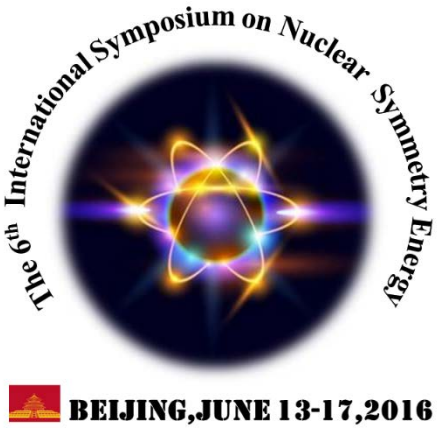


中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Isospin dynamics in high-energy heavy-ion collisions

Zhao-Qing Feng (冯兆庆)

Institute of Modern Physics (IMP), CAS

Outline

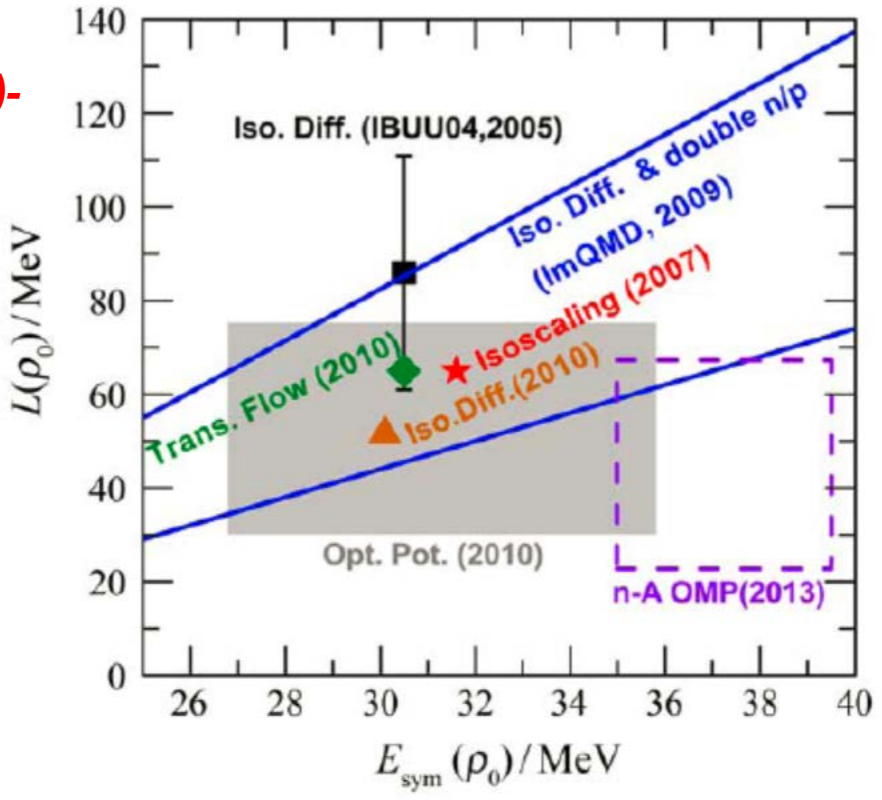
- Introduction
- Brief description: Lanzhou Quantum Molecular Dynamics (LQMD) transport model
  - Isospin, density and momentum dependent mean-field potentials
  - Particle production (pseudoscalar mesons(π, η, K), hyperons etc) and isospin particle-nucleon potential
- Observables to probe the high-density SE from HICs
- Summary

I. Introduction

Symmetry energy : $(0.5\rho_0 < \rho < 1.2\rho_0)$

Isospin observables from proton (electron)-nucleus and heavy-ion collisions:

- Proton-nucleus elastic scattering in inverse kinematics
- n/p ratio of fast, pre-equilibrium nucleons
- Double n/p ratios of isotopic reaction systems
- Isospin fractionation and isoscaling in nuclear multifragmentation
- Isospin diffusion/transport
- Neutron-proton differential flow
- Neutron-proton correlation functions at low relative momenta
- t/^{3}He ratio



Lie-Wen Chen, Nucl. Phys. Rev. 273 (2014) 284
《原子核物理评论》

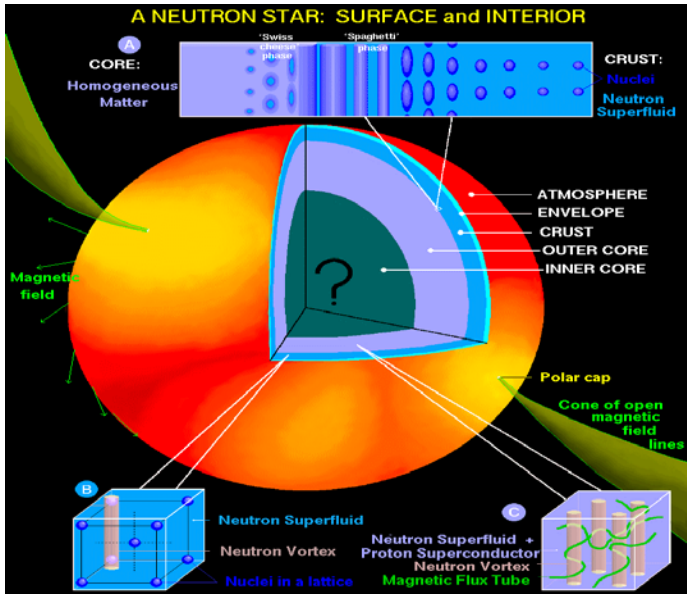
Based on several complementary approaches with available data

$E_{sym}(\rho_0)=32.5 \pm 2.5$ MeV, $L=55 \pm 25$ MeV

Refs: B. A. Li et al., Phys. Rep. 464 (2008) 113; Shetty et al., PRC75 (07) 034602; Tsang et al., PRL 102, 122701 (2009); C. Xu et al.,Phys Rev C 82 (2010) 054607

Symmetry energy ($\rho > 1.2\rho_0$)

J. M. Lattimer and M. Prakash, Science 304, 536 (2004)

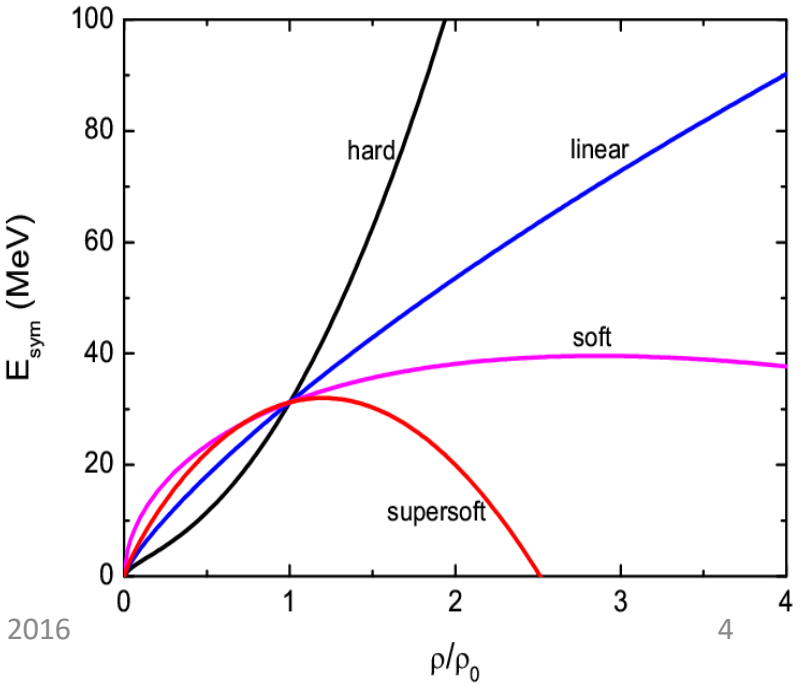


Isospin observables from heavy-ion collisions :

- π^-/π^+ ratio, K^0/K^+ ratio, Σ^-/Σ^+ ratio
- Neutron-proton differential flow
- Double n/p, π^-/π^+, K^0/K^+ ratios of isotopic systems
- Nucleon elliptical flow at high transverse momenta
- n/p ratio of squeeze-out emission

…

The information of high-density symmetry energy is poorly known, which is of importance in understanding the structure of neutron star, supernova explosion etc.



Heavy-ion accelerator systems at Institute of Modern Physics

HIAF (***H**igh-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Huizhou)~1.1GeV/u, 10^{22} ppp for $^{238}U^{+34}$*

II. Model description

Lanzhou Quantum Molecular Dynamics (LQMD) model:

Nuclear dynamics from 5 MeV/nucleon – 10 GeV/nucleon for HICs, antiproton (proton, π, K, etc)

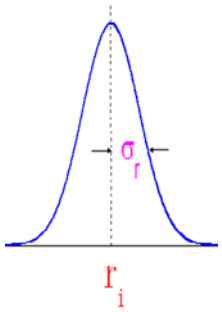
- **Dynamics of low-energy heavy-ion collisions** (dynamical interaction potential, barrier distribution, neck dynamics, fusion/caption excitation functions etc)
- **Isospin physics at intermediate energies** (constraining nuclear symmetry energy at sub- and supra- saturation densities in HICs and probing isospin splitting of nucleon effective mass from HICs)
- **In-medium properties of hadrons in dense nuclear matter from heavy-ion collisions** (extracting optical potentials, i.e., Δ(1232), N*(1440), N*(1535)), hyperons ($\Lambda,\Sigma,\Xi,\Omega$) and mesons ($\pi$,K,$\eta,\rho,\omega,\phi\ldots$), hypernucleus dynamics)
- **Hadron (antiproton, proton, $\pi^{\pm}$, $K^{\pm}$) induced reactions** (hypernucleus production, e.g., $\Lambda(\Sigma)$X, $\Lambda\Lambda$X, ΞX, $\bar{\Lambda}$X(S=1), in-medium modifications of hadrons, cold QGP)

Dynamics of many-body hadronic system:

J. Aichelin, *Phys. Rep.*, 202 (1991) 233

Wave function of system $\Phi(\mathbf{r},t)=\prod_i \phi_i(\mathbf{r},\mathbf{r}_i,\mathbf{p}_i,t)$

with $\phi_i(\mathbf{r},t)=\frac{1}{(2\pi\sigma_r^2)^{3/4}}\exp\left[-\frac{(\mathbf{r}-\mathbf{r}_i(t))^2}{4\sigma_r^2}\right]\cdot\exp\left(\frac{i\mathbf{p}_i(t)\cdot\mathbf{r}}{\hbar}\right)$



$$\mathbf{L}=\left\langle\Phi\left|i\hbar\frac{d}{dt}-H\right|\Phi\right\rangle \qquad H=\sum_i T_i+\frac{1}{2}\sum_{\substack{i,j\\ j\neq i}} V_{ij}$$

$$\mathbf{L}=\sum_i\left[-\mathbf{r}_i\cdot\dot{\mathbf{p}}_i-\frac{\mathbf{p}_i^2}{2m_i}-\frac{1}{2}\sum_{\substack{j\\ j\neq i}}<V_{ij}>-\frac{3}{8m_iL}\right]$$

Euler-Langrange equations:

$$\frac{d}{dt}\frac{\partial\mathbf{L}}{\partial\dot{q}_\upsilon}-\frac{\partial\mathbf{L}}{\partial q_\upsilon}=0 \quad\Rightarrow\quad \dot{\mathbf{r}}_i=\frac{\partial H}{\partial\mathbf{p}_i} \qquad \dot{\mathbf{p}}_i=-\frac{\partial H}{\partial\mathbf{r}_i}$$

PHYSICAL REVIEW C 84, 024610 (2011)

Momentum dependence of the symmetry potential and its influence on nuclear reactions

Zhao-Qing Feng*
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China
(Received 11 July 2011; published 19 August 2011)

The mean-field potential of nucleons

$$V_{loc}(\rho) = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{1+\gamma}\frac{\rho^{1+\gamma}}{\rho_0^{\gamma}} + E_{sym}^{loc}(\rho)\rho\delta^2 + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{sur}^{iso}}{2\rho_0}\left[\nabla(\rho_n - \rho_p)\right]^2,$$

$$U_{loc} = \int V_{loc}(\rho(\mathbf{r}))\, d\mathbf{r}$$

J. Aichelin et al., Phys. Rev. Lett. 58, 1926 (1987)

$$U_{mom} = \frac{1}{2\rho_0}\sum_{i,j,j\neq i}\sum_{\tau,\tau'} C_{\tau,\tau'}\delta_{\tau,\tau_i}\delta_{\tau',\tau_j}\int\int\int d\mathbf{p}\, d\mathbf{p}'\, d\mathbf{r}\, f_i(\mathbf{r},\mathbf{p},t)$$

$$\times\left[\ln\left(\epsilon(\mathbf{p}-\mathbf{p}')^2+1\right)\right]^2 f_j(\mathbf{r},\mathbf{p}',t).$$

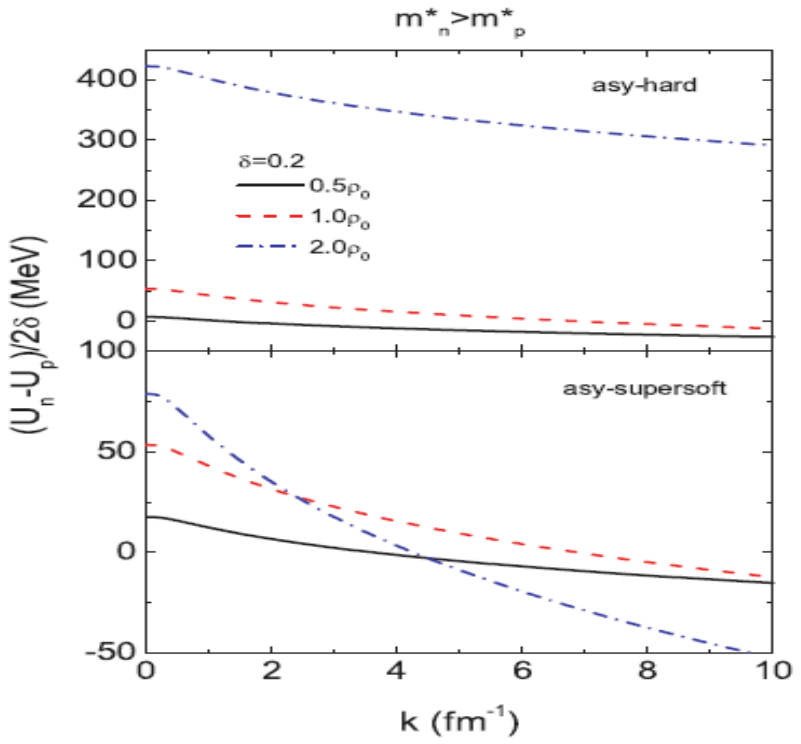
$$E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}\left(\frac{3}{2}\pi^2\rho\right)^{2/3} + E_{sym}^{loc}(\rho) + E_{sym}^{mom}(\rho).$$

$$E_{sym}^{loc}(\rho) = \frac{1}{2}C_{sym}(\rho/\rho_0)^{\gamma_s} \qquad E_{sym}^{loc}(\rho) = a_{sym}(\rho/\rho_0) + b_{sym}(\rho/\rho_0)^2.$$

Density, isospin and momentum-dependent single-nucleon potential in LQMD

$$U_\tau(\rho,\delta,\mathbf{p}) = \alpha\frac{\rho}{\rho_0} + \beta\frac{\rho^\gamma}{\rho_0^\gamma} + E_{\rm sym}^{\rm loc}(\rho)\delta^2 + \frac{\partial E_{\rm sym}^{\rm loc}(\rho)}{\partial\rho}\rho\delta^2 + E_{\rm sym}^{\rm loc}(\rho)\rho\frac{\partial\delta^2}{\partial\rho_\tau}$$
$$+ \frac{1}{\rho_0}C_{\tau,\tau}\int d\mathbf{p}'\, f_\tau(\mathbf{r},\mathbf{p})[\ln(\epsilon(\mathbf{p}-\mathbf{p}')^2+1)]^2$$
$$+ \frac{1}{\rho_0}C_{\tau,\tau'}\int d\mathbf{p}'\, f_{\tau'}(\mathbf{r},\mathbf{p})[\ln(\epsilon(\mathbf{p}-\mathbf{p}')^2+1)]^2.$$

Zhao-Qing Feng, Phys. Rev. C 84 (2011) 024610



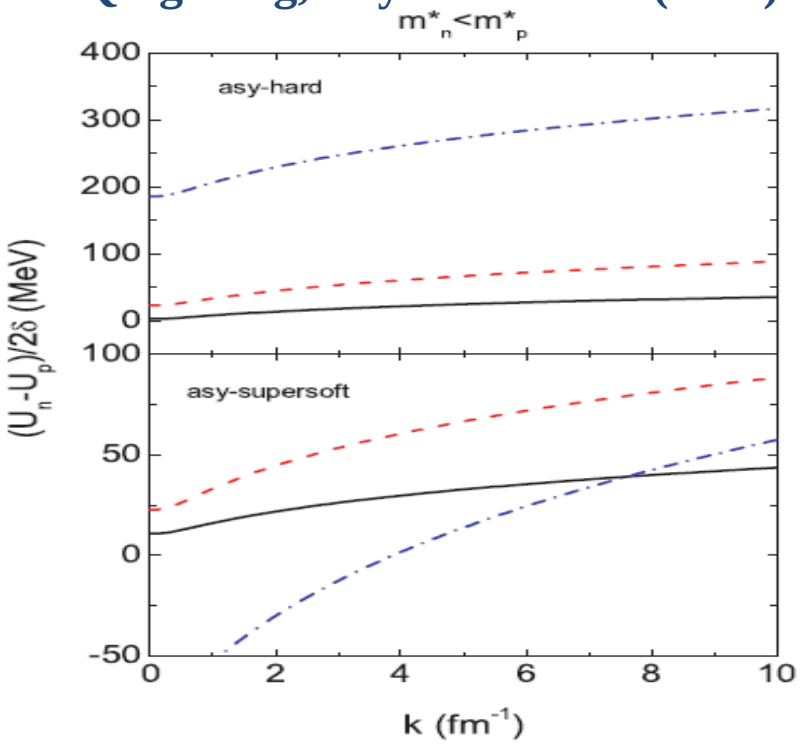
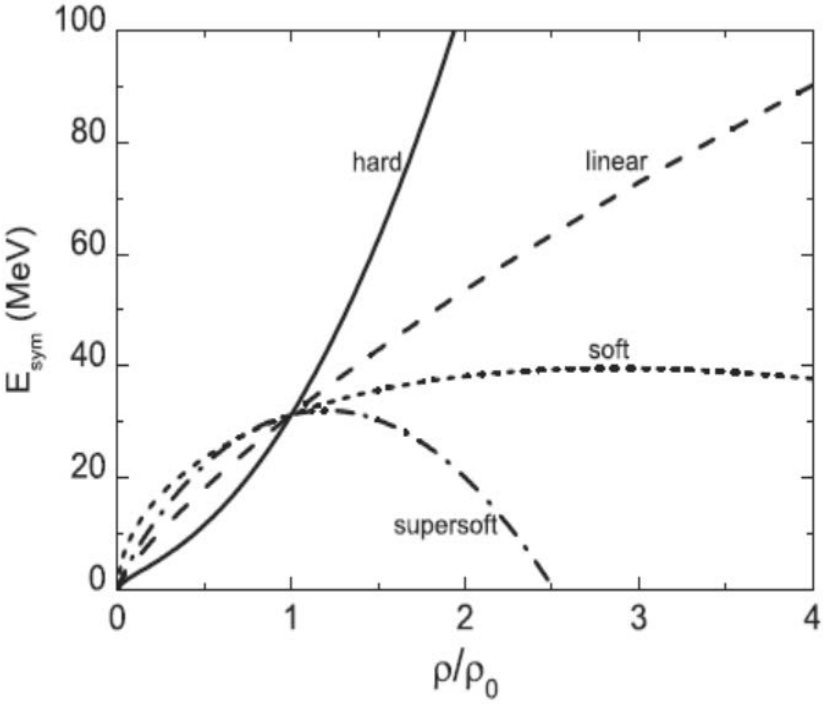
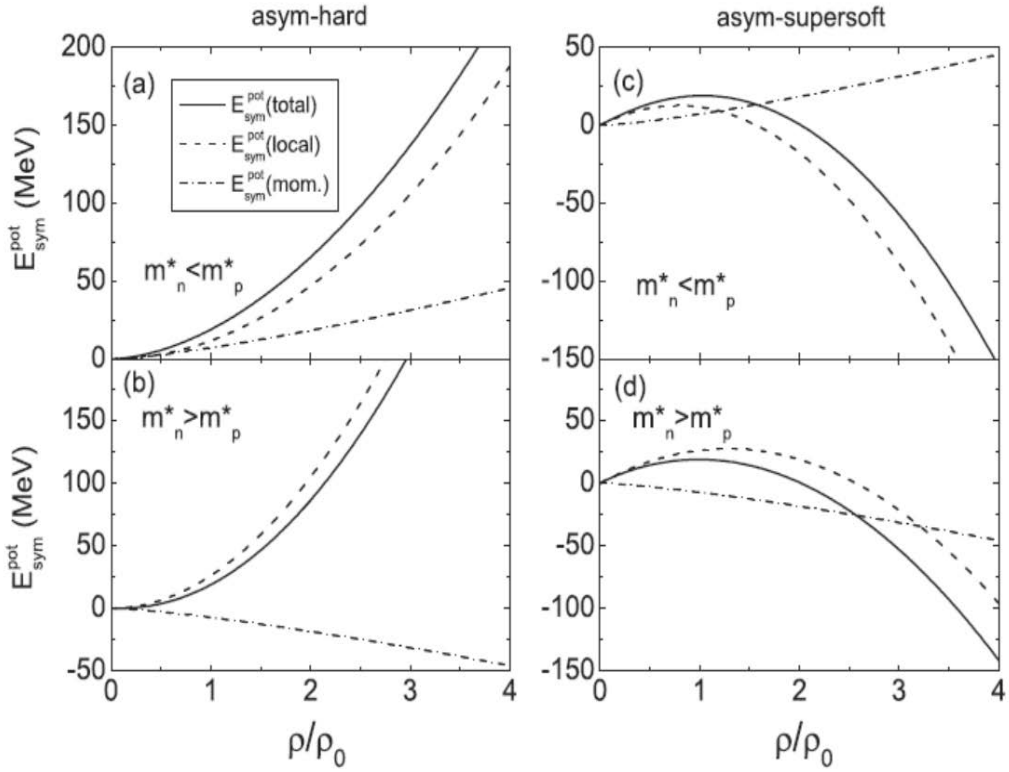


Table 1: The parameters and properties of isospin symmetric EoS used in the LQMD model at the density of 0.16 fm^{-3}.

Parameters	α (MeV)	β (MeV)	γ	C_{mom} (MeV)	ϵ (c^2/MeV^2)	m^*_∞/m	K_∞ (MeV)
PAR1	-215.7	142.4	1.322	1.76	5×10^{-4}	0.75	230
PAR2	-226.5	173.7	1.309	0.	0.	1.	230





Particle production in LQMD:

π and resonances (Δ(1232), N*(1440), N*(1535), …) production:

$$NN \leftrightarrow N\Delta, \quad NN \leftrightarrow NN^*, \quad NN \leftrightarrow \Delta\Delta, \quad \Delta \leftrightarrow N\pi,$$
$$N^* \leftrightarrow N\pi, \quad NN \leftrightarrow NN\pi(s-state), \quad N^*(1535) \leftrightarrow N\eta$$

Collisions between resonances, NN*↔NΔ, NN*↔NN*

Strangeness channels:

$$BB \rightarrow BYK, \quad BB \rightarrow BBK\overline{K}, \quad B\pi \rightarrow YK,$$
$$B\pi \rightarrow NK\overline{K}, \quad Y\pi \rightarrow N\overline{K}, \quad N\overline{K} \rightarrow Y\pi, \quad YN \rightarrow \overline{K}NN$$

Reaction channels with antiproton:

$$\overline{p}N \rightarrow \overline{N}N, \quad \overline{N}N \rightarrow \overline{N}N, \overline{N}N \rightarrow \overline{B}B, \overline{N}N \rightarrow \overline{Y}Y$$
$$\overline{N}N \rightarrow \mathtt{annihilation}(\pi, \eta, \rho, \omega, K, \overline{K}, K^*, \overline{K}^*, \phi)$$

Statistical model with SU(3) symmetry
(E.S. Golubeva et al., Nucl. Phys. A 537, 393 (1992))
The **PYTHIA** and **FRITIOF** code are used for baryon(meson)-baryon and antibaryon-baryon collisions at high invariant energies

Isospin and momentum dependent pion-nucleon potential

$$\omega_{\tau_z}(\rho,\vec{p}) = \omega_{isoscalar}(\rho,\vec{p}) + C_{iso}^{\pi}\tau_z\delta\left(\frac{\rho}{\rho_0}\right)^{\gamma_\pi}$$

$C_\pi = \rho_0\hbar^3/(4f_\pi^2) = 36$ MeV, τ_z=1, 0, -1 for π-, π0 and π+

Z. Q. Feng et al., Phys. Rev. C 92 (2015) 044604

Evaluation of $\omega_{isoscalar}$

1) phenomenological ansatz from pionic atom

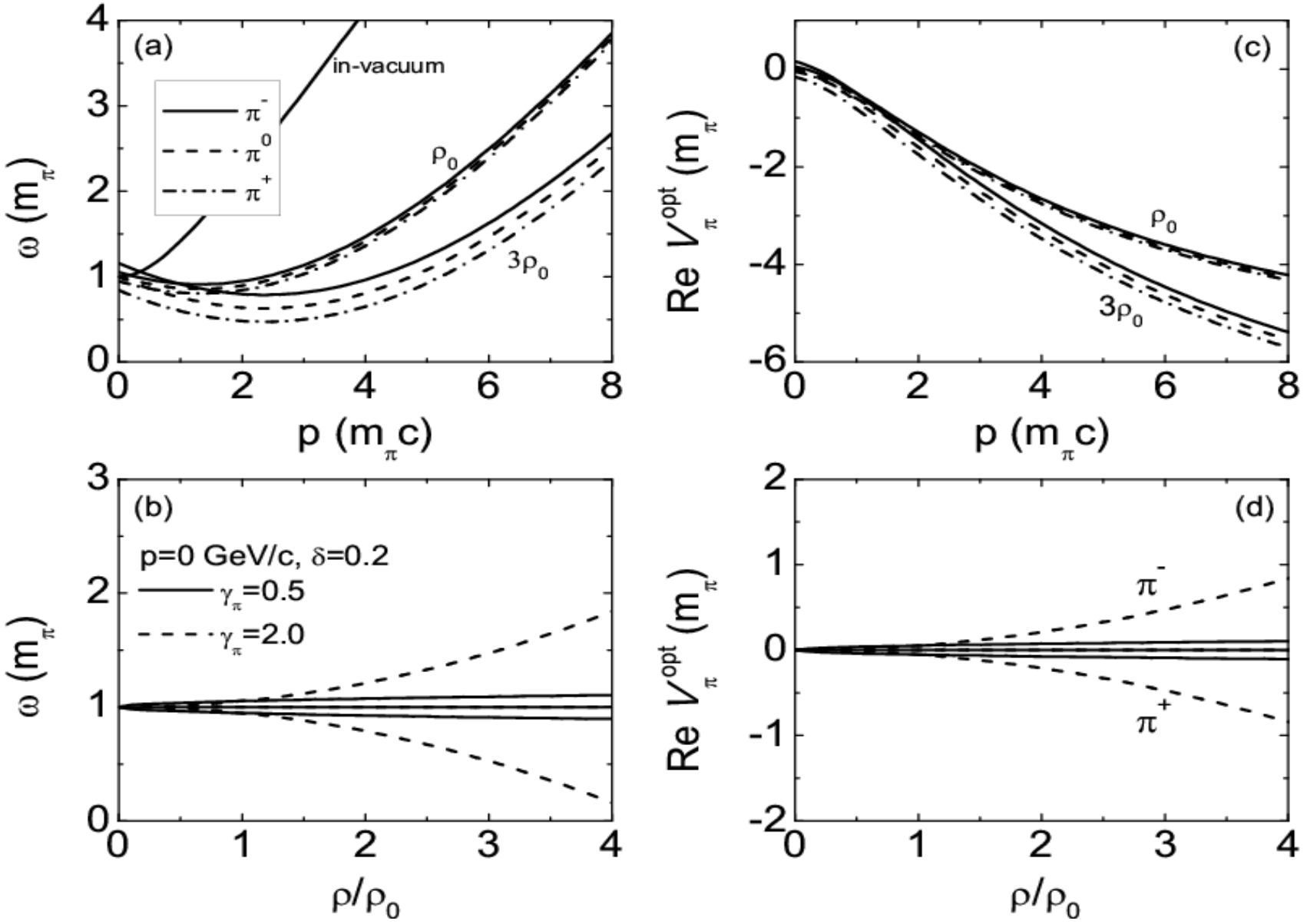
C. Gale and J. Kapusta, Phys. Rev. C 35, 2107 (1987);
C. Fuchs et al., Phys. Rev. C 55, 411 (1997);
Z. Q. Feng and G. M. Jin, Phys. Rev. C 82, 044615 (2010)

$$\omega(\mathbf{p}_i,\rho_i) = \sqrt{(|\mathbf{p}_i| - p_0)^2 + m_0^2} - U, \qquad V_\pi^{\rm opt}(\mathbf{p}_i,\rho_i) = \omega_\pi(\mathbf{p}_i,\rho_i) - (m_\pi^2 + \mathbf{p}_i^2)^{1/2}$$

$$U = \sqrt{p_0^2 + m_0^2} - m_\pi,$$

$$m_0 = m_\pi + 6.5(1 - x^{10})m_\pi,$$

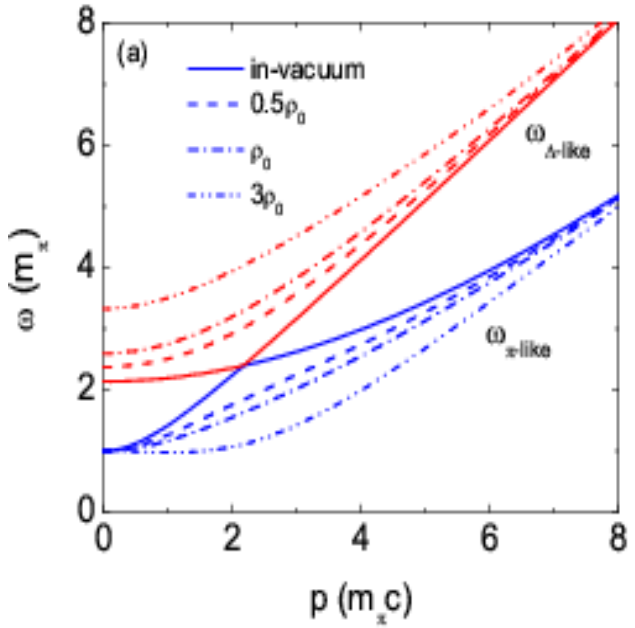
$$p_0^2 = (1-x)^2 m_\pi^2 + 2m_0 m_\pi (1-x). \qquad x(\rho_i) = \exp[-a(\rho_i/\rho_0)]$$

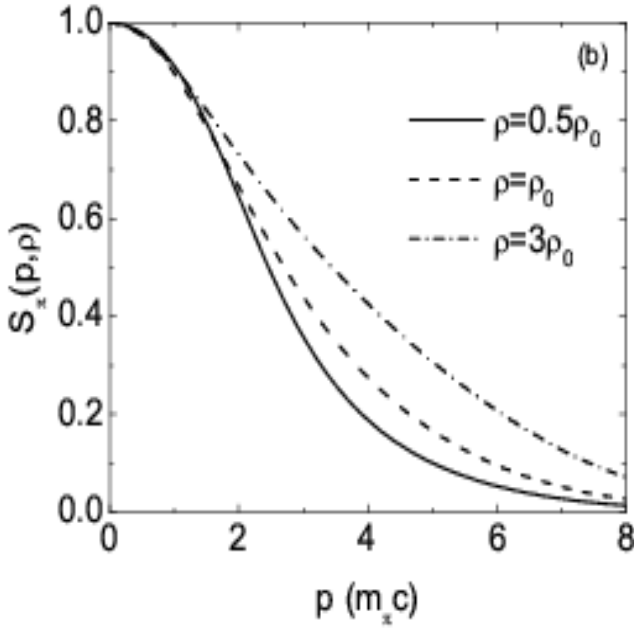

(a)
in-vacuum
π^-
π^0
π^+
ρ_0
$3\rho_0$
$\omega\ (m_\pi)$
$p\ (m_\pi c)$
(c)
ρ_0
$3\rho_0$
$\mathrm{Re}\ V_\pi^{opt}\ (m_\pi)$
$p\ (m_\pi c)$
(b)
p=0 GeV/c, δ=0.2
γ_π=0.5
γ_π=2.0
$\omega\ (m_\pi)$
ρ/ρ_0
(d)
π^-
π^+
$\mathrm{Re}\ V_\pi^{opt}\ (m_\pi)$
ρ/ρ_0

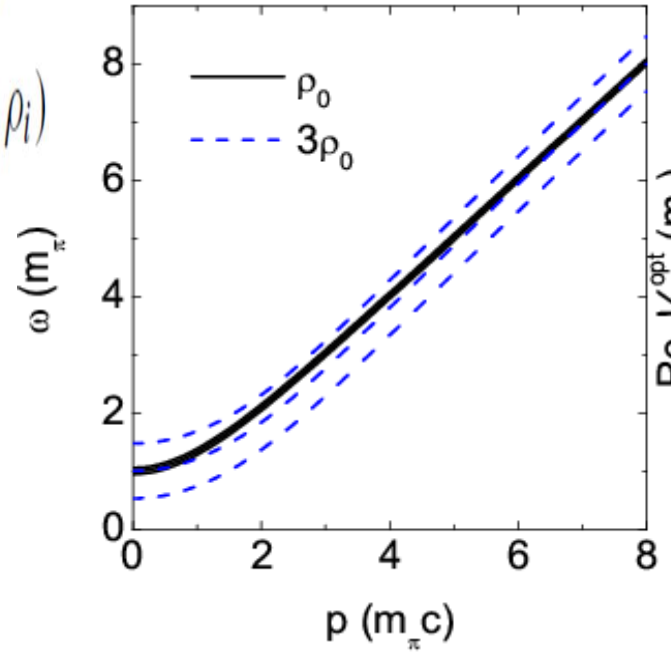
2) Δ-hole model

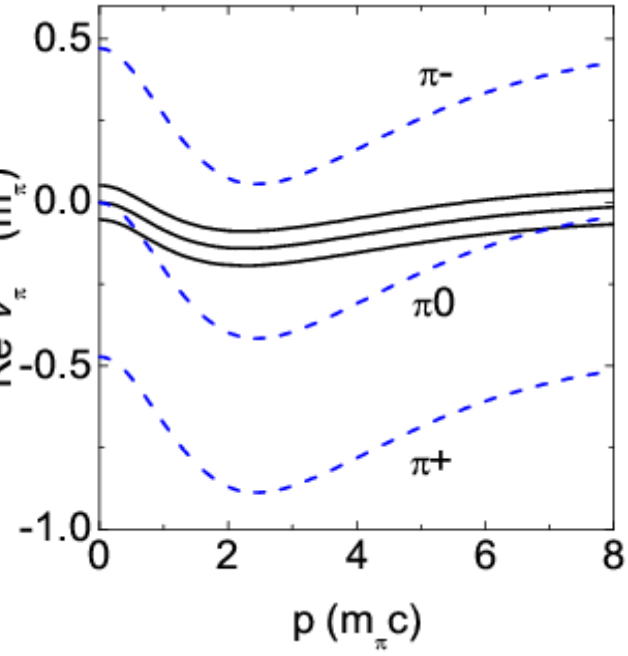
L. Xiong, C. M. Ko, V. Koch, Phys. Rev. C 47, 788 (1993); C. Fuchs et al., Phys. Rev. C 55, 411 (1997)

$$\omega_{\text{isoscalar}}(\mathbf{p}_i,\rho_i) = S_\pi(\mathbf{p}_i,\rho_i)\omega_{\pi\text{-like}}(\mathbf{p}_i,\rho_i) + S_\Delta(\mathbf{p}_i,\rho_i)\omega_{\Delta\text{-like}}(\mathbf{p}_i,\rho_i)$$





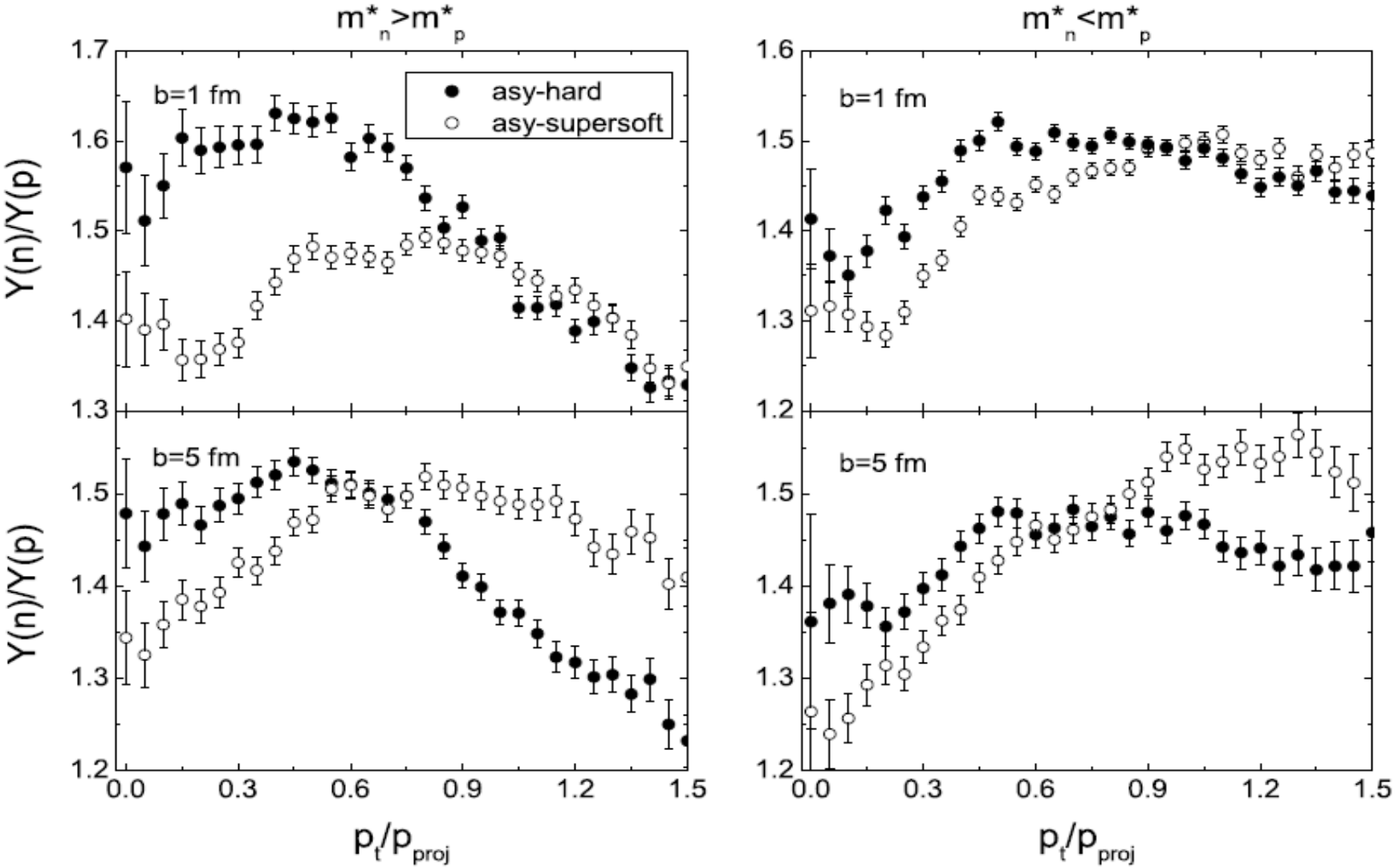




Observables to probe the high-density SE from HICs

1. Pre-equilibrium nucleon emissions from heavy-ion collisions

Mid-rapidity nucleon emission in the $^{124}Sn+^{124}Sn$ reaction at incident energy of 400 MeV/nucleon (Z. Q. Feng, Phys. Lett. B 707 (2012) 83-87)



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Transverse emission of isospin ratios as a probe of high-density symmetry energy in isotopic nuclear reactions

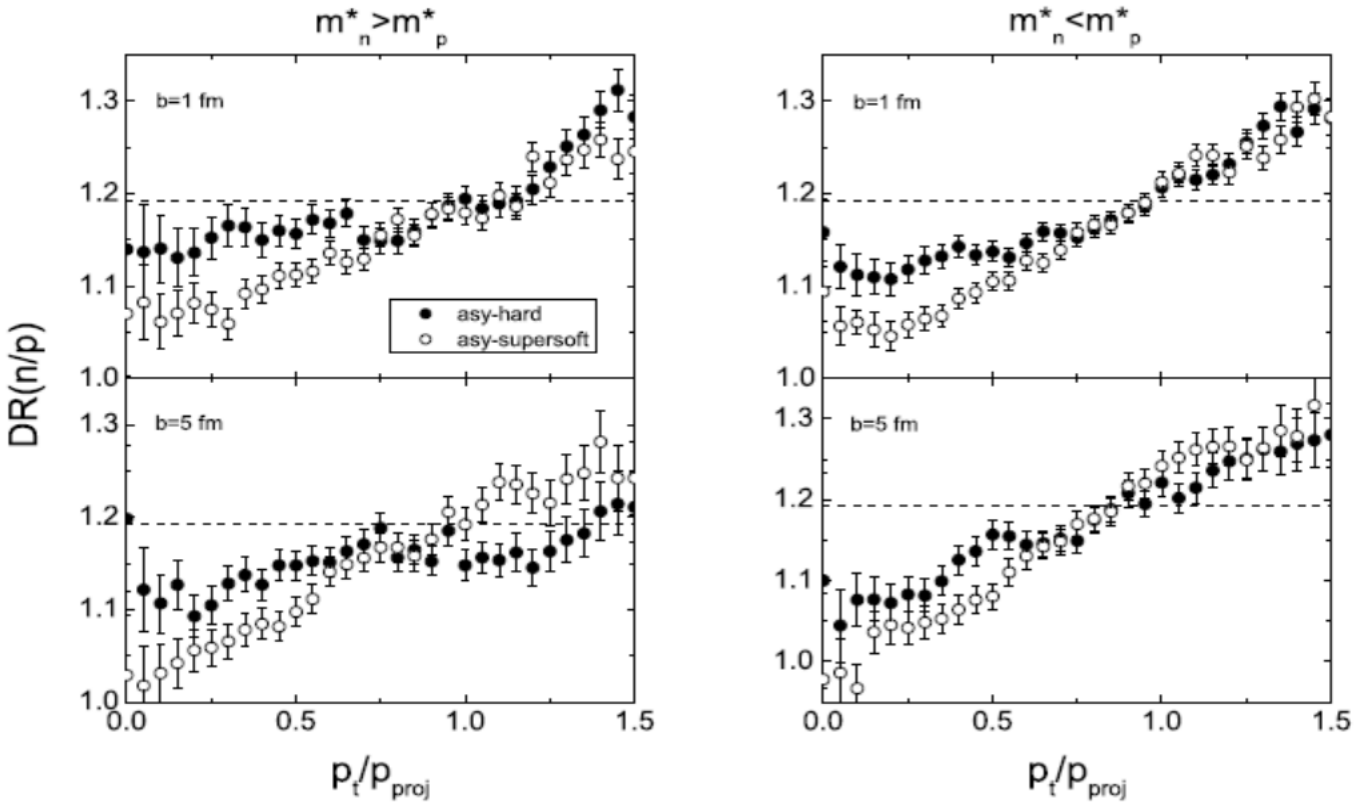
Zhao-Qing Feng *

Institute of Modern Physics, Chinese Academy

DR(n/p)=
(n/p(^{124}Sn+^{124}Sn))/
(n/p (^{112}Sn+^{112}Sn))

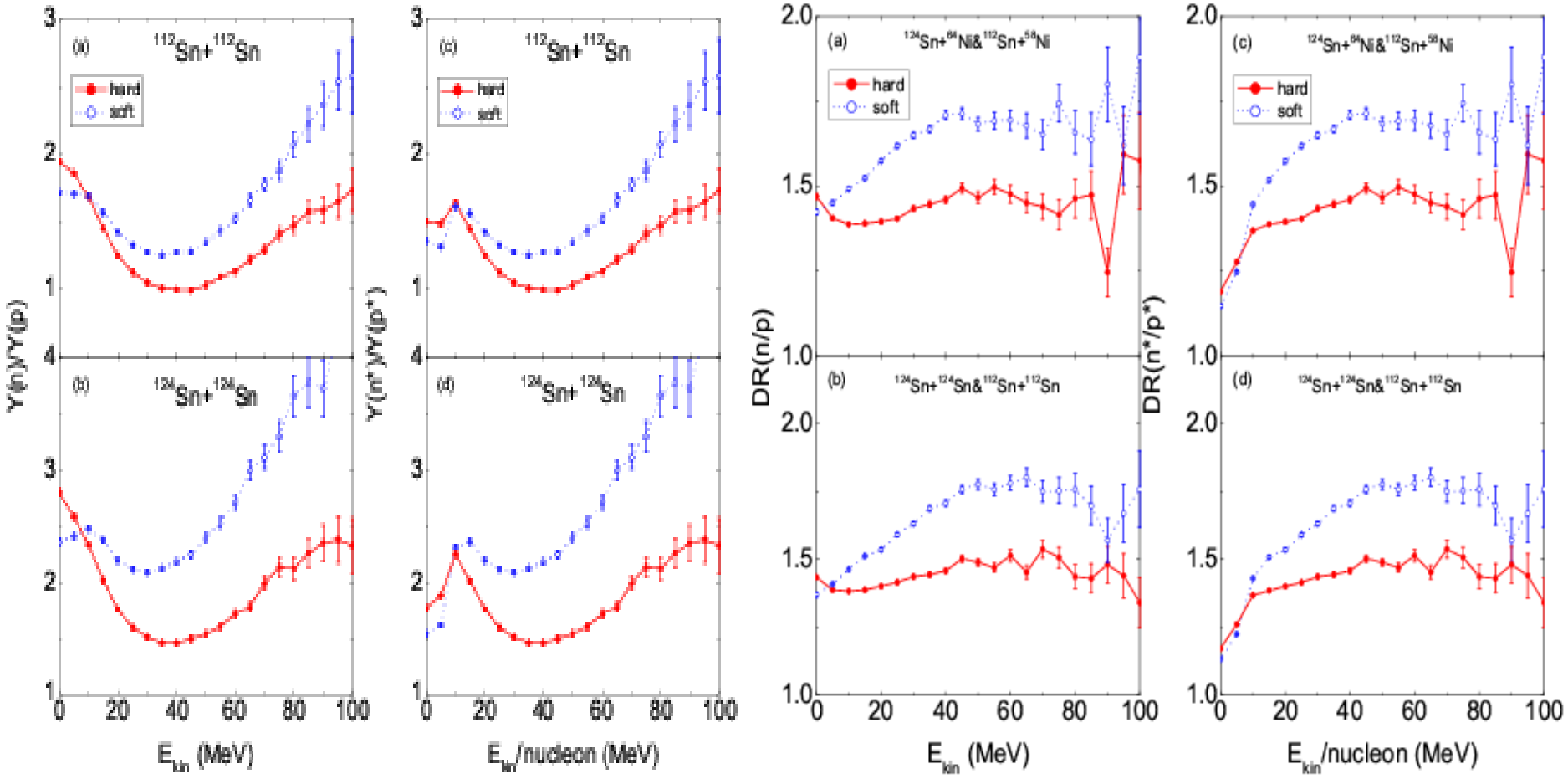
Sensitive to symmetry energy!

Independent on mass splitting!

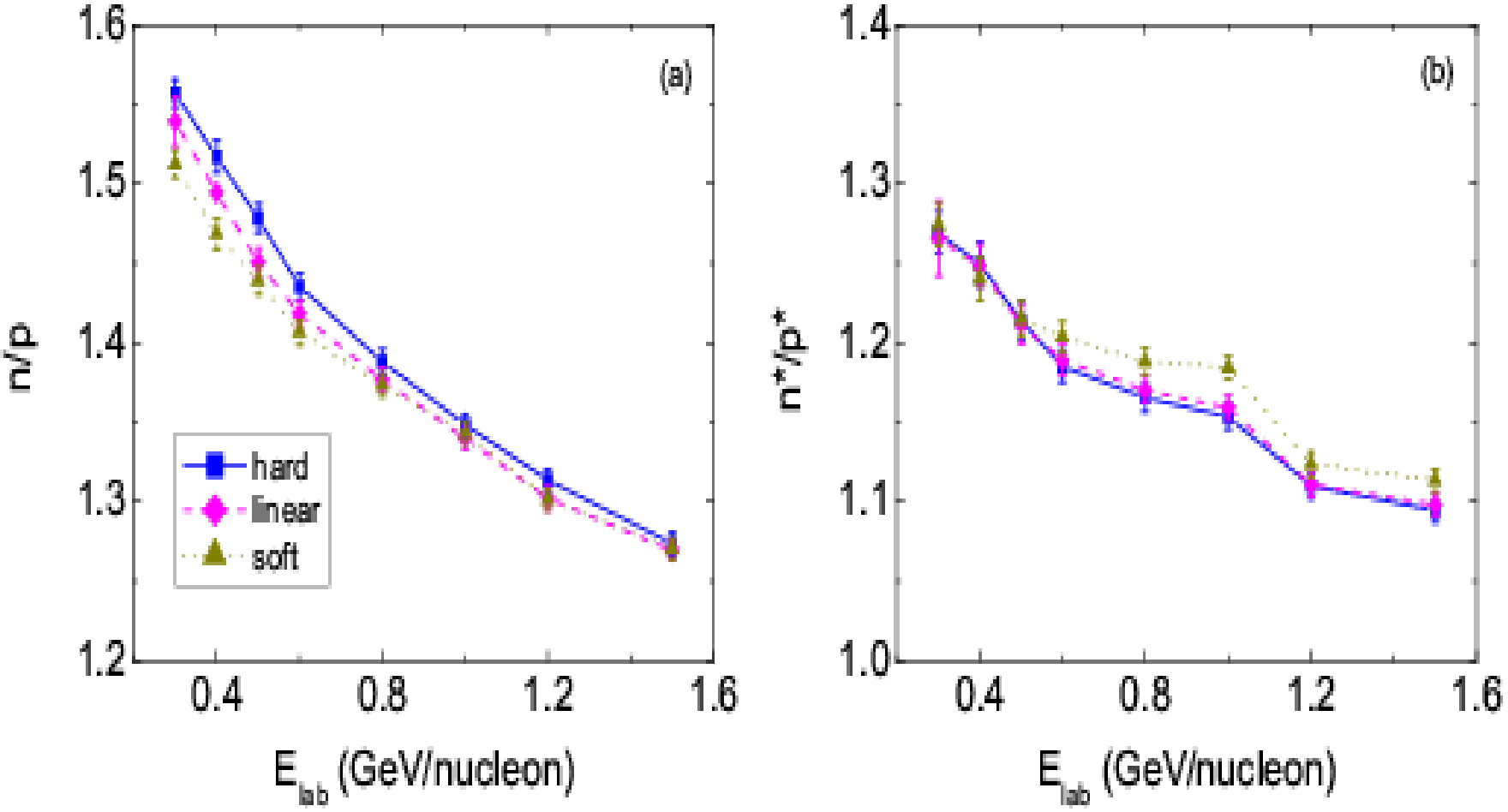


Comparison to the Fermi-energy HICs within the rapidity bin of $|y/y_{proj}| < 0.2$: 35 *A* MeV

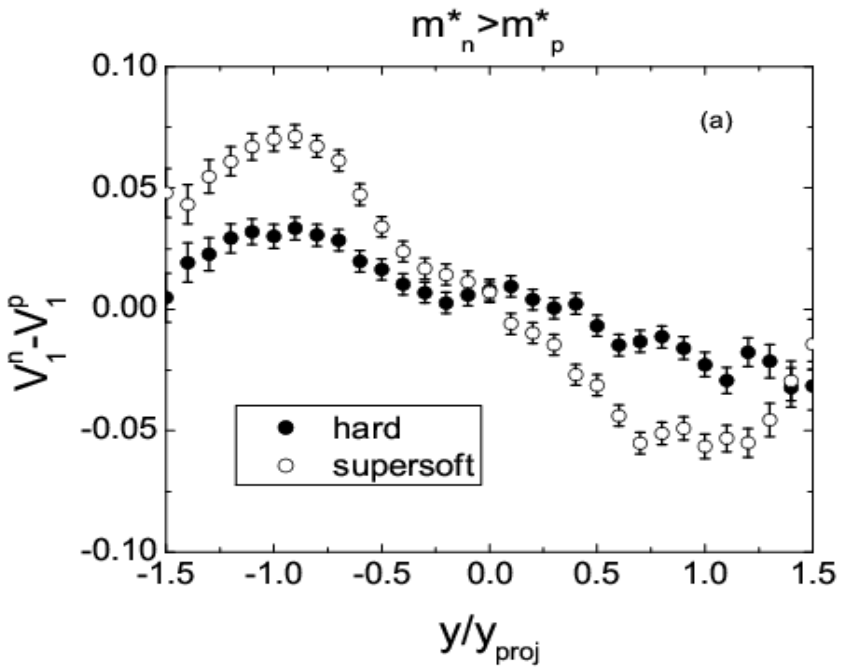
Z. Q. Feng, arXiv: 1603.07138 (Phys. Rev. C submitted)

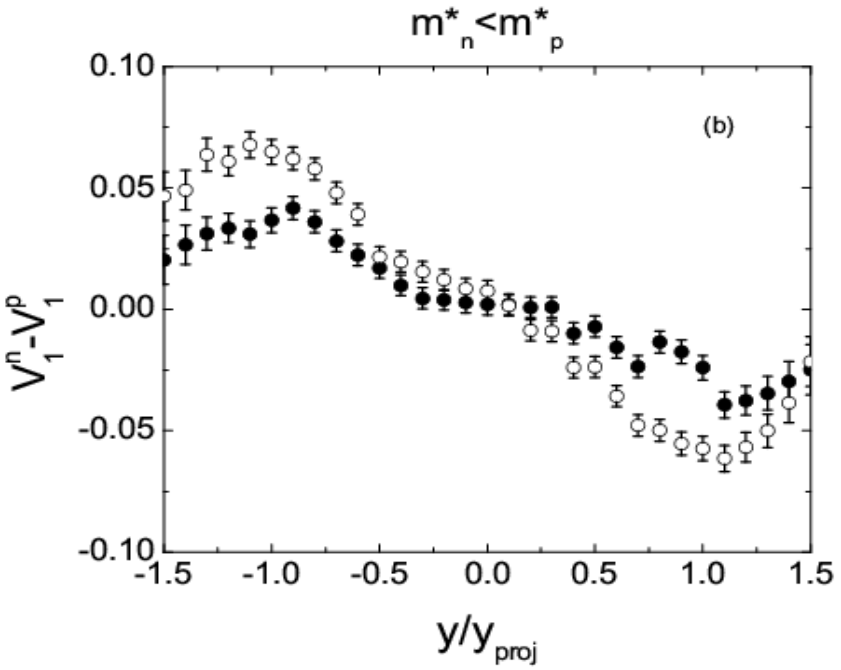


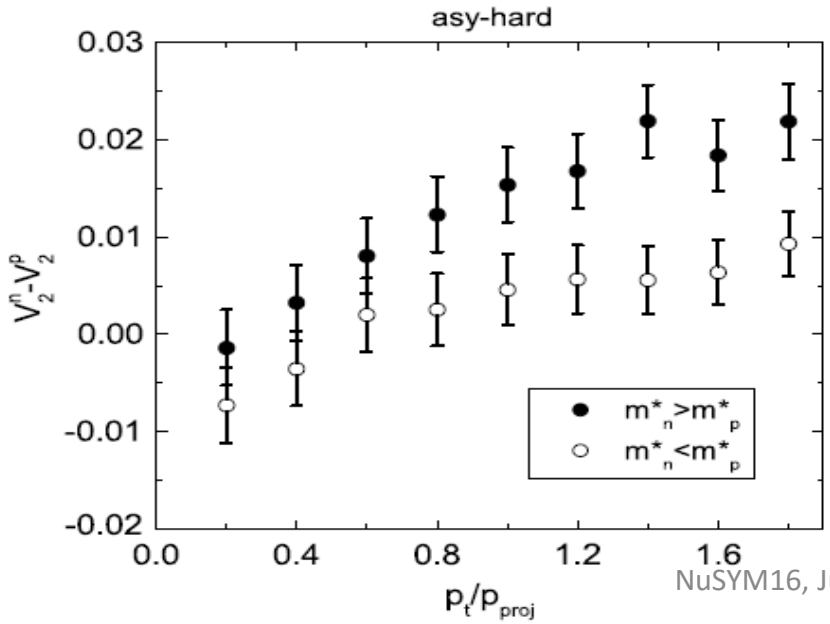
The n/p of free nucleons and light fragments within the rapidity bin of $|y/y_{proj}| < 0.2$ and within the azimuthal angles of $70^o \sim 110^o$ and $250^o \sim 290^o$ in ^{197}Au+^{197}Au & 300 *A* MeV

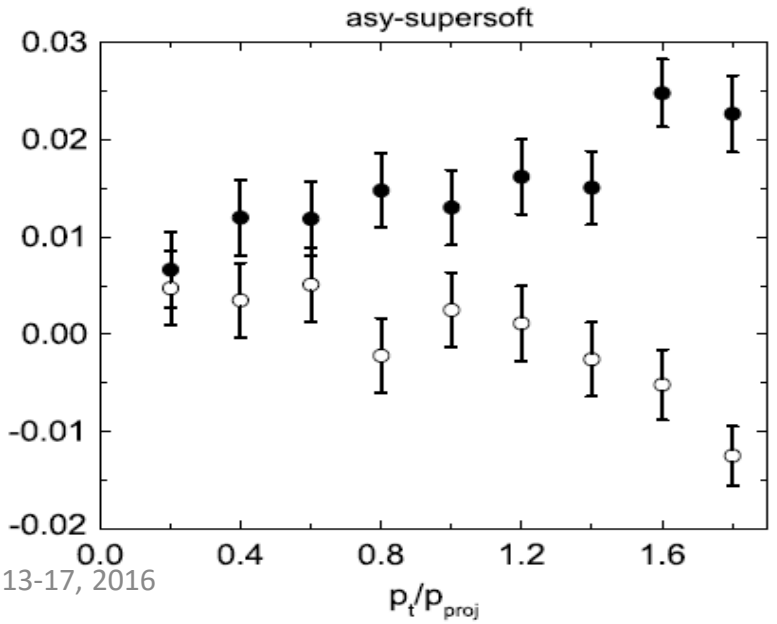


^{197}Au+^{197}Au@400 MeV/nucleon, b=6 fm (Zhao-Qing Feng, Nuclear Physics A 878 (2012) 3-13)



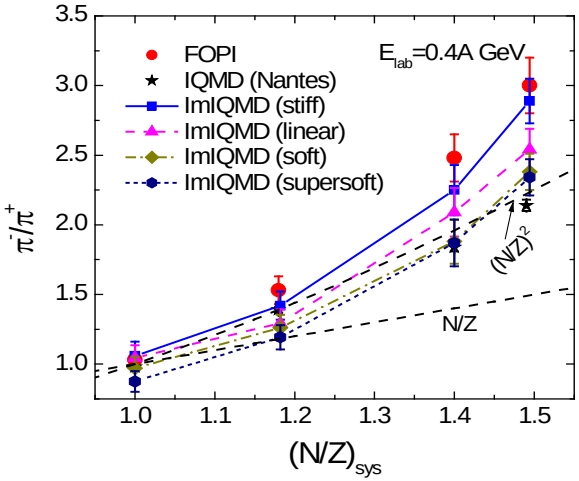


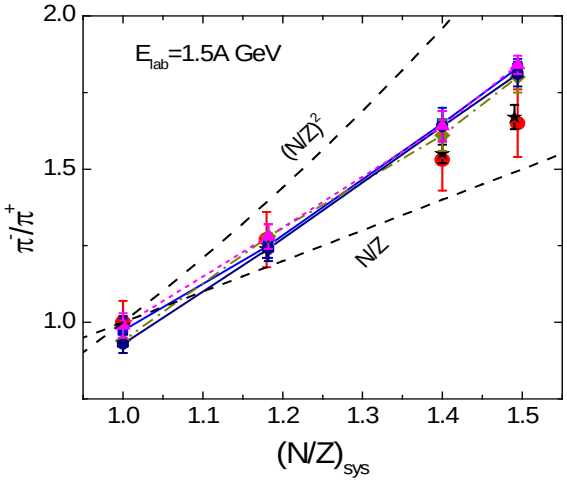




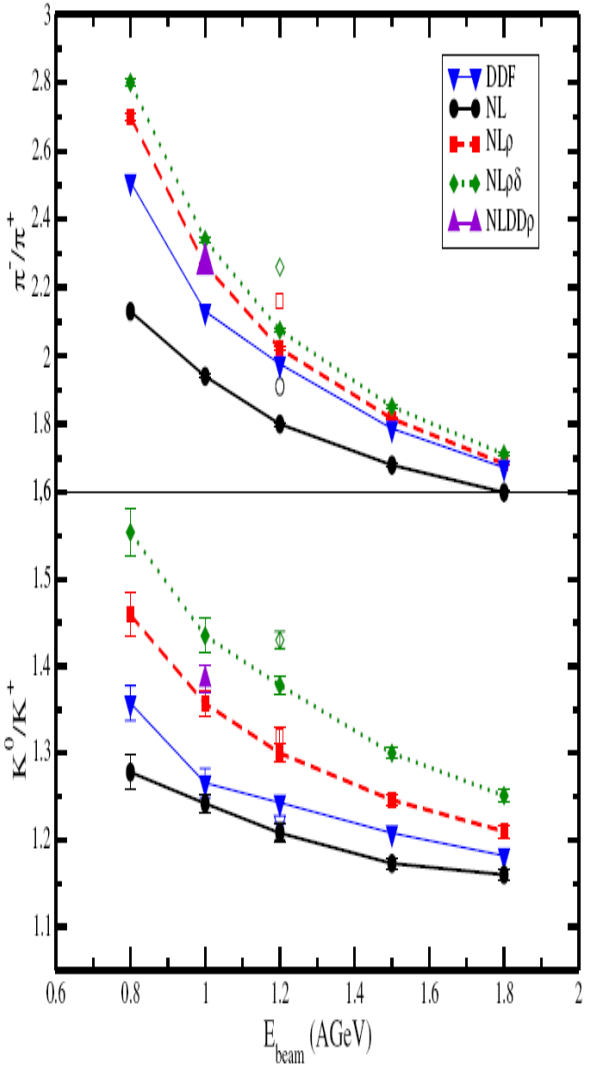
2. Pion production near threshold energies in heavy-ion collisions

LQMD: Phys. Lett. B 683 (2010) 140

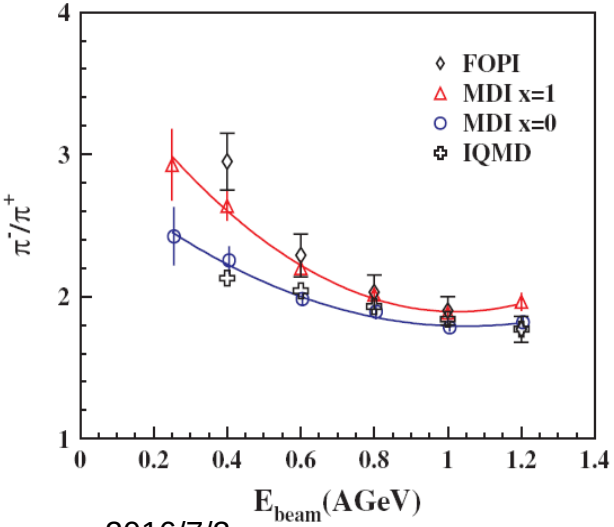


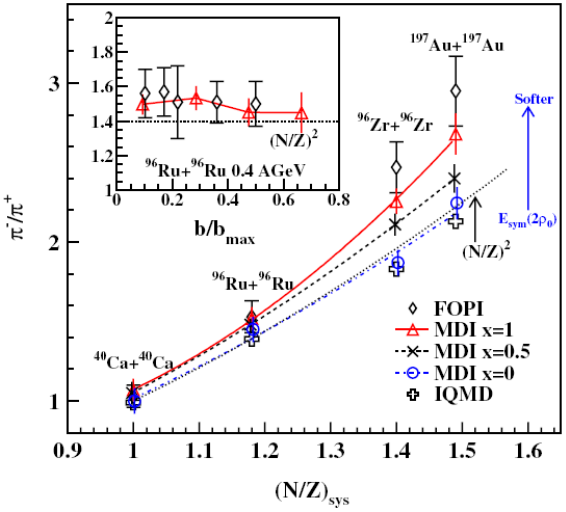


RBUU: PRL97 (2006) 202301



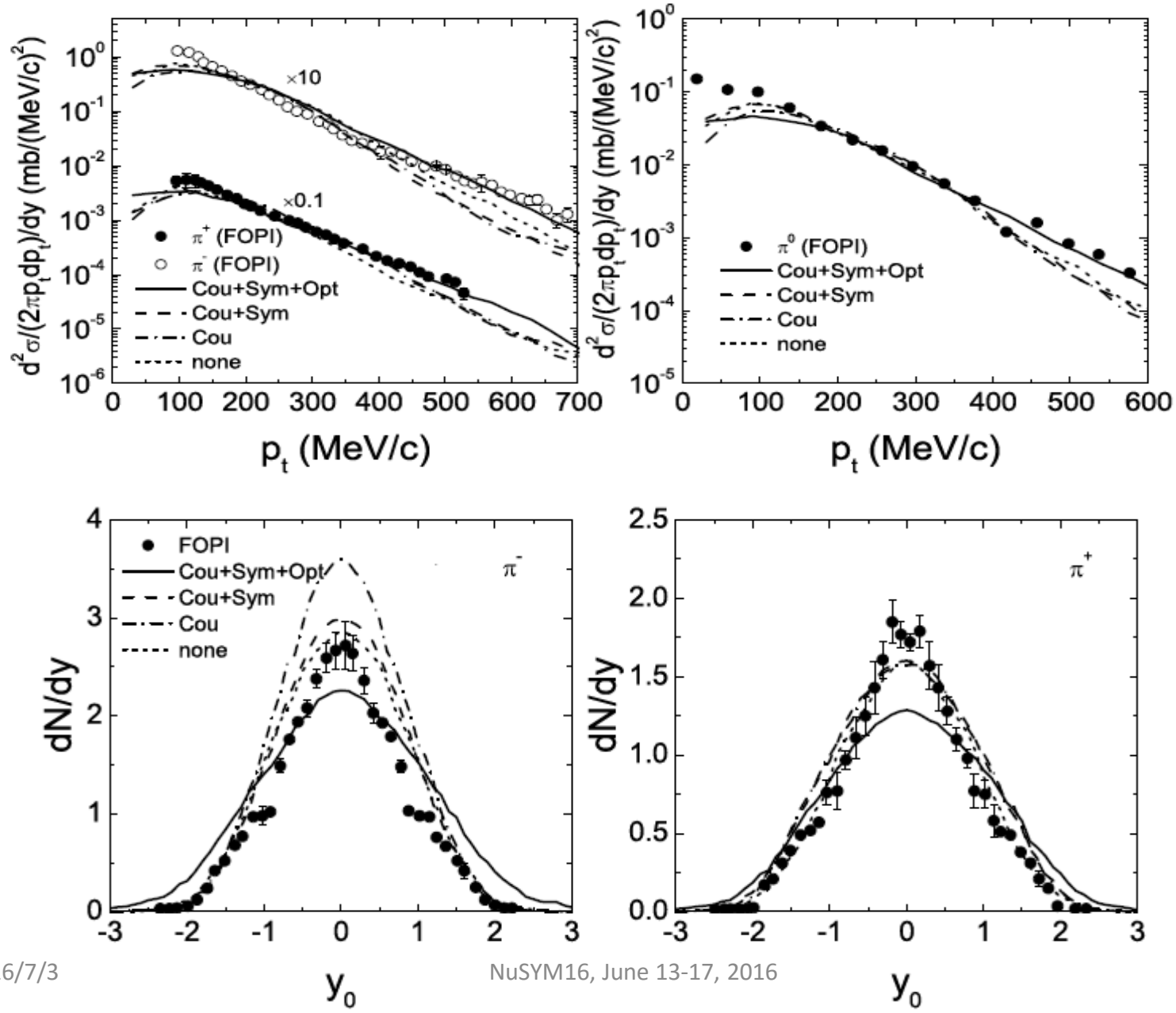
IBUU04: PRL102(2009)062502





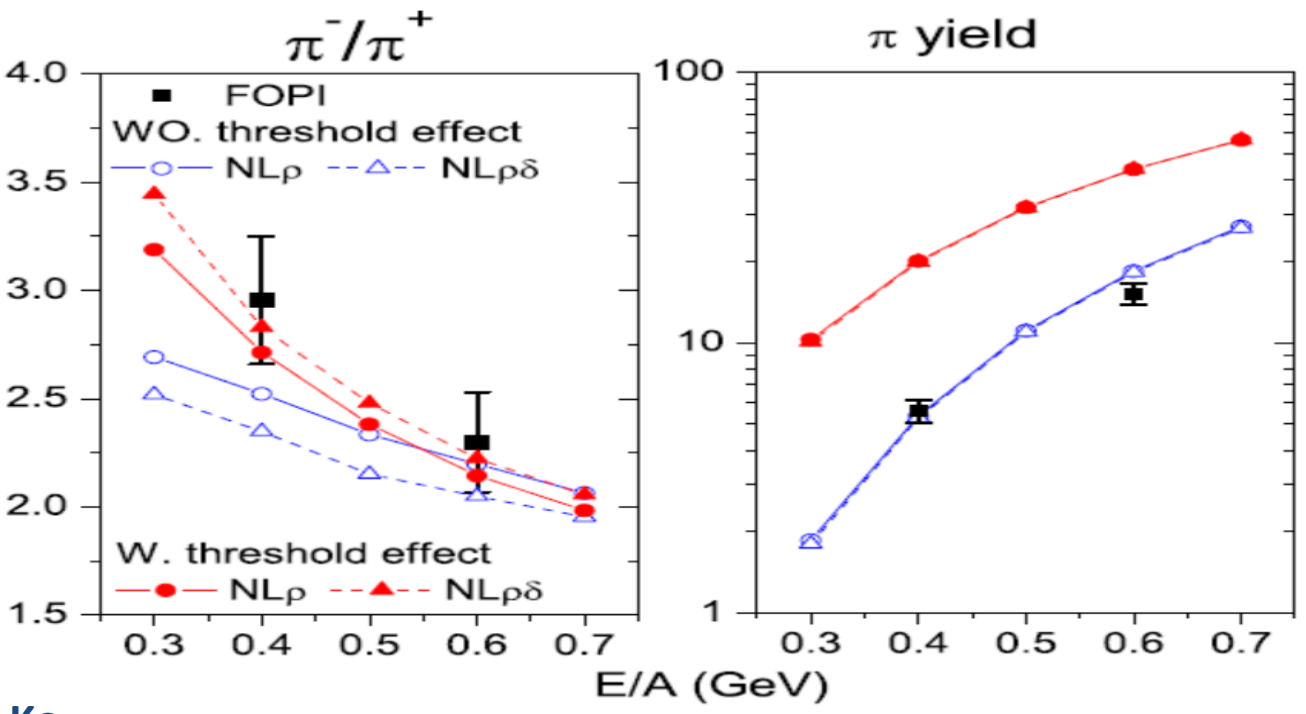
Pion dynamics in Au+Au collisions at 1A GeV, πN potential@SE

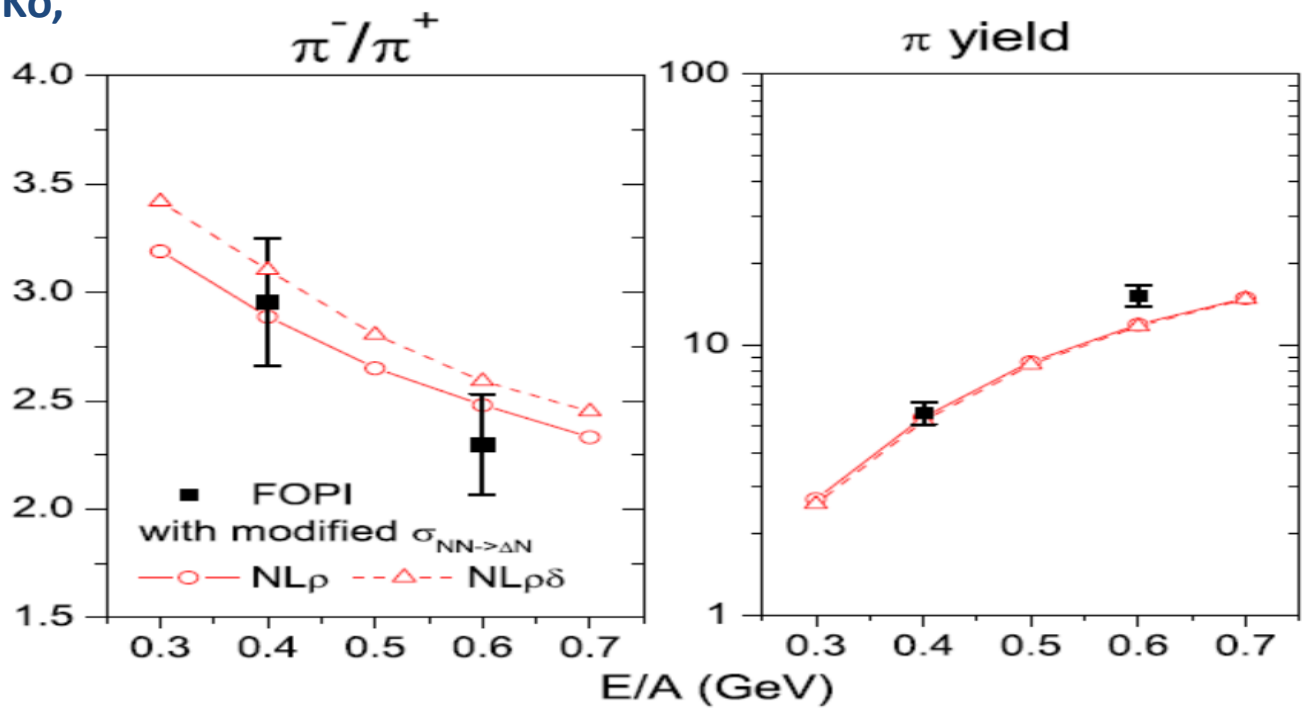
Z. Q. Feng, G. M. Jin, Phys. Rev. C 82 (2010) 044615



Threshold effects of Δ production!

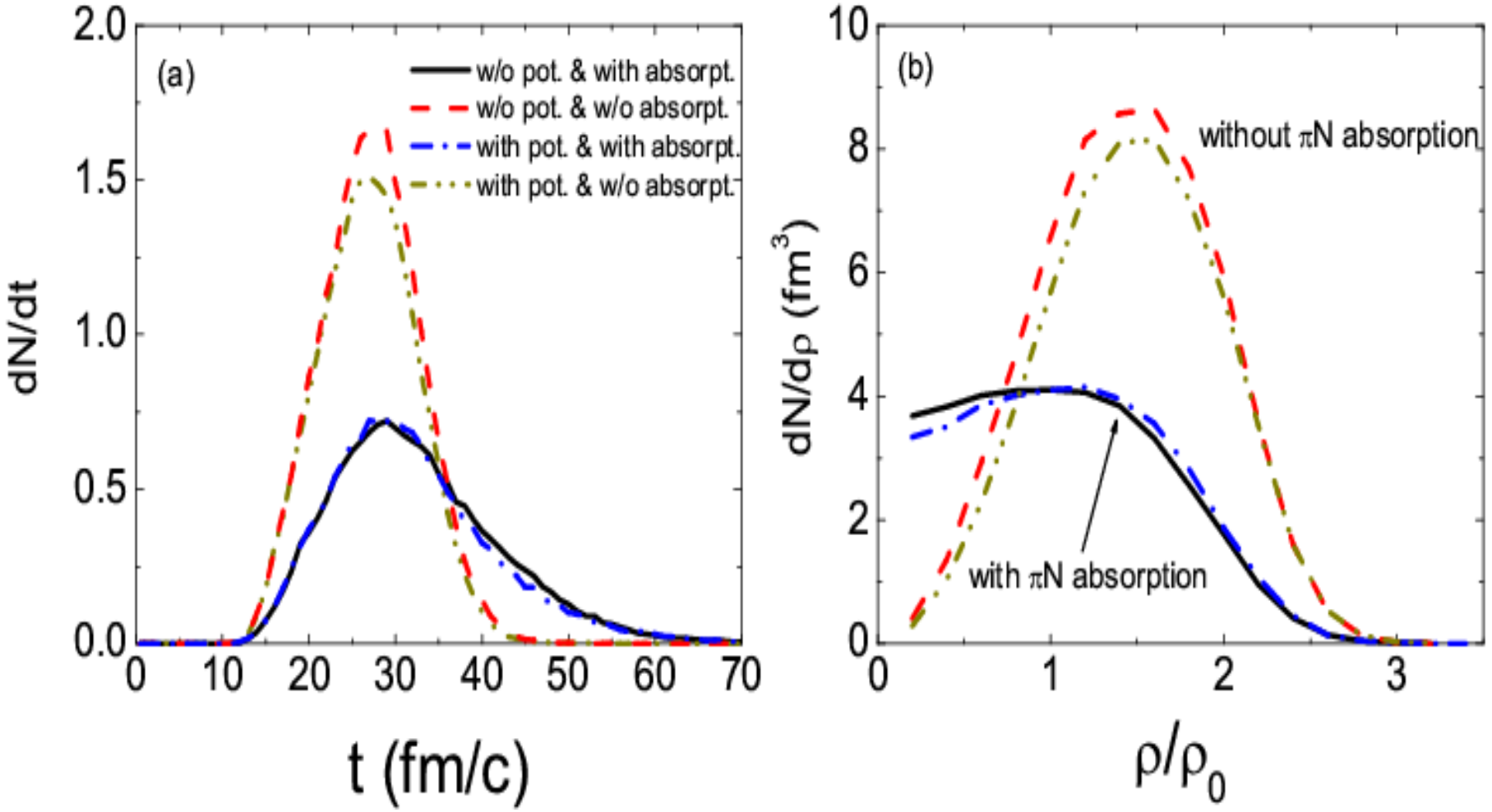
Taesoo Song, Che Ming Ko, Phys. Rev. C 91, 014901 (2015)





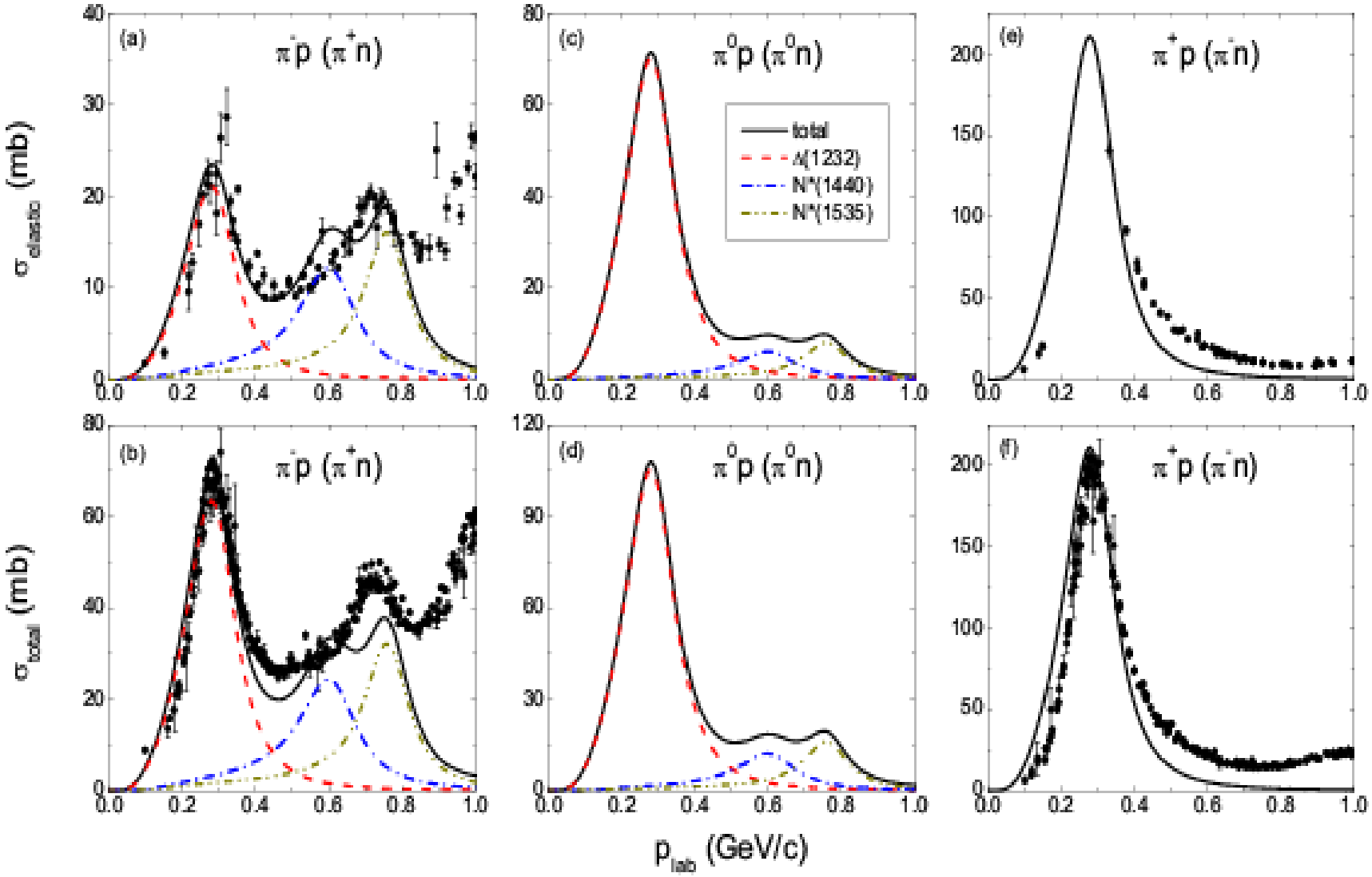
Production rate and density profiles of pions in ^{197}Au+^{197}Au & 300 *A* MeV

Z. Q. Feng, arXiv: 1606.01083 (Phys. Rev. C submitted)



Pion-nucleon scattering cross sections

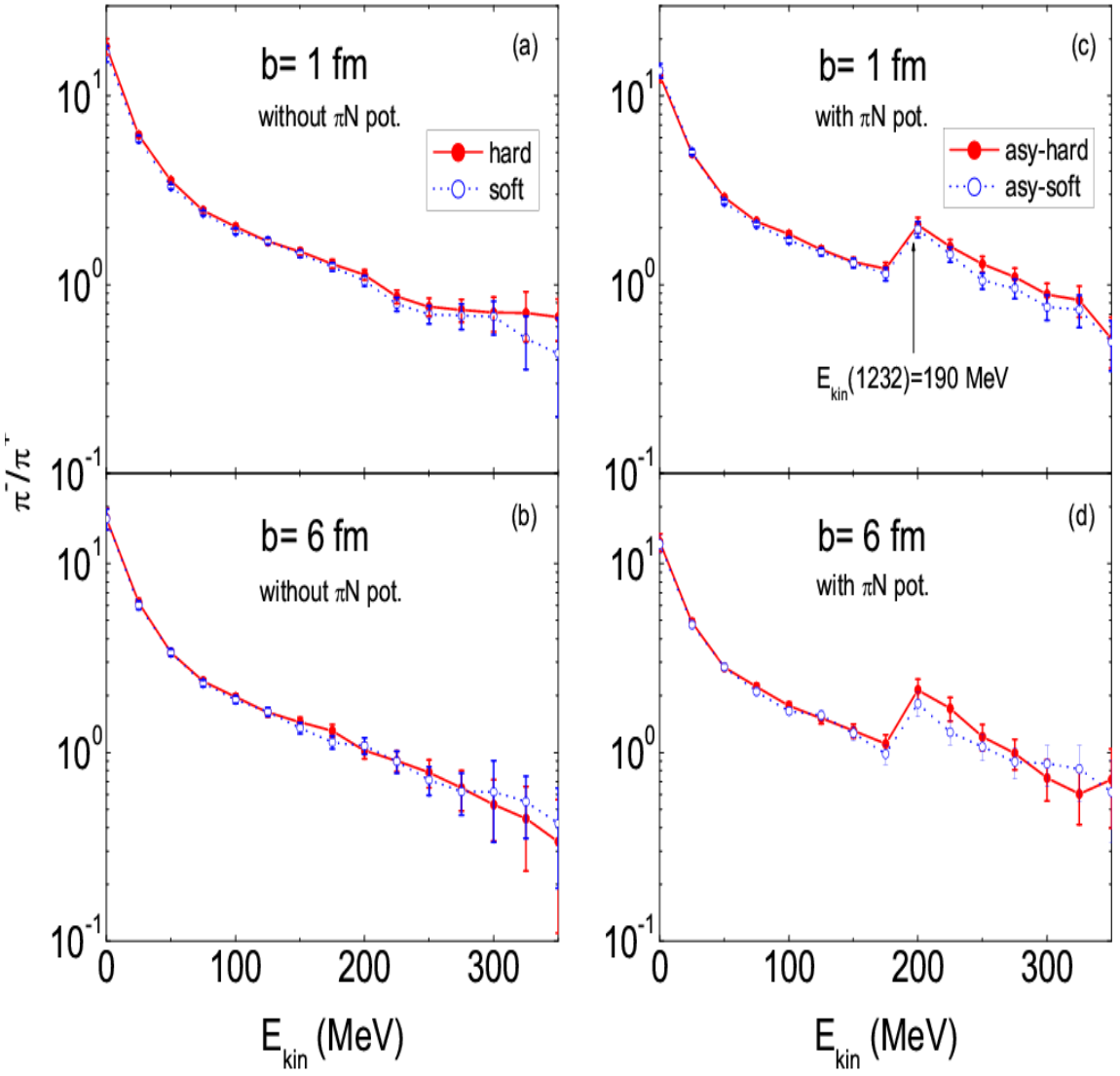
K. A. Olive, et al. (Particle Data Group), *Chin. Phys. C* 38, 090001 (2014)

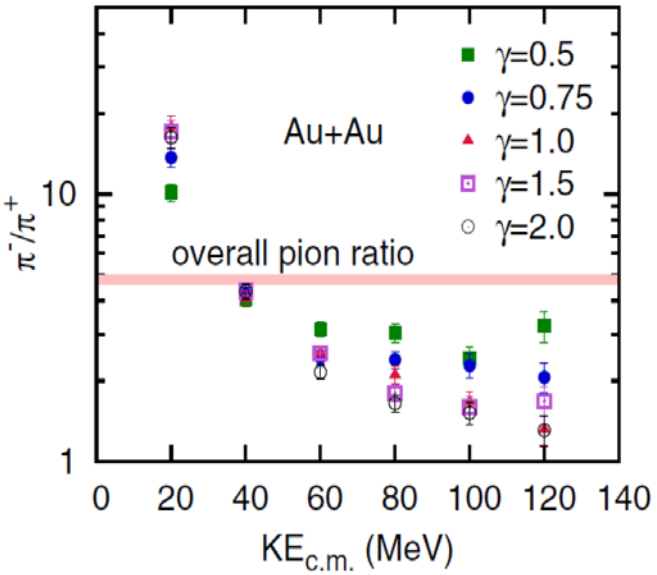


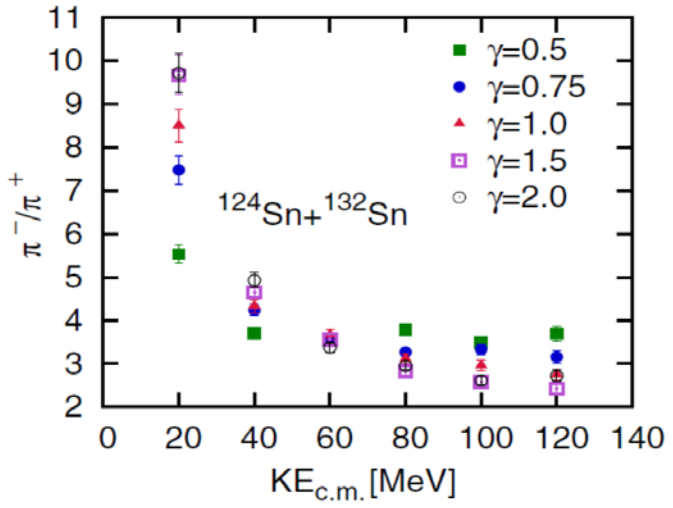
Z. Q. Feng, arXiv: 1606.01083 LQMD

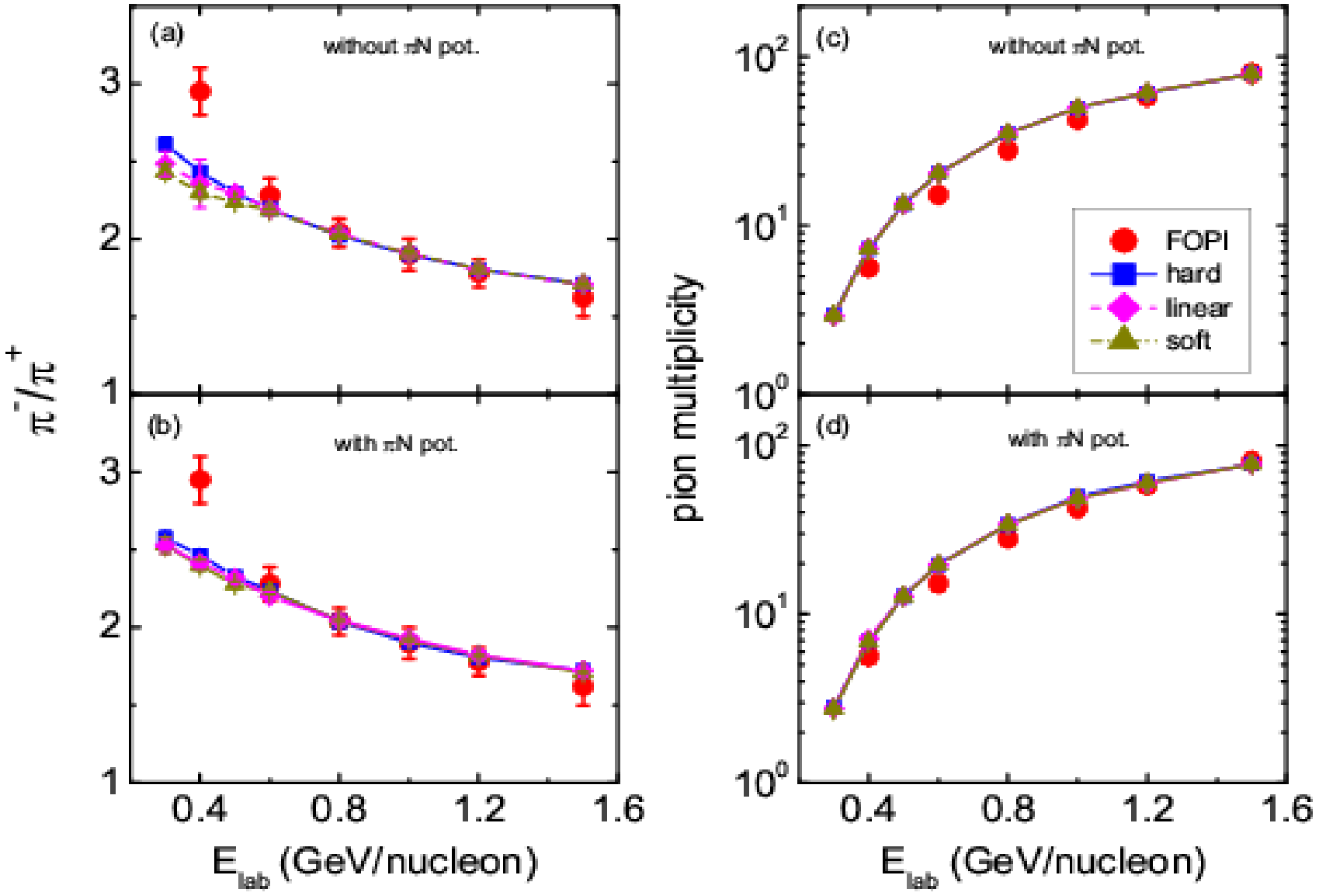
$^{197}Au+^{197}Au$ @ E_{lab} = 300 MeV/nucleon

Jun Hong and P. Danielewicz, Phys. Rev. C 90, 024605 (2014) pBUU



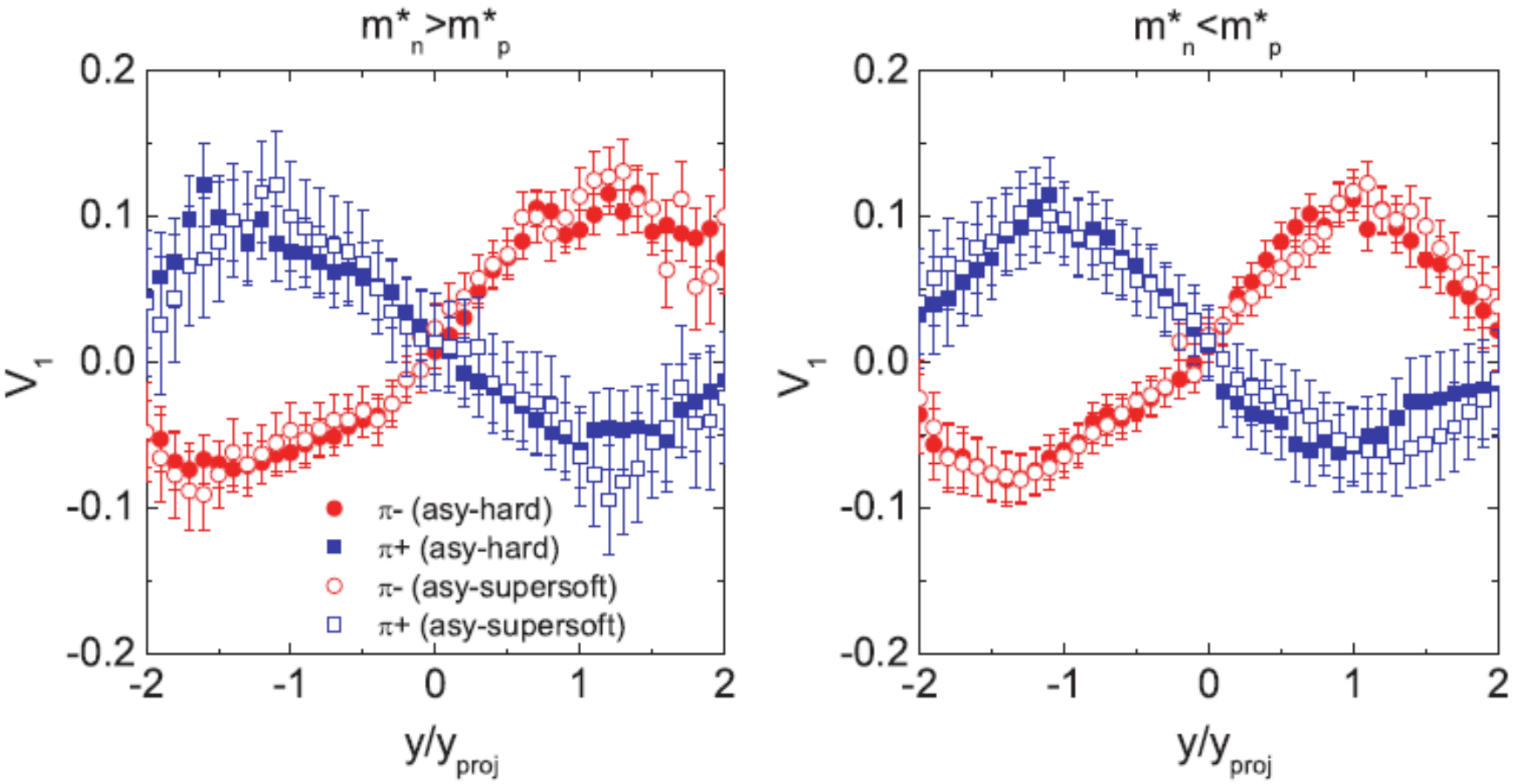





(a)
without πN pot.
(b)
with πN pot.
π^-/π^+
E_{lab} (GeV/nucleon)
(c)
without πN pot.
(d)
with πN pot.
pion multiplicity
FOPI
hard
linear
soft
E_{lab} (GeV/nucleon)

Directed flows of charged pions in the $^{197}Au+^{197}Au$ reaction at an incident energy of 400 *A MeV for semi-central (b = 6 fm) collisions*

Zhao-Qing Feng, Phys. Rev. C 85, 014604 (2012)



Impact factors on the pion dynamics in heavy-ion collisions near threshold energies:

1. Threshold energy corrections (Δ-nucleon potential)

2. pion-nucleon potential

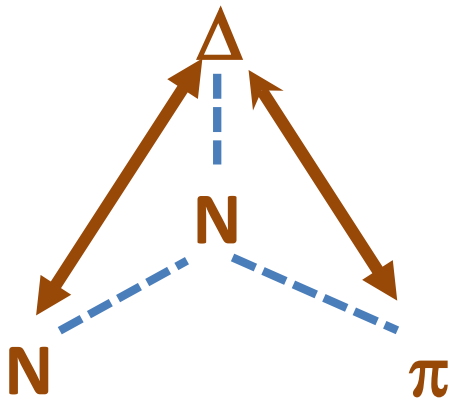
3. Reabsorption of Δ by surrounding nucleons

4. Reabsorption of pions by surrounding nucleons

5. In-medium decay width of Δ

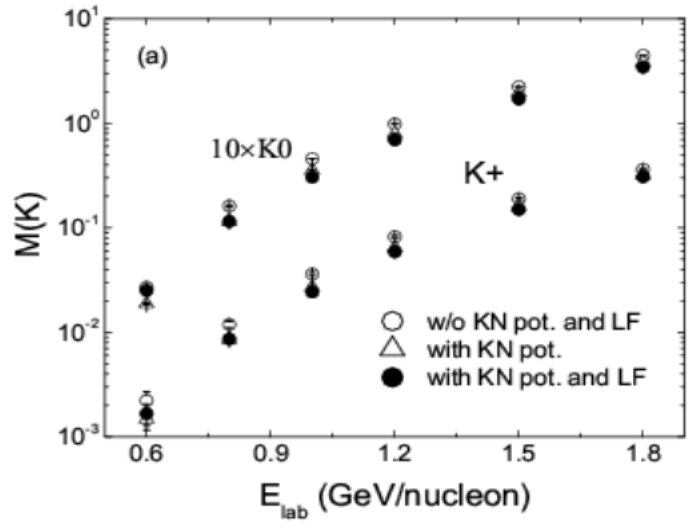
6. Elastic scattering between Δ and nucleons

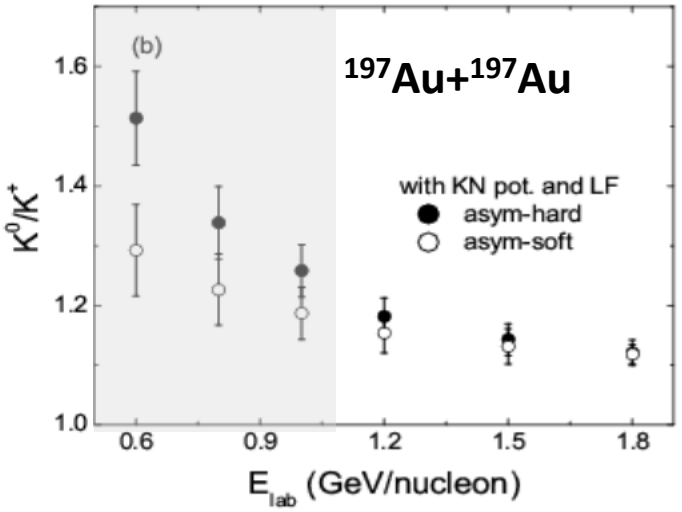
…

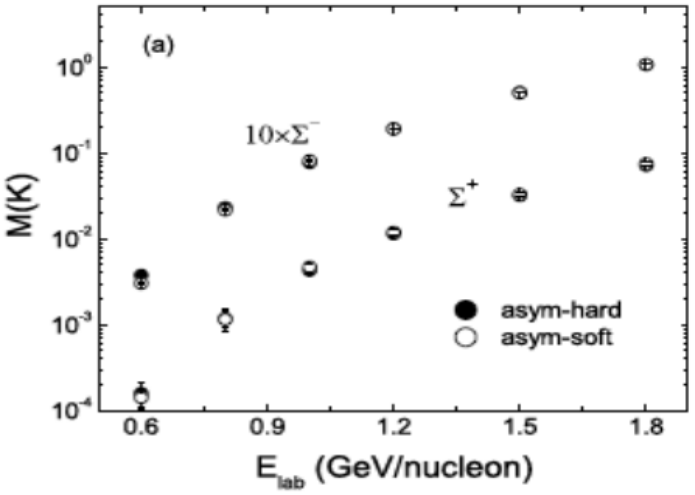


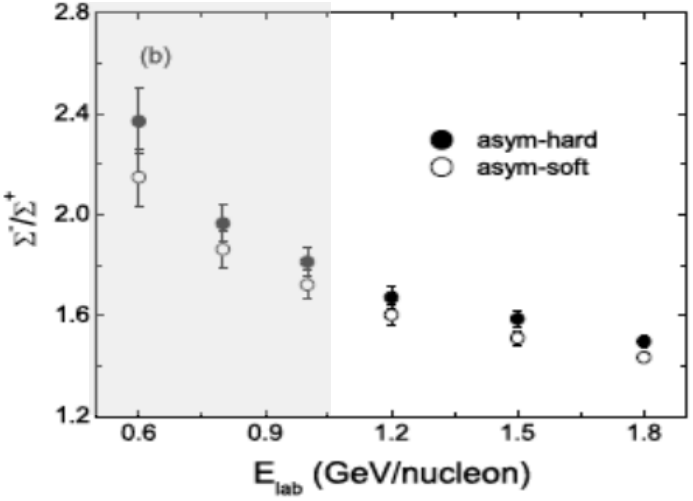
3. Strangeness production

Z. Q. Feng, Nucl. Phys. A 919 (2013) 32-45









VI. Summary

- Nucleons squeezed out in nucleus-nucleus collisions are sensitive to the stiffness of symmetry energy, in particular P_T distribution of n/p and double ratio, flow difference could be a nice experimental observables.
- The π^-/π^+ ratio as probes of the high-density symmetry energy is related to the in-medium properties of π and Δ, e.g., mean-field potentials, production and reabsorption cross sections etc.


Thanks for your attention