Extracting high-density symmetry energy from FOPI / FOPI-LAND data

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- Short-range correlations of nucleon-nucleon
- IBUU transport model
- Current status of the high-density symmetry energy
- Pion data and symmetry energy
- Elliptic flow data and symmetry energy
- Summary

Short-rang correlations (SRC)

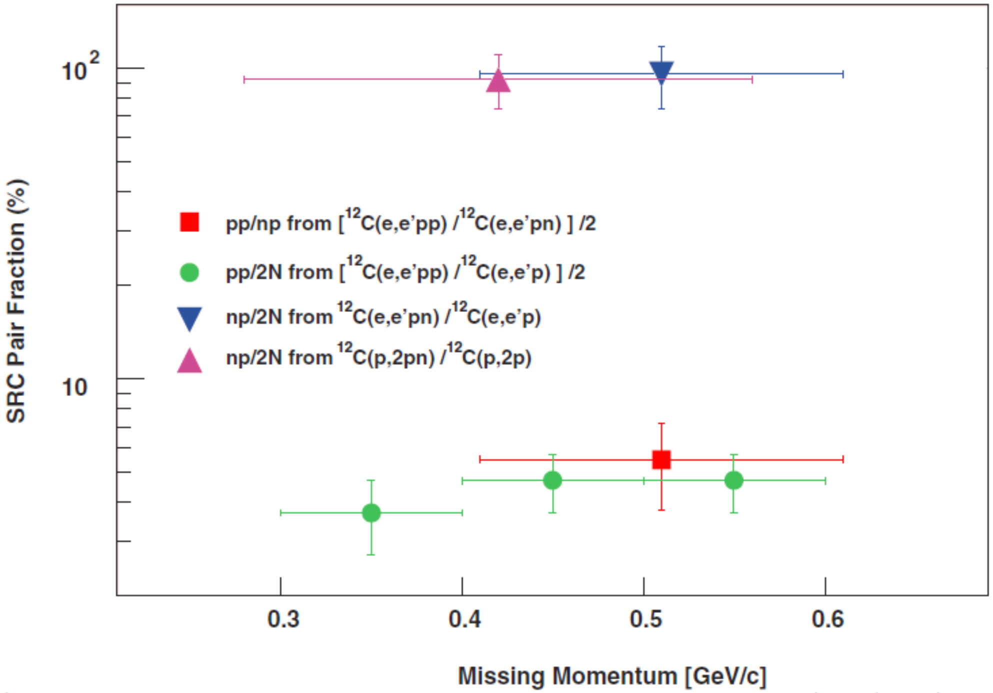


Fig. 2. The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data. The results and references are listed in table S1.

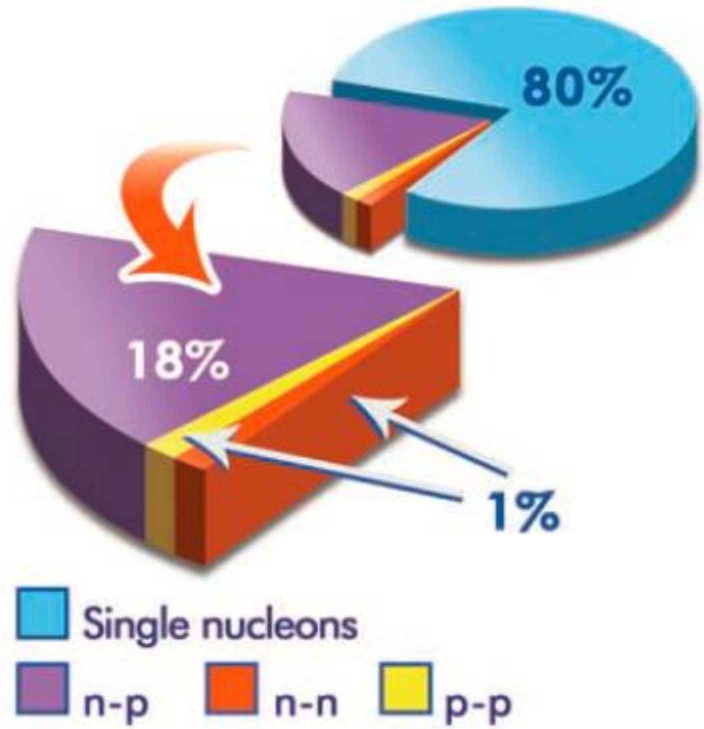


Fig. 3. The average fraction of nucleons in the various initial-state configurations of ^{12}C.

R. Subedi et al. (Hall A. Collaboration), Science 320, 1476 (2008).

High-momentum tail (HMT)

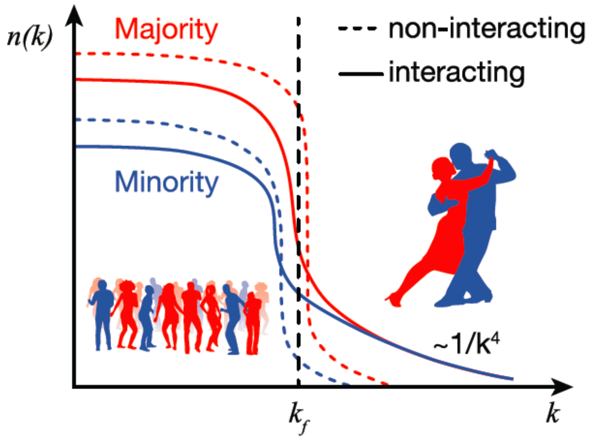


Fig. 1. A schematic representation of the momentum distribution, n(k), of two-component imbalanced Fermi systems. The dashed lines show the non-interacting system whereas the solid lines show the effect of including a short-range interaction between different fermions. Such interactions create a high-momentum ($k>k_F$ where k_F is the Fermi momentum of the system) tail. This is analogous to a dance party with a majority of girls, where boy-girl interactions will make the average boy dance more than the average girl.

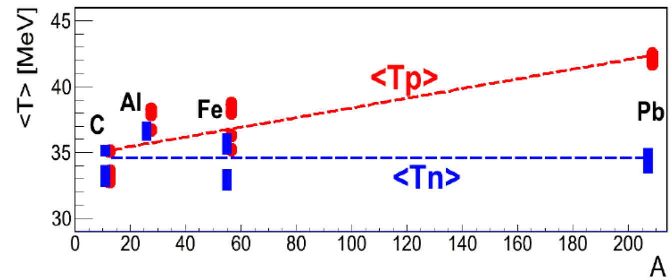


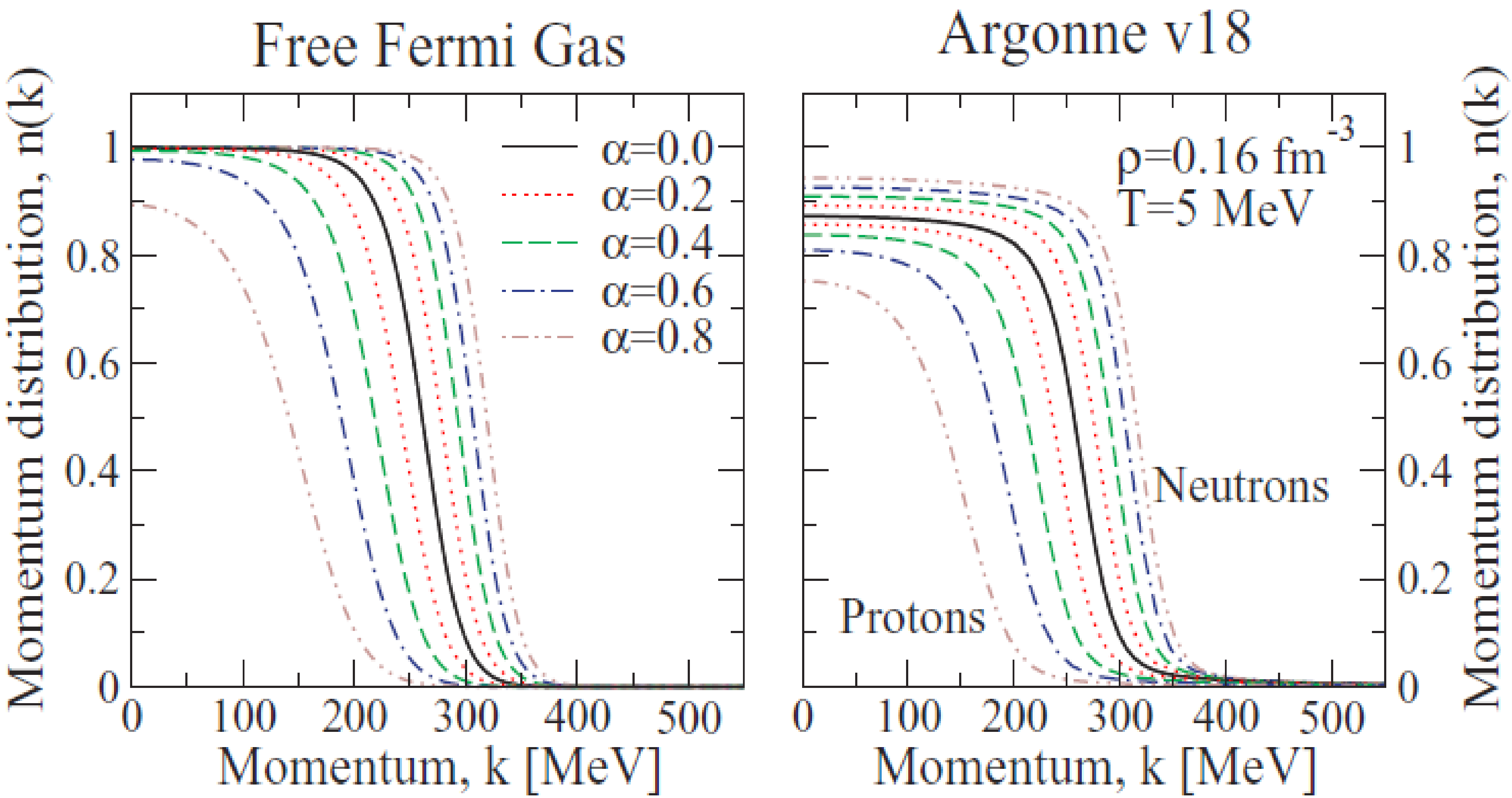
Fig. S1.
The average proton and neutron kinetic energy calculated within the np-dominance model described by Eq. S3. See text for details.

High-momentum tail (HMT) of nucleon distribution

This kinetic energy is different from SCGF !
PRC89, 0440303 (2014),
A. Rios, A. Polls, W.H. Dickhoff

O. Hen et al. (the CLAS Collaboration), Science 346, 614 (2014).

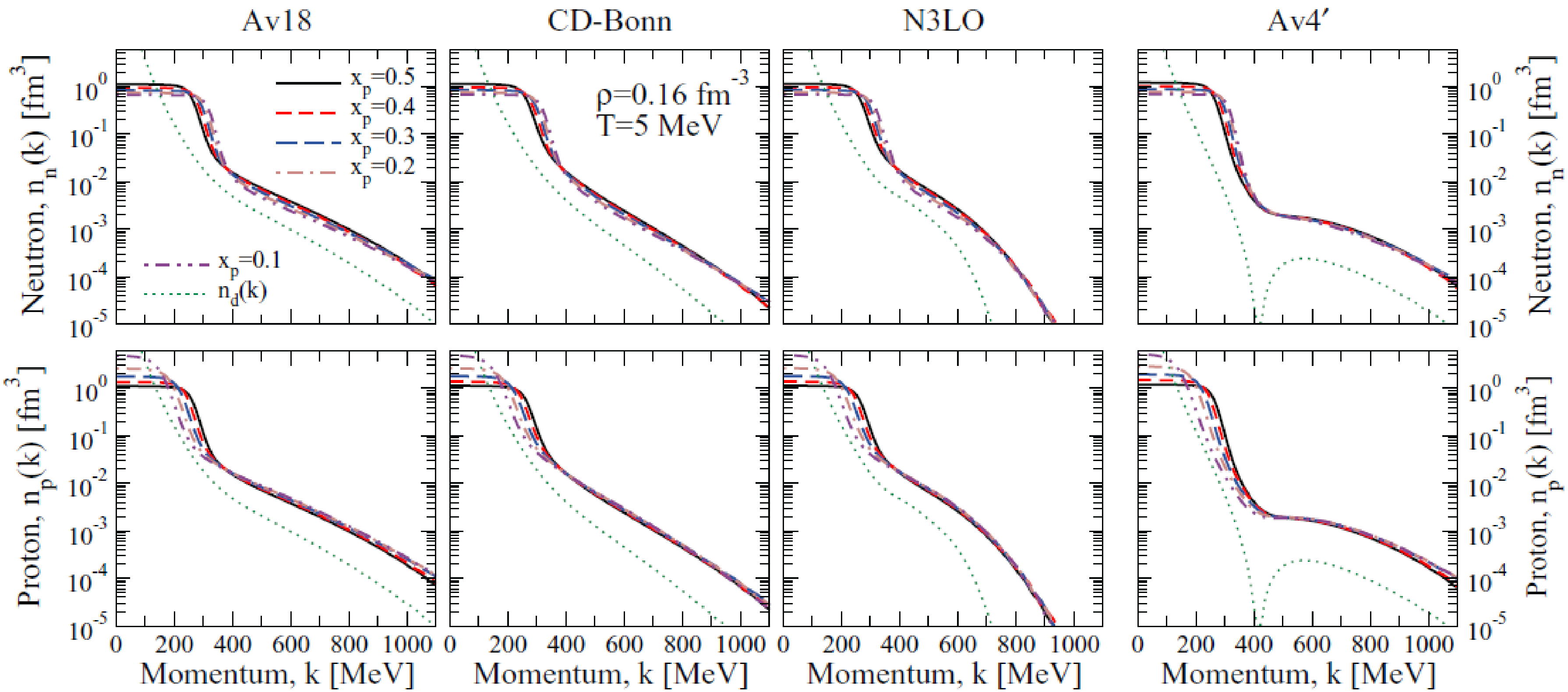
Depletion of the nuclear Fermi sea



$$\alpha = \frac{\rho_n - \rho_p}{\rho}$$

A. Rios, A. Polls, W.H. Dickhoff, PRC 79, 064308 (2009)

Increase in high-momentum tail



For different asymmetries, tails look alike

A. Rios, A. Polls, W.H. Dickhoff, PRC 89, 044303 (2014)

Modeling SRC in BUU transport

$$\frac{\partial f}{\partial t} + \nabla_{\vec{p}} E \cdot \nabla_{\vec{r}} f - \nabla_{\vec{r}} E \cdot \nabla_{\vec{p}} f = I_c$$

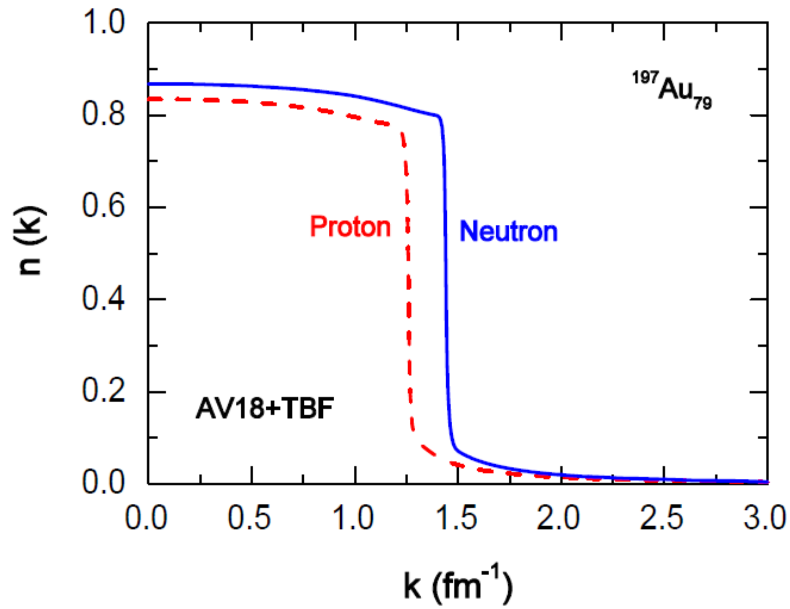
$$E = Ekin + U$$

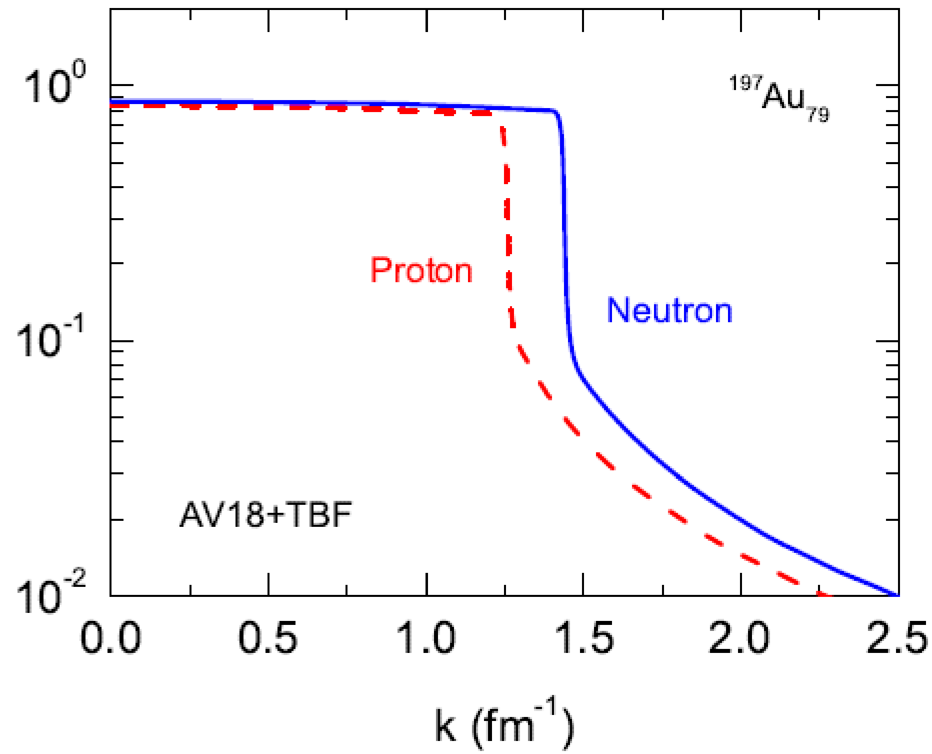
$f(r,p)_{t=0}$: corrected

U: corrected

I_c: did not

Initialization of colliding nuclei





15% depletion of nuclear Fermi sea
Stability is not well resolved
runs at relatively high beam energy

FIG. 1: Momentum distributions of neutron and proton in nucleus $^{197}Au_{79}$ calculated with BHF with Av18+TBF [11].

G.C. Yong, arXiv: 1503.08523

Random distribution in sphere

No bound pair state
No local high density

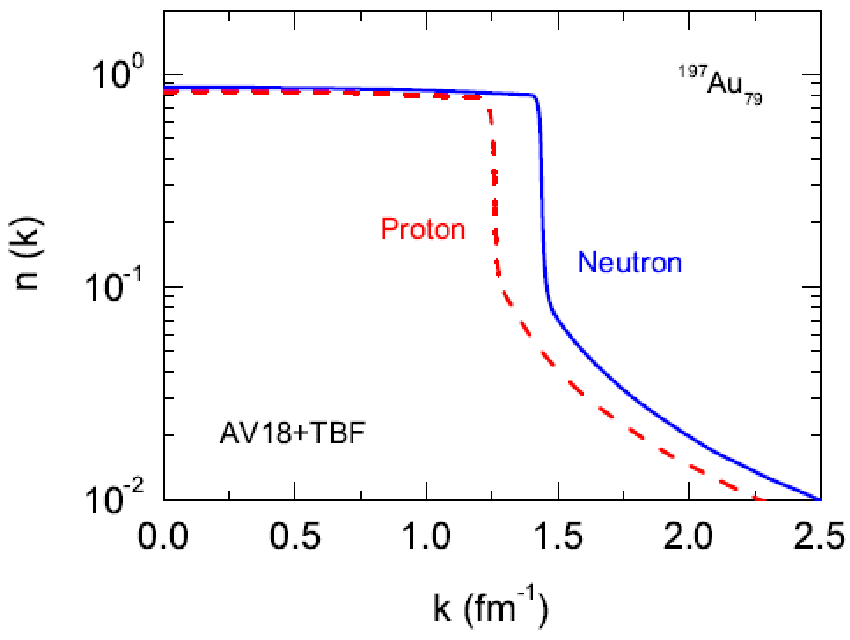
$$r = R(x_1)^{1/3}; cos\theta = 1 - 2x_2; \phi = 2\pi x_3;$$

$$x = rsin\theta cos\phi; y = rsin\theta sin\phi; z = rcos\theta.$$

$x1, x2, x3\ are\ 3\ random\ numbers$

G.C. Yong, arXiv: 1503.08523

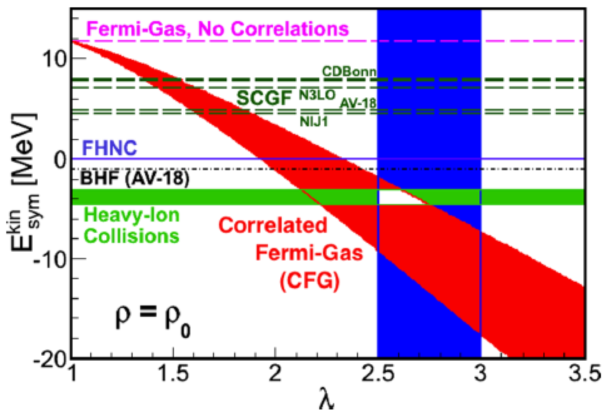
Energy correction

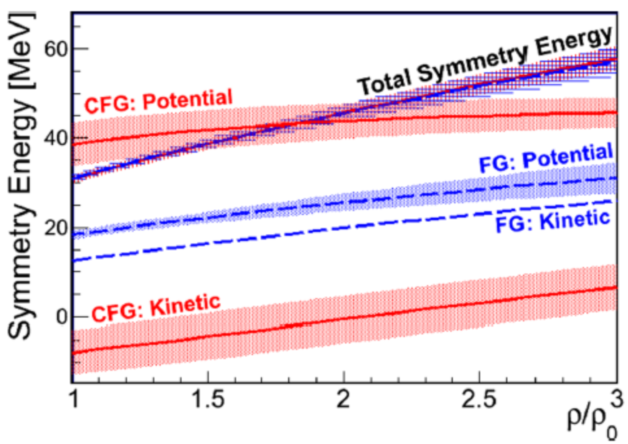


Ground-state nucleus energy may be not equal to Experimental data, thus need correction

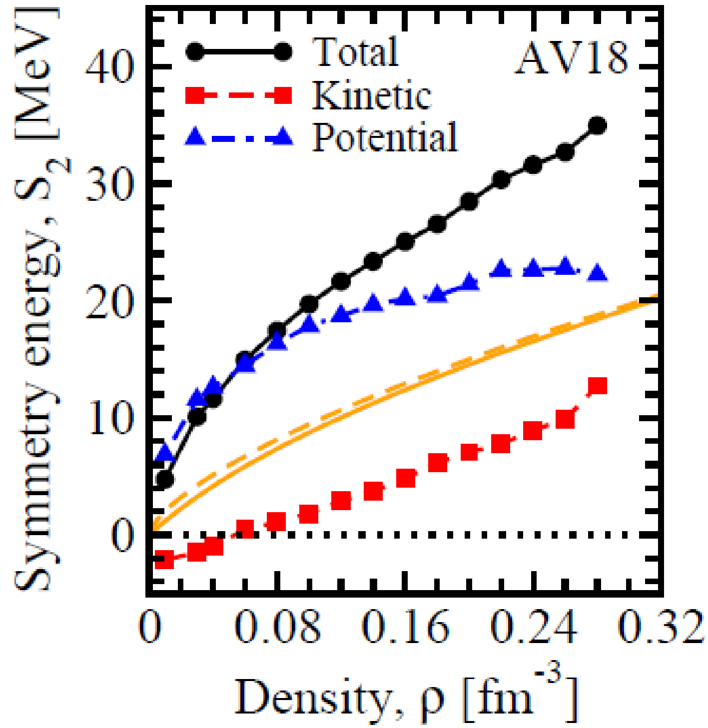
Plus or minus from system total energy

Kinetic symmetry energy





Hen, Li, Guo, Weinstein, Piasetzky,
PRC91, 025803 (2015)



Carbone, Polls, Rios,
Europhys. Lett. 97, 22001 (2012)

Mean-field potential

$$
\begin{aligned}
U(\rho, \delta, \vec{p}, \tau) \; = \; & A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} \\
& + B(\frac{\rho}{\rho_0})^\sigma (1 - x\delta^2) - 8x\tau \frac{B}{\sigma + 1} \frac{\rho^{\sigma - 1}}{\rho_0^\sigma} \delta \rho_{\tau'} \\
& + \frac{2C_{\tau,\tau}}{\rho_0} \int d^3 \vec{p'} \frac{f_\tau(\vec{r}, \vec{p'})}{1 + (\vec{p} - \vec{p'})^2/\Lambda^2} \\
& + \frac{2C_{\tau,\tau'}}{\rho_0} \int d^3 \vec{p'} \frac{f_{\tau'}(\vec{r}, \vec{p'})}{1 + (\vec{p} - \vec{p'})^2/\Lambda^2}, \qquad (2)
\end{aligned}
$$

Table 7. Kinetic, $\langle K \rangle$, and potential, $\langle V \rangle$, contributions to E_{PNM}, E_{SNM}, E_{sym} and L. Units are given in MeV.

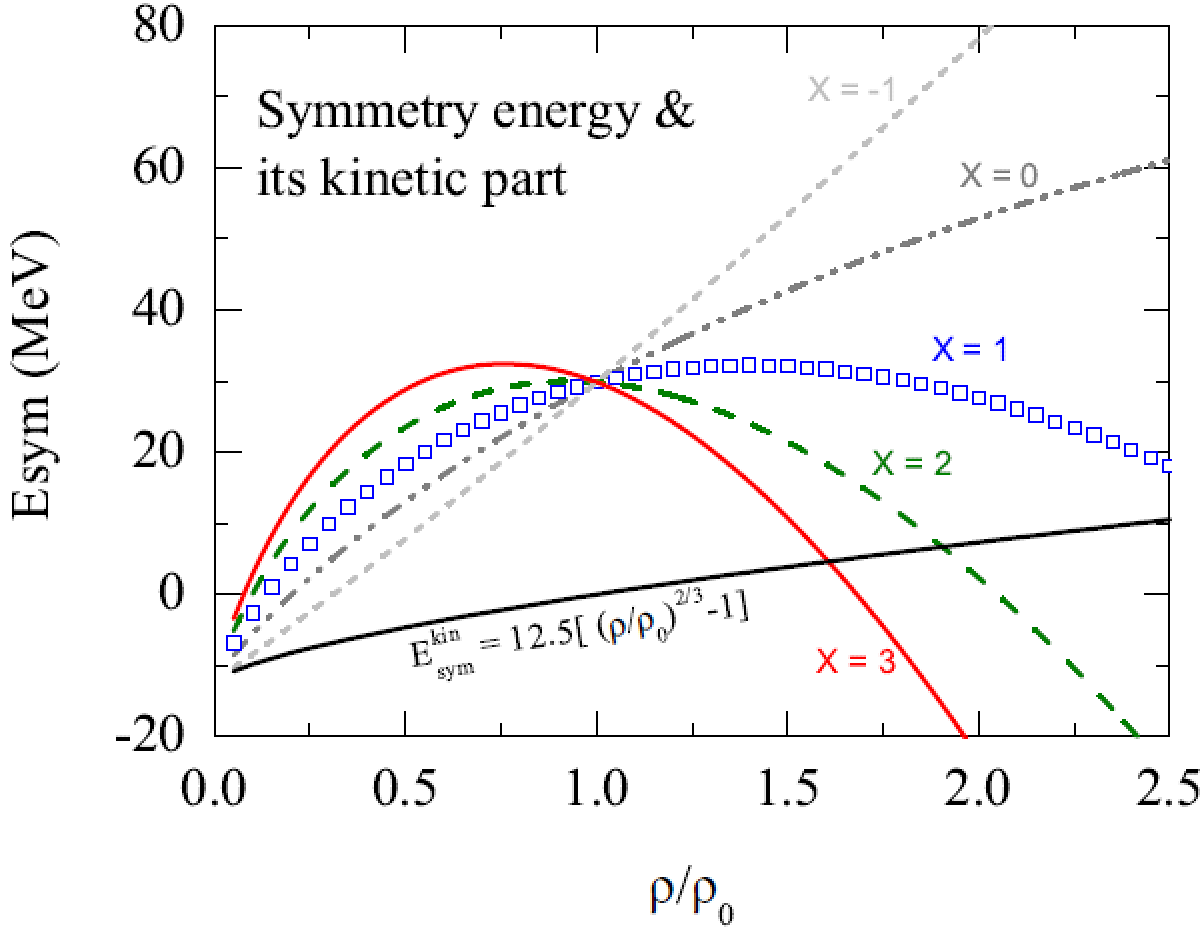
	E_{PNM}	E_{SNM}	E_{sym}	L
$\langle K \rangle$	53.321	54.294	-0.973	14.896
$\langle V \rangle$	-34.251	-69.524	35.273	51.604
Total	19.070	-15.230	34.300	66.500

Arianna Carbone et al., arXiv:1308.1416

$Esym^{kin}$=0, $Esym^{pot}$=30 (at ρ_0)

Das, et al, PRC67, 034611 (2003); Xu, et al., PRC91, 014611 (2015); G.C. Yong, arXiv: 1504.02528

Modeling the symmetry energy (Esym)



G.C. Yong, arXiv: 1504.02528

Baryon-baryon cross section

$reduced\ in\ medium$

$$R_{medium}(\rho,\delta,\vec{p}) \equiv \sigma^{medium}_{BB_{elastic}}/\sigma^{free}_{BB_{elastic}} = (\mu^*_{BB}/\mu_{BB})^2,$$

μ∗NN μNN

Reduced masses of colliding baryon pairs
In medium and free -space

$$\frac{m^*_\tau}{m_\tau} = \left[1 + \frac{m_\tau}{p}\frac{dU}{dp}\right]^{-1}$$

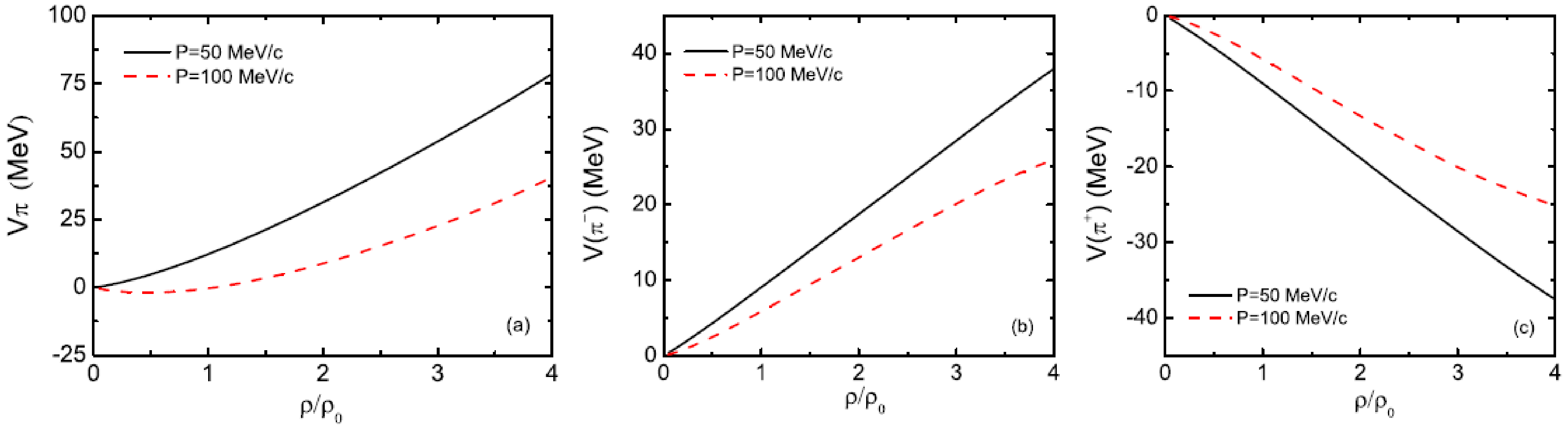
Extended this reduced factor to all baryon-baryon scatterings.

Li, et al., Nucl.Phys.A735:563-584,2004

Li, Chen, Phys.Rev.C72:064611,2005

Pion potential

isoscalar **Isovector potential**



O. Buss, diploma thesis, Justus-Liebig-Universität Gießen, 2004 (unpublished), https://gibuu.hepforge.org/trac/wiki/Paper#Diplomatheses.

Guo, Yong, Liu, Zuo, PRC 91, 054616 (2015)

Delta resonance potential

U_0 : *isoscalar potential*

U_Δ :

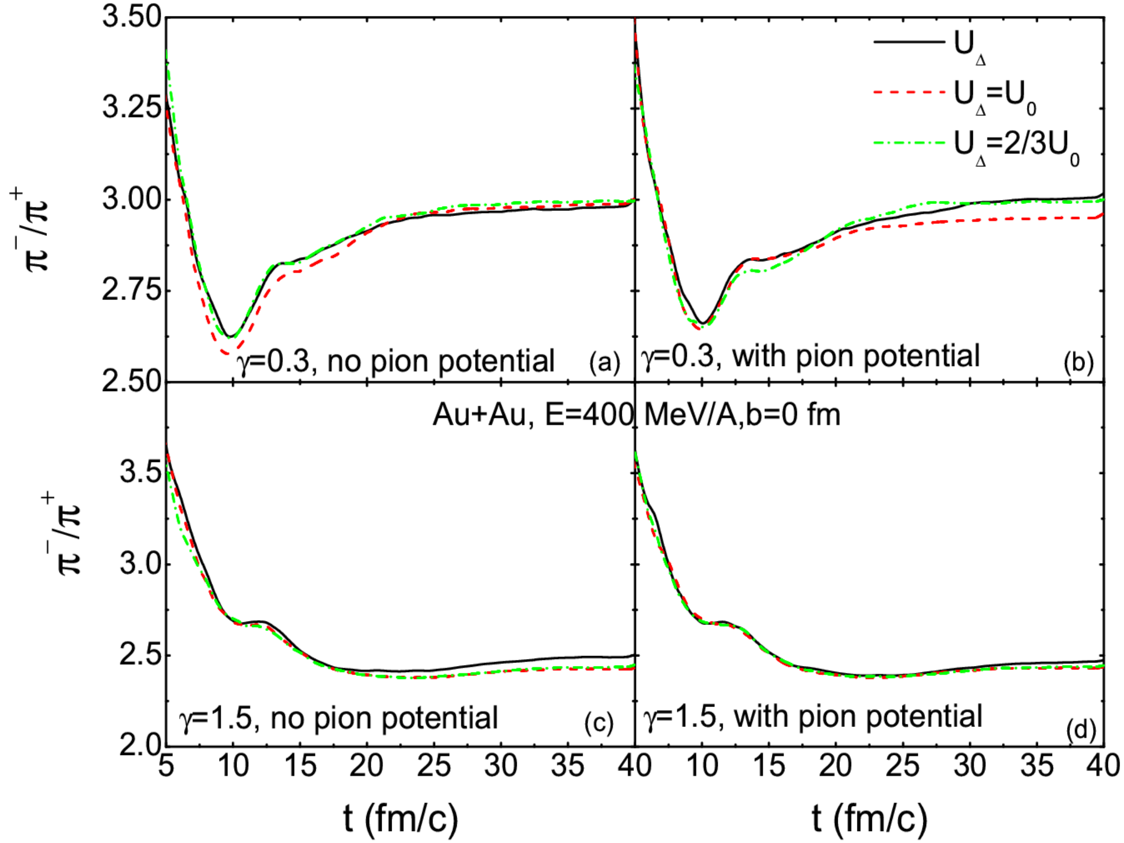
$$v_{asy}(\Delta^-) = v_{asy}(n),$$

$$v_{asy}(\Delta^0) = \frac{2}{3}v_{asy}(n) + \frac{1}{3}v_{asy}(p),$$

$$v_{asy}(\Delta^+) = \frac{1}{3}v_{asy}(n) + \frac{2}{3}v_{asy}(p),$$

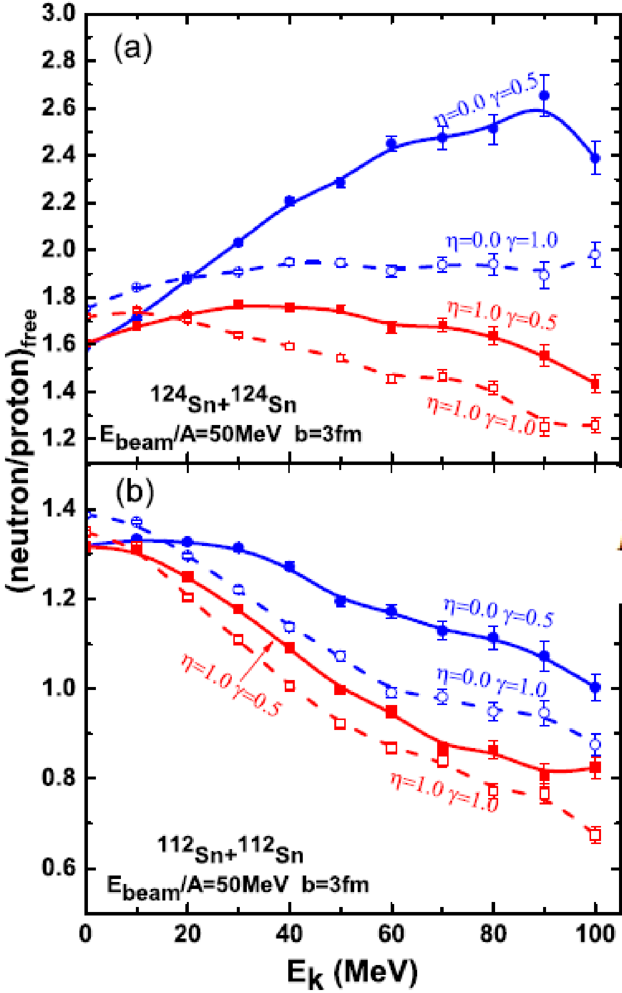
$$v_{asy}(\Delta^{++}) = v_{asy}(p).$$

B.A. Li, Nucl. Phys. A708 (2002) 365-390



Guo, Yong, Zuo, preliminary

Effects of isovector potential



With SRC

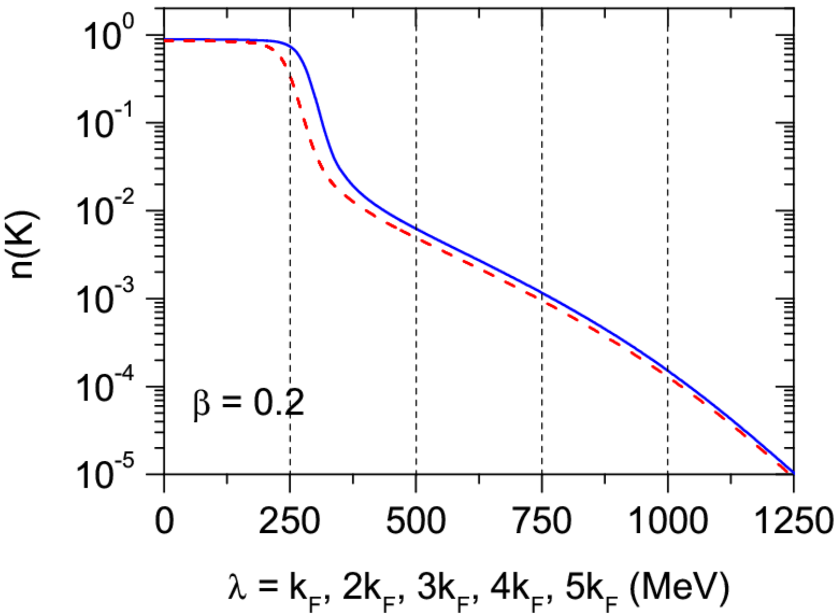
Without SRC

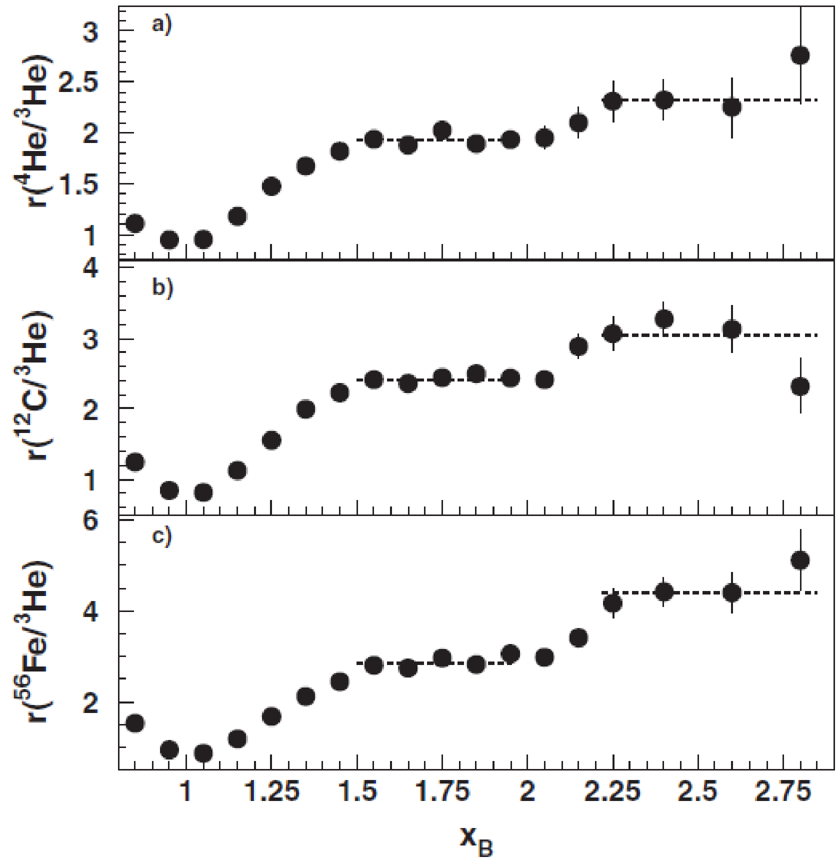
$$E_{\text{sym}}(\rho) = \eta \cdot E^{\text{kin}}_{\text{sym}}(\text{FG})(\rho) + \left[S_0 - \eta \cdot E^{\text{kin}}_{\text{sym}}(\text{FG})(\rho_0)\right]\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

$$U^{n/p}_{\text{sym}}(\rho,\delta) = \left[S_0 - \eta \cdot E^{\text{kin}}_{\text{sym}}(\rho_0)(FG)\right] \cdot (\rho/\rho_0)^{\gamma} \cdot \left[\pm 2\delta + (\gamma - 1)\delta^2\right]$$

B.A. Li et al, PRC91, 044601 (2015)

The length of HMT





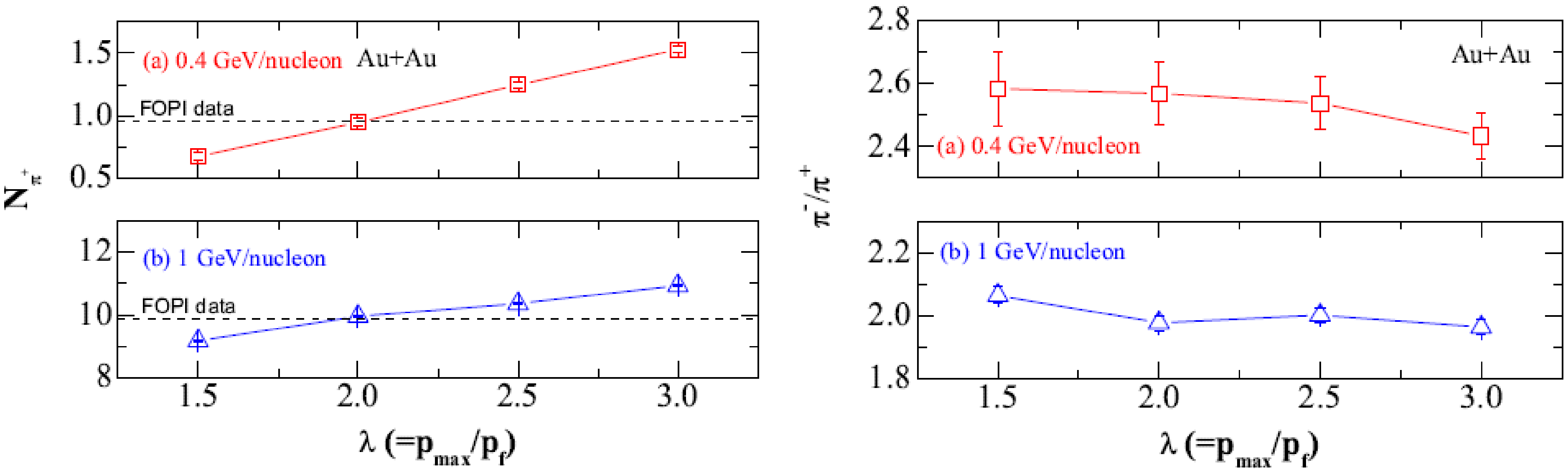
High-momentum tail from SCGF

We assume a cutoff

$$k_{\min} \approx 500 \pm 20 \text{ MeV}$$

K. S. Egiyan, et al.,
Phys. Rev. Lett. 96, 082501 (2006)

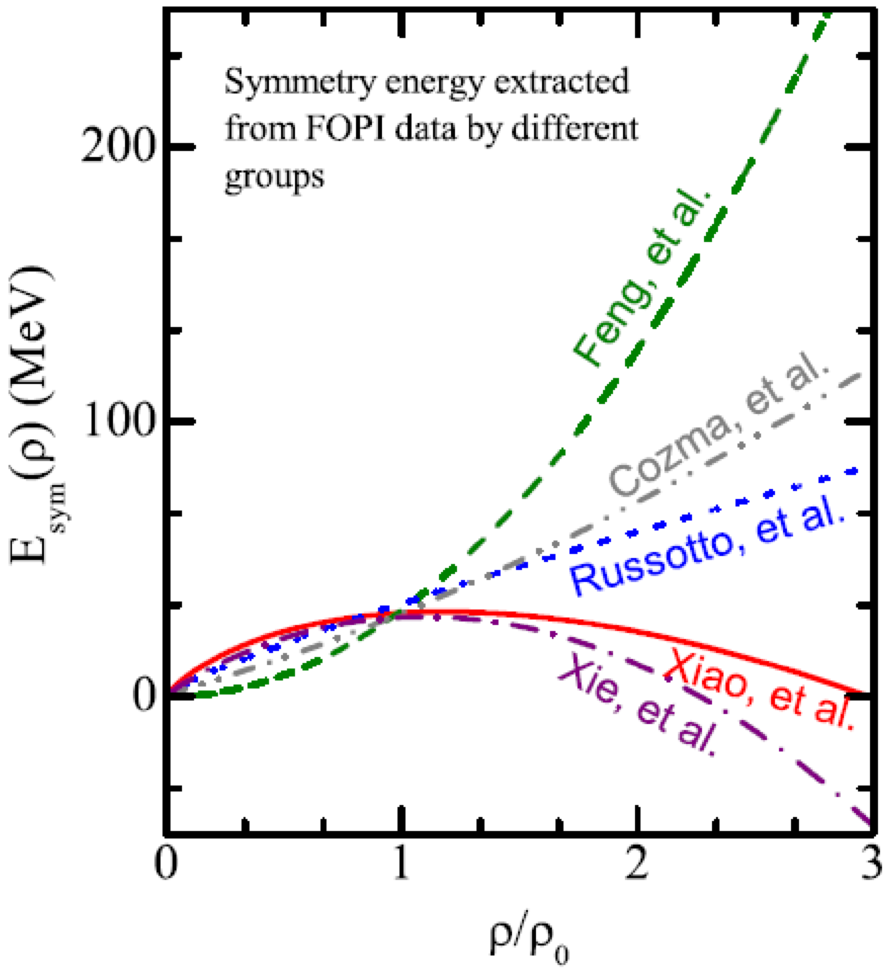
Effects of the length of HMT



Fit data very well at two beam energies

G.C. Yong, arXiv: 1503.08523

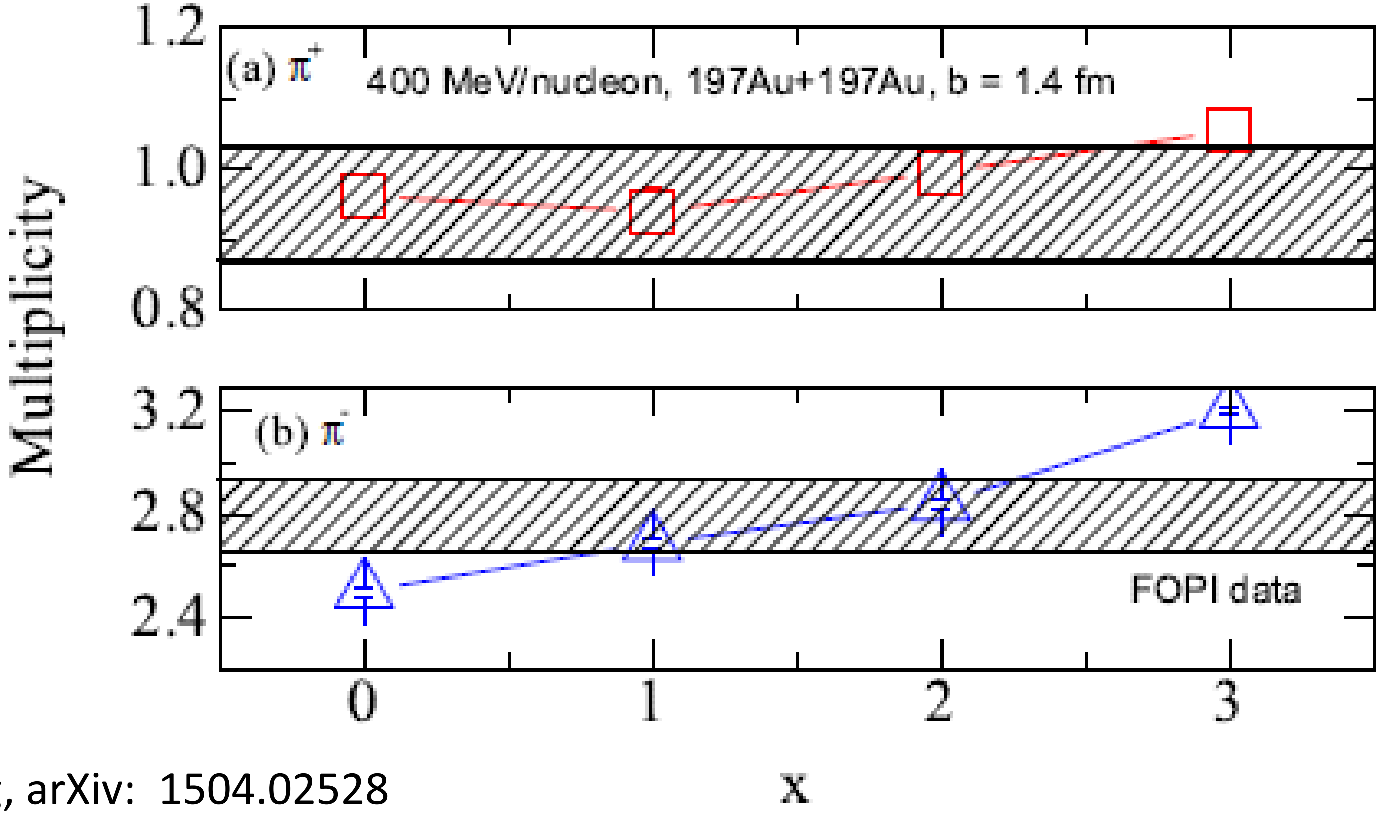
Current status of high-density Esym



Comparison with FOPI and FOPI-LAND Data.

Guo, et al., Phys. Lett. B738, 397 (2014)

Comparison with FOPI pion data

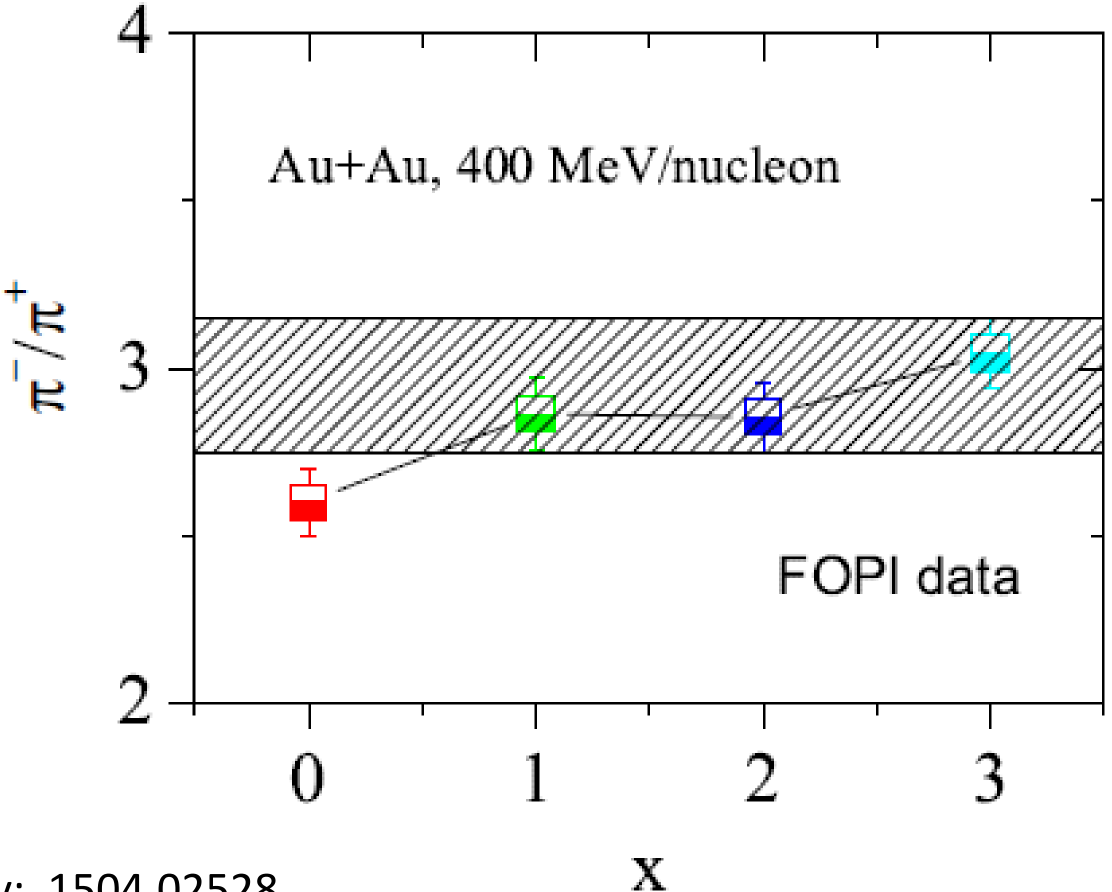


G.C. Yong, arXiv: 1504.02528

W. Reisdorf et al. (FOPI Collaboration), Nucl. Phys. A 848, 366 (2010).

Rule out x = 0, x = 3

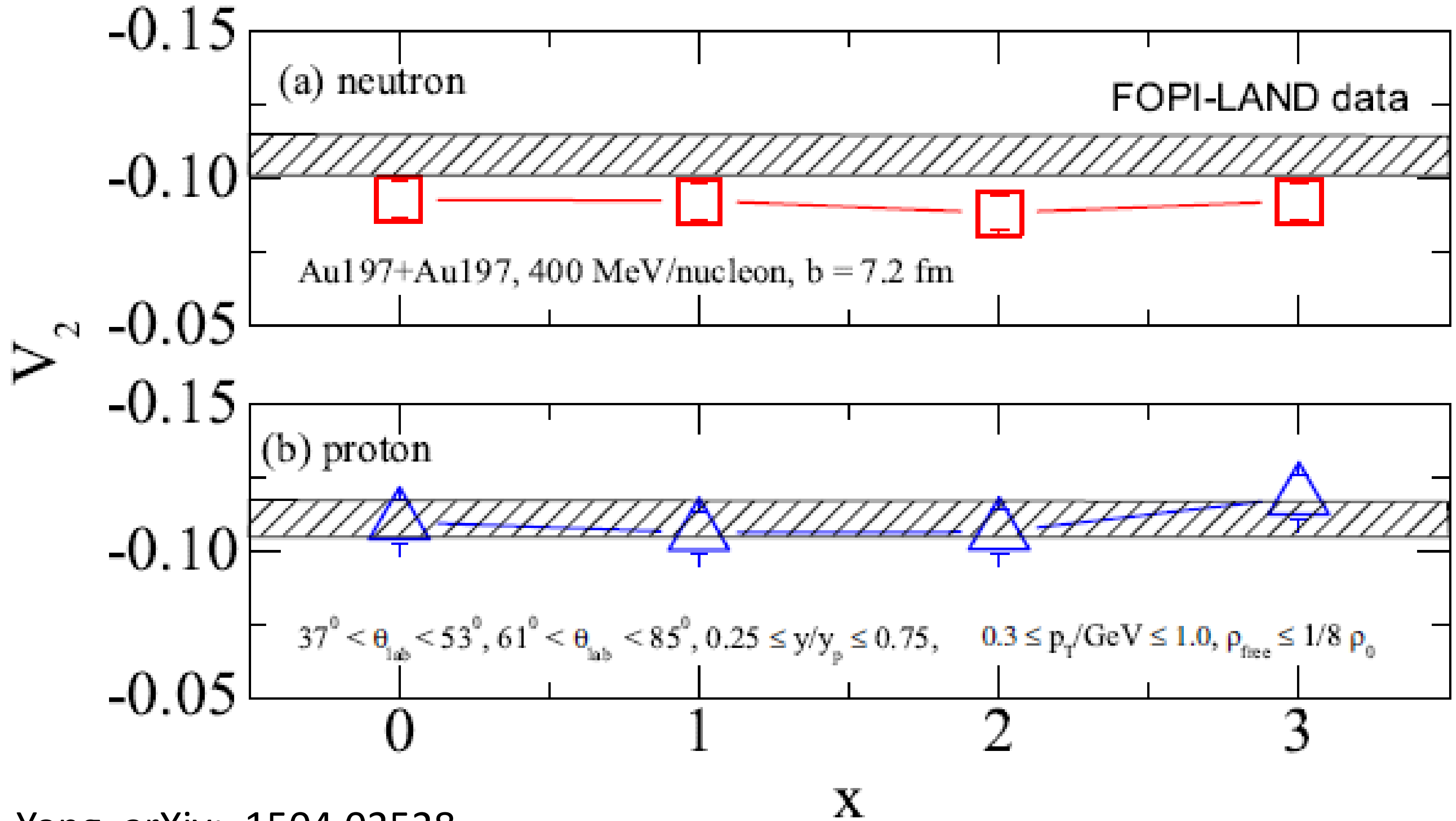
Comparison with FOPI pion data



G.C. Yong, arXiv: 1504.02528

Rule out x = 0

Comparison with FOPI-LAND flow data

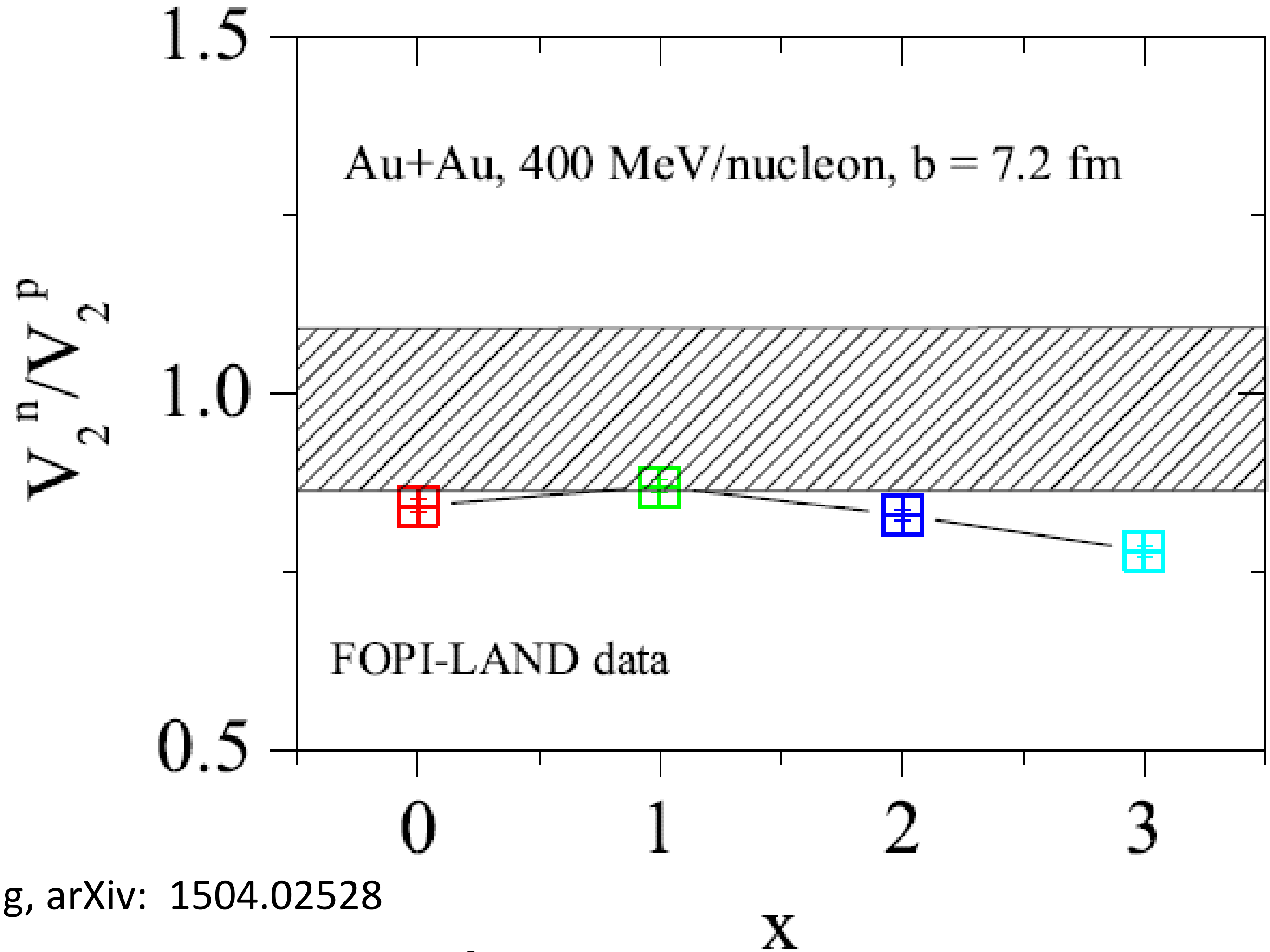


G.C. Yong, arXiv: 1504.02528

M. D. Cozma, Y. Leifels, W. Trautmann, Q. Li, P. Russotto, Phys. Rev. C 88, 044912 (2013)

Rule out x = 2 **Not sensitive**

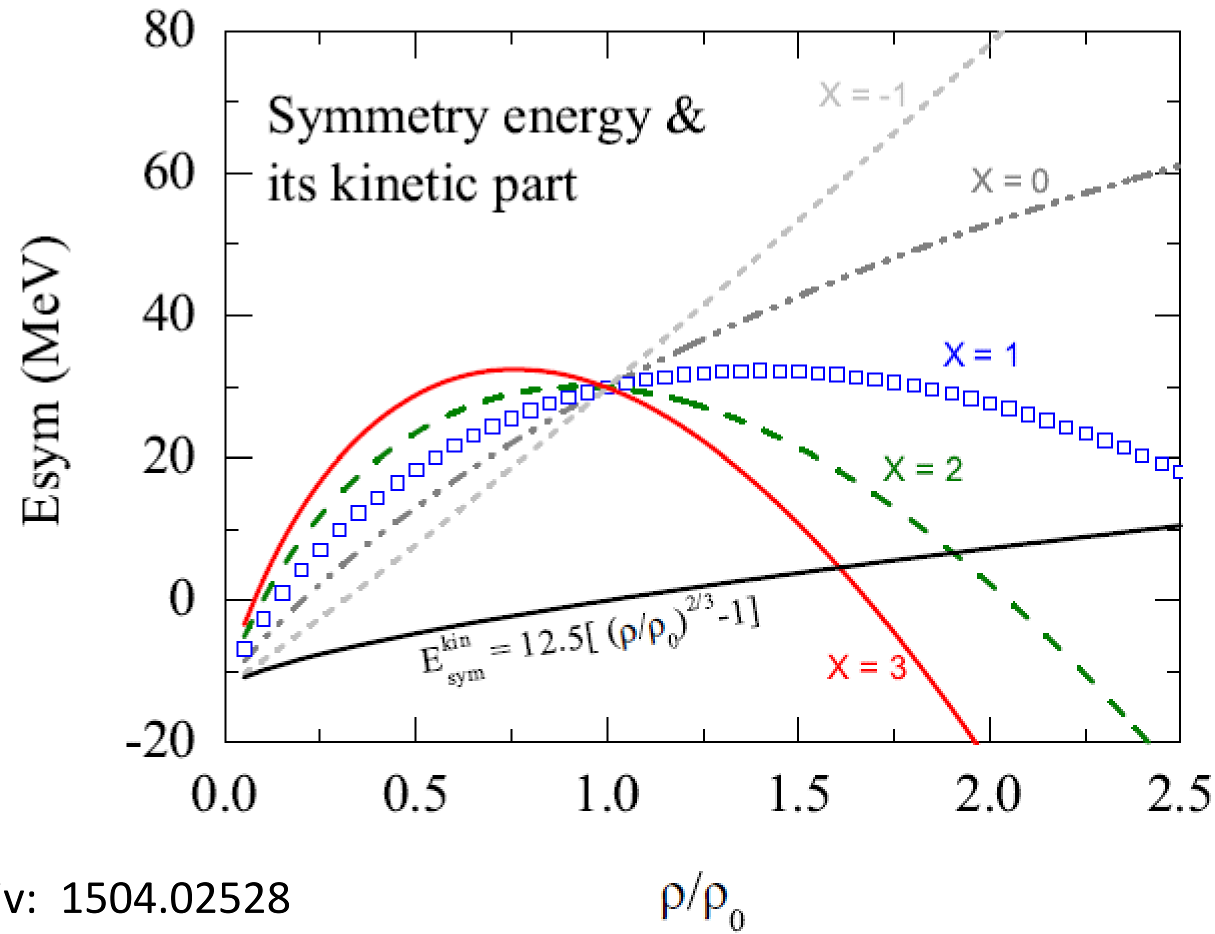
Comparison with FOPI-LAND flow data



G.C. Yong, arXiv: 1504.02528

Rule out x = 3

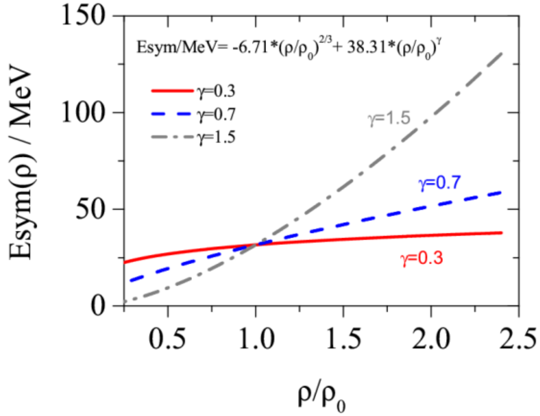
Extracted high-density Esym



G.C. Yong, arXiv: 1504.02528

Left x = 1 $(L(\rho_0) \equiv 3\rho_0 dEsym(\rho)/d\rho)$

Using momentum-independent inputs



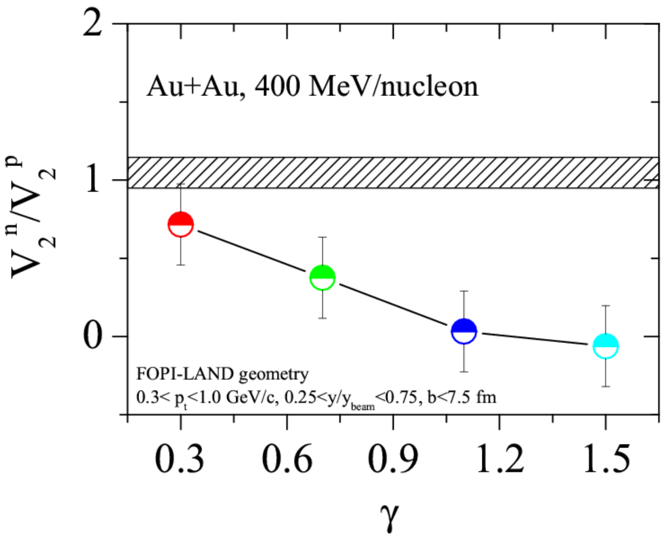
$$U(\rho) = A(\rho/\rho_0) + B(\rho/\rho_0)^{\sigma}$$

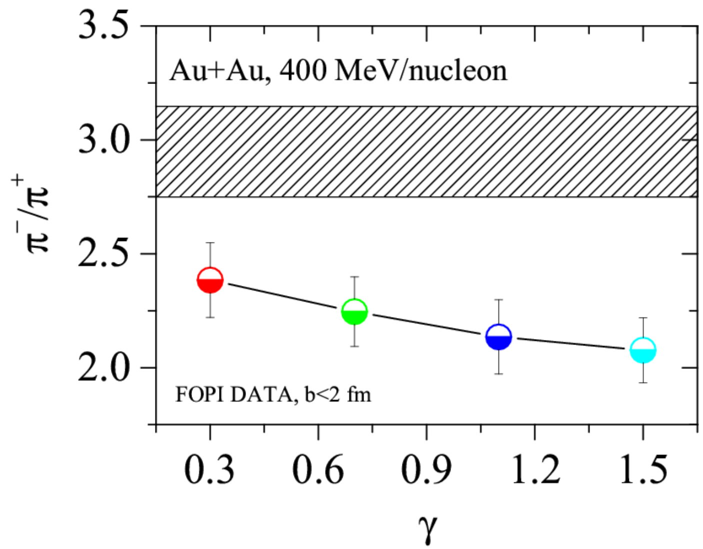
$$U^{n/p}_{\mathrm{sym}}(\rho, \delta) = 38.31(\rho/\rho_0)^{\gamma} \times [\pm 2\delta + (\gamma - 1)\delta^2]$$

$$E_{sym} = -6.71(\rho/\rho_0)^{2/3} + 38.31(\rho/\rho_0)^{\gamma}$$

$$\sigma^{BB,elastic}_{medium} = (\frac{1}{3} + \frac{2}{3}e^{-u/0.54568}) \times (1 \pm 0.85\delta) \times \sigma^{BB,elastic}_{free}$$

$$\sigma^{BB,inelastic}_{medium} = (e^{-1.3u}) \times (1 \pm 0.85\delta) \times \sigma^{BB,inelastic}_{free}$$





G.C. Yong, arXiv: 1504.02528

Summary

- SRC has enough evidences
- SRC plays important role
- Principal characters of SRC are modeled
- A mildly soft symmetry energy is extracted

More important

- Is it necessary to embed SRC into the transport model ?

  if yes,

- How to embed SRC into the semi-classical transport model?

Comments/criticisms/suggestions are welcome!

Thanks !