



Probing nuclear structure with spectator particles in relativistic heavy-ion collisions

Jun Xu (徐骏)

Main collaborators: Lu-Meng Liu(刘鹿蒙)(Fudan)、Song-Jie -Li(李松桀)(Tongji)
Hai-Cheng Wang(王海澄)(Tongji)、Chun-Jian Zhang(张春健)(Fudan)
Jiangyong Jia(贾江涌)(Stony Brook)、Zhong-Zhou Ren(任中洲)(Tongji)
Guang-Xiong Peng(彭光雄)(UCAS)、Xu-Guang Huang(黄旭光)(Fudan)

Directly probing existence of α -cluster structure in ^{20}Ne by relativistic heavy-ion collisions

Lu-Meng Liu, Hai-Cheng Wang, Song-Jie Li, Chun-Jian Zhang, JX*, Zhong-Zhou Ren*, Jiangyong Jia*, and Xu-Guang Huang*,
Phys. Rev. C 111, L021901 (2025), arXiv: 2502.08057 [nucl-th]

Probing configuration of α clusters with spectator particles in relativistic heavy-ion collisions

Lu-Meng Liu, Song-Jie Li, Zhen Wang, JX*, Zhong-Zhou Ren*, and Xu-Guang Huang,
Phys. Lett. B 854, 138724 (2024), arXiv: 2312.13572 [nucl-th]

Measuring deformed neutron skin with free spectator nucleons in relativistic heavy-ion collisions

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

Free spectator nucleons in ultracentral relativistic heavy-ion collisions as a probe of neutron skin

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

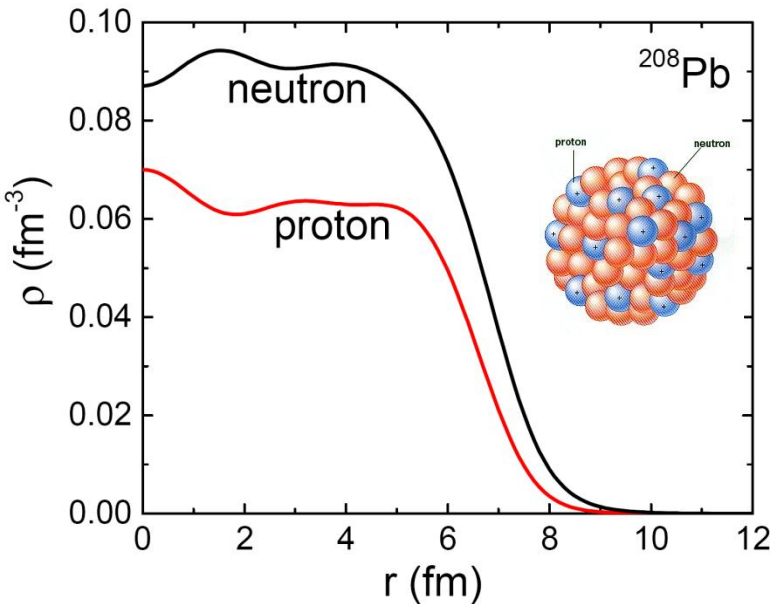
Probing neutron-skin thickness with free spectator neutrons in ultracentral high-energy isobaric collisions

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]

Content

- **Probe nucleus structure**
 - Neutron-skin thickness $\Delta r_{np} \sim L$, $\Delta r_{np}(\theta) \sim SO$
 - α -cluster structure
 - HMT induced by SRC
- **Model setup**
 - Initial density distribution
 - Glauber model
 - Multifragmentation process

Neutron skin and E_{sym}



Neutron-Skin Thickness:

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

For ^{208}Pb :

- $\Delta r_{\text{np}} = 0.211^{+0.054}_{-0.063}$ fm from proton scattering
- $\Delta r_{\text{np}} = 0.16 \pm 0.07$ fm from pion scattering
- $\Delta r_{\text{np}} = 0.18 \pm 0.04(\text{expt.}) \pm 0.05(\text{theor.})$ fm from $\bar{p}$ annihilation
- $\Delta r_{\text{np}} = 0.15 \pm 0.03(\text{stat.})^{+0.01}_{-0.03}(\text{sys.})$ fm from coherent pion photoproduction
- $\Delta r_{\text{np}} = 0.283 \pm 0.071$ fm from parity-violating electron scatterings

Energy per nucleon
in asymmetric matter

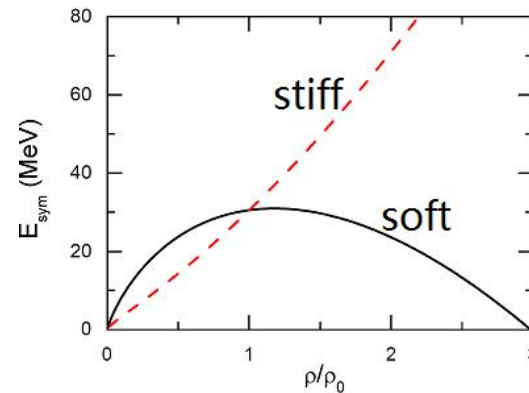
Symmetry energy

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

Energy per nucleon
in symmetric matter

$$\rho = \rho_n + \rho_p$$

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



Expansion around saturation density ρ_0

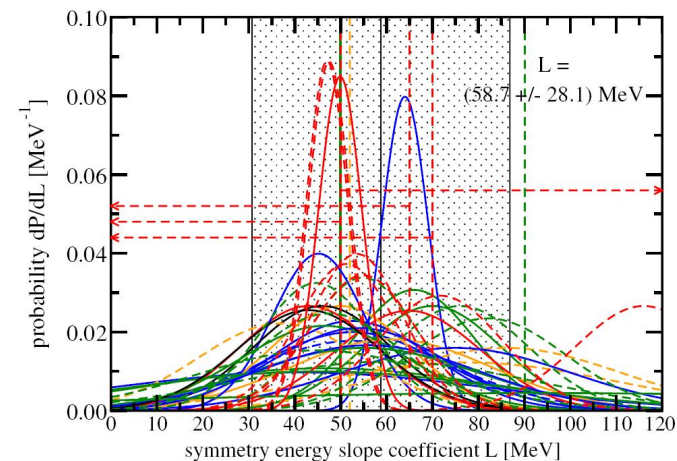
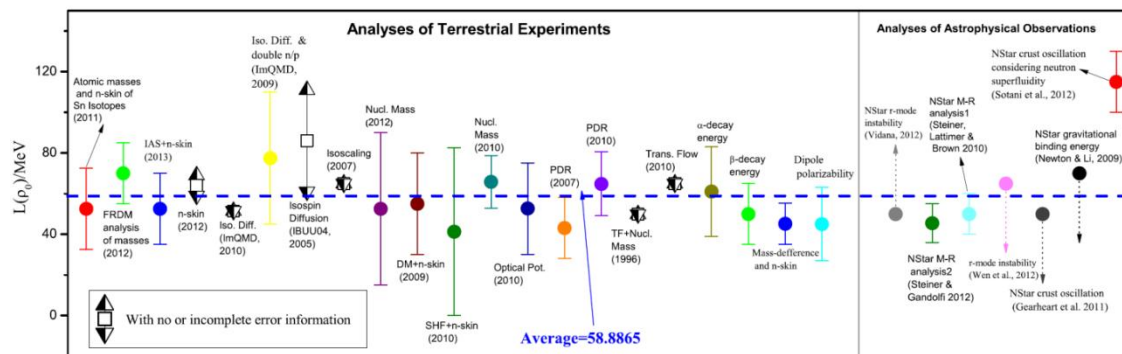
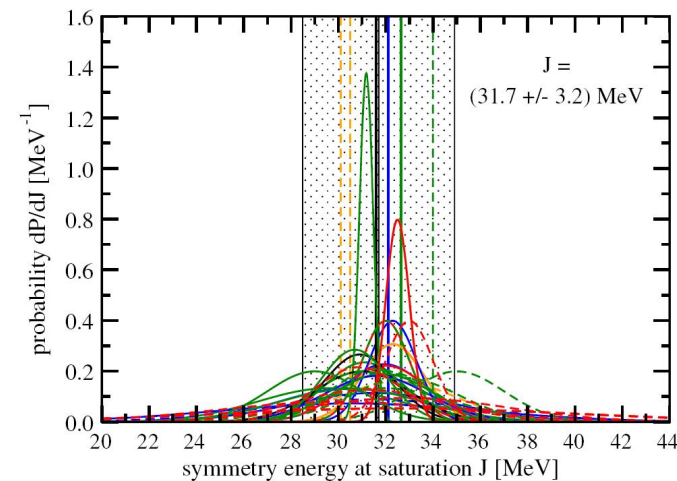
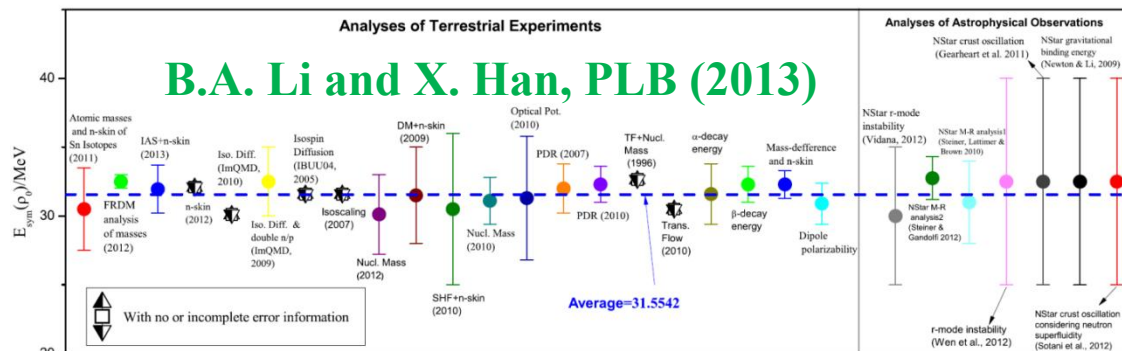
$$E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0) + L\chi + \dots$$

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

Slope parameter

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

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

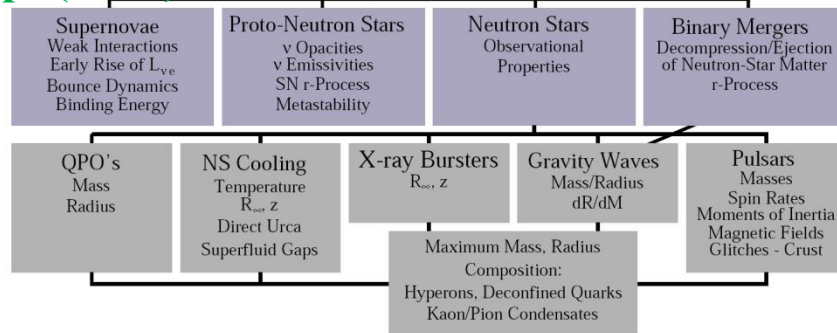


Isospin Dependence of Strong Interactions



Many-Body Theory

Symmetry Energy
(Magnitude and Density Dependence)



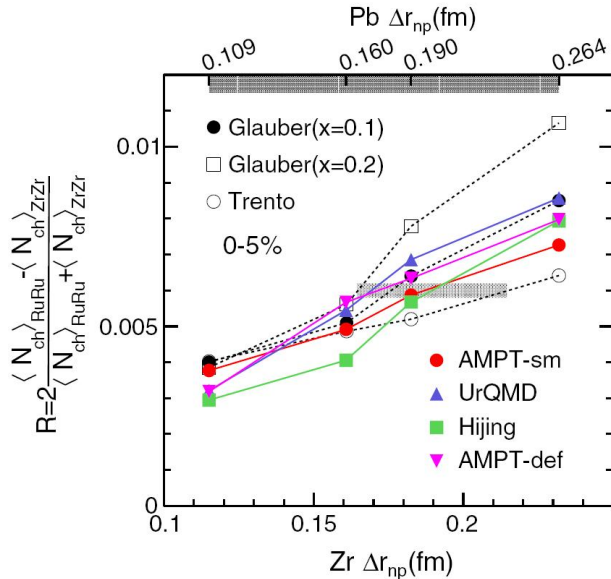
M. Oertel et al., RMP (2017)

Symmetry energy PACS: 21.65.Ef

More reliable probes are still needed

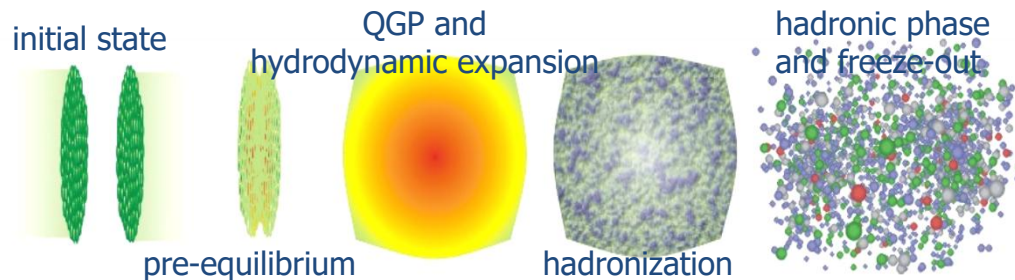
probe neutron skin with mid-rapidity observables at RHIC and LHC

Charged-particle multiplicity



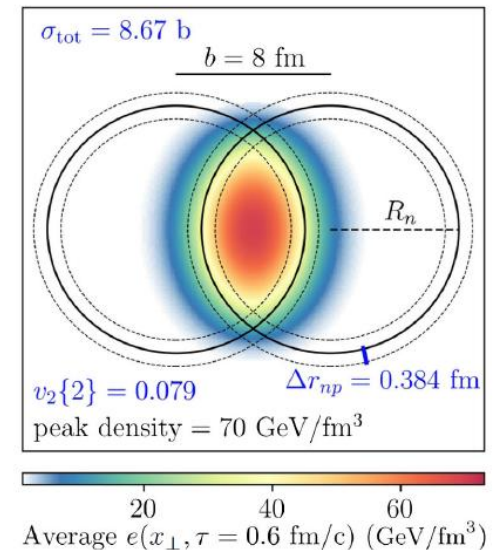
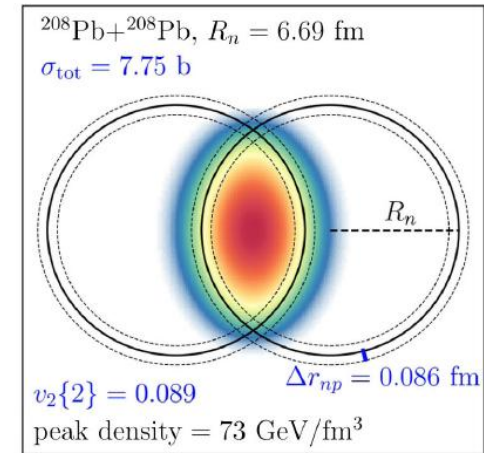
H.L. Li et al., PRL (2020)

probe the density distribution of colliding nuclei



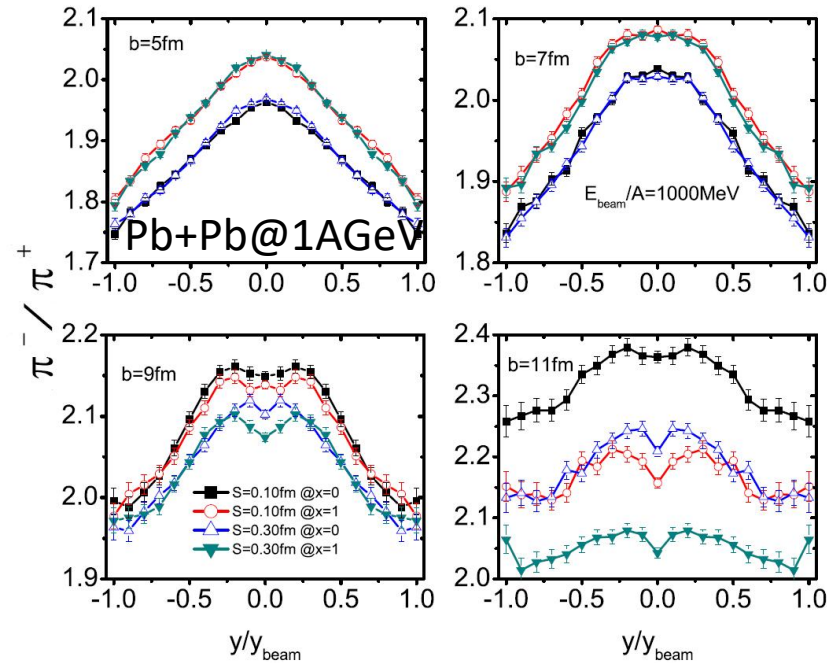
Observables at midrapidities suffer from complicated dynamics and model dependence

v_2 and $\langle p_T \rangle$

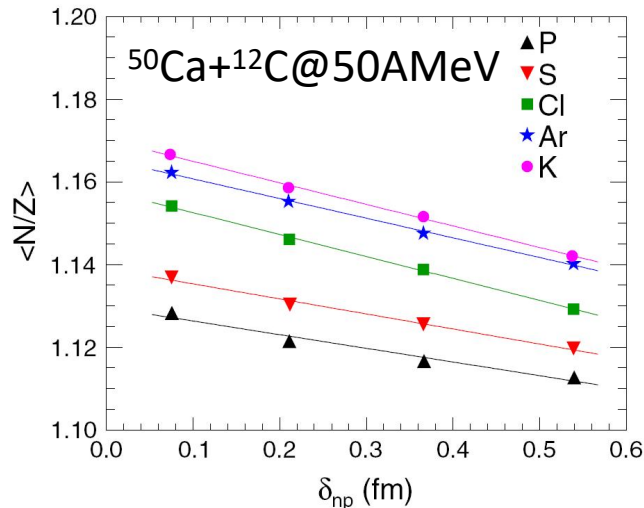


G. Giacalone, G. Nijs,
and W. van der Schee, PRL (2023)

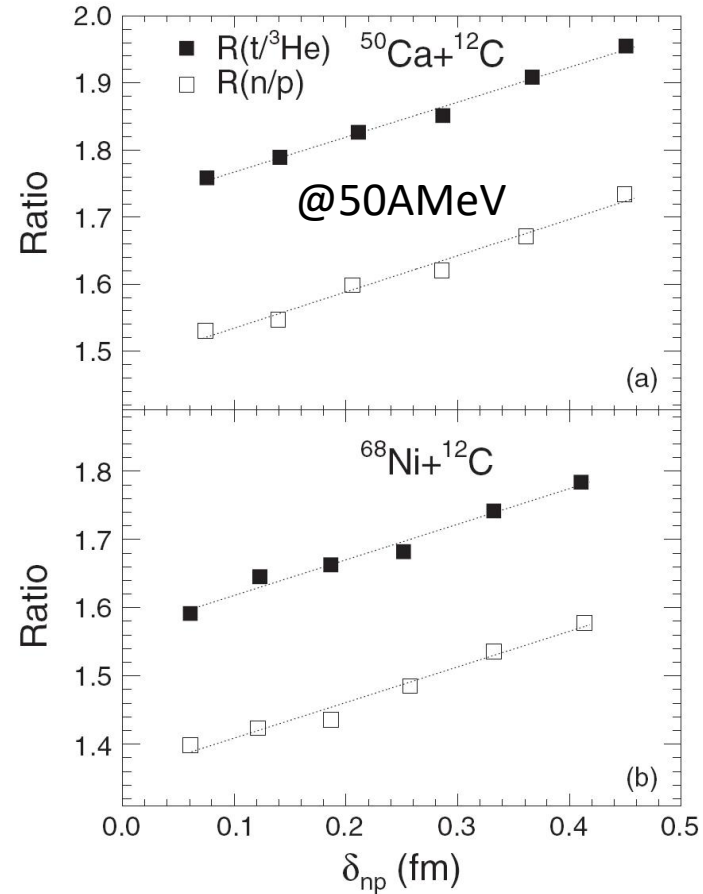
probe neutron skin with intermediate-energy HIC



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



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

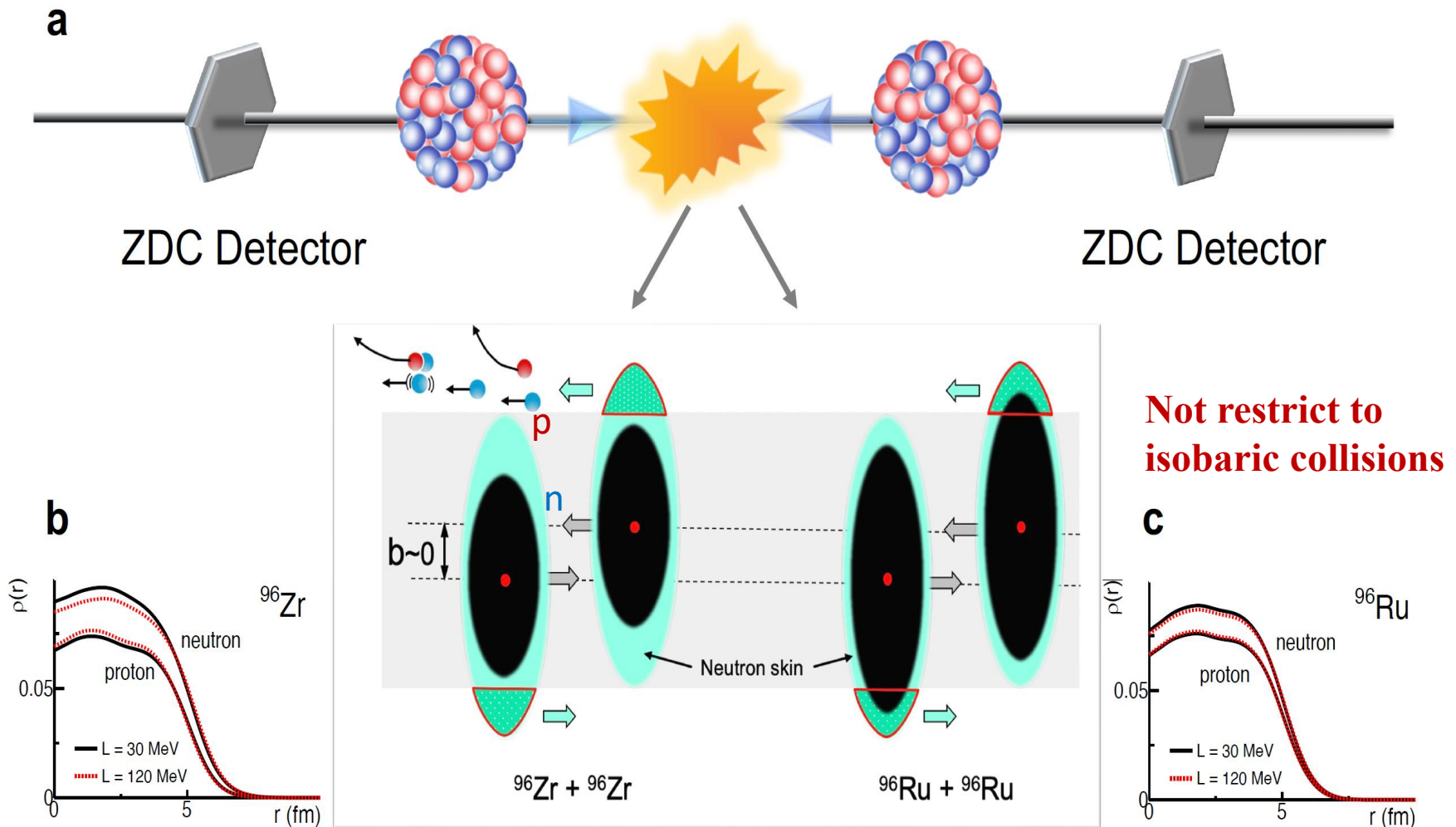


Z.T. Dai et al., PRC (2014)

Suffer from:

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

Basic idea of our studies



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:

$$\begin{aligned}
 v(\vec{r}_1, \vec{r}_2) = & t_0(1 + x_0 P_\sigma) \delta(\vec{r}) \\
 & + \frac{1}{2} t_1(1 + x_1 P_\sigma) [\vec{k}'^2 \delta(\vec{r}) + \delta(\vec{r}) \vec{k}^2] \\
 & + t_2(1 + x_2 P_\sigma) \vec{k}' \cdot \delta(\vec{r}) \vec{k} \\
 & + \frac{1}{6} t_3(1 + x_3 P_\sigma) \rho^\alpha(\vec{R}) \delta(\vec{r}) \\
 & + i W_0 (\vec{\sigma}_1 + \vec{\sigma}_2) [\vec{k}' \times \delta(\vec{r}) \vec{k}].
 \end{aligned}$$

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+3σ})	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	$E_{\text{sym}}(\rho_0)$ (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)**

Pairing interaction

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

Hartree-Fock method:

$$\begin{aligned}
 E = & \sum_i \left\langle i \left| \frac{p^2}{2m} \right| i \right\rangle + \frac{1}{2} \sum_{ij} \langle ij | \bar{v}_{12} | ij \rangle \\
 & \frac{\delta}{\delta \phi_i} \left(E - \sum_i e_i \int |\phi_i(\vec{r})|^2 d^3r \right) = 0 \\
 & \left[-\vec{\nabla} \cdot \frac{\hbar^2}{2m_q^*(\vec{r})} \vec{\nabla} + U_q(\vec{r}) + \vec{W}_q(\vec{r}) \cdot (-i)(\vec{\nabla} \times \vec{\sigma}) \right] \phi_i = e_i \phi_i
 \end{aligned}$$

Particle density

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

Hartree-Fock-Bogoliubov method:

$$\begin{aligned}
 \int d^3r' \sum_{\sigma'} \begin{pmatrix} h(\mathbf{r}\sigma, \mathbf{r}'\sigma') & \tilde{h}(\mathbf{r}\sigma, \mathbf{r}'\sigma') \\ \tilde{h}(\mathbf{r}\sigma, \mathbf{r}'\sigma') & -h(\mathbf{r}\sigma, \mathbf{r}'\sigma') \end{pmatrix} \begin{pmatrix} \varphi_1(E, \mathbf{r}'\sigma') \\ \varphi_2(E, \mathbf{r}'\sigma') \end{pmatrix} \\
 = \begin{pmatrix} E + \lambda & 0 \\ 0 & E - \lambda \end{pmatrix} \begin{pmatrix} \varphi_1(E, \mathbf{r}\sigma) \\ \varphi_2(E, \mathbf{r}\sigma) \end{pmatrix}
 \end{aligned}$$

Particle density

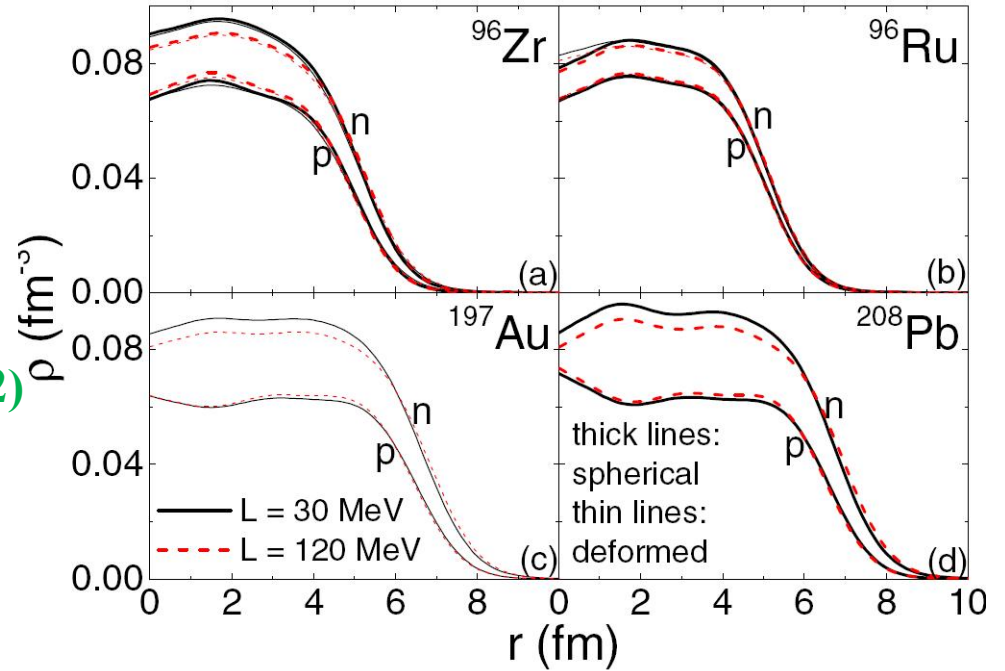
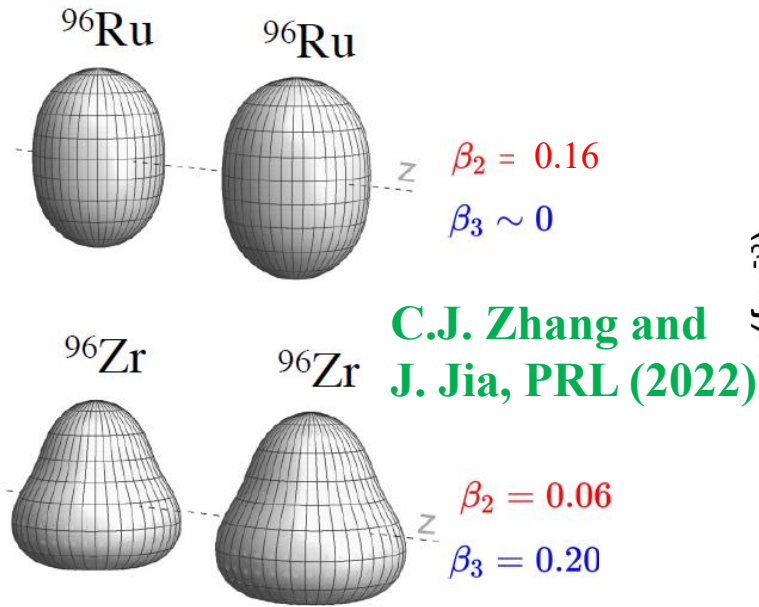
Pairing density

$$\rho(r) = \sum_i \varphi_2(E_i, r)^2 \quad \tilde{\rho}(r) = - \sum_i \varphi_1(E_i, r) \varphi_2(E_i, r)$$

Reproduce E_b and R_c within 1.5%

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

Model setup: initial density distribution



Multipole moments

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

Deformation parameters

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

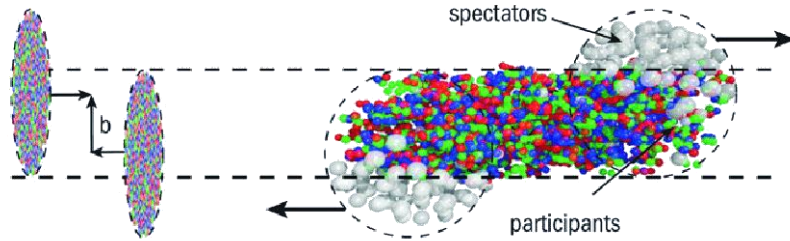
**Constrained SHFB calculation
with fixed $Q_{\lambda}(\beta_{\lambda})$**

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

Nucleus	β_2, β_3	Δr_{np} (fm)	
		$L = 30$ 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

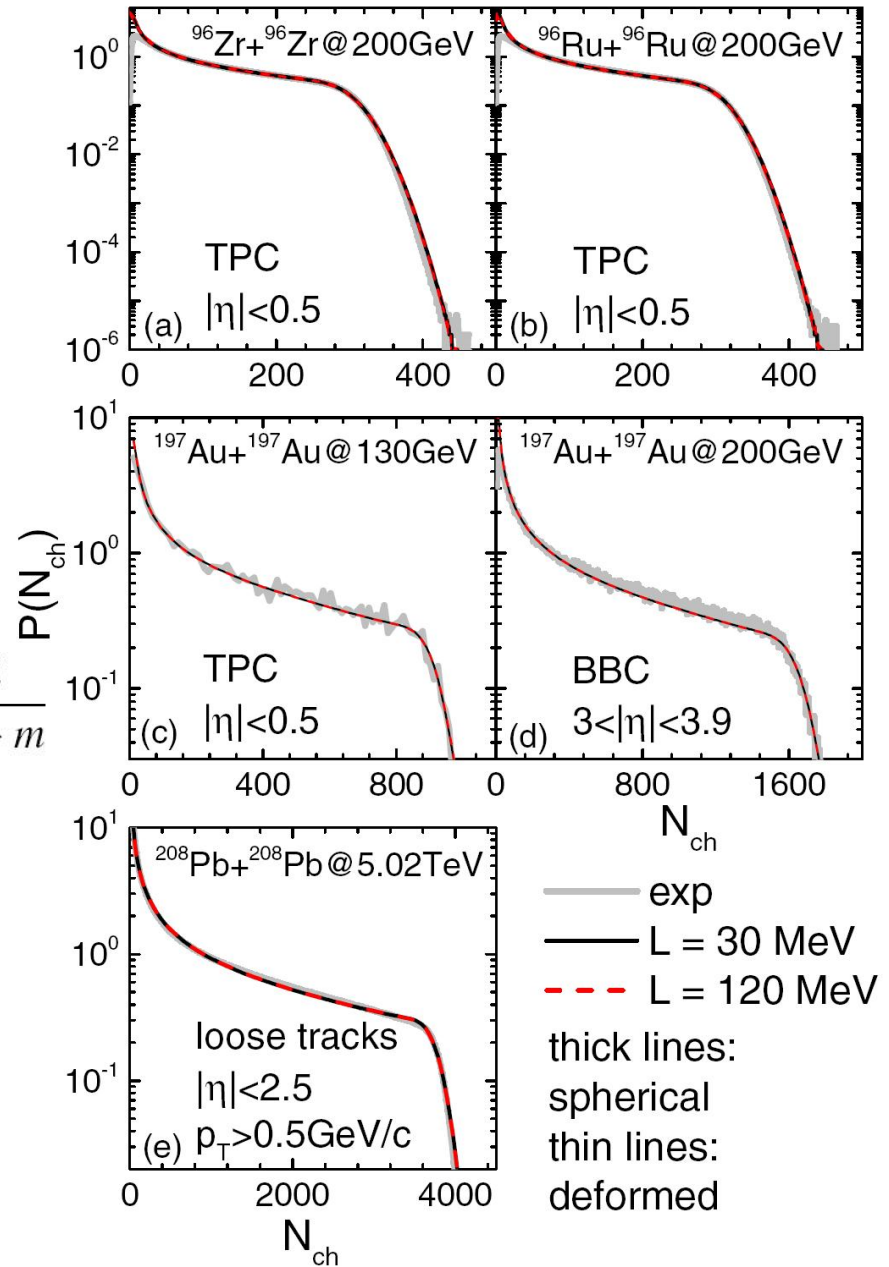
$$N_s = (1 - x) \frac{N_{\text{part}}}{2} + x N_{\text{coll}}$$

Particle production n from each source

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

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

$\sqrt{s_{NN}}$	130 GeV	200 GeV	5.02 TeV	
σ_{NN}	40 mb	42 mb	68 mb	
	$\sqrt{s_{NN}}$	x	$\bar{n}$	m
$^{96}\text{Zr} + ^{96}\text{Zr}$	200 GeV	0.12	2.3	2.0
$^{96}\text{Ru} + ^{96}\text{Ru}$	200 GeV	0.12	2.3	2.2
$^{197}\text{Au} + ^{197}\text{Au}$	130 GeV	0	4.8	4.6
$^{197}\text{Au} + ^{197}\text{Au}$	200 GeV	0.10	5.8	2.3
$^{208}\text{Pb} + ^{208}\text{Pb}$	5.02 TeV	0.09	10.3	3.2

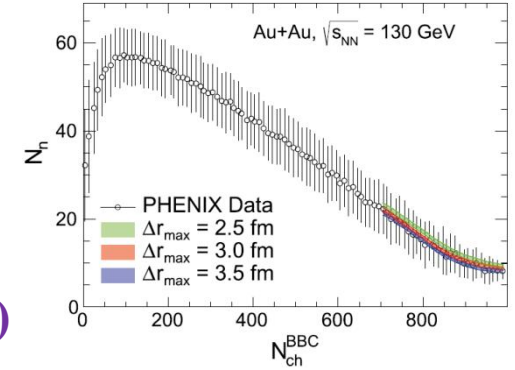


Model setup: multifragmentation process

Dynamics of participant matter is neglected!

A. Formation of heavy ($A > 3$) clusters

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



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

1. Excitation energy

$$E = \frac{1}{N_{TP}} \sum_i \left(\sqrt{m^2 + p_i^2} - m \right)$$

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

**Simplified
SHF EDF**

$$+ \int d^3r \left[\frac{a}{2} \left(\frac{\rho}{\rho_0} \right)^2 + \frac{b}{\sigma + 1} \left(\frac{\rho}{\rho_0} \right)^{\sigma + 1} \right] + \int d^3r \left\{ \frac{G_S}{2} (\nabla \rho)^2 - \frac{G_V}{2} [\nabla(\rho_n - \rho_p)]^2 \right\}$$

$$+ \int d^3r E_{sym}^{pot} \left(\frac{\rho}{\rho_0} \right)^\gamma \frac{(\rho_n - \rho_p)^2}{\rho} + \frac{e^2}{2} \int d^3r d^3r' \frac{\rho_p(\vec{r}) \rho_p(\vec{r}')}{|\vec{r} - \vec{r}'|} - \frac{3e^2}{4} \int d^3r \left[\frac{3\rho_p}{\pi} \right]^{4/3} - E_{GS}$$

2. Angular momentum

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

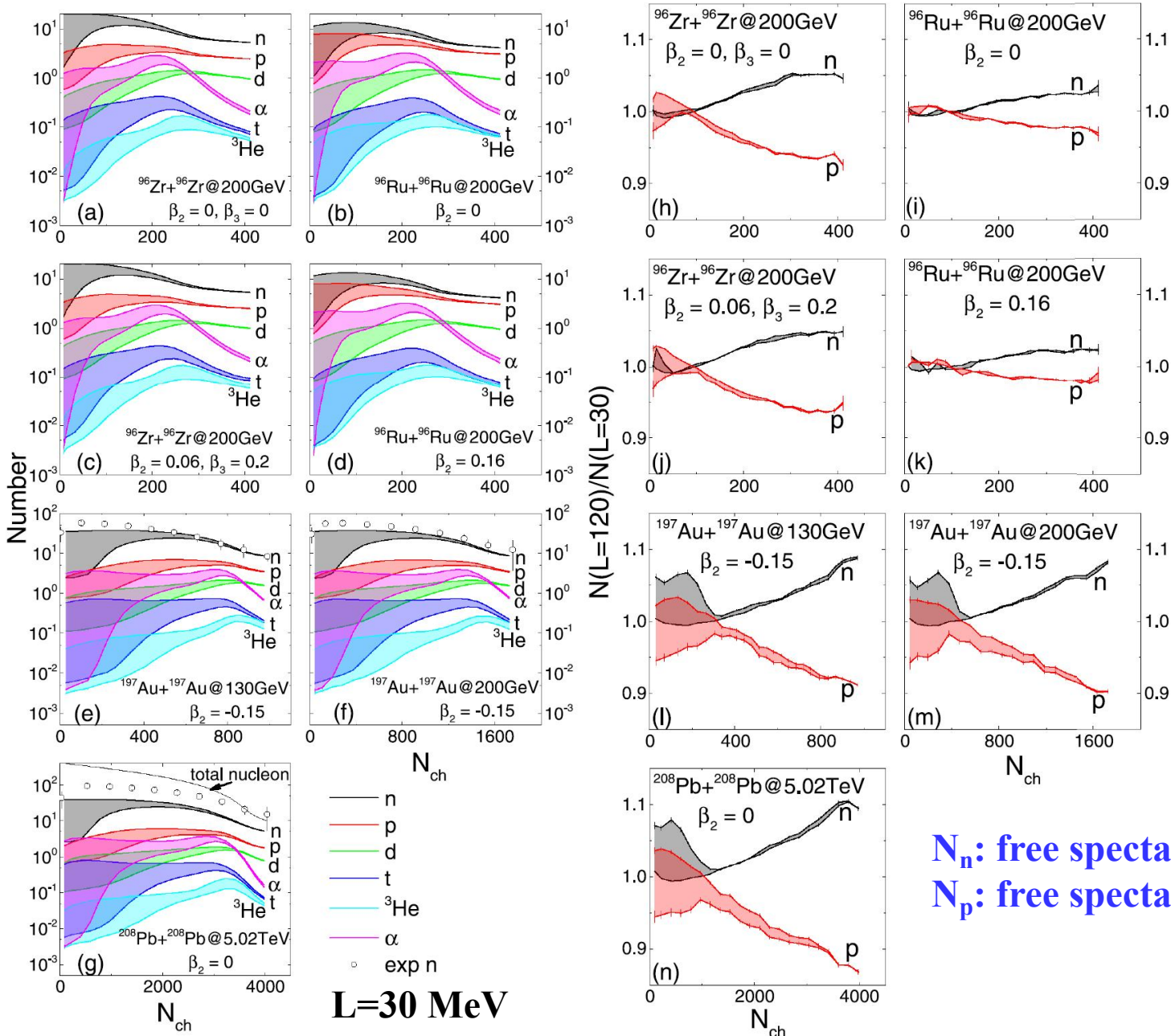
Free nucleons:

- 1) Direct production from A and residue from C
- 2) Deexcitation from B

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

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

Results and discussions: spectator particle yield

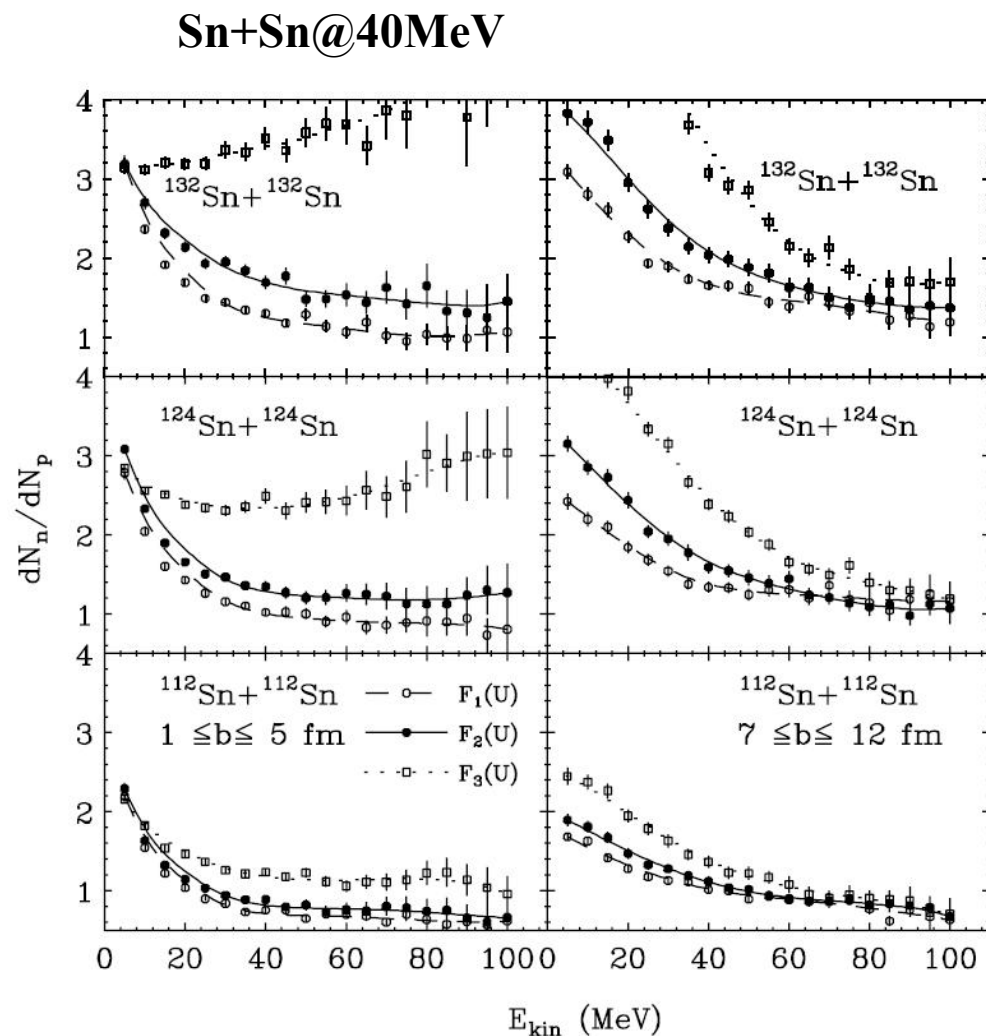
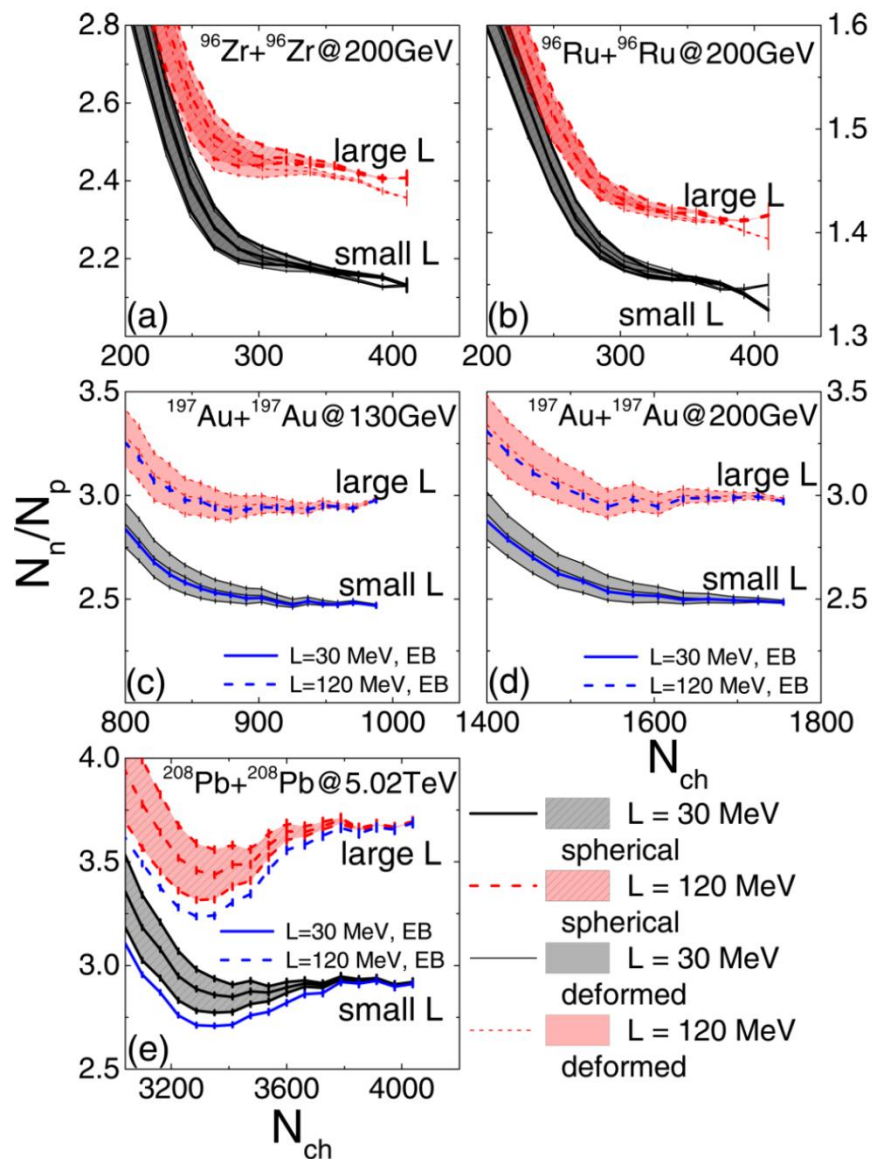


Band:
 $E/A \pm 1 \text{ MeV}$

- **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**

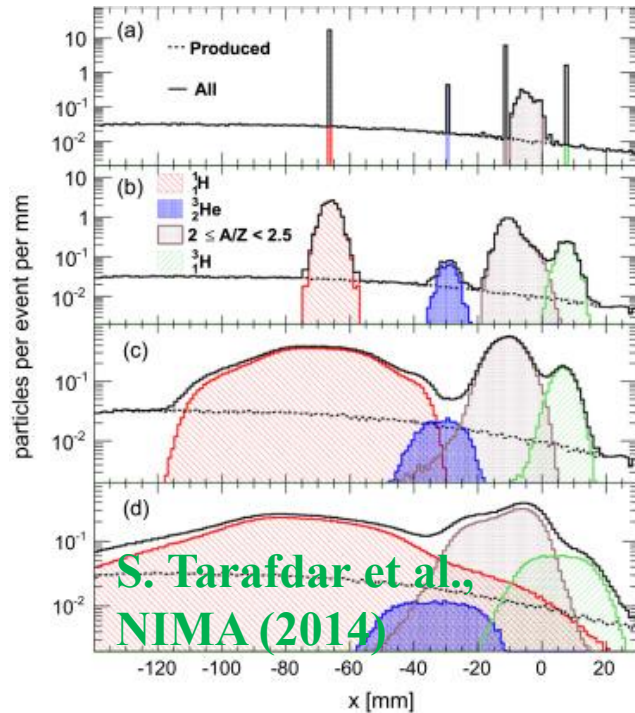
N_n : free spectator neutron number
 N_p : free spectator proton number

Results and discussions: probing L or Δr_{np}

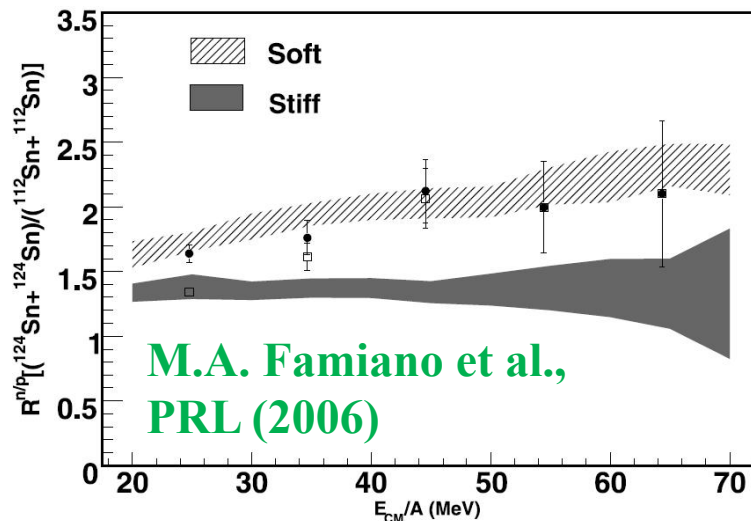


B.A. Li, C.M. Ko, and Z.Z. Ren, PRL (1997)

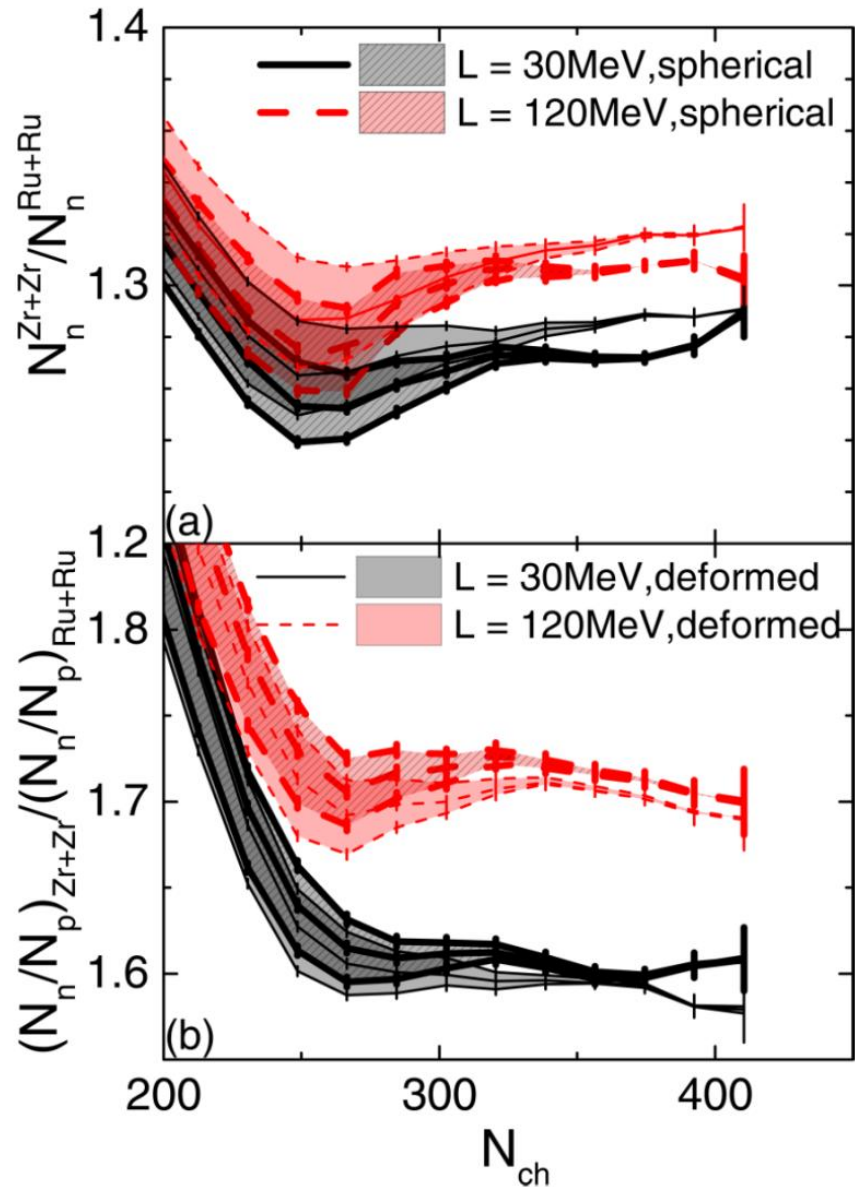
Results and discussions: probing L or Δr_{np}



S. Tarafdar et al.,
NIMA (2014)



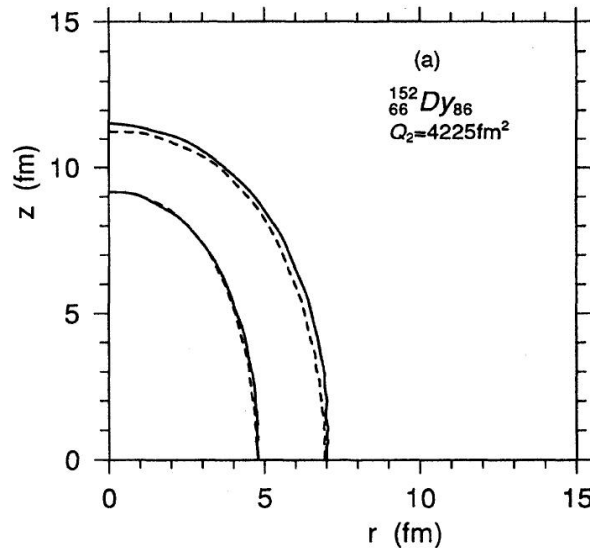
M.A. Famiano et al.,
PRL (2006)



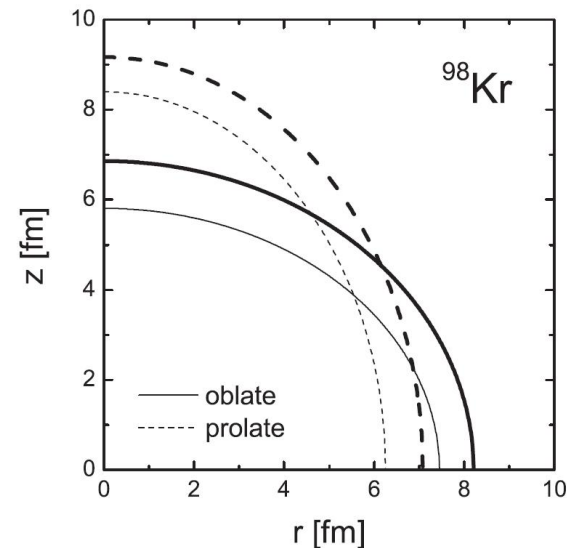
Relevant studies on $\Delta r_{np}(\theta)$ in deformed nuclei

Similar Δr_{np} in r and z directions

SHF+BCS



Different Δr_{np} in r and z directions

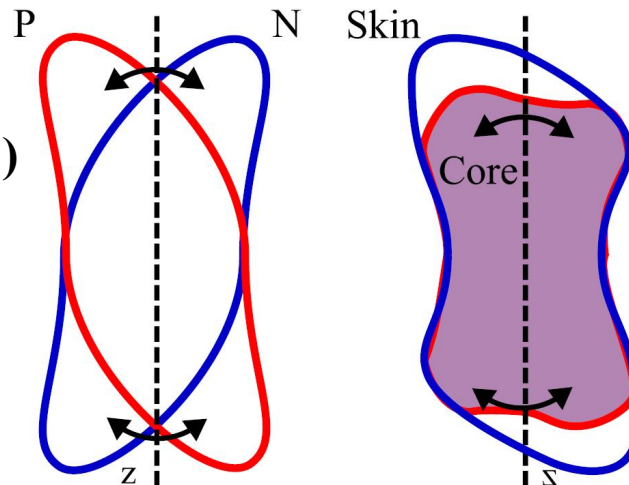


I. Hamamoto and X.Z. Zhang, PRC (1995)

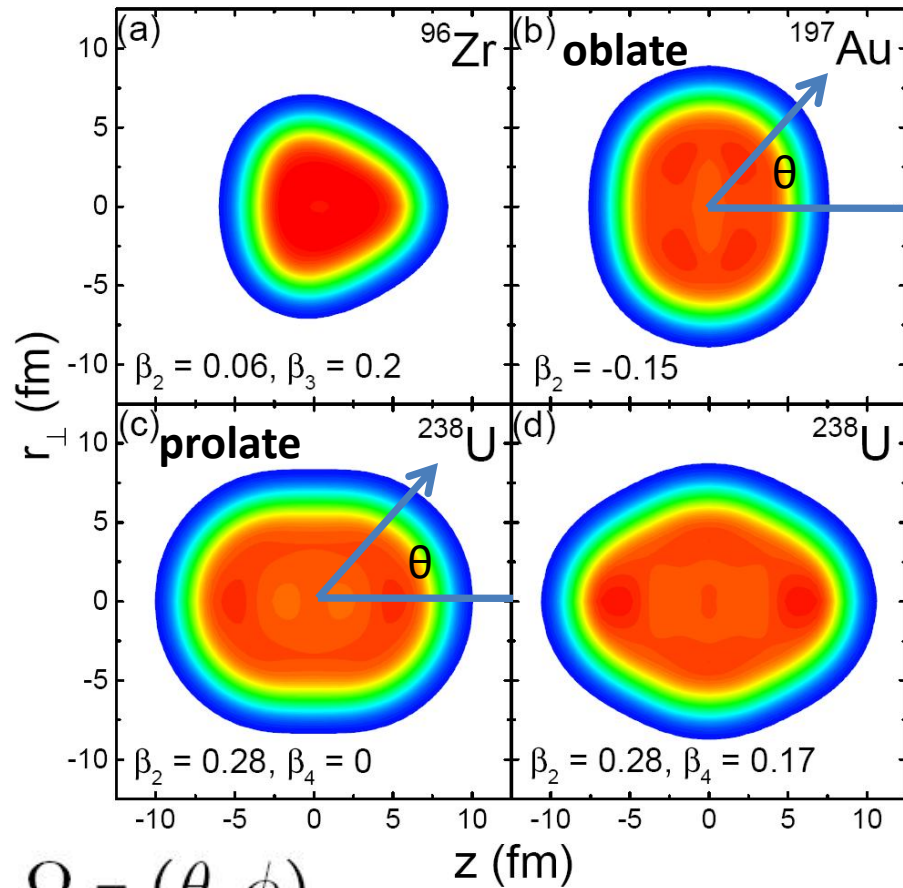
P. Sarriguren et al., PRC (2007)

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

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

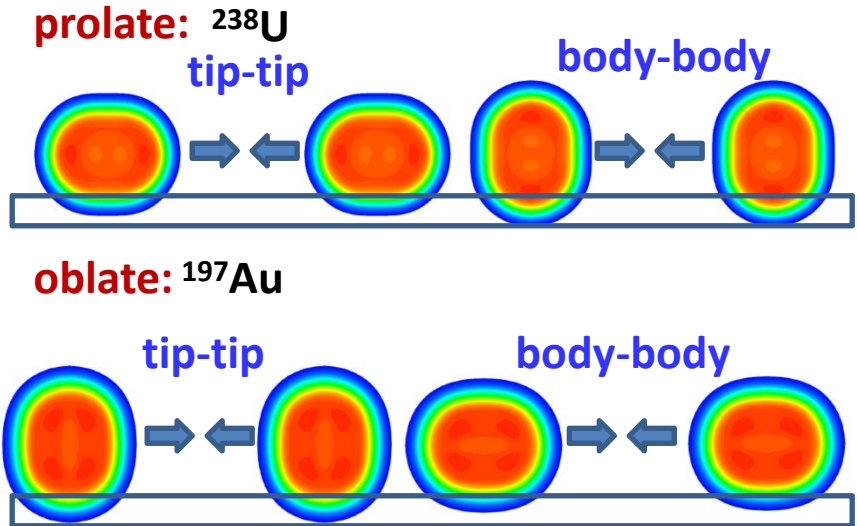


Δr_{np} effect from different collision configurations



Nucleus	Deformation(s)	$\overline{\Delta r_{np}}$ (fm)	
		$L = 30 \text{ MeV}$	$L = 120 \text{ MeV}$
^{96}Zr	$\beta_2=0.06, \beta_3=0.2$ [43]	0.145	0.227
^{197}Au	$\beta_2=-0.15$ [44]	0.127	0.243
^{238}U	$\beta_2=0.28$ [42], $\beta_4=0$	0.156	0.291
	$\beta_2=0.28$ [42], $\beta_4=0.17$	0.153	0.291

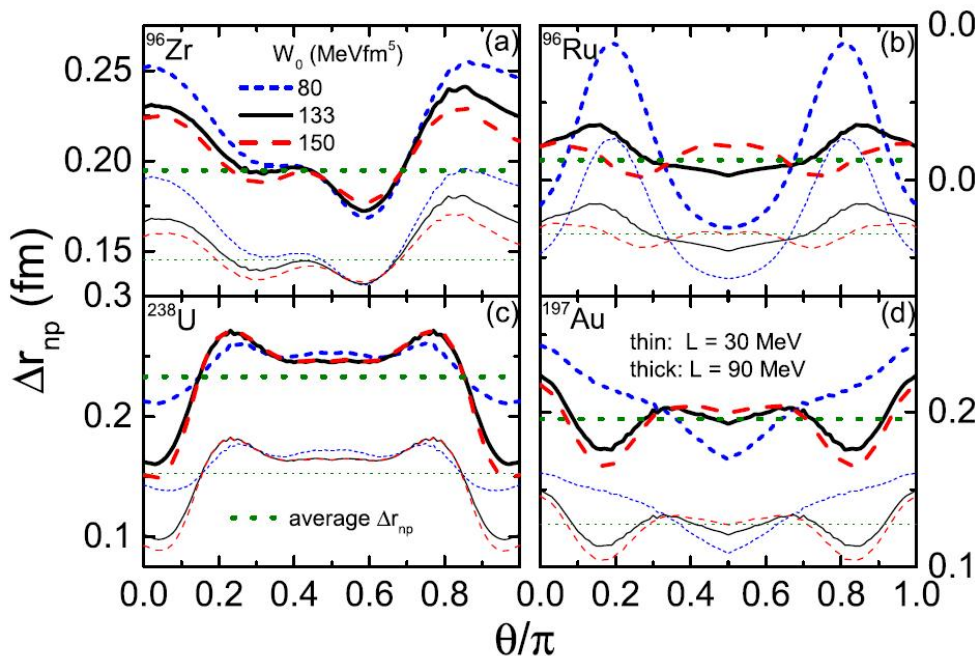
Select Δr_{np} at different θ



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

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

Deformed Δr_{np} from different SO interactions

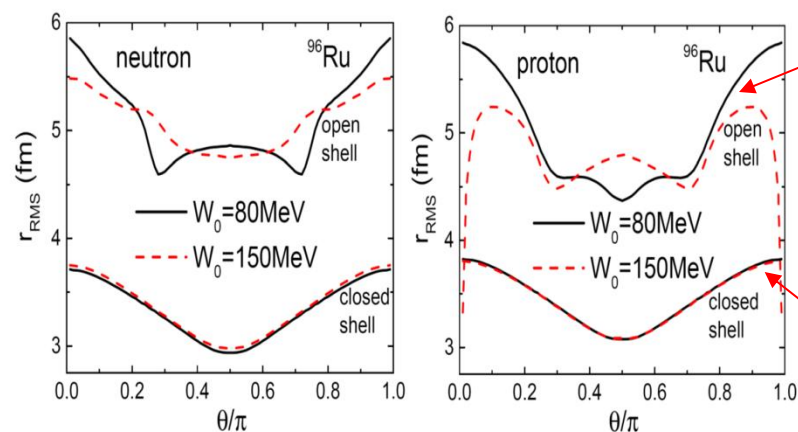
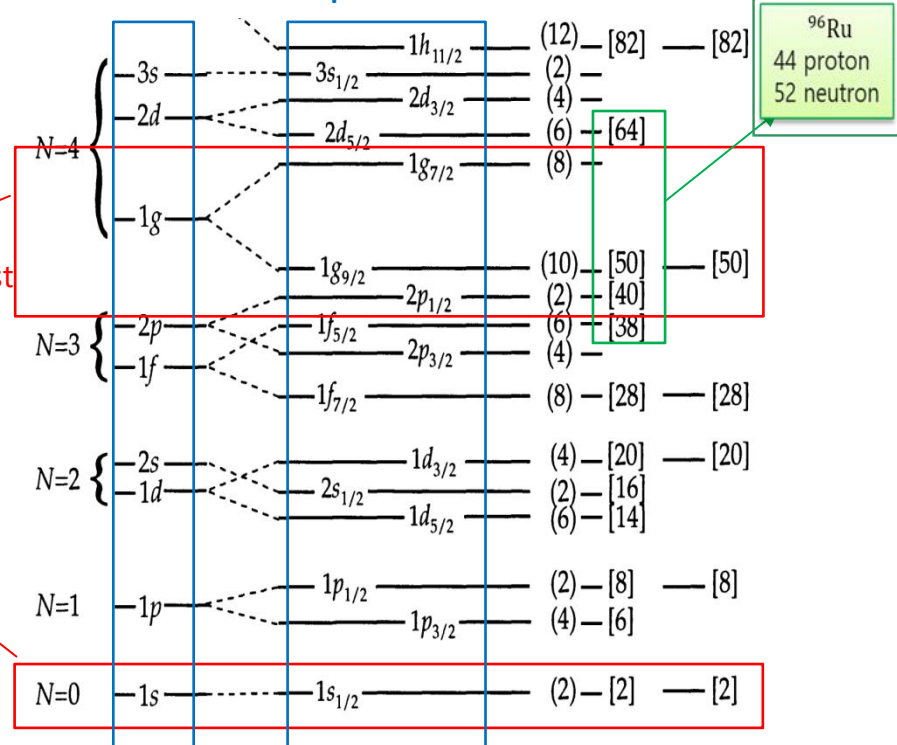


SO interaction: affect nucleons in open shells for spin unsaturated nuclei, which contribute to the angular dependence of Δr_{np}
 $L \sim U_n - U_p$ has a global effect

Spin-orbit interaction (SOI)

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

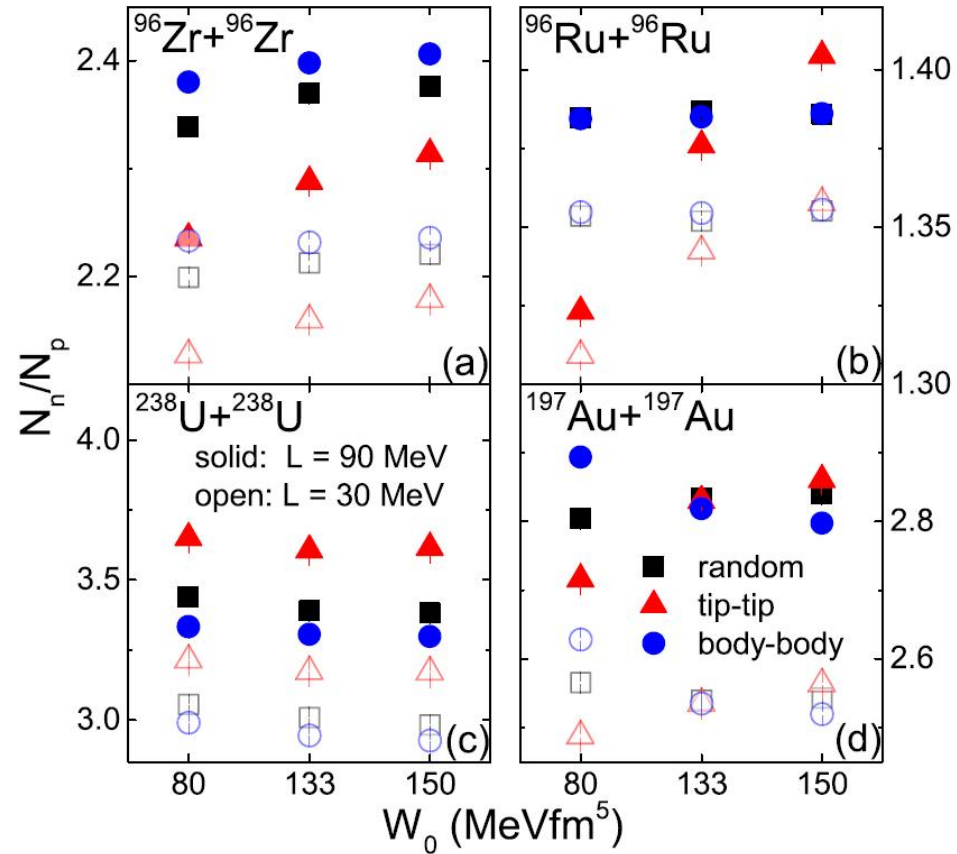
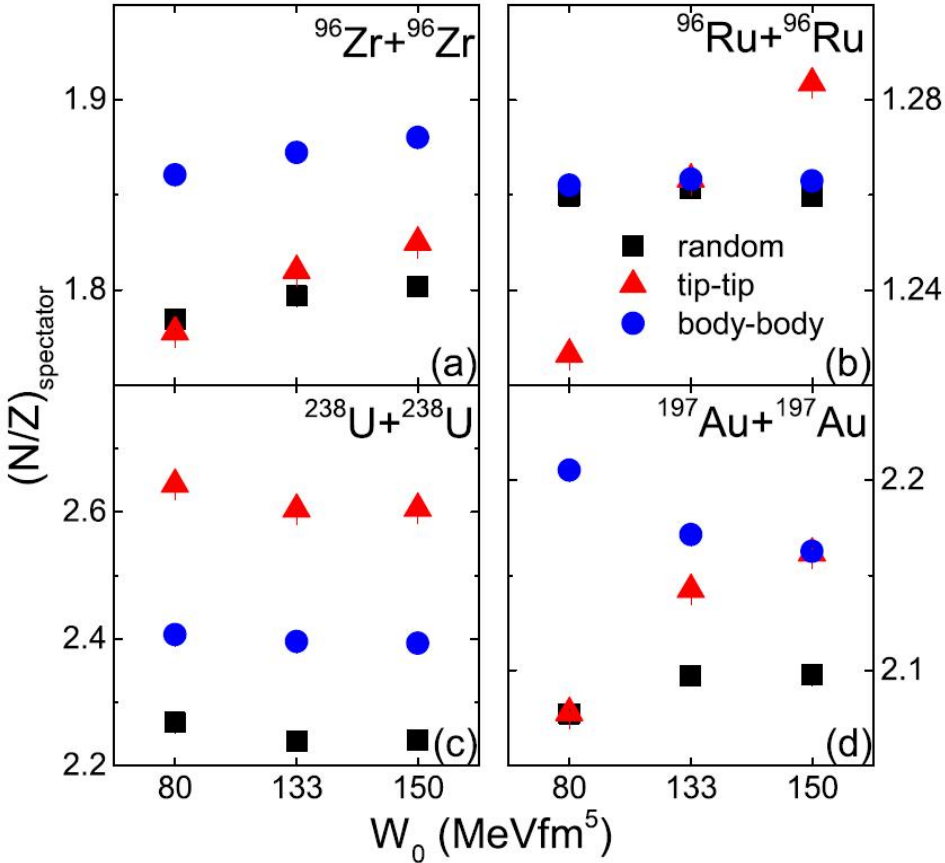
Orbit Spin-orbit



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

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

α -cluster structure in light nuclei from Brink wave function

Hamiltonian

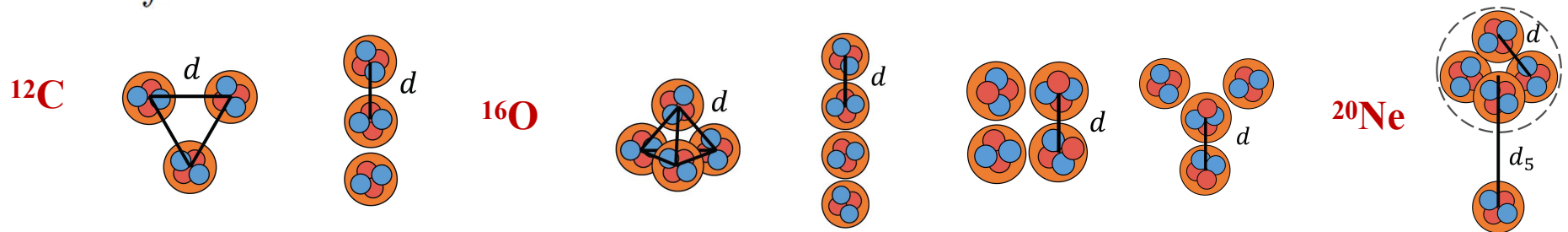
$$\hat{H} = \sum_{i=1}^A E_i^{\text{c.m.}} + \sum_{i<j} V^{NN}(r_{ij}) + \sum_{i<j} V^{\text{Coul}}(r_{ij}) + \sum_{i<j} V^{ls}(r_{ij})$$

Volkov No.2 force $V^{NN}(r_{ij}) = (V_1 e^{-\alpha_1 r_{ij}^2} - V_2 e^{-\alpha_2 r_{ij}^2}) (W - M \hat{P}_\sigma \hat{P}_\tau + B \hat{P}_\sigma - H \hat{P}_\tau)$

spin-orbit interaction $V^{ls}(r_{ij}) = u_{ls} (e^{-\alpha_3 r_{ij}^2} - e^{-\alpha_4 r_{ij}^2}) \vec{L} \cdot \vec{S} \hat{P}_{31}$

$$|\Phi^{\text{Brink}}\rangle = (C_\alpha^\dagger)^n |\text{vac}\rangle$$

$$C_\alpha^\dagger = \int d^3 r_1 \cdots d^3 r_4 \phi(\vec{r}_1 - \vec{R}) a_{\sigma_1, \tau_1}^\dagger(\vec{r}_1) \cdots \phi(\vec{r}_4 - \vec{R}) a_{\sigma_4, \tau_4}^\dagger(\vec{r}_4).$$



Distance parameters are determined by minimizing the energy for a particular configuration

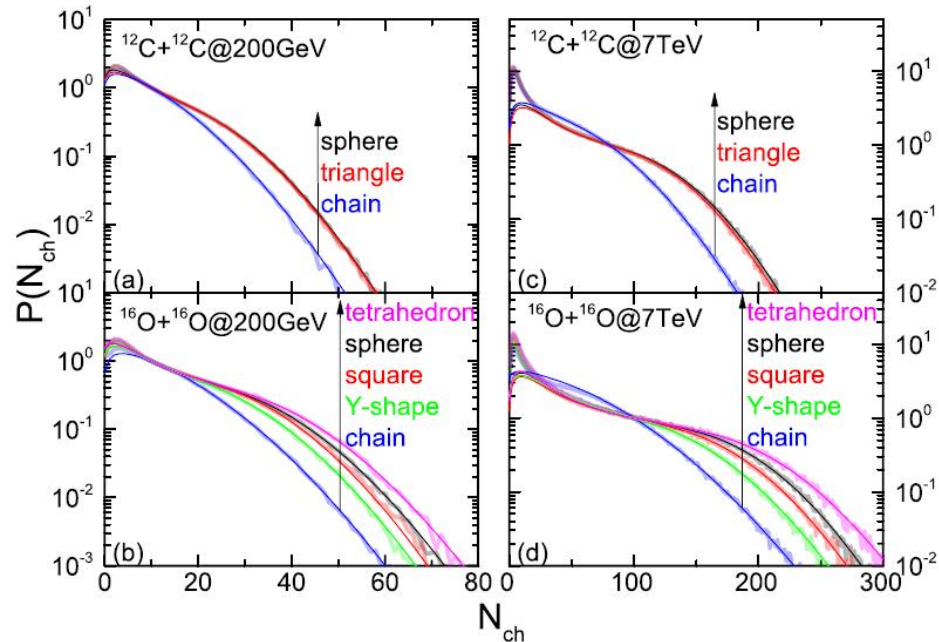
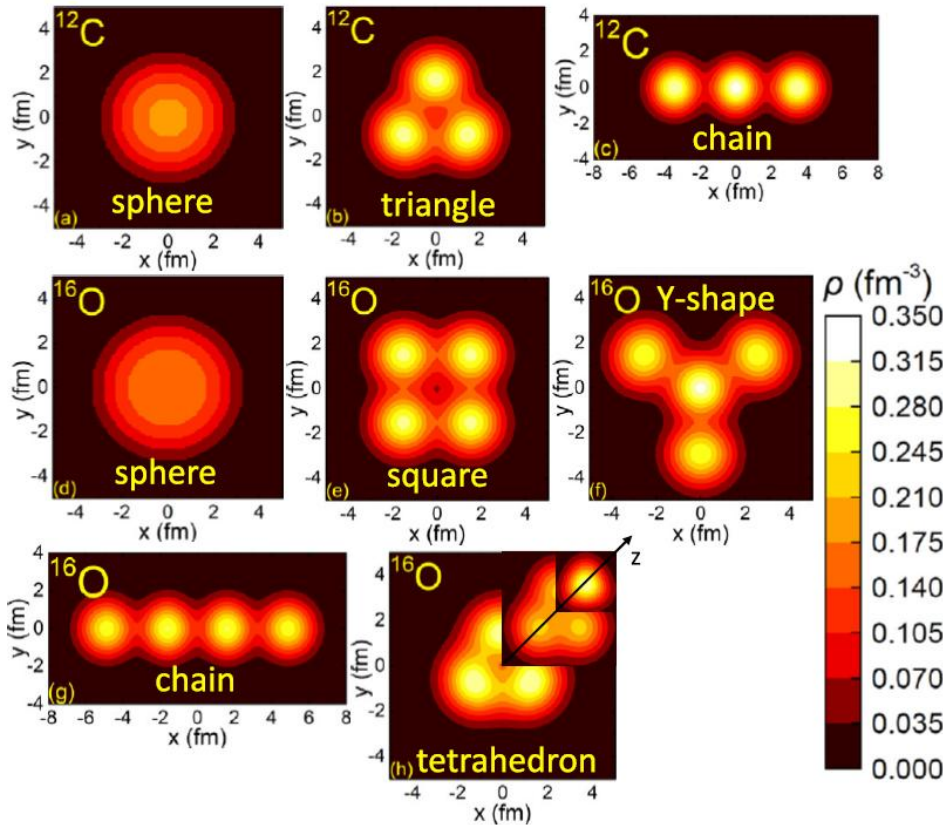
density distribution $\rho(\vec{a}) = \frac{\langle \Phi | \sum_{i=1}^A \delta(\vec{r}_i - \vec{a}) | \Phi \rangle}{\langle \Phi | \Phi \rangle} = \sum_{i=1}^A \rho_i(\vec{a})$

Forward/backward particle yields as a probe of α -cluster configuration in ^{12}C and ^{16}O

Root-mean-square (RMS) radii in fm of ^{12}C and ^{16}O for different configurations.

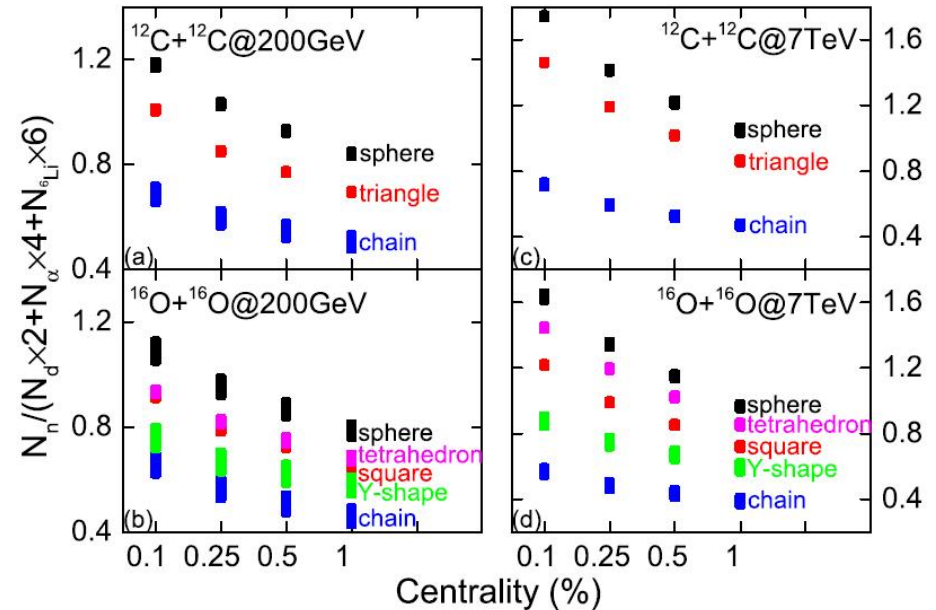
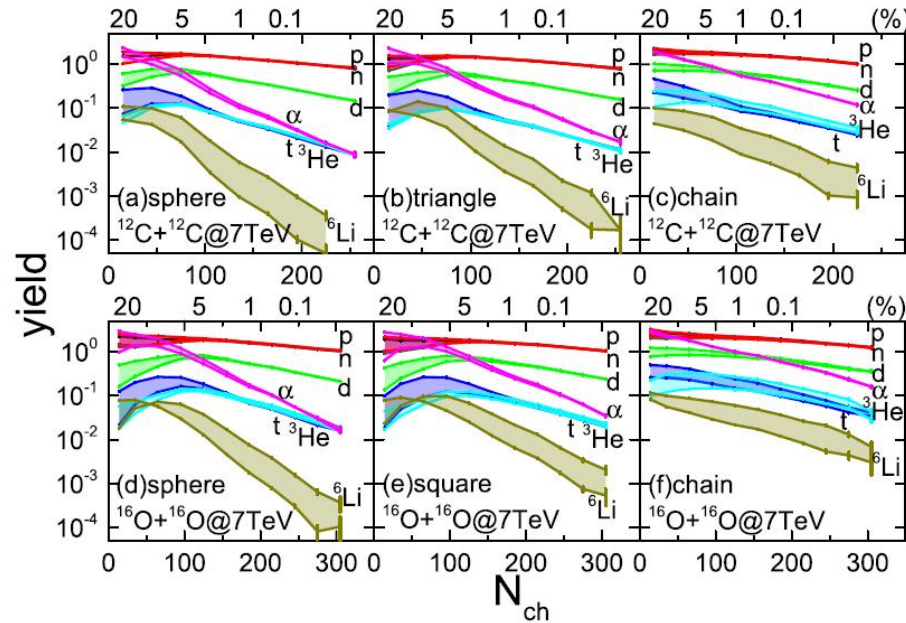
	sphere	triangle	square	chain	Y-shape	tetrahedron
^{12}C	2.49	2.45	-	3.29	-	-
^{16}O	2.69	-	2.77	4.06	3.09	2.45

charged-particle multiplicity distribution from AMPT



L.M. Liu, S.J. Li, Z. Wang, JX, Z.Z.Ren, and X.G. Huang, PLB (2024)

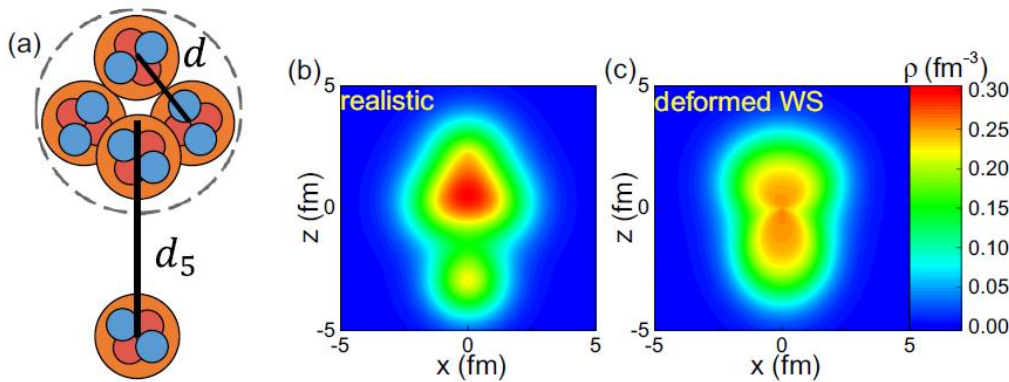
Forward/backward particle yields as a probe of α -cluster configuration in ^{12}C and ^{16}O



- With initially α -cluster structure, neutrons and protons are more likely to form α particles or light nuclei at forward/backward rapidities.
- Chain configuration leads to more α particles or light nuclei compared to more compact configurations.
- The uncertainties in the deexcitation process are largely reduced in ultracentral collisions.

L.M. Liu, S.J. Li, Z. Wang, JX, Z.Z. Ren, and X.G. Huang, PLB (2024)

Directly probing existence of α -cluster structure in ^{20}Ne

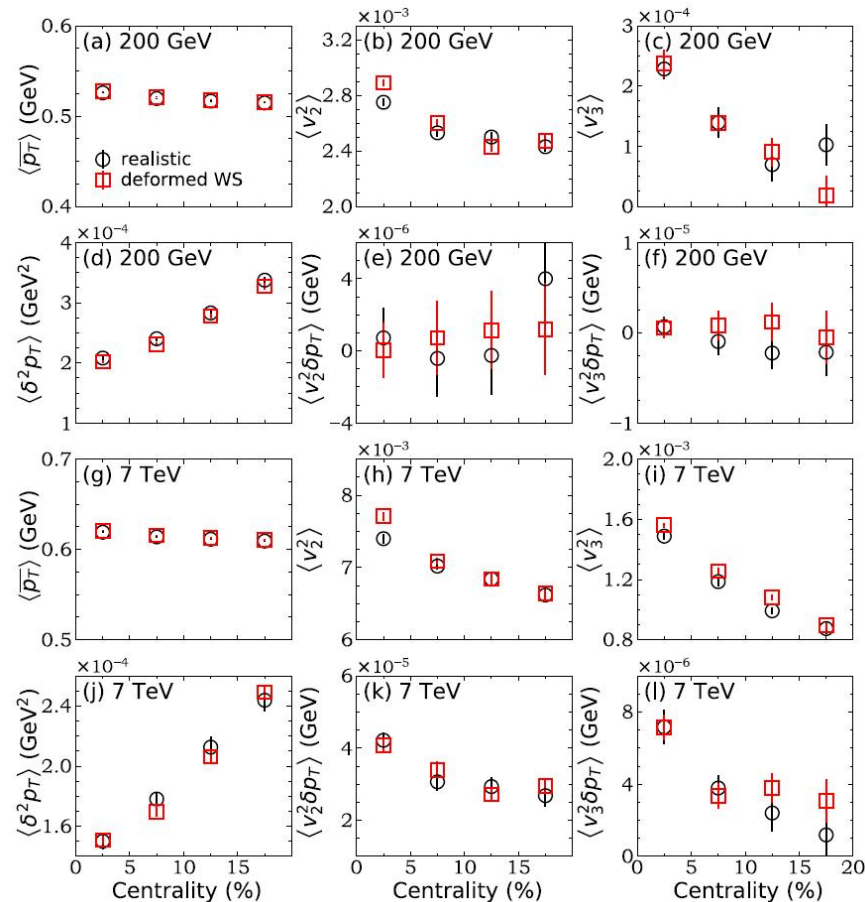


We fit the realistic density distribution with the deformed WS form, so they have the overall similar shape.

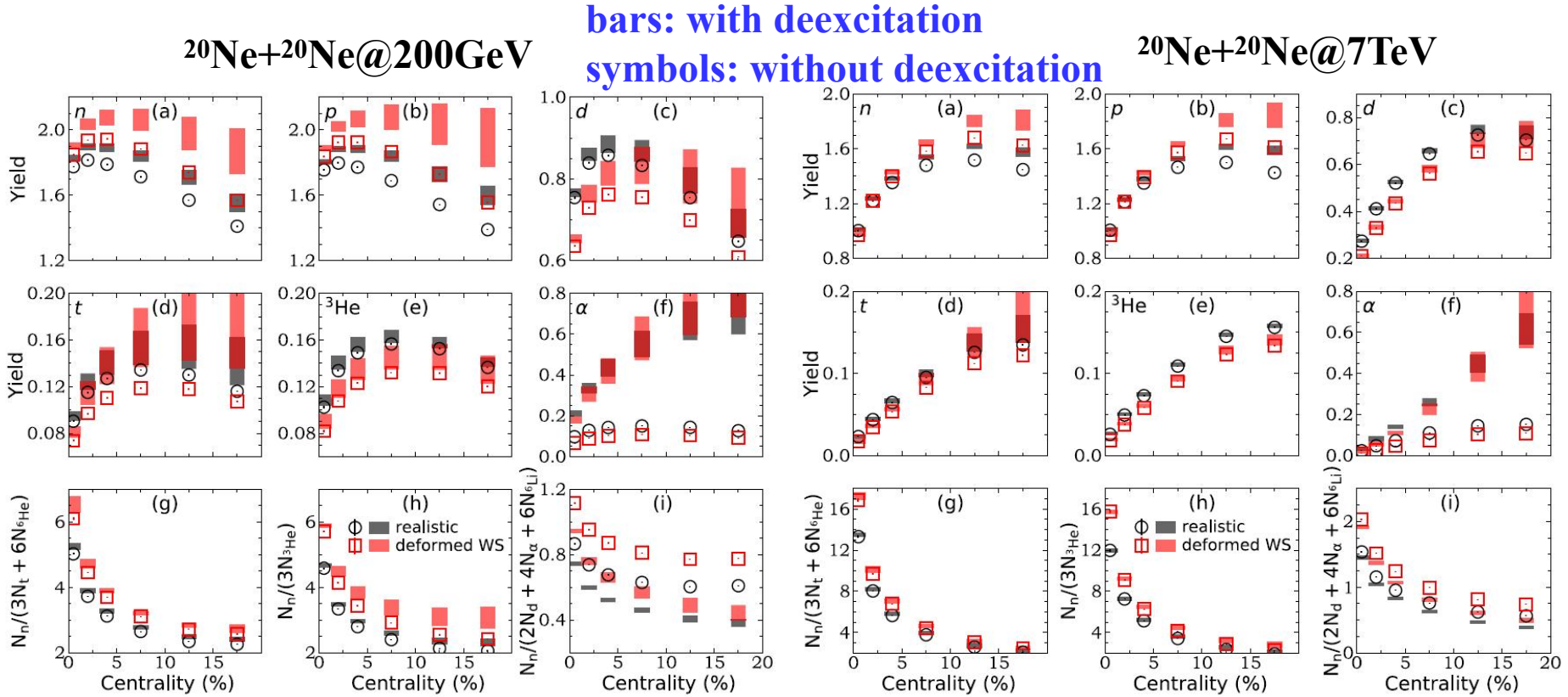
$$\rho(r, \theta) = \frac{\rho_0}{1 + \exp[(r - R(\theta))/a]}$$

$$R(\theta) = R_0 \left[1 + \sum_{n=2,3} \beta_n Y_{n,0}(\theta) \right]$$

It is difficult to distinguish the two cases through mid-rapidity observables in $^{20}\text{Ne}+^{20}\text{Ne}$ collisions based on AMPT.

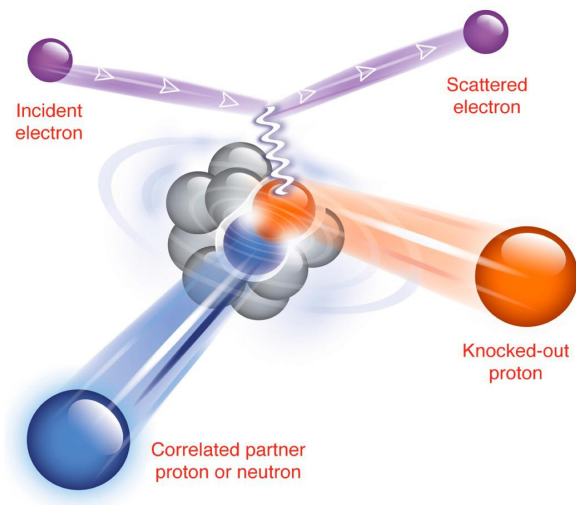
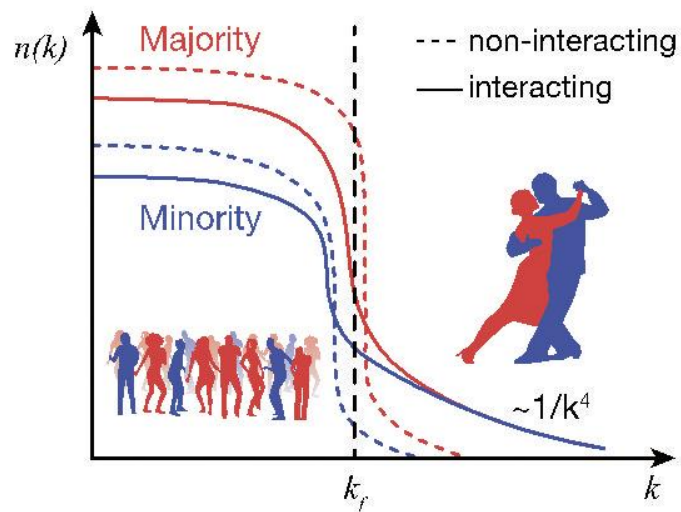


Directly probing existence of α -cluster structure in ^{20}Ne



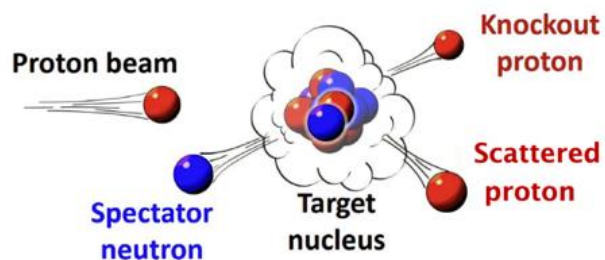
- Small spectator nucleon yield and larger yields of α particles and light nuclei are observed with initially α -cluster structure in UCC.
- Taking the yield ratio further reduces the theoretical uncertainty.
- 20% effect at RHIC and 25% effect at LHC

Measure HMT induced by SRC

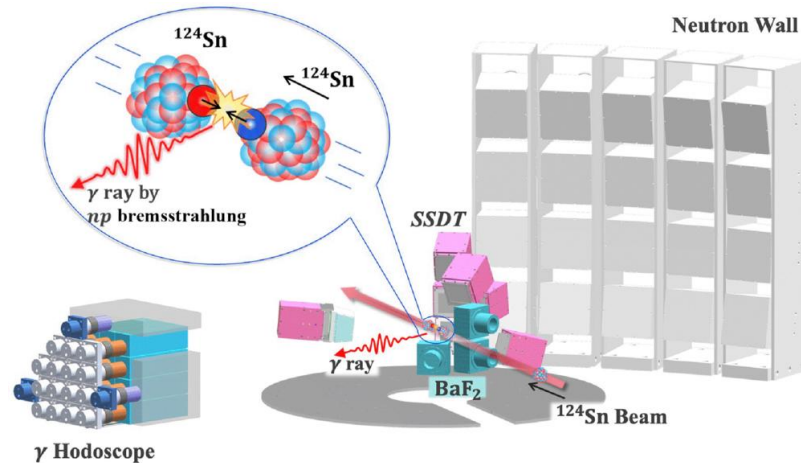
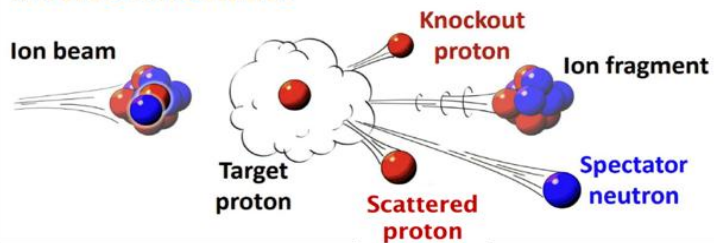


Cartoons from Zhi-Hong Ye

Normal kinematics

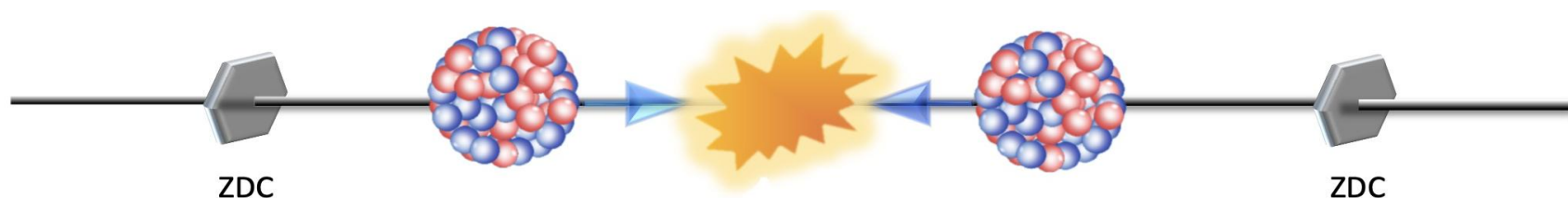


Inverse kinematics



measurement by Zhi-Gang Xiao's group

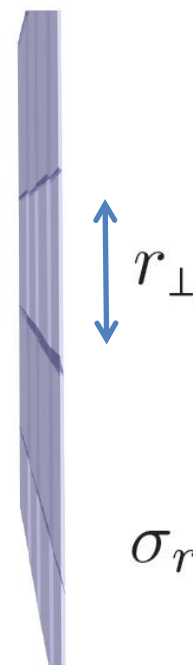
Measure HMT using spectator nucleons?



ZDC array

spectator
nucleon

$l = 18$ m at RHIC



$$k_T \approx r_{\perp} \times \frac{\sqrt{s_{\text{NN}}/4 - m^2}}{l}$$

$$\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$$

$$\sigma_{r_{\perp}} \sim 1-2 \text{ cm} \Rightarrow \sigma_{k_T} \sim 50 - 100 \text{ MeV}/c$$

Fit global properties

$$f_J(\mathbf{r}, \mathbf{k}) = 2 \times \begin{cases} \Delta_J, & 0 < |\mathbf{k}| < k_0, \\ C \left[\frac{k_0(\mathbf{r})}{|\mathbf{k}|} \right]^4, & k_0 < |\mathbf{k}| < \phi k_0. \end{cases}$$

$$\int f_J(\mathbf{r}, \mathbf{k}) \frac{d^3 \mathbf{k}}{(2\pi)^3} = \rho_J(\mathbf{r})$$

one-body momentum distribution

$$n_J(k) = \int f_J(\mathbf{r}, \mathbf{k}) d^3 \mathbf{r}$$

nucleon number in HMT
(300 ~ 600 MeV/c)

$$\tilde{N}_J = \frac{1}{2\pi^2} \int_{k_l}^{k_u} n_J(k) k^2 dk$$

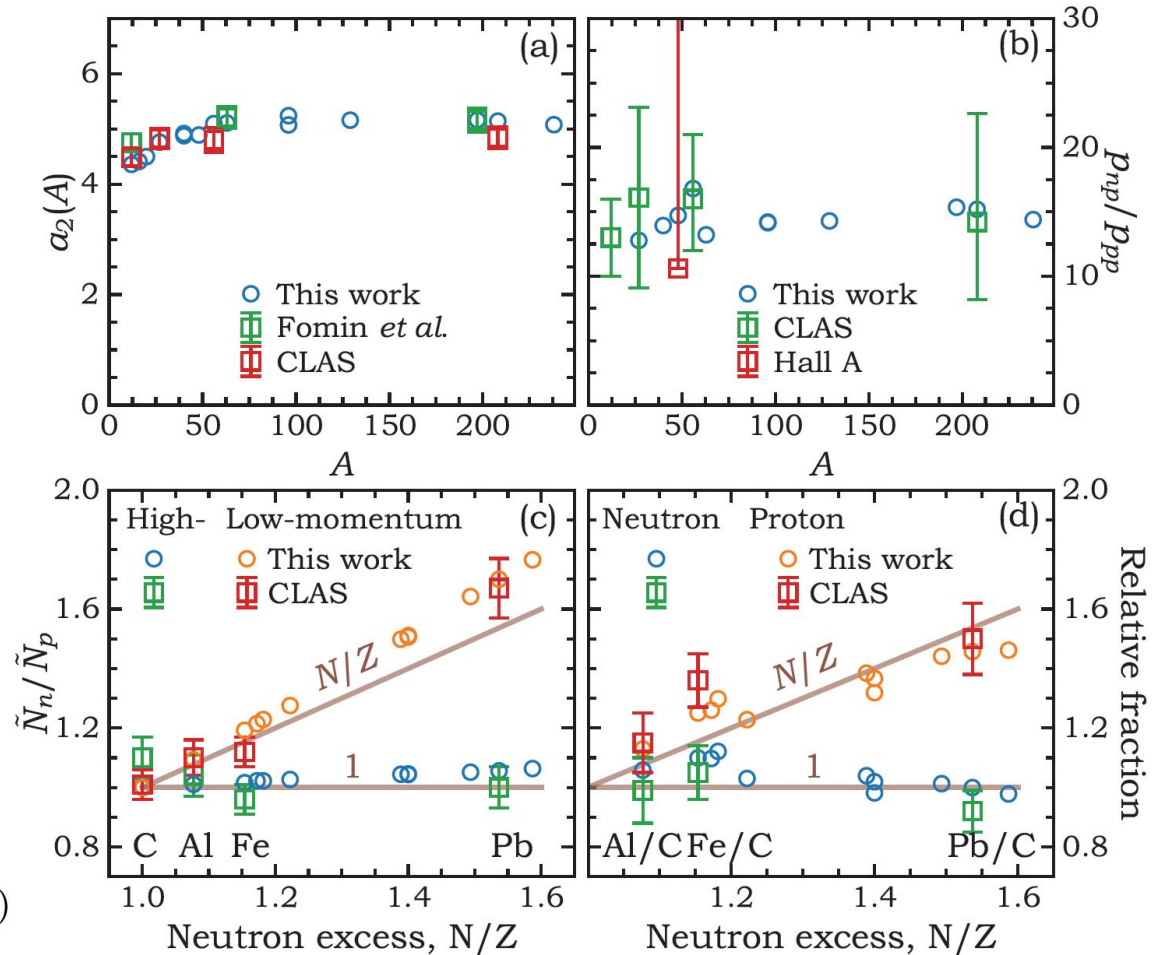
$$a_2(A) \approx \frac{2}{A} \frac{\tilde{N}_n(A) + \tilde{N}_p(A)}{2\tilde{N}_p(d)}$$

$$\tilde{N}_n \approx N_{np} + 2N_{nn}$$

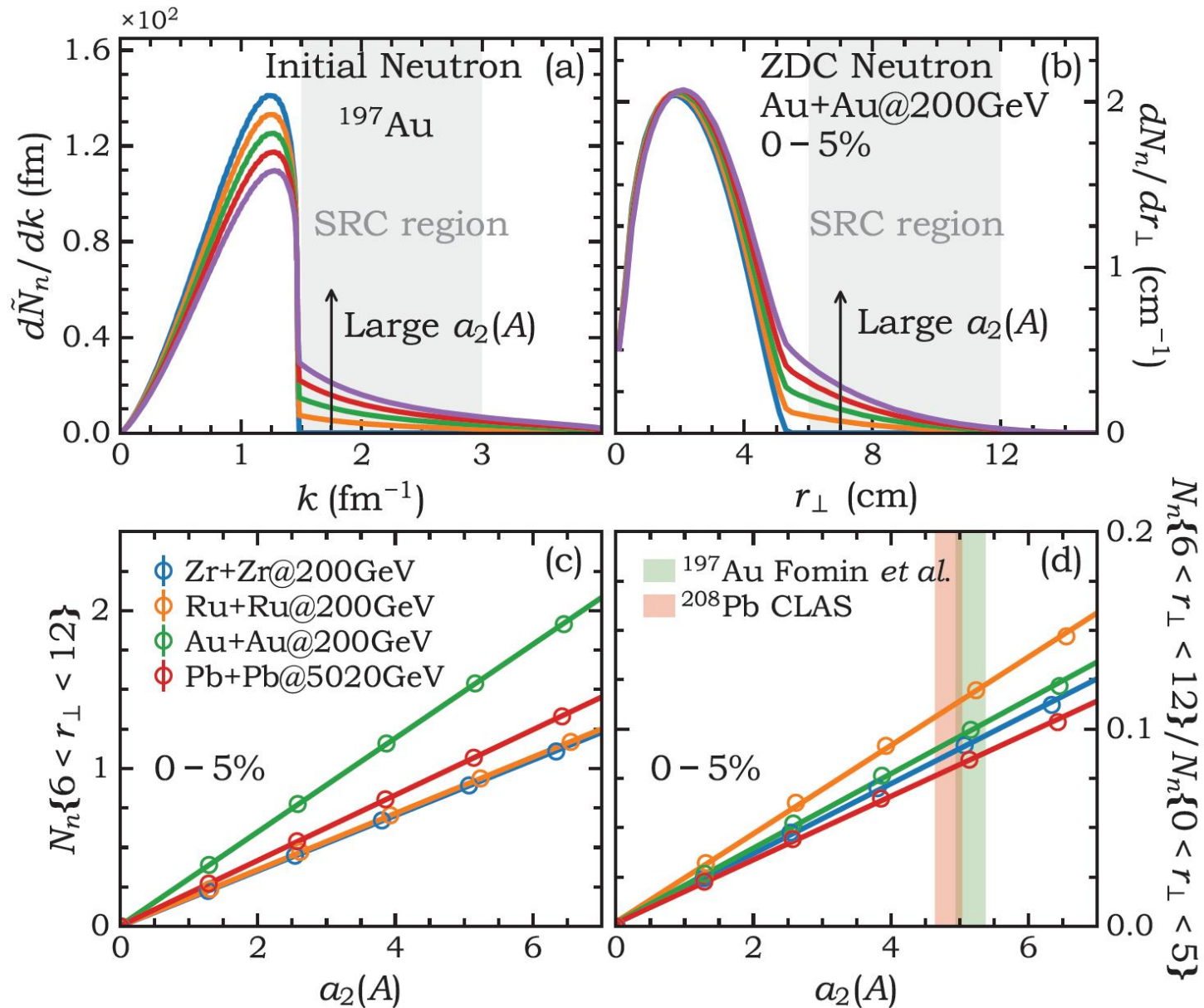
$$= [N \cdot Z \cdot p_{np} + N \cdot (N-1) \cdot p_{pp}] \cdot f_{sr}(A)$$

$$\tilde{N}_p \approx N_{np} + 2N_{pp}$$

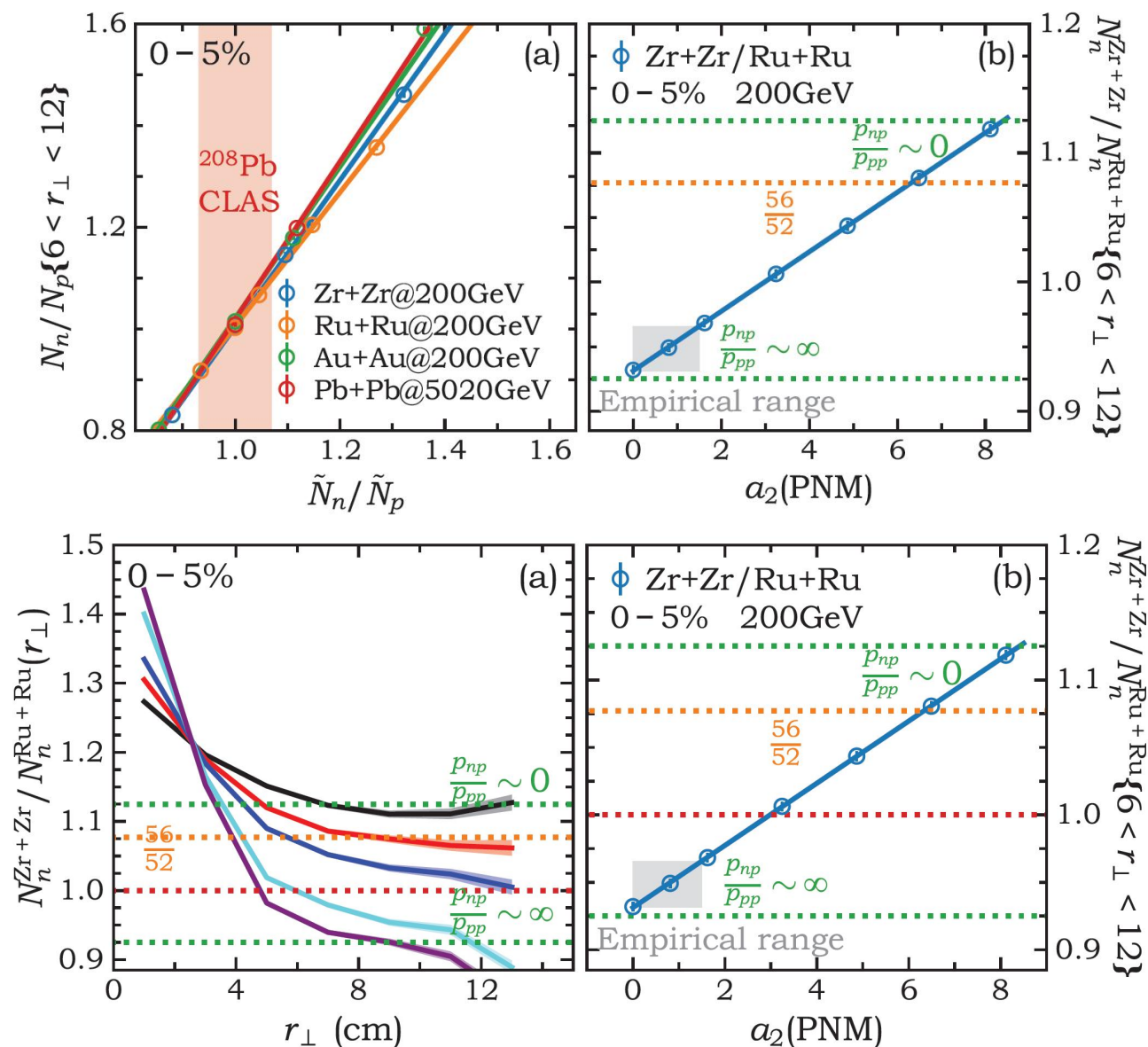
$$= [N \cdot Z \cdot p_{np} + Z \cdot (Z-1) \cdot p_{pp}] \cdot f_{sr}(A).$$



Measure $a_2(A)$ with $N_n(r_\perp)$



Measure isospin dependence of HMT



Summary

- Free spectator particle yield: **clean probes**
- Ultracentral HIC: **free from deexcitations**
- Probe neutron-skin thickness $\Delta r_{np} \sim L$
 - $(N_n)^{Zr+Zr}/(N_n)^{Ru+Ru}$ **reduce uncertainties**
 - $(N_n/N_p)^{Zr+Zr}/(N_n/N_p)^{Ru+Ru}$ **cancel detecting efficiency**
- Triggering collision configurations: $\Delta r_{np}(\theta) \sim SO$
- Probe α -cluster structure/configuration in $^{16}O+^{16}O$ and $^{20}Ne+^{20}Ne$
 - $N_n/(2N_d+4N_\alpha+6N^6_{Li})$
 - $N_n/(3N_t+6N^6_{He})$
 - $N_n/(3N^3_{He})$
- Probe magnitude and isospin dependence of HMT
 - $N_n(\text{large } r_\perp)/N_n(\text{small } r_\perp)$
 - $N_n^{Zr+Zr}(\text{large } r_\perp)/N_n^{Ru+Ru}(\text{large } r_\perp)$

Thank you!

junxu@tongji.edu.cn