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Probing neutron skin with free spectator nucleons in ultracentral relativistic heavy-ion collisions

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Chun-Jian Zhang (张春健)(Stony Brook)

Lu-Meng Liu, Chun-Jian Zhang, Jia Zhou, JX*, Jiangyong Jia*, and Guang-Xiong Peng,
Phys. Lett. B 834, 137441 (2022), arXiv: 2203.09924 [nucl-th]

Lu-Meng Liu, Chun-Jian Zhang, JX*, Jiangyong Jia*, and Guang-Xiong Peng,
Phys. Rev. C 106, 034913 (2022), arXiv: 2209.03106 [nucl-th]

Lu-Meng Liu, JX*, and Guang-Xiong Peng,
Nucl. Phys. Rev. 40, 2022095 (2023), arXiv: 2301.08251 [nucl-th]

Lu-Meng Liu, JX*, and Guang-Xiong Peng,
Phys. Lett. B 838, 137701 (2023), arXiv: 2301.07893 [nucl-th]

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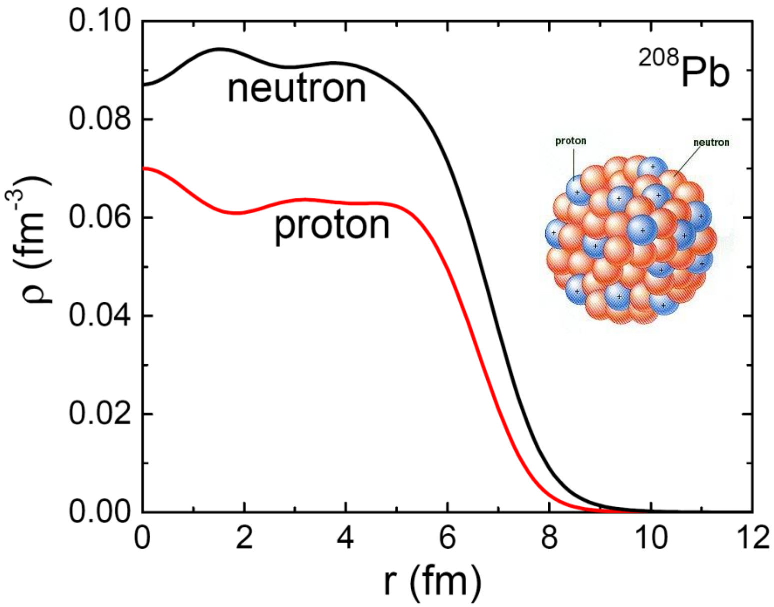
Neutron skin and E_{sym}



Neutron-Skin Thickness:

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

For ^{208}Pb:

$\Delta r_{np} = 0.211^{+0.054}_{-0.063}$ fm **from proton scattering**

$\Delta r_{np} = 0.16 \pm 0.07$ fm **from pion scattering**

$\Delta r_{np} = 0.18 \pm 0.04(\text{expt.}) \pm 0.05(\text{theor.})$ fm **from $\bar{p}$ annihilation**

$\Delta r_{np} = 0.15 \pm 0.03(\text{stat.})^{+0.01}_{-0.03}(\text{sys.})$ fm **from coherent pion photoproduction**

$\Delta r_{np} = 0.283 \pm 0.071$ fm **from parity-violating electron scatterings**

Energy per nucleon in asymmetric matter

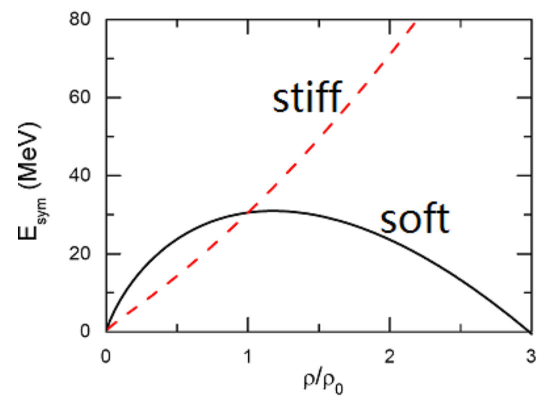
Symmetry energy

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

Energy per nucleon in symmetric matter

$\rho = \rho_n + \rho_p$

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



Expansion around saturation density ρ_0

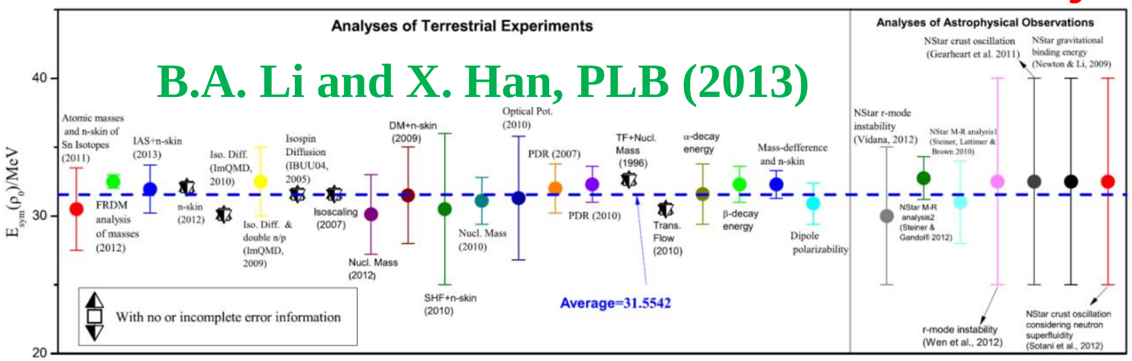
$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \ldots$$

$$\chi = \frac{\rho - \rho_0}{3\rho_0}$$

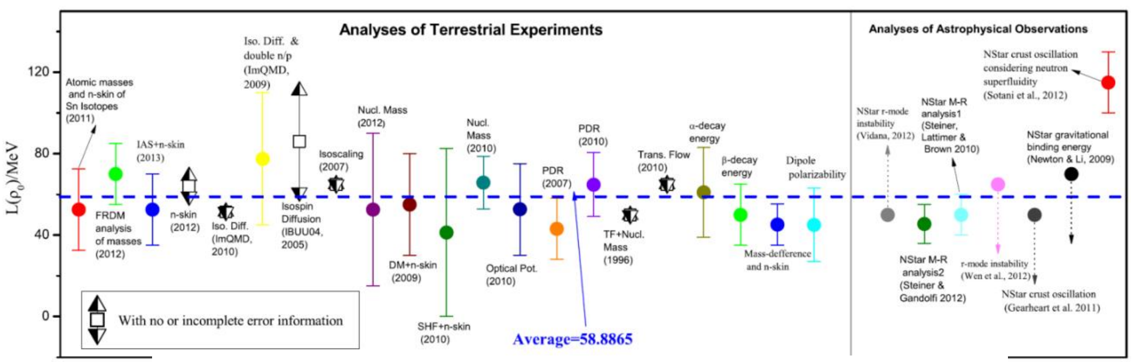
Slope parameter

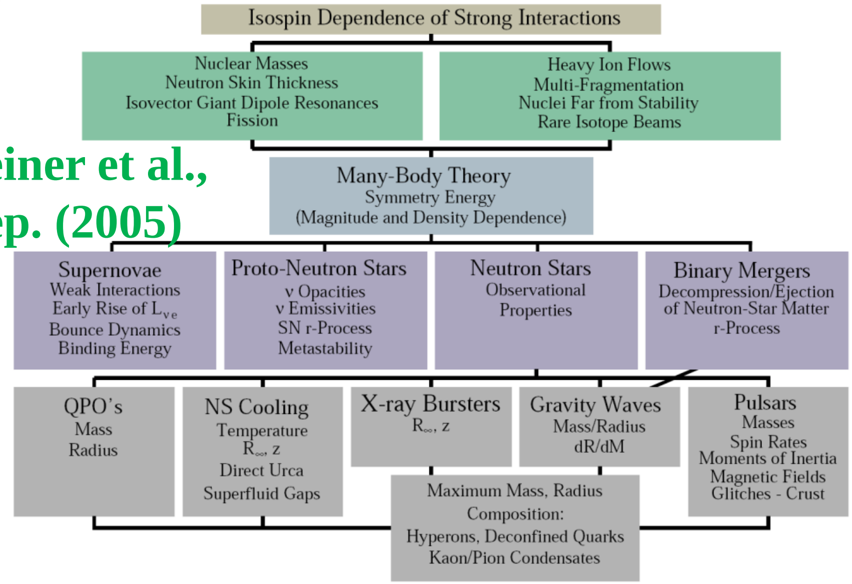
$$L = 3\rho_0 \left[\frac{\partial E_{sym}(\rho)}{\partial \rho} \right]_{\rho=\rho_0}$$

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

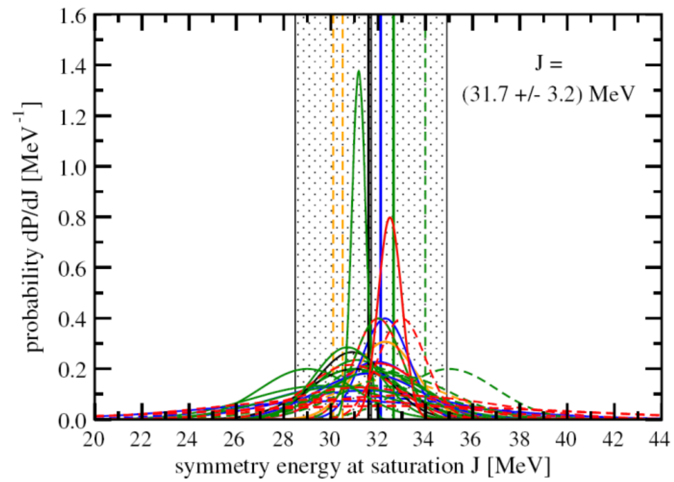


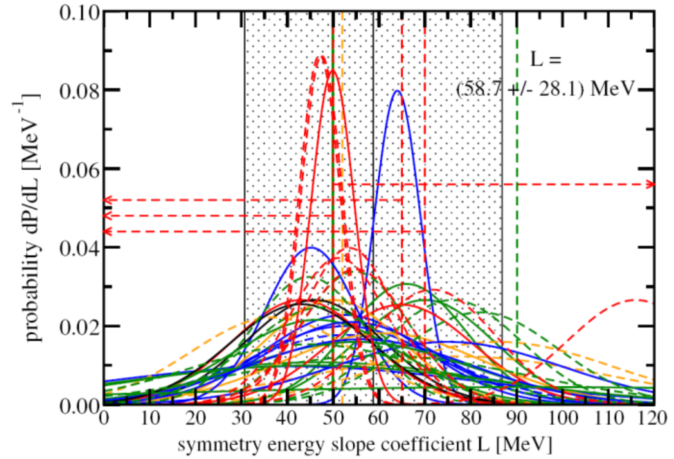
B.A. Li and X. Han, PLB (2013)





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



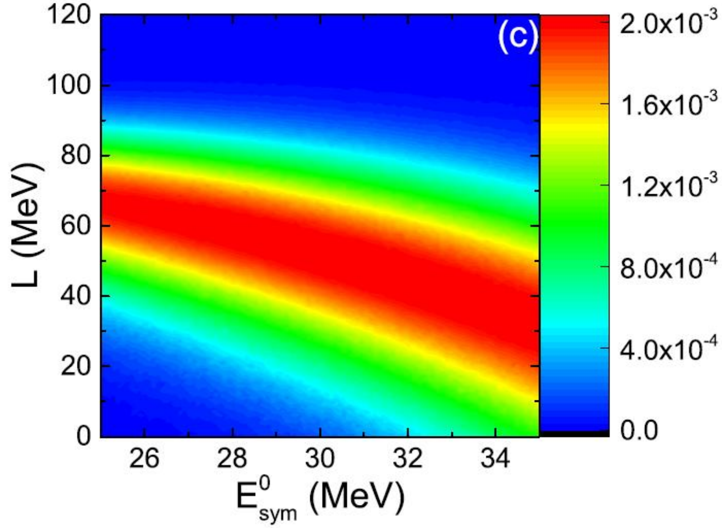


M. Oertel et al., RMP (2017)

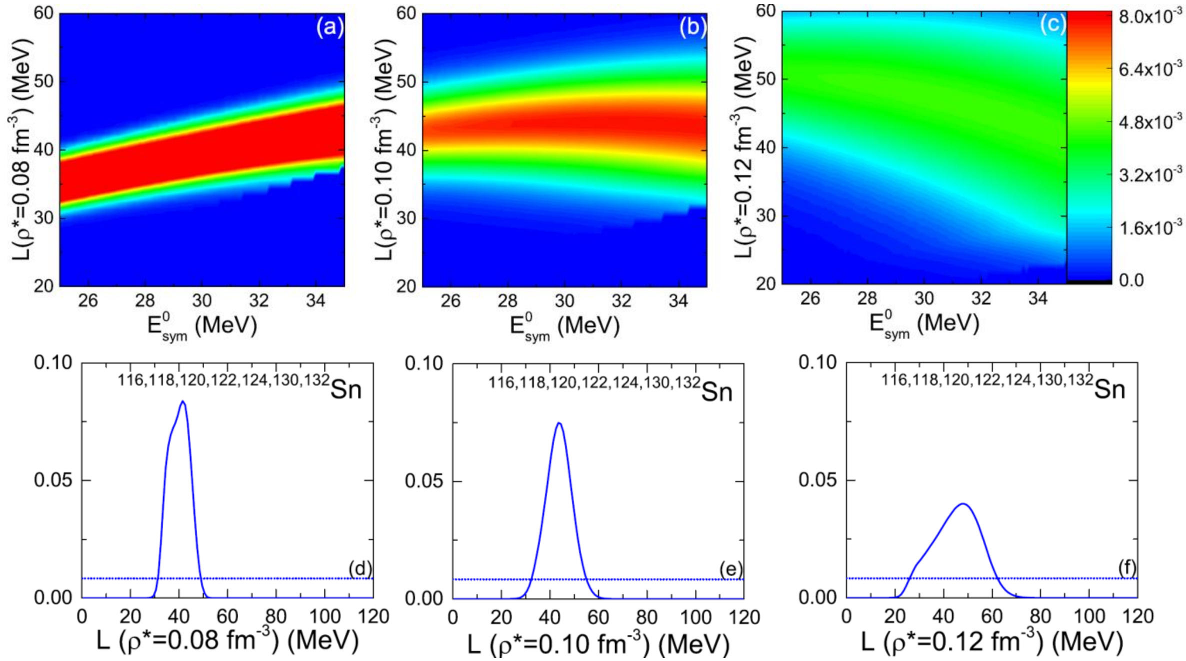
Symmetry energy PACS: 21.65.Ef

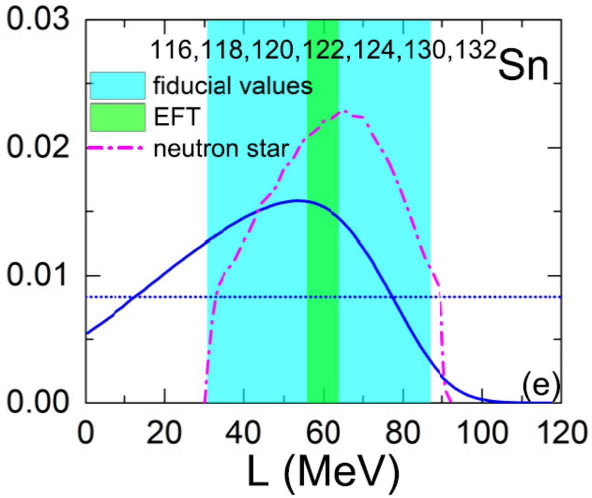
More reliable probes are still needed

Constraint on E_{sym} from Δr_{np}

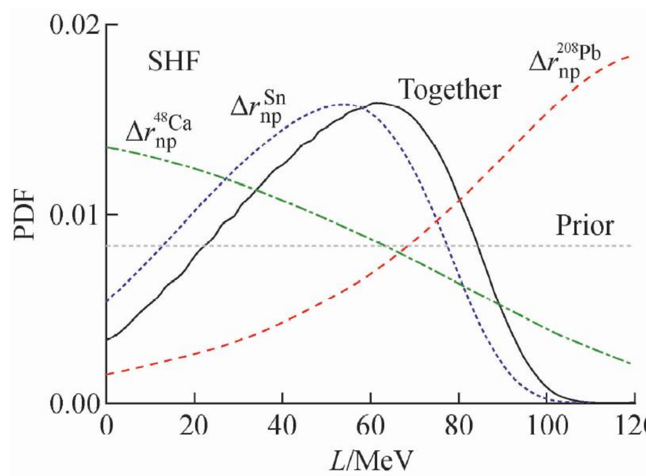


Δr_{np} **dominated by L(0.10)** $L(\rho^\star) = 3\rho^\star(dE_{sym}/d\rho)_{\rho^\star}$





^{208}**Pb: PREXII**
Sn: p-Sn scatterings
^{48}**Ca: CREX**

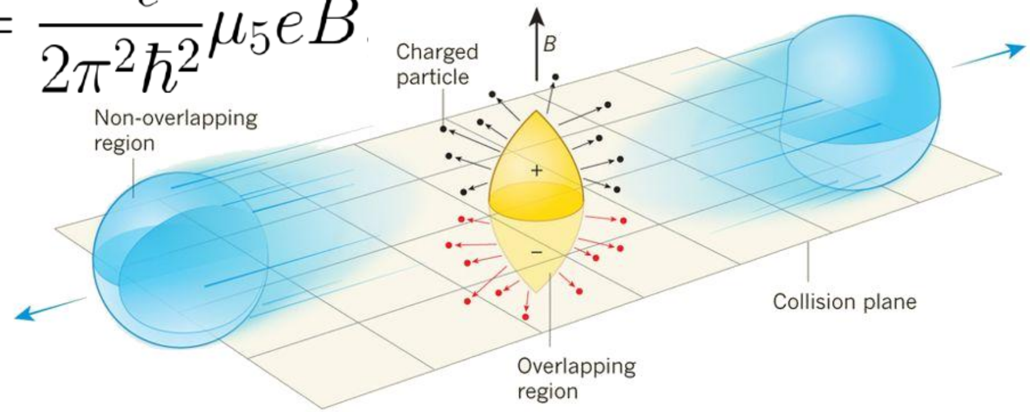


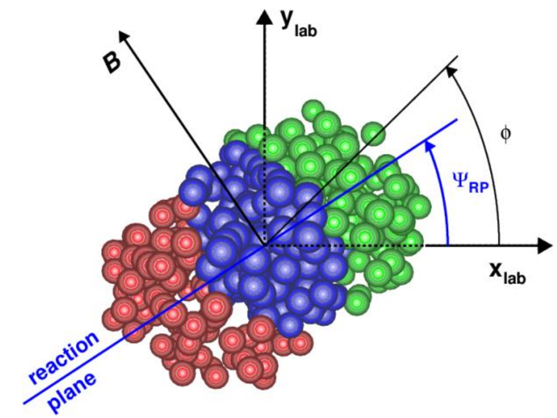
JX, W.J. Xie, and B.A. Li, PRC (2020)

JX, arXiv: 2301.07884 [nucl-th]

CME and isobaric collisions

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

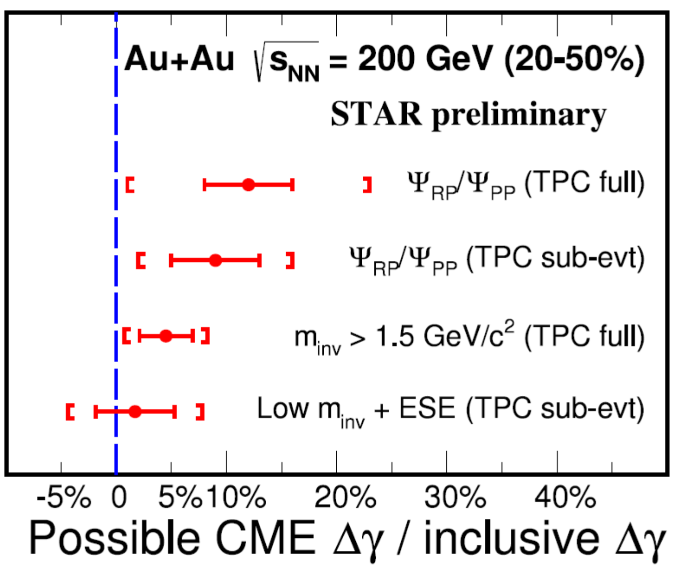




$$\gamma_{\alpha\beta} = \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle$$

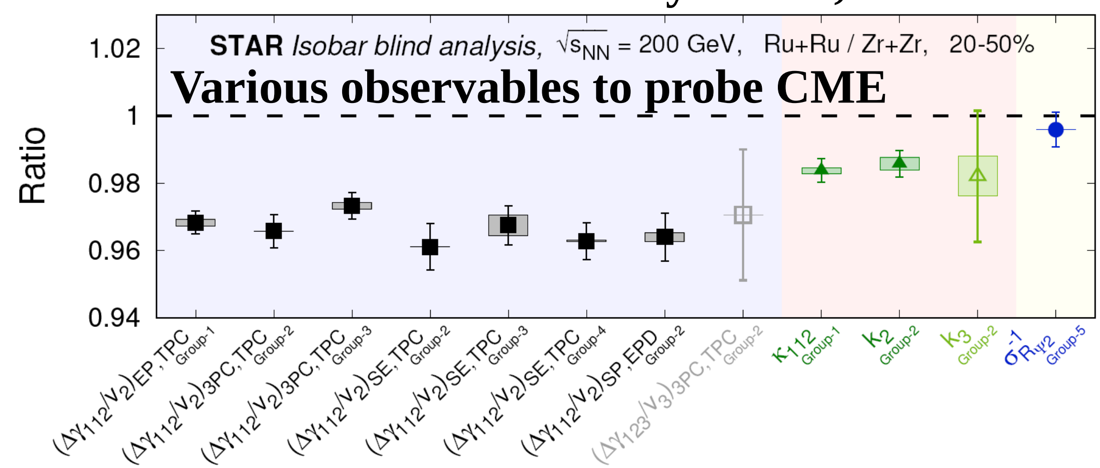
S. A. Voloshin, PRC (2004)

Significant background contribution



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

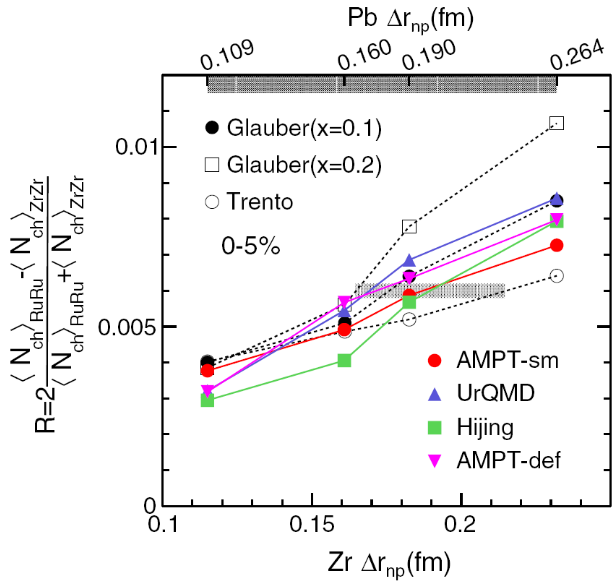
Isobaric collisions: similar bulk dynamics, different B



STAR, PRC (2022)

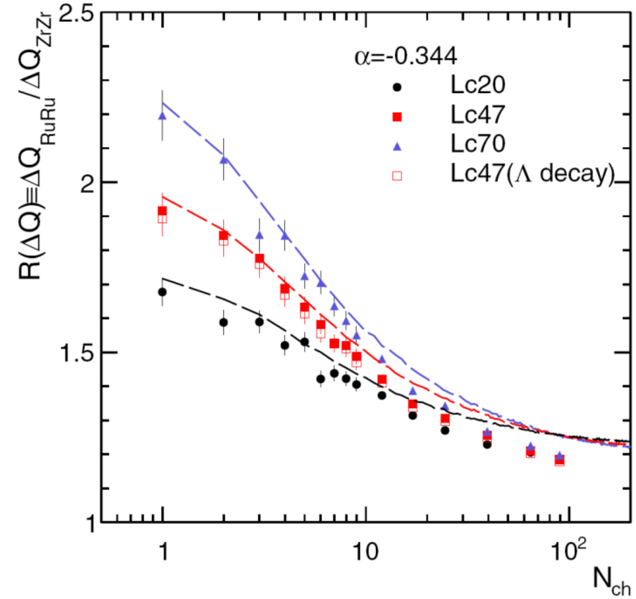
Isobaric collisions to probe neutron skin

Charged-particle multiplicity



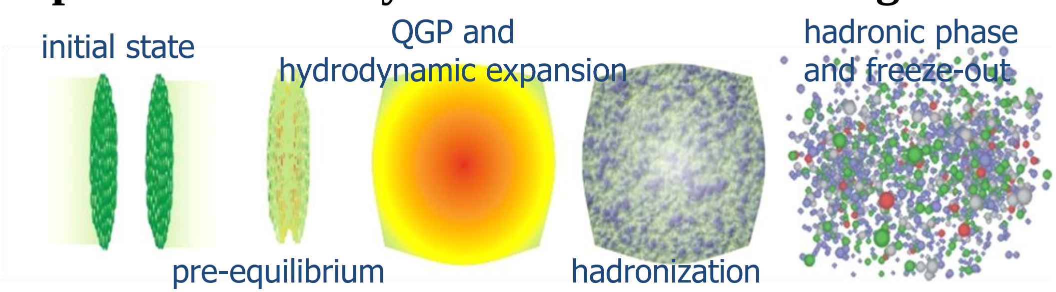
H.L. Li et al., PRL (2020)

Net-charge multiplicity

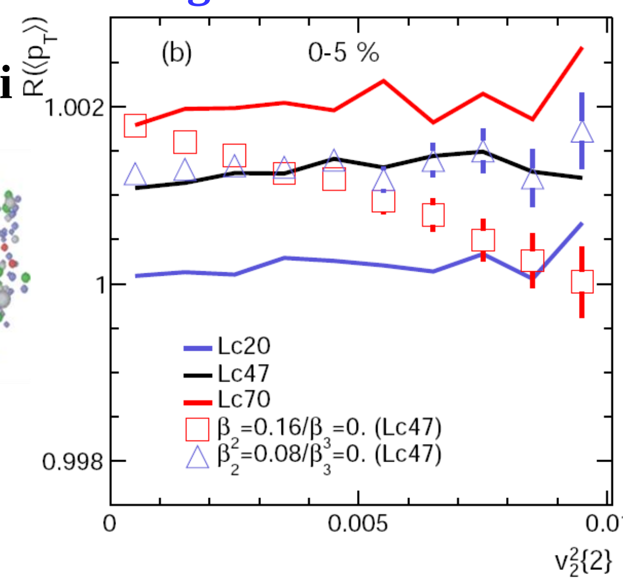


H.J. Xu et al., PRC (2020)

probe the density distribution of colliding nuclei



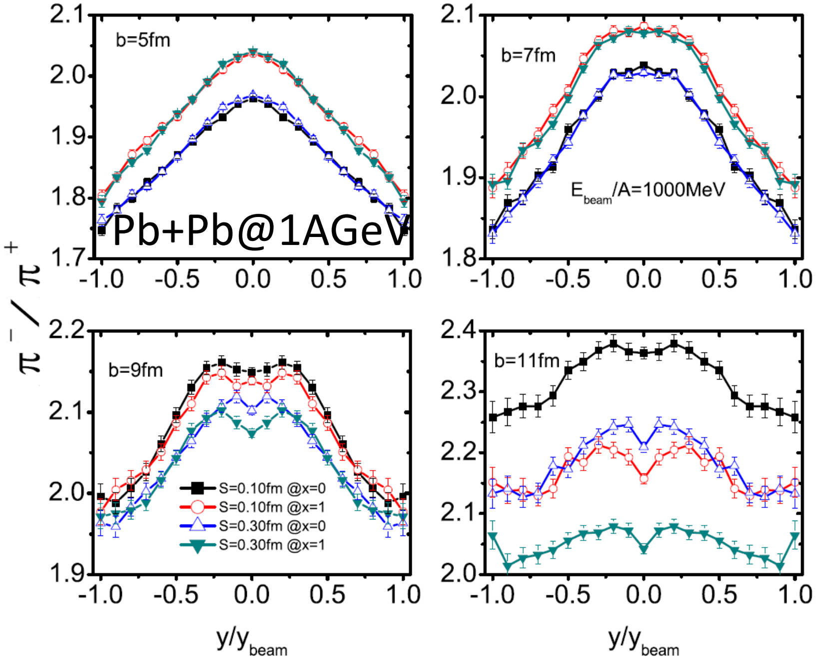
Average transverse momentum



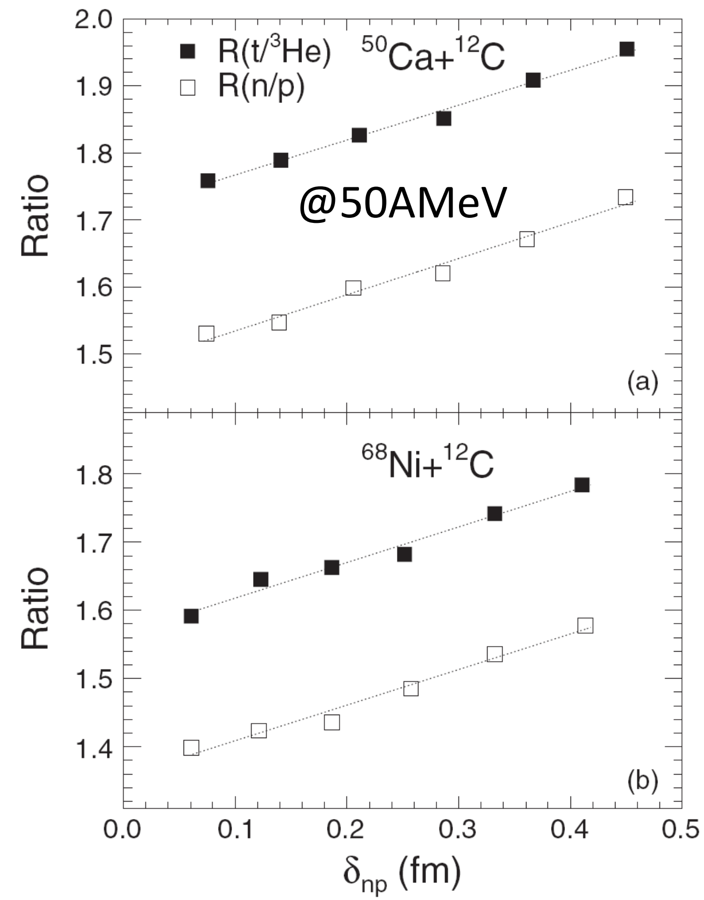
H.J. Xu et al., arXiv: 2111.14812 [nucl-th]

Observables at midrapidities suffer from complicated dynamics and model dependence

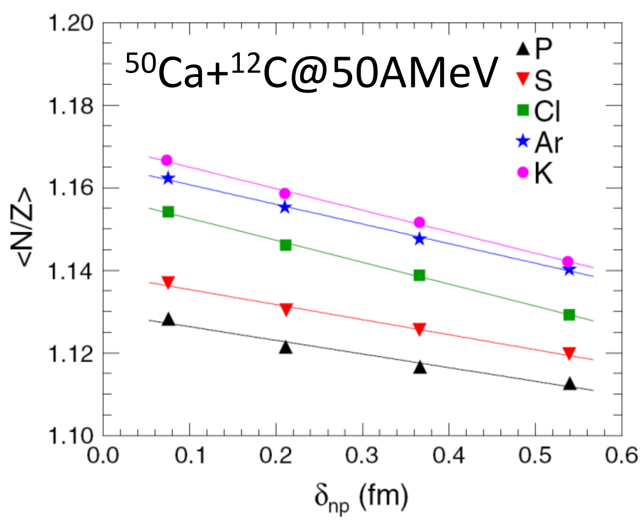
Intermediate-energy HIC to probe neutron skin



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



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

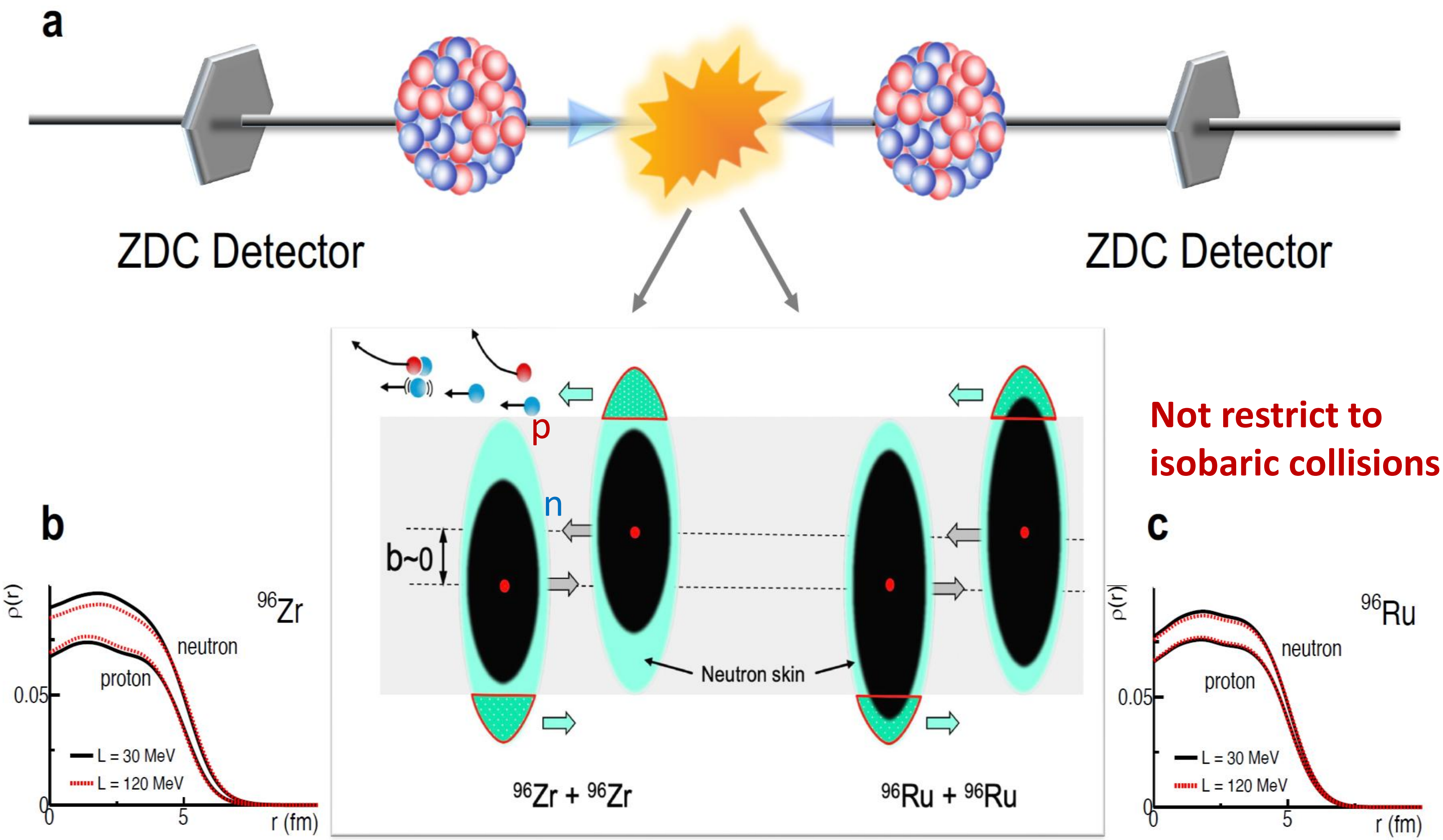


Z.T. Dai et al., PRC (2015)

Suffer from:

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

Basic idea of our studies



Not restrict to isobaric collisions

Advantages:

1) **Spectator matter has almost no interaction with participant matter**
2) **UCC region, free from uncertainties of clusterization/multifragmentation**

Model setup: initial density distribution

Skyrme-Hartree-Fock (SHF) model:

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

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, C.M. Ko, B.A. Li, and JX PRC (2010)

Paring interaction

$$V_{\rm pair}^{(n,p)} = V_0^{(n,p)}\left(1-\frac{1}{2}\frac{\rho(\vec{r})}{\rho_0}\right)\delta(\vec{r}_1-\vec{r}_2)$$

Hartree-Fock method:

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

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

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

Hartree-Fock-Bogoliubov method:

$$\int d^3\mathbf{r}'\sum_{\sigma'}\begin{pmatrix} h(\mathbf{r}\sigma,\mathbf{r}'\sigma') & \tilde{h}(\mathbf{r}\sigma,\mathbf{r}'\sigma') \\ \tilde{h}(\mathbf{r}\sigma,\mathbf{r}'\sigma') & -h(\mathbf{r}\sigma,\mathbf{r}'\sigma')\end{pmatrix}\begin{pmatrix}\varphi_1(E,\mathbf{r}'\sigma')\\ \varphi_2(E,\mathbf{r}'\sigma')\end{pmatrix}$$

$$=\begin{pmatrix} E+\lambda & 0 \\ 0 & E-\lambda\end{pmatrix}\begin{pmatrix}\varphi_1(E,\mathbf{r}\sigma)\\ \varphi_2(E,\mathbf{r}\sigma)\end{pmatrix}$$

Particle density

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

Particle density

$$\rho(r)=\sum_i\varphi_2(E_i,r)^2$$

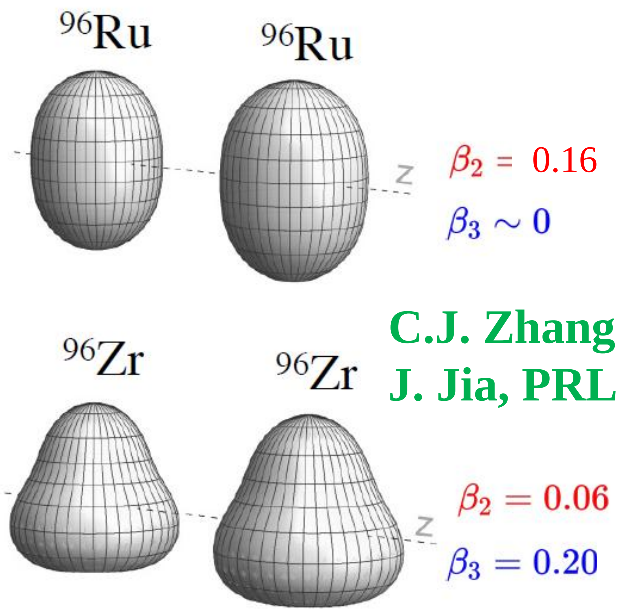
Pairing density

$$\tilde{\rho}(r)=-\sum_i\varphi_1(E_i,r)\varphi_2(E_i,r)$$

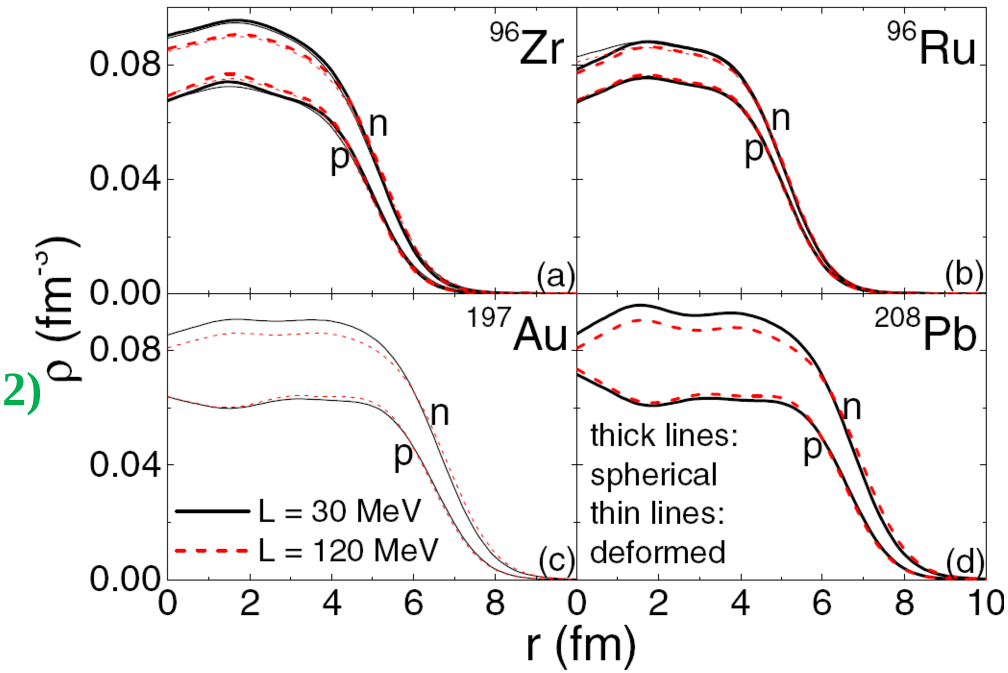
Reproduce E_b and R_c within 1.5%

M.V. Stoitsov et al., CPC (2013)

Model setup: initial density distribution



C.J. Zhang and J. Jia, PRL (2022)



Multipole moments

$$Q_{\lambda,\tau} = \int \rho_\tau(\vec{r}) r^\lambda Y_{\lambda 0}(\theta) d^3 r$$

Deformation parameters

$$\beta_{\lambda,\tau} = \frac{4\pi Q_{\lambda,\tau}}{3 N_\tau R^\lambda}$$

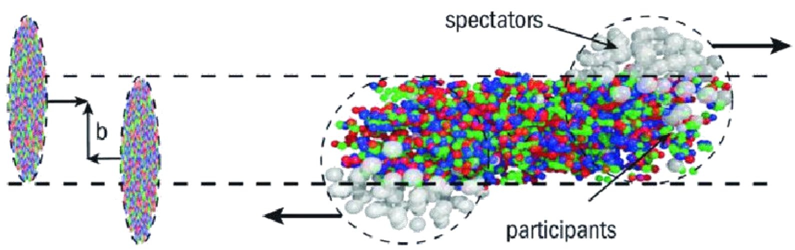
Constrained SHFB calculation with fixed Q_λ (β_λ)

TABLE II. Neutron-skin thicknesses $\Delta r_{\rm np}$ and deformation parameters β_2 and β_3 for different nuclei using different slope parameters L of the symmetry energy from SHFB calculations.

		$\Delta r_{\rm np}$ (fm)	
Nucleus	β_2, β_3	$L = 30$ MeV	$L = 120$ MeV
^{96}Zr	0, 0	0.147	0.231
	0.06, 0.2 [43]	0.145	0.227
^{96}Ru	0, 0	0.028	0.061
	0.16, 0 [43]	0.026	0.058
^{197}Au	−0.15, 0 [44,45]	0.127	0.243
^{208}Pb	0, 0	0.149	0.281

Model setup: Glauber model

Schematic Monte-Carlo Glauber model



Numbers of sources

$$N_s = (1-x)\frac{N_{\mathrm{part}}}{2} + xN_{\mathrm{coll}}$$

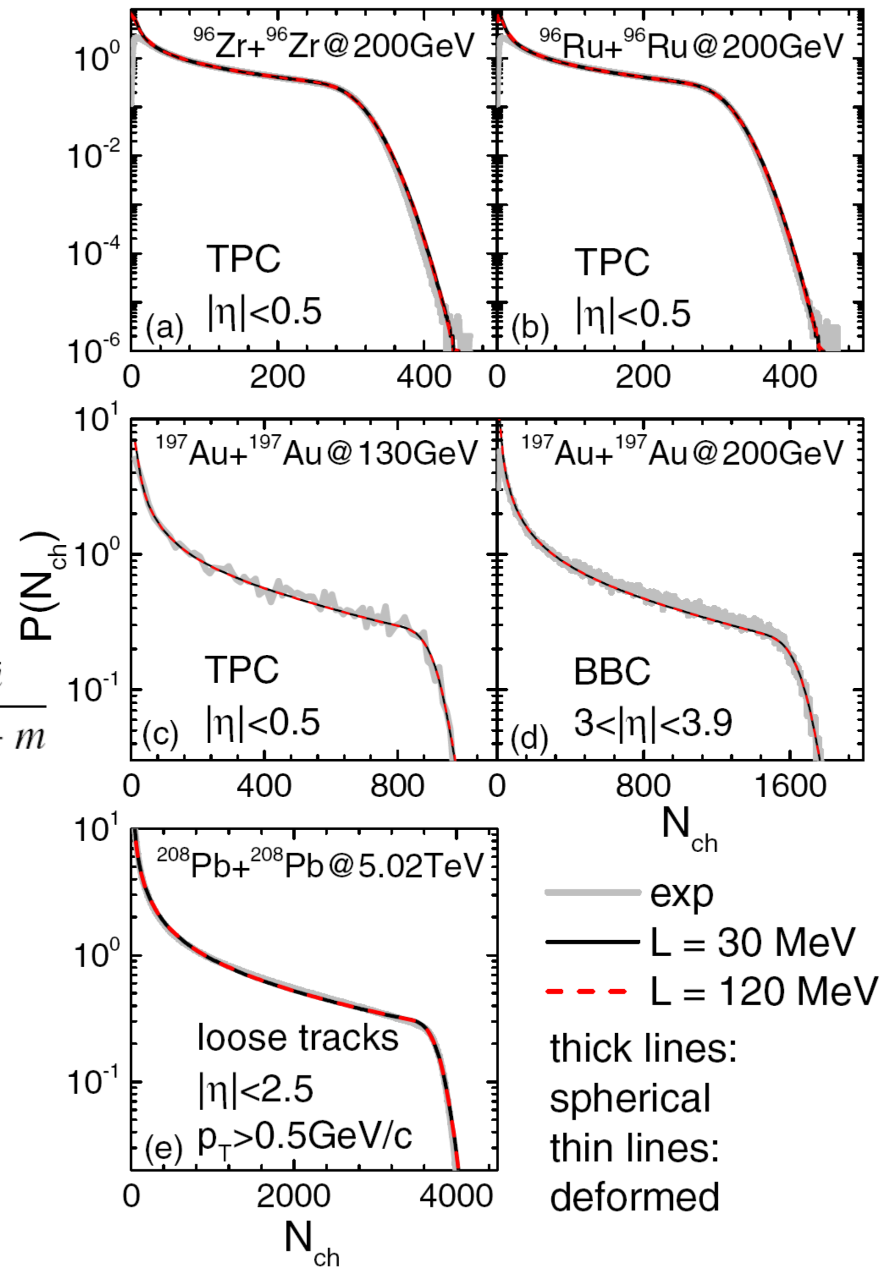
Particle production n from each source

$$p_{\mathrm{nbd}}(n;m,p) = \frac{(n+m-1)!}{(m-1)!n!}p^n(1-p)^m$$

$$p = \frac{\bar{n}}{\bar{n}+m}$$

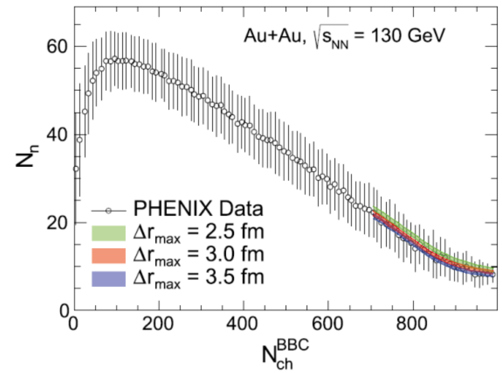
$\sqrt{s_{NN}}$	130 GeV	200 GeV	5.02 TeV
σ_{NN}	40 mb	42 mb	68 mb

	$\sqrt{s_{\mathrm{NN}}}$	x	$\bar{n}$	m
^{96}Zr + ^{96}Zr	200 GeV	0.12	2.3	2.0
^{96}Ru + ^{96}Ru	200 GeV	0.12	2.3	2.2
^{197}Au + ^{197}Au	130 GeV	0	4.8	4.6
^{197}Au + ^{197}Au	200 GeV	0.10	5.8	2.3
^{208}Pb + ^{208}Pb	5.02 TeV	0.09	10.3	3.2



Model setup: multifragmentation process

Dynamics of participant matter is neglected!



A. Formation of heavy (A>3) clusters

MST

Δr < 3 fm (empirical nucleon interaction range)

Δp < 300 MeV/c (empirical Fermi momentum at ρ_0)

B. Heavy (A>3) cluster deexcitation with GEMINI

1. Excitation energy

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

Simplified SHF EDF

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

2. Angular momentum

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

Free nucleons:

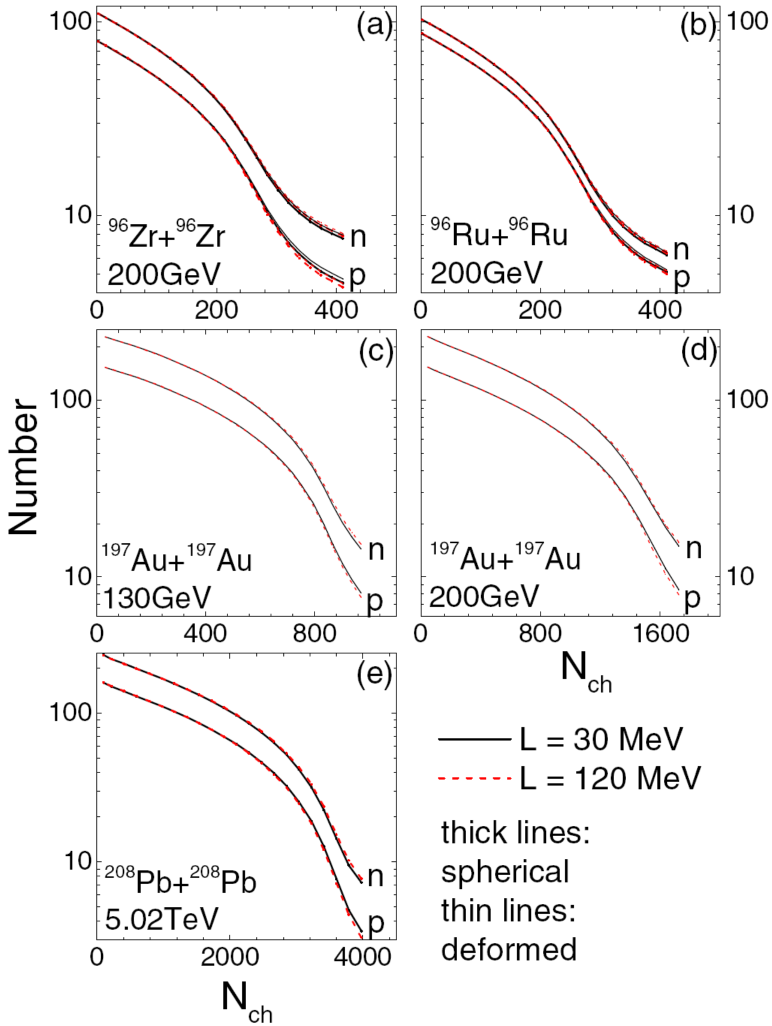
1) Direct production from A and residue from C

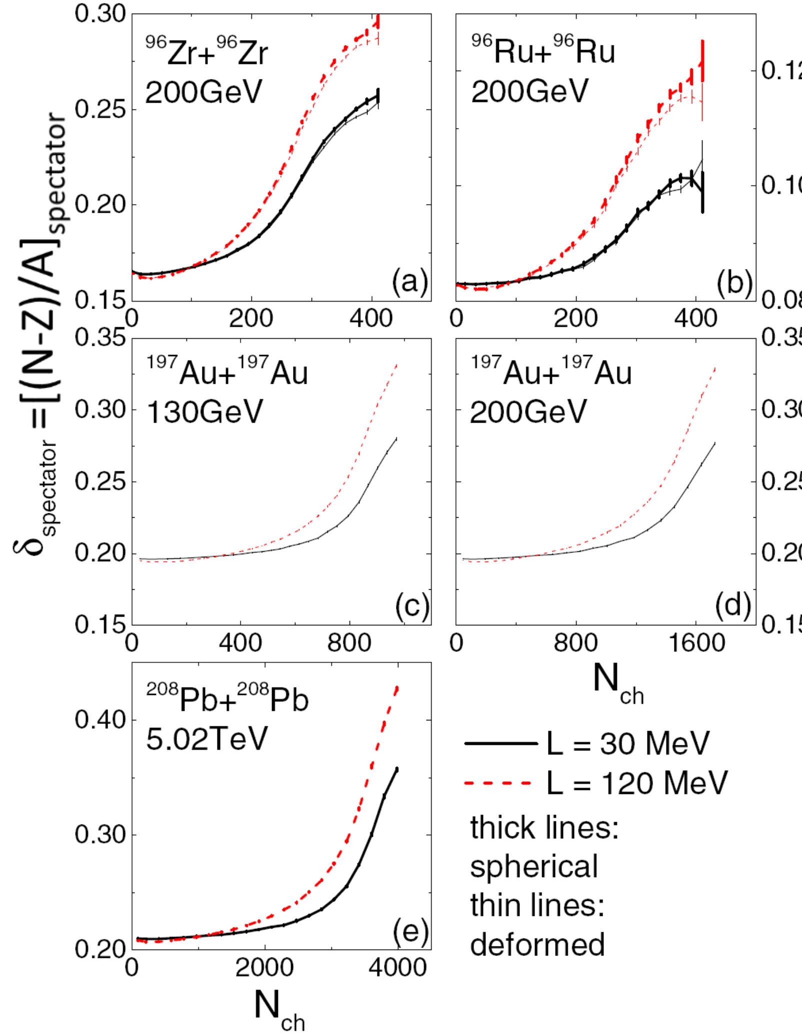
2) Deexcitation from B

C. Coalescence for light (A=2,3) clusters

$$f_d=8g_d\exp\left(-\frac{\rho^2}{\sigma_d^2}-p_\rho^2\sigma_d^2\right) \qquad f_{t/^3\mathrm{He}}=8^2g_{t/^3\mathrm{He}}\exp\left[-\left(\frac{\rho^2+\lambda^2}{\sigma_{t/^3\mathrm{He}}^2}\right)-(p_\rho^2+p_\lambda^2)\sigma_{t/^3\mathrm{He}}^2\right]$$

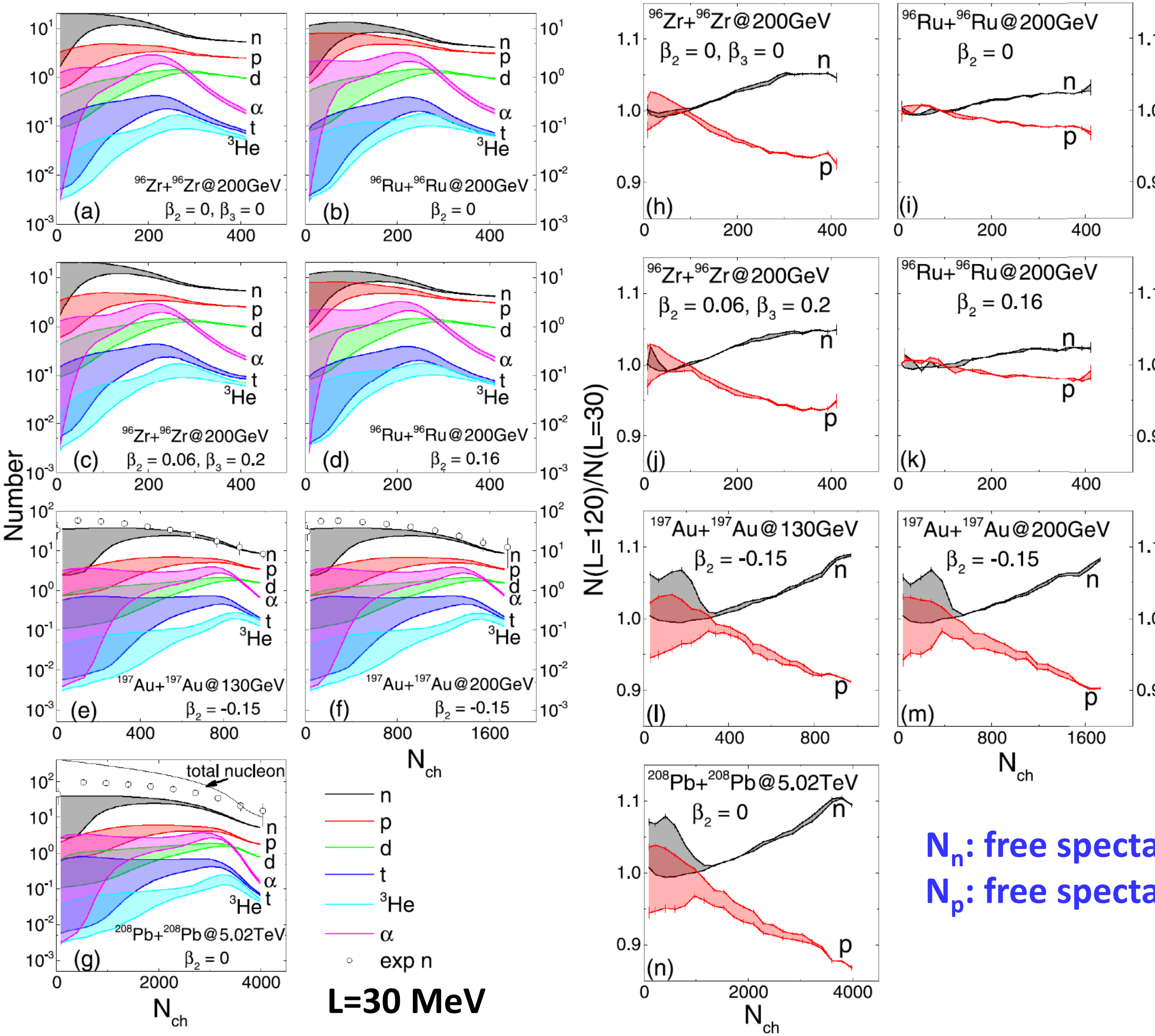
Results and discussions: spectator matter





- **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 a thicker neutron skin Δr_{np}**

Results and discussions: spectator particle yield



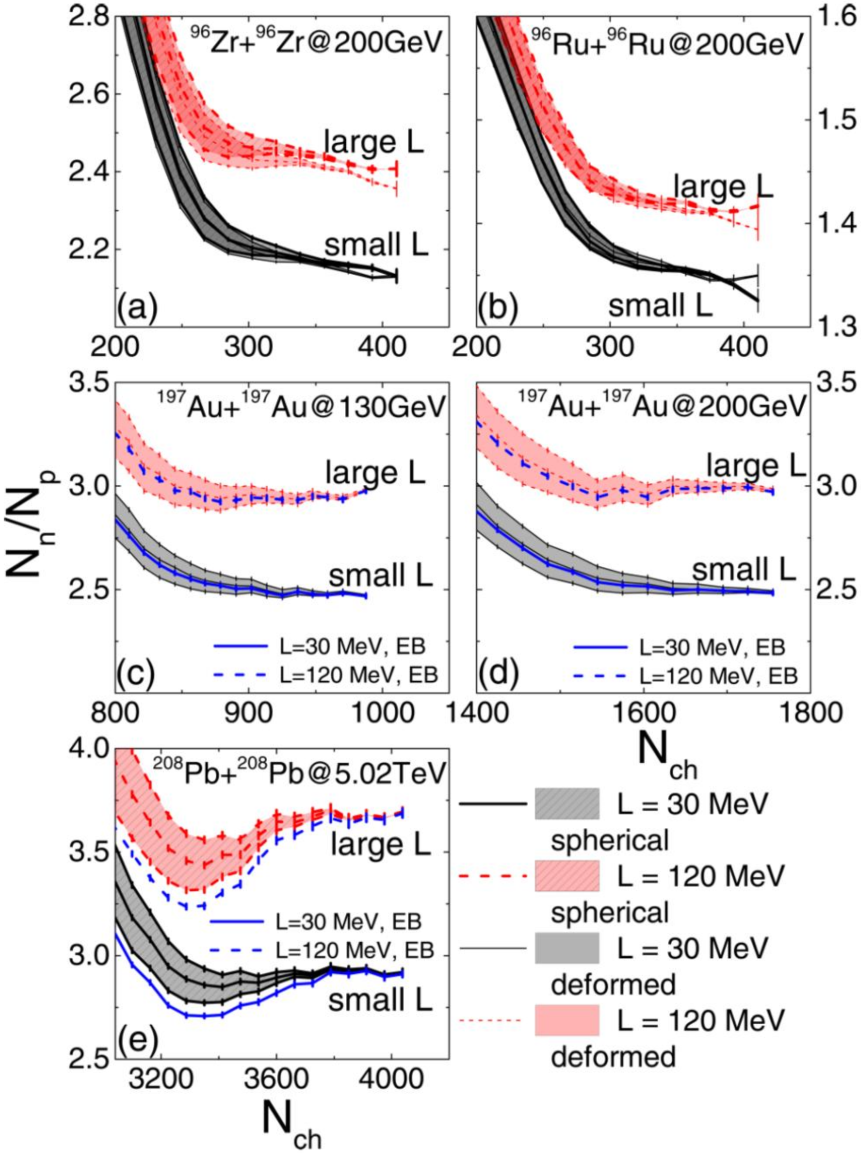
L=30 MeV

Band:
E/A ±1 MeV

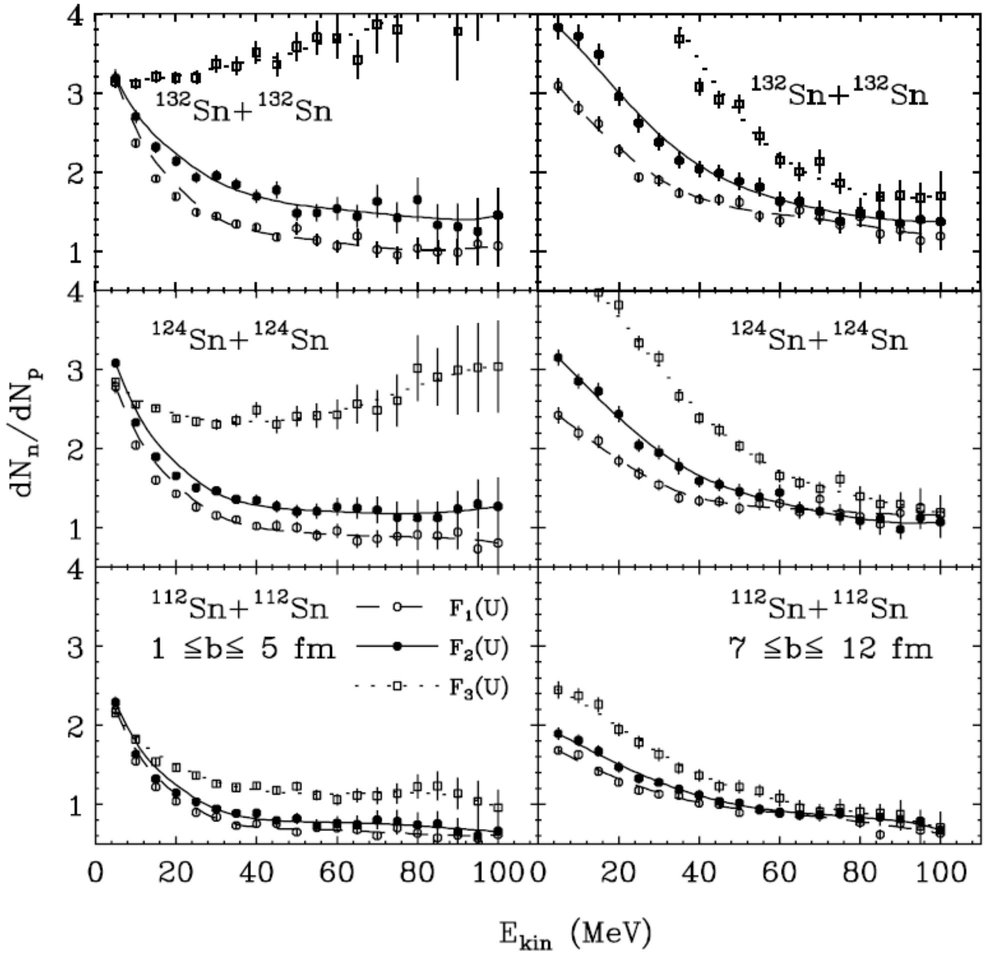
- **Non monitonic dependence on N_{ch}**
- **Difference between N_n and N_p large at UCC, increasing with L or Δr_{np}, with small band**
- **Underestimate N_n at high energies (background?)**

N_n: free spectator neutron number
N_p: free spectator proton number

Results and discussions: probing L or Δr_{np}

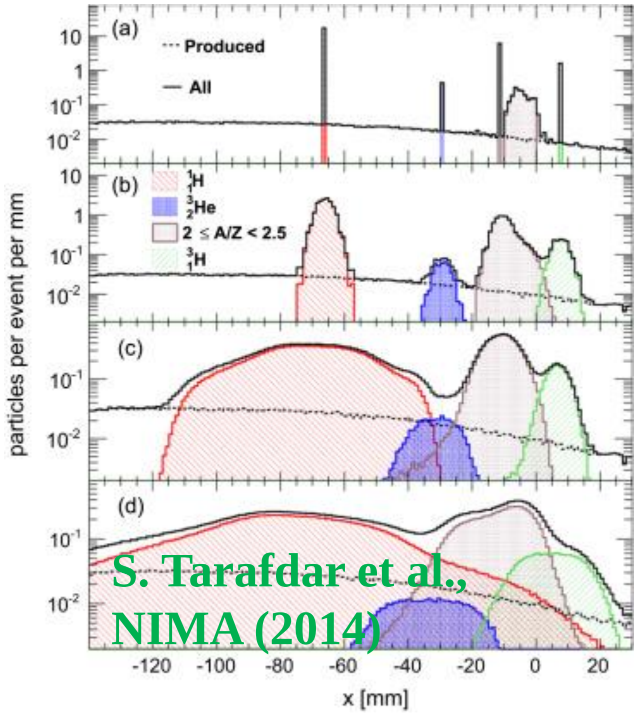


Sn+Sn@40MeV

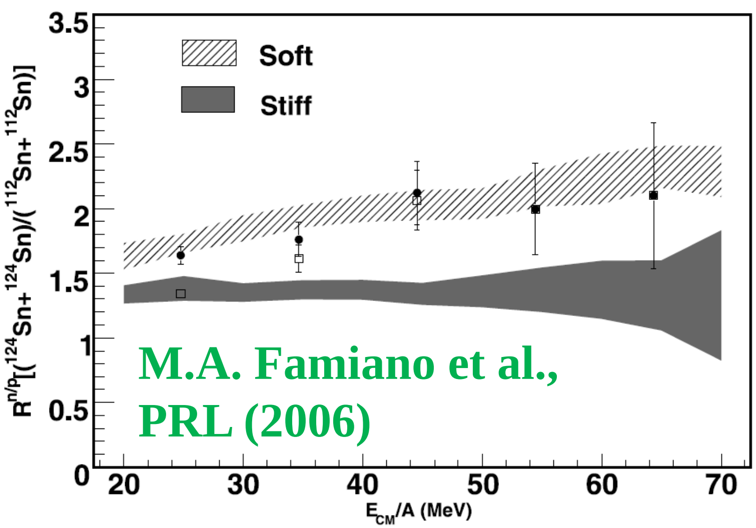


B.A. Li, C.M. Ko, and Z.Z. Ren, PRL (1997)

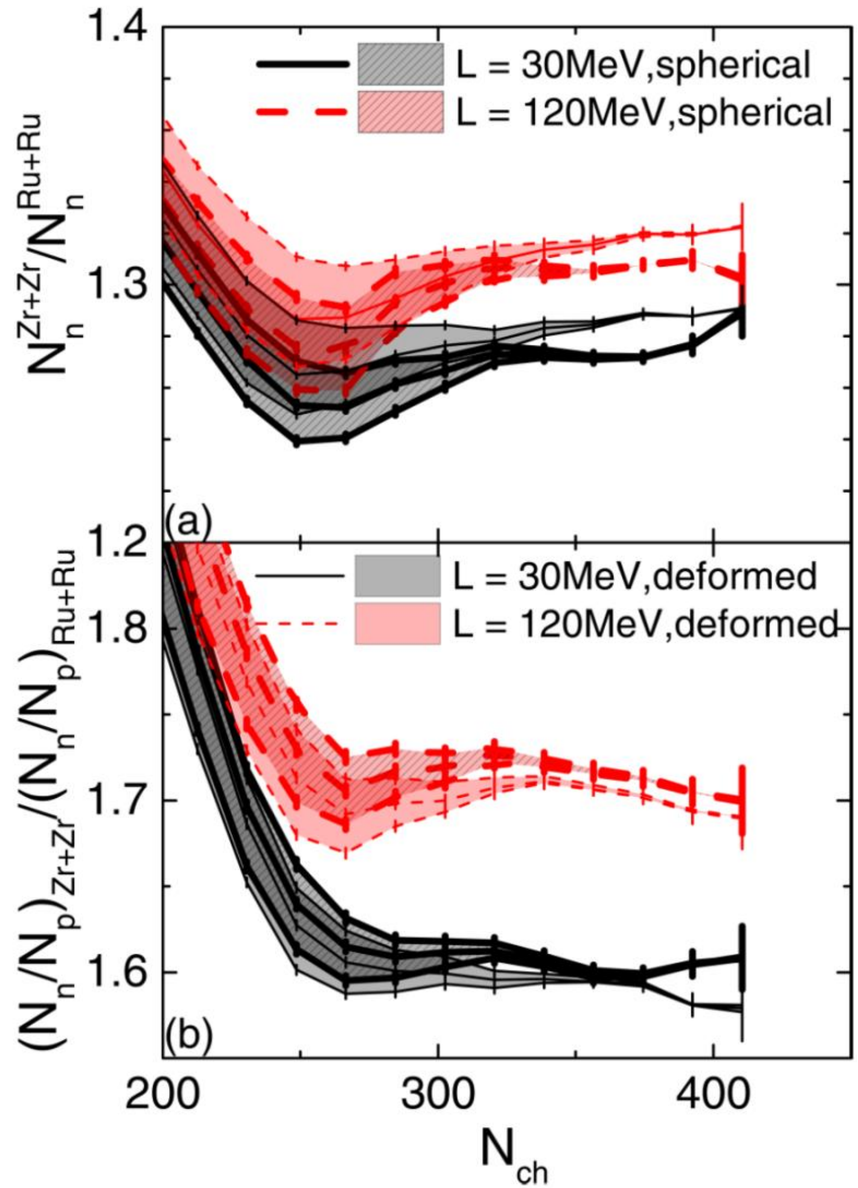
Results and discussions: probing L or Δr_{np}



S. Tarafdar et al., NIMA (2014)

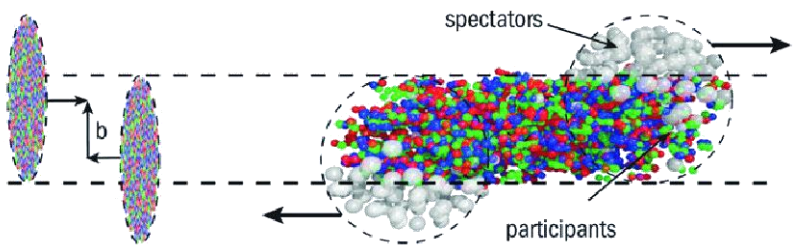


M.A. Famiano et al., PRL (2006)



Results and discussions: effects from EB field

Spectator protons pushed by EB field generated by another colliding nucleus



Lienard-Wiechert formulas

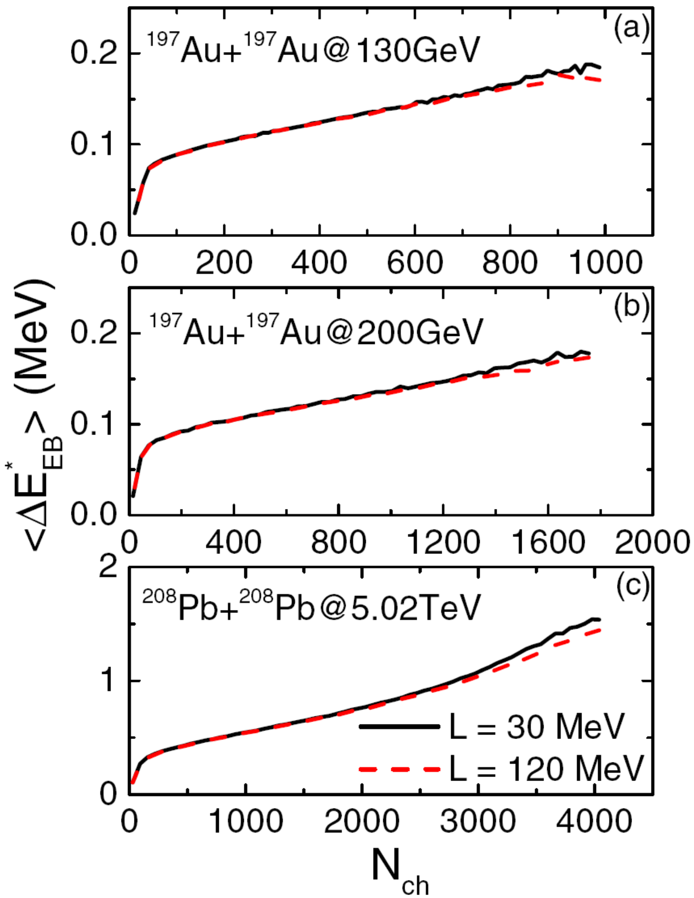
$$e\vec{E}(t,\vec{r}) = \frac{e^2}{4\pi\epsilon_0}\sum_i Z_i \frac{1-v_i^2}{(R_i-\vec{R}_i\cdot\vec{v}_i)^3}(\vec{R}_i - R_i\vec{v}_i)$$

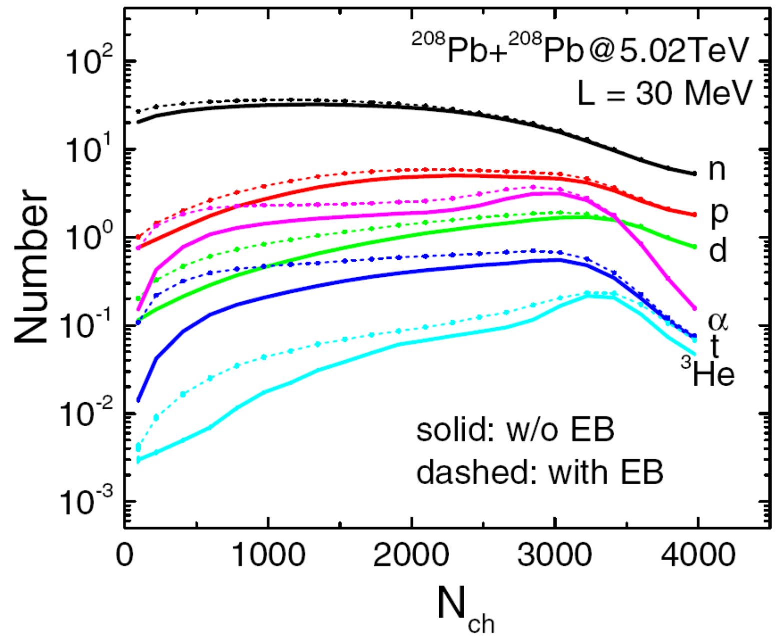
$$e\vec{B}(t,\vec{r}) = \frac{e^2}{4\pi\epsilon_0}\sum_i Z_i \frac{1-v_i^2}{(R_i-\vec{R}_i\cdot\vec{v}_i)^3}\vec{v}_i\times\vec{R}_i,$$

Assuming free propagation of nucleons

$$\frac{\mathrm{d}p_i^0}{\mathrm{d}t} = eZ_i[\vec{E}(t,\vec{r}_i)+\vec{v}_i\times\vec{B}(t,\vec{r}_i)]\cdot\vec{v}_i$$

$$\frac{\mathrm{d}\vec{p}_i}{\mathrm{d}t} = eZ_i[\vec{E}(t,\vec{r}_i)+\vec{v}_i\times\vec{B}(t,\vec{r}_i)].$$



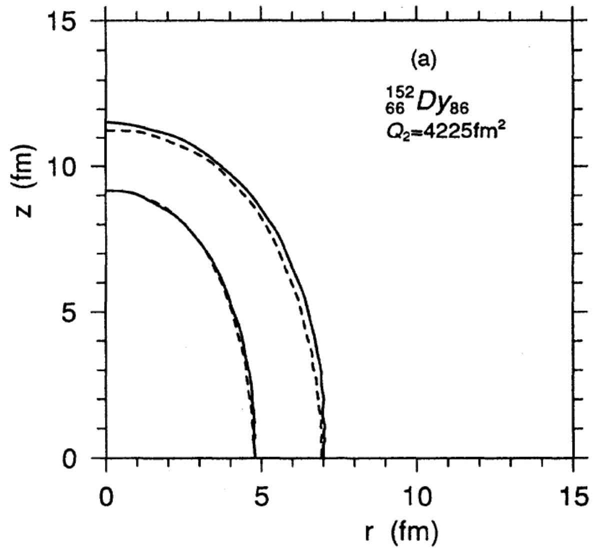


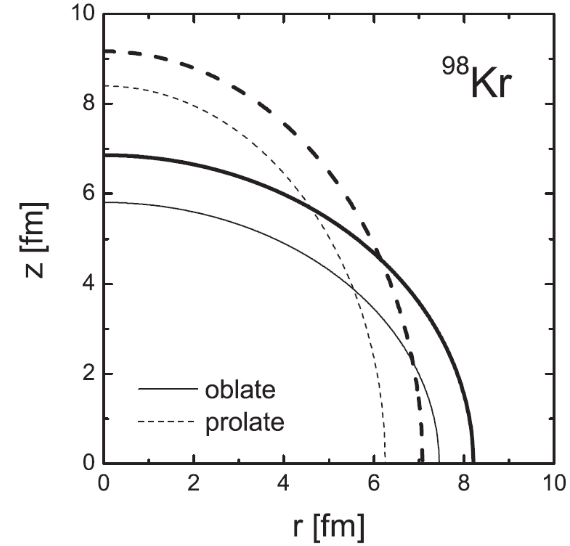
Relevant studies on $\Delta r_{np}(\theta)$ in deformed nuclei

Similar Δr_{np} in r and z directions

Different Δr_{np} in r and z directions

SHF+BCS



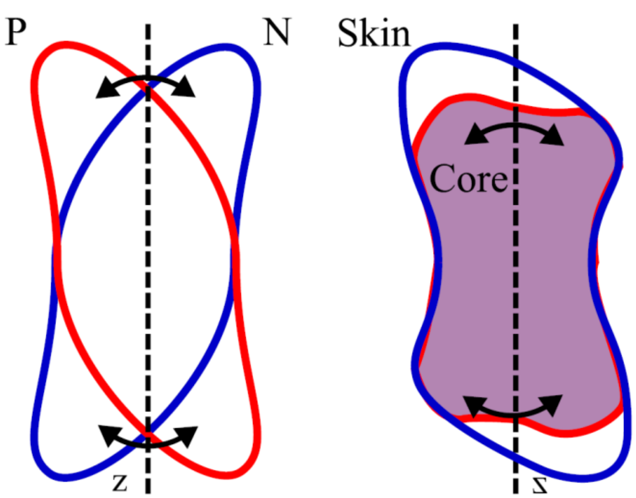


I. Hamamoto and X.Z. Zhang, PRC (1995)

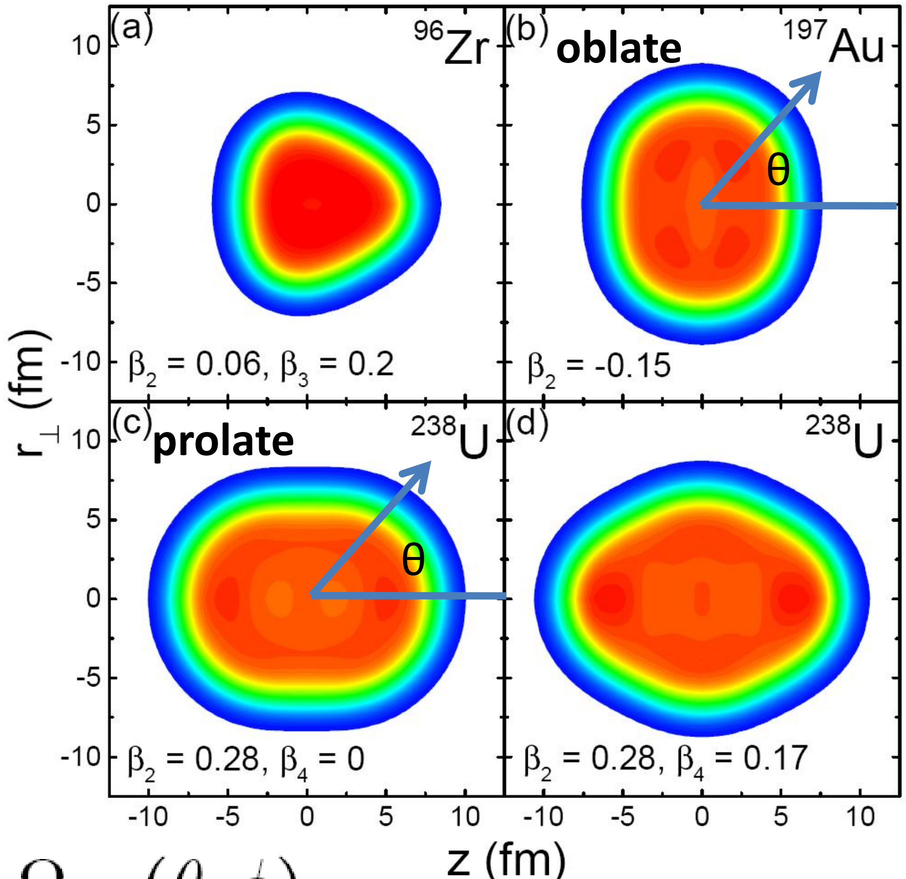
P. Sarriguren et al., PRC (2007)

Affect the scissor-like motion (M1) in deformed nuclei

D. Pena Arteaga and P. Ring, arXiv: 0912.0908 [nucl-th]



Δr_{np} effect from different collision configurations

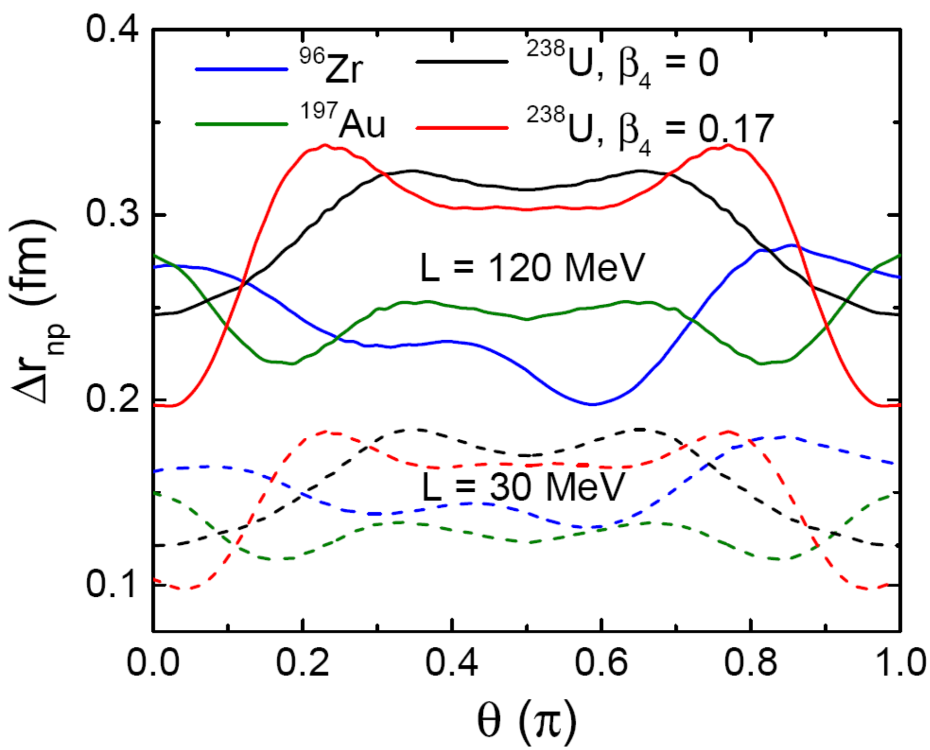


Nucleus	Deformation(s)	$\overline{\Delta r_{np}}$ (fm)	
		L = 30 MeV	L = 120 MeV
^{96}Zr	β_2=0.06, β_3=0.2 [43]	0.145	0.227
^{197}Au	β_2=-0.15 [44]	0.127	0.243
^{238}U	β_2=0.28 [42], β_4=0	0.156	0.291
	β_2=0.28 [42], β_4=0.17	0.153	0.291

$$\Omega = (\theta, \phi)$$

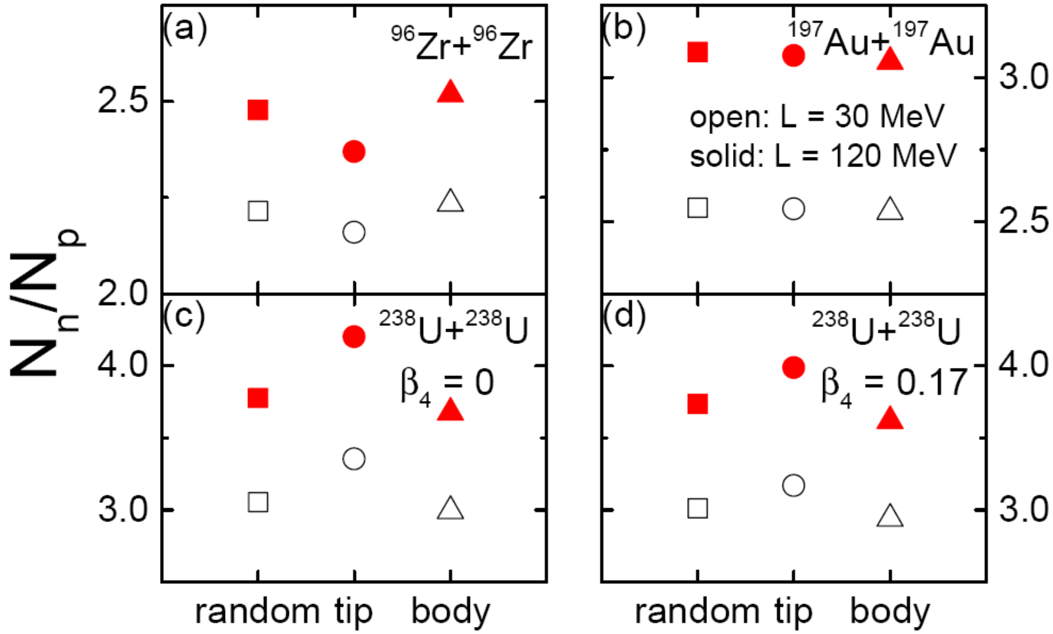
$$\Delta r_{\rm np}(\Omega) = \sqrt{\langle r_{\rm n}^2(\Omega)\rangle} - \sqrt{\langle r_{\rm p}^2(\Omega)\rangle}$$

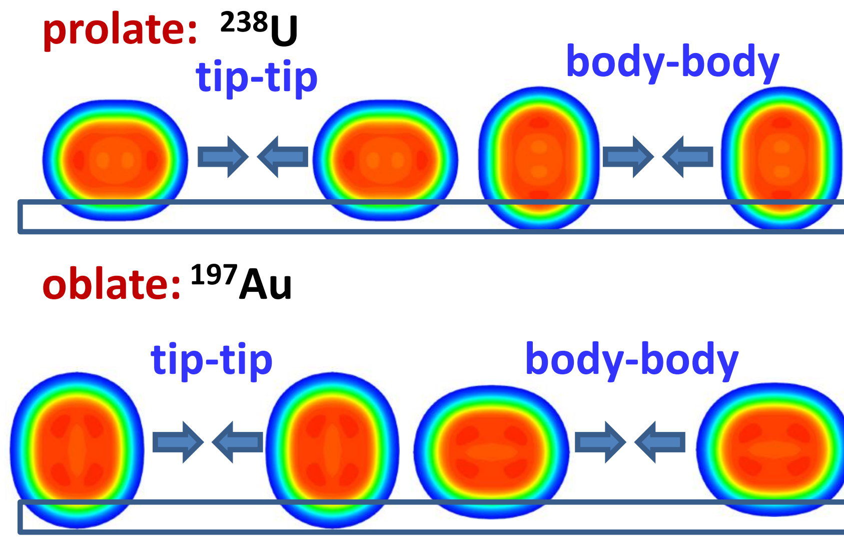
$$\sqrt{\langle r_\tau^2(\Omega)\rangle} = \left(\frac{\int \rho_\tau(r,\Omega) r^4 dr}{\int \rho_\tau(r,\Omega) r^2 dr}\right)^{1/2}$$



Δr_{np} effect from different collision configurations

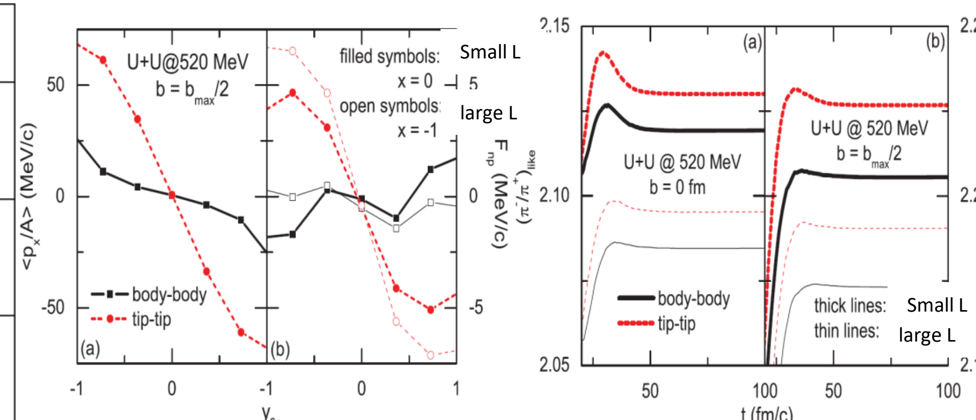
b=0 fm





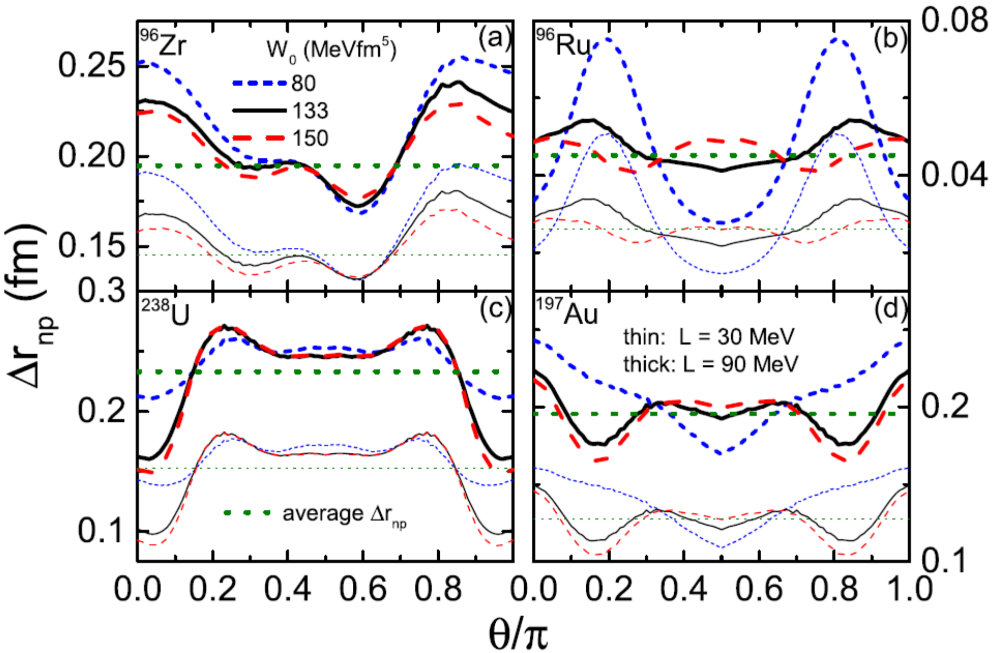
		N_n/N_p		$\Delta(N_n/N_p)$
		L = 30 MeV	L = 120 MeV	
Random	^{96}Zr+^{96}Zr @200 GeV	2.214±0.002	2.478±0.003	0.263±0.004
Tip-tip		2.160±0.002	2.370±0.003	0.210±0.004
Body-body		2.234±0.002	2.518±0.003	0.284±0.004
Random	^{197}Au+^{197}Au @200 GeV	2.548±0.003	3.088±0.003	0.540±0.004
Tip-tip		2.544±0.003	3.076±0.003	0.532±0.004
Body-body		2.535±0.003	3.054±0.003	0.520±0.004
Random	^{238}U+^{238}U @193 GeV β_4 = 0	3.052±0.003	3.774±0.004	0.722±0.005
Tip-tip		3.355±0.004	4.202±0.005	0.847±0.006
Body-body		2.992±0.003	3.676±0.004	0.684±0.005
Random	^{238}U+^{238}U @193 GeV β_4 = 0.17	3.010±0.003	3.734±0.004	0.725±0.005
Tip-tip		3.167±0.003	3.987±0.004	0.818±0.005
Body-body		2.940±0.003	3.618±0.004	0.677±0.005

E_{sym} effect from different collision configurations at lower collision energy



JX, Z. Martinot, and B.A. Li, PRC (2012)

Deformed Δr_{np} from different SO interactions

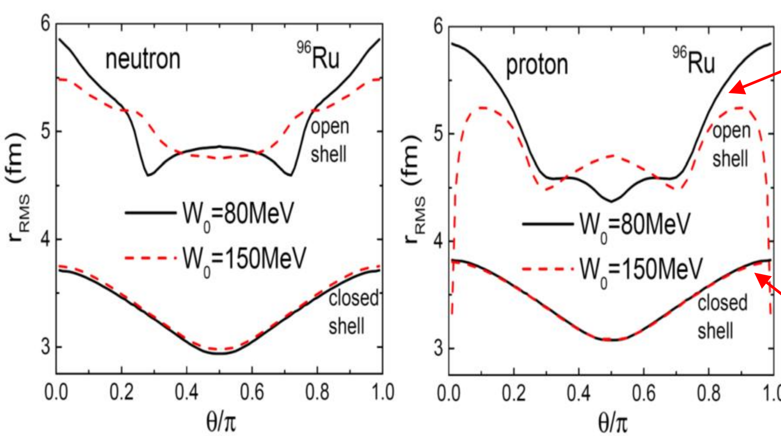


SO interaction: affect nucleons in open shells for spin unsaturated nuclei, which contribute to the angular dependence of Δr_{np}

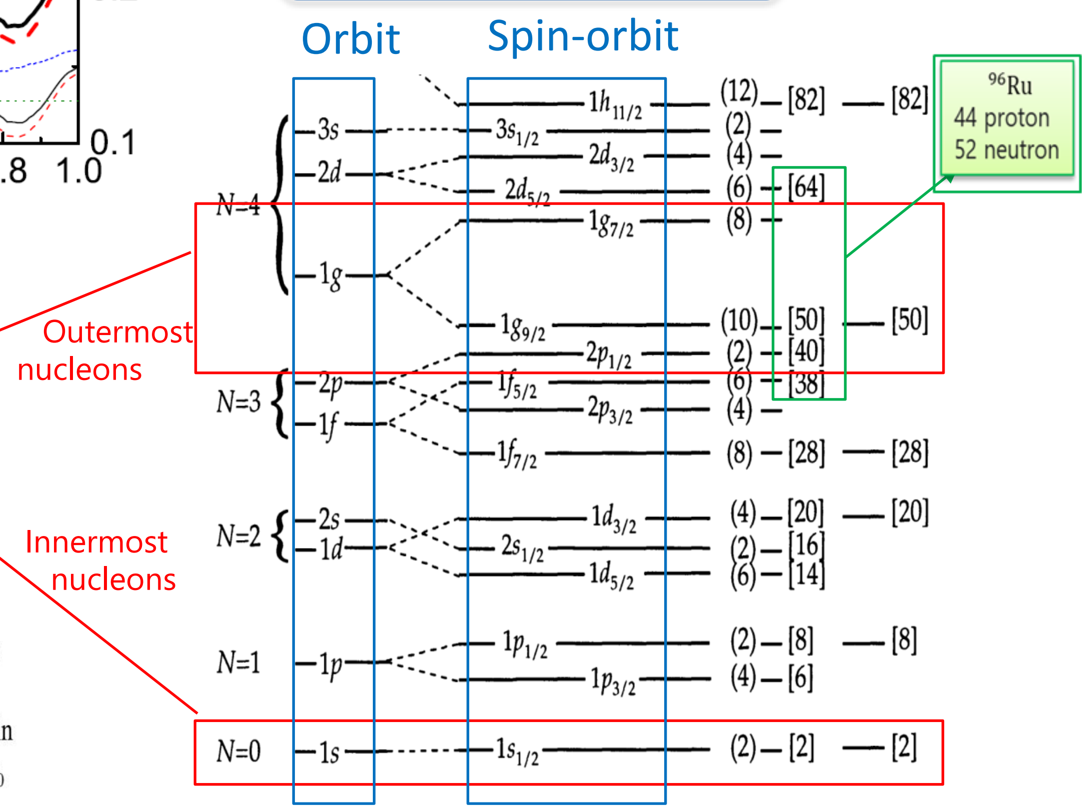
$L \sim U_n - U_p$ has a global effect

Spin-orbit interaction (SOI)

$$v_{so} = iW_0(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{k}' \times \delta(\vec{r}_1 - \vec{r}_2)\vec{k}$$



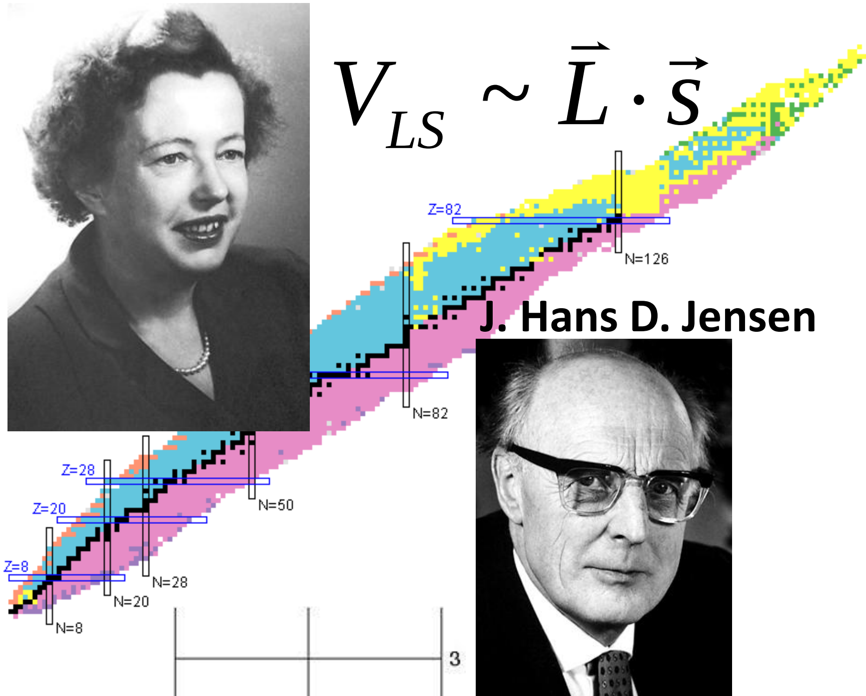
Angular distributions of the RMS radii for typical neutrons (left) and protons (right) in loosely-bound open shells and tightly-bound closed shells of ^{96}Ru using different W_0



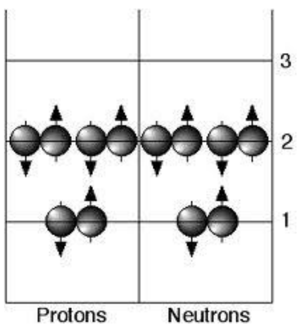
Importance of SO interaction

Maria Goeppert Mayer

$$V_{LS} \sim \vec{L} \cdot \vec{s}$$



J. Hans D. Jensen



- **Skyrme-Hartree-Fock model**

$$h_q = \frac{p^2}{2m} + U_q + \vec{W}_q \cdot (\vec{p} \times \vec{\sigma}), (q = n, p)$$

Hartree-Fock method

$$\vec{W}_q = \frac{W_0}{2}\left(\nabla\rho + \nabla\rho_q\right)$$

Schrödinger equation: $h_q \varphi_q = e_q \varphi_q$

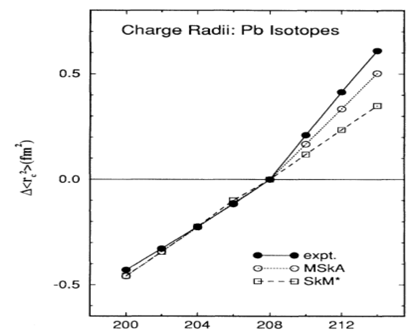
- **Relativistic mean-field model**

Dirac equation

Non-relativistic expansion

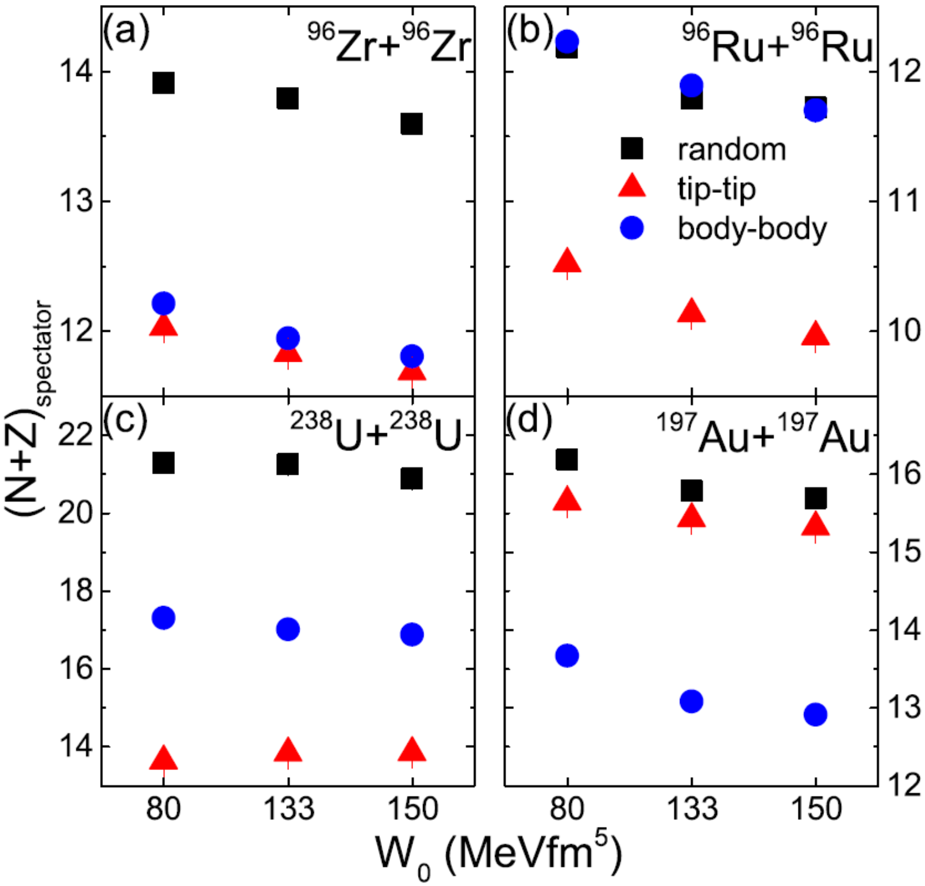
$$\vec{W}_q = \frac{C}{(2m - C\rho)^2} \nabla\rho, C = \frac{g_\sigma^2}{m_\sigma^2} + \frac{g_\omega^2}{m_\omega^2}$$

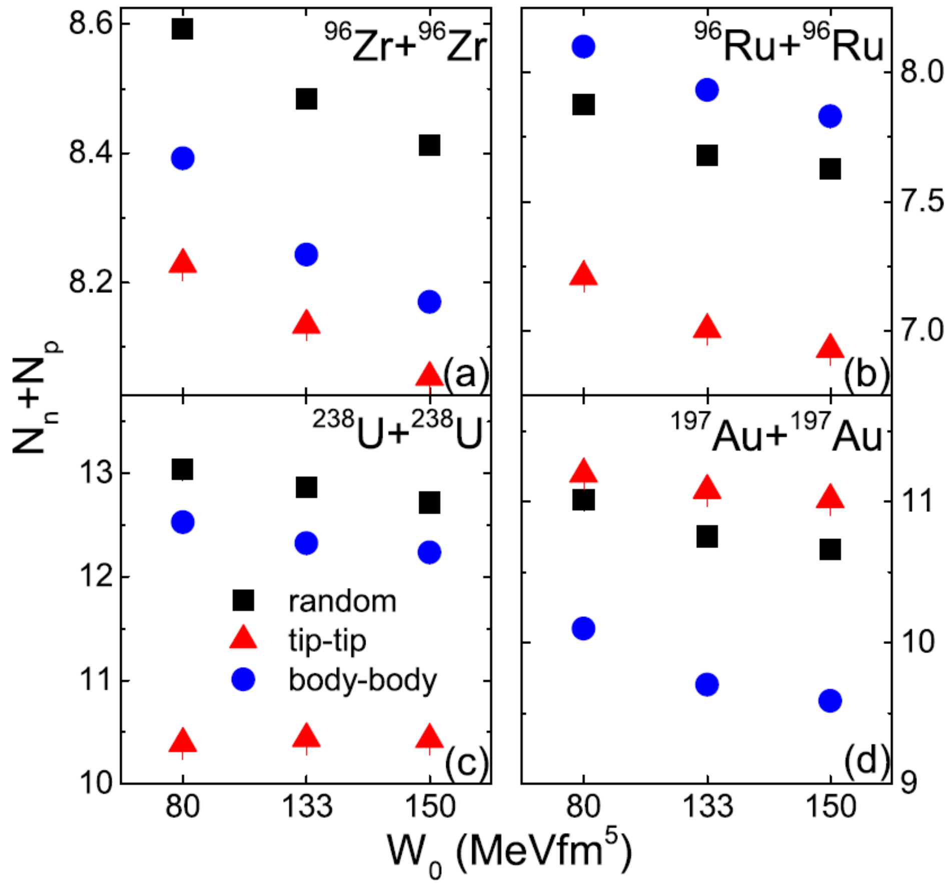
- **Strength: W_0 = 80~150 MeV fm^5**
- **Isospin dependence: kink of Pb isotope charge radii**
- **Density dependence: bubble nuclei**



Spectator nucleons from different W_0

b=0 fm

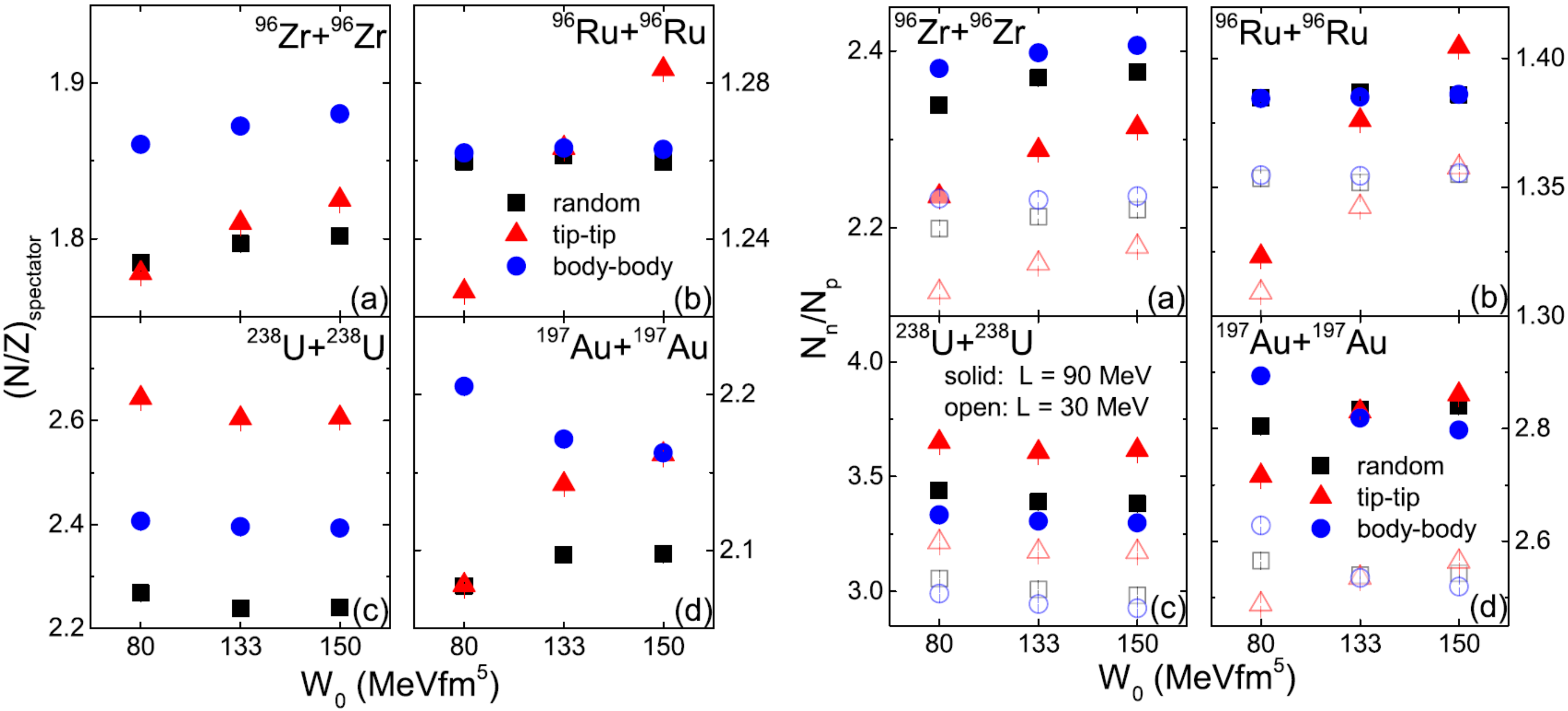




- **Collisions with random orientation generally have the largest $(N+Z)_{spectator}$**
- **Tip-tip (body-body) collisions by prolate (oblate) nuclei have the smallest $(N+Z)_{spectator}$**
- **About 2/3 spectator nucleons become free nucleons**

Spectator nucleons from different W_0

b=0 fm



- **Isospin asymmetry increased for free spectator nucleons compared to spectator matter**
- **Comparing N_n/N_p in triggered tip-tip and body-body Ru+Ru as well as Au+Au collisions may probe $\Delta r_{np}(\theta)$ and W_0**
- **Such effect is independent of L**

Summary

- **Free spectator nucleons N_n, N_p: clean probes**
- **Ultracentral HIC: free from deexcitations**
- **Ratio of neutron-rich to neutron-poor system:**
  - **$(N_n)^{Zr+Zr}/(N_n)^{Ru+Ru}$ reduce uncertainties**
  - **$(N_n/N_p)^{Zr+Zr}/(N_n/N_p)^{Ru+Ru}$ cancel detecting efficiency**
- **Triggering collision configurations: measure $\Delta r_{np}(\theta)$**

Key question:
way to unify different/contradictory experimental data
PREXII and CREX, ^{208}Pb nskin and other probes

Thank you!

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About anti E^0_{sym}-L correlation from Nskin

We illustrate the idea with a popularly used symmetry energy of the following form,

$$E_{\rm sym}(\rho) = E^0_{\rm sym}\left(\frac{\rho}{\rho_0}\right)^{\gamma}. \quad \text{(A1)}$$

Thus, the slope parameter L of the symmetry energy can be expressed as

$$L = 3\rho_0\left[\frac{dE_{\rm sym}(\rho)}{d\rho}\right]_{\rho_0} = 3E^0_{\rm sym}\gamma. \quad \text{(A2)}$$

For a fixed symmetry energy at a subsaturation density $\rho^\star$,

$$E_{\rm sym}(\rho^\star) = E^0_{\rm sym}\left(\frac{\rho^\star}{\rho_0}\right)^{\gamma}, \quad \text{(A3)}$$

the expression of L in terms of $E^0_{\rm sym}$ is

$$L = 3E_{\rm sym}(\rho^\star)\left[\frac{E^0_{\rm sym}}{E_{\rm sym}(\rho^\star)}\right]\frac{\ln\left[E^0_{\rm sym}/E_{\rm sym}(\rho^\star)\right]}{\ln(\rho_0/\rho^\star)}. \quad \text{(A4)}$$

It is obviously seen that L increases with increasing $E^0_{\rm sym}$ (see Ref. [64] as an example). The slope parameter at $\rho^\star$ can be expressed as

$$L(\rho^\star) = 3\rho^\star\left[\frac{dE_{\rm sym}(\rho)}{d\rho}\right]_{\rho^\star} = L\left(\frac{\rho^\star}{\rho_0}\right)^{\gamma}, \quad \text{(A5)}$$

where $L(\rho^\star)$ is seen to be smaller than L. For a fixed $L(\rho^\star)$, the expression of $E^0_{\rm sym}$ in terms of L is

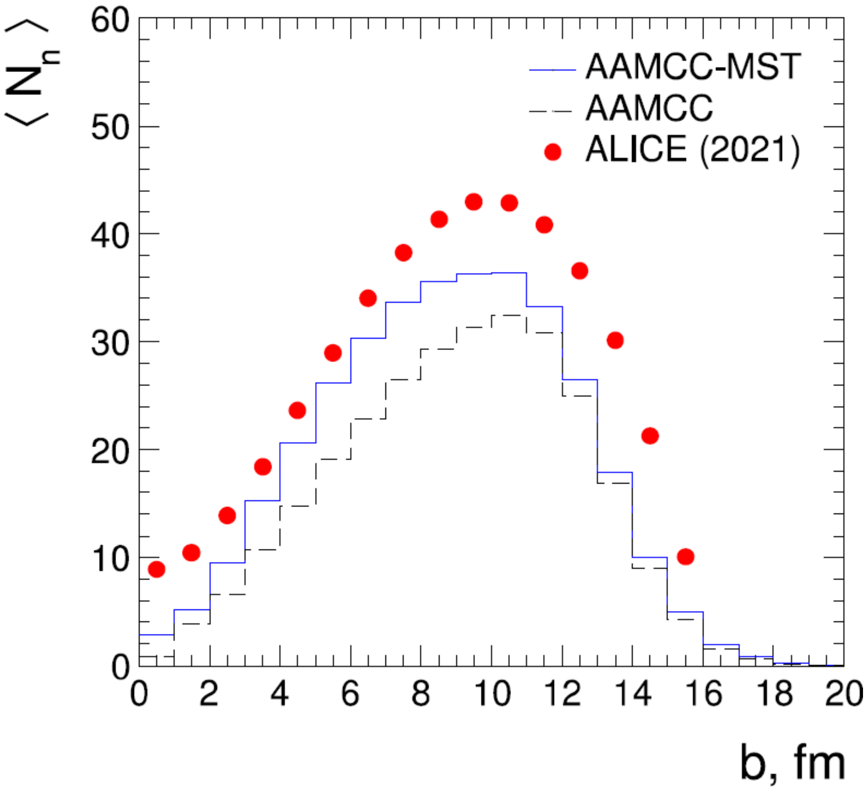
$$E^0_{\rm sym} = \frac{L(\rho^\star)}{3}\frac{\ln(\rho^\star/\rho_0)}{[L(\rho^\star)/L]\ln[L(\rho^\star)/L]}. \quad \text{(A6)}$$

The function $x\ln(x)$ is negative for $x < 1$ and increases with increasing x for $x > 0.4$. Thus, $E^0_{\rm sym}$ generally increases with increasing $x = L(\rho^\star)/L$. Because L decreases with increasing x, this leads to an anticorrelation between L and $E^0_{\rm sym}$. This conclusion is general and helps us understand the results shown in Fig. 2 of the present manuscript.

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

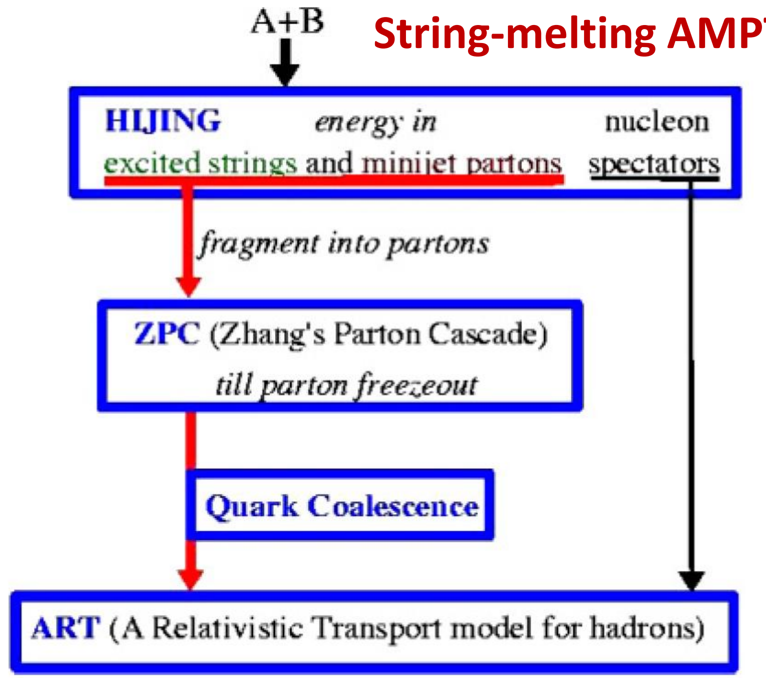
Results and discussions: ZDC background

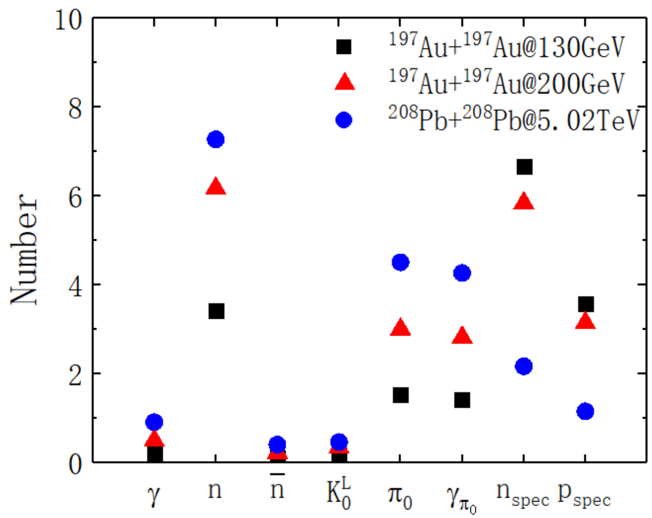
^{208}Pb+^{208}Pb@5.02TeV



R. Nepeivoda et al., Particles (2022)

String-melting AMPT





|η|>5.9
|η|>5.9
|η|>8.3

ZDC acceptance