RBRC Workshop: Physics Opportunities from the RHIC Isobar Run
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Measuring neutron-skin thickness with forward/backward rapidity neutrons in ultracentral relativistic isobaric collisions

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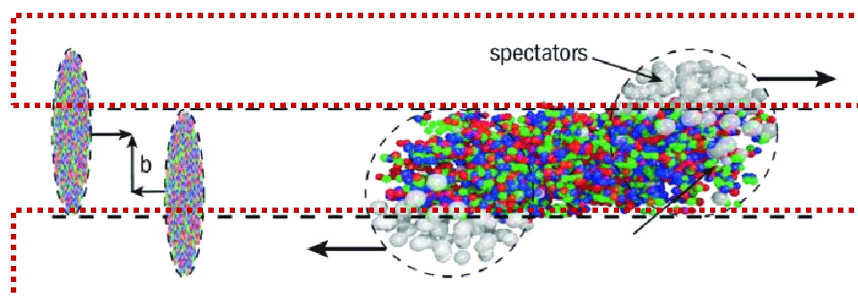
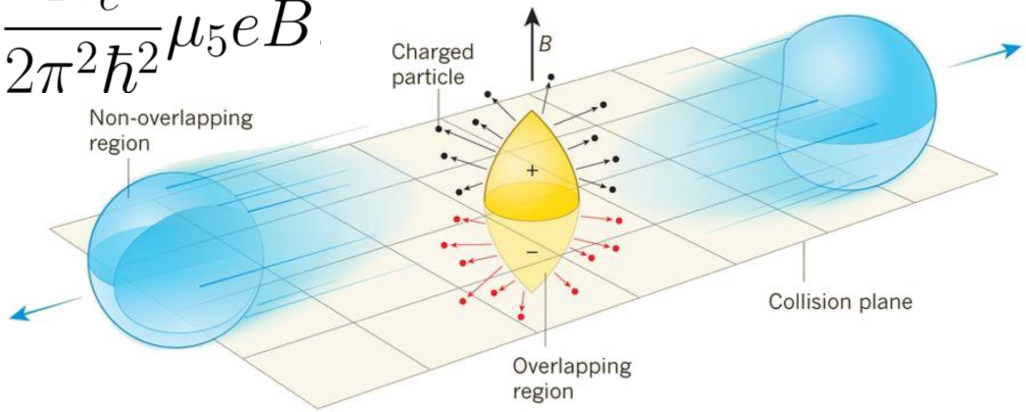
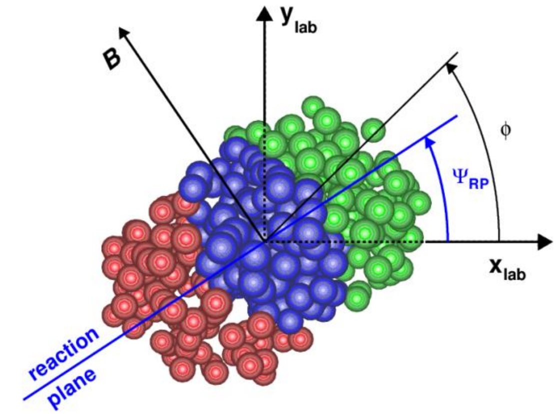


CME and isobaric collisions

$$\vec{J} = \frac{N_c}{2\pi^2\hbar^2}\mu_5 e\vec{B}$$

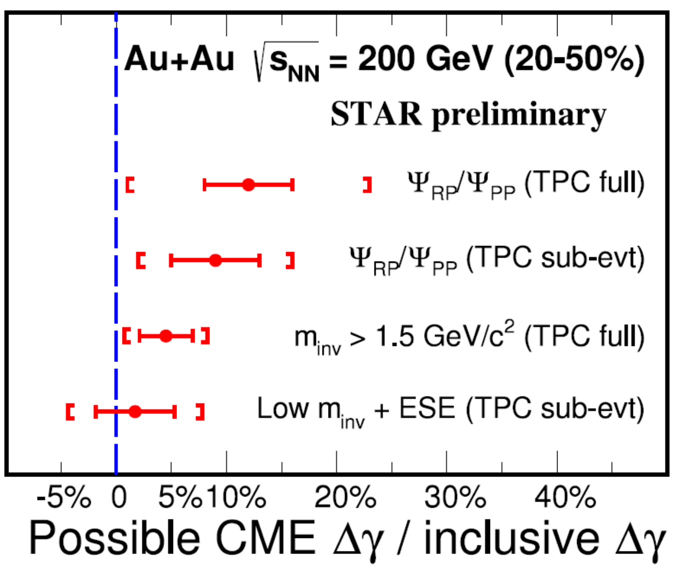




$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$

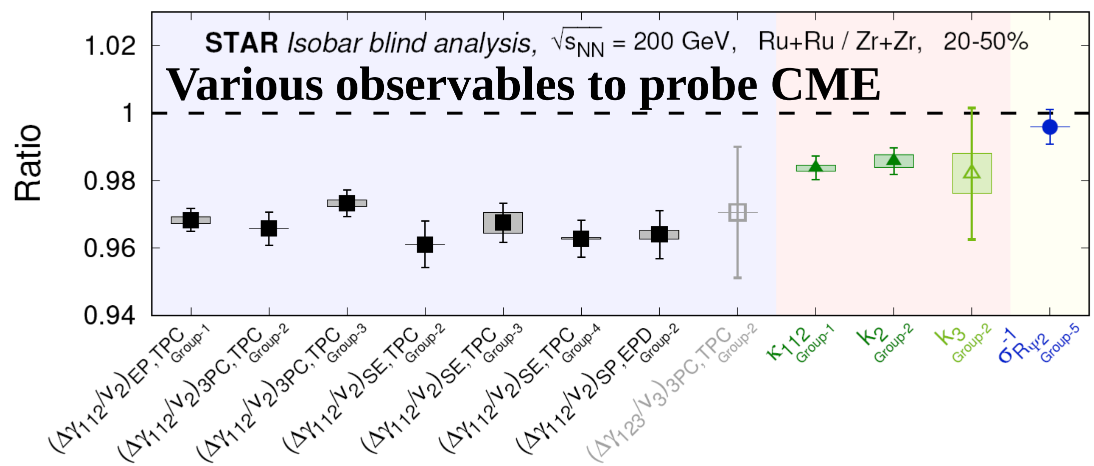
S. A. Voloshin, PRC (2004)

Significant background contribution



J. Zhao and F. Q. Wang, PPNP (2019)

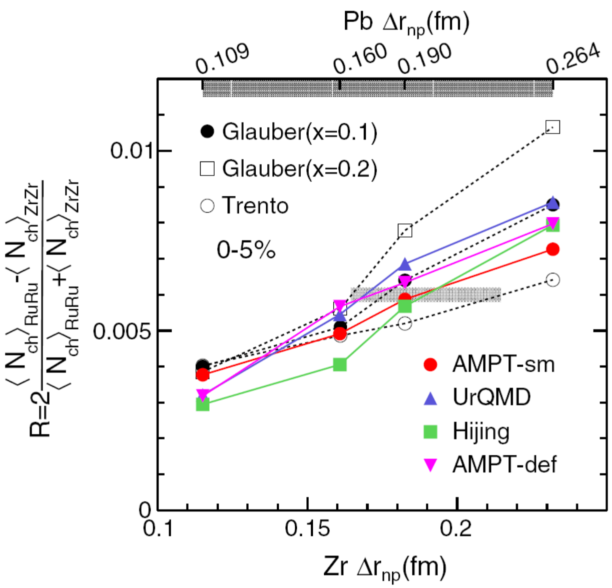
Isobaric collisions: similar bulk dynamics, different B



STAR, arXiv: 2109.00131 [nucl-ex]

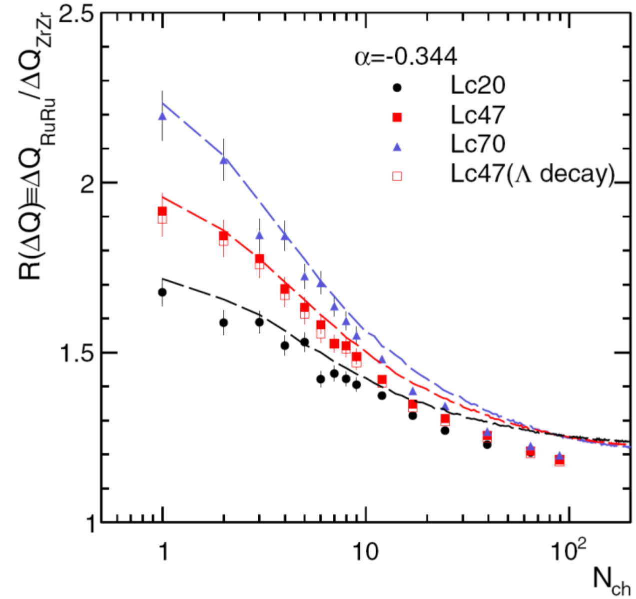
Isobaric collisions to probe neutron skin

Charged-particle multiplicity



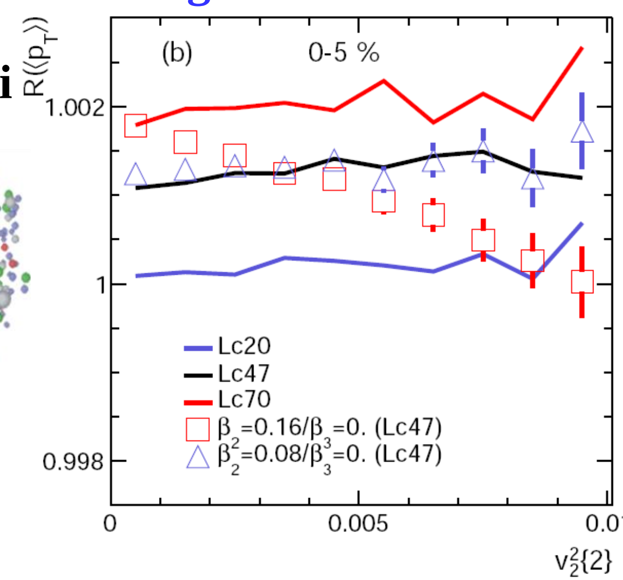
H. L. Li et al., PRL (2020)

Net-charge multiplicity



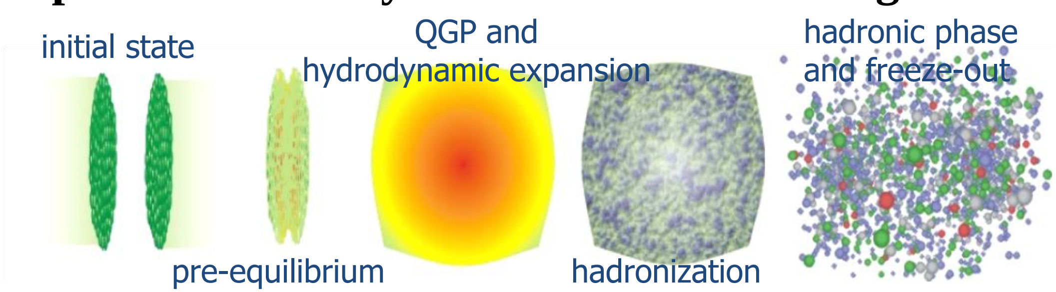
H. J. Xu et al., PRC (2020)

Average transverse momentum



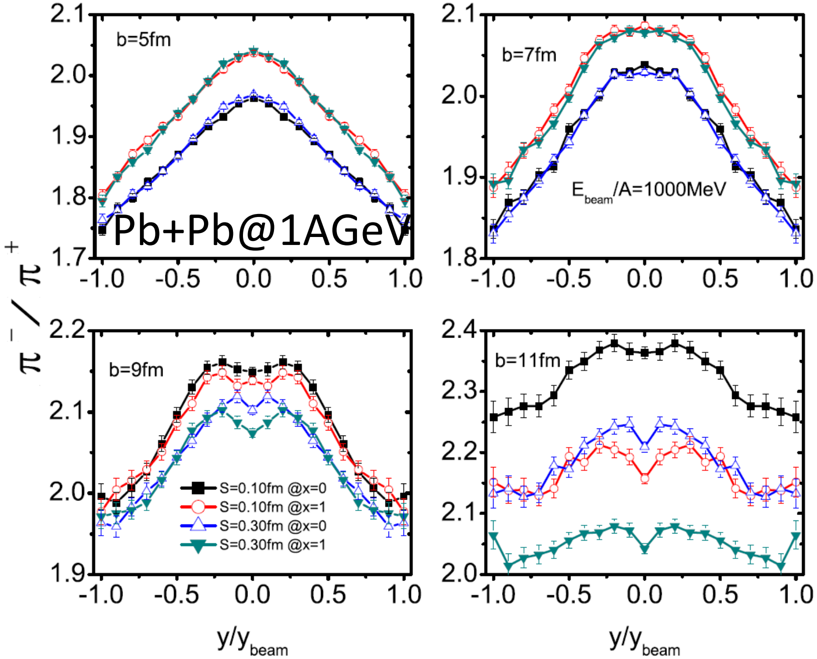
H. J. Xu et al., arXiv: 2111.14812 [nucl-th]

probe the density distribution of colliding nuclei

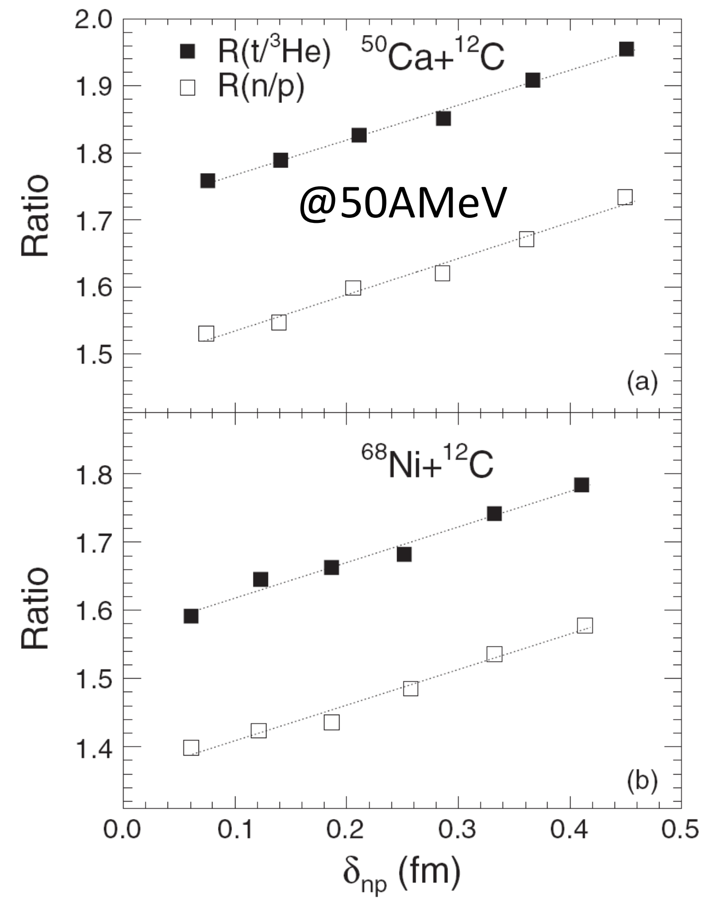


Observables at midrapidities suffer from complicated dynamics and model dependence

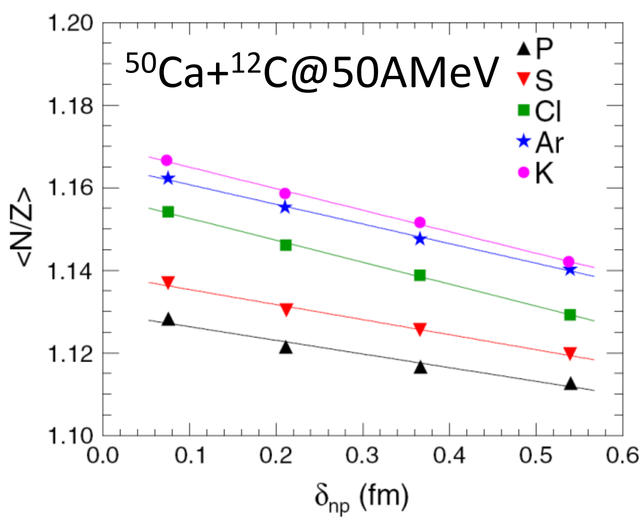
Intermediate-energy HIC to probe neutron skin



G. F. Wei et al., PRC (2014)



Z. T. Dai et al., PRC (2014)

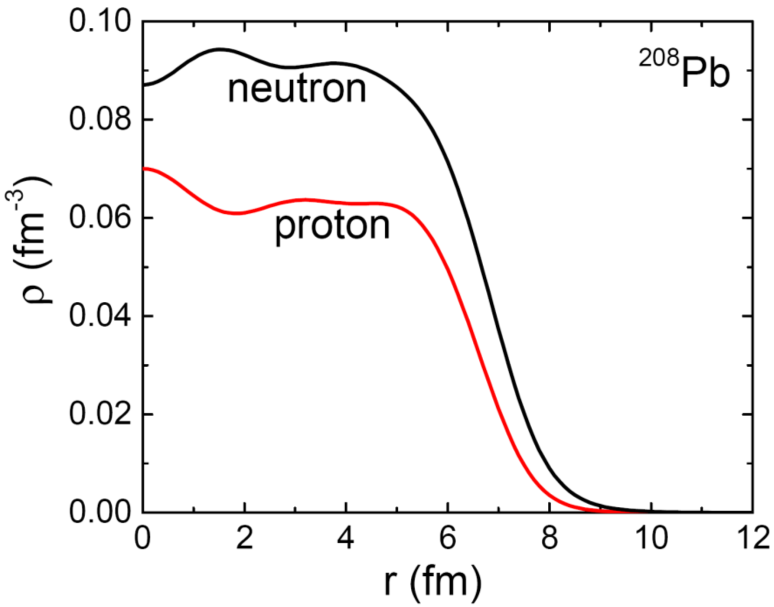


Z. T. Dai et al., PRC (2015)

Suffer from:

1) Model dependence
2) Interaction between spectator and participant
3) Uncertainties of clusterization/fragmentation

Neutron skin and E_{sym}



Energy per nucleon in asymmetric matter

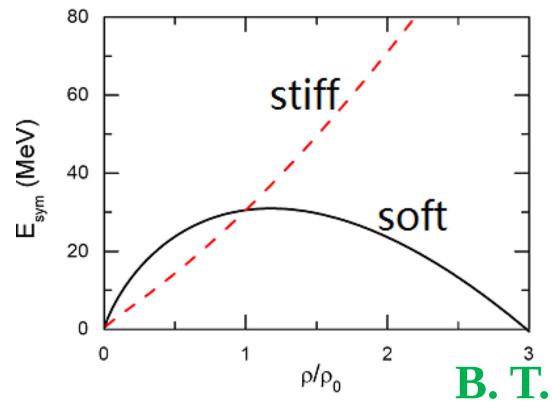
Symmetry energy

$$E(\rho,\delta) \approx E_0(\rho) + \boxed{E_{sym}(\rho)}\delta^2$$

Energy per nucleon in symmetric matter

$\rho=\rho_n+\rho_p$

$\delta=(\rho_n-\rho_p)/\rho$

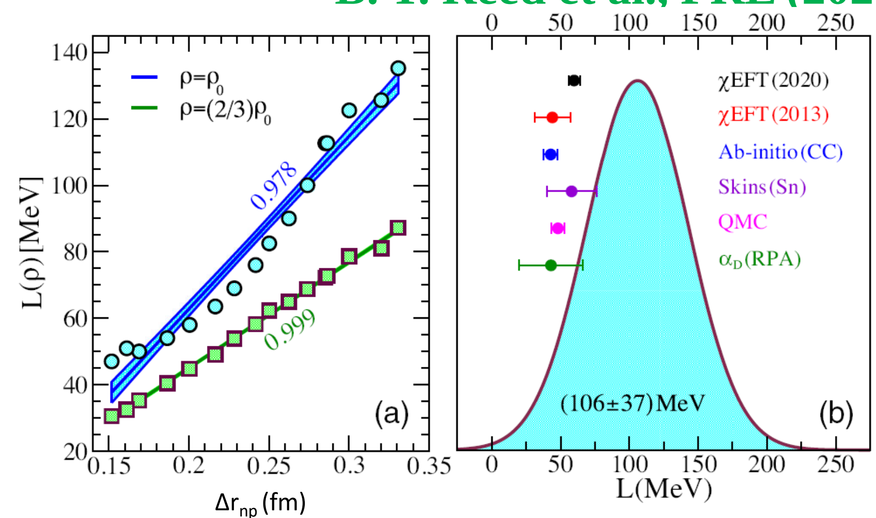


Neutron-Skin Thickness:

$$\Delta r_{np} = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle} \quad \text{(fm)}$$

PREXII data of ^{208}Pb favors a large L

B. T. Reed et al., PRL (2021)

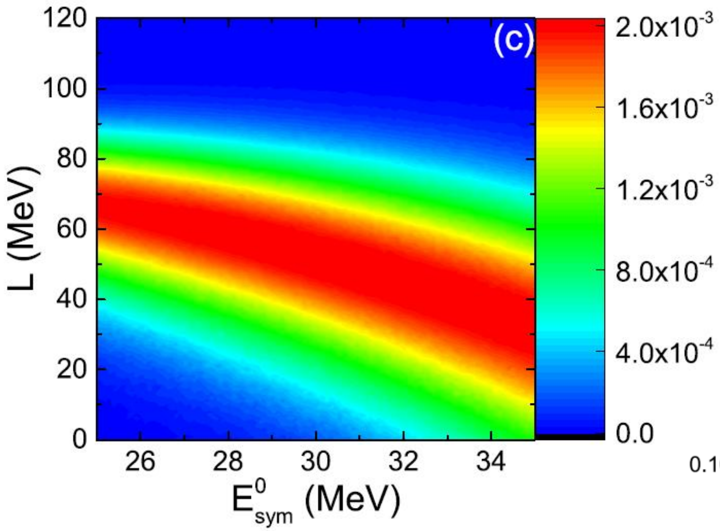


Expansion around saturation density ρ_0

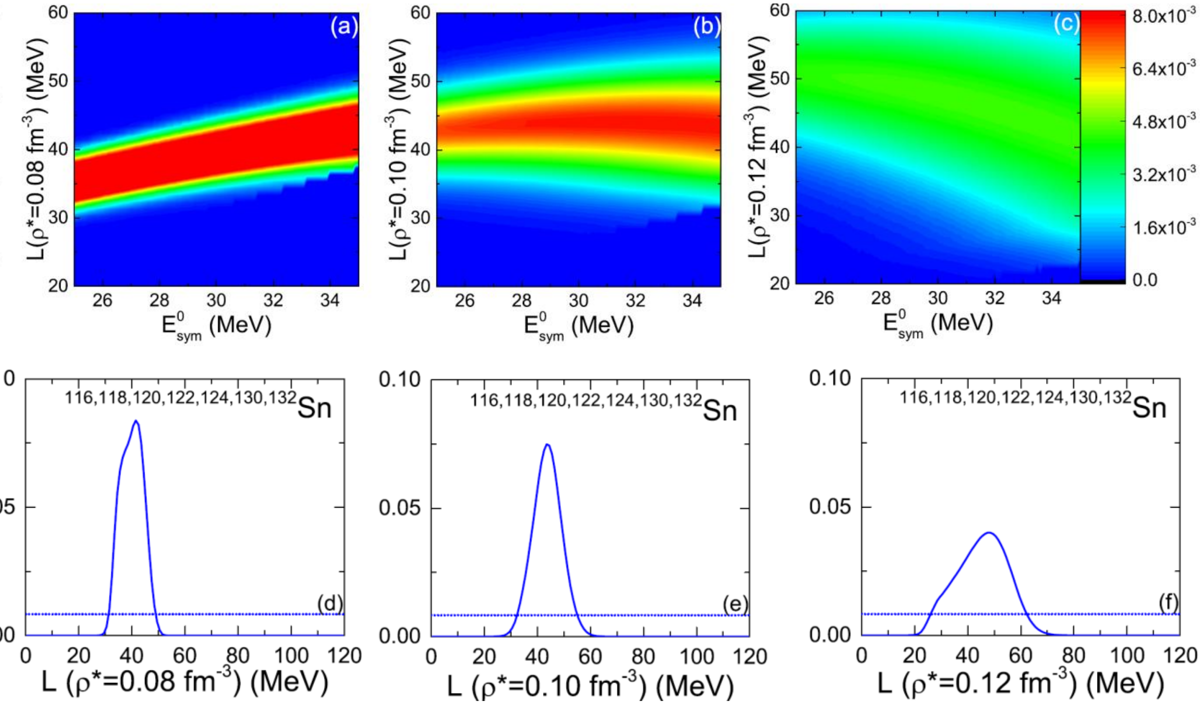
$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \ldots \qquad \chi = \frac{\rho-\rho_0}{3\rho_0}$$

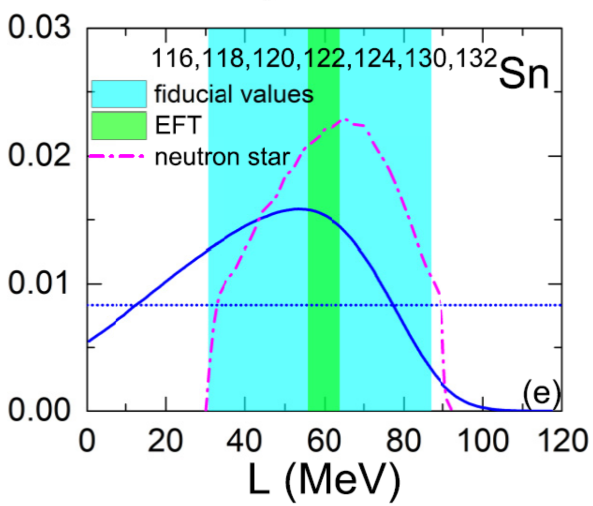
Slope parameter $$L = 3\rho_0\left[\frac{\partial E_{sym}(\rho)}{\partial \rho}\right]_{\rho=\rho_0}$$

Bayesian inference of E_{sym} from Δr_{np} of Sn



Δr_{np} dominated by L(0.10)



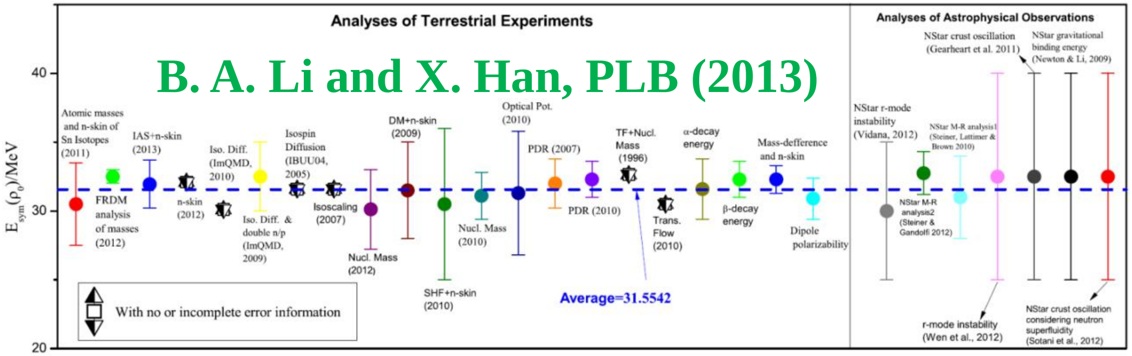


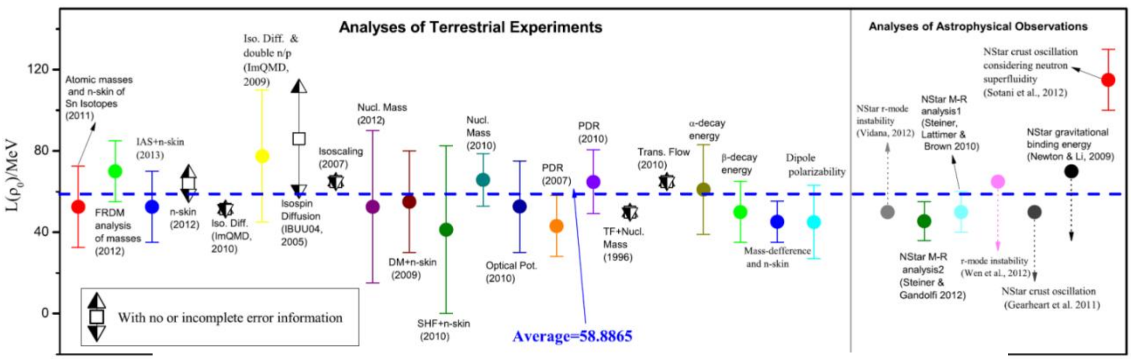
Δr_{np} from p-Sn scattering favors a smaller L compared with Δr_{np} of ^{208}Pb by PREXII

JX, W. J. Xie, and B. A. Li, PRC (2020)

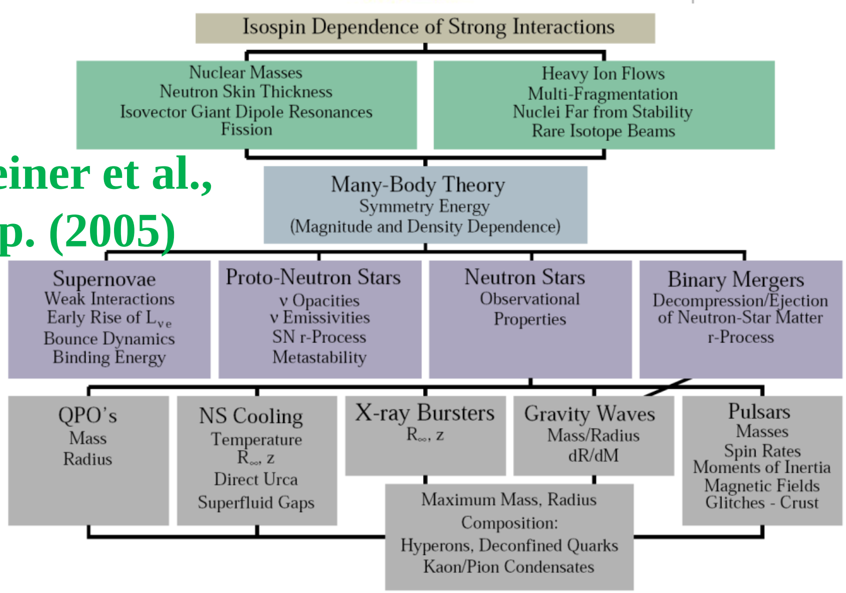
Various constraints on $E_{sym}(\rho_0)$ and $L(\rho_0)$

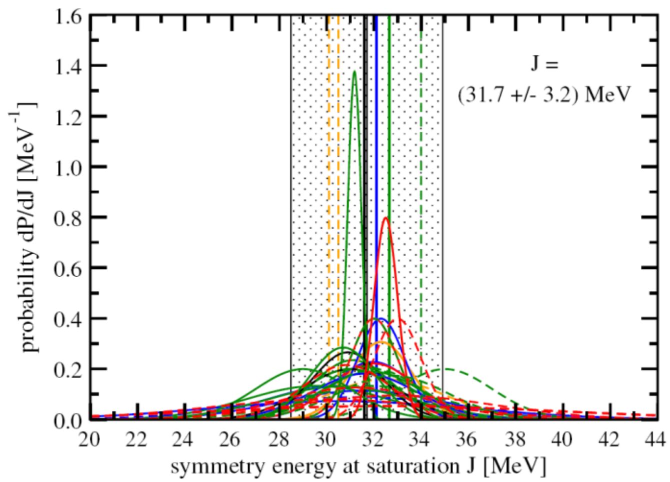
B. A. Li and X. Han, PLB (2013)

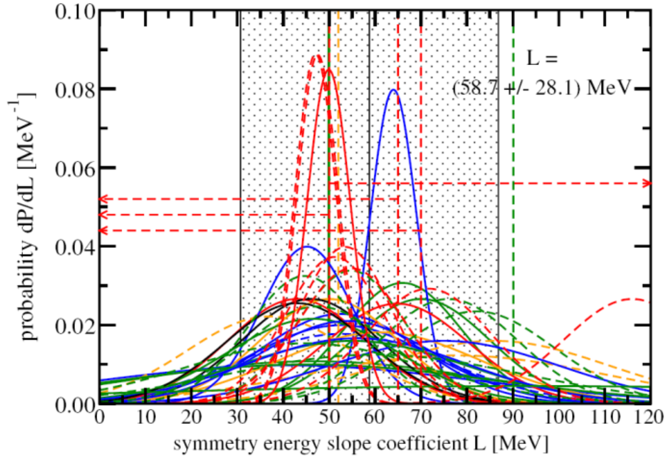




A. W. Steiner et al., Phys. Rep. (2005)







M. Oertel et al., RMP (2017)

Symmetry energy PACS: 21.65.Ef

More reliable probes are still needed

Model setup: initial density distribution

Skyrme-Hartree-Fock (SHF) model:

$$
\begin{aligned}
v(\vec{r}_1,\vec{r}_2) &= t_0(1+x_0P_\sigma)\delta(\vec{r}) \\
&+ \frac{1}{2}t_1(1+x_1P_\sigma)[\vec{k}'^2\delta(\vec{r})+\delta(\vec{r})\vec{k}^2] \\
&+ t_2(1+x_2P_\sigma)\vec{k}'\cdot\delta(\vec{r})\vec{k} \\
&+ \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha(\vec{R})\delta(\vec{r}) \\
&+ iW_0(\vec{\sigma}_1+\vec{\sigma}_2)[\vec{k}'\times\delta(\vec{r})\vec{k}].
\end{aligned}
$$

$$E = \sum_i \left\langle i \left| \frac{p^2}{2m} \right| i \right\rangle + \frac{1}{2}\sum_{ij}\langle ij|\,\tilde{v}_{12}\,|ij\rangle$$

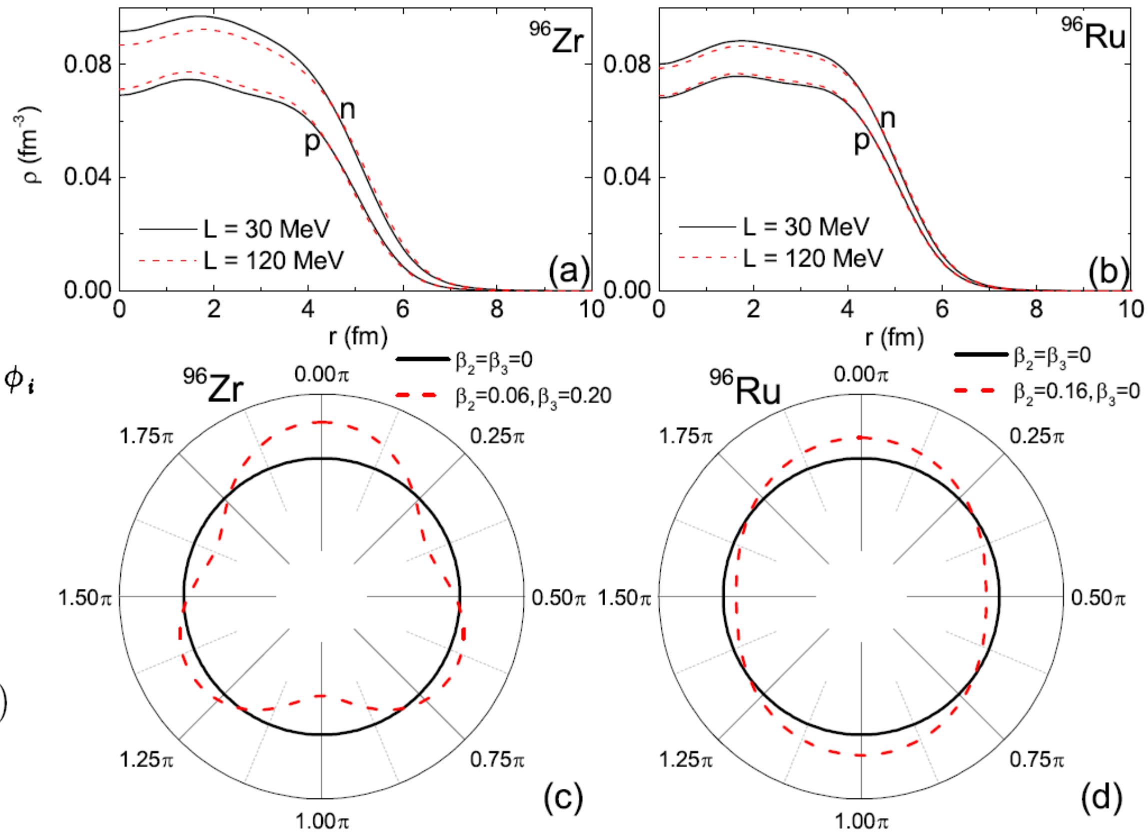
$$\frac{\delta}{\delta\phi_i}\left(E - \sum_i e_i \int |\phi_i(\vec{r})|^2 d^3r\right) = 0$$

$$\left[-\vec{\nabla}\cdot\frac{\hbar^2}{2m_q^*(\vec{r})}\vec{\nabla} + U_q(\vec{r}) + \vec{W}_q(\vec{r})\cdot(-i)(\vec{\nabla}\times\vec{\sigma})\right]\phi_i = e_i\phi_i$$

$$\rho_q(\vec{r}) = \sum_{i,\sigma} |\phi_i(\vec{r},\sigma,q)|^2$$

Quantity	MSL0	Quantity	MSL0
t_0 (MeV fm^5)	−2118.06	ρ_0 (fm^{-3})	0.16
t_1 (MeV fm^5)	395.196	E_0 (MeV)	−16.0
t_2 (MeV fm^5)	−63.953 1	K_0 (MeV)	230.0
t_3 (MeV fm$^{3+3\sigma}$)	128 57.7	$m^*_{s,0}/m$	0.80
x_0	−0.070 949 6	$m^*_{v,0}/m$	0.70
x_1	−0.332 282	$E_{\rm sym}(\rho_0)$ (MeV)	30.0
x_2	1.358 30	L (MeV)	60.0
x_3	−0.228 181	G_S (MeV fm^5)	132.0
σ	0.235 879	G_V (MeV fm^5)	5.0
W_0 (MeV fm^5)	133.3	$G_0'(\rho_0)$	0.42

L. W. Chen et al., PRC (2010)



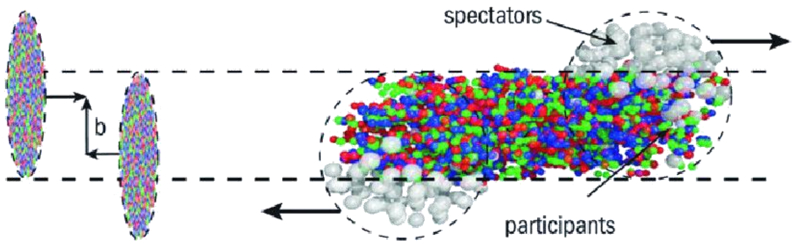
Possible deformation effect

$$\rho'(r,\theta) = [1+\alpha_2 Y_{20}(\theta) + \alpha_3 Y_{30}(\theta))]\rho(r)$$

$(\alpha_2,\alpha_3) \Leftrightarrow (\beta_2,\beta_3)$

Model setup: Glauber model

Schematic Monte-Carlo Glauber model

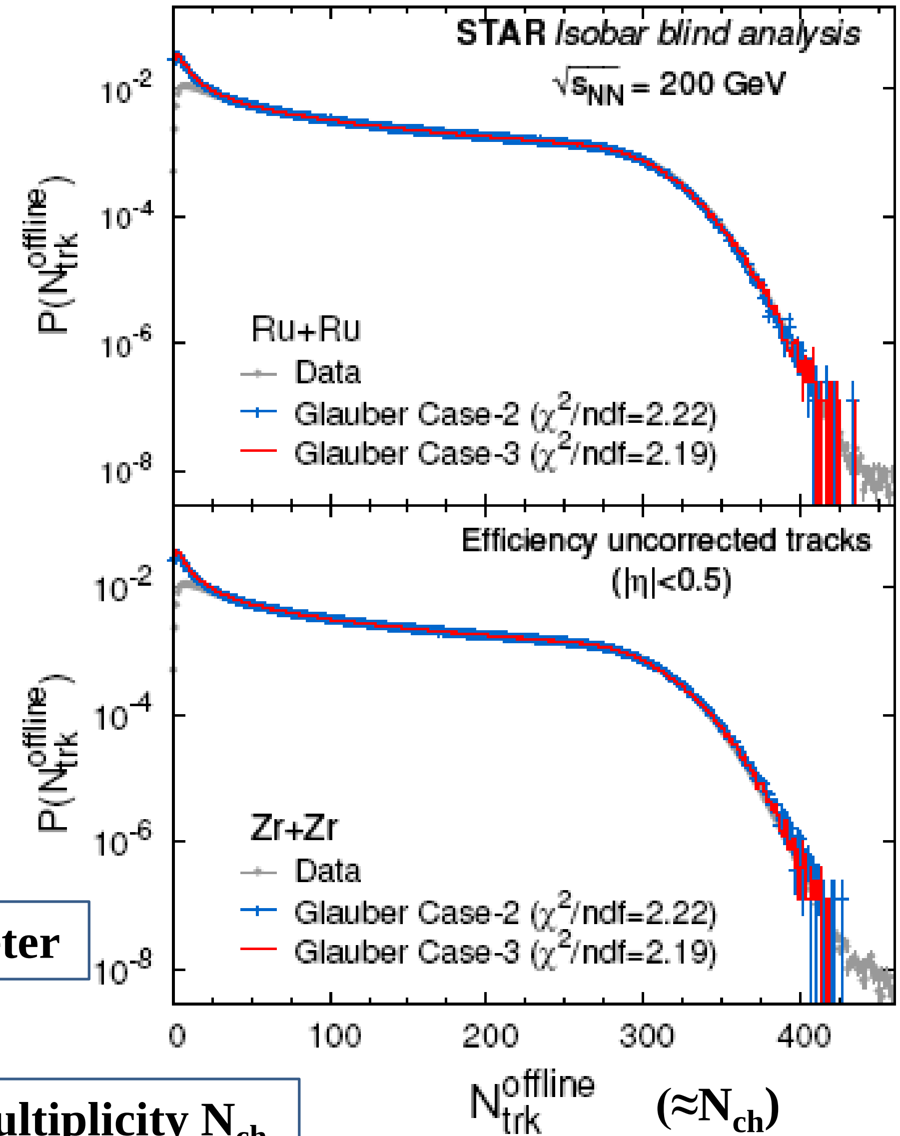


σ_{NN} **= 42 mb @200GeV**

$$N_{\mathrm{trk}}^{\mathrm{Glauber}} = n_{pp}\left[(1-x)N_{\mathrm{part}}/2 + xN_{\mathrm{coll}}\right]$$

$$P_{\mathrm{NBD}}(n_{pp}, k; n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \cdot \frac{(n_{pp}/k)^n}{(1+n_{pp}/k)^{n+k}}$$

Fit P(N_{ch}) from preliminary STAR data



Observables as a function of impact parameter

Comparable to ⇕ **experimental data**

Observables as a function of charged-particle multiplicity N_{ch}

STAR, arXiv: 2109.00131 [nucl-ex]

Model setup: clusterization and deexcitation

Dynamics of participant matter is neglected!

A. Clusterization with coalescence parameter

$\Delta r < 3$ fm (empirical nucleon interaction range)
$\Delta p < 300$ MeV/c (empirical Fermi momentum at ρ_0)

B. Cluster deexcitation with GEMINI

1. Excitation energy

(test-particle method for parallel events with similar collision configuration)

Simplified SHF EDF

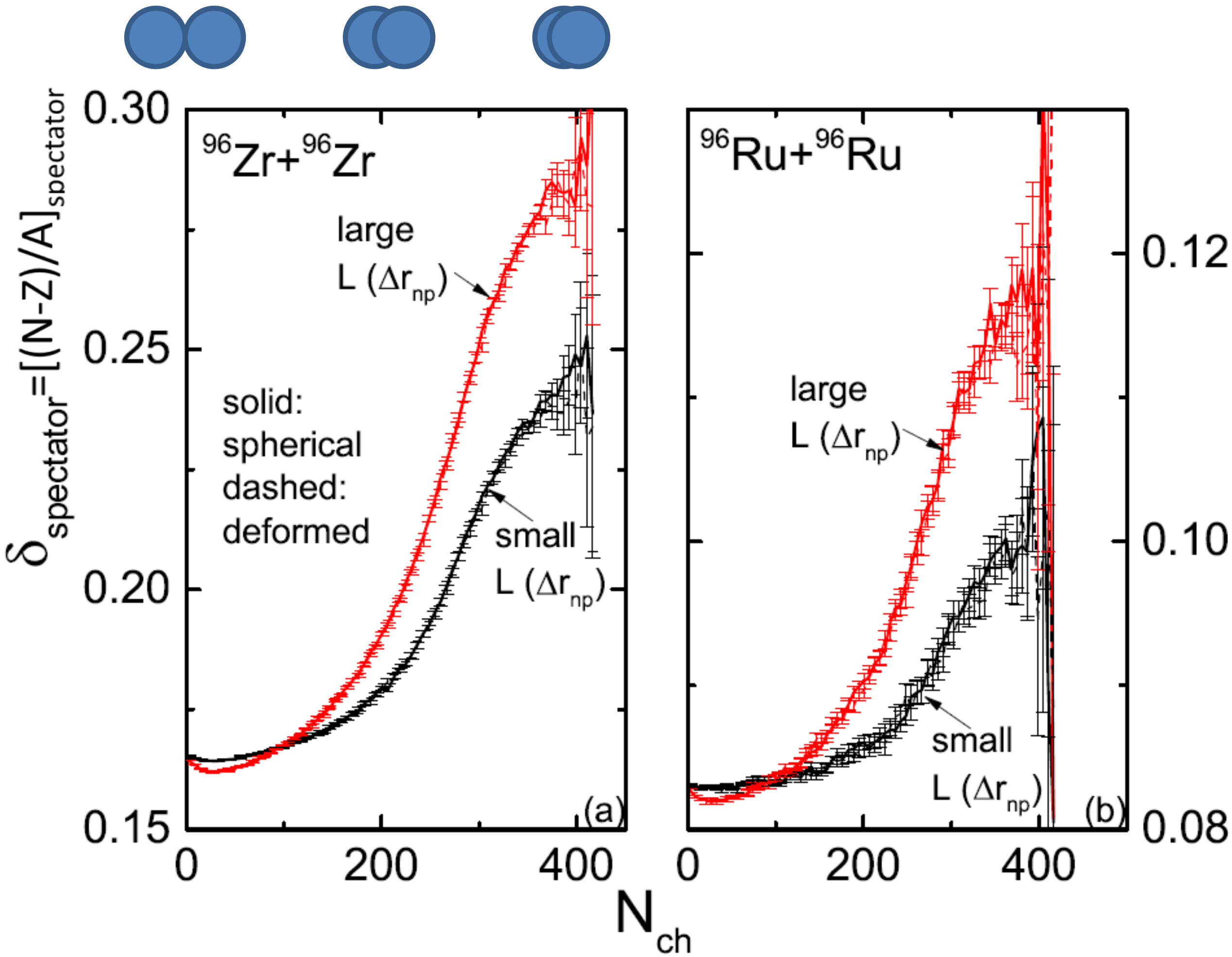
$$E = \frac{1}{N_{TP}}\sum_i\left(\sqrt{m^2+p_i^2}-m\right) + \int d^3r\left[\frac{a}{2}\left(\frac{\rho}{\rho_0}\right)^2+\frac{b}{\sigma+1}\left(\frac{\rho}{\rho_0}\right)^{\sigma+1}\right] + \int d^3r\left\{\frac{G_S}{2}(\nabla\rho)^2-\frac{G_V}{2}[\nabla(\rho_n-\rho_p)]^2\right\} + \int d^3r E_{sym}^{pot}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\frac{(\rho_n-\rho_p)^2}{\rho} + \frac{e^2}{2}\int d^3r d^3r' \frac{\rho_p(\vec{r})\rho_p(\vec{r}')}{|\vec{r}-\vec{r}'|} - \frac{3e^2}{4}\int d^3r\left[\frac{3\rho_p}{\pi}\right]^{4/3} - E_{GS}$$

2. Angular momentum

$$\vec{L} = \sum_i \vec{r}_i \times \vec{p}_i$$

A and B are two sources of free nucleons

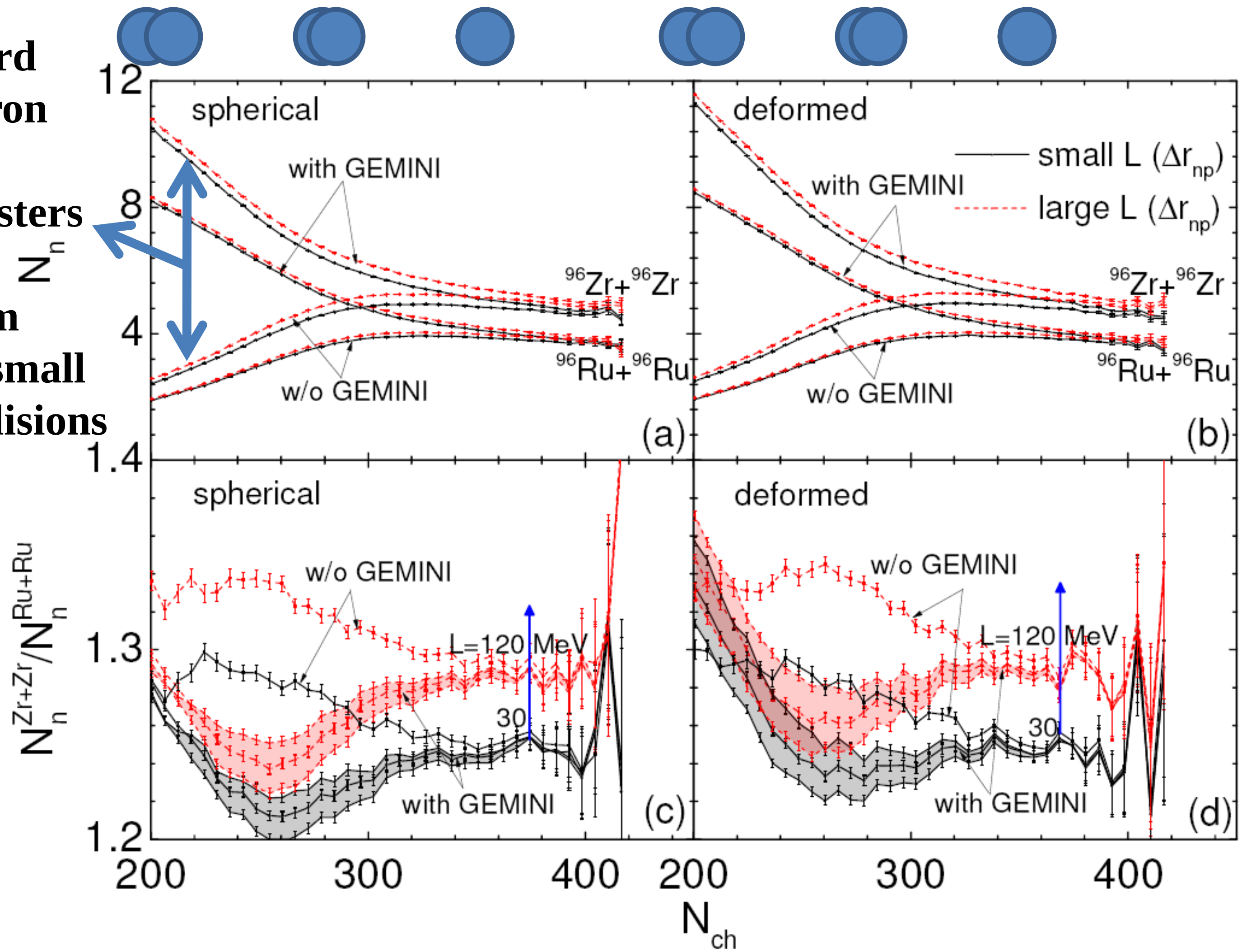
Results and discussions



- More neutron-rich spectator matter in more neutron-rich system
- More neutron-rich spectator matter in more central collisions (large N_{ch})
- More neutron-rich spectator matter with a larger L or thicker neutron-skin thickness Δr_{np}

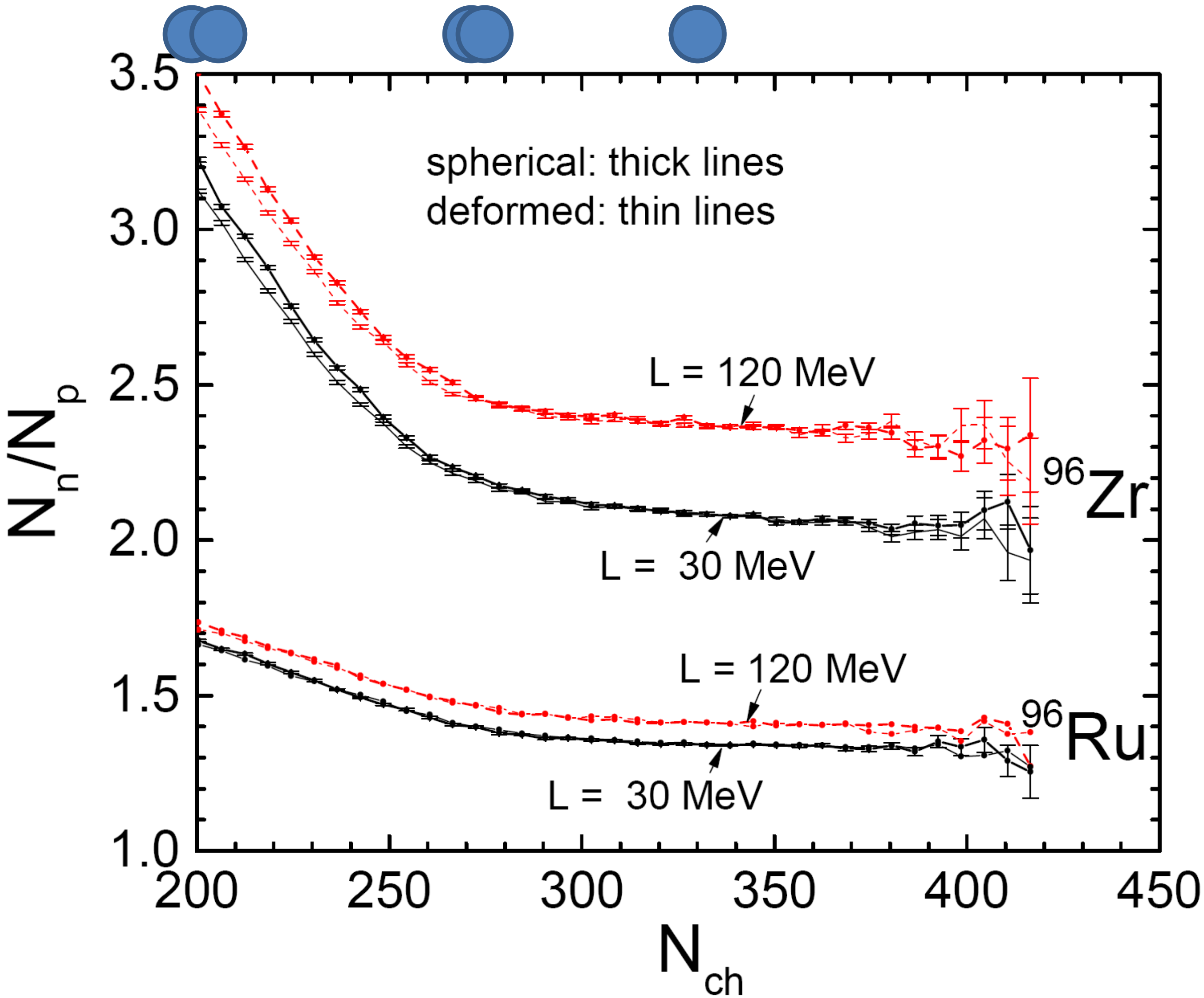
Results and discussions

- **Forward/backward rapidity free neutron numbers N_n from deexcitation of clusters**
- **Contribution from deexcitation very small in ultracentral collisions**



- **Taking ratios largely cancels theoretical/experimental uncertainties**
- **Deformation effect seems to be small**

Results and discussions



Yield ratio of forward/backward rapidity neutrons over protons could be more sensitive to L

Summary and outlook

- **Forward/backward rapidity nucleons: clean probes**
- **Ultracentral HIC: free from deexcitations**
- **Ratio of neutron-rich to neutron-poor system: reduce uncertainties**
- **Extension: yield ratio of neutrons/protons, at RHIC or LHC**

Acknowledgement

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Thank you!

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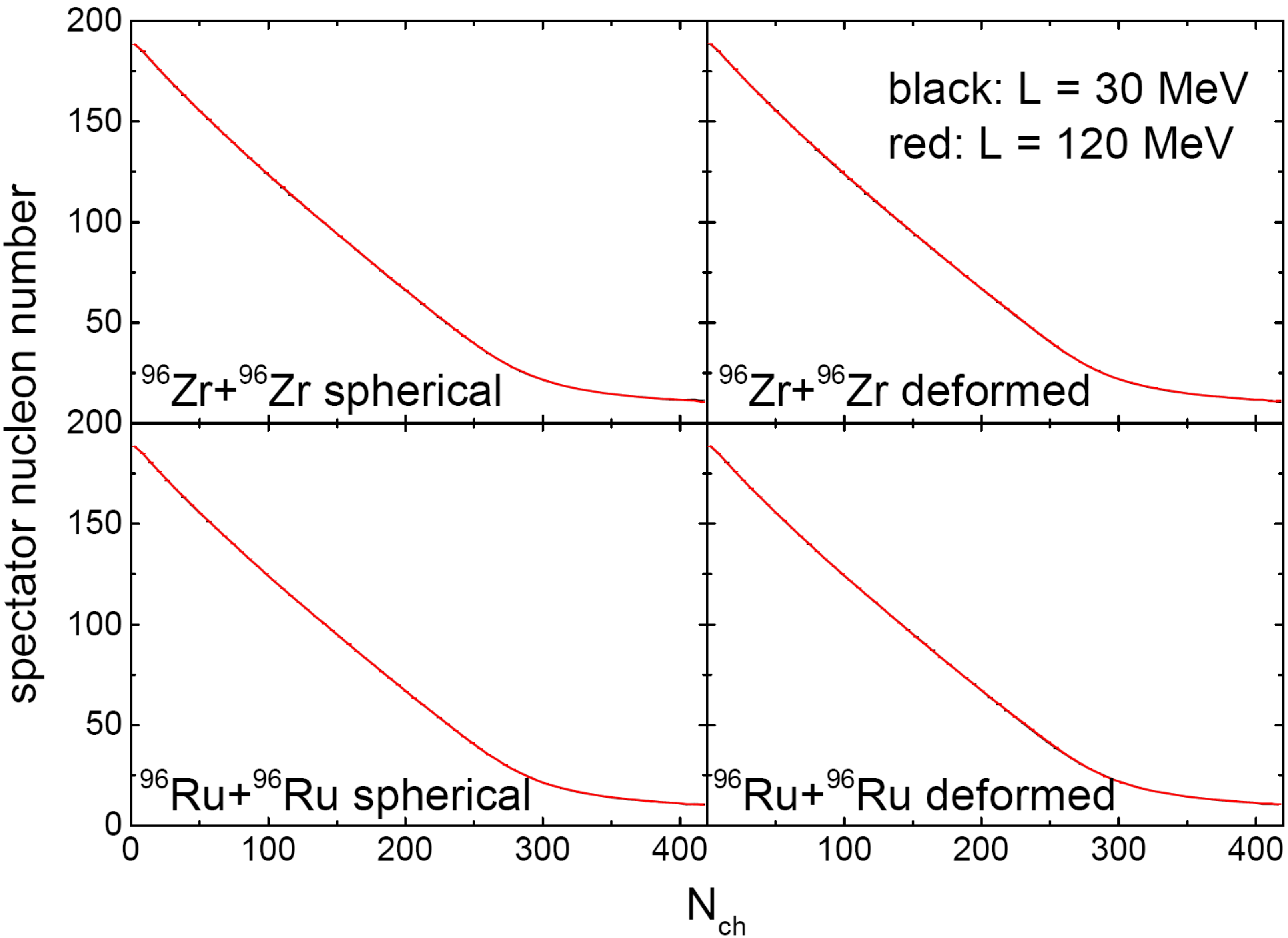
black: L = 30 MeV
red: L = 120 MeV
spectator nucleon number
N_ch
96Zr+96Zr spherical
96Zr+96Zr deformed
96Ru+96Ru spherical
96Ru+96Ru deformed
0
50
100
150
200
0
100
200
300
400