Fluctuations and correlations driven by the nuclear structure in relativistic heavy ion collisions

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Outline

I. Nuclear structure and relativistic isobar collisions

II. Probe the neutron skin thickness in relativistic isobar collisions

III. Impact of initial fluctuations on ratio observables

III. Summary

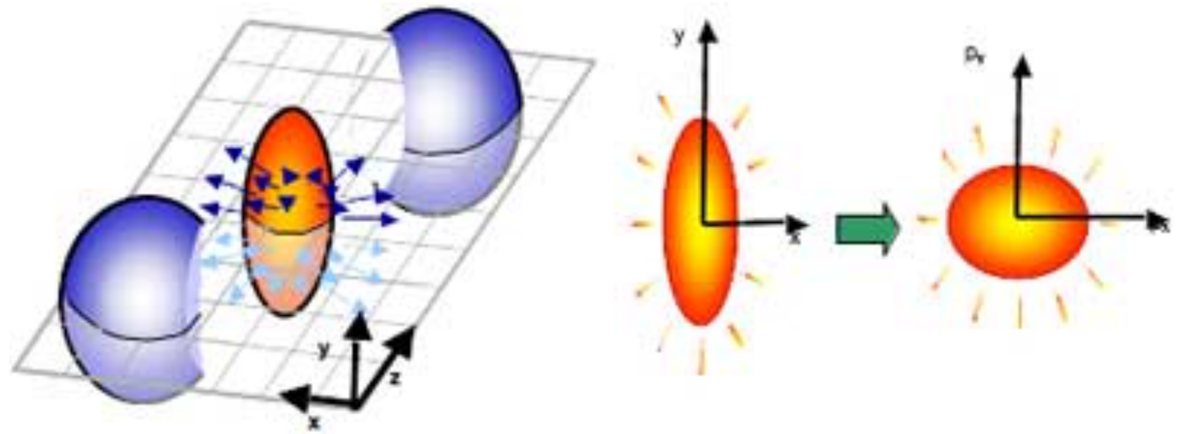
I. Nuclear structure and relativistic isobar collisions

Relativistic Heavy ion collisions

Woods-Saxon distributions

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

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

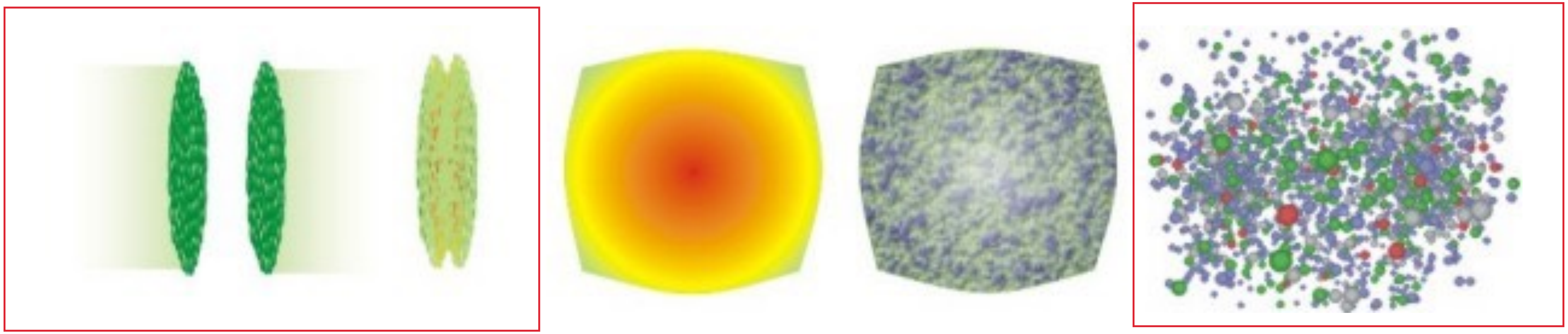


Anisotropic flow,
Flow fluctuations
HBT,
....

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

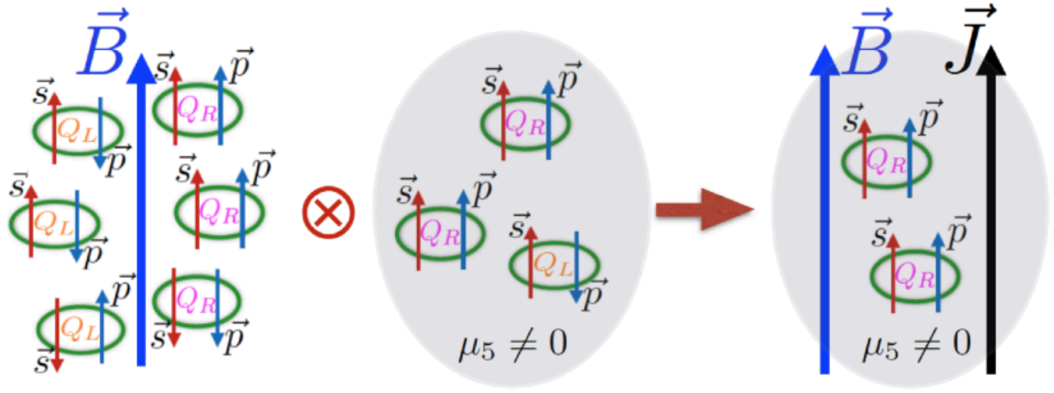
Initial geometry

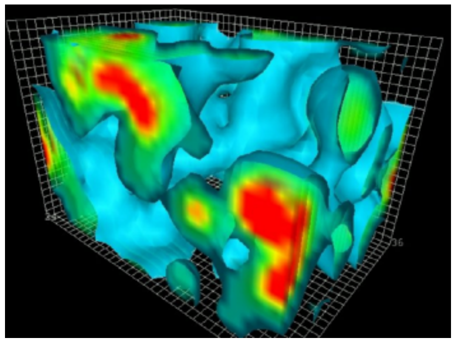
Final observables

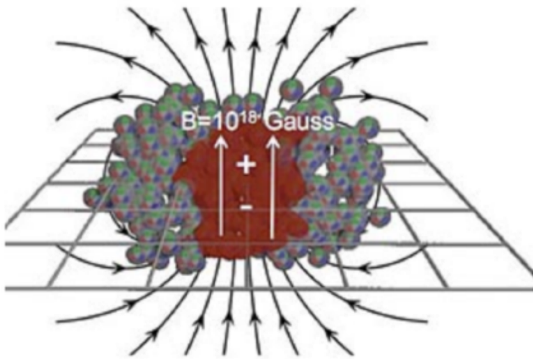


Relativistic isobaric collisions and chiral magnetic effect

Chiral magnetic effect (CME)





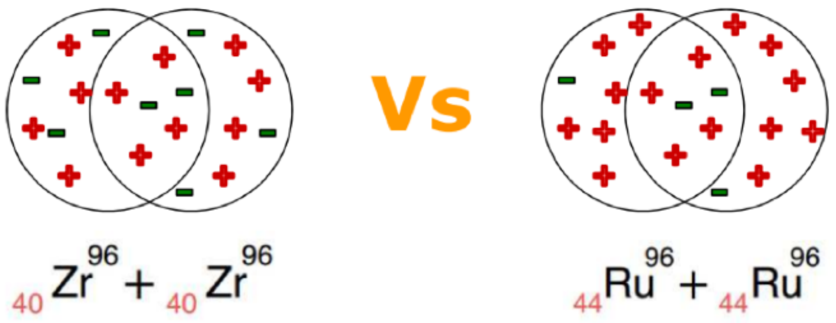


$$\mathbf{J}_{\mathbf{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B},$$

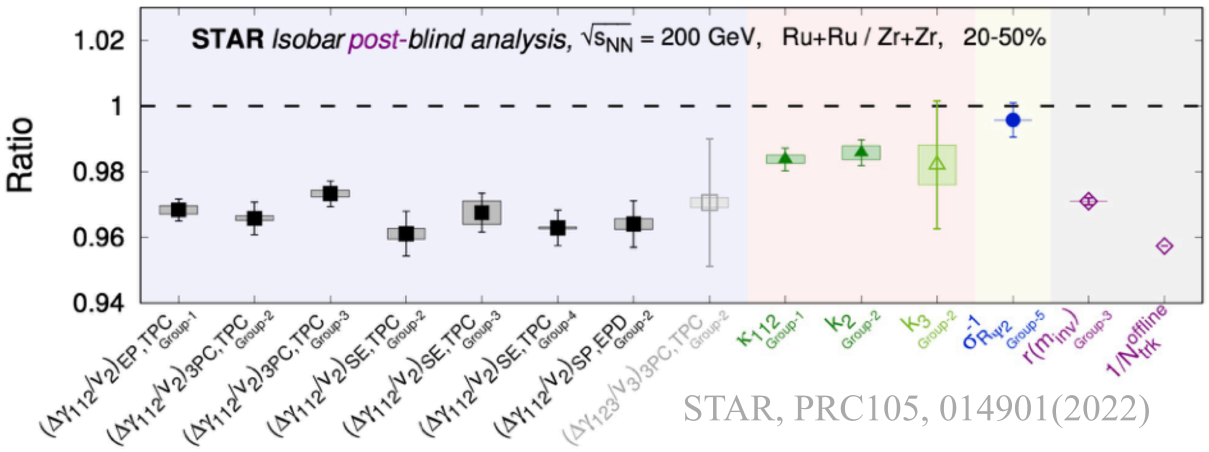
D. Kharzeev,et.al., PPNP88, 1(2016)

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!!!

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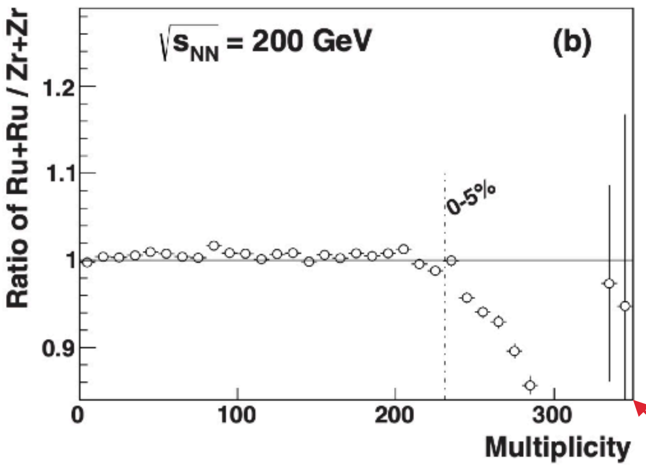
Predictions from charge density distributions

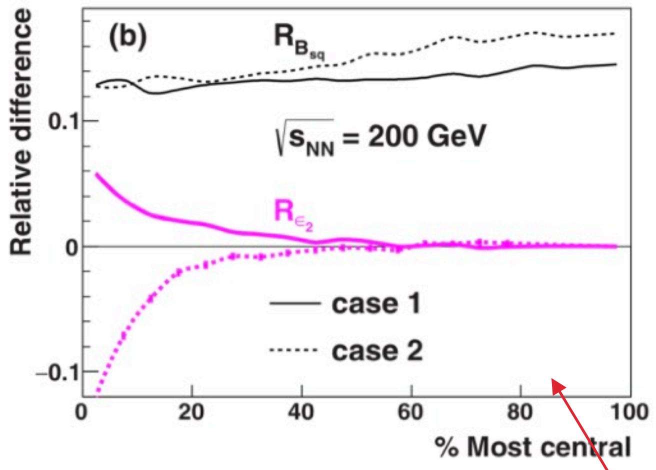
$$\rho = \frac{\rho_0}{1 + \exp\left[\frac{r - R}{a}\right]}$$

	R	a	beta2
Zr	5.02	0.46	0.08/0.217
Ru	5.085	0.46	0.158/0.053

WS parameters extracted from charge density distributions

W. Deng, X. Huang, et.al., PRC94,041901(2016)

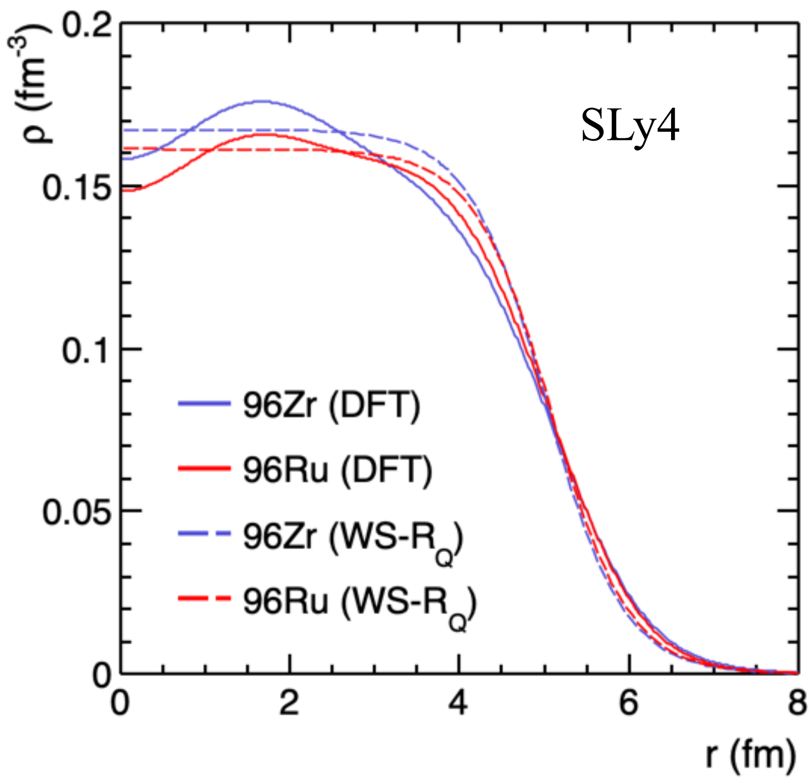




$$\Delta\gamma_{\text{bkg}} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle = \frac{N_{\text{cluster}}}{N_\alpha N_\beta} \times \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\text{cluster}}) \rangle \times v_{2,\text{cluster}}$$

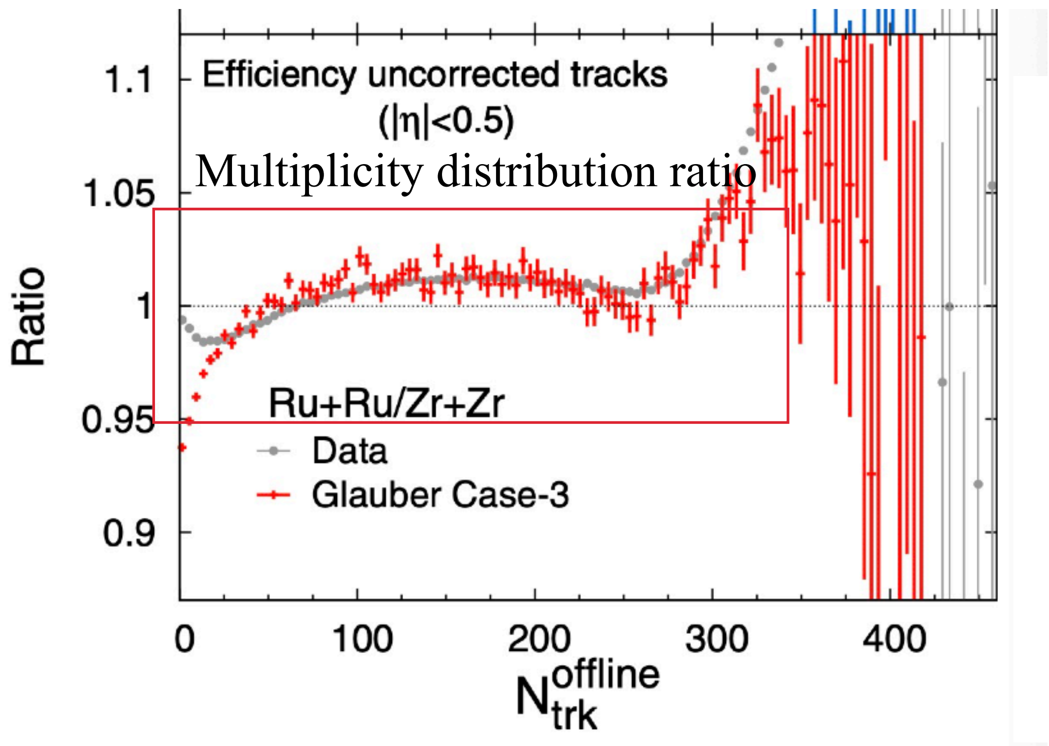
Nuclear structure calculation by DFT

- **Charge density ≠ nuclear density.**
- The proton and neutron densities obtained from the energy density functional theory (DFT)

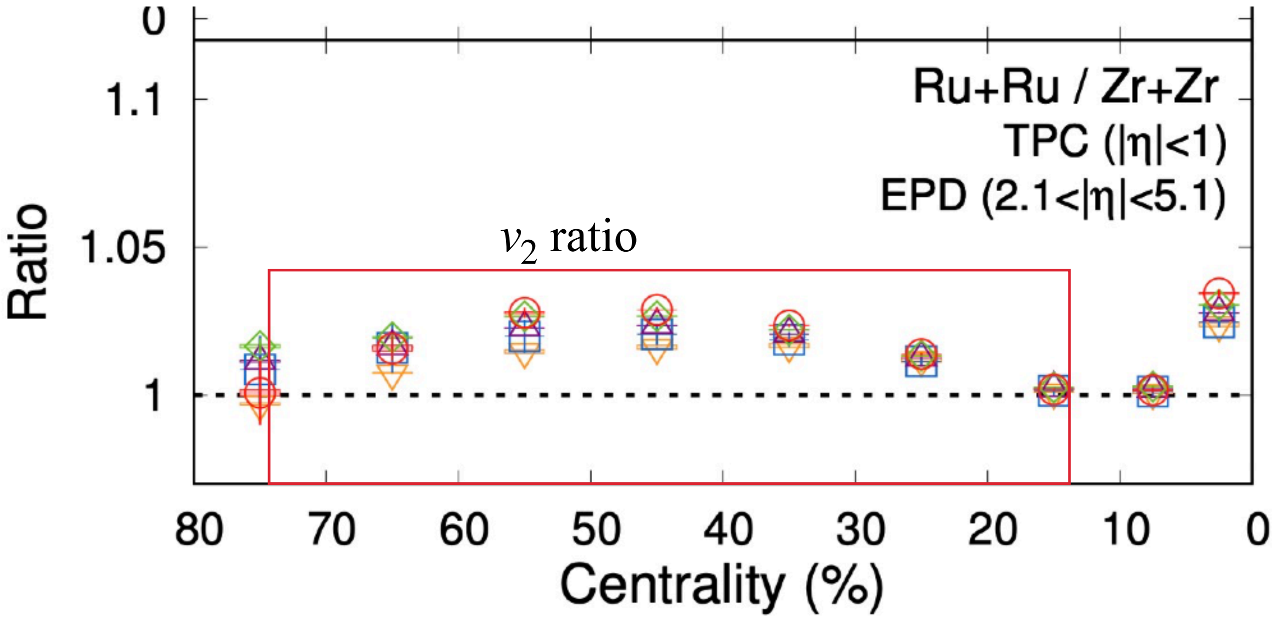


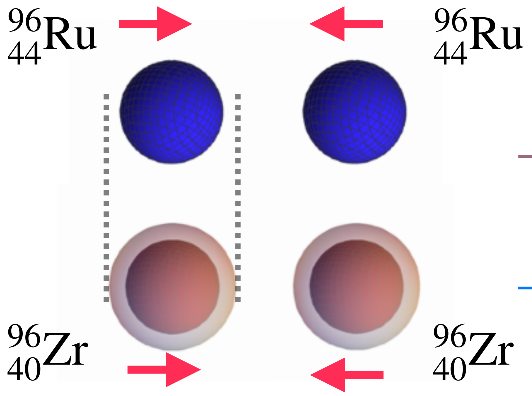
HJX, et.al., PRL121, 022301 (2018)
H. Li, HJX, et.al., PRC98, 054907(2018)

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 $\langle p_T \rangle$

HJX, et.al., PRL121, 022301 (2018)
H. Li, HJX, et.al., PRC98, 054907 (2018)
HJX, et.al., PLB819, 136453 (2021)

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II. Probe neutron skin thickness and nuclear symmetry energy using isobar collisions

Neutron skin: sensitive probe of symmetry energy

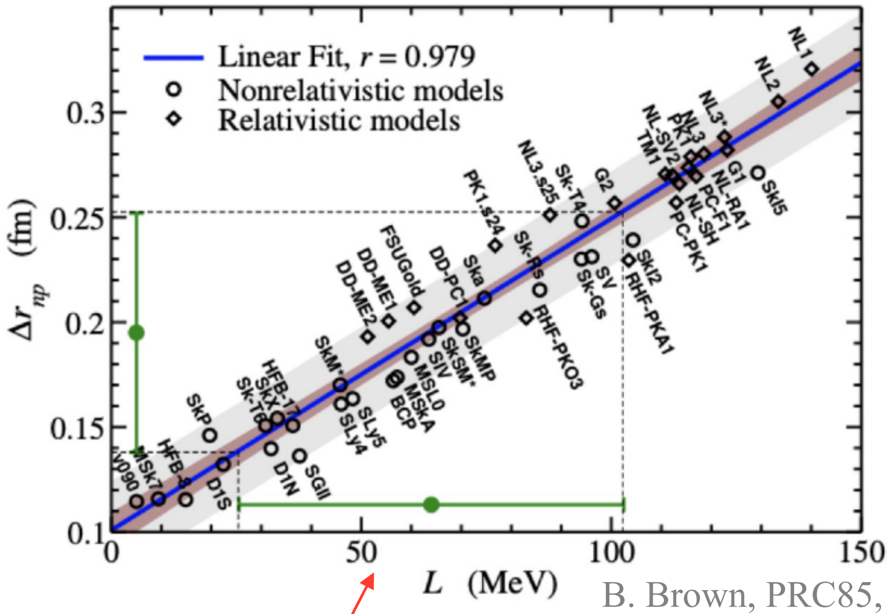
$^{96}_{40}\mathrm{Zr}:(N-Z)/A=0.167$

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

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

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.

Neutron skin and nuclear symmetry energy

Z. Zhang, PRC94, 064326(2016)
H. Li, HJX, et.al., PRL125, 222301(2020)

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

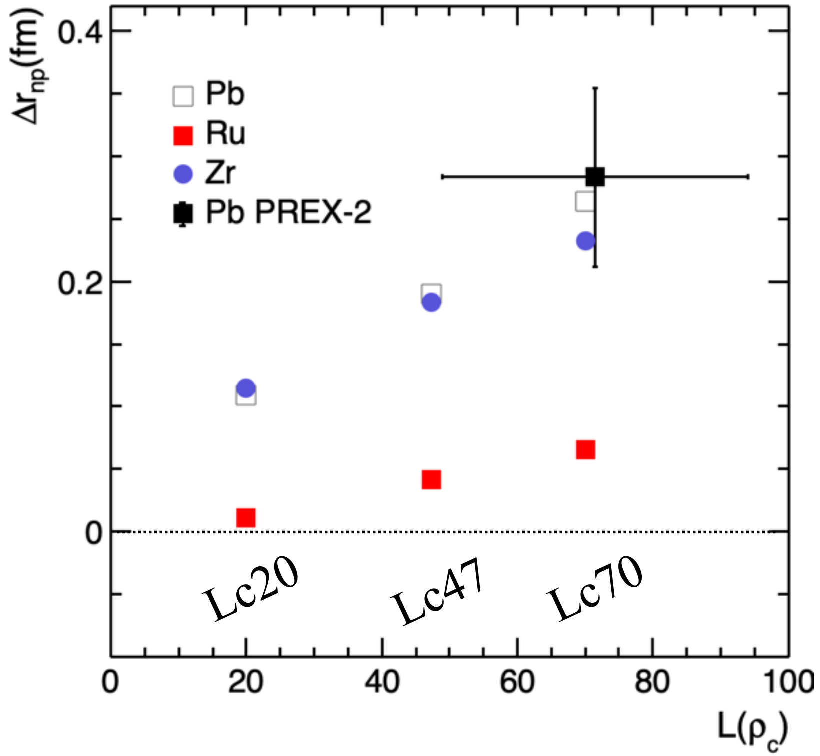
$$\begin{aligned} v_{i,j} &= t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}) + \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha(\boldsymbol{R})\delta(\boldsymbol{r}) \\ &+ \frac{1}{2}t_1(1+x_1P_\sigma)[K'^2\delta(\boldsymbol{r})+\delta(\boldsymbol{r})K^2] \\ &+ t_2(1+x_2P_\sigma)\boldsymbol{K}'\cdot\delta(\boldsymbol{r})\boldsymbol{K}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

Extended

$$E(\rho,\delta) = E_0(\rho) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

$$\rho = \rho_n + \rho_p;\ \delta = \frac{\rho_n - \rho_p}{\rho}$$

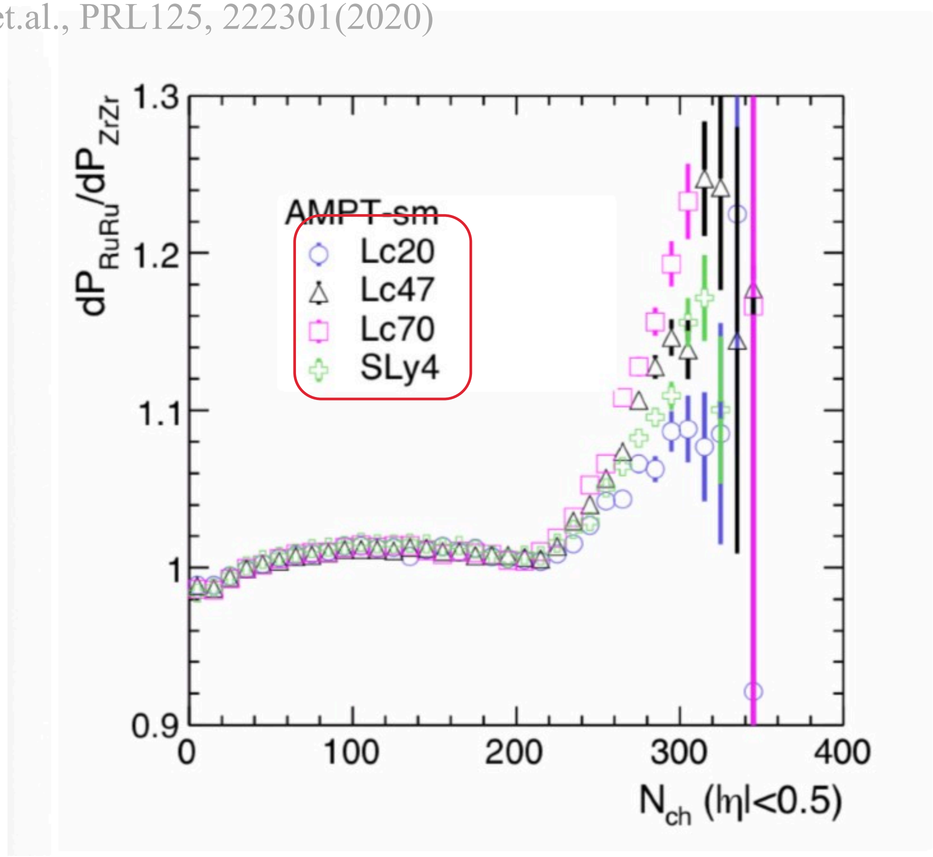
$$L(\rho_c) = 3\rho_c\left[\frac{dE_{sym}(\rho)}{d\rho}\right]_{\rho=\rho_c};\ \rho_c \simeq 0.11\mathrm{fm}^{-3}$$

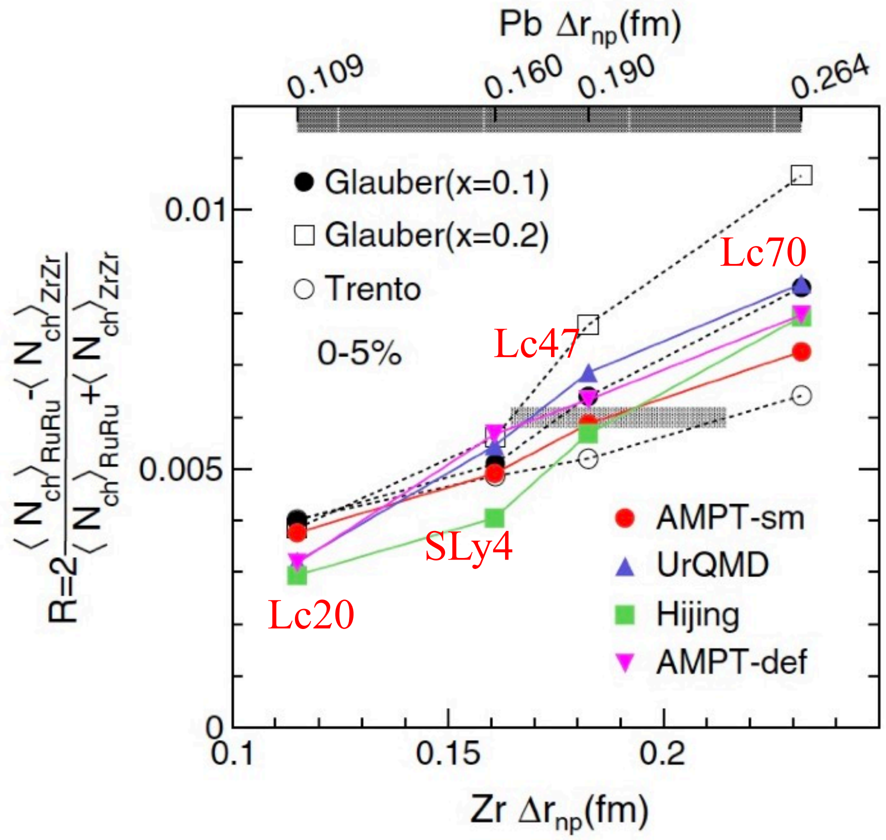


	$L(\rho_c)$	$L(\rho_0)$	^{96}Zr r_n	^{96}Zr r_p	^{96}Zr Δr_{np}	^{96}Ru r_n	^{96}Ru r_p	^{96}Ru Δr_{np}	^{208}Pb Δr_{np}
Lc20	20	13.1	4.386	4.27	0.115	4.327	4.316	0.011	0.109
Lc47	47.3	55.7	4.449	4.267	0.183	4.360	4.319	0.042	0.190
Lc70	70	90.0	4.494	4.262	0.232	4.385	4.32	0.066	0.264
SLy4	42.7	46.0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

Method I: multiplicity distribution ratio

H. Li, HJX, et.al., PRL125, 222301(2020)

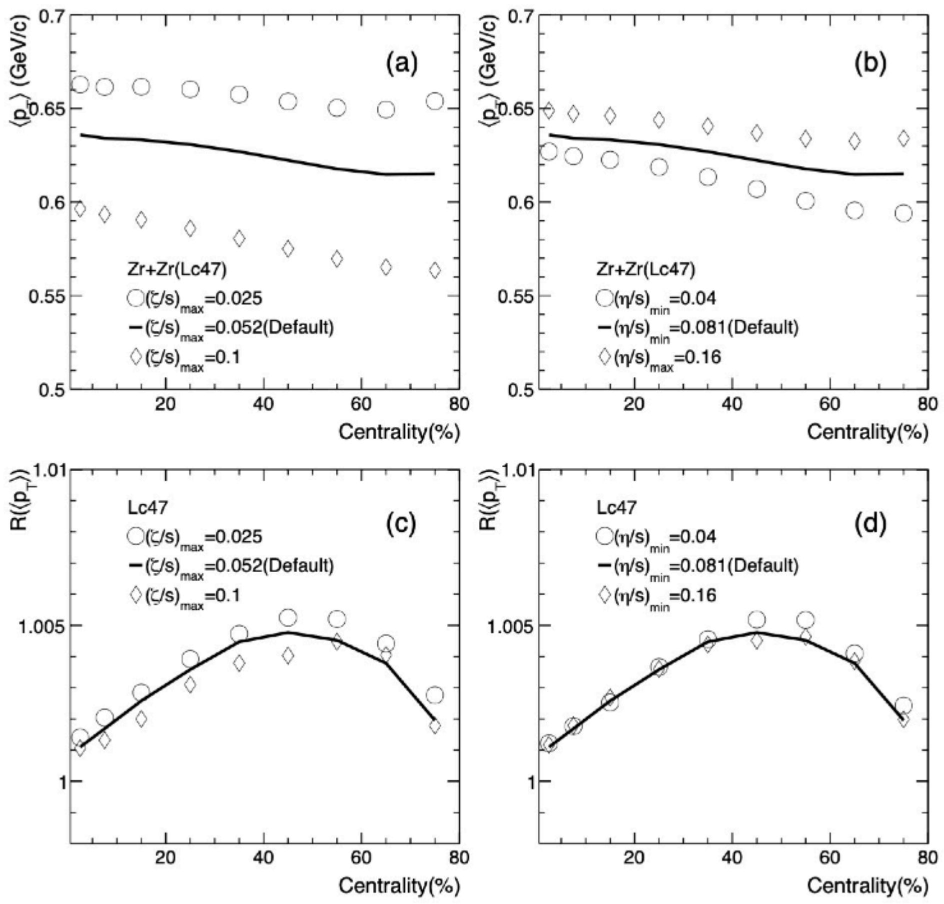




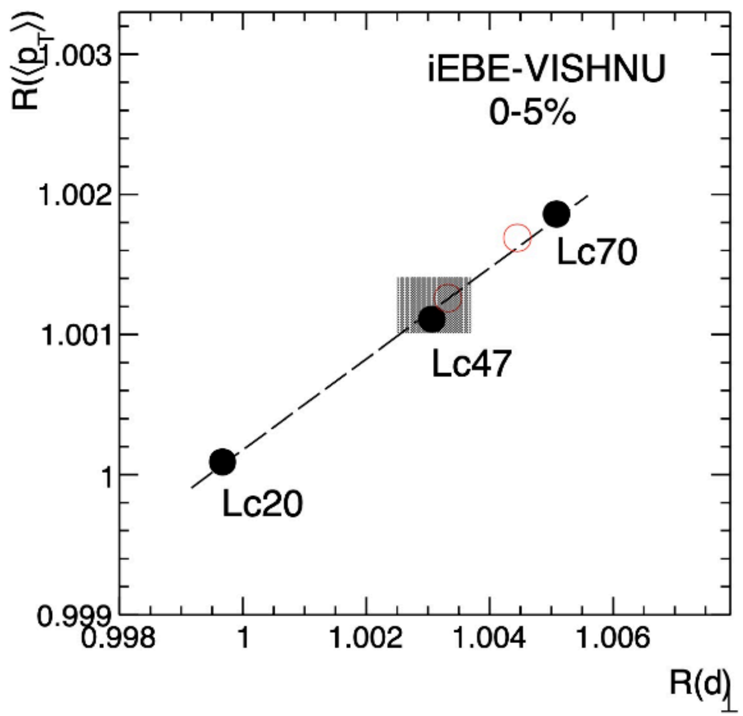
- The ratio of N_{ch} distributions highlight the differences
- To quantify the differences, we use the R observable of N_{ch} at top 5% centrality.
- R is a relative measure, **much of experimental effects cancel**

Method II: mean p_T ratio

HJX, et.al, arXiv:2111.14812



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



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

STAR measurements

Compare to world wide data

HJX(STAR)[18], QM2022

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:

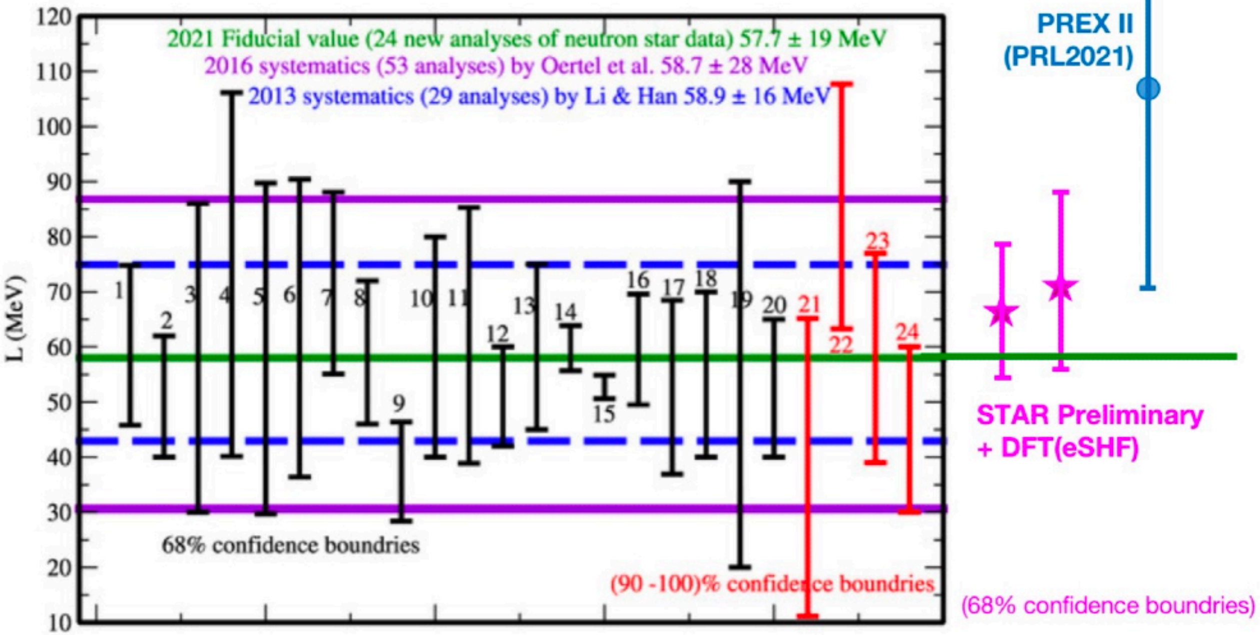
  $L(\rho_c) = 56.8 \pm 0.4 \pm 10.4$ MeV

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

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α is the ΔQ ratio in nn to pp interaction:

Pytha: $\alpha = -0.352$

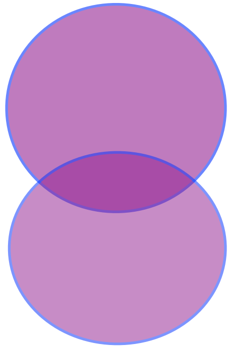
Hijing: $\alpha = -0.389$

UrQMD: $\alpha = -0.344$

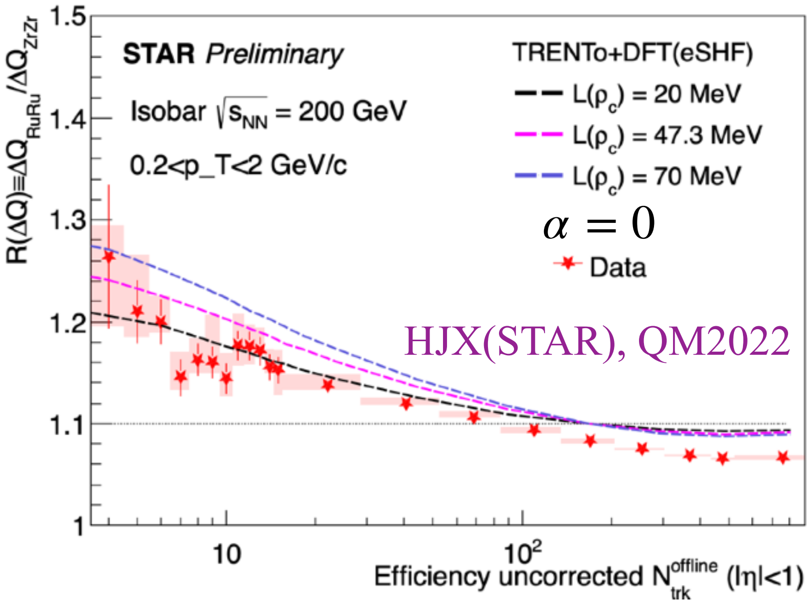
Method III: net-charge ratio in very peripheral collisions

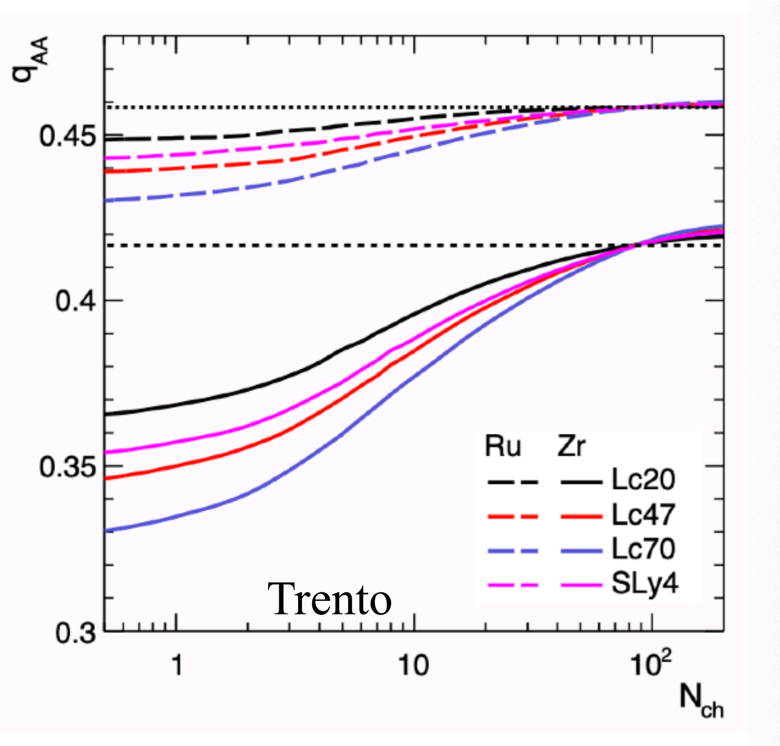
HJX, et.al., PRC105, L011901 (2022)

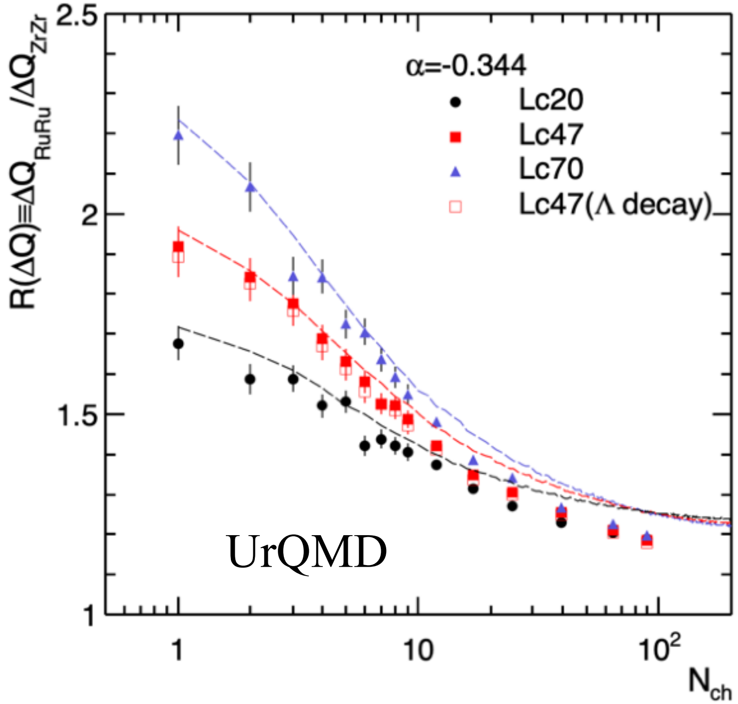
For the colliding nuclei with large neutron skin thickness



more n+n collisions at most peripheral collisions; Less participant charges, thus less final net-charges







The curves are calculated by superimposition assumption

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

where $q_{RuRu/ZrZr}$ are the fraction of protons among the participant nucleons, obtained by the Trento model.

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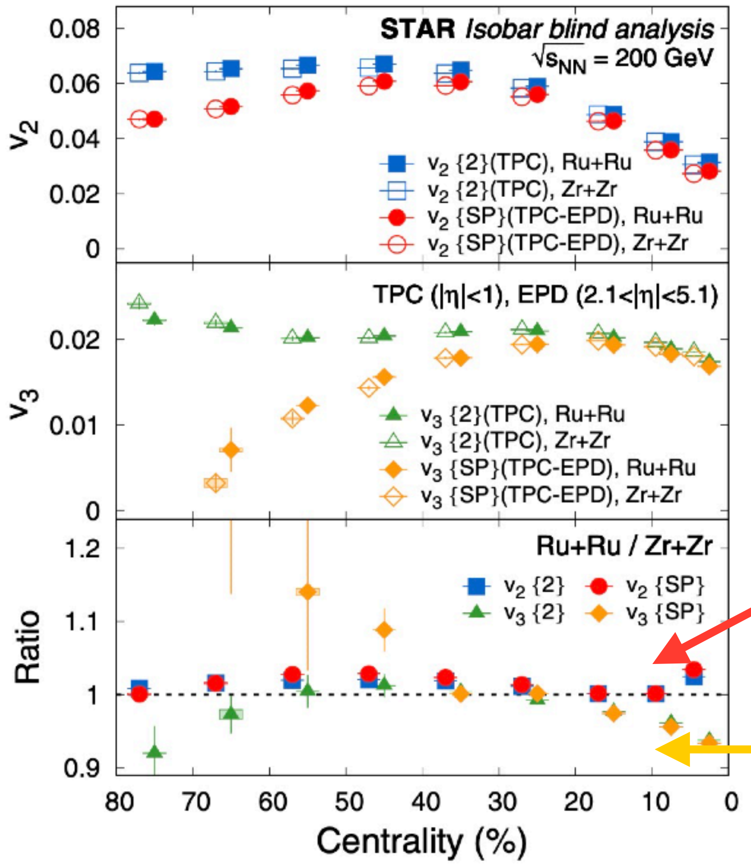
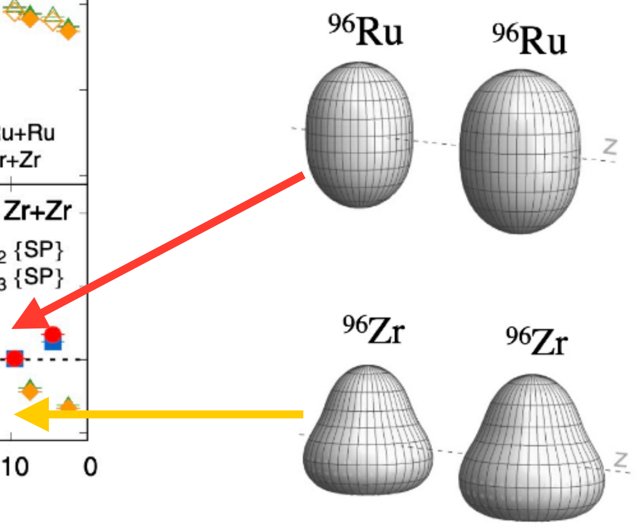
Nuclear deformation

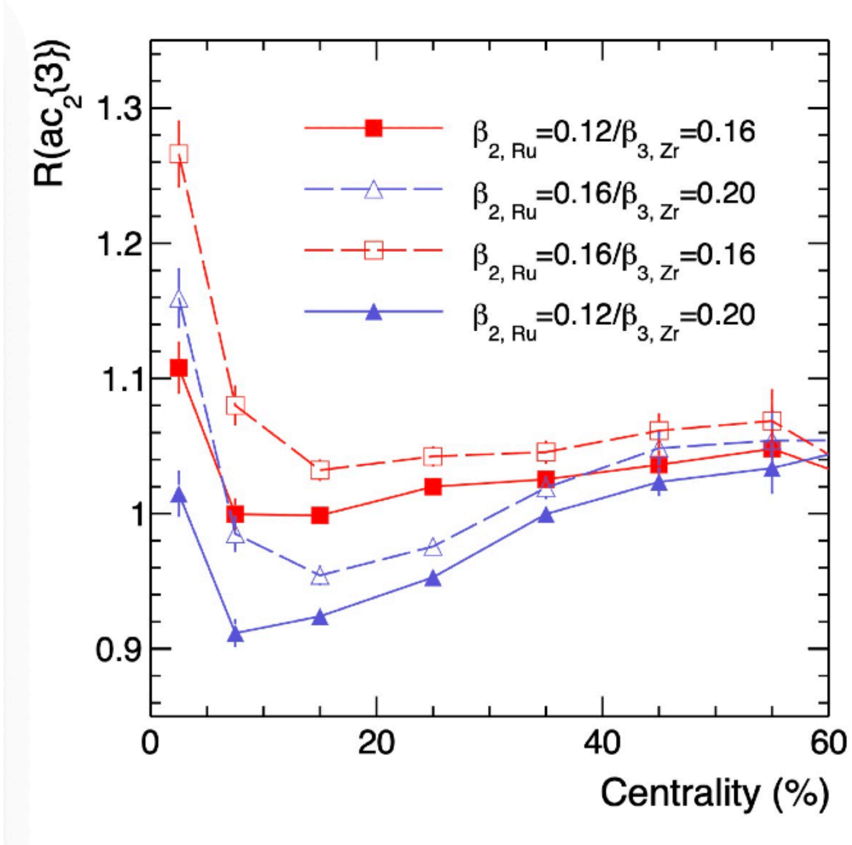
STAR, PRC105, 014901 (2022)
C. Zhang, J. Jia, PRL128, 022301(2022)





S. Zhao, HJX, et.al, PLB839, 137838 (2023)

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



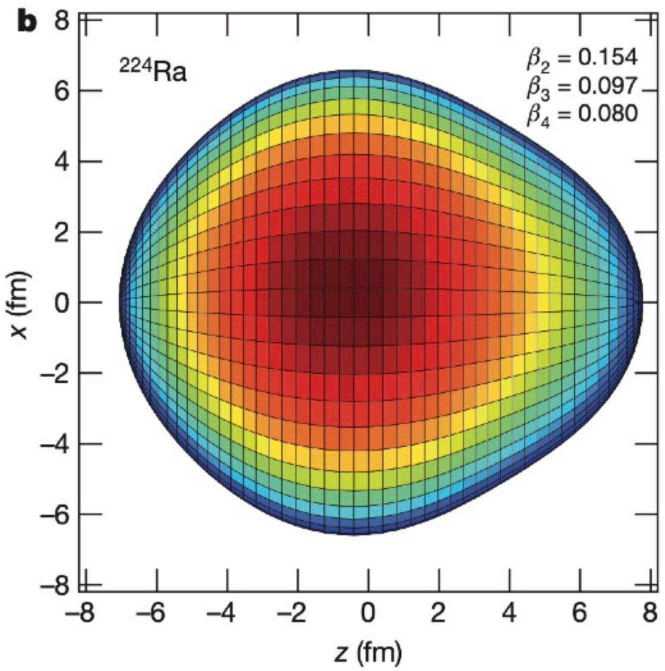
Sizable v_2 and v_3 ratios in central collisions indicate
shape difference between isobars

III. Impact of initial fluctuations on ratio observables in relativistic isobar collisions

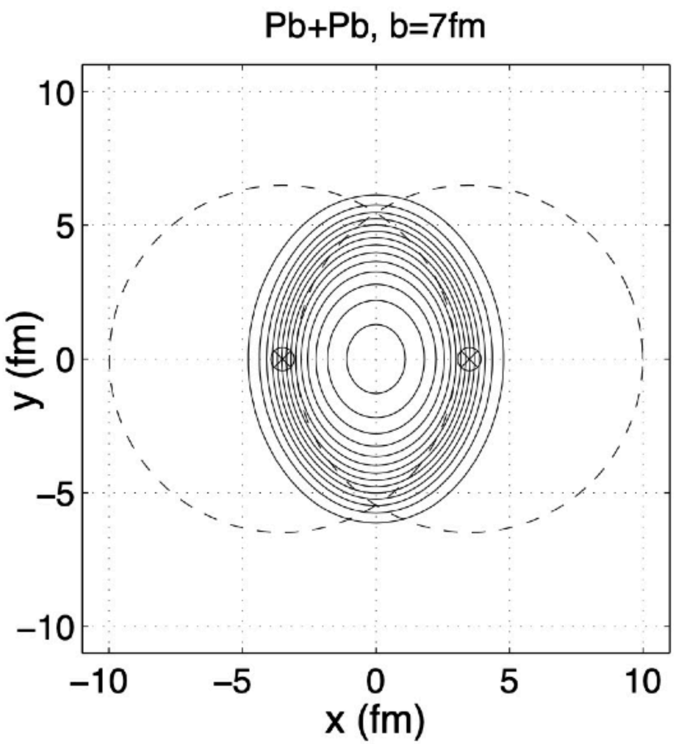
J. Wang, HJX, et.al, arXiv:2305.xxxxx

Nuclear structure and event-by-event fluctuations

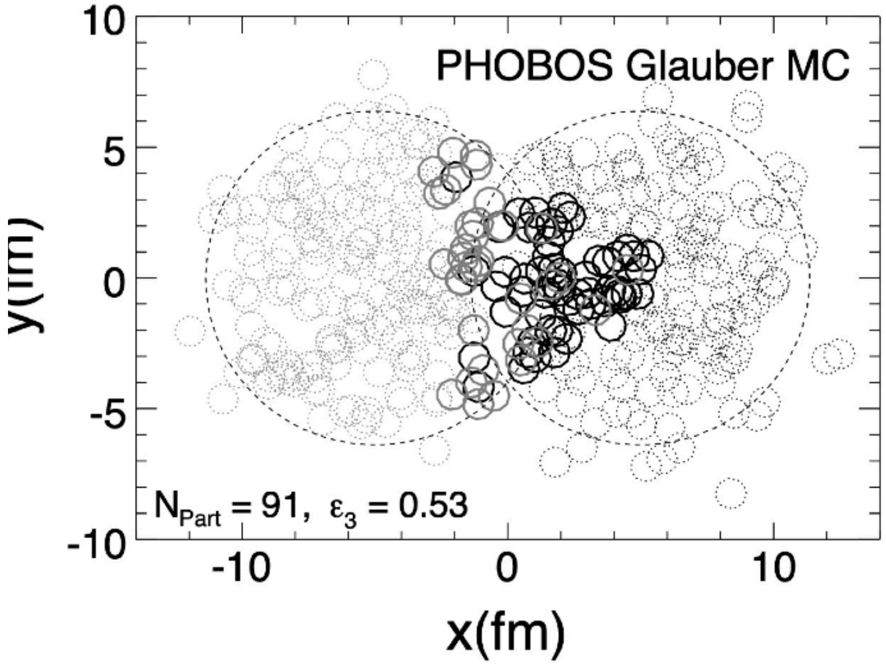
L. Gaffney, et.a l, Nature, 497, 199-204 (2013)



P. Kolb, J. Sollfrank, U. Heinz, PRC



B. Alver, G. Roland, PRC81, 054905 (2010)



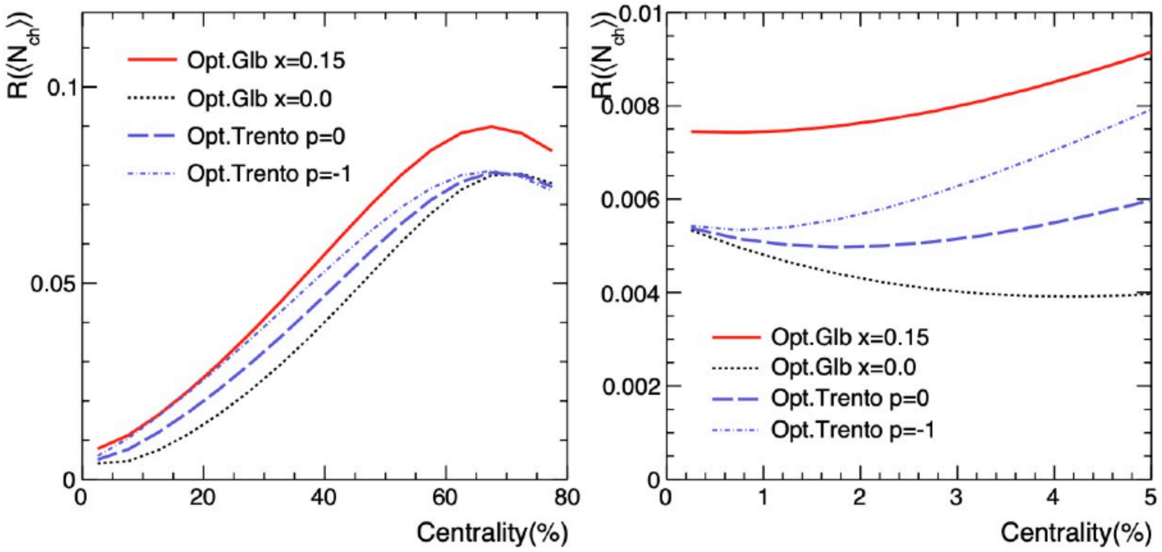
Event-by-event fluctuation are crucial for the anisotropic flow observables, especially for the triangular flow v_3

Multiplicity differences and particle production mechanism

Two-component models $N_{ch} = n_{pp}[(1-x)N_{part}/2 + xN_{coll}]$, $x = 0$

$N_{ch} \propto N_{part}$

Trento model $N_{ch} \propto \int s(r_\perp) d^2 r_\perp \propto \int \left(\frac{T_A^p(r_\perp) + T_B^p(r_\perp)}{2} \right)^{1/p} d^2 r_\perp$ $p = 1$



$$R(X) \equiv 2\frac{X_{RuRu} - X_{ZrZr}}{X_{RuRu} + X_{ZrZr}}.$$

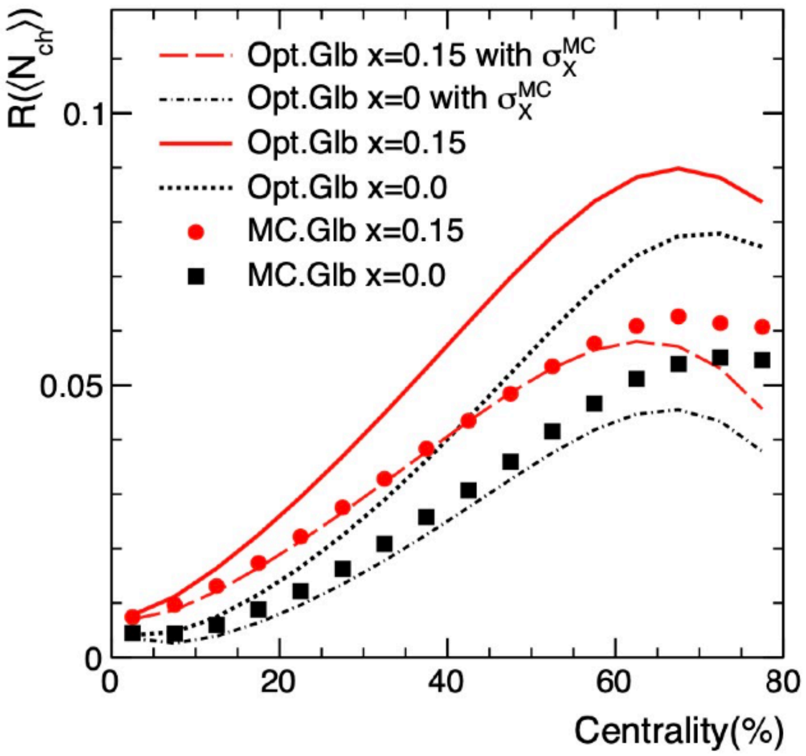
- $R(\langle N_{ch}\rangle)$ distributions depend on model parameters x and p.
- Under Trento scenario, $R(\langle N_{ch}\rangle)$ is independent of p at most central collisions.

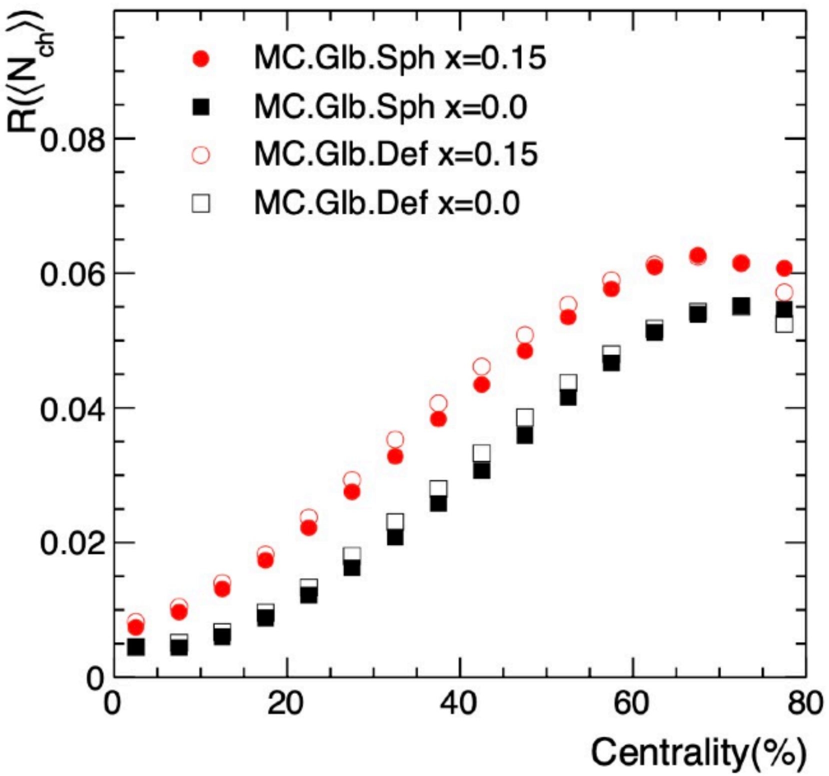
Optical model, GPU parallel computing technology

J. Wang, HJX, et.al, arXiv:2305.xxxxx

Effect of deformations and fluctuations on $R(\langle N_{ch}\rangle)$

J. Wang, HJX, et.al, arXiv:2305.xxxxx





$\beta_2^{Ru} = 0.16$

$\beta_3^{Zr} = 0.20$

$\langle r\rangle_{Def} = \langle r\rangle_{Sph}$

$\langle r^2\rangle_{Def} = \langle r^2\rangle_{Sph}$

- The $R(\langle N_{ch}\rangle)$ distributions are different from Optical and Monte Carlo simulations due to the different total cross section.
- The effect of nuclear deformations on the uncertainties of $R(\langle N_{ch}\rangle)$ distributions are considerably small when the volume and RMS radius of the colliding nuclei are constrained.

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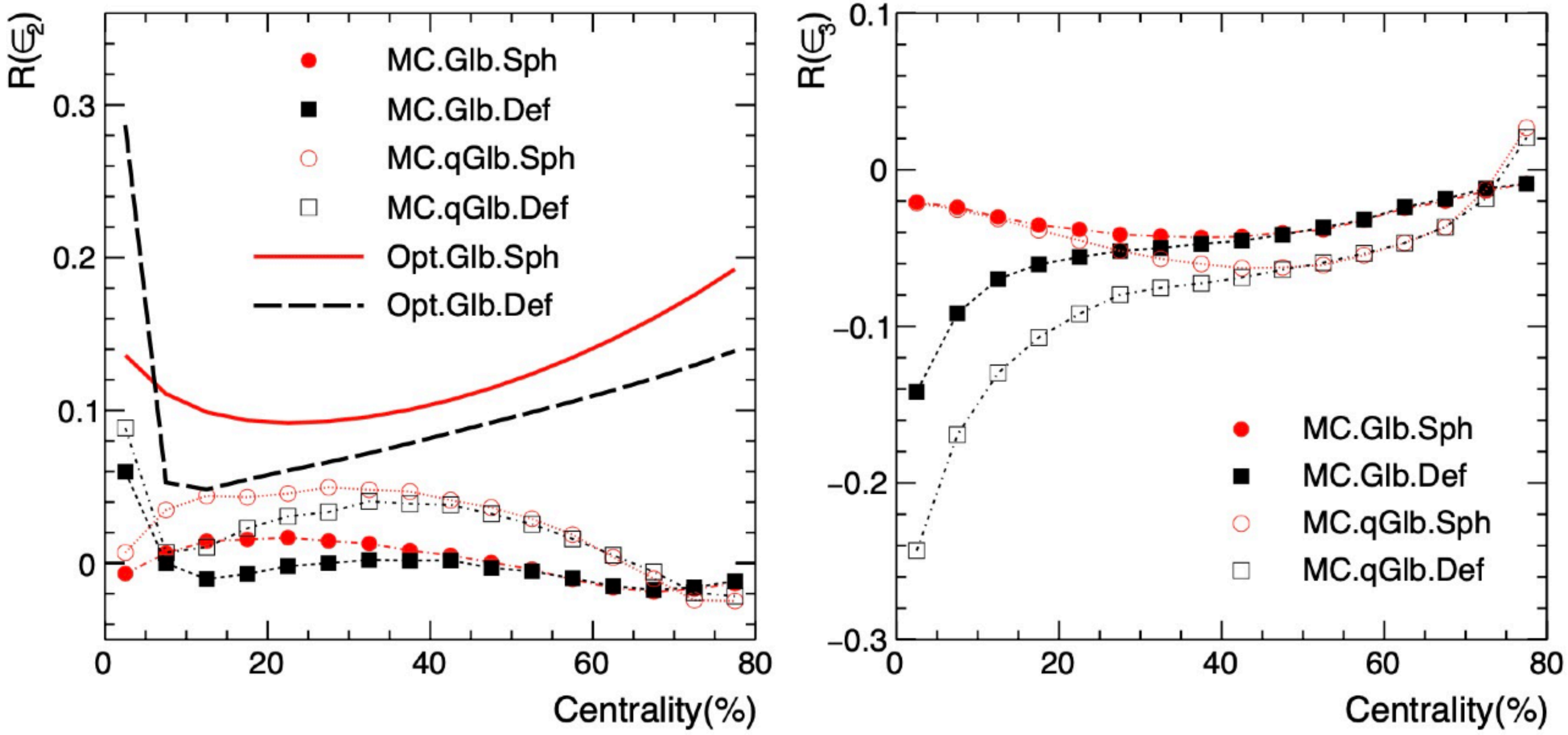
Effect of deformations and fluctuations on $R(\langle N_{ch} \rangle)$

J. Wang, HJX, et.al, arXiv:2305.xxxxx



PHYSICAL REVIEW C **67**, 064905 (2003)

Nucleon participants or quark participants?

S. Eremin[1,2] and S. Voloshin[1]

- Eccentricities driven by the nuclear diffuseness and nuclear deformation have been **largely suppressed by the initial fluctuations**.
- Such effect can **be compensated** by the sub-nucleon structure **with more constituents.**

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SUMMARY

- The STAR isobar data indicate **thick halo-type neutron skin in Zr**, consistent with **DFT** calculations
- Precision isobar data can be used to **probe the neutron skin and symmetry energy**
- The **event-by-event fluctuations** are important for the anisotropic flow ratios in isobar collisions