In-medium threshold effects on charged pion ratio in HIC

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- Introduction
  - Symmetry energy effects
  - Pion potential effects
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- Pion production in transport models
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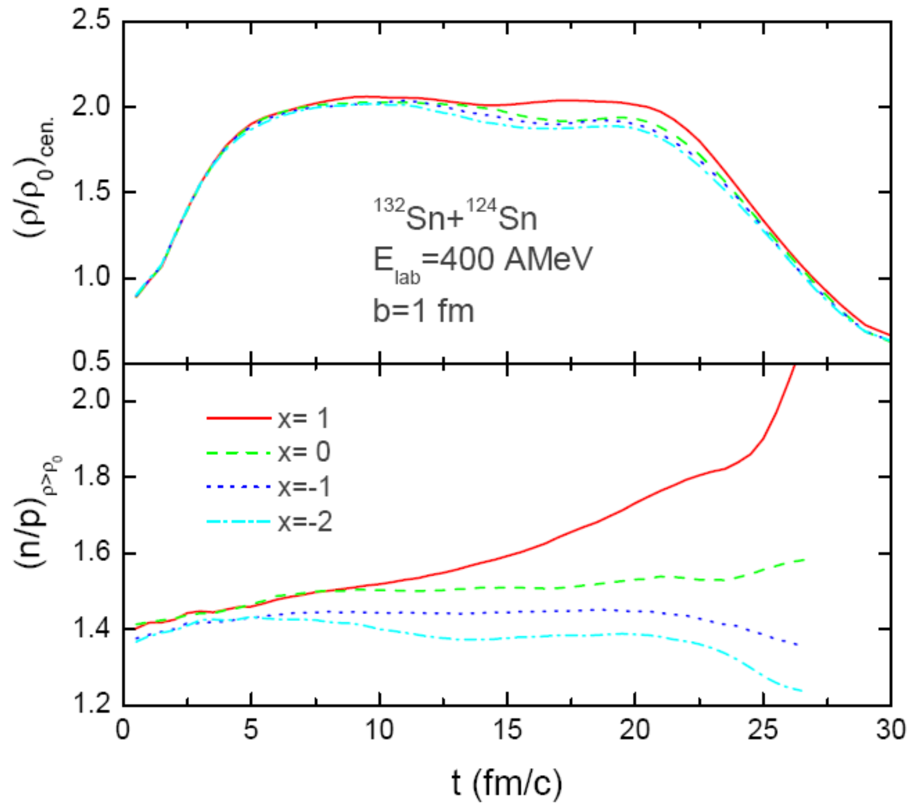
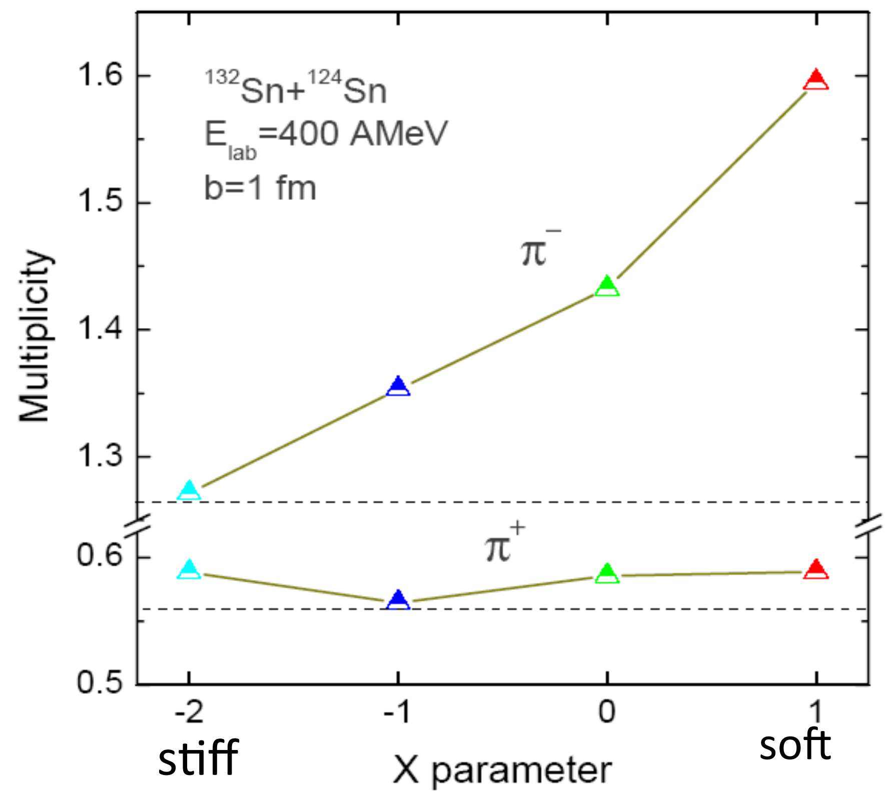
Based on work in collaboration with **Taesoo Song**
[PRC 91, 014901 (2015)]

Supported by US Department of Energy and the Welch Foundation

Near-threshold pion production with high energy radioactive beams (IBUU)

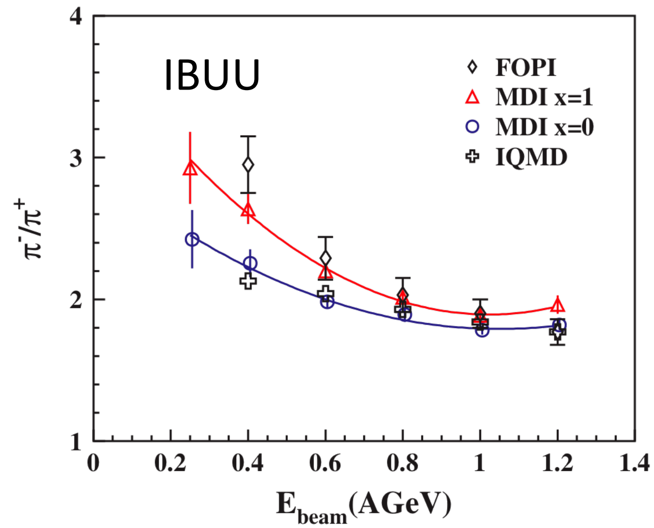
B. A. Li, PRL 88, 192701 (2002)



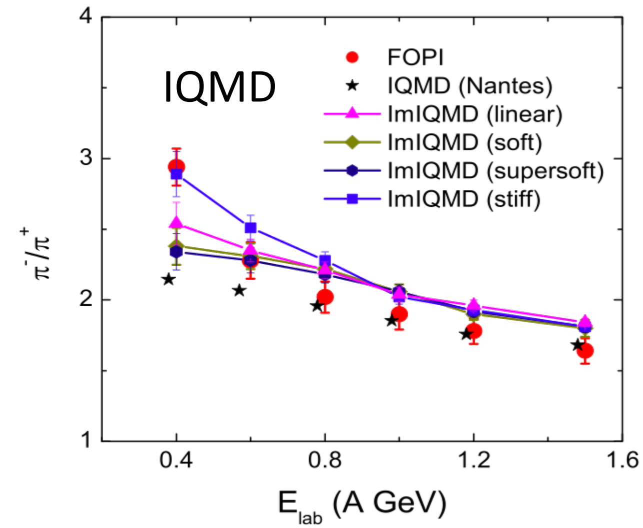


π^- yield is sensitive to the symmetry energy $E_{sym}(\rho)$ since they are mostly produced in the neutron-rich region, with softer one (x=1) giving more π^- than stiffer one (x=-1).

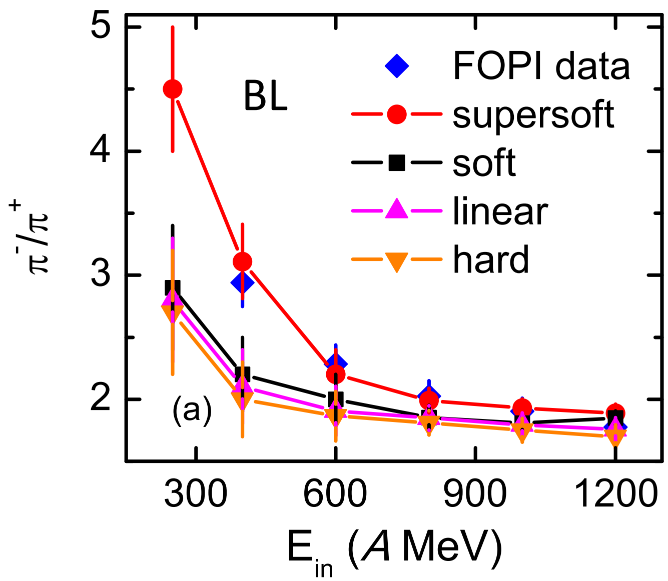
Conflicting results on symmetry energy from charged pion ratio



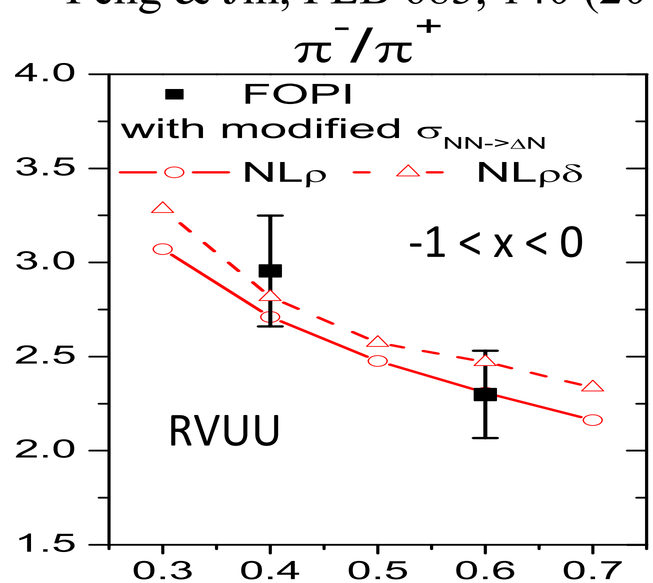
Xiao et al, PRL 102, 062502 (2009)



Feng & Jin, PLB 683, 140 (2010)



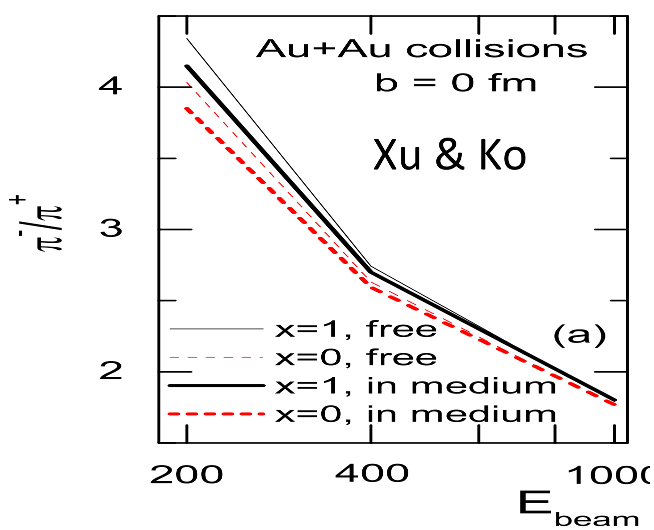
Shi et al., PLB 718, 1510 (2013)

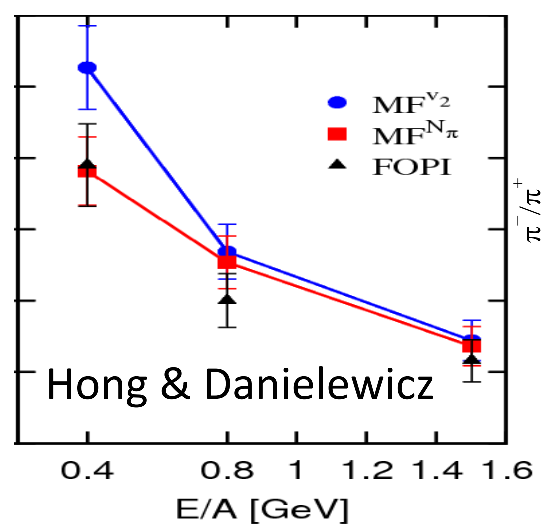


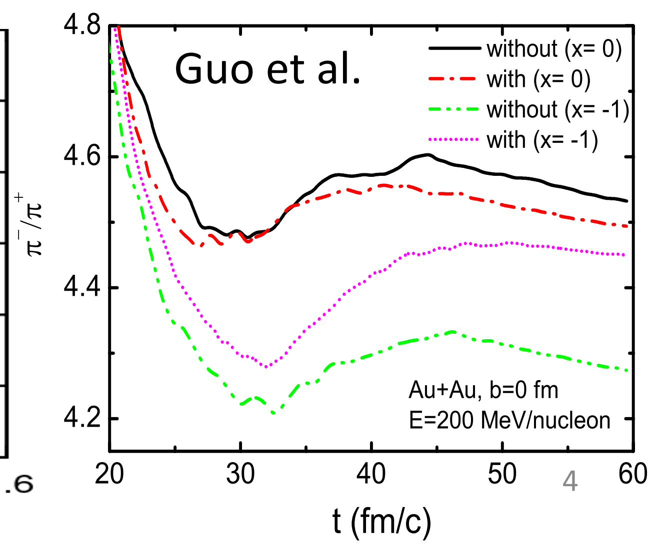
Song & Ko, PRC 91, 014901 (2015)

Pion potential effects on charged pion ratio

- Xu & Ko, PRC 81, 024910 (2010); Xu, Chen, Ko, Li & Ma, PRC 87, 067601 (2013): Thermal model → Including both pion s- and p-wave interactions, which have opposite effects, decreases the π^-/π^+ ratio.
- Hong and Danielewicz, PRC 90, 024605 (2014): pBUU → π^-/π^+ ratio is insensitive to stiffness of symmetry energy after including pion s-wave potential.
- Guo, Yong, Liu & Zuo, PRC 91, 054616 (2015): IBUU → pion s- and p-wave potentials and symmetry potential have opposite effects. (p-wave potential essentially vanishes in this study because of average over the pion and Delta-hole branches.)
- Feng, arXiv:1606.01083 [nucl-th]: LQMD → similar to Guo et al.







In-medium threshold effects on pion production

$$U_{asy}^{\Delta^{++}} = U_{asy}^{p}, \quad U_{asy}^{\Delta^{+}} = \frac{2}{3}U_{asy}^{p} + \frac{1}{3}U_{asy}^{n}, \quad U_{asy}^{\Delta^{0}} = \frac{1}{3}U_{asy}^{p} + \frac{2}{3}U_{asy}^{n}, \quad U_{asy}^{\Delta^{-}} = U_{asy}^{n}$$

- $pn \rightarrow p\Delta^0$

  Initial-state potential: U_p+U_n

  Final-state potential: $U_p+U_{\Delta 0}=U_p+U_p/3+2/3U_n$

  $\rightarrow$ difference in initial and final potentials: $(U_n-U_p)/3>0$ in neutron-rich matter

  $\rightarrow$ reduced production threshold

- First studied by Ferini, Colonna, Gaitanos and Di Toro (NPA 762, 147 (2005)) in a relativistic transport model

Nonlinear relativistic mean-field model

$$
\begin{aligned}
L &= \bar{N}\Big[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu - g_\rho\boldsymbol{\tau}\cdot\boldsymbol{\rho}^\mu) - (m_N - g_\sigma\sigma - g_\delta\boldsymbol{\tau}\cdot\boldsymbol{\delta})\Big]N \\
&+ \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{a}{3}\,\sigma^3 - \frac{b}{4}\,\sigma^4 \\
&- \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}(\partial_\mu\boldsymbol{\delta}\partial^\mu\boldsymbol{\delta} - m_\delta^2\boldsymbol{\delta}\cdot\boldsymbol{\delta}) \\
&- \frac{1}{4}\boldsymbol{R}_{\mu\nu}\cdot\boldsymbol{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu
\end{aligned}
$$

$$
\Omega_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu, \quad \boldsymbol{R}_{\mu\nu} = \partial_\mu\boldsymbol{\rho}_\nu - \partial_\nu\boldsymbol{\rho}_\mu
$$

N: nucleon

σ: isoscalar scalar (m_σ = 550 MeV)

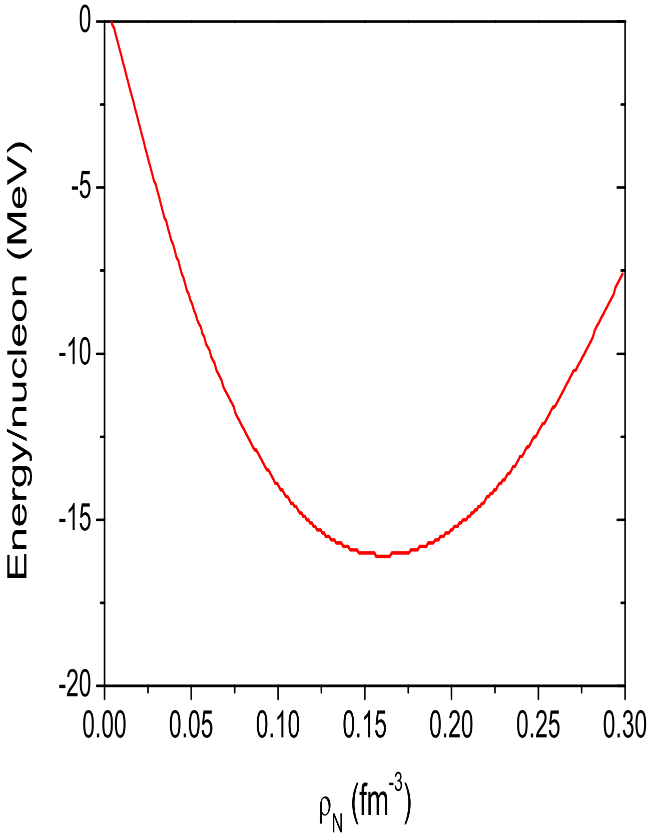
ω: isoscalar vector (m_ω = 782 MeV)

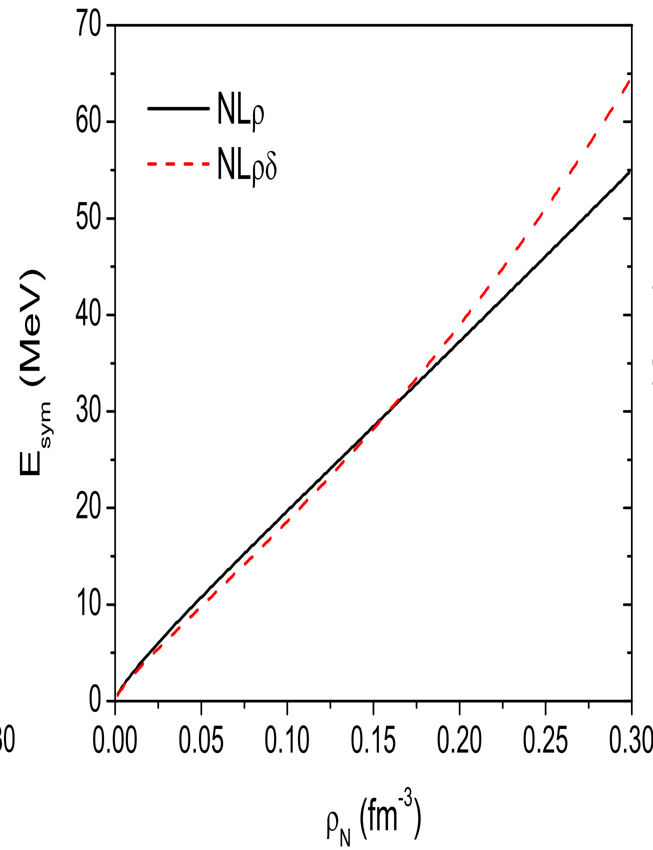
δ: isovector scalar (m_δ = 983 MeV)

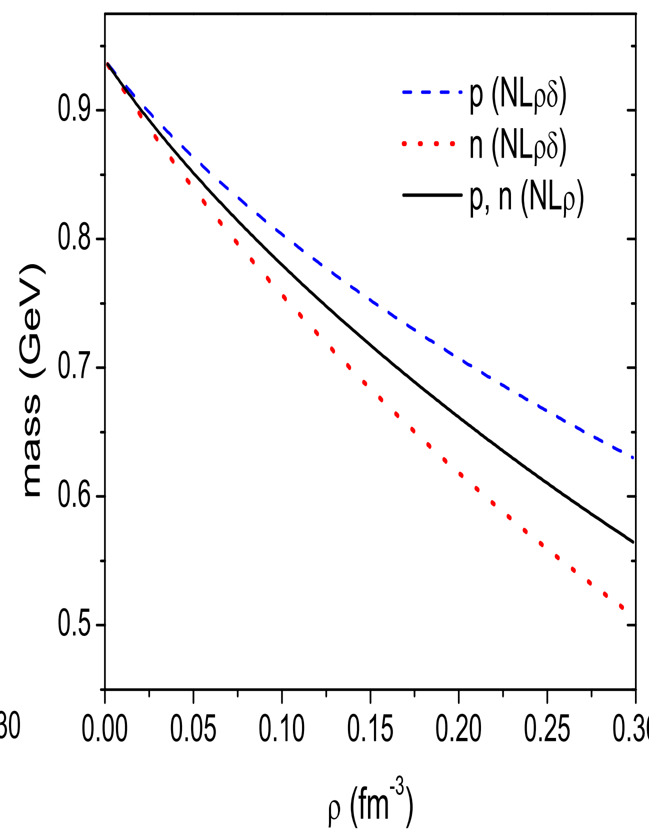
ρ: isovector vector (m_ρ = 769 MeV)

	$NL\rho$	$NL\rho\delta$
$f_i \equiv (g_i/m_i)^2$		
f_σ (fm^2)	10.33	
f_ω (fm^2)	5.42	
f_ρ (fm^2)	0.95	3.15
f_δ (fm^2)	0	2.5
a/g_σ^3 (fm^{-1})	0.033	
b/g_σ^4	-0.0048	

Nuclear matter properties in relativistic mean-field models







- Both give same EOS (K = 240 MeV).
- NLρδ (L = 98 MeV) has a stiffer symmetry energy than NLρ (L = 83 MeV); (-1 < x < 0).
- Proton has a larger effective mass than neutron in NLρδ.

Relativistic Vlasov-Uehling-Uhlenbeck model

Ko, NPA 495, 321 (1989)

$$\frac{\partial}{\partial t} f + \vec{v} \cdot \nabla_r f - \nabla_r H \cdot \nabla_p f = \mathcal{C}[f]$$

Mean-field potential $$H = \sqrt{m^{*2} + p^{*2}} + g_\omega \omega^0 \pm g_\rho (\rho_3)_0$$

Collisional integral $C[f]$ includes nucleon-nucleon elastic scattering NN → NN based on empirical cross sections as well as inelastic scattering NN → NΔ and its inverse reaction NΔ → NN using cross sections from the one-boson exchange model of Huber and Aichelin [NPA 573, 587 (1994)]

Delta resonances satisfy a similar RVUU equation with mean-field potentials related to those of nucleons via their isospin structures in terms of those of nucleons and pions

$$\begin{aligned}
m^*_{\Delta^{++}} &= m_\Delta - g_\sigma \sigma - g_\delta \delta_3, & p^{\mu *}_{\Delta^{++}} &= p^\mu_\Delta - g_\omega \omega^\mu - g_\rho \rho^\mu_3 \\
m^*_{\Delta^{+}} &= m_\Delta - g_\sigma \sigma - \frac{1}{3} g_\delta \delta_3, & p^{\mu *}_{\Delta^{+}} &= p^\mu_\Delta - g_\omega \omega^\mu - \frac{1}{3} g_\rho \rho^\mu_3 \\
m^*_{\Delta^{0}} &= m_\Delta - g_\sigma \sigma + \frac{1}{3} g_\delta \delta_3, & p^{\mu *}_{\Delta^{0}} &= p^\mu_\Delta - g_\omega \omega^\mu + \frac{1}{3} g_\rho \rho^\mu_3 \\
m^*_{\Delta^{-}} &= m_\Delta - g_\sigma \sigma + g_\delta \delta_3, & p^{\mu *}_{\Delta^{-}} &= p^\mu_\Delta - g_\omega \omega^\mu + g_\rho \rho^\mu_3, \\
m^2_\delta \delta_3 &= g_\sigma (\phi_p - \phi_n) & m^2_\rho \rho^\mu_3 &= g_\rho (j^\mu_p - j^\mu_n)
\end{aligned}$$

Medium modification of Delta production threshold

Threshold energy for NN → NΔ (1+2 → 3+4) is determined by requiring the kinetic momenta of final nucleon and Delta are zero in the frame where their total kinetic momentum vanishes ($\mathbf{p}_3^*+\mathbf{p}_4^*=0$)

$$\sqrt{s}_{\rm th} = \sqrt{(m_3^* + \Sigma_3^0 + m_4^* + \Sigma_4^0)^2 - |\mathbf{\Sigma}_3 + \mathbf{\Sigma}_4|^2}$$

where Σ^μ is vector self energy of nucleon or Delta. Since the initial energy of the two nucleons is

$$\sqrt{s_{\rm in}} = \sqrt{(E_1^* + \Sigma_1^0 + E_2^* + \Sigma_2^0)^2 - |\mathbf{\Sigma}_1 + \mathbf{\Sigma}_2|^2}$$

difference between the initial and threshold energies in static nuclear matter ($\mathbf{\Sigma}_i=0$, $\mathbf{p}_i^*\approx 0$) is

$$\sqrt{s}_{\rm in} - \sqrt{s}_{\rm th} \simeq E_1^* + E_2^* + \Sigma_1^0 + \Sigma_2^0 - m_3^* - m_4^* - \Sigma_3^0 - \Sigma_4^0$$

In nonrelativistic limit

$$\begin{aligned}\sqrt{s}_{\rm in} - \sqrt{s}_{\rm th} &\simeq m_1 + m_2 - m_3 - m_4 + \Sigma_1^s + \Sigma_2^s - \Sigma_3^s - \Sigma_4^s \\ &+ \frac{|\mathbf{p_1^*}|^2}{2m_1^*} + \frac{|\mathbf{p_2^*}|^2}{2m_2^*} + \Sigma_1^0 + \Sigma_2^0 - \Sigma_3^0 - \Sigma_4^0\end{aligned}$$

Initial and final scalar and vector mean-field differences in Delta production from nucleon-nucleon scattering

	$\Sigma_1^s + \Sigma_2^s - \Sigma_3^s - \Sigma_4^s$	$\Sigma_1^\mu + \Sigma_2^\mu - \Sigma_3^\mu - \Sigma_4^\mu$
$pp \to n\Delta^{++}$	$-2g_\delta\delta_3$	$2g_\rho\rho_3^\mu$
$pp \to p\Delta^{+}$	$-(2/3)g_\delta\delta_3$	$(2/3)g_\rho\rho_3^\mu$
$pn \to n\Delta^{+}$	$-(2/3)g_\delta\delta_3$	$(2/3)g_\rho\rho_3^\mu$
$pn \to p\Delta^{0}$	$(2/3)g_\delta\delta_3$	$-(2/3)g_\rho\rho_3^\mu$
$nn \to n\Delta^{0}$	$(2/3)g_\delta\delta_3$	$-(2/3)g_\rho\rho_3^\mu$
$nn \to p\Delta^{-}$	$2g_\delta\delta_3$	$-2g_\rho\rho_3^\mu$

- Since δ_3 and ρ_3^0 are negative in neutron-rich matter, changes in isovector scalar mean fields enhance Δ^{++} and Δ^+ production and suppress Δ^0 and Δ^- production, while changes in isovector vector mean fields have an opposite effect.
- Since $\delta_3 = 0$ in NLρ, Δ^{++} and Δ^+ are suppressed while Δ^0 and Δ^- are enhanced.
- Since difference in isovector scalar fields is smaller than that in isovector vector fields and the net difference in NLρδ is larger than the difference in NLρ, Δ^{++} and Δ^+ are more suppressed while Δ^0 and Δ^- are more enhanced in NLρδ (stiffer symmetry energy) than in NLρ (softer symmetry energy).

Initial and final scalar and vector mean-field difference in Delta decay

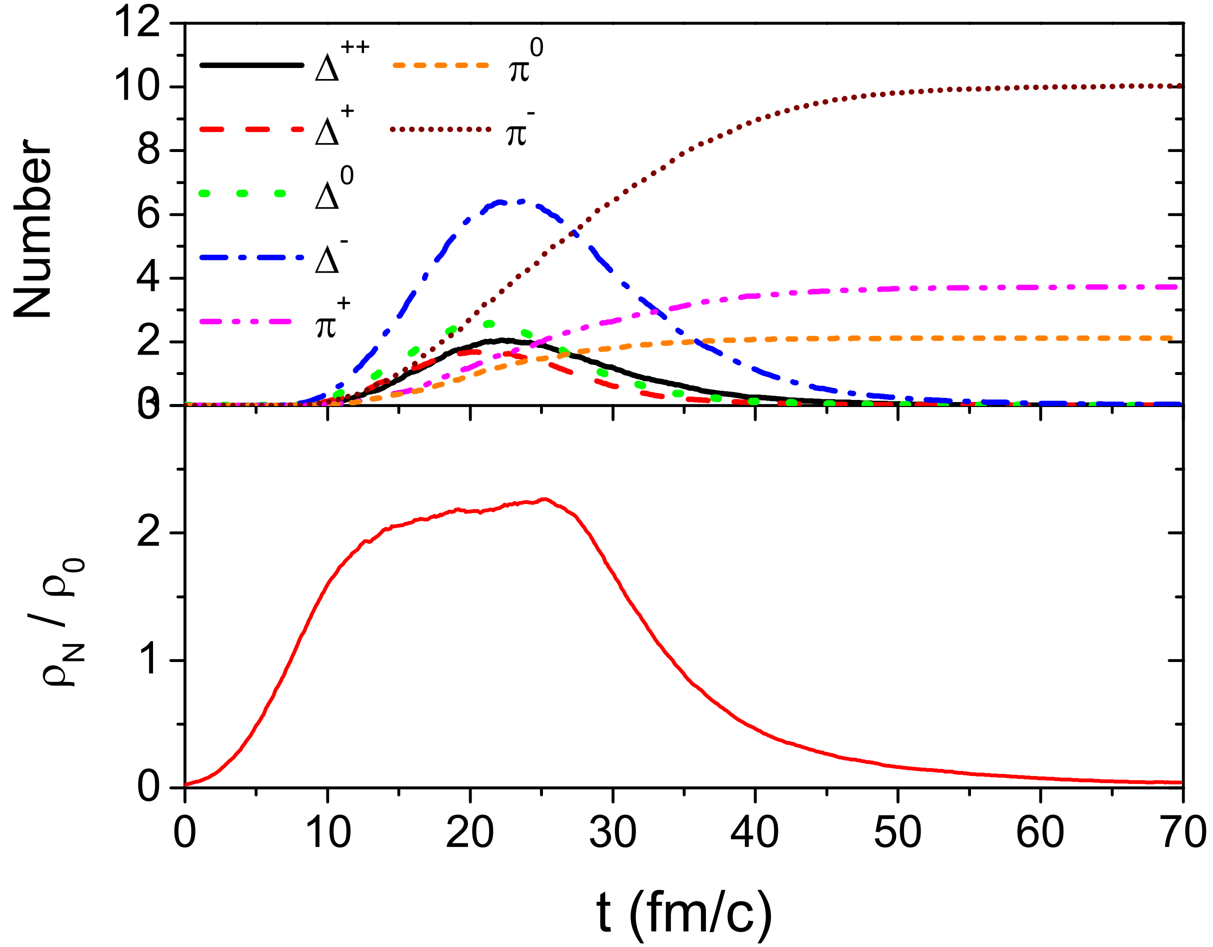
	$\Sigma_1^s - \Sigma_2^s$	$\Sigma_1^\mu - \Sigma_2^\mu$
$\Delta^{++} \to p\pi^+$	0	0
$\Delta^+ \to p\pi^0$	$(2/3)g_\delta\delta_3$	$-(2/3)g_\rho\rho_3^\mu$
$\Delta^+ \to n\pi^+$	$-(4/3)g_\delta\delta_3$	$(4/3)g_\rho\rho_3^\mu$
$\Delta^0 \to p\pi^-$	$(4/3)g_\delta\delta_3$	$-(4/3)g_\rho\rho_3^\mu$
$\Delta^0 \to n\pi^0$	$-(2/3)g_\delta\delta_3$	$(2/3)g_\rho\rho_3^\mu$
$\Delta^- \to n\pi^-$	0	0

- Isovector scalar field reduces $\Delta^+ \to p\pi^0$ and $\Delta^0 \to p\pi^-$ but enhance $\Delta^+ \to n\pi^+$ and $\Delta^0 \to n\pi^0$; isovector vector field has opposite effects.

$\longrightarrow$

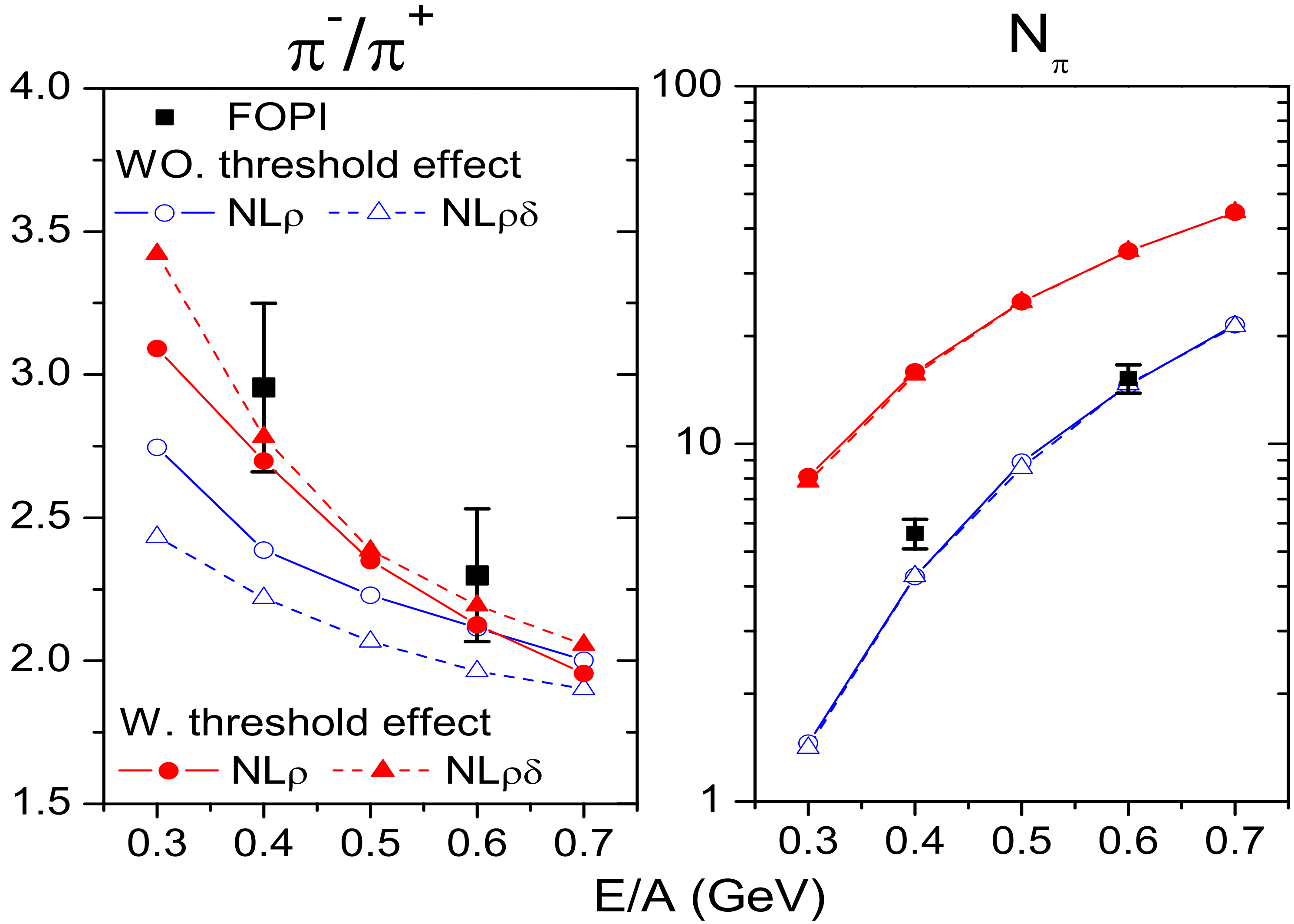
- π^-/π^+ ratio is enhanced in NLρ (softer symmetry energy) and is even more enhanced in NLρδ (stiffer symmetry energy).

Pion production in Au+Au collisions at E = 400 AMeV and b= 1fm



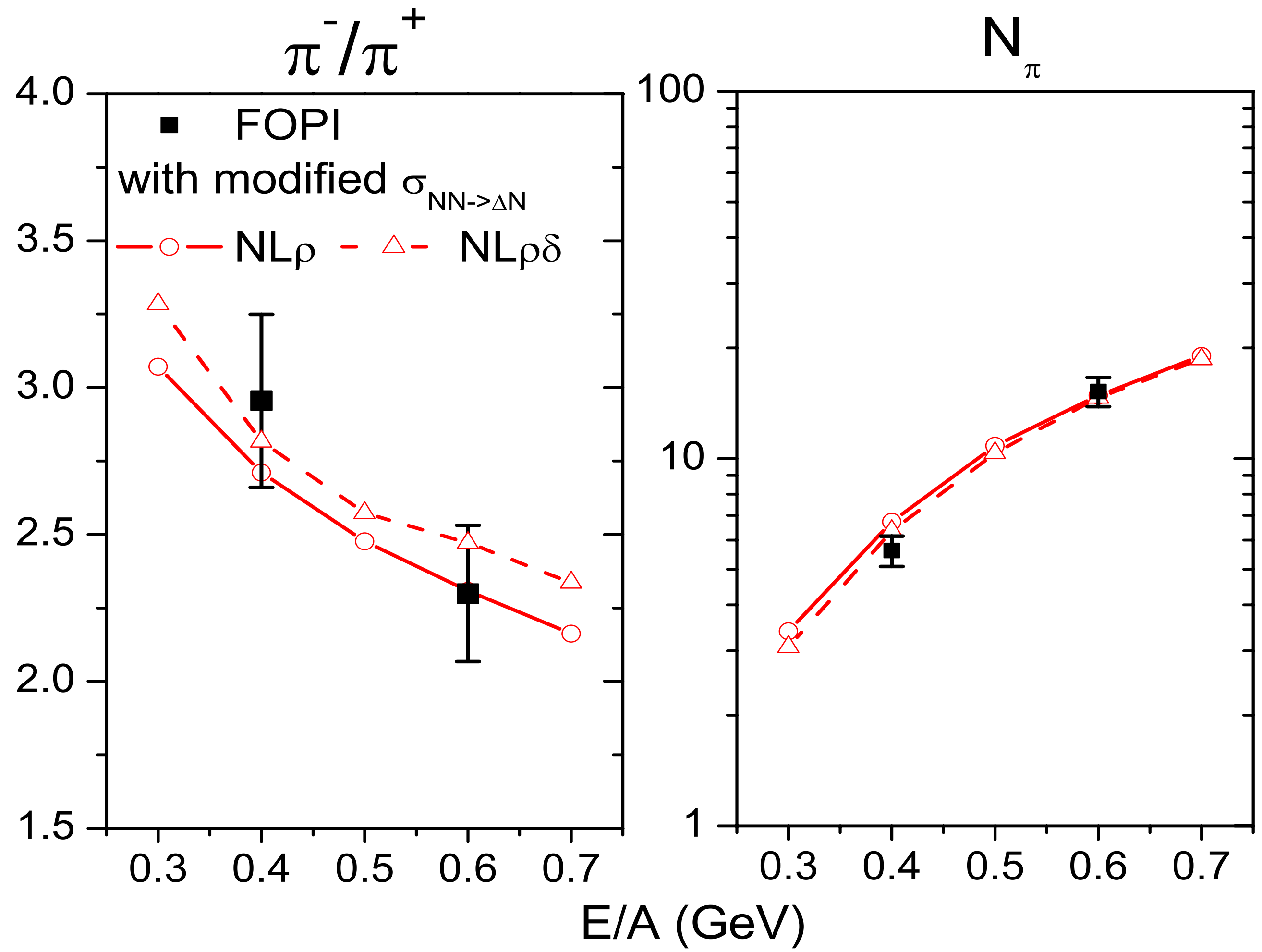
- Deltas are produced during high density stage and decay to pions as the matter expands.

In-medium threshold effects on π^-/π^+ ratio



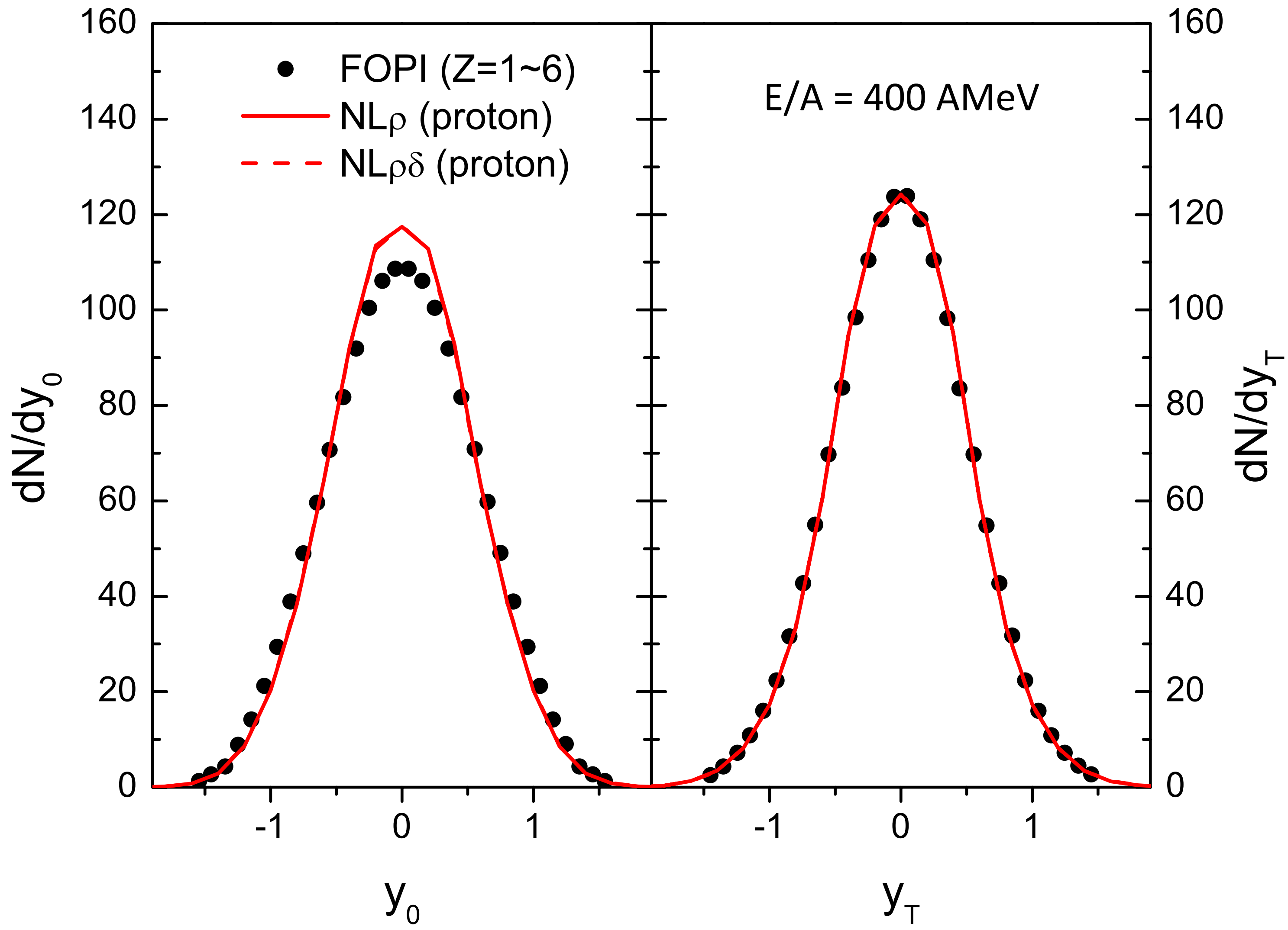
- In-medium threshold effects increase the total pion yield, the π^-/π^+ ratio, and reverse the effect of symmetry energy.

Effects of in-medium Delta production cross sections



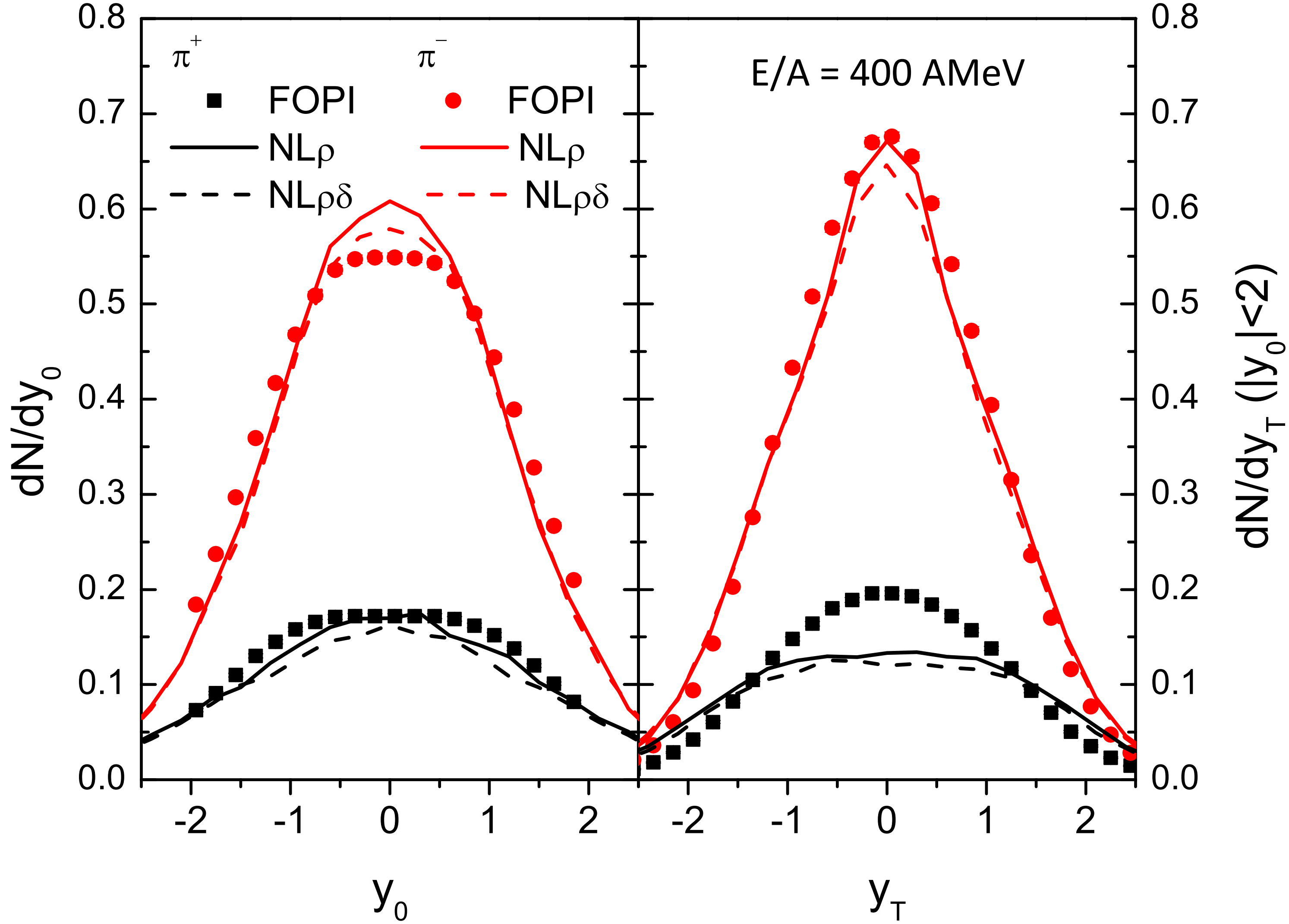
- Reproducing total pion yield requires density-dependent Delta production cross section $\sigma_{NN\to N\Delta}(\rho) = \sigma_{NN\to N\Delta}(0)\exp(-1.65\rho/\rho_0)$, similar to those by Larionov and Mosel, NPA 728, 135 (2003) and Prassa et al., NPA 789, 311 (2007).

Proton longitudinal and transverse rapidity distributions



$$y_0 = \ln\left(\frac{1+\beta_z}{1-\beta_z}\right) / \left(\frac{1+\beta_0}{1-\beta_0}\right), \qquad y_T = \ln\left(\frac{1+\beta_x}{1-\beta_x}\right) / \left(\frac{1+\beta_0}{1-\beta_0}\right)$$

Pion longitudinal and transverse rapidity distributions



- Discrepancy in π^+ at small y_T due to neglect of pion in-medium effects? [Xiong, Ko & Koch, PRC 47, 788 (1993)]

Pion production in transport models

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **31** (2005) S741–S757 doi:10.1088/0954-3899/31/6/015

Transport theories for heavy-ion collisions in the 1 *A* GeV regime

E E Kolomeitsev[1,2], C Hartnack[3], H W Barz[4], M Bleicher[5], E Bratkovskaya[5], W Cassing[6], L W Chen[7,8], P Danielewicz[9], C Fuchs[10], T Gaitanos[11], C M Ko[7], A Larionov[6,13], M Reiter[5], Gy Wolf[12] and J Aichelin[3,14]

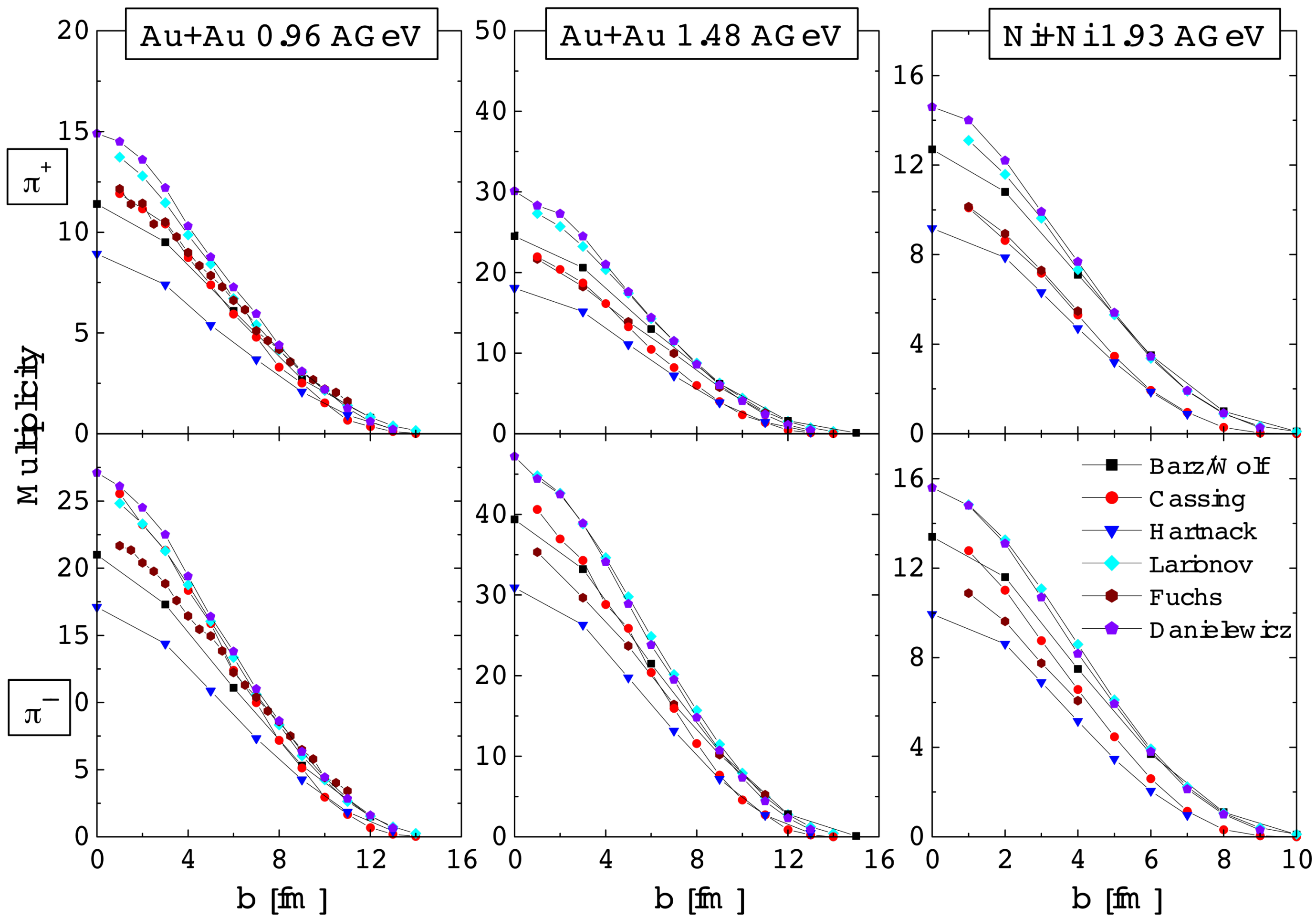
Abstract

We compare multiplicities as well as rapidity and transverse momentum distributions of protons, pions and kaons calculated within presently available transport approaches for heavy-ion collisions around 1 *A* GeV. For this purpose, three reactions have been selected: Au+Au at 1 and 1.48 *A* GeV and Ni+Ni at 1.93 *A* GeV.

Transport model predictions for pion production in HIC

- Centrality dependence

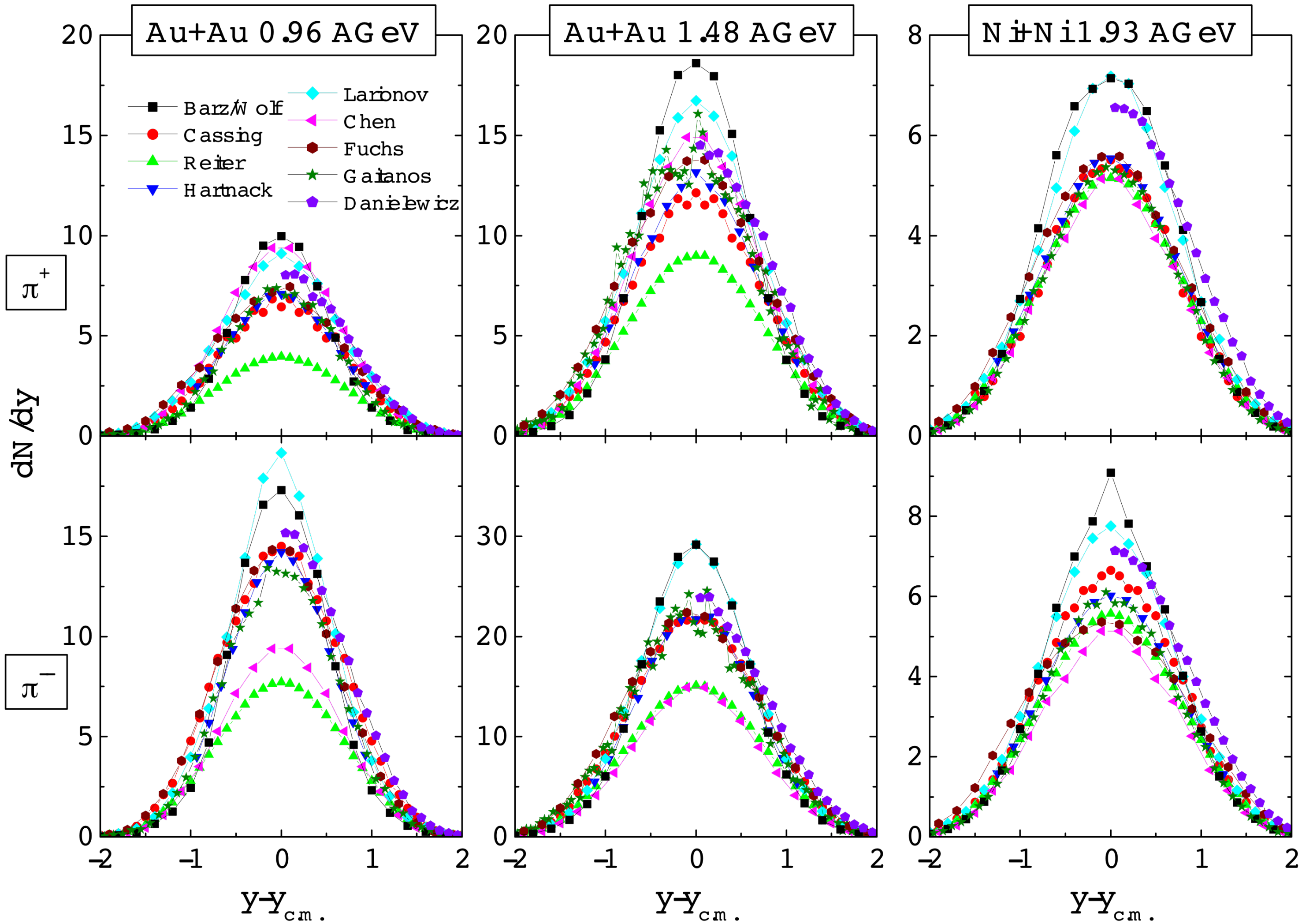
Kolomeitsev et al., J. Phys. G 31, S741 (2005)



- Results from different transport models can differ by ~ 2.

- Rapidity distributions:

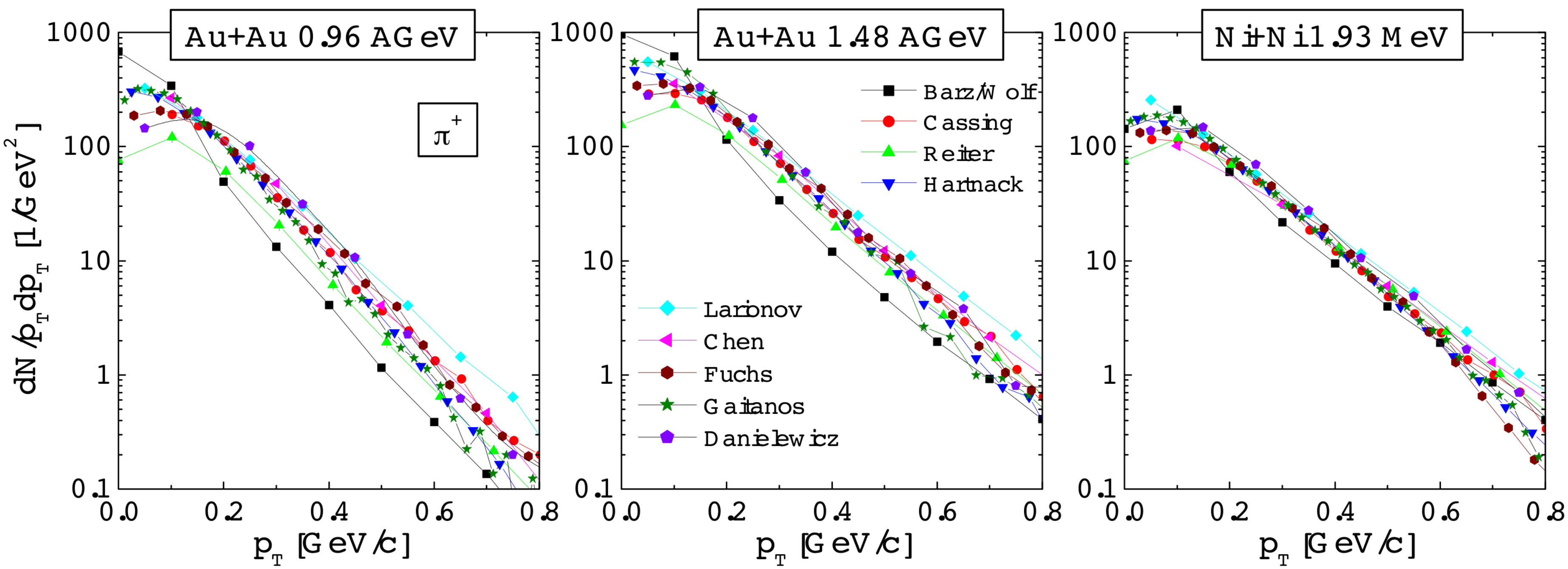
Impact parameter b = 1fm,
Delta width Γ_Δ = 120 MeV



- Results from different transport models can differ by ~ 2, particularly at midraipidy.

- Transverse momentum spectra

Impact parameter b = 1fm, Rapidity $|y_{c.m.}| \le 0.5$,
Delta width Γ_Δ = 120 MeV



- Results from different transport models can differ by ~ 2, particularly at low energy collisions.

Summary

- Nuclear symmetry energy affects the π^-/π^+ ratio in HIC (B. A. Li).

However,

- Results depend on the transport model used in a study.
- With inclusion of pion s-wave potential, π^-/π^+ ratio is insensitive to stiffness of symmetry energy (Danielewicz and Hong)
- With inclusion of both pion s- and p-wave potential, symmetry energy effect is reduced (Guo et al., Feng)
- Pion in-medium effects decrease the π^-/π^+ ratio, and the effect is larger at lower collision energies (Jun Xu et al.).
- In-medium threshold effects increase the total pion yield, the π^-/π^+ ratio, and reverse the effect of symmetry energy (Ferini et al, Song and Ko)

→ Require better theoretical modeling of pion production in HIC to extract information on the stiffness of nuclear symmetry energy at high density from the ratio of charged pions. **Another comparison study of transport models?**