PROBING THE NEUTRON SKIN WITH RELATIVISTIC ISOBAR COLLISIONS AT STAR —QM2022 ABSTRACT

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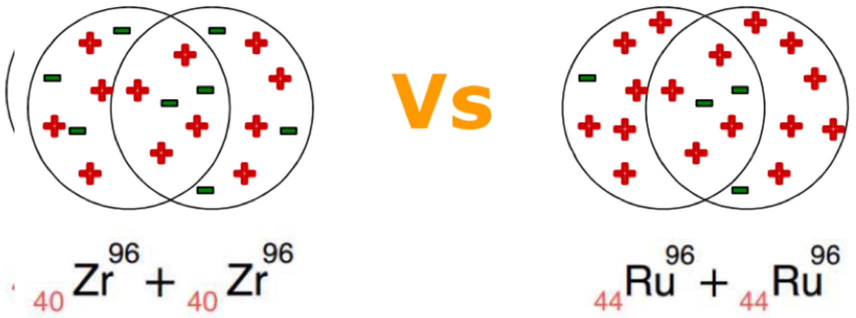
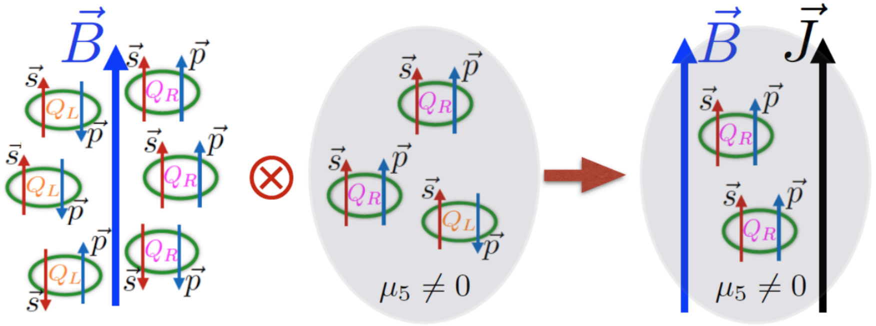
STAR FCV PWG MEETING, OCT. 27, 2021

Isobar structure and CME measurement

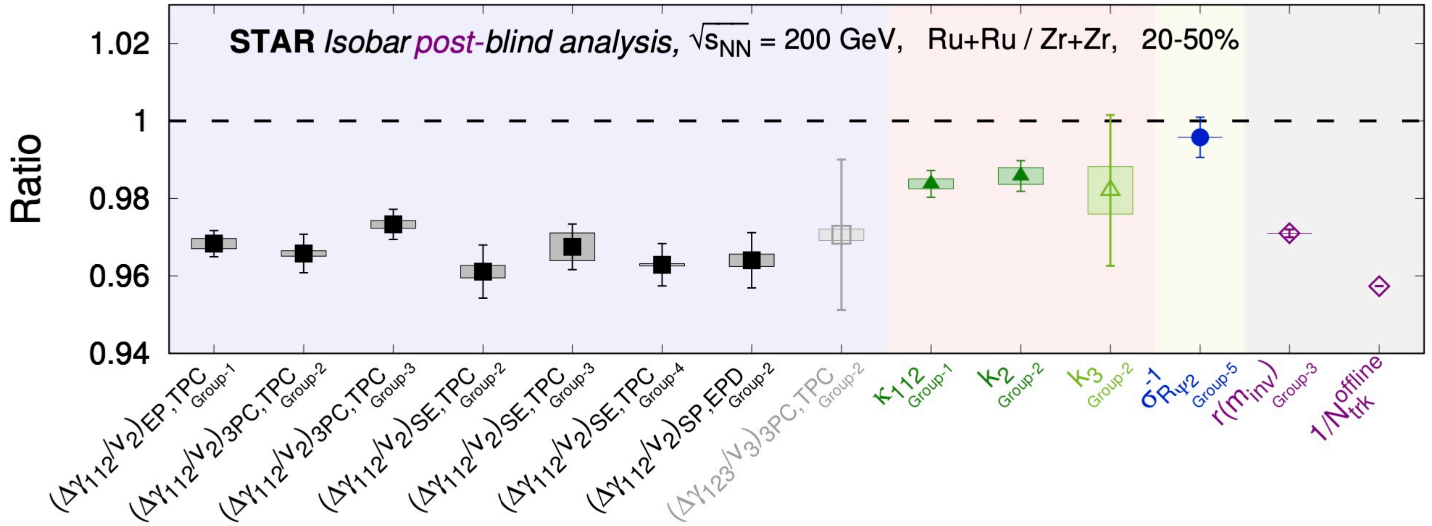




$$\mathbf{J_{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B},$$

D. Kharzeev, PPNP88, 1(2016)

STAR Collaboration, arXiv:2109.00131



The isobar nuclear densities are crucial for the Chiral Magnetic Effect(CME) search in the isobar collisions at RHIC

Neutron skin and symmetry energy

Nuclear density distribution:

- Proton distribution — Can be accurately measured in experiment.
- Neutron distribution — Poorly known

Neutron skin: RMS radii differences between neutron distribution and proton distribution

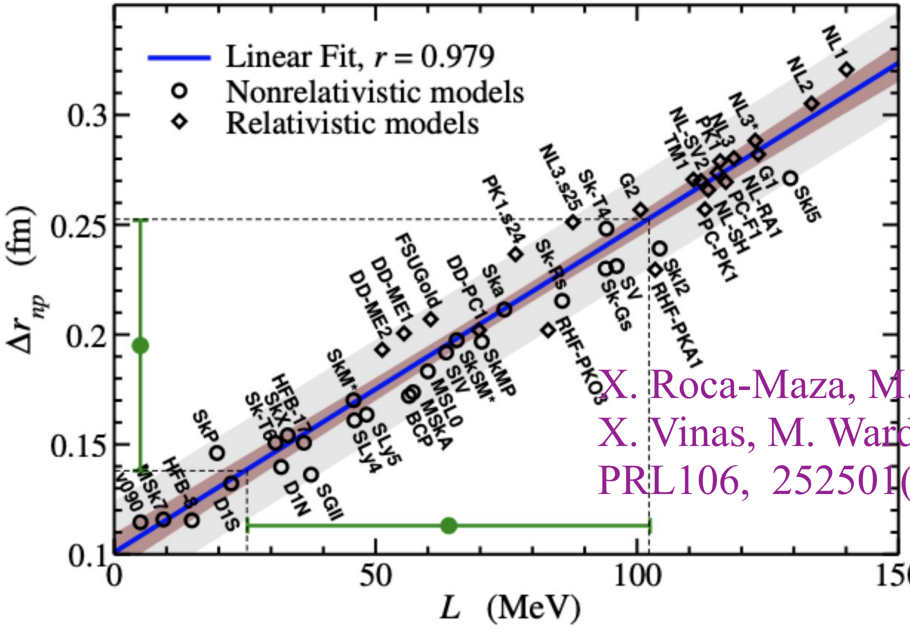
$$\Delta r_{np} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

Neutron skin and symmetry energy:

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

$$\rho = \rho_n + \rho_p;\ \ \delta = \frac{\rho_n - \rho_p}{\rho};\ \ \rho_c \simeq 0.11 \mathrm{fm}^{-3}$$

$$L(\rho_c) = 3\rho_c \left[\frac{dE_{\rm sym}(\rho)}{d\rho}\right]_{\rho=\rho_c}$$



X. Roca-Maza, M. Centelles, X. Vinas, M. Warda, PRL106, 252501(2011)

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.

Current status of neutron skin measurements

PREX-2 Collaboration, PRL126, 172502(2021); B. Reed, F. Fattoyev, C. Horowitz, J. Piekarewicz, PRL126, 172503(2021)

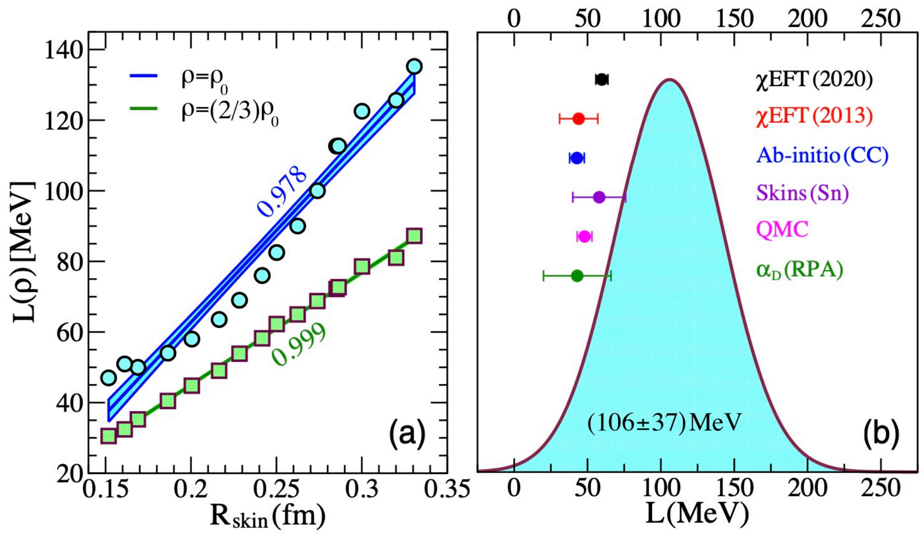
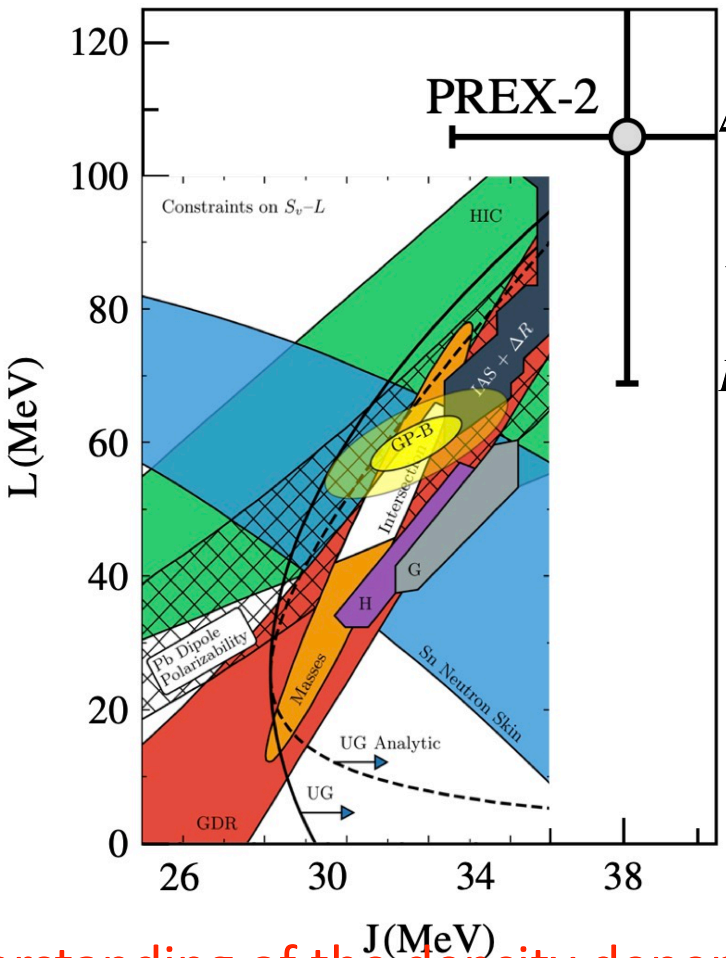


FIG. 1. Left: slope of the symmetry energy at nuclear saturation density ρ_0 (blue upper line) and at $(2/3)\rho_0$ (green lower line) as a function of $R_{\rm skin}^{208}$. The numbers next to the lines denote values for the correlation coefficients. Right: Gaussian probability distribution for the 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].



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

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

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

This PREX-2 results challenges our present understanding of the density dependence of symmetry energy extracted from various experimental and theoretical analyses.

Proposed methods in isobar collisions at STAR

The differences between Ru+Ru collisions and Zr+Zr collisions

- Multiplicity distribution ratio: $R(P(N_{\rm ch}) = \dfrac{P(N_{\rm ch})_{\rm RuRu}}{P(N_{\rm ch})_{\rm ZrZr}}$

  H. Li, HJX, Y. Zhou, X. Wang, J. Zhao, L. Chen, F. Wang, PRL125, 222301(2020)

- Mean transverse momentum ratio: $R(\langle p_T\rangle) = \dfrac{\langle p_T\rangle_{\rm RuRu}}{\langle p_T\rangle_{\rm ZrZr}}$

  HJX, et.al arXiv:2111.xxxxx (2021)

- Net charge ratio: $R(\Delta Q) = \dfrac{\Delta Q_{\rm RuRu}}{\Delta Q_{\rm ZrZr}}$

  HJX, H. Li, Y. Zhou, X. Wang, J. Zhao, L. Chen, F. Wang, arXiv:2105.04052 (2021)

Data analysis

Data analysis details

Event-wise cuts:

- MB events: 600001, 600011, 600021, 600031, 600041, 600051
- Pile-up rejection: same as CME paper
- Badruns removal: same as CME paper
- $-35 < v_z < 25$ cm
- $v_r = \sqrt{v_x^2 + v_y^2} < 2$ cm
- $|v_z - \text{VpdVz}| < 5$ cm

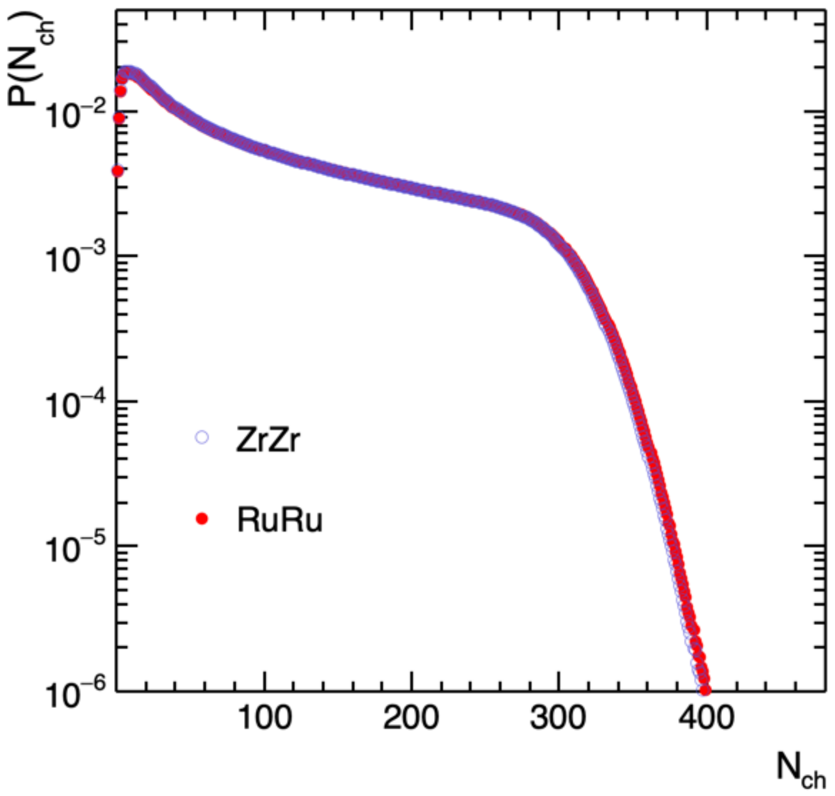
Track-wise cuts:

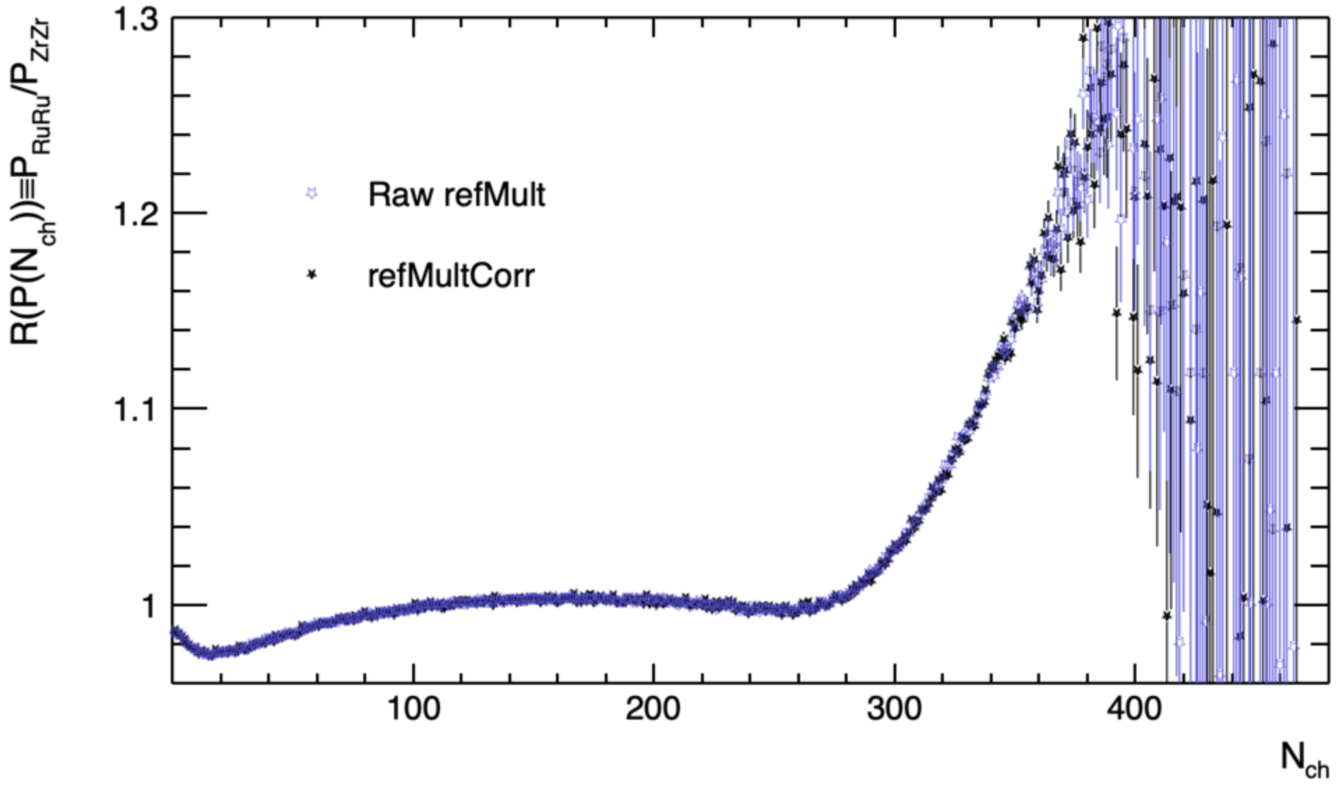
- Primary tracks
- 0.2<$p_T < 5\text{GeV}/c$
- $|\eta| < 1$
- $\text{dca} < 3$ cm
- $15 < \text{nHitFits} < 50$
- $0.52 < \text{nHitFits}/\text{nHitmax} < 1.05$

Datasets:

- RuRu 200GeV Run18
- ZrZr 200GeV Run18
- Good runs: 778(RuRu) + 812(ZrZr) - 167(Bad) = 1423 good runs

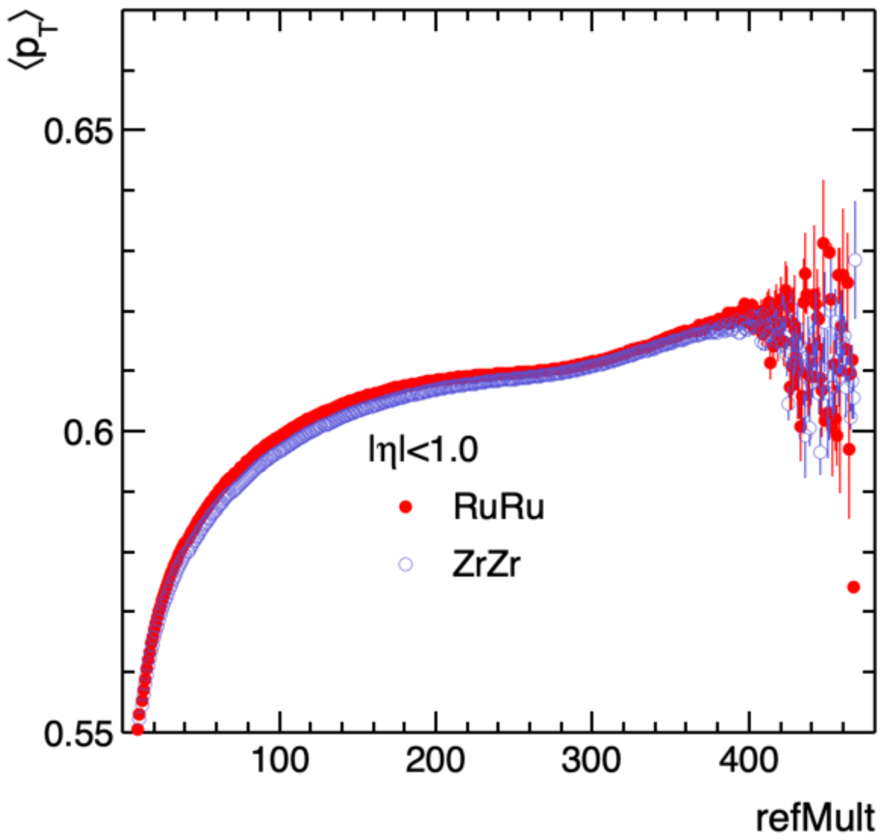
Results (1): Multiplicity distribution ratio

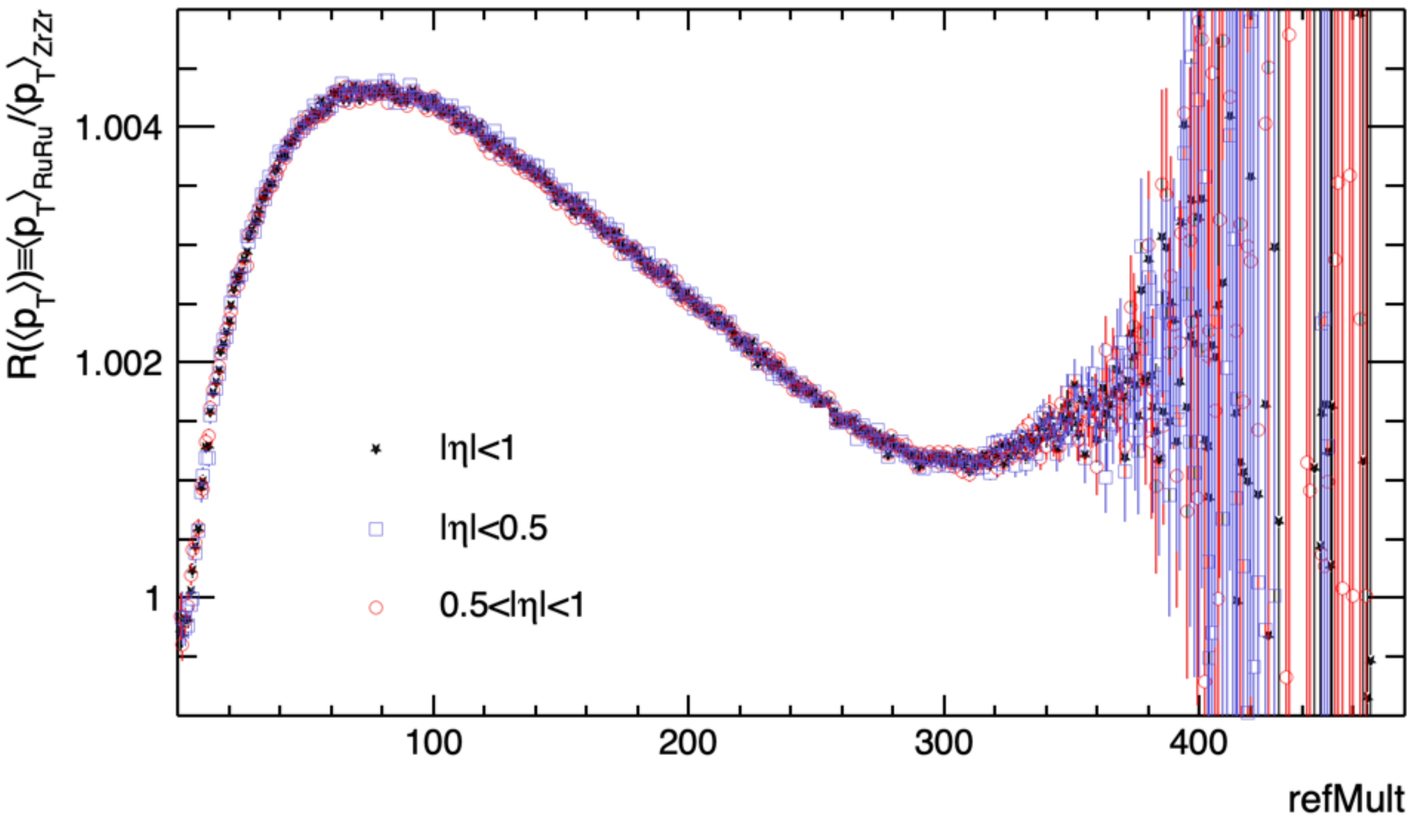




The pseudo-rapidity cut of refMult $|\eta| < 0.5$

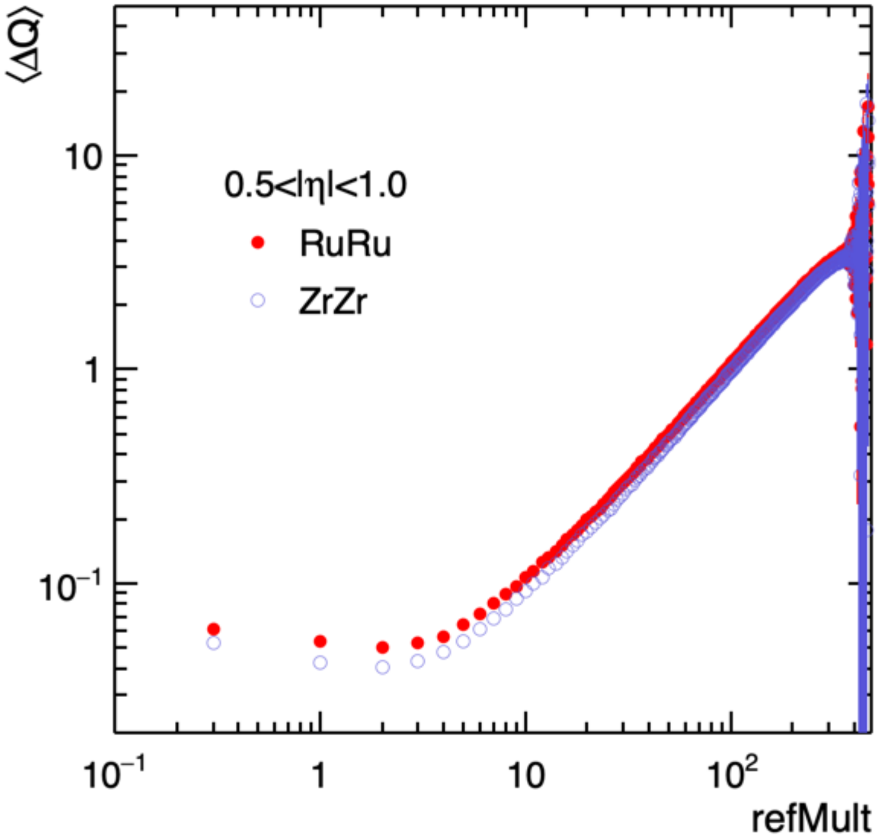
Results (2): mean pT ratio

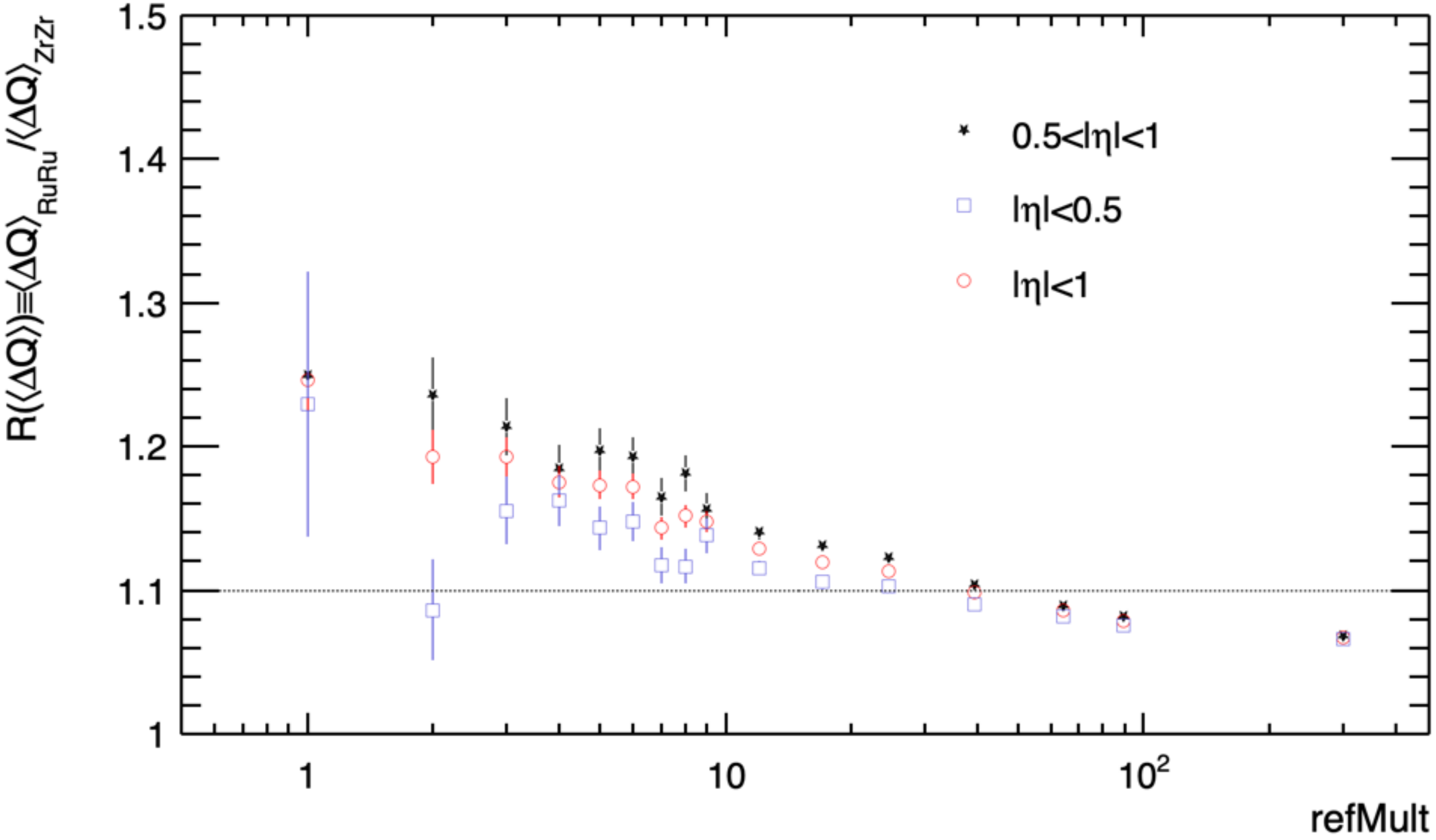




Take $\eta| < 1$ as default

Results (3): net charge ratio





- Excluding (anti-)protons with $p_T < 0.4$ GeV/c
- Use $0.5 < |\eta| < 1$ as default to avoid the auto correlations between POI and refMult

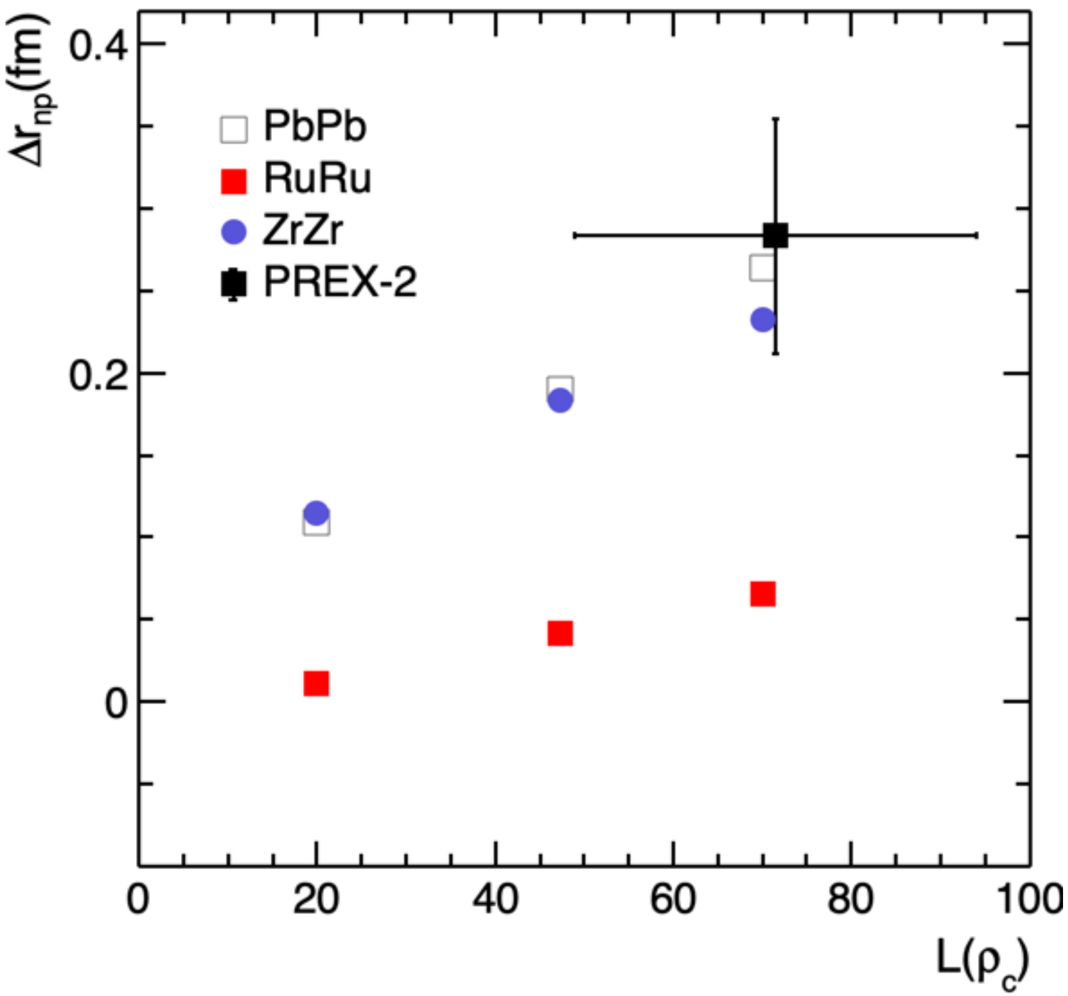
Physical interpretation

Extended Skyrme-Hartree-Fock model

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

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

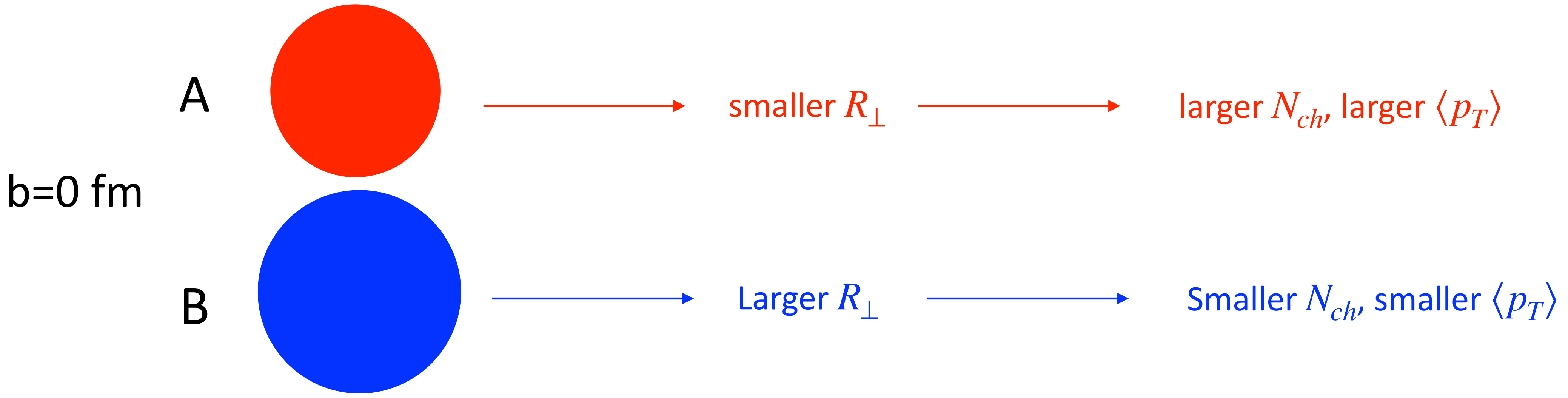
	Lc20	Lc47	Lc70
$L(\rho_c)$(MeV)	20.000	47.300	70.000
$E_{\rm sym}(\rho_c)$(MeV)	26.650	26.650	26.650
$\rho_0(\rm fm^{-3})$	0.15414	0.15267	0.15059
$t_0(\rm MeV\cdot fm^3)$	−2063.0	−2037.3	−1855.3
$t_1(\rm MeV\cdot fm^5)$	442.48	524.18	576.91
$t_2(\rm MeV\cdot fm^5)$	−562.02	−521.60	−76.702
$t_3(\rm MeV\cdot fm^{3+3\alpha})$	14726.	13734.	12367.
$t_4(\rm MeV\cdot fm^{5+3\beta})$	−1532.5	−1615.7	−1650.2
$t_5(\rm MeV\cdot fm^{5+3\gamma})$	3037.5	2153.2	−436.51
x_0	0.92728	0.29070	−0.26752
x_1	1.3163	0.37275	−0.51268
x_2	−0.55463	−0.55121	3.1558
x_3	0.98695	0.13143	−0.83906
x_4	1.7600	0.29499	−1.5709
x_5	−0.83852	−0.65206	−4.1683
α	0.28356	0.27858	0.31853
β	1	1	1
γ	1	1	1
$W_0(\rm MeV\cdot fm^5)$	92.759	100.14	113.61



Lc20
Lc47
Lc70

Most central collisions: multiplicity distribution and mean p_T

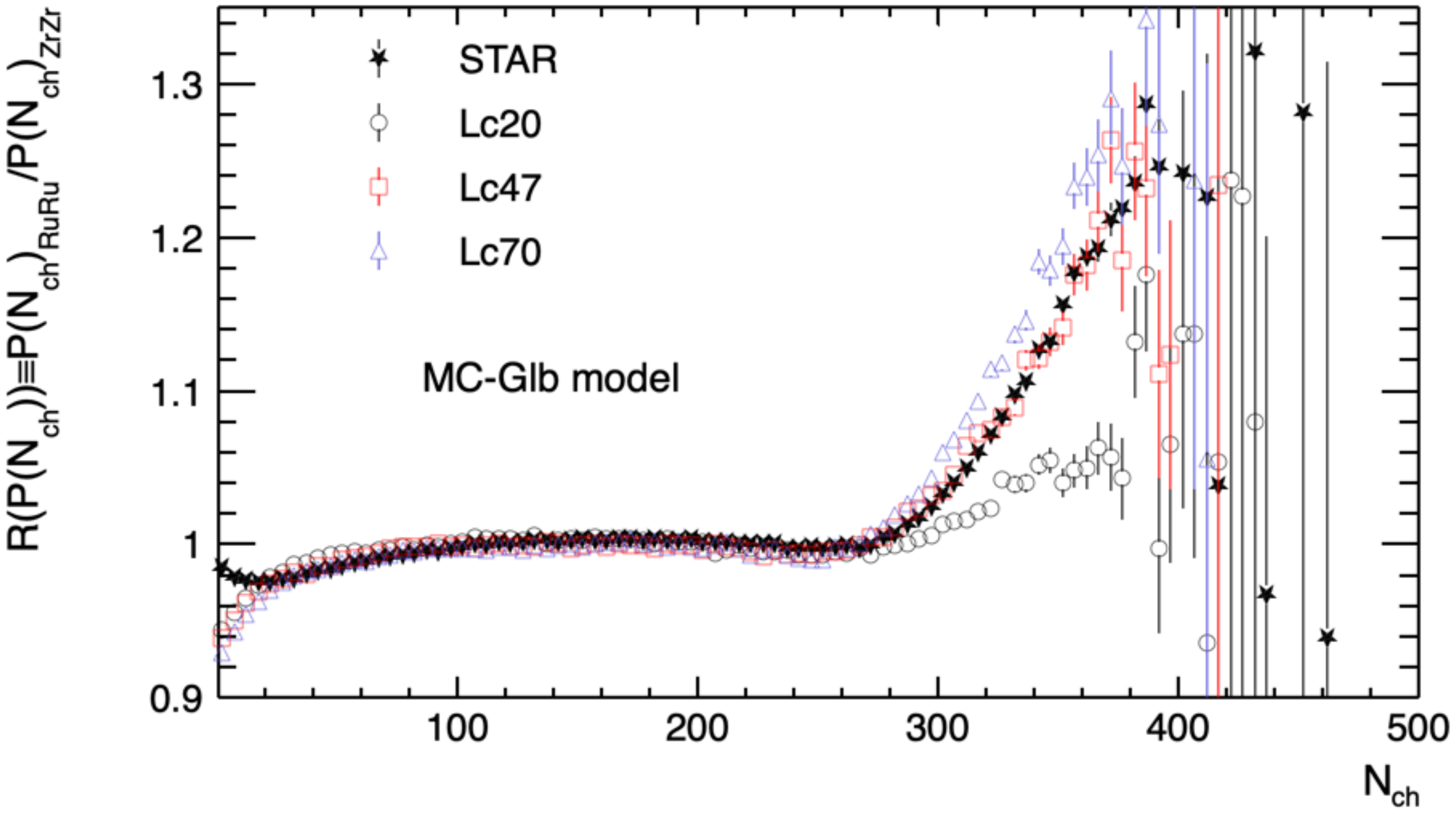
Isobar nuclei have the same mass number, thus for the isobar species A and B, the larger the nuclear size, the dense the nuclear density. Take $b = 0$ fm as example.



Based on the charge radii measurements $\left(\sqrt{\langle r_{ch}^2 \rangle} = 4.393\text{fm}\right)_{Ru} > \left(\sqrt{\langle r_{ch}^2 \rangle} = 4.349\text{fm}\right)_{Zr}$, we known that $\left(\sqrt{\langle r_p^2 \rangle}\right)_{Ru} > \left(\sqrt{\langle r_p^2 \rangle}\right)_{Zr}$.

But the nuclear structure theory always give $\left(\Delta r_{\text{np}}\right)_{Ru} < \left(\Delta r_{\text{np}}\right)_{Zr}$, and the differences become larger at larger L. Therefore, the multiplicity distribution ratio $R(P(N_{ch}))$ and mean p_T ratio $R(\langle p_T \rangle)$ at most central collisions can be used to probe the nuclear size difference of isobar nuclei, and thus the neutron skin thickness and L parameter of symmetry energy.

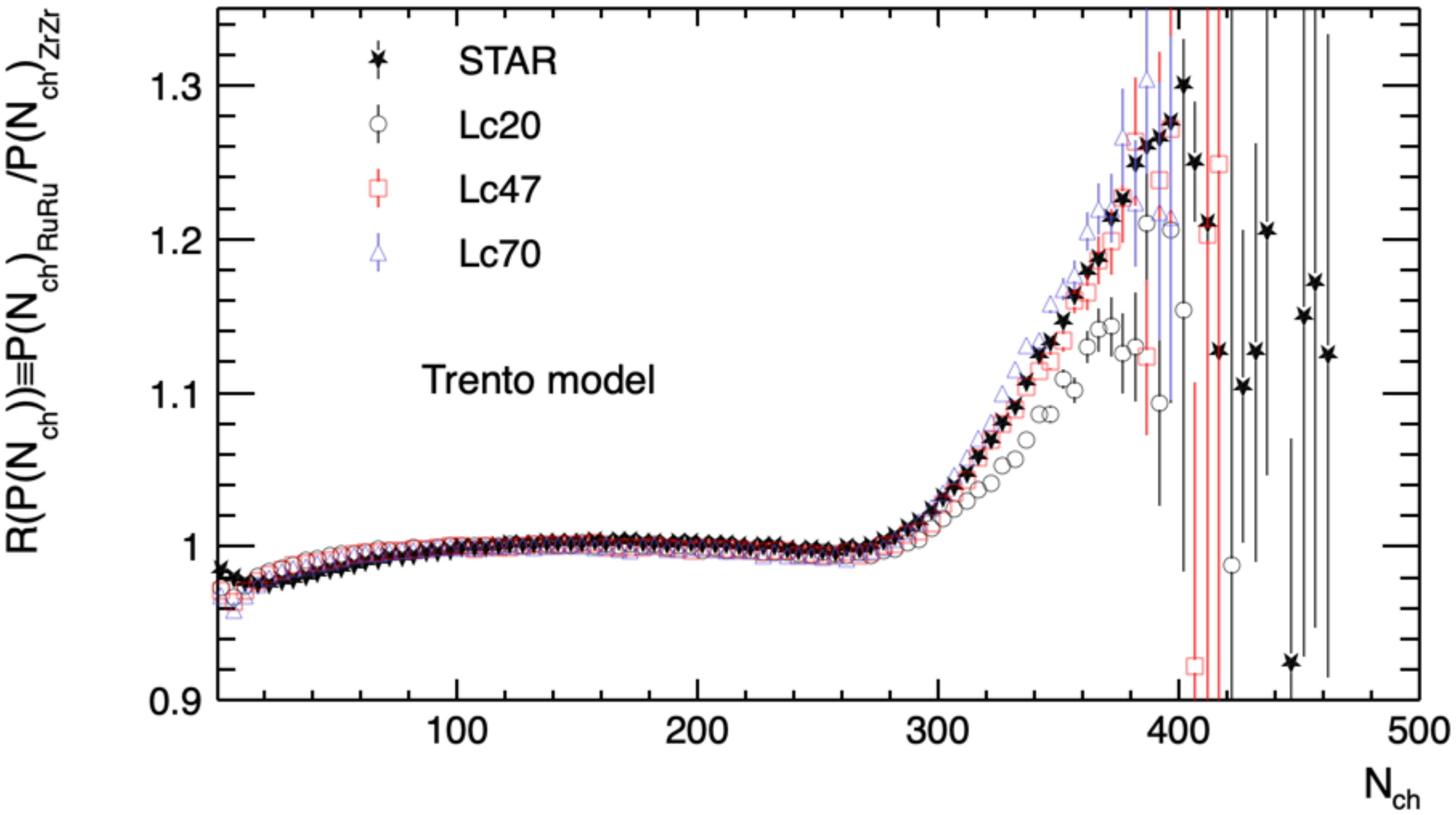
(1) Multiplicity distribution ratios



Lc47: Fitting to the data from terrestrial nuclear experiments and astrophysical observations. Based on strong, EM, and gravitational measurements.
Y. Zhou, L. Chen, Z. Zhang, PRD99, 121301R(2021)

The parameters for MC Glauber model are taken from STAR centrality group for the CME analysis with case 3 Woods-Saxon parameter set (https://drupal.star.bnl.gov/STAR/system/files/IsobarCentralityDefinition_20210603.pdf).

(1) Multiplicity distribution ratios



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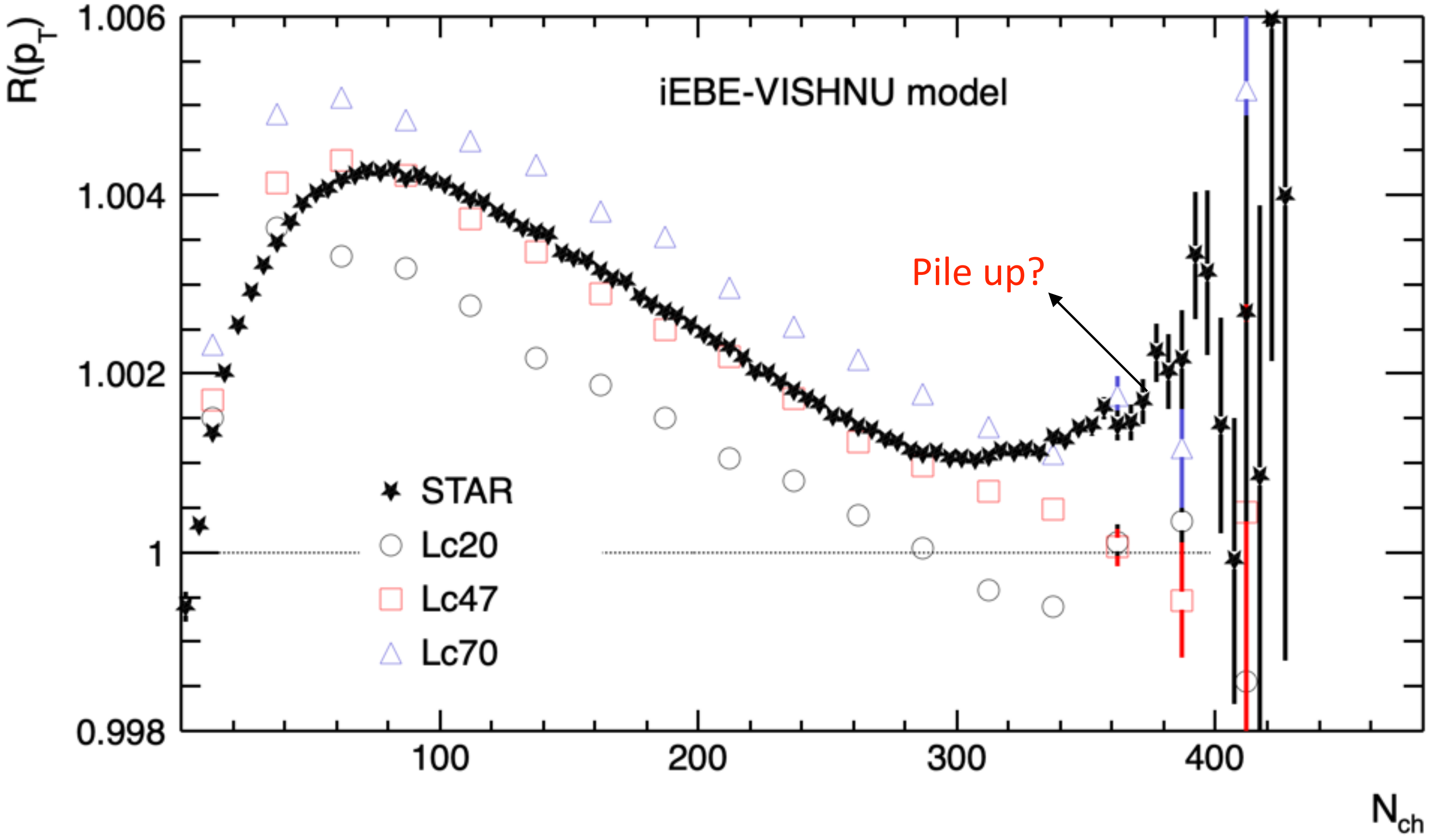
Except the normalization factor, all the parameters for Trento model are taken from
J. Bernhard, J. Moreland, S. Bass, Nature Physics, 15(2019), 11, 1113-1117

(2) Mean p_T ratios



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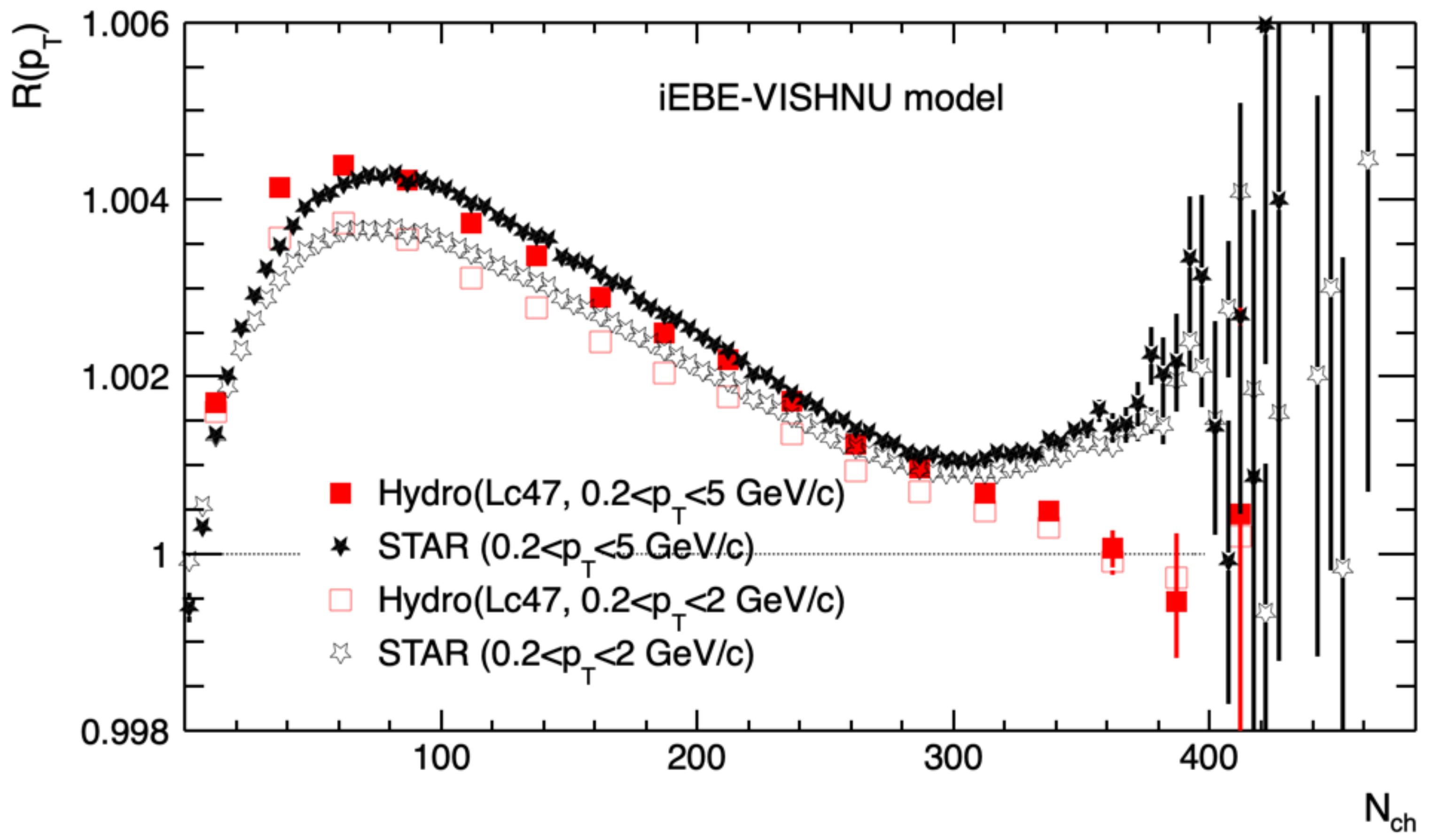
Except the normalization factor, all the parameters for iEBE-VISHNU model are taken from
J. Bernhard, J. Moreland, S. Bass, Nature Physics, 15(2019), 11, 1113-1117

(2) Mean p_T ratios: effect of p_T cut



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Y. Zhou, L. Chen, Z. Zhang, PRD99, 121301R(2021)

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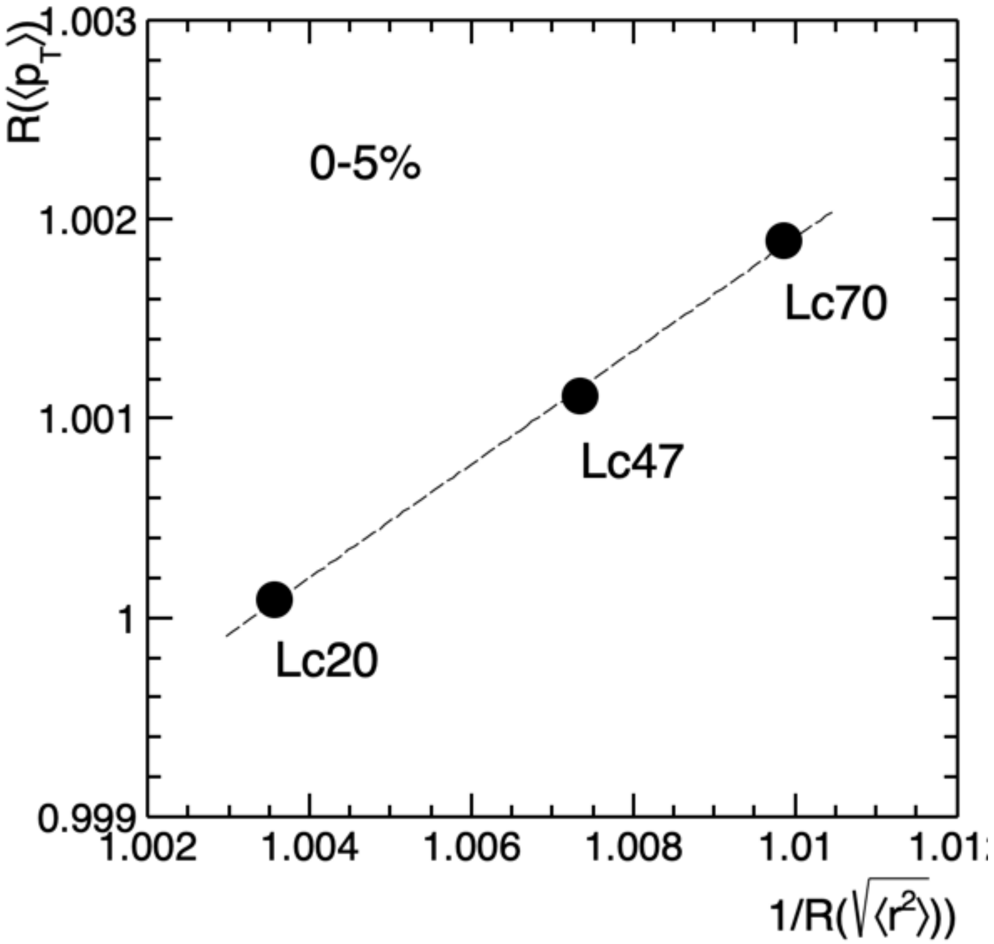
J. Bernhard, J. Moreland, S. Bass, Nature Physics, 15(2019), 11, 1113-1117

(2) Mean p_T ratios



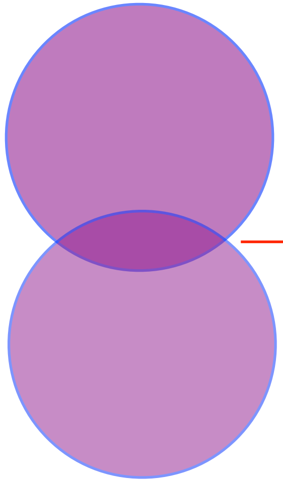
HJX, et.al, arXiv:2111.xxxxx (2021)

The $R(\langle p_T \rangle)$ are proportional to the inverse of nuclear size ratio of colliding nuclei $R\left(1/\sqrt{\langle r^2 \rangle}\right)$ at most central collisions (0-5% centrality).

Except the normalization factor, all the parameters for iEBE-VISHNU model are taken from J. Bernhard, J. Moreland, S. Bass, Nature Physics, 15(2019), 11, 1113-1117

Most peripheral collisions: net charge ratios

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

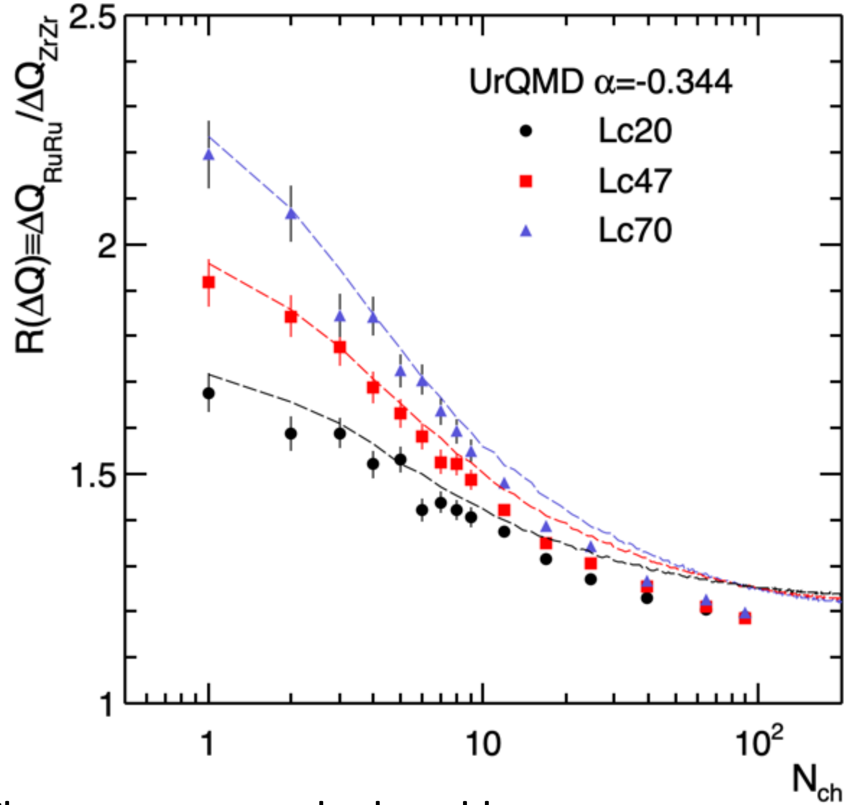
Assume species A and B have same proton density distribution (except the normalization factor), then

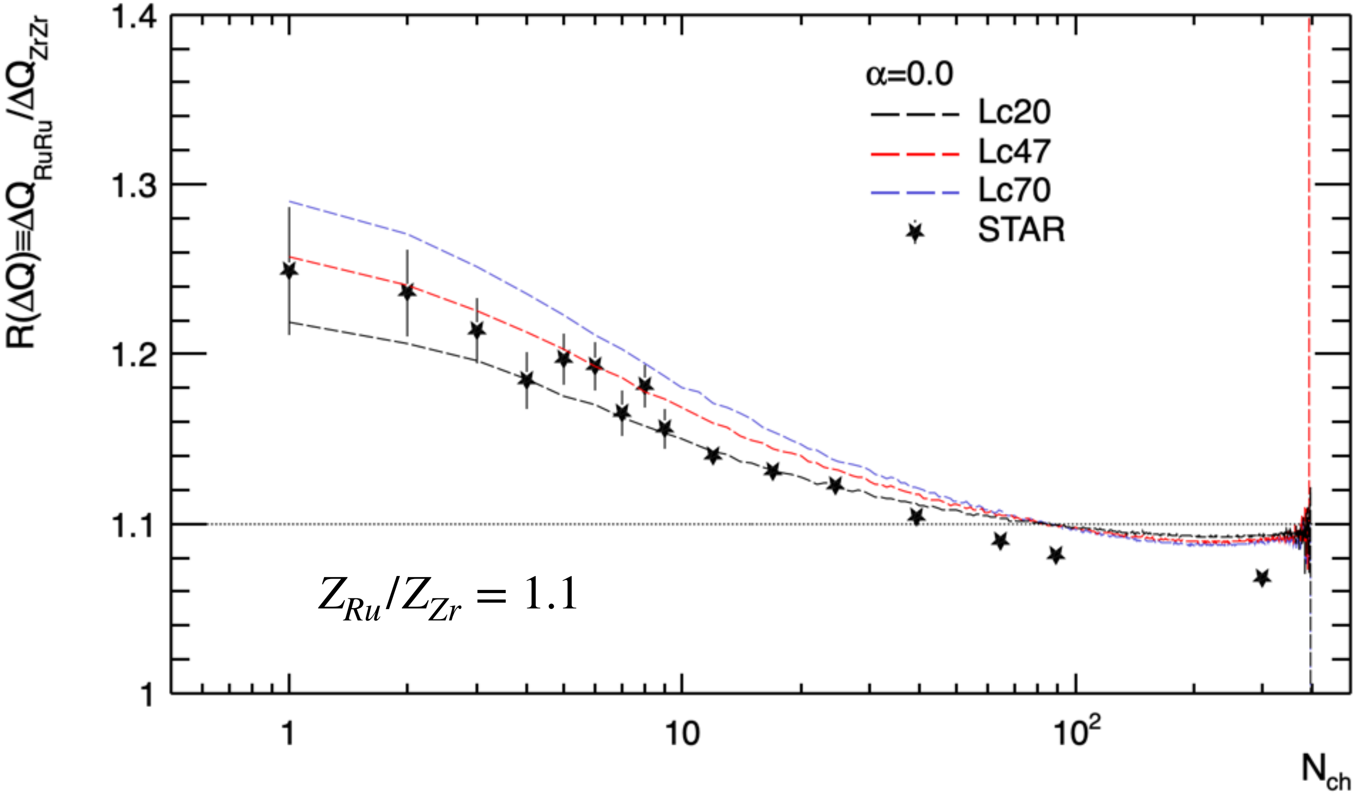
- If A and B have the same neutron density distribution, then $(\Delta Q)_{AA}/(\Delta Q)_{BB} = Z_A/Z_B$
- If B have a larger neutron skin thickness than A, then $(\Delta Q)_{AA}/(\Delta Q)_{BB} > Z_A/Z_B$ at most peripheral collisions, and the value become larger as the impact parameter increase.

Contrary to the observables at most central collisions, i.e, $R(P(N_{ch}))$ and $R(\langle p_T \rangle)$, the net charge ratios $R(\Delta Q)$ at most peripheral collisions is an isospin-sensitive observable.

(3) Net charge ratios

HJX, H. Li, Y. Zhou, X. Wang, J. Zhao, L. Chen, F. Wang, arXiv:2105.04052 (2021)





The curves are calculated by

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

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

α is the ΔQ ratio in nn to pp interaction:

Pytha: $\alpha = -0.352$

Hijing: $\alpha = -0.389$

UrQMD: $\alpha = -0.344$

Data: $\alpha \sim 0$

QM abstract

To-do list

- We've plotted so far as functions of Nch. We'll also make plots as functions of centrality. We'd like to use improved centrality definition (additional bad runs, improved high-end fit, float boundaries and precise centrality fractions, finer centrality bins).

  Centrality meeting(Oct. 19) : https://drupal.star.bnl.gov/STAR/system/files/Post_blind_Isobar_Centrality.pdf
- Systematically study.
- We plan to incorporate nuclear deformations.

Thank you for your attention!

Haojie Xu(徐浩洁)

Huzhou University(湖州师范学院)

Backup

Heavy ion models

- Particle production:
  - MC Glauber model
  - Treno mode
- Mean pT:
  - iEBE-VISHNU model
- Net charges:
  - UrQMD
  - Trento