (2016) 064326
B.A. Brown, PRL 85 (2000) 5296
R. Furnstahl, NPA 706 (2002) 85
X. Roca-Maza et al, PRL 106 (2011) 252501

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

$$\begin{aligned} v_{i,j} \; = \; & t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}) + \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha(\boldsymbol{R})\delta(\boldsymbol{r}) \\ & + \frac{1}{2}t_1(1+x_1P_\sigma)[K'^2\delta(\boldsymbol{r})+\delta(\boldsymbol{r})K^2] \\ & + t_2(1+x_2P_\sigma)\boldsymbol{K}'\cdot\delta(\boldsymbol{r})\boldsymbol{K} \\ & + \frac{1}{2}t_4(1+x_4P_\sigma)[K'^2\delta(\boldsymbol{r})\rho(\boldsymbol{R})+\rho(\boldsymbol{R})\delta(\boldsymbol{r})K^2] \\ & + t_5(1+x_5P_\sigma)\boldsymbol{K}'\cdot\rho(\boldsymbol{R})\delta(\boldsymbol{r})\boldsymbol{K} \\ & + iW_0(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\cdot[\boldsymbol{K}'\times\delta(\boldsymbol{r})\boldsymbol{K}], \qquad (4) \end{aligned}$$

Extended





Larger L, harder EOS ←→ need small δ to lower E ←→ smaller ρ_n, larger Δr_{np}

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

$$E_{\text{sym}}(\rho) \approx E_{\text{sym}}(\rho_0) + L(\rho_0)\chi + \frac{1}{2}K_{\text{sym}}(\rho_0)\chi^2; \quad \chi \equiv \frac{\rho-\rho_0}{3\rho_0}$$

$$L(\rho_c) = 3\rho_c \left.\frac{\partial E_{\text{sym}}(\rho)}{\partial\rho}\right|_{\rho=\rho_c} = \left(L(\rho_0) + K_{\text{sym}}\frac{\rho_c-\rho_0}{3\rho_0}\right)\frac{\rho_c}{\rho_0}$$

^{96}Zr: (N-Z)/A = 0.167
^{96}Ru: (N-Z)/A = 0.083

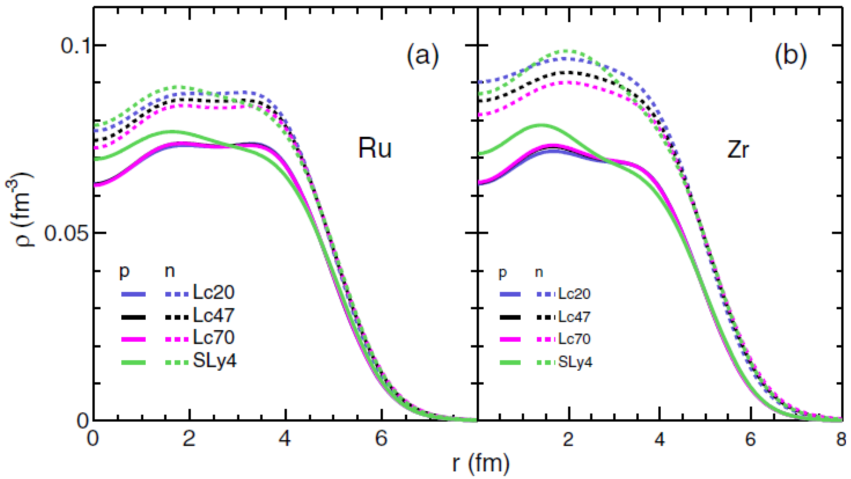
$$\rho_c \approx 0.11\ \text{fm}^{-3} \approx 2\rho_0/3$$
$$L \approx 3L_c/2 + K_{\text{sym}}/9$$

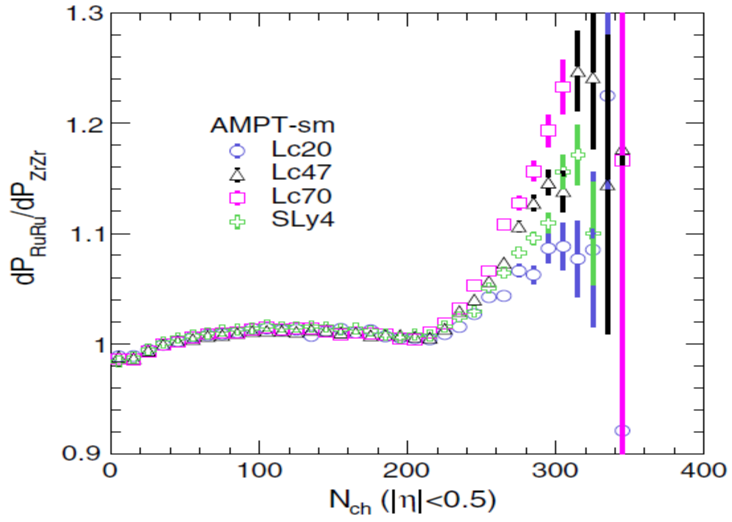
			^{96}Zr			^{96}Ru			^{208}Pb
	$L(\rho_c)$	$L(\rho_0)$	r_n	r_p	Δr_{np}	r_n	r_p	Δr_{np}	Δr_{np}
Lc20	20	13.1	4.386	4.27	0.115	4.327	4.316	0.011	0.109
Lc47	47.3	55.7	4.449	4.267	0.183	4.360	4.319	0.042	0.190
Lc70	70	90.0	4.494	4.262	0.232	4.385	4.32	0.066	0.264
SLy4	42.7	46.0	4.432	4.271	0.161	4.356	4.327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

HOW TO DO IT?

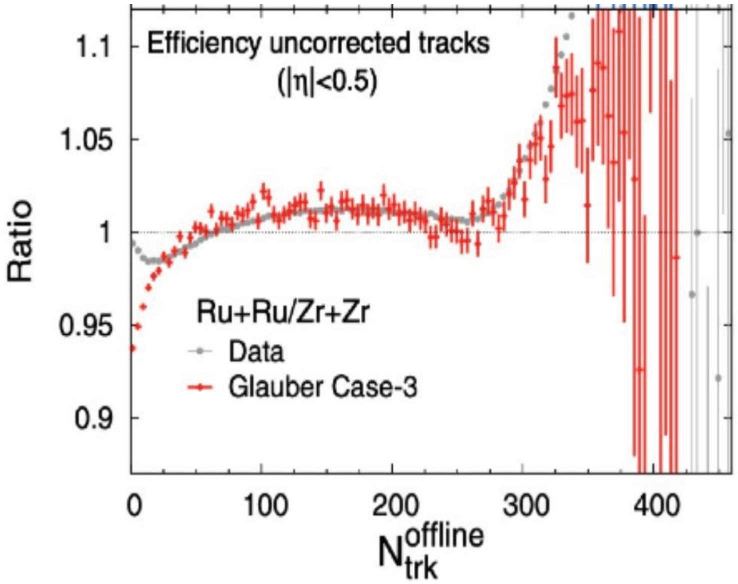
Calculate DFT with a few L parameters, compare outcome to measurements (multiplicity, <p_T>, etc.)

H. Li, H-j Xu et al, PRL 125 (2020) 222301





STAR, PRC 105 (2022) 014901



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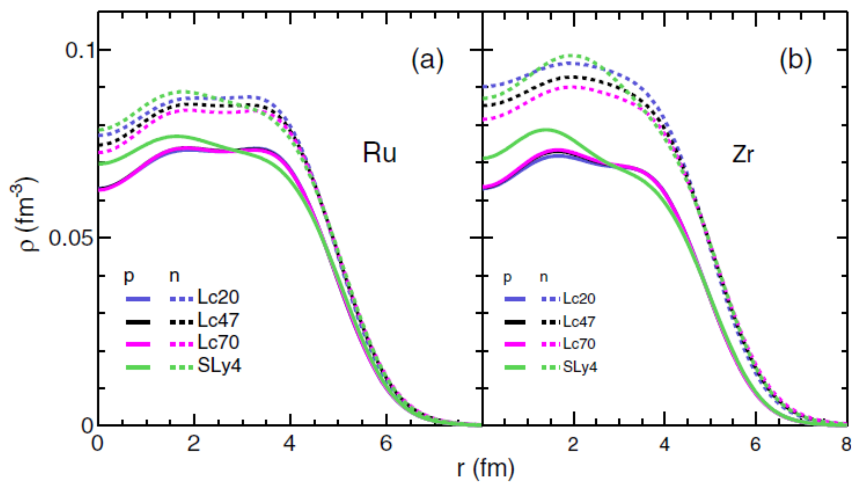
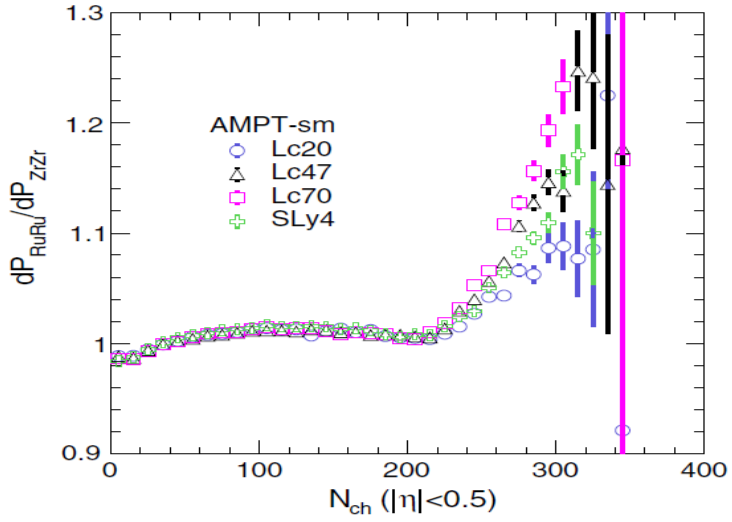
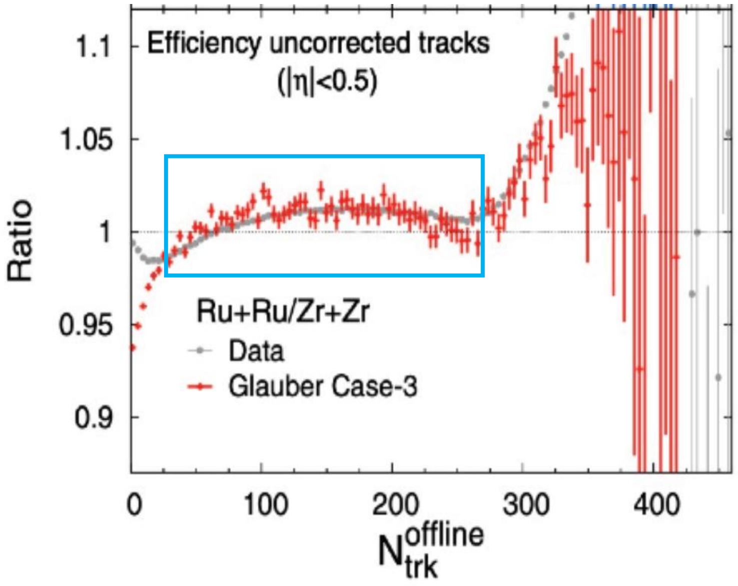
H. Li, H-j Xu et al, PRL 125 (2020) 222301



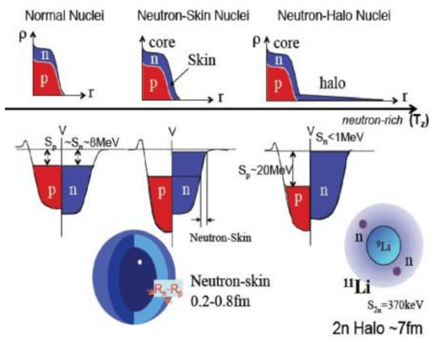


STAR, PRC 105 (2022) 014901



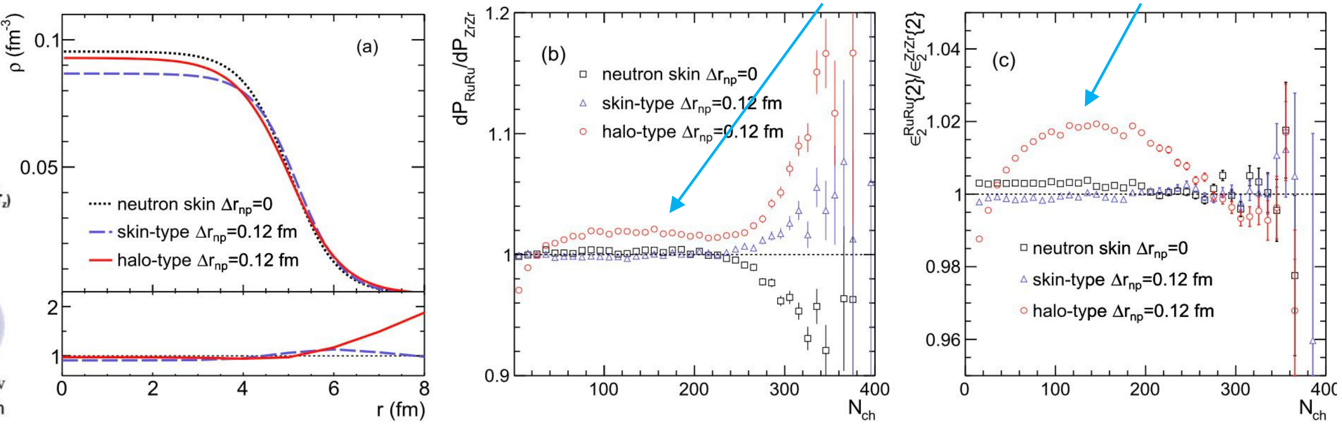
$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}$$

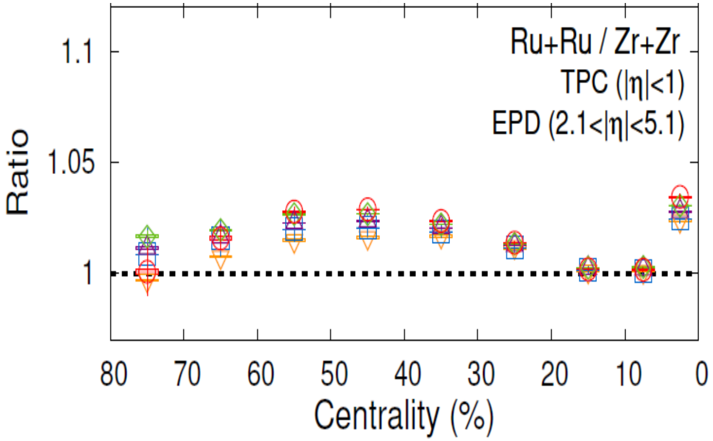
$$R = R_0\,[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$



H-j Xu et.al., PLB 819 (2021) 136453

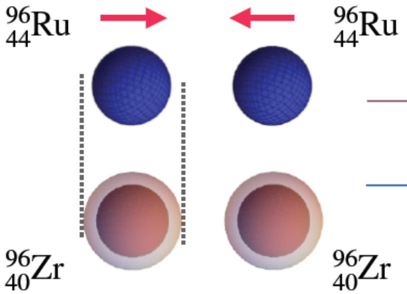
These shapes can distinguish between skin- and halo-type





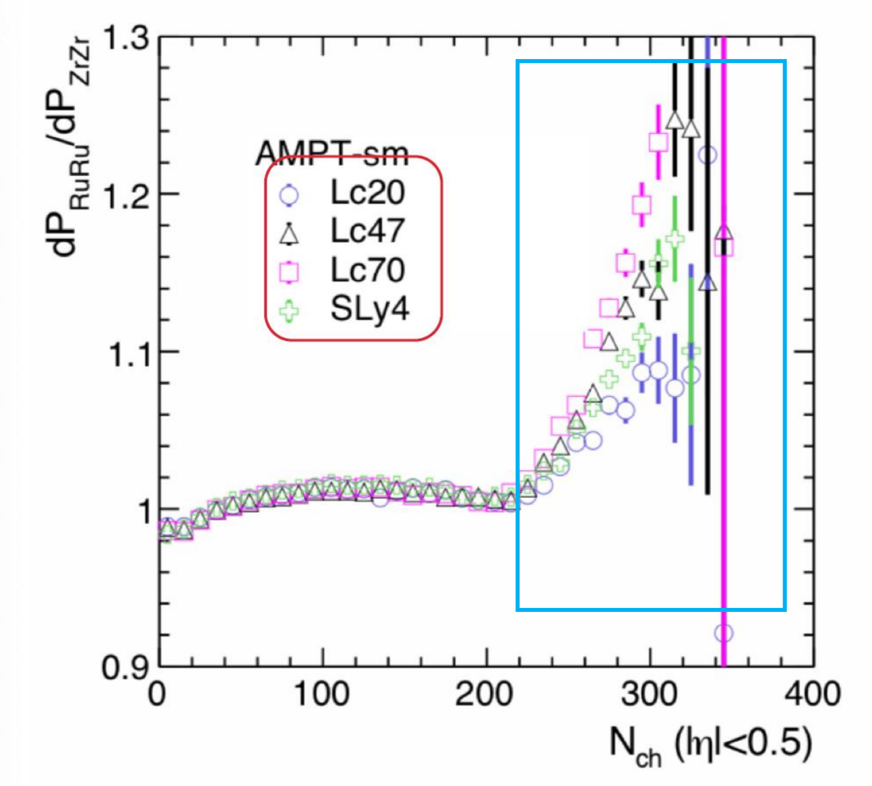
CENTRAL COLLISION MULTIPLICITY

H. Li, H-j Xu et al, PRL 125 (2020) 222301



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

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

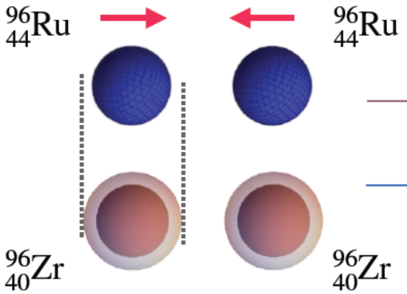


Central collisions:

Multiplicity tail ultrasensitive to neutron skin

CENTRAL COLLISION MULTIPLICITY

H. Li, H-j Xu et al, PRL 125 (2020) 222301



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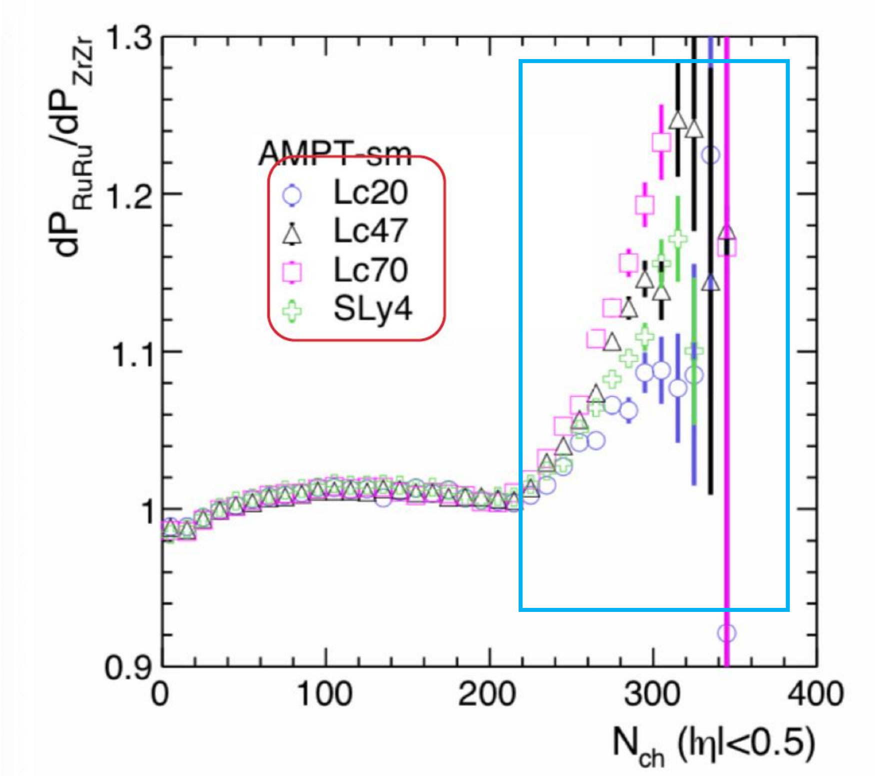

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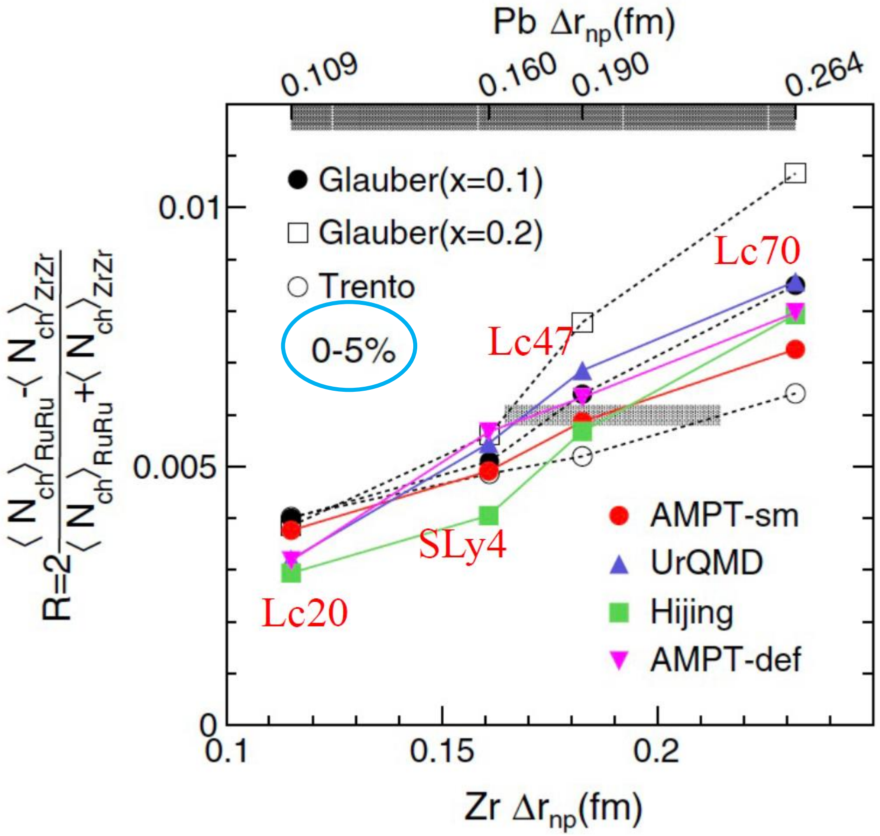
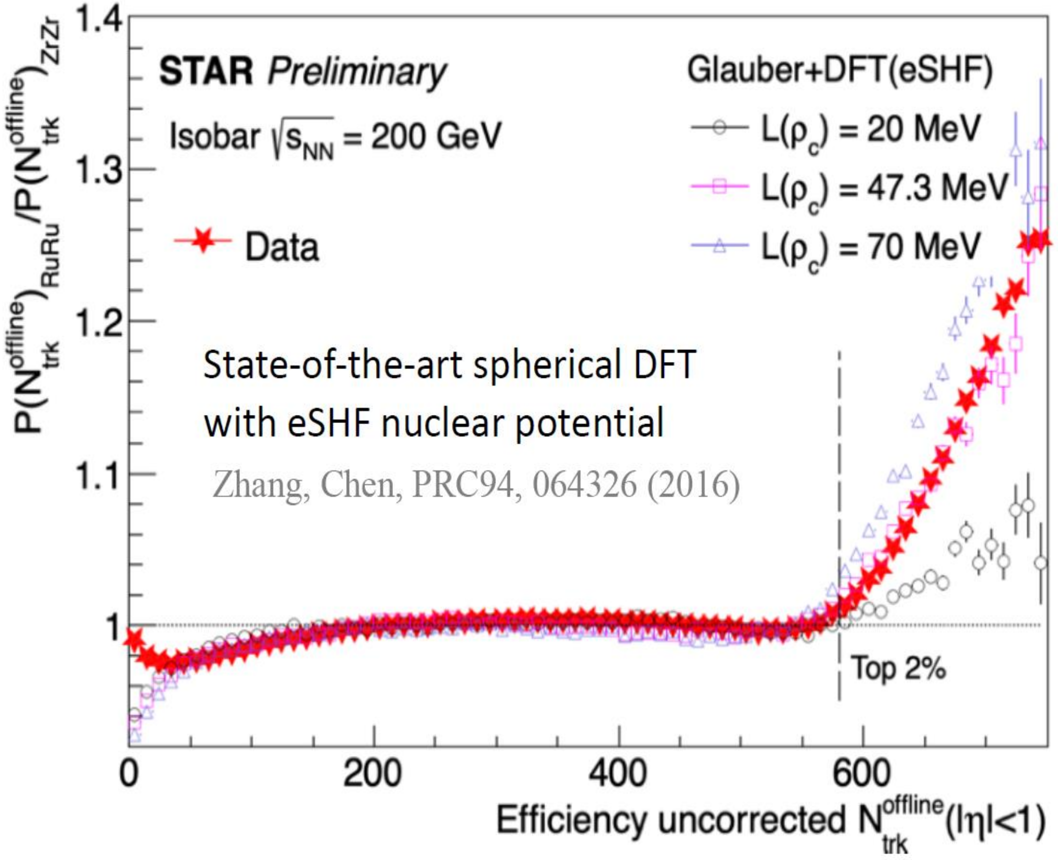
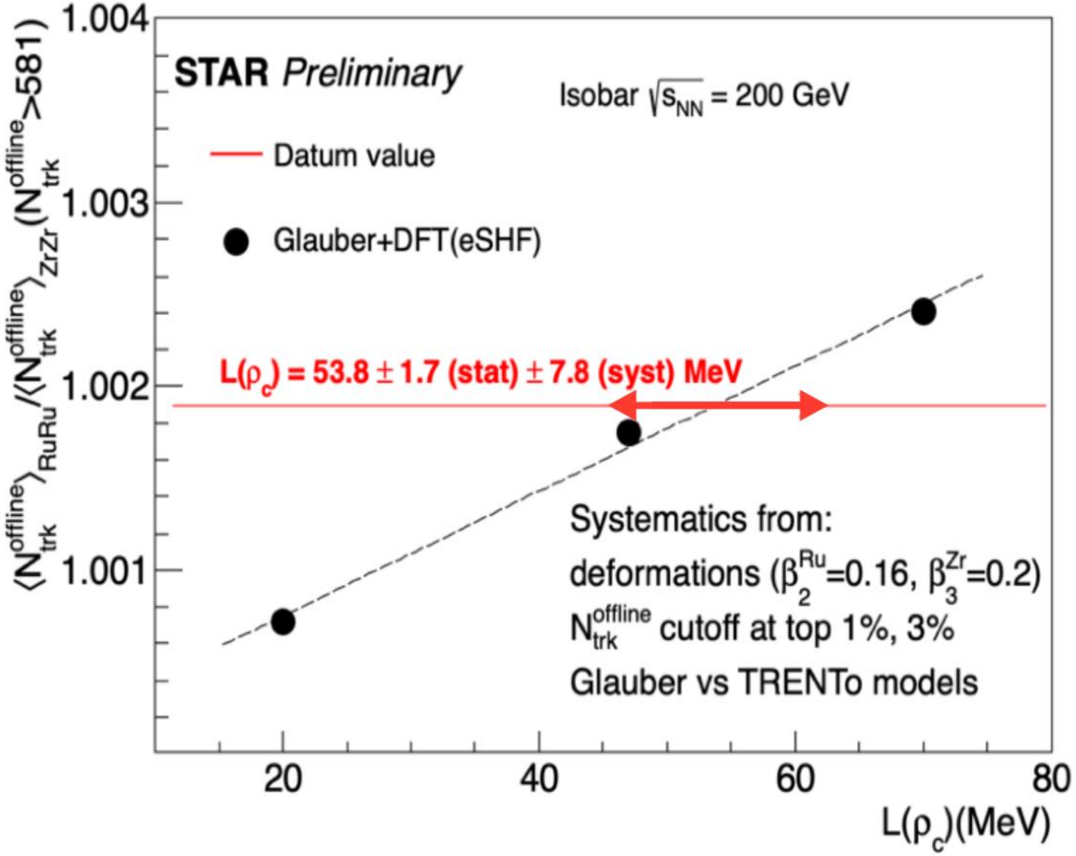


CENTRAL COLLISION MULTIPLICITY

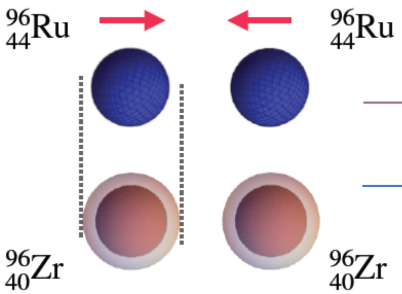
H. Li, H-j Xu et al, PRL 125 (2020) 222301
H-j Xu (STAR), 2208.06149, QM'2022





OTHER VARIABLES: <p_T>

H-j Xu et al, PRC 108 (2023) L011902



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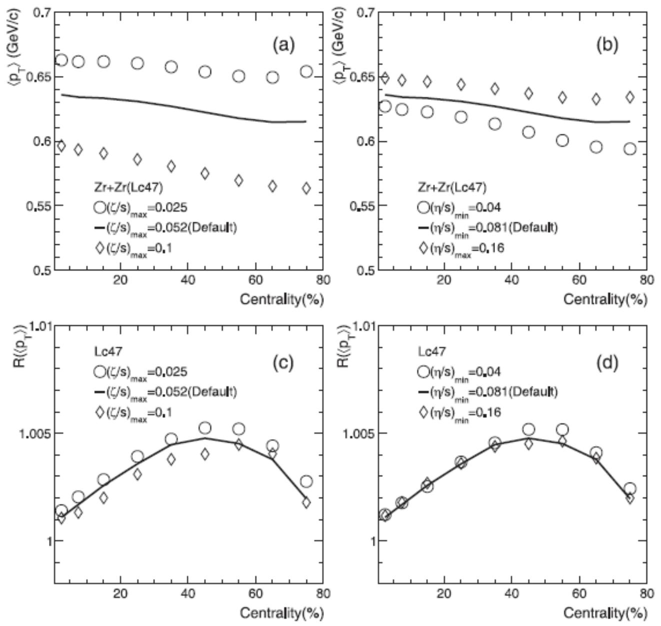
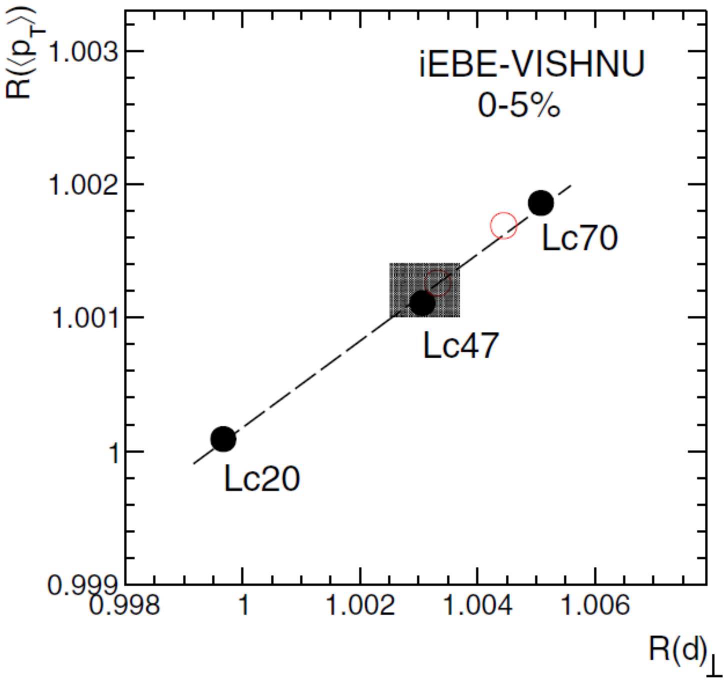
<p_T> ratio insensitive to model details





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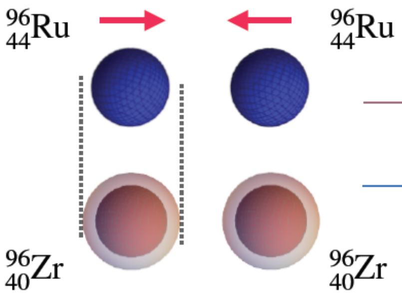
H-j Xu et al, PRC 108 (2023) L011902



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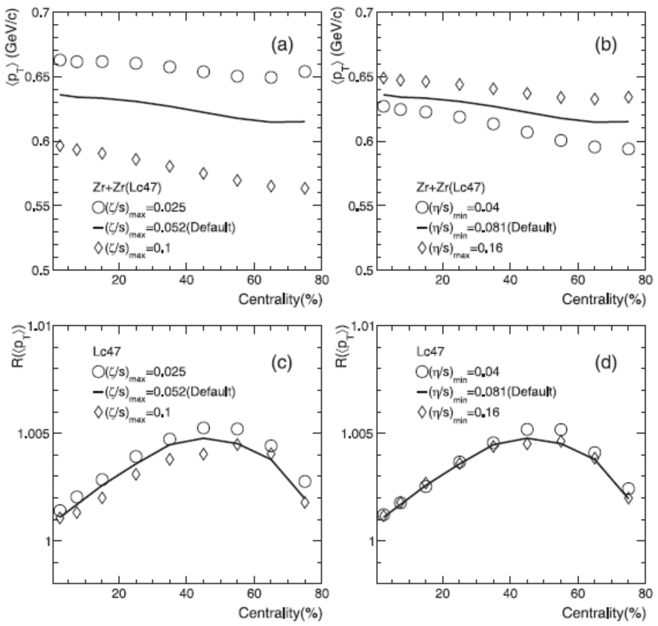
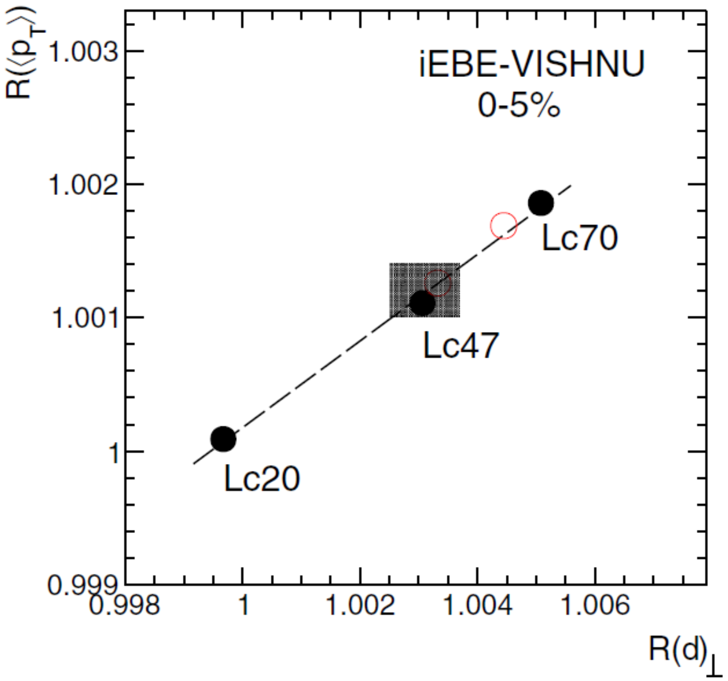
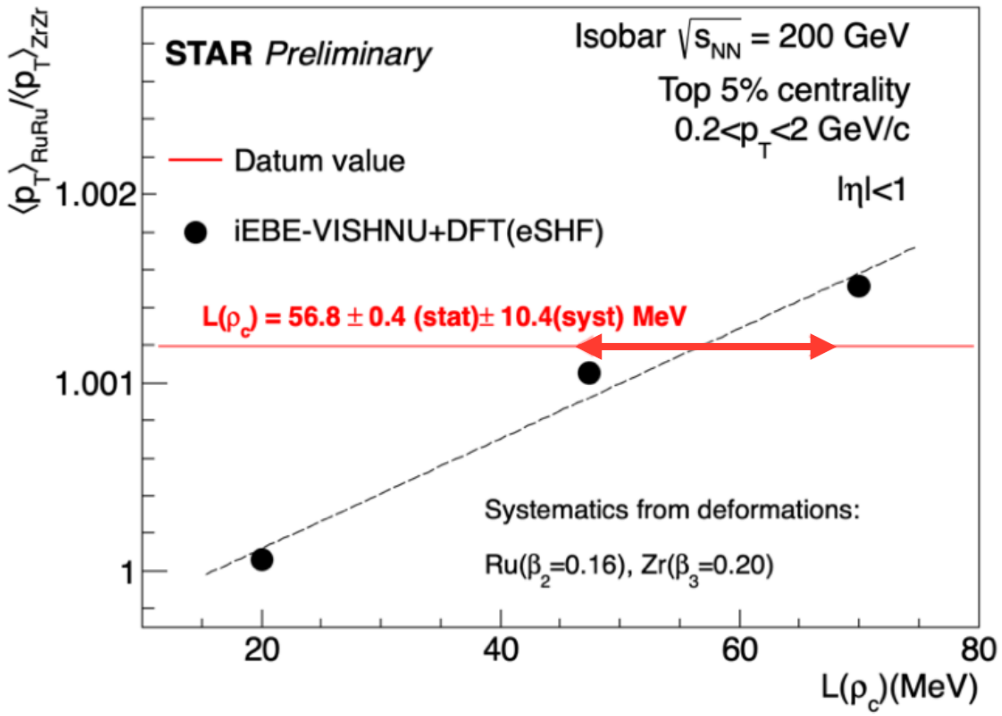
<p_T> ratio insensitive to model details

H-j Xu (STAR), 2208.06149, QM'2022



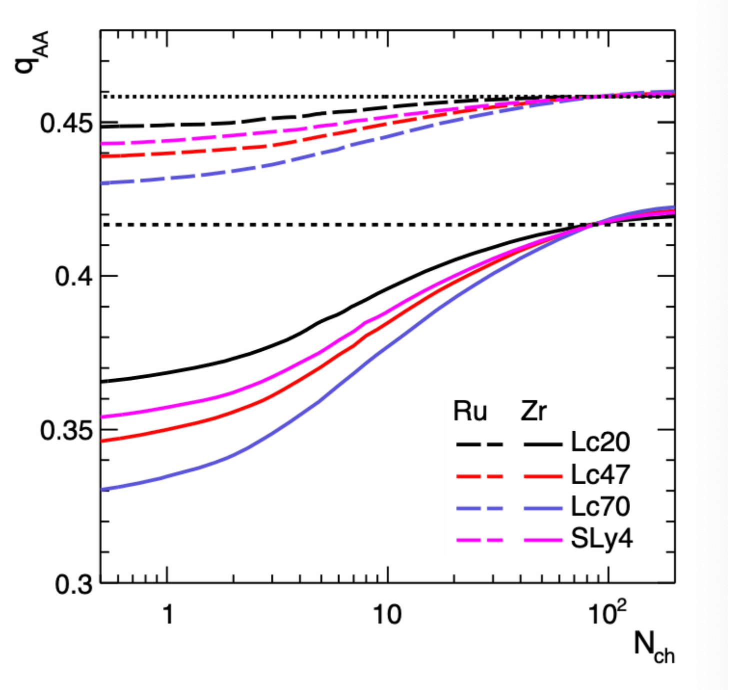


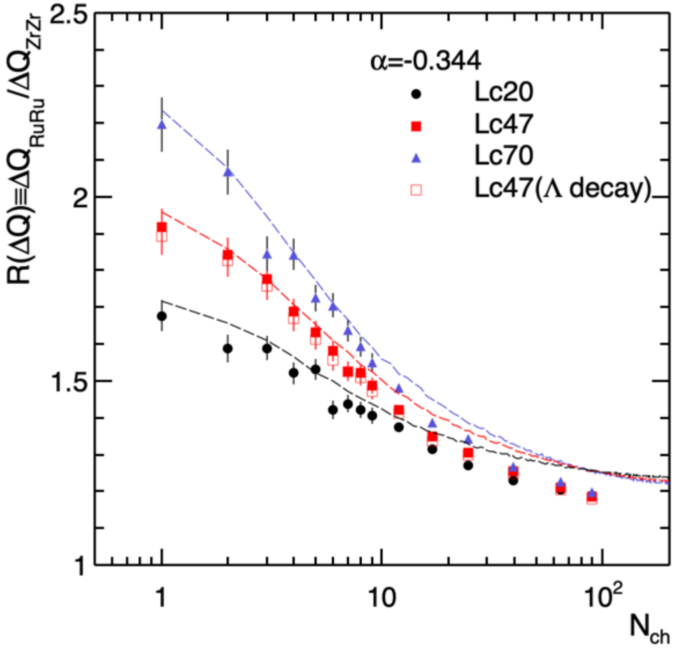


NET-CHARGE IN PERIPHERAL

H-j Xu et al, PRC 105 (2022) L011901

Grazing peripheral collisions directly sensitive to neutron skin





q_{AA} = fraction of protons participating in the collision
Fewer charge participants, smaller final-state net-charge

α = ΔQ ratio in nn to pp interaction

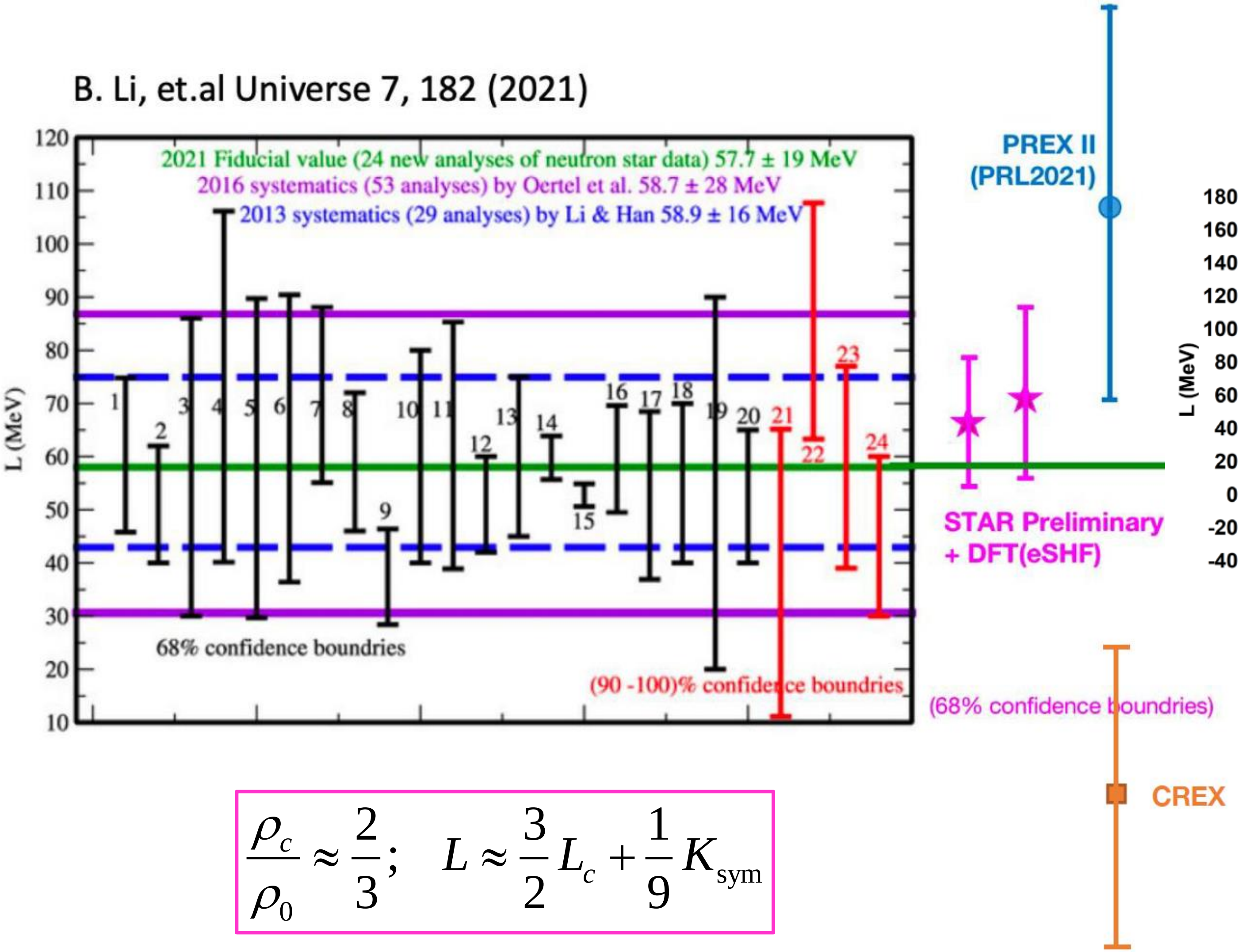
Curves: NN superimposition assumption

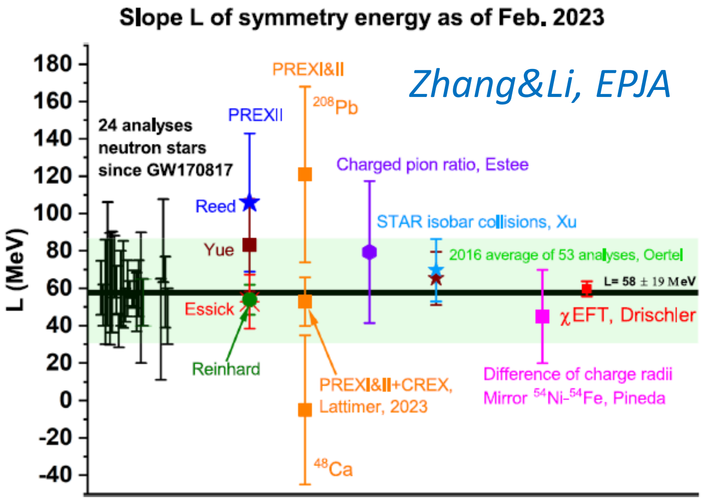
$$R(\Delta Q) = \frac{q_{RuRu} + \alpha/(1-\alpha)}{q_{ZrZr} + \alpha/(1-\alpha)}$$

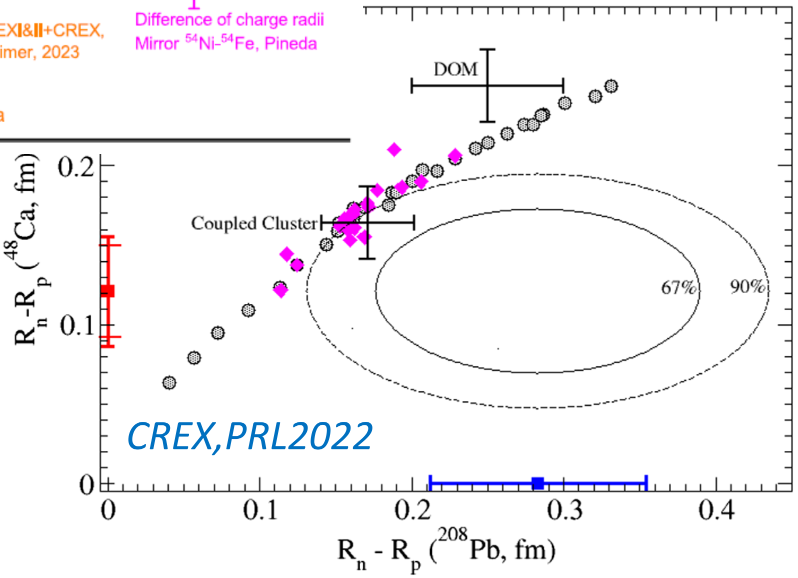
IN CONTEXT OF WORLD DATA

Adhikari et al (PREX), PRL 126 (2021) 172502
Reed et al, PRL 126 (2021) 172503
Adhikari et al (CREX), PRL 129 (2022) 042501
Tagami et al, PLB 43 (2022) 106037
Kumar et al, PRC 107 (2023) 055801
N-B Zhang & B-A Li, EPJA 59 (2023) 86
H-j Xu (STAR), 2208.06149, QM'2022

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





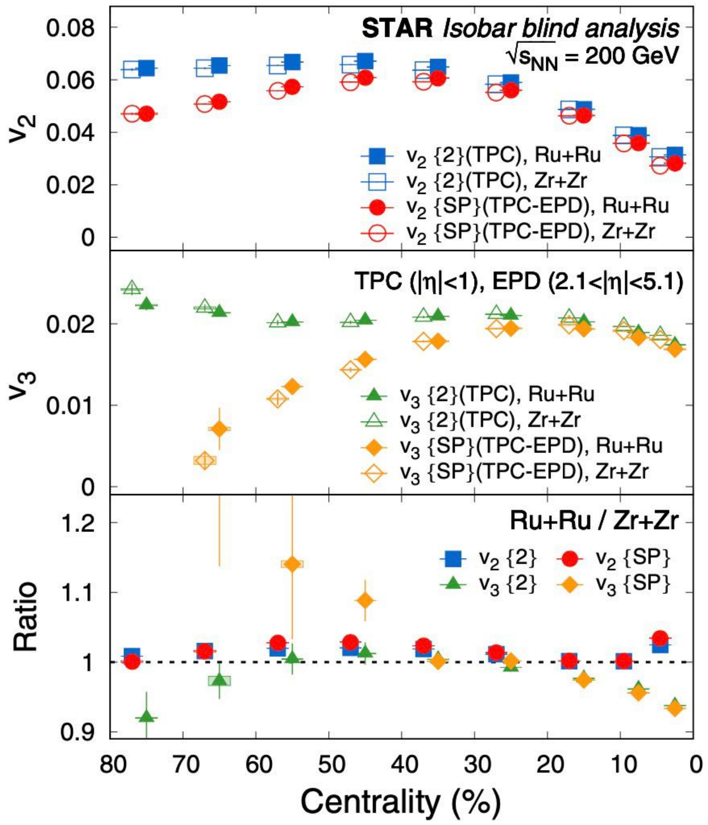


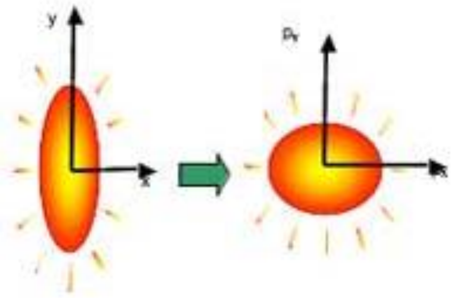
$$\frac{\rho_c}{\rho_0} \approx \frac{2}{3}; \quad L \approx \frac{3}{2} L_c + \frac{1}{9} K_{\mathrm{sym}}$$

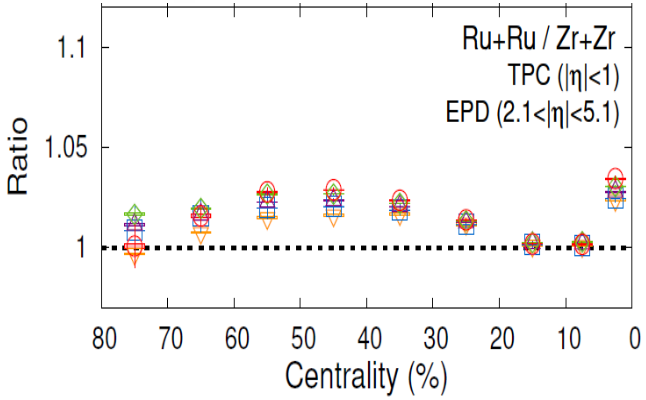
NUCLEAR SHAPES

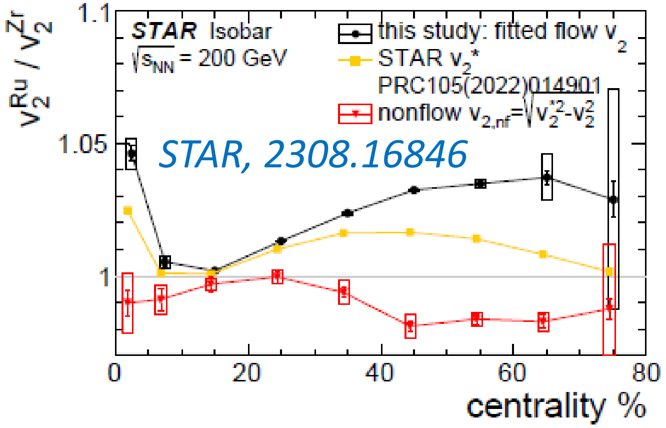
What physics can be extracted from nuclear shape?

STAR, PRC 105 (2022) 014901

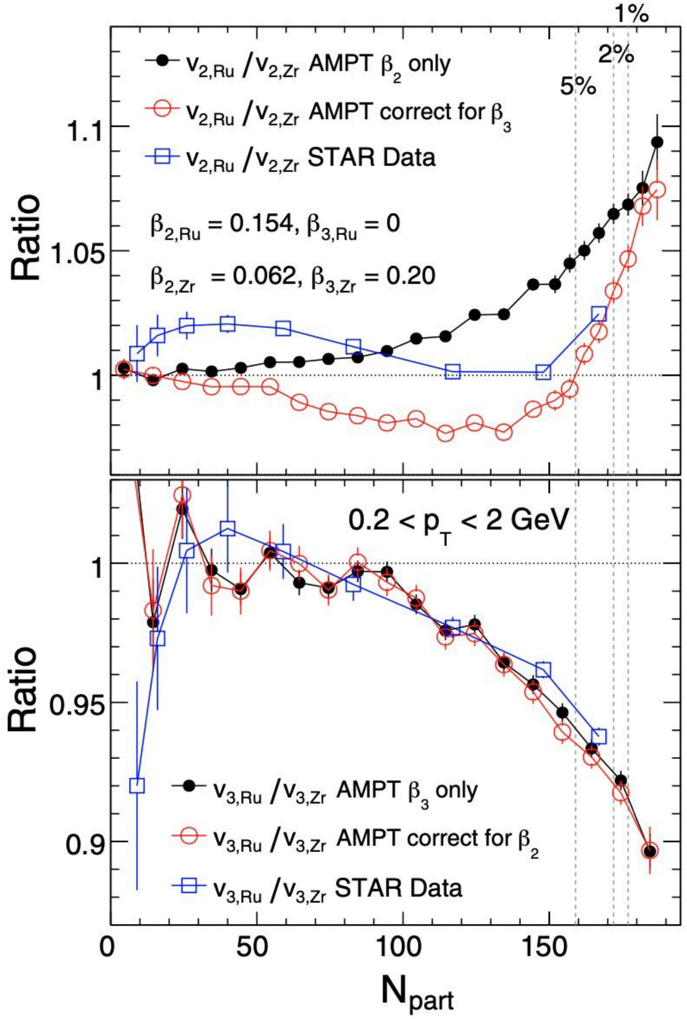


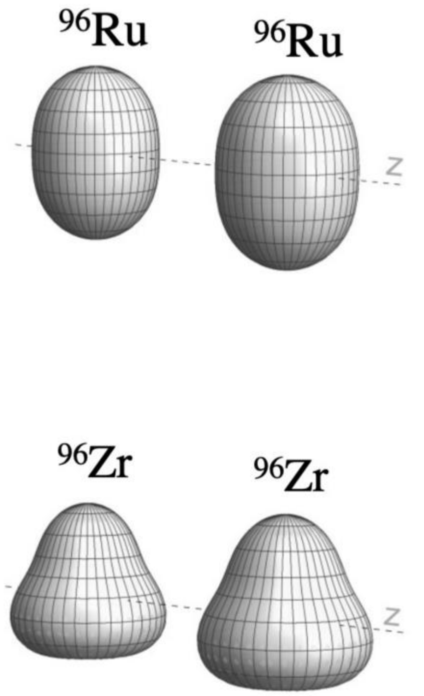






C. Zhang, J. Jia, PRL 128 (2022) 022301





SUMMARY

- Nuclear structure has effects on final-state particle production and distributions in heavy ion collisions at relativistic energies
- High precision isobar collision data are sensitive enough to provide information to nuclear structure and symmetry energy, valuable input with totally different systematics from conventional means
- The extracted symmetry energy density slope parameter is consistent with world data with comparable uncertainties.
- Final-state anisotropy measurements can probe nuclear shape and deformation, via hydrodynamic calculations bridging initial condition and final state.

Question: What physics can be extracted from nuclear shape / deformation?

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

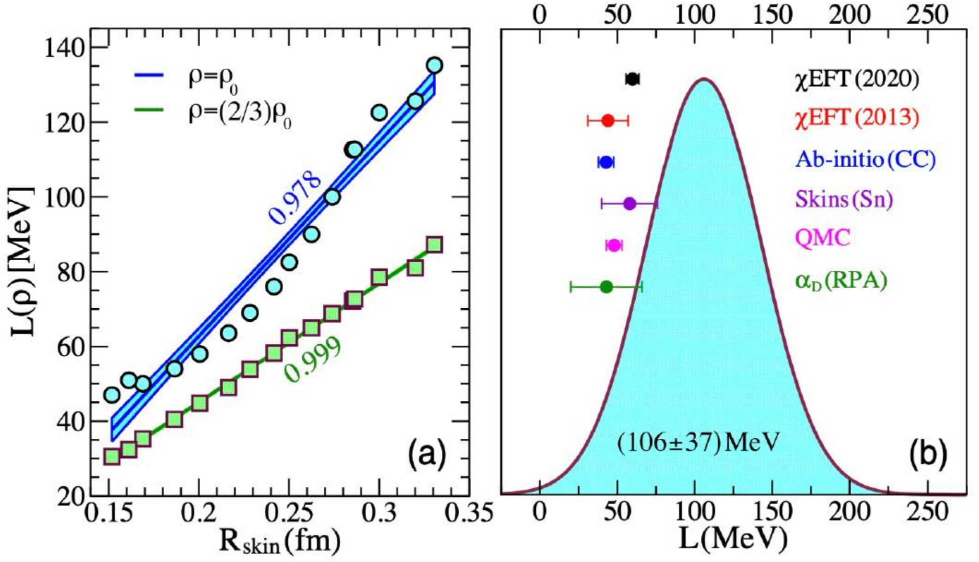
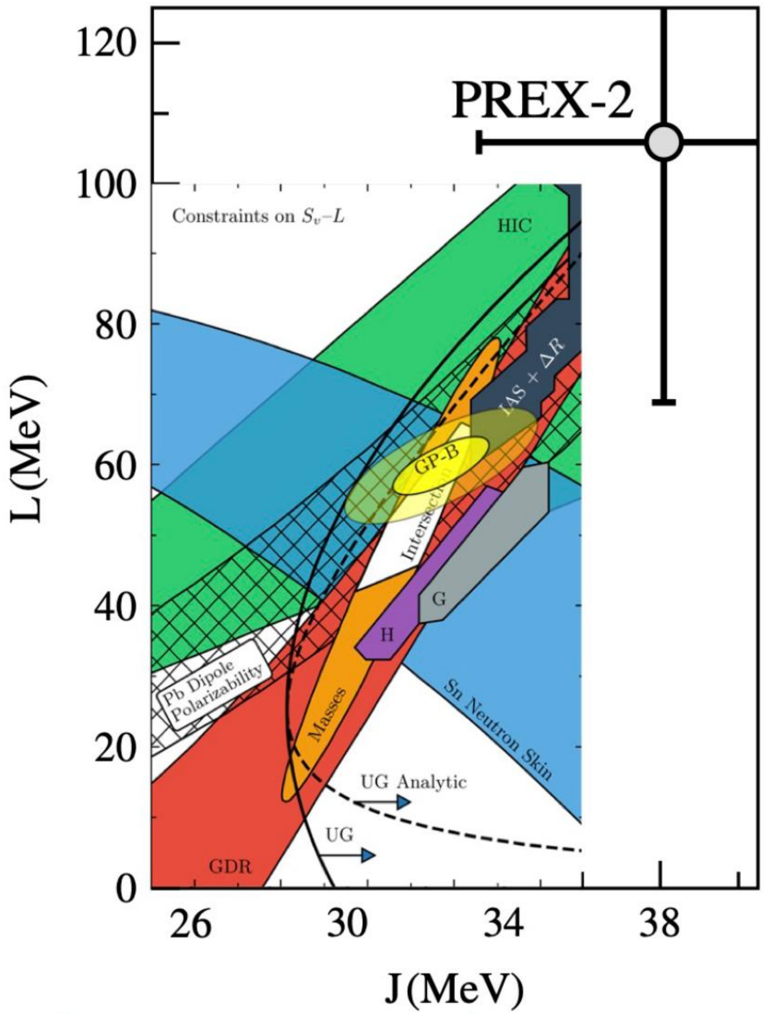


FIG. 1. Left: slope of the symmetry energy at nuclear saturation density ρ_0 (blue upper line) and at $(2/3)\rho_0$ (green lower line) as a function of $R_{\rm skin}^{208}$. The numbers next to the lines denote values for the correlation coefficients. Right: Gaussian probability distribution for the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



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

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

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

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

$$E_{\text{sym}}(\rho) \approx E_{\text{sym}}(\rho_0) + L(\rho_0)\chi + \frac{1}{2}K_{\text{sym}}(\rho_0)\chi^2; \quad \chi \equiv \frac{\rho-\rho_0}{3\rho_0}$$

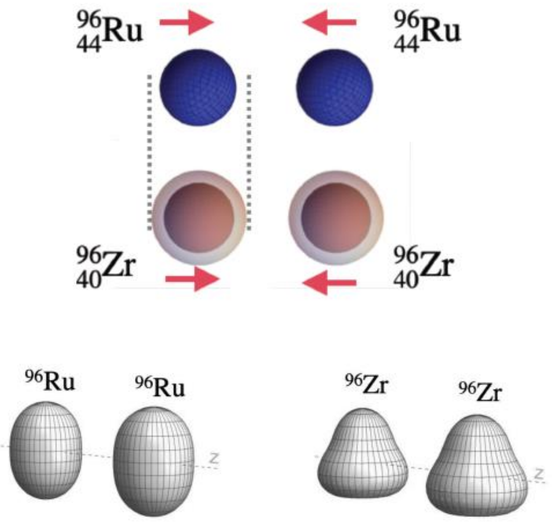
$$L(\rho_c) = 3\rho_c \left.\frac{\partial E_{\text{sym}}(\rho)}{\partial \rho}\right|_{\rho=\rho_c} = L(\rho_0)\left.\frac{\partial \chi}{\partial \rho}\right|_{\rho=\rho_c} + K_{\text{sym}}(\rho_0)\,\chi \left.\frac{\partial \chi}{\partial \rho}\right|_{\rho=\rho_c}$$

$$L_c = \left(L + K_{\text{sym}}\frac{\rho_c - \rho_0}{3\rho_0}\right)\frac{\rho_c}{\rho_0}; \quad L \equiv L(\rho_0), L_c \equiv L(\rho_c), K_{\text{sym}} \equiv K_{\text{sym}}(\rho_0)$$

$$L = \frac{\rho_0}{\rho_c}L_c - K_{\text{sym}}\frac{\rho_c - \rho_0}{3\rho_0}$$

$$\rho_c \approx 0.11\ \text{fm}^{-3} \approx 2\rho_0/3, \quad L \approx 3L_c/2 + K_{\text{sym}}/9$$

Incompressibility K_{sym} = –137 MeV



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