On the Isospin Dependence of the EoS of Nuclear Matter

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Heavy-Ion Collisions from the Coulomb Barrier to the Quark-Gluon Plasma

Erice

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OVERVIEW

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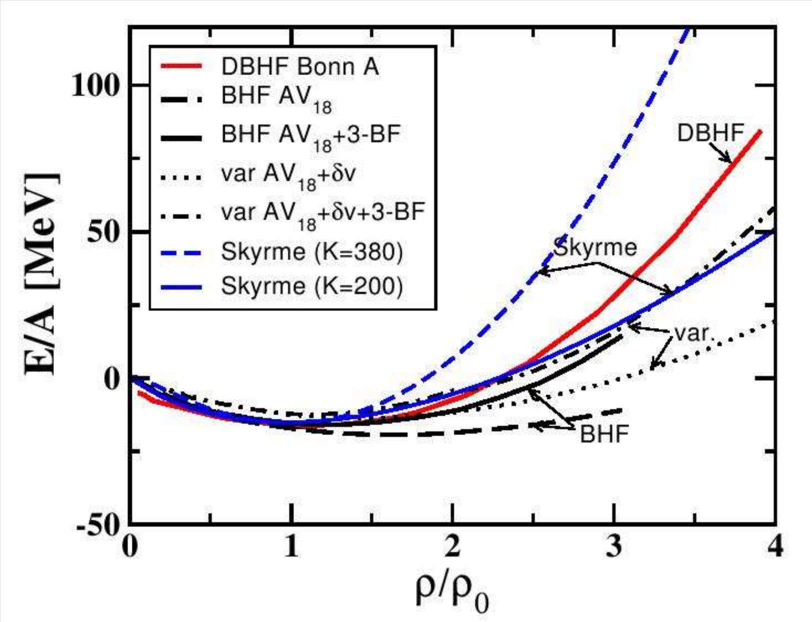
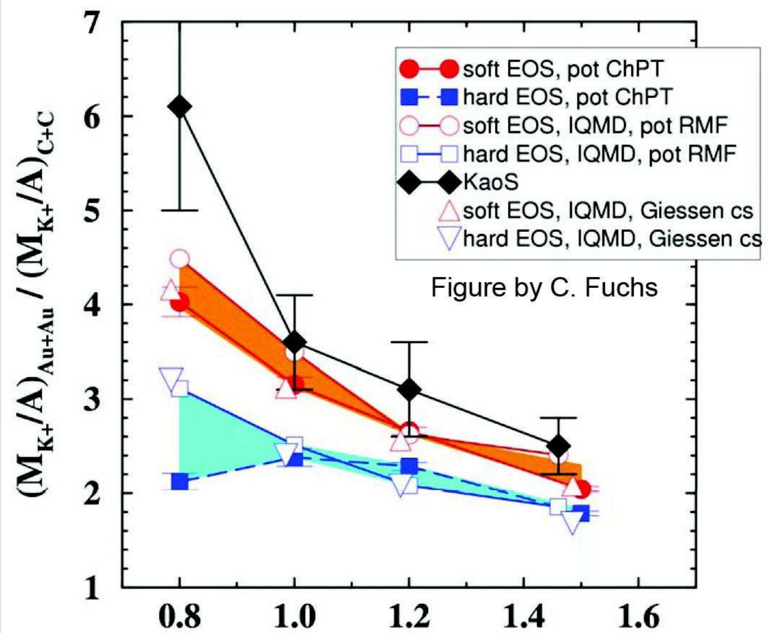
Introduction

Nuclear Equation of State: E/A=$\mathcal{E}(\rho)$

sources: finite nuclei $\rho/\rho_0 \leq 1$
heavy-ions $\rho/\rho_0 \leq 3$
neutron stars $\rho/\rho_0 \leq 10$





Fuchs PRL86, 1974

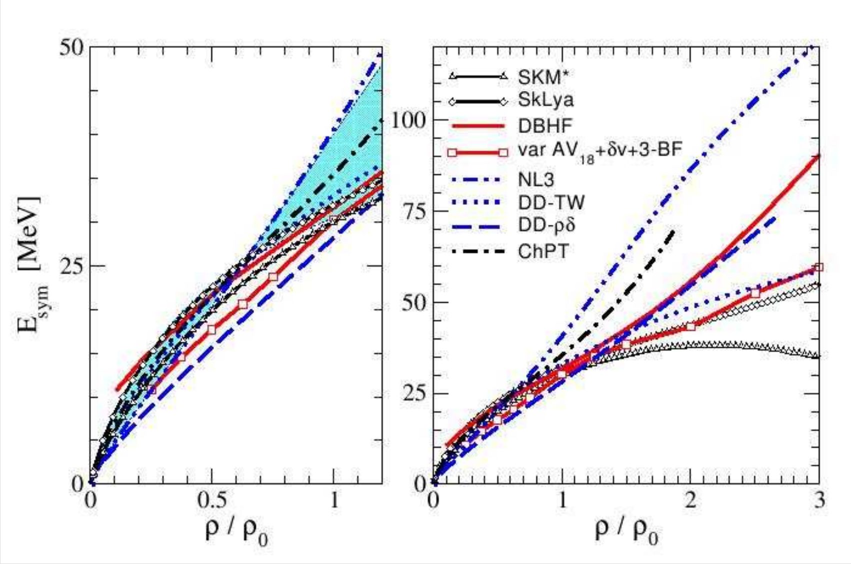
Motivation

Equation of State of asymmetric nuclear matter:
Symmetry energy:

$$\mathcal{E}(\rho,\beta) = \mathcal{E}(\rho) + \mathcal{E}_{sym}(\rho)\,\beta^2 + \cdots \qquad \beta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$\mathcal{E}_{sym}(\rho) = \frac{1}{2}\,\frac{\partial \mathcal{E}(\rho,\beta)}{\partial \beta^2}|_{\beta=0} = a_4 + \frac{p_0}{\rho_0^2}(\rho - \rho_0)$$

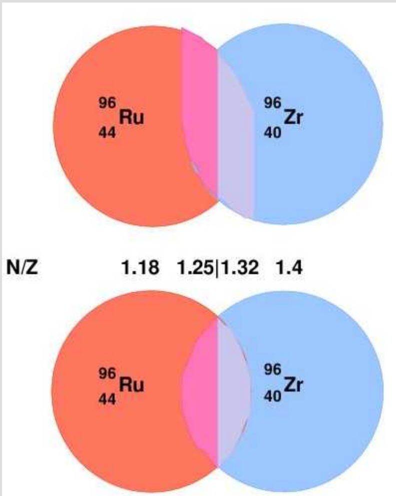
- phenomenological models constrained in the low ρ region diverge at high density

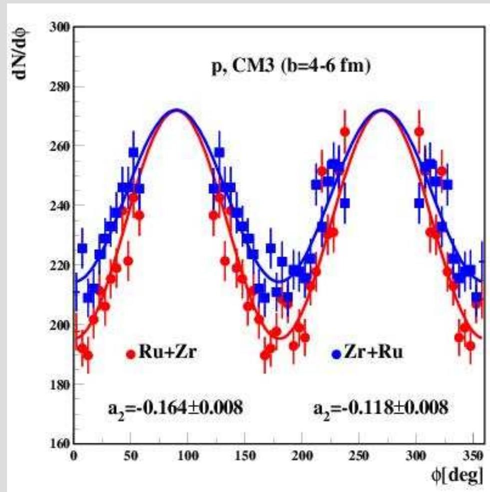


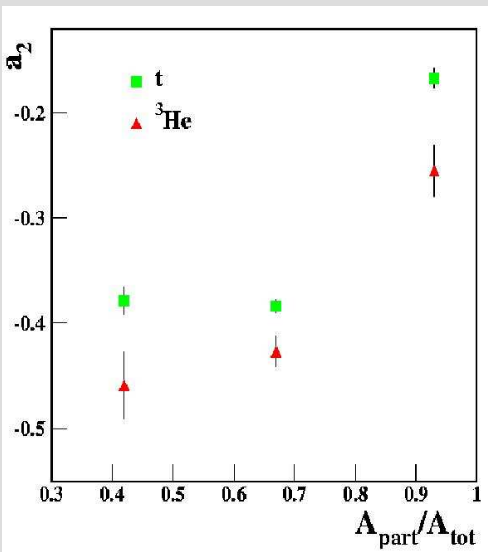
Motivation

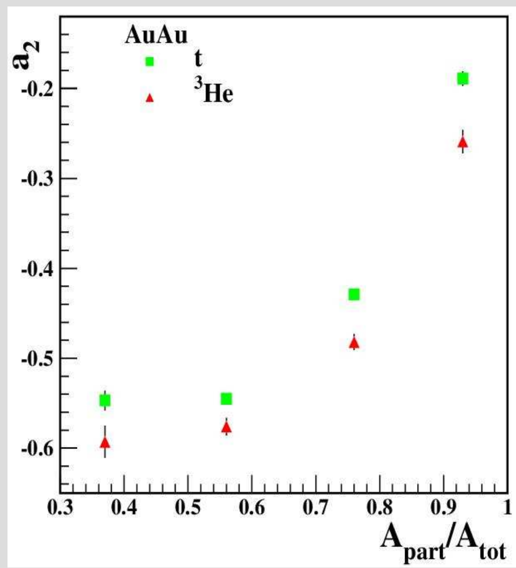
FOPI Collaboration: RuZr and AuAu @ 400 AMeV

Rami et al., PRL 84,1120; Hong et al., PRC 66, 034901









Transport Model

Transport model: **Quantum Molecular Dynamics**

Monte Carlo cascade + Mean field + Pauli-blocking
+ in medium cross section
all 4^* resonances below 2 GeV - 10 Δ^* and 11 N^*

- included baryon-baryon collisions:

  all elastic channels

  inelastic channels $NN \rightarrow NN^\star$, $NN \rightarrow N\Delta^\star$, $NN \rightarrow \Delta N^\star$, $NN \rightarrow \Delta\Delta^\star$, $NR \rightarrow NR'$

- included pion-absorption $\rightleftharpoons$ resonance-decay channels:

  $\Delta \rightleftharpoons N\pi$, $\Delta^\star \rightleftharpoons \Delta\pi$, $\Delta^\star \rightleftharpoons N_{1440}\pi$, $N^\star \rightleftharpoons N\pi$,

  $N^\star \rightleftharpoons N\pi\pi$, $(N^\star \rightleftharpoons \Delta\pi$, $N^\star \rightleftharpoons N_{1440})$

QMD: Essential Ingredients

Inclusion of collisions:

- binary collisions: geometric criterion
- one needs consistent cross-section $\leftrightarrow$potential parameters (mean field)
- use fit to available experimental data; if not available use detailed balance and isospin symmetry

$$\sigma_{1,2\to 3,4}(\sqrt{s}) \quad \sim \quad (2S_3+1)(2S_4+1)\frac{\langle p_{3,4}\rangle}{\langle p_{1,2}\rangle}\frac{1}{s}\left|\mathcal{M}(m_3,m_4)\right|^2$$

$$\sigma_{f\to i} \quad = \quad \frac{p_i^2}{p_f^2}\frac{g_i}{g_f}\,\sigma_{i\to f}$$

- Pauli blocking due to Fermi statistics: collision allowed with probability $(1-f_1')(1-f_2')$
- angular distributions of two-body scattering: same as $NN\to NN$ (determined from an effective model)

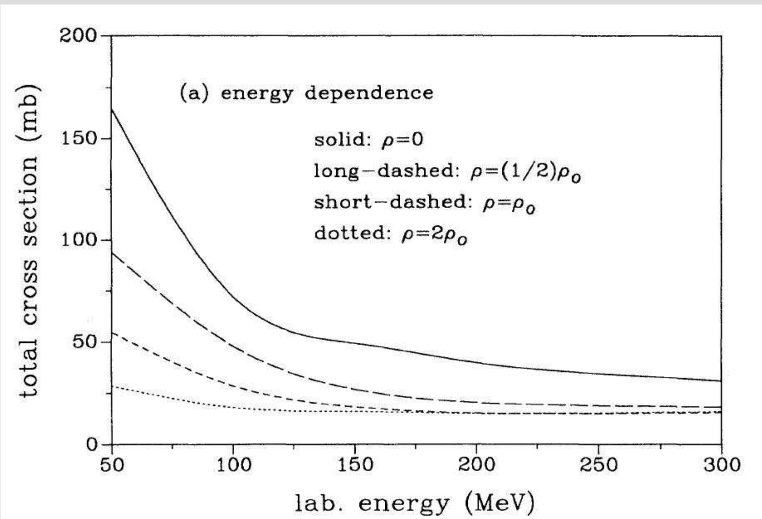
Nucleon-Nucleon Interaction

Vacuum NN Interaction: - microscopical OBE model (Bonn)

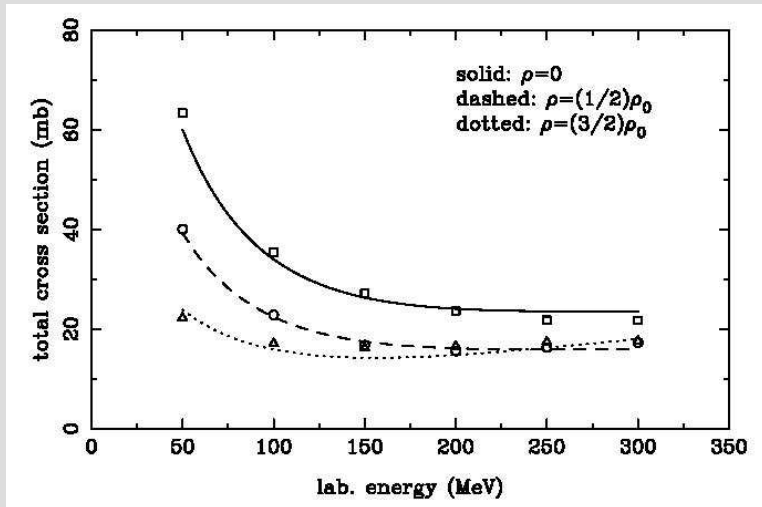
$$T(\vec{q}',\vec{q}) \quad = \quad V(\vec{q}',\vec{q}) + \mathcal{P}\int \frac{d^3k}{(2\pi)^3} V(\vec{q}',\vec{k}) \frac{m^2}{E_k^2} \frac{1}{2E_q - 2E_k} T(\vec{k},\vec{q})$$

In-Medium NN interaction: - Dirac-Brueckner approach

$$G(\vec{q}',\vec{q}|\vec{P},z) = V^*(\vec{q}',\vec{q}) + \mathcal{P}\int \frac{d^3k}{(2\pi)^3} V^*(\vec{q}',\vec{k}) \frac{m_*^2}{E^2_{1/2\vec{P}+\vec{k}}} \frac{Q(\vec{k},\vec{P})}{z - 2E_{1/2\vec{P}+\vec{k}}} G(\vec{k},\vec{q}|\vec{P},z)$$



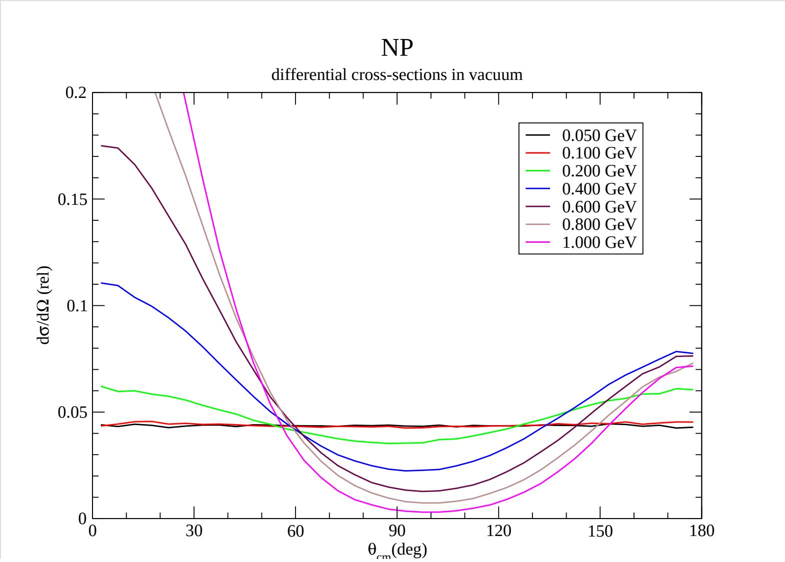
Li, Machleidt PRC 48, 1702

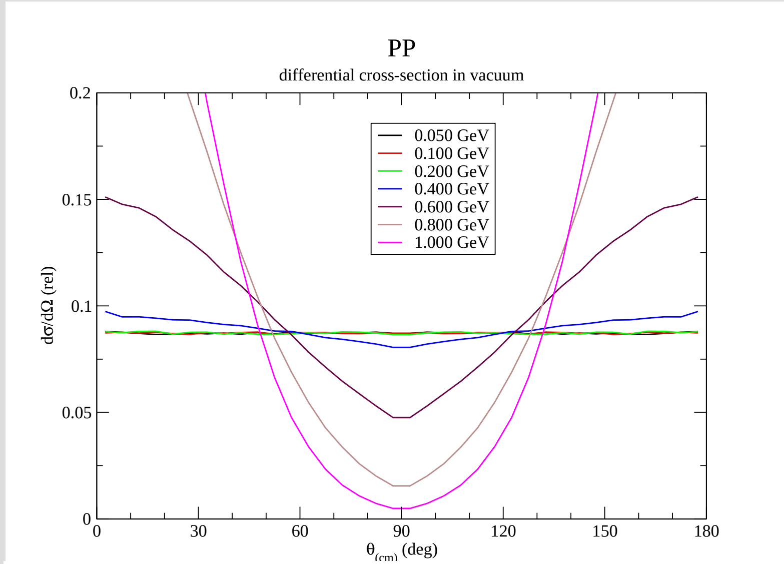


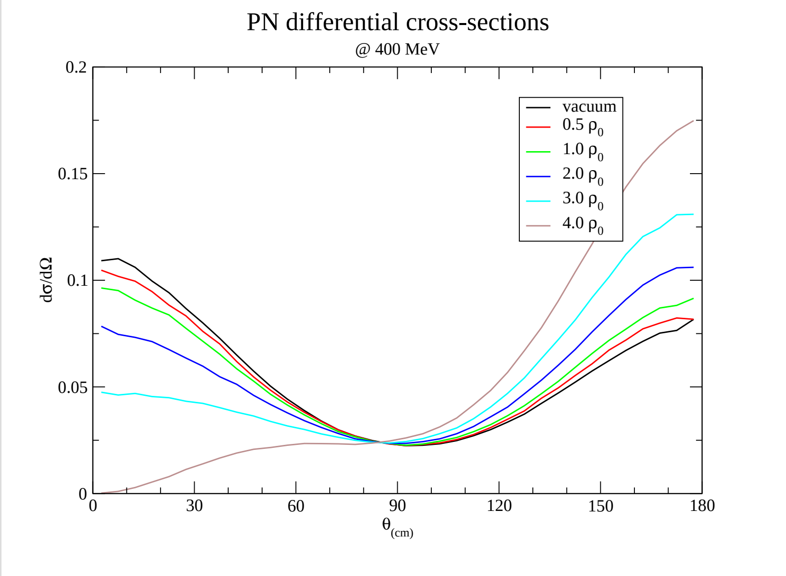
Li, Machleidt PRC 49, 566

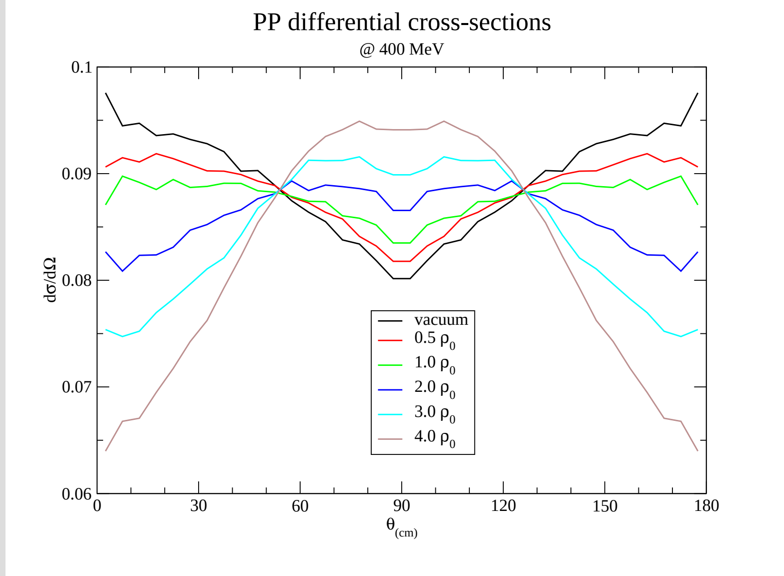
Nucleon-Nucleon Interaction

Li, Machleidt PRC 48, 1702; C. Fuchs, PRC 64, 024003









Isospin dependence

EoS of isospin asymmetric nuclear mater:

$$V^{n(p)}(\rho,\beta) = a\,u + b\,u^{\gamma} + V_{mdi} + V_c^p + V_{asym}^{n(p)}(\rho,\beta)$$

$$\mathcal{E}_a(\rho,\beta) = e_a\,\rho\,F(u)\,\beta^2 \qquad V_{asym}^{n(p)} = \partial\mathcal{E}_a(\rho,\beta)/\partial\,\rho_{n(p)}$$

$$F_1(u) = \frac{2u^2}{1+u} \qquad F_2(u) = u \qquad F_3(u) = u^{1/2}$$

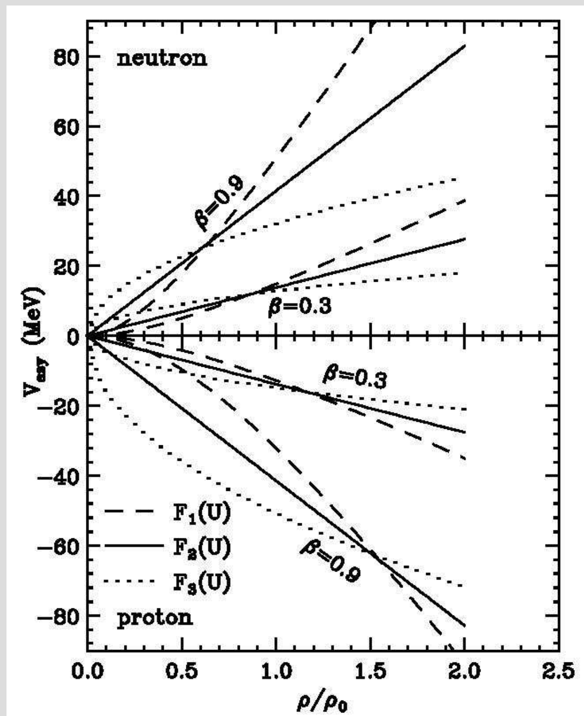
nucleons and resonances propagate in an isospin dependent mean field

$$V_{asym}(n^*) = V_{asym}(\Delta^0) = V_{asym}^n$$

$$V_{asym}(p^*) = V_{asym}(\Delta^+) = V_{asym}^p$$

$$V_{asym}(\Delta^{++}) = 2V_{asym}^p - V_{asym}^n$$

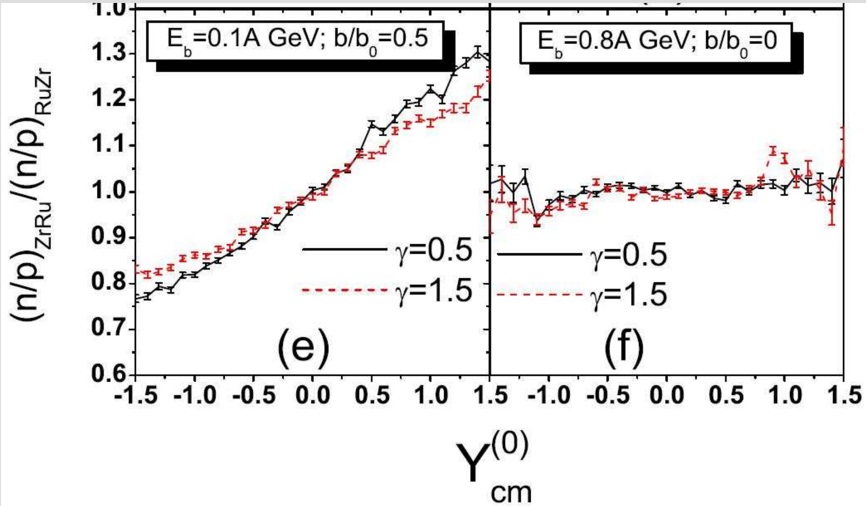
$$V_{asym}(\Delta^-) = 2V_{asym}^n - V_{asym}^p$$

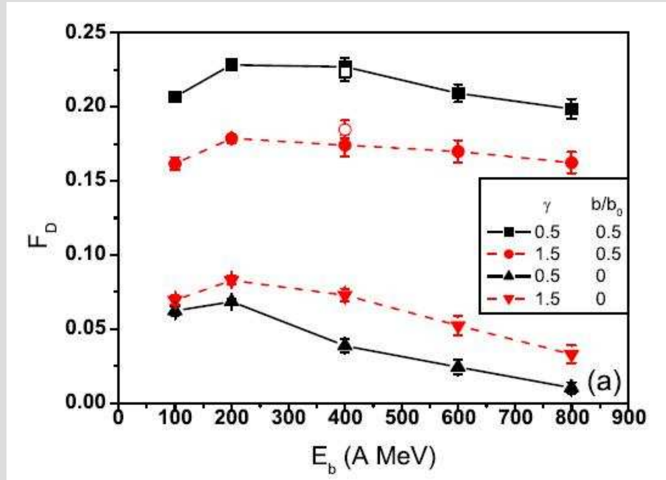


Li, Ko, Ren PRL78, 1644

Observables

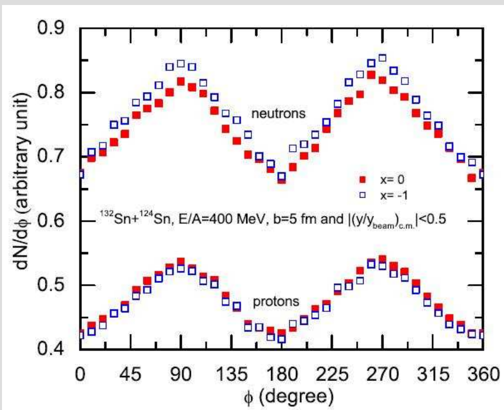
double neutron to proton ratio (n/p)$_{AB}$/(p/n)$_{BA}$

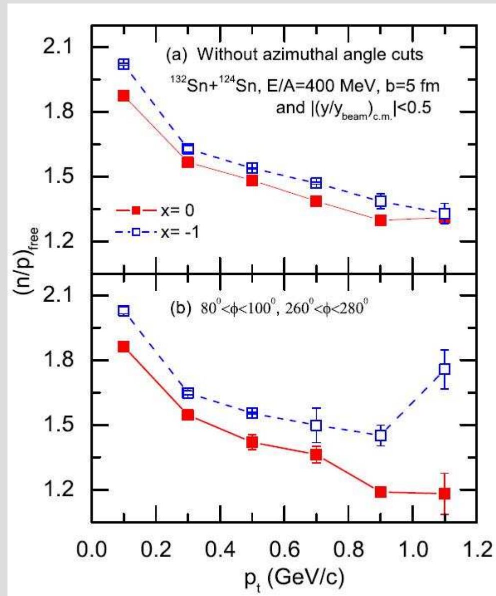




Li,Li, Stocker PRC 73, 051601

neutron/proton ratio at midrapidity





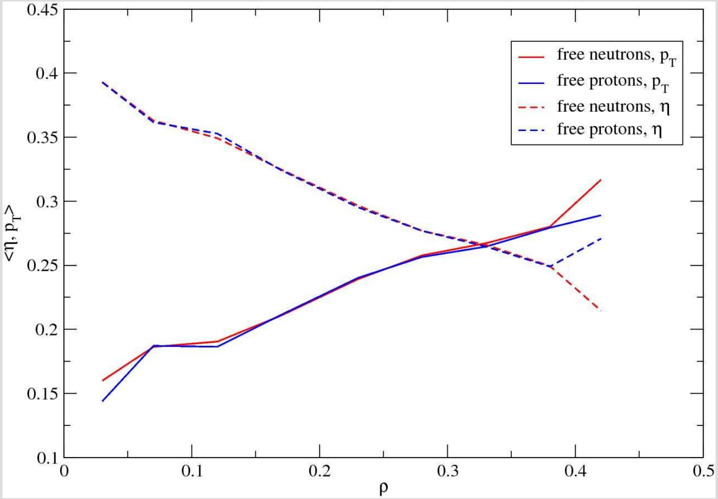
Yong, Li, Chen PLB650, 344

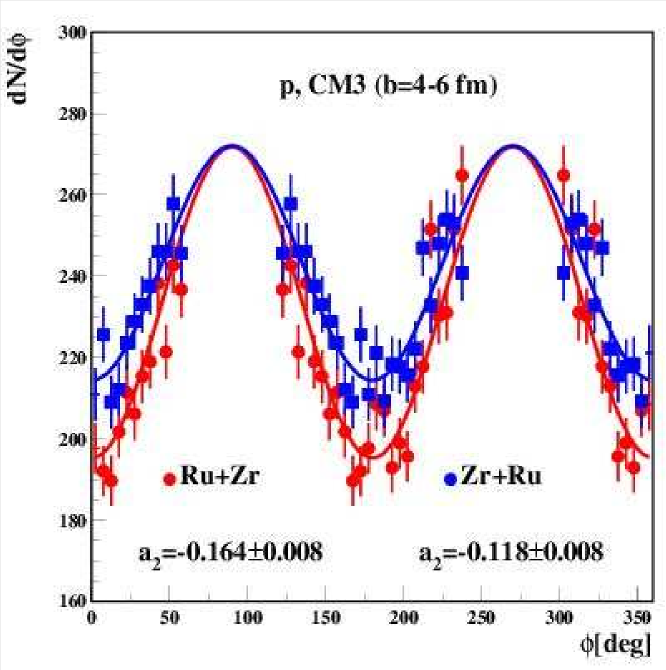
Observables

Elliptic flow and Differential Elliptic Flow

$$\frac{dN}{d\phi} = a_0\left(1 + a_1 cos(\phi) + a_2 cos(\phi)\right)$$

$$a_2 = \frac{1}{N}\sum_i \frac{p_x^{i^2} - p_y^{i^2}}{p_t^{i^2}}$$





Elliptic flow (EoS and in-medium NN dep)

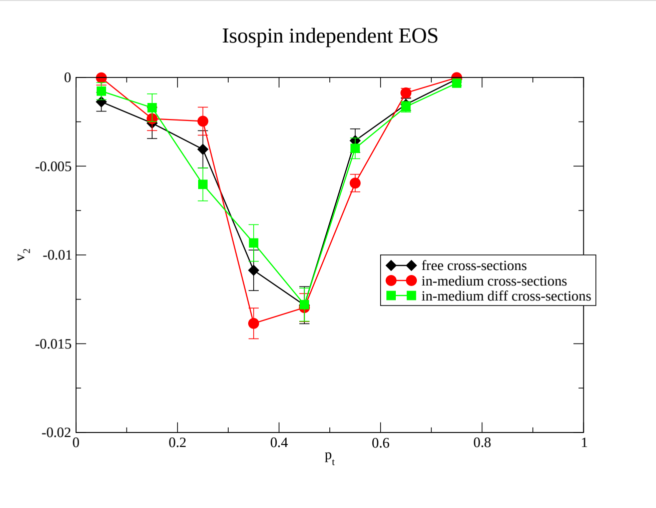
$$\frac{dN}{d\phi} = a_0\,(1 + a_1 cos(\phi) + a_2 cos(\phi))$$

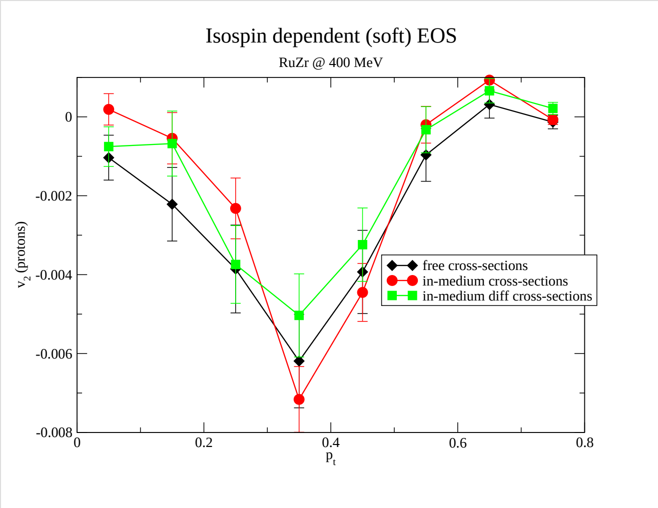
constraints: |y|<0.50, b=5 fm, Ru+Zr @ 400 MeV

EOS + Cross-sections	n+p	n	p
Isospin indep + Free c.s.	-0.040	-0.042	-0.036
Isospin indep + Dens. Dep. c.s.	-0.038	-0.038	-0.038
Isospin indep + Dens. Dep. diff. c.s.	-0.038	-0.040	-0.036
Isospin dep soft + Free c.s.	-0.018	-0.019	-0.017
Isospin dep soft + Dens. Dep. c.s.	-0.014	-0.015	-0.013
Isospin dep soft + Dens. Dep. diff. c.s.	-0.016	-0.018	-0.014
Isospin dep stiff + Free c.s.	-0.014	-0.017	-0.014
Isospin dep stiff + Dens. Dep. c.s.	-0.017	-0.020	-0.014
Isospin dep stiff + Dens. Dep. diff. c.s.	-0.020	-0.022	-0.018
Isospin dep linear + Free c.s.	-0.013	-0.017	-0.008
Isospin dep linear + Dens. Dep. c.s.	-0.017	-0.022	-0.010
Isospin dep linear + Dens. Dep. diff. c.s.	-0.016	-0.022	-0.009

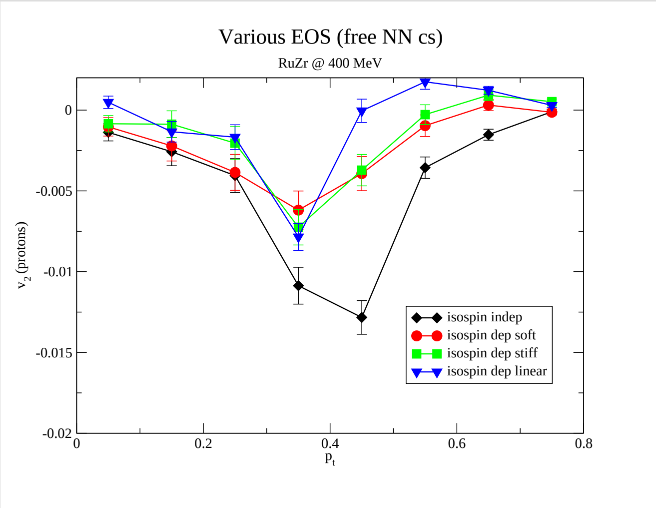
Differential elliptic flow

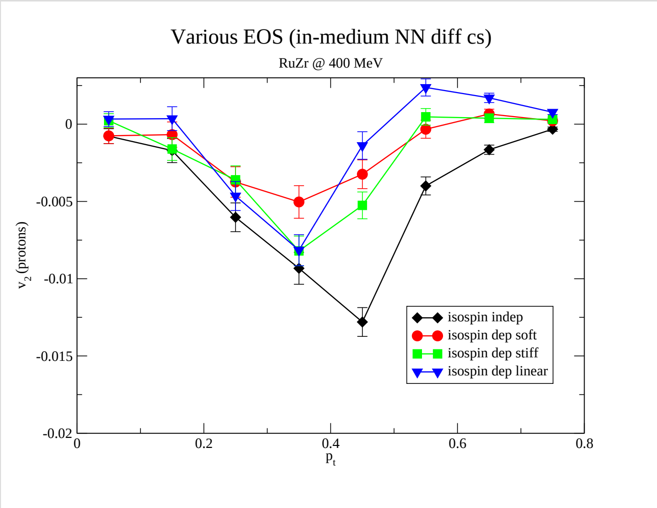
sensitivity to in-medium NN interaction





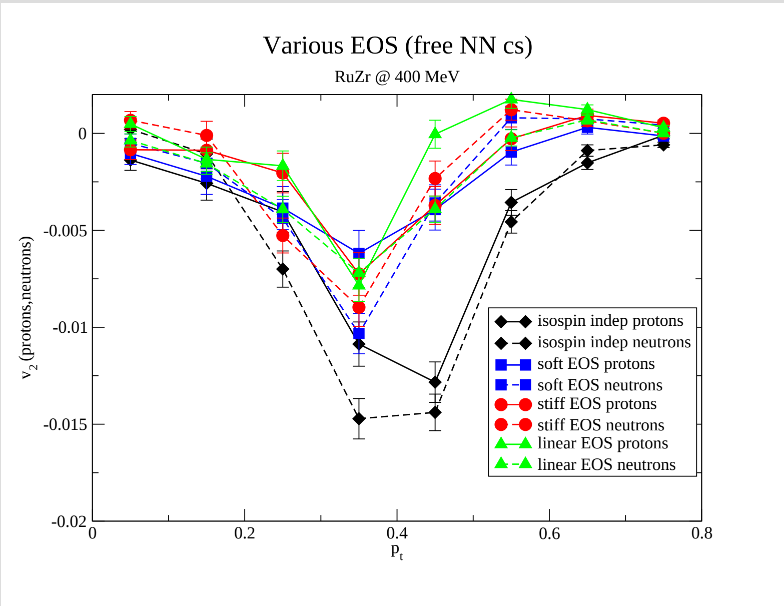
sensitivity to EOS

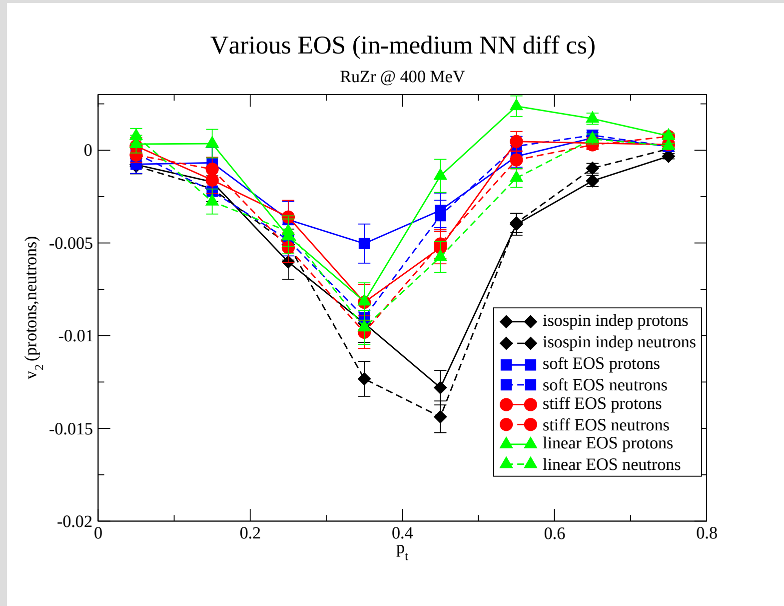




Differential elliptic flow

splitting of the n vs. p values





Problem ! differential elliptic flow at high p_T

Summary

- Message: - a_2 sensitive to isospin dependent part of EoS; density dependent NN cross-section of secondary importance
  - no clear preference for the isospin dependent part of the equation of state
- Consistency: - vacuum isospin dependent NN interaction $\rightarrow$ in-medium NN cross-sections, equation of state
- Improvements: - determine the origin of the differential elliptic flow at large p_T;
  - introduce momentum dependence in the symmetry energy terms and account for neutron-proton mass splitting
- To Be Done: - implement in transport code explicit production channels for deuterium and compare with results from coalescence models;
  - study the emission of ^3H and ^3He from a coalescence model