Recent progress on constraining the asymmetric nuclear EOS at supra-saturation densities in heavy ion collisions

Zhigang Xiao
Department of Physics, Tsinghua University, Beijing, China

Collaborators
M. Zhang, H. S. Xu, G. C. Yong, B. A. Li , L. W. Chen

Content

Introduction: $E_{sym}(\rho)$ at GeV/u regime

Recent progress on $E_{sym}(\rho)$ at $\rho > \rho_0$

- Experimental setup and model description
- Softening of $E_{sym}(\rho)$ at supra-density from π probe

Simulations for further experimental studies

- system size and beam energies optimizations
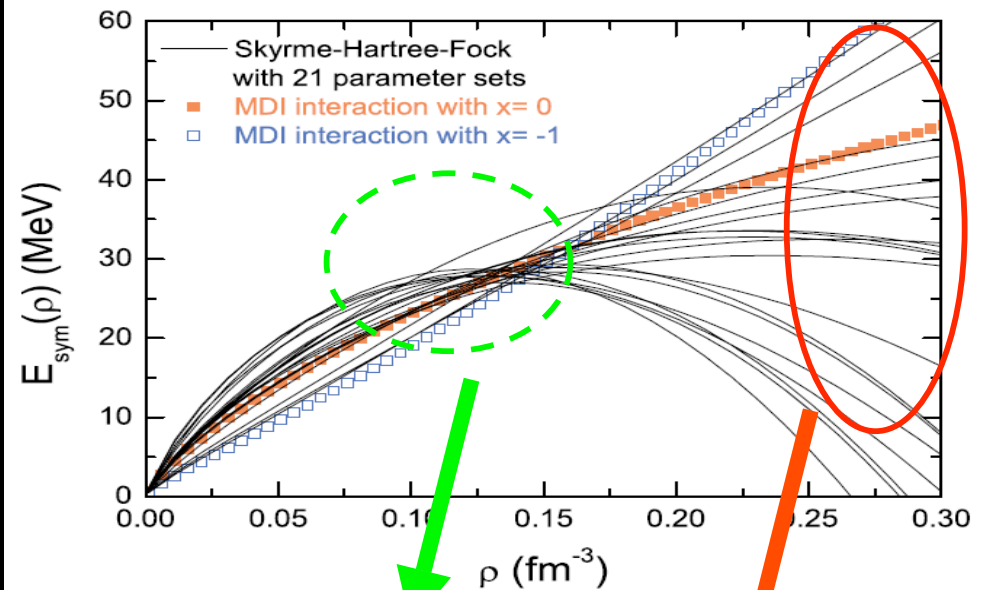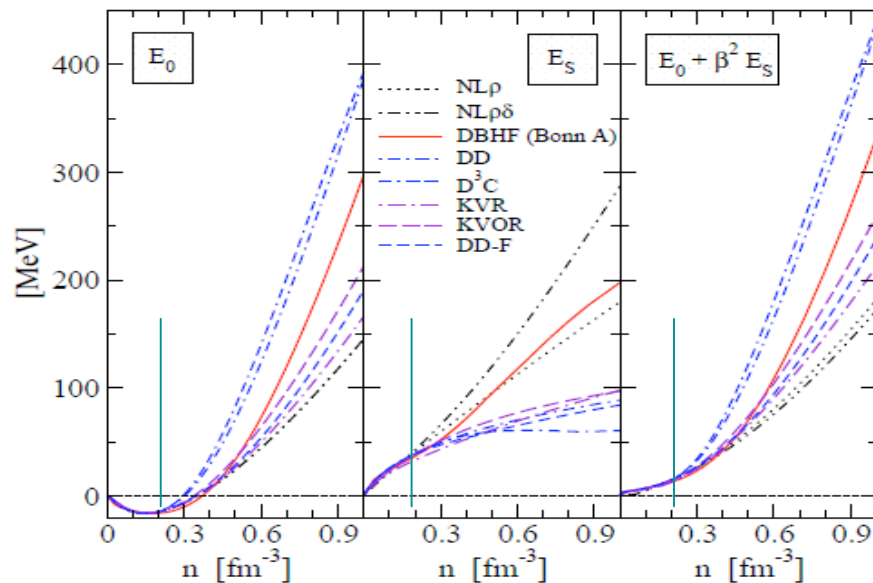- Differential sensitivity in phase space

Summary

Equation of State of nuclear matter

$$E(\rho,\delta) = E_0(\rho) + \delta^2 E_{\mathrm{sym}}(\rho) = a_V + \frac{\kappa}{18}\varepsilon^2 - \frac{\kappa^2}{162}\varepsilon^3 + ... + \delta^2\left(E_{sym} + \frac{L}{3}\varepsilon + ...\right)$$

$$E_{\mathrm{sym}}(\rho) = E_{\mathrm{sym}}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

κ:Compressibility

E_{sym}
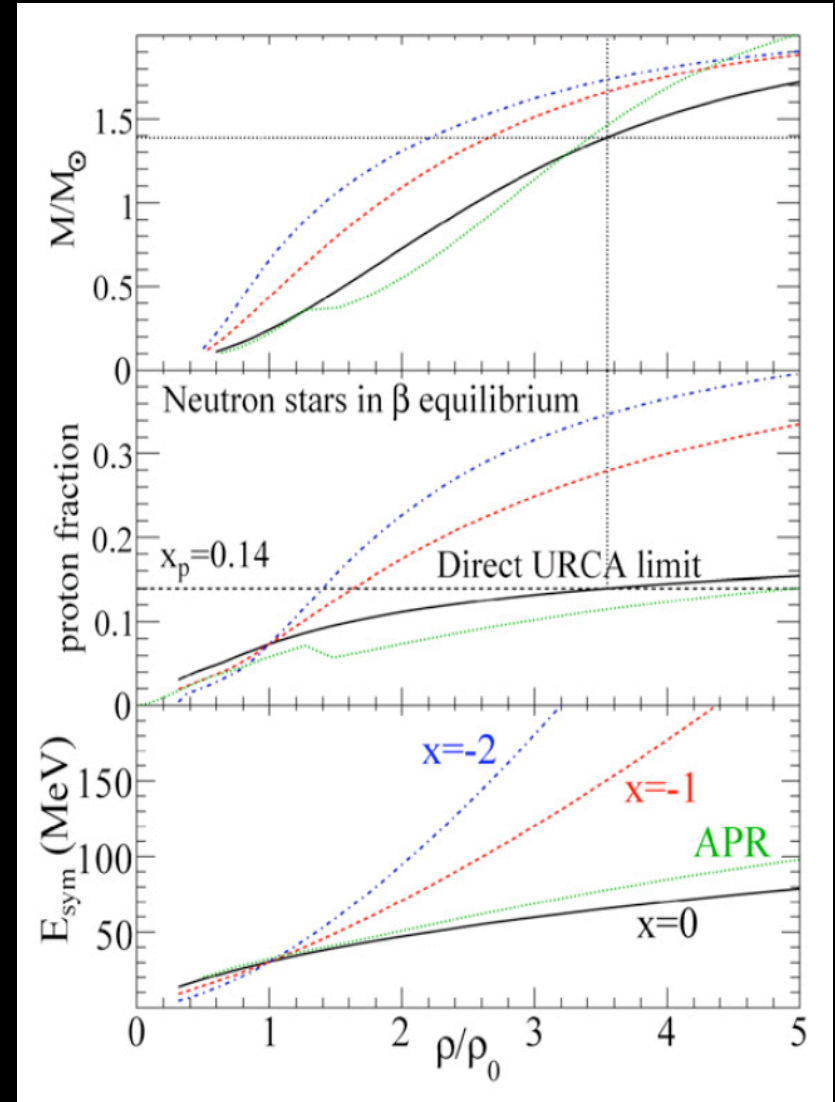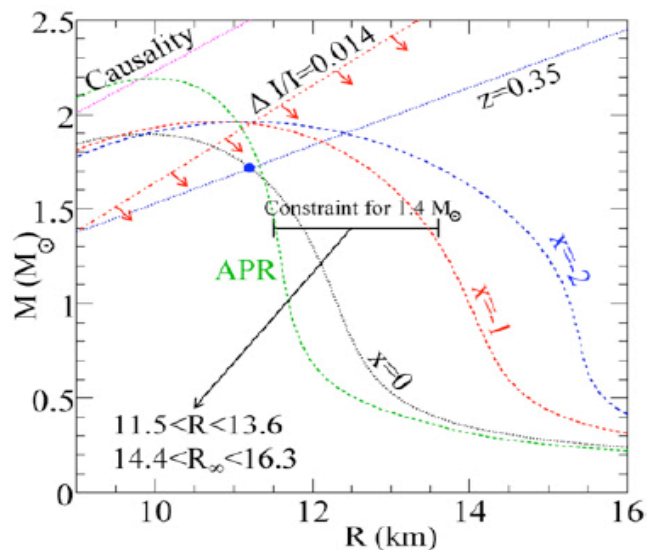

T. Klaehn et al., Phys. Rev. C 74, 035802 (2006)

< 100MeV/u   300~1000MeV/u

$E_{sym}(\rho)$ controls NS structural properties

- Proton fraction
- M-R relation
- ρ_c for D-Urca
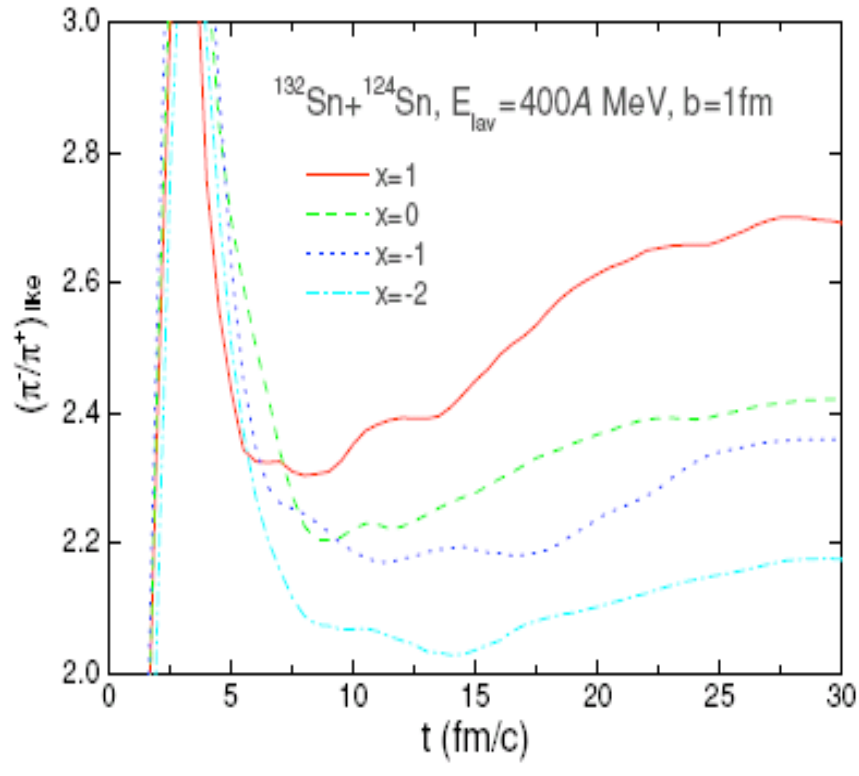- Transition density

- ……

Phy. Rep. 442(2007) 109;   NPA777(2006)479
PRC76(2007),025801;   PRC75(2007) 015801
PRC74 (2006),035802
Astro. J. 676 (2008) 1170
Phy. Rep. 411(2005) 325

B. A. Li et al., PLB 642, 436 (2006)
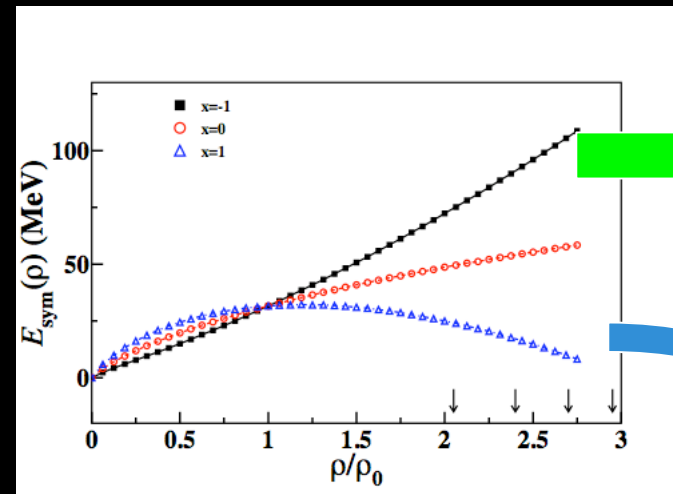
Probes to $E_{sym}(\rho)$ at high density in HIC

Probe: π^-/π^+ ratio

$^{132}Sn+^{124}Sn$, $E_{lav}=400A$ MeV, b=1fm

- x=1
- x=0
- x=-1
- x=-2

B. A. Li PRC71 (2005)014608

Isobaric Model

$$\pi^-/\pi^+ \approx (N/Z)^2_{dens}$$

stiff: n tends to LD

- x=-1
- x=0
- x=1

Soft: n tends to HD

==> Isospin fractionation
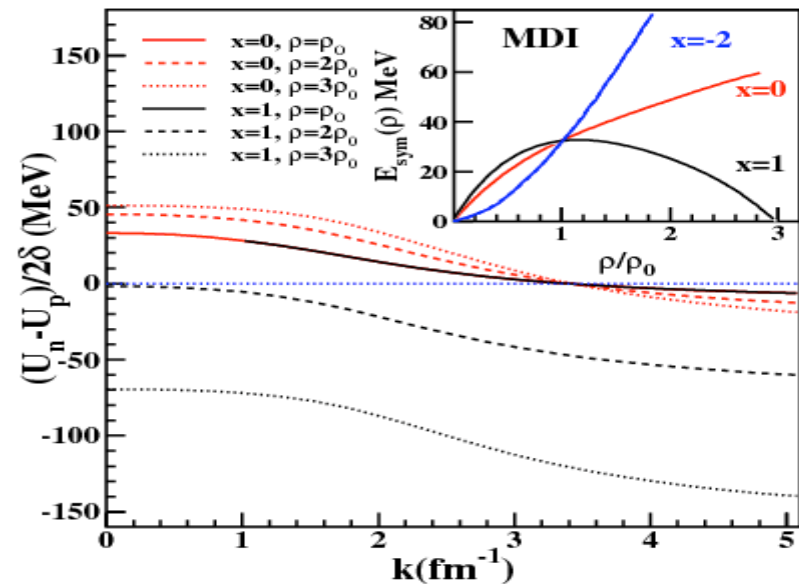
$E_{sym}(\rho)$ ← $(N/Z)_{dens}$ ← π^-/π^+

▼ Content

Experimental setup and model description

Experiment: FOPI at GSI
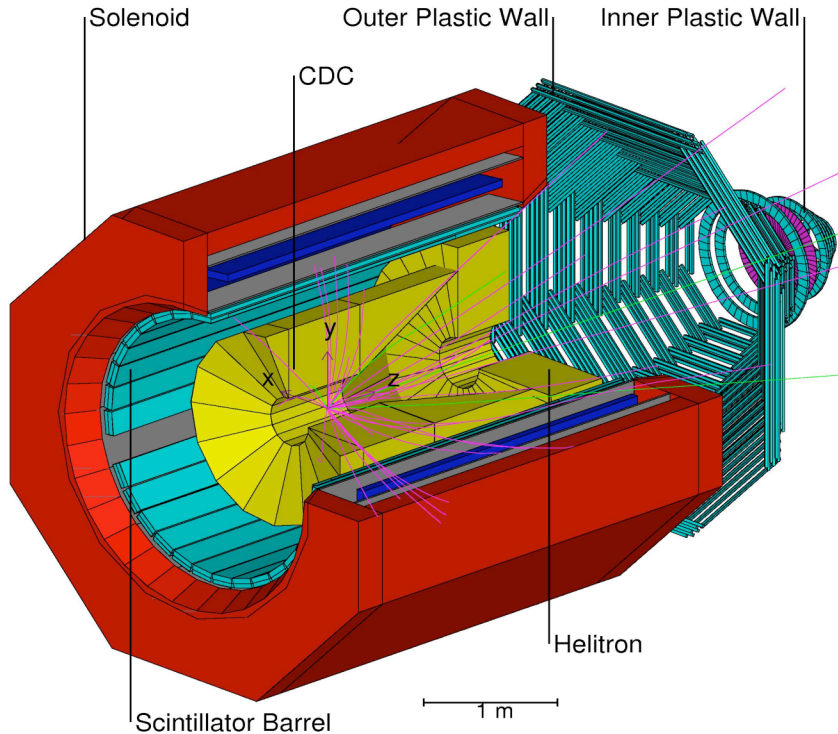
Model: IBUU04 by B. A. Li et al.

$$U(\rho, \delta, \mathbf{p}, \tau) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0}$$

$$+ B\left(\frac{\rho}{\rho_0}\right)^\sigma (1 - x\delta^2) - 8x\tau \frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'}$$

$$+ \frac{2C_{\tau,\tau}}{\rho_0}\int d^3p' \frac{f_\tau(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p}-\mathbf{p}')^2/\Lambda^2}$$

$$+ \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3p' \frac{f_{\tau'}(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p}-\mathbf{p}')^2/\Lambda^2}. \qquad (1)$$
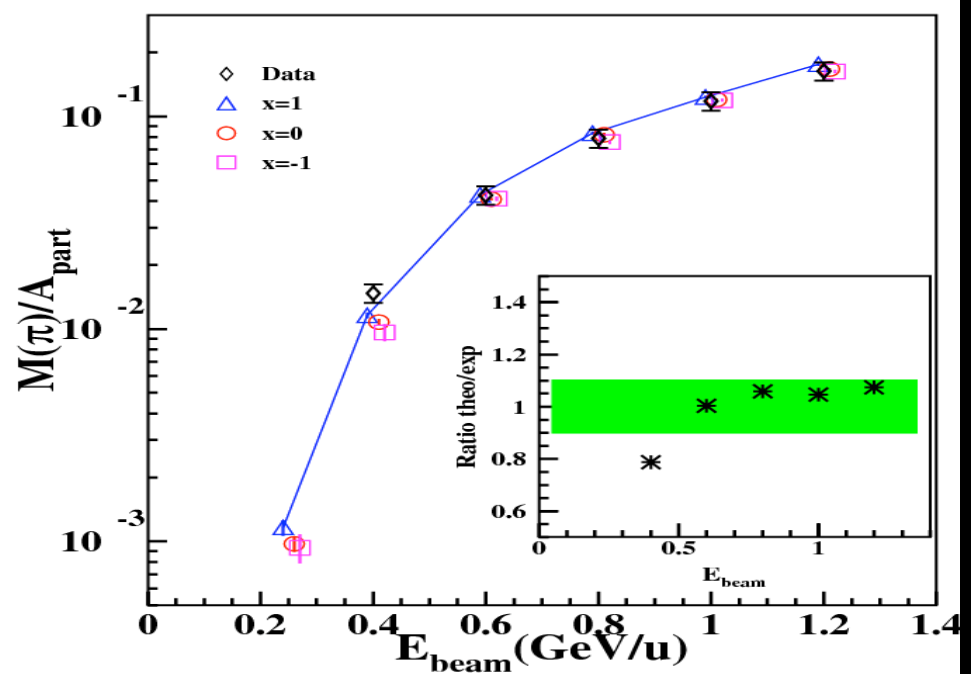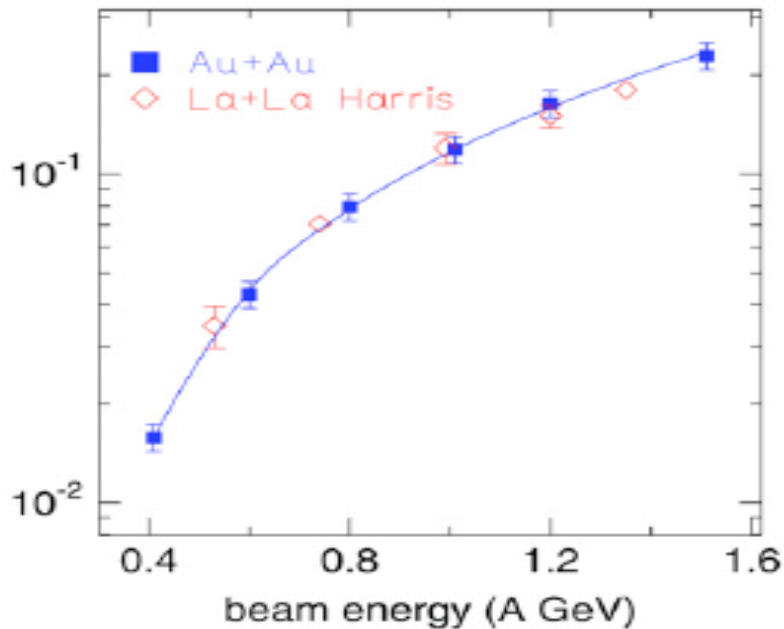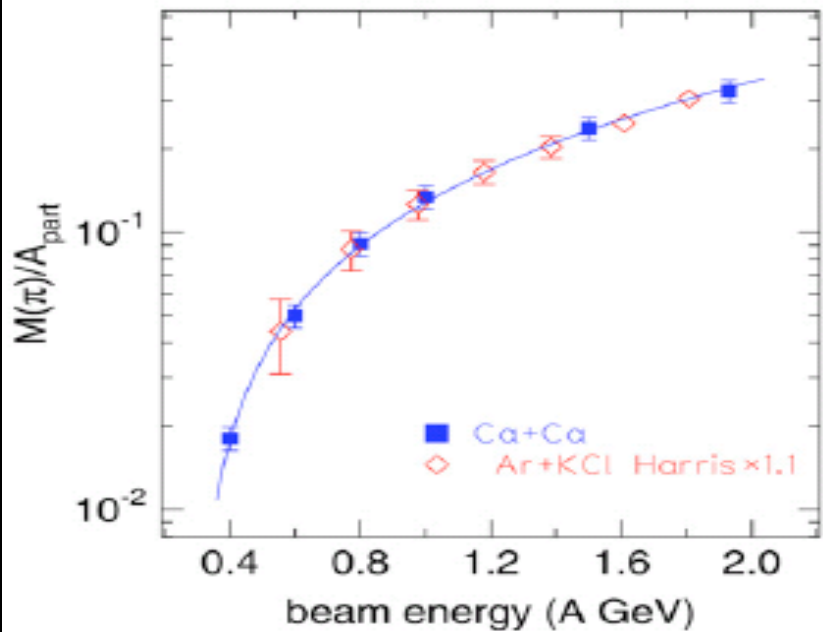

W. Reisdorf et al. for FOPI collaboration

NPA 781(2007) 459

C. B. Das et al., PRC67(2003) 034611;   B. A. Li et al., Phys. Rep. 442(2007) 109
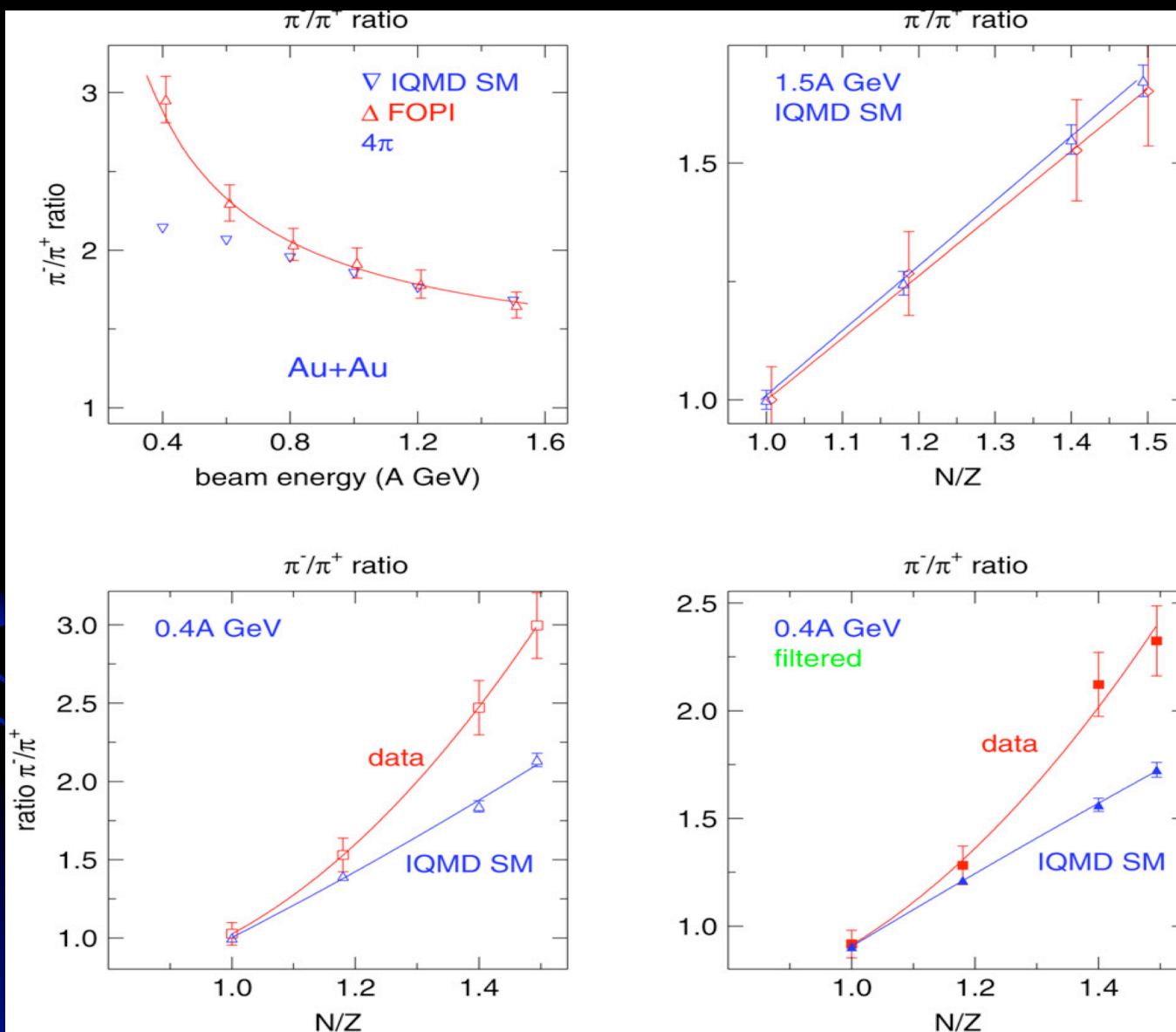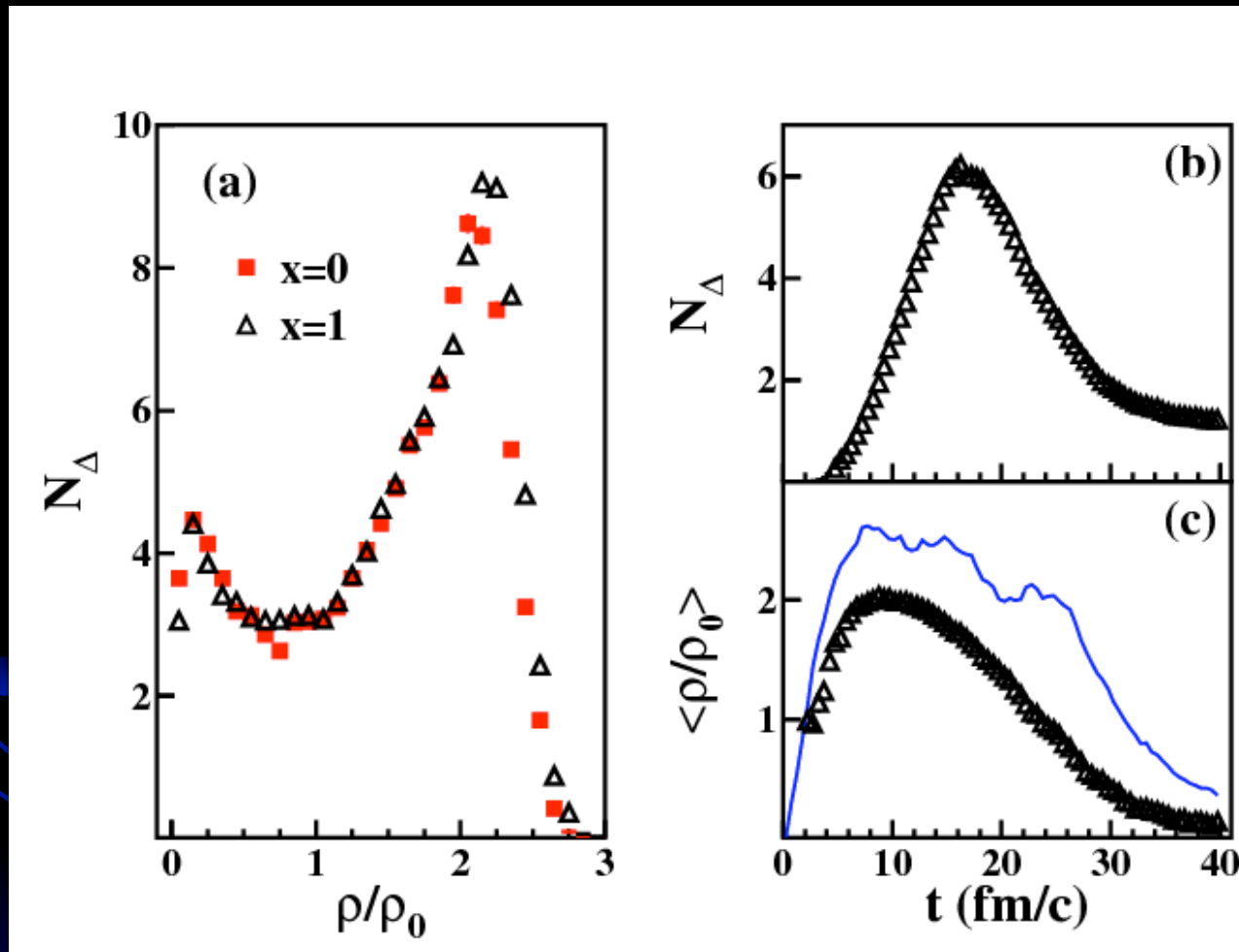
Complete set of π multiplicity (I)

Multiplicity

Multiplicity reproduced by the model, But shows insignificant sensitivity on the $E_{sym}(\rho)$.

Complete set of π multiplicity (II)

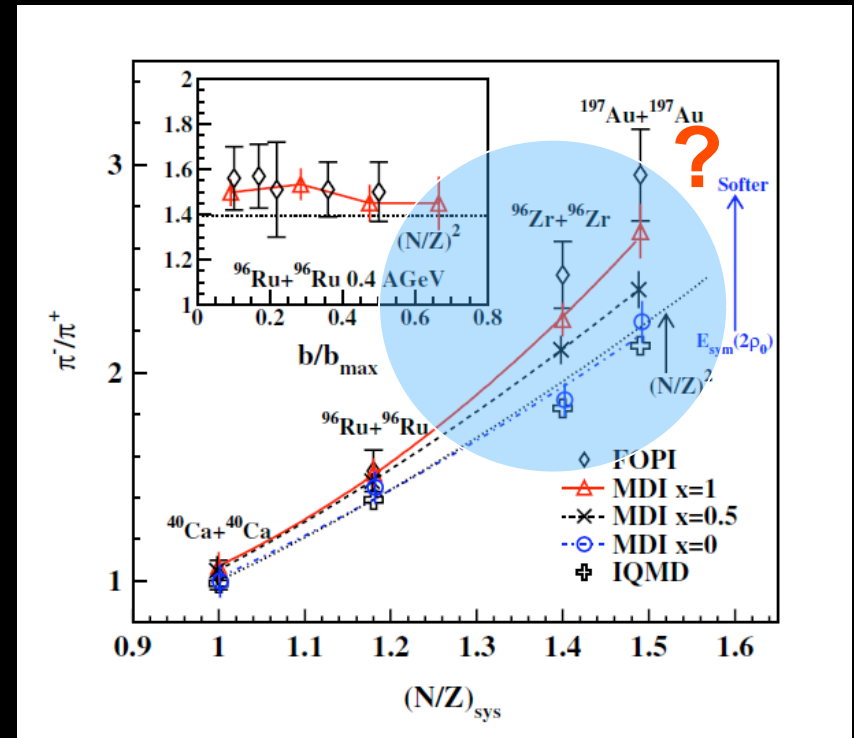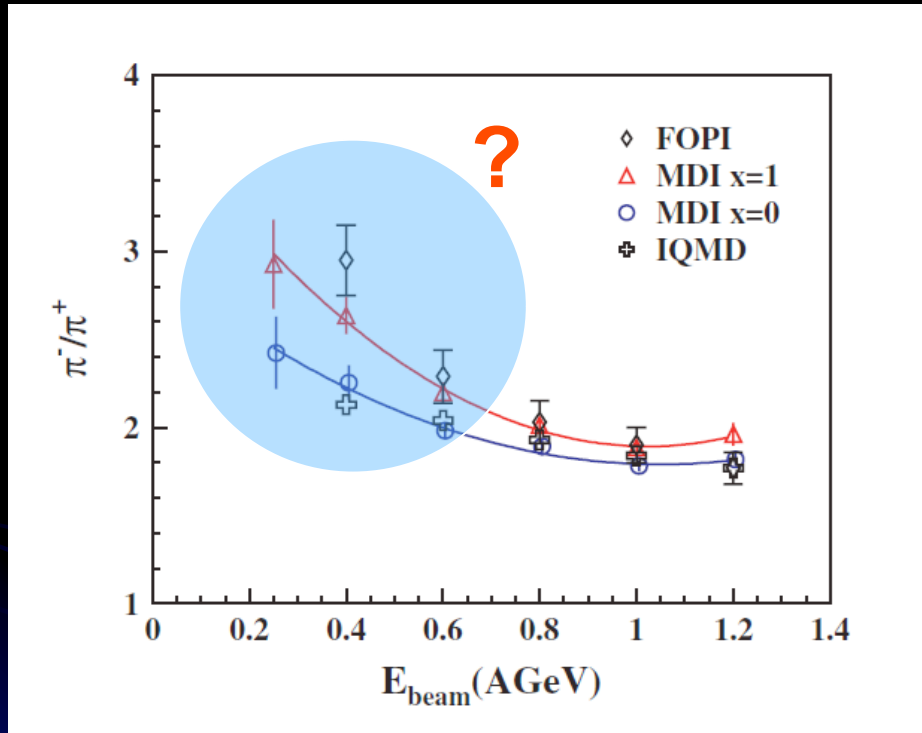W. Reisdorf et al. for FOPI collaboration NPA 781(2007) 459

Density profile of Δ production

- Δs are mainly produced at $\rho > \rho_0$

Circumstantial Evidence for a Soft Nuclear Symmetry Energy at Supra-saturation Densities

A rather soft nuclear symmetry energy is more favored by FOPI data!!!

Z.G. Xiao, B.A. Li, L.W. Chen, G.C. Yong and M. Zhang, Phys. Rev. Lett. 102 (2009) 062502

▼ **Content**

Beam Energy and System Size effect

$^{48}Ca+^{48}Ca$ **1.40**

$^{124}Sn+^{124}Sn$ **1.48**

$^{197}Au+^{197}Au$ **1.49**
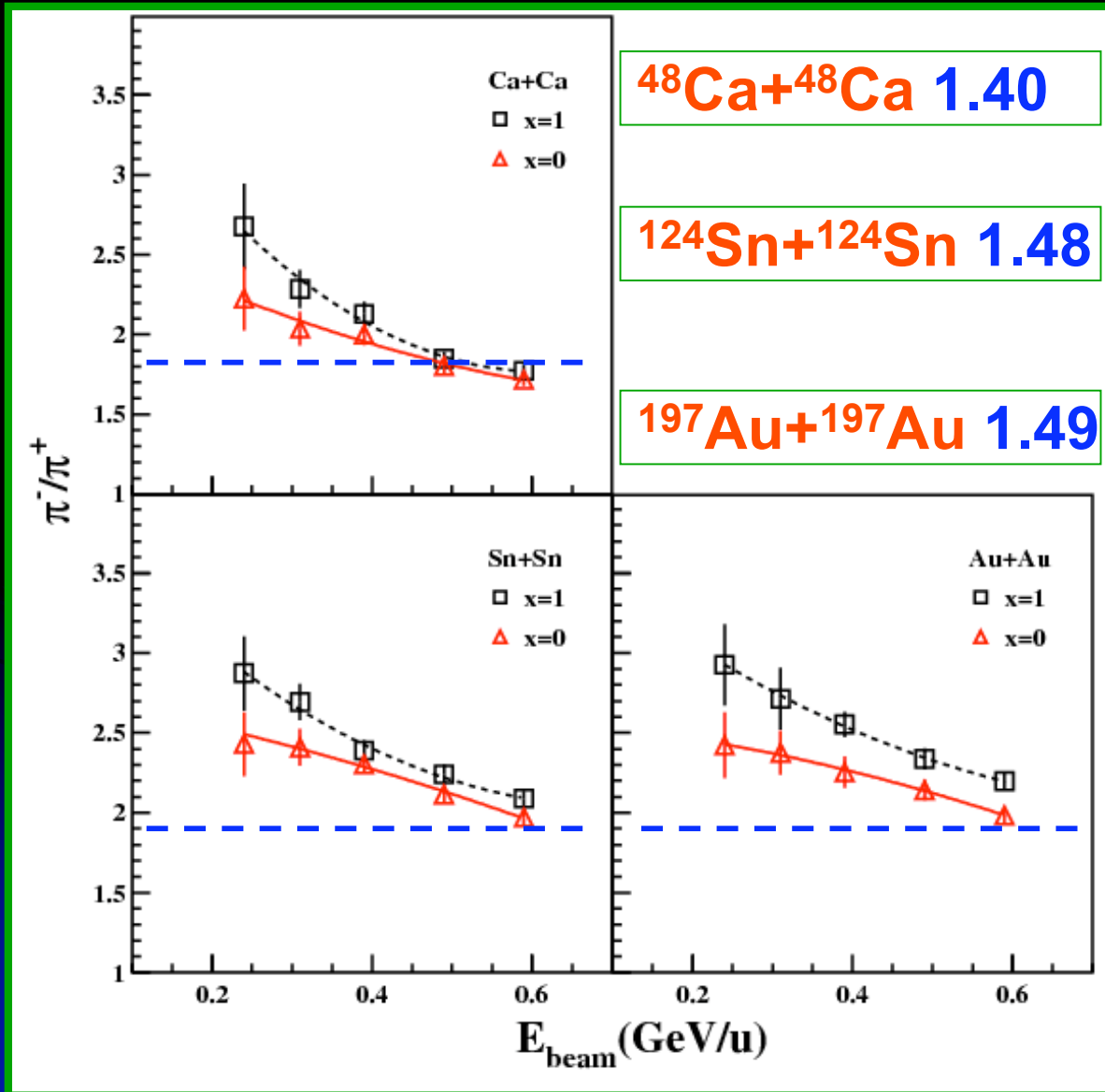
$S= (\pi^-/\pi^+)_{x=1} / (\pi^-/\pi^+)_{x=0}$

1. π^-/π^+ > Isobar Model

2. E_{beam} ↘ π^-/π^+ ↗

3. E_{beam} ↘   S ↗
   A_{sys} ↘   S ↗

Degree of isospin fractionation correlates with the sensitivity of probing Esym

Sensitivity： $S= (\pi^-/\pi^+)_{x=1} / (\pi^-/\pi^+)_{x=0}$

Degree of IF： $(\pi^-/\pi^+)_{tran} - (\pi^-/\pi^+)_{isob}$
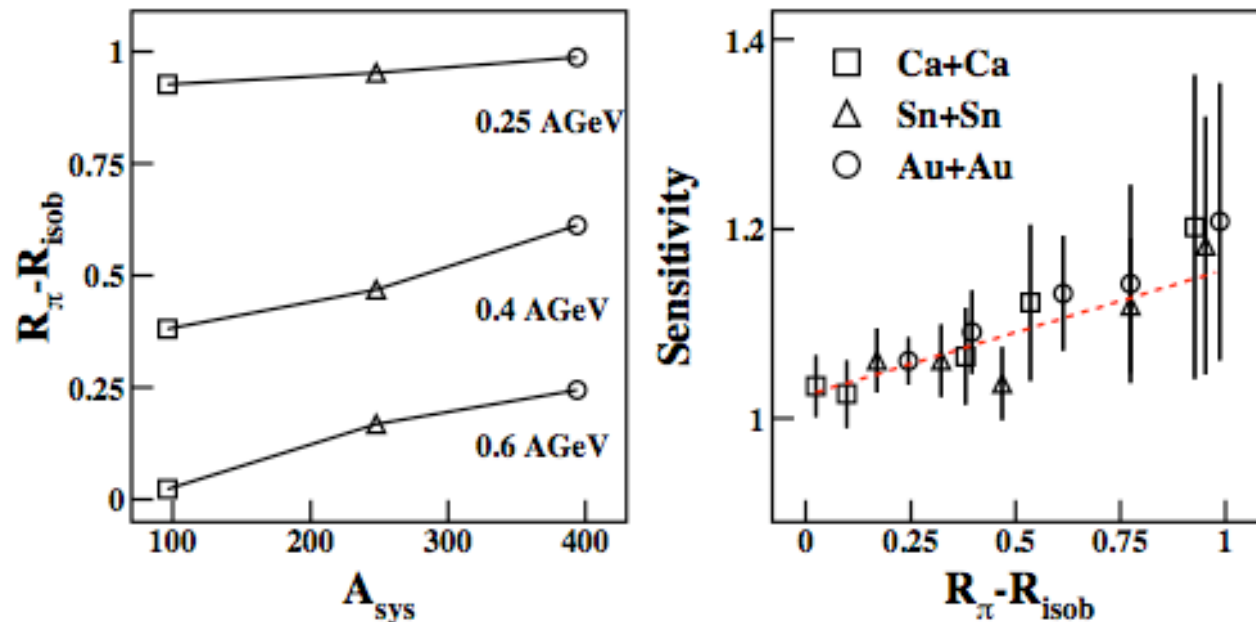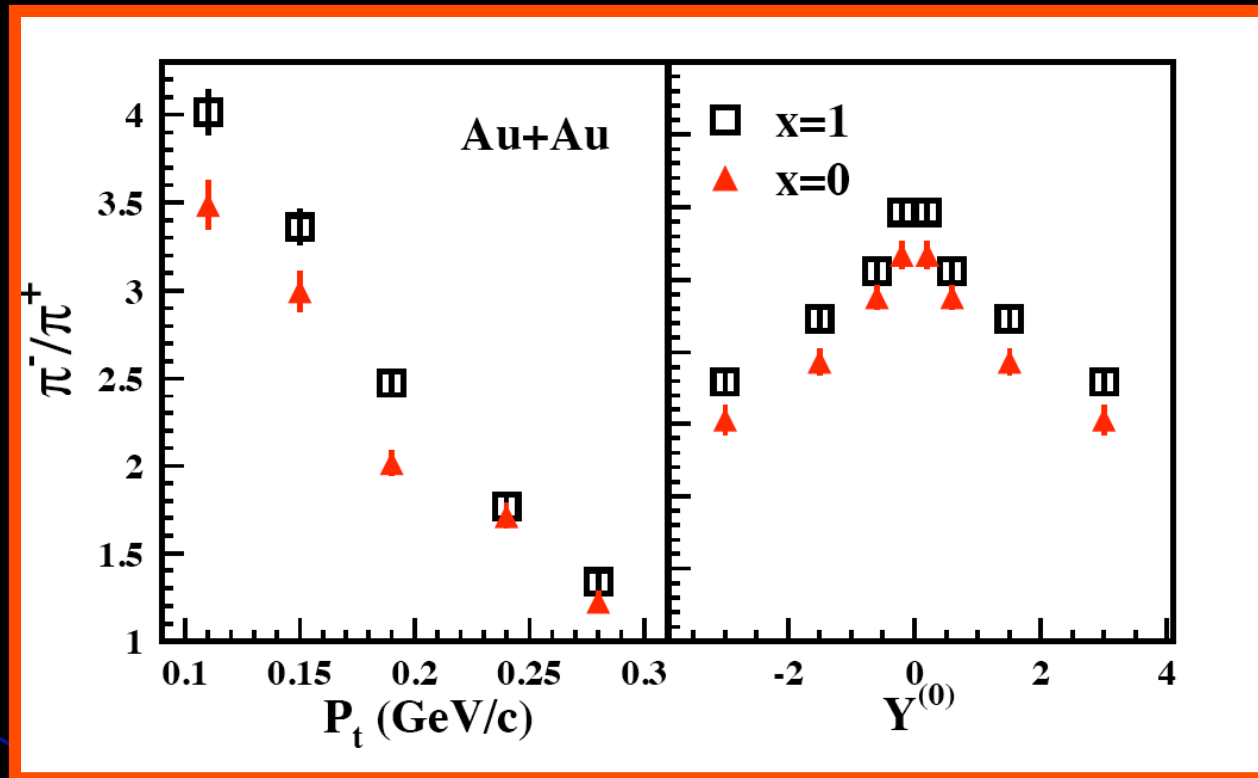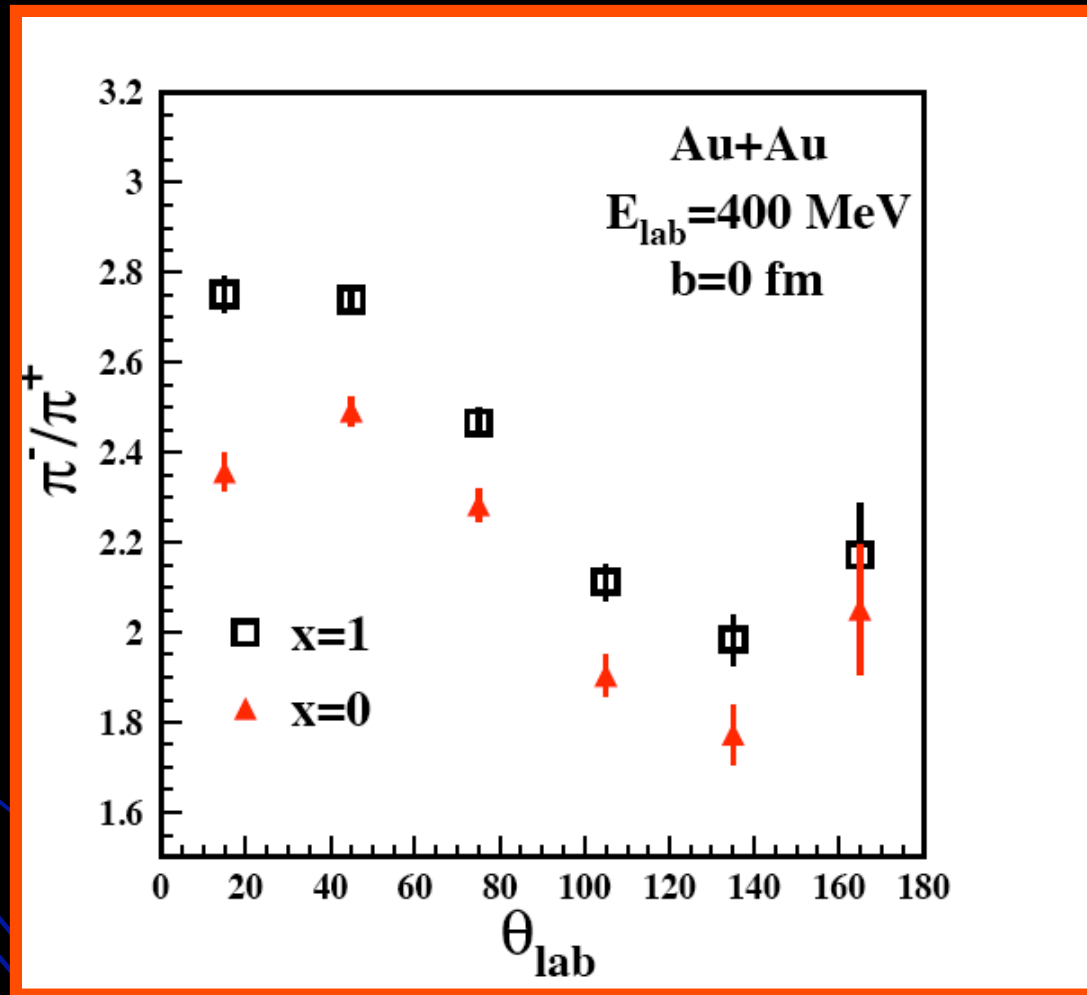

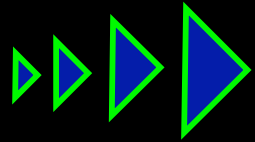M. Zhang, XZG et al., PRC 80, 034616 (2009)

Simulation of phase space

- Sensitivity at small Pt is higher than the overall one
- Sensitivity at large rapidity is higher than the overall one
  $\Rightarrow$ Importance of measuring pion ratio at forward angle?

Sensitivity varying with Laboratory angle

- Sensitivity increase in small angle in Lab.

Summary

▸ Within the framework of IBUU04, the most recent and complete π data set an partial constraint on $E_{\text{sym}}(\rho)$. We observed a softening of $E_{\text{sym}}(\rho)$ at supra-density, which might have many astrophysical indications. More experimental and theoretic work are desirable to convincingly constrain $E_{\text{sym}}(\rho)$.

▸ For further experiments, the sensitivity of the π probe on $E_{\text{sym}}(\rho)$ increases with decreasing the beam energy or increasing the system size. **Heavier colliding systems at relatively lower beam energy** are preferential for the study of $E_{\text{sym}}(\rho)$ via pion probe. The sensitivity is enhanced at forward area.

The fate of Spinosaurid …

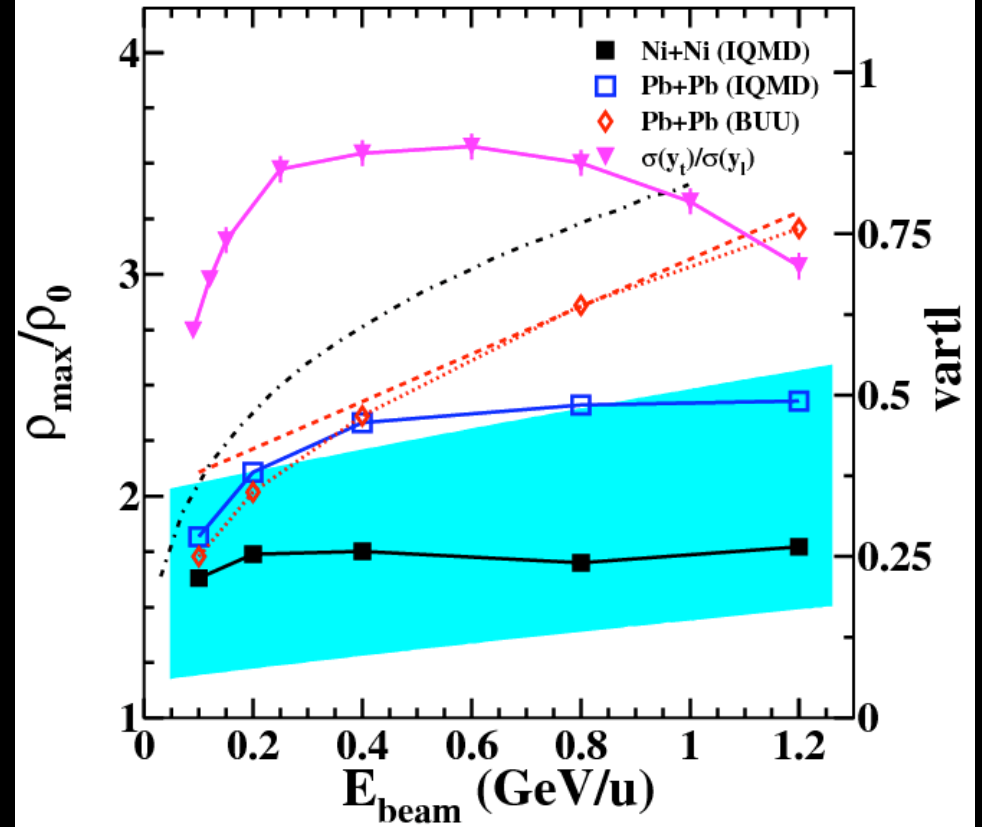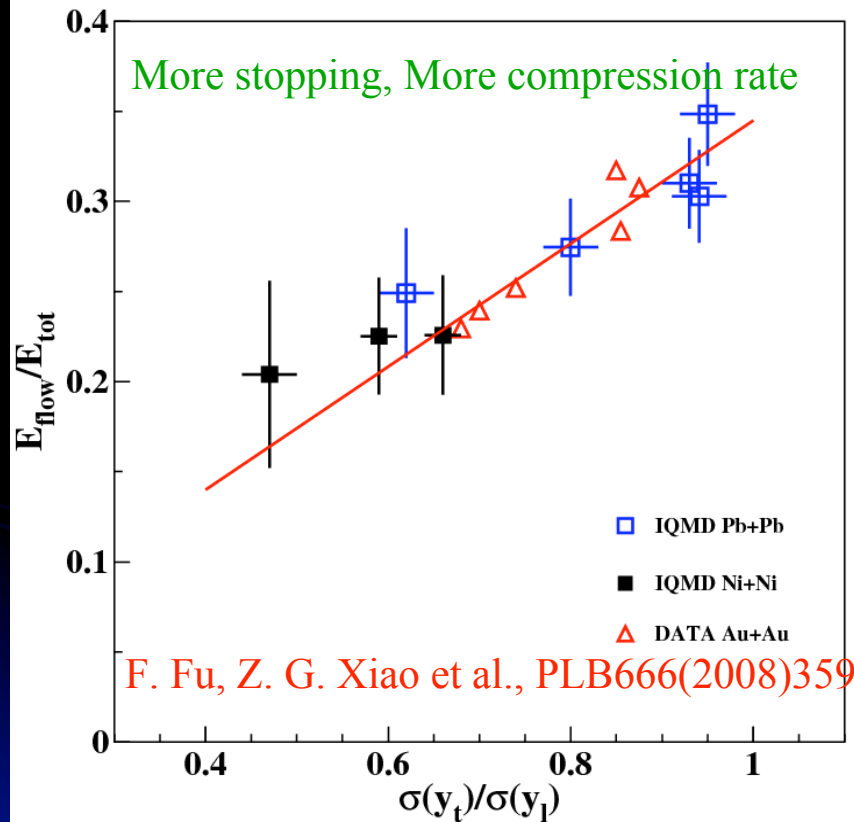P.C. Sereno *et al*. **Science**, Nov. 13, 1298(1998).   **(Spinosaurid)**

For about 50 years Spinosaurid has been vegetarian, now it is a carnivore.
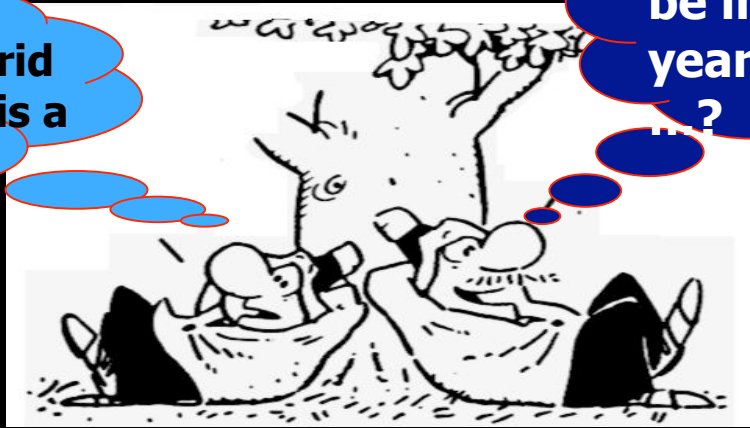
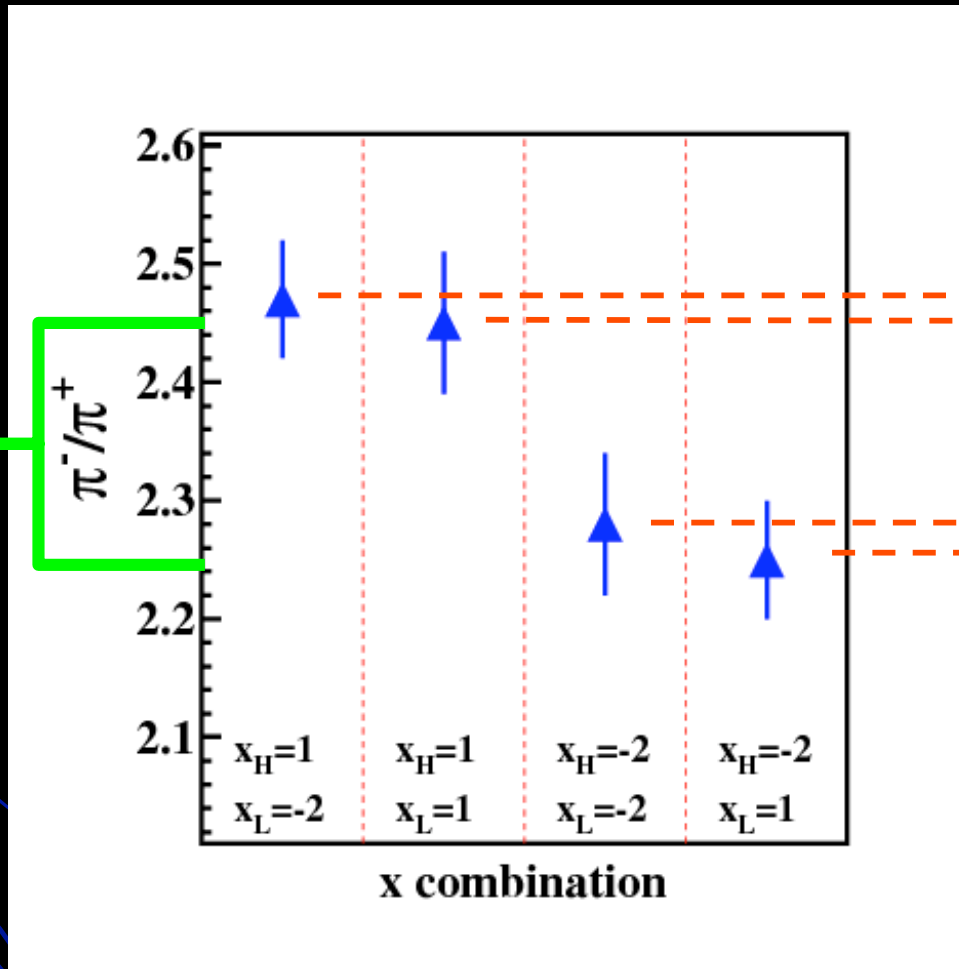*Imagine* what it'll be in the next 50 years, 100 years, …?

Thank you!

Stopping vs Nuclear compression & density gain

More stopping, More compression rate

F. Fu, Z. G. Xiao et al., PLB666(2008)359

Effect of switching x in transport
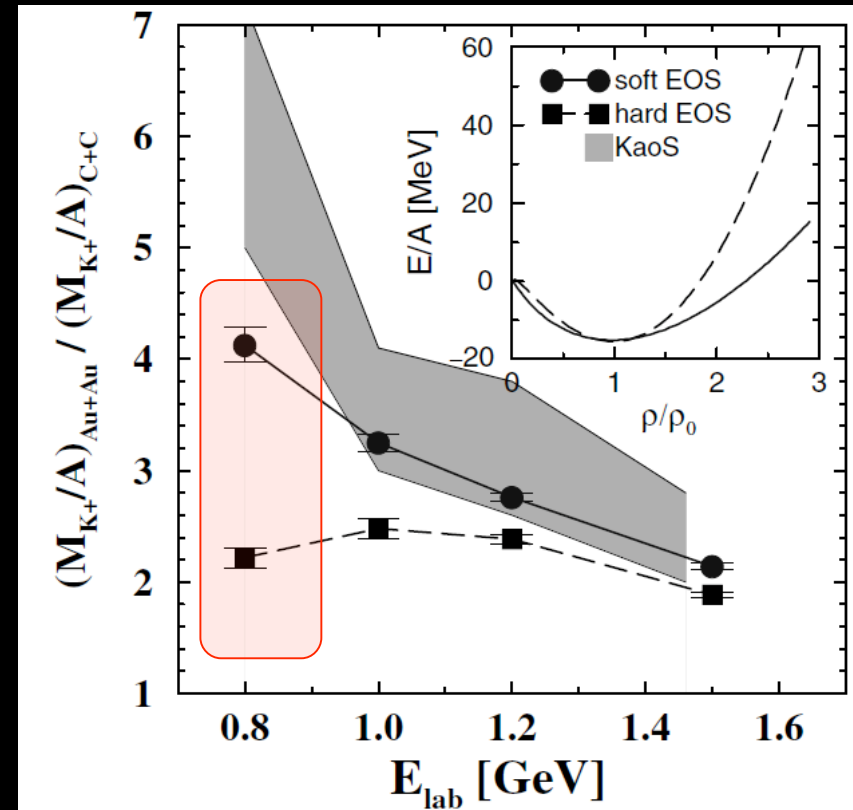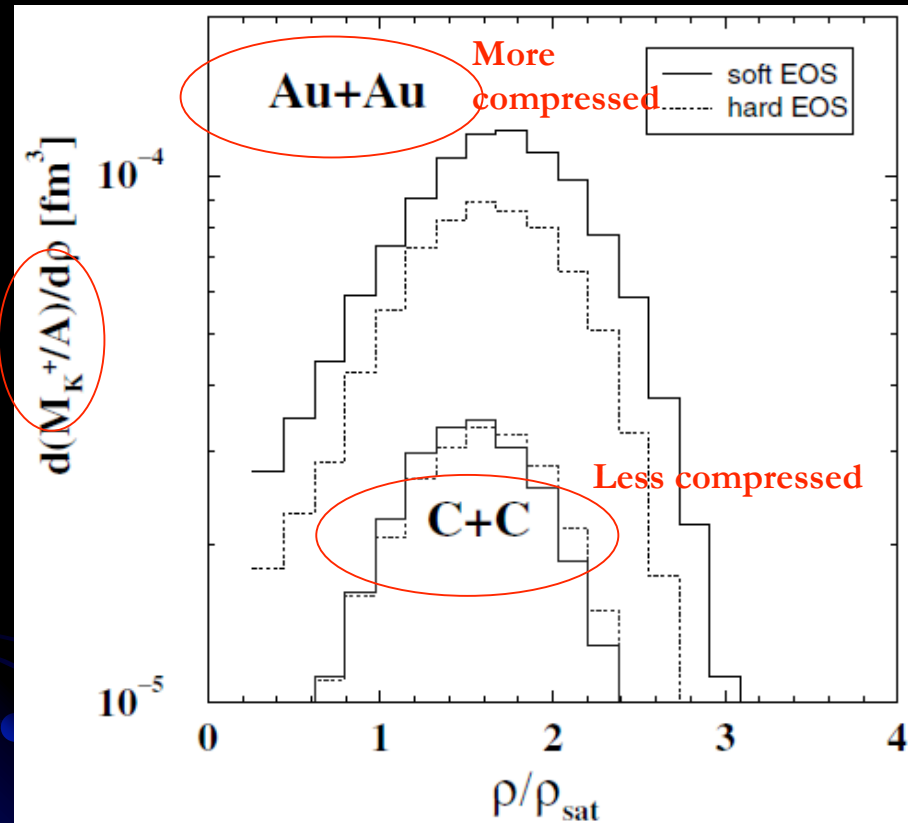

Switch x at $\rho>\rho 0$

Switch x at $\rho<\rho 0$

Switch x at $\rho<\rho 0$

- Ratio is sensitive to the change of x at supra-density

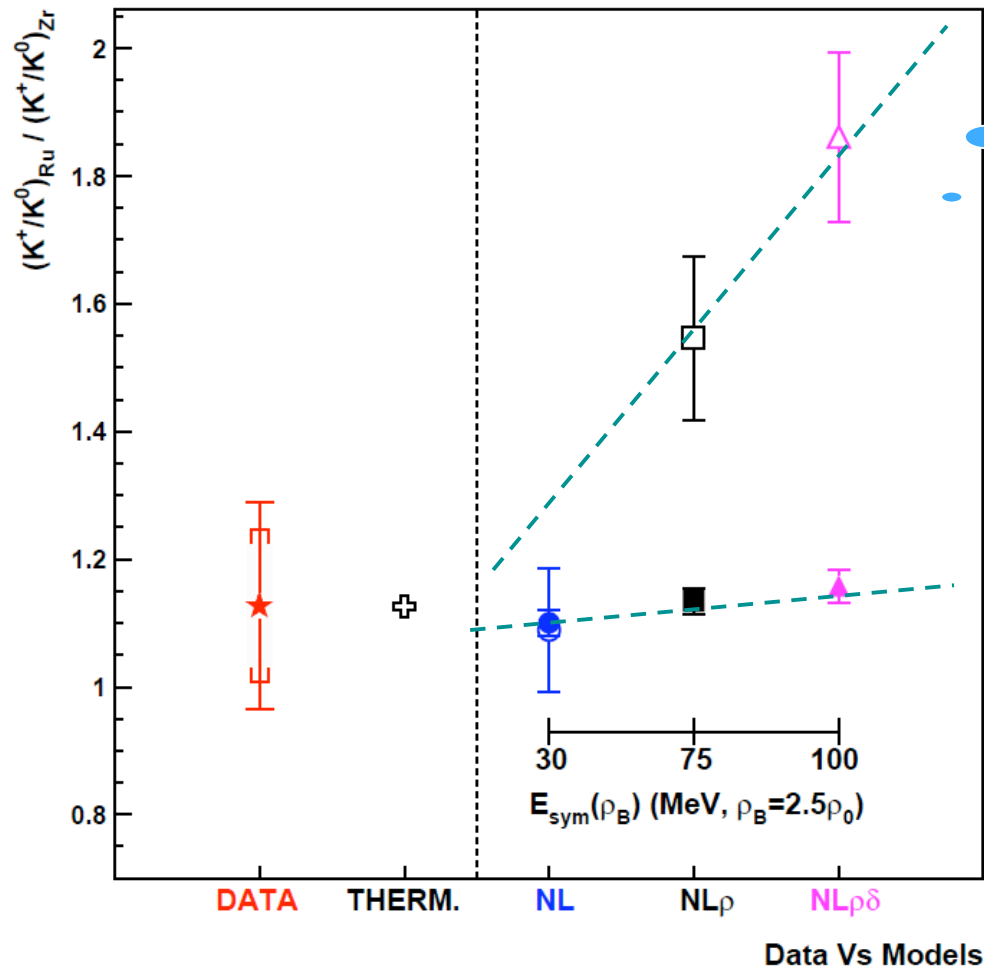# Compressibility of symmetric nuclear matter:

K^+ and κ

C. Fuchs et al., Phys. Rev. Lett 86, 1974 (2001)

- NOTICE 1: Insensitive in light system C+C
- NOTICE 2: Higher sensitivity found at low energies

…No experimental confirmation !

Why ???

→Collision dynamic effect reduces the sensitivity

→Experimental precision not high enough to pin down E_{sym}

→nn→$p\Delta^-$ cancels out part of the N/Z asymmetry;

- Not only EOS is unknown;
- Dynamics of HIC plays essential role in the determination of EOS (may reduce the sensitivity!)

FOPI collaboration, PRC 75, 011901 (2007)