Impact of the pion potential on pion observables in intermediate energy heavy-ion collisions

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Motivation & Contents

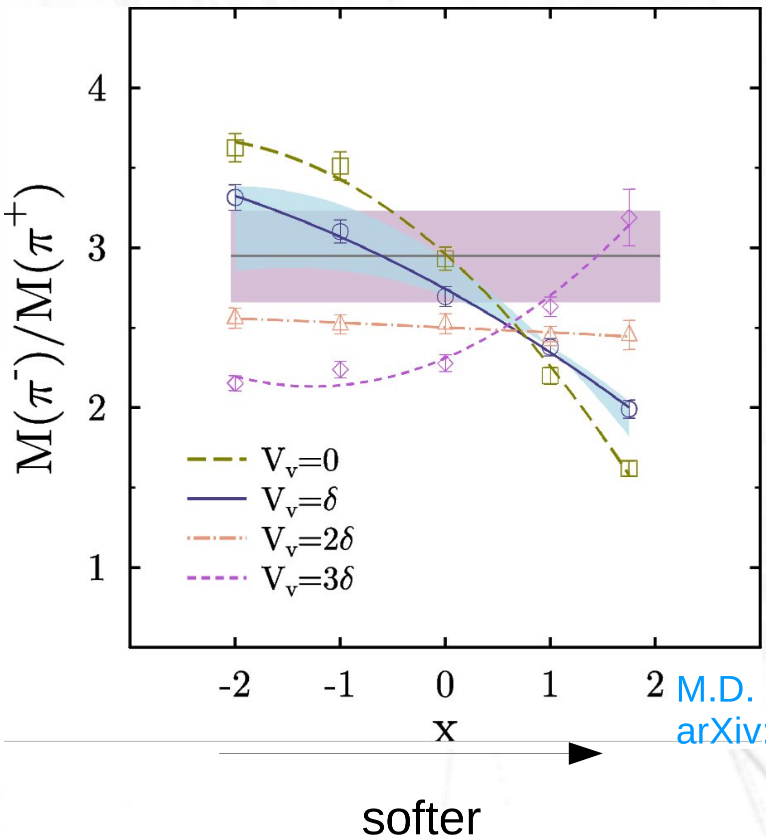
$$V(\Delta^{++}) = V_s + \frac{3}{2} V_v$$

$$V(\Delta^{+}) = V_s + \frac{1}{2} V_v \qquad V_s = \frac{1}{2}(V_n + V_p)$$

$$V(\Delta^{0}) = V_s - \frac{1}{2} V_v \qquad \delta = \frac{1}{3}(V_n - V_p)$$

$$V(\Delta^{-}) = V_s - \frac{3}{2} V_v$$

B.-A. Li, NPA 708, 365 (2002)



M.D. Cozma arXiv:1409.3110 (2014)

The Model
- Pion Production
- Isovector Potential
- Energy Conservation

Pion Potential
- S Wave Component
- P Wave Component

Observables
- Pion Multiplicities
- Pion Average p_T

Constraints on SE Stiffness

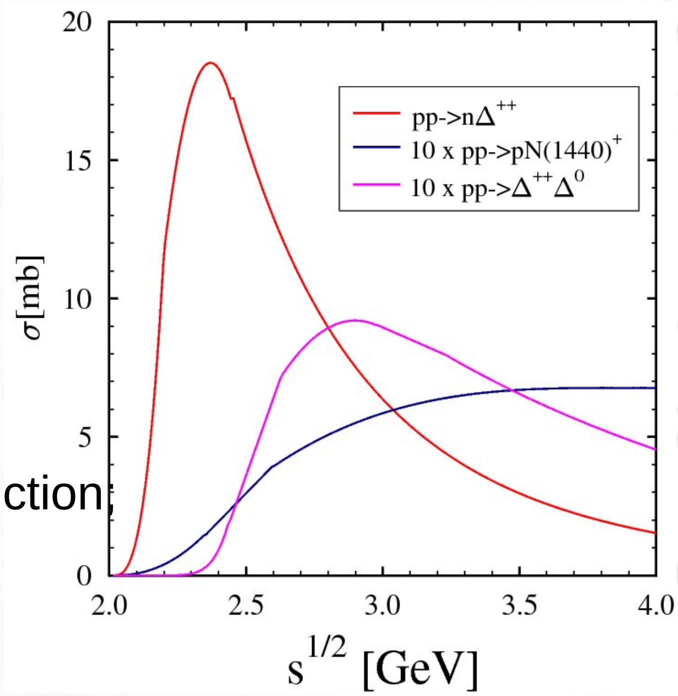
Summary & Conclusions

Pion production

two step process:

- resonance excitation in baryon-baryon collisions
  parametrization of the OBE model of
  S.Huber et al., NPA 573, 587 (1994)
- resonance decay:
  Breit-Wigner shape of the resonance spectral function;
  parameters -> K. Shekhter, PRC 68, 014904 (2003)
  decay channels: $R \rightarrow N\pi,\quad R \rightarrow N\pi\pi$

$$R \rightarrow \Delta(1232)\pi,\quad R \rightarrow N(1440)\pi$$



pion absorption:

-resonance model (all 4* resonances below 2 GeV)
K. Shekhter, PRC 68, 014904 (2003)

additional channels:

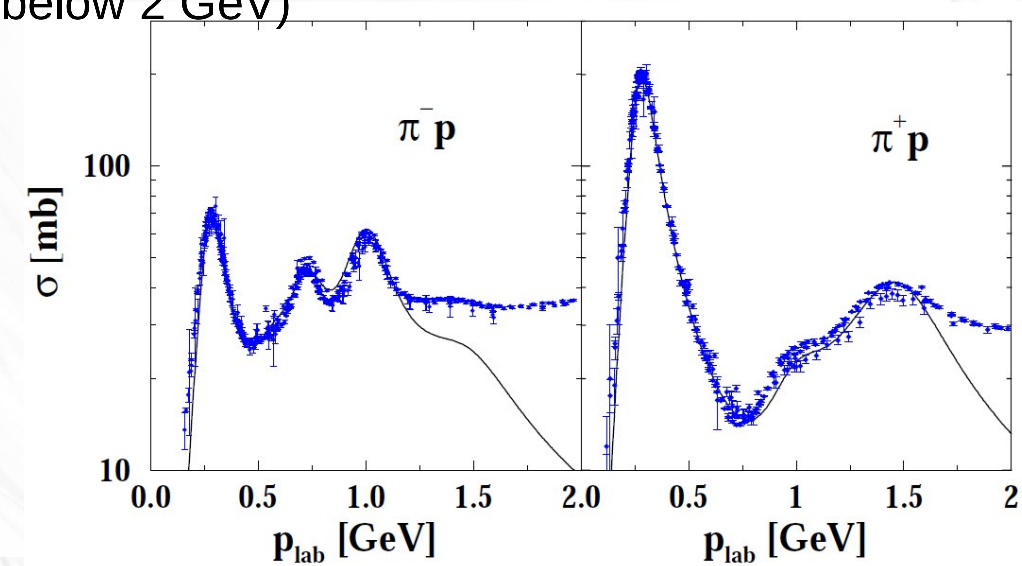
vector meson production/absorption

$$V+B \rightarrow \pi+B', \pi+\pi+B'$$
$$\pi+B \rightarrow V+B'$$

vector meson decay $\rho \rightarrow \pi+\pi$

$$\omega \rightarrow 3\pi,\ 2\pi^0$$

pion annihilation $\pi+\pi \rightarrow \rho$



Isospin dependence of EoS

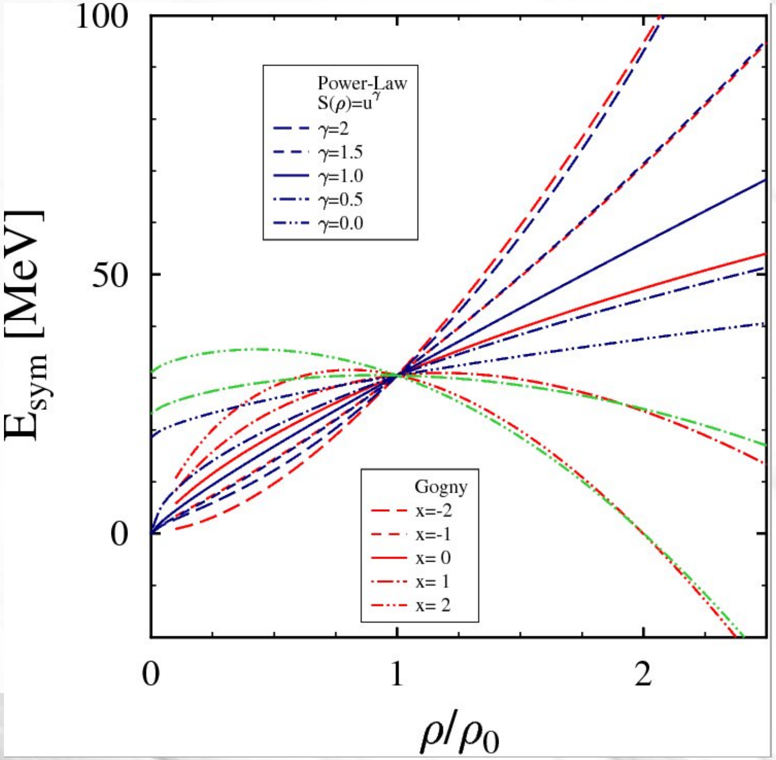
a) momentum dependent – generalization of the Gogny interaction:

Das, Das Gupta, Gale, Li PRC67, 034611 (2003)

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

$$S(\rho)=S(\rho_0)+\frac{L_{sym}}{3}\frac{\rho-\rho_0}{\rho_0}+\frac{K_{sym}}{18}\frac{(\rho-\rho_0)^2}{\rho_0^2}$$

x	L_{sym} [MeV]	K_{sym} [MeV]
-2	152	418
-1	106	127
0	61	-163
1	15	-454
2	-301	-745



b) momentum dependent – power law

$$U_{sym}(\rho,\beta)=\begin{cases} S_0(\rho/\rho_0)^\gamma - linear, stiff \\ a+(18.5-a)(\rho/\rho_0)^\gamma - soft, supersoft \end{cases}$$

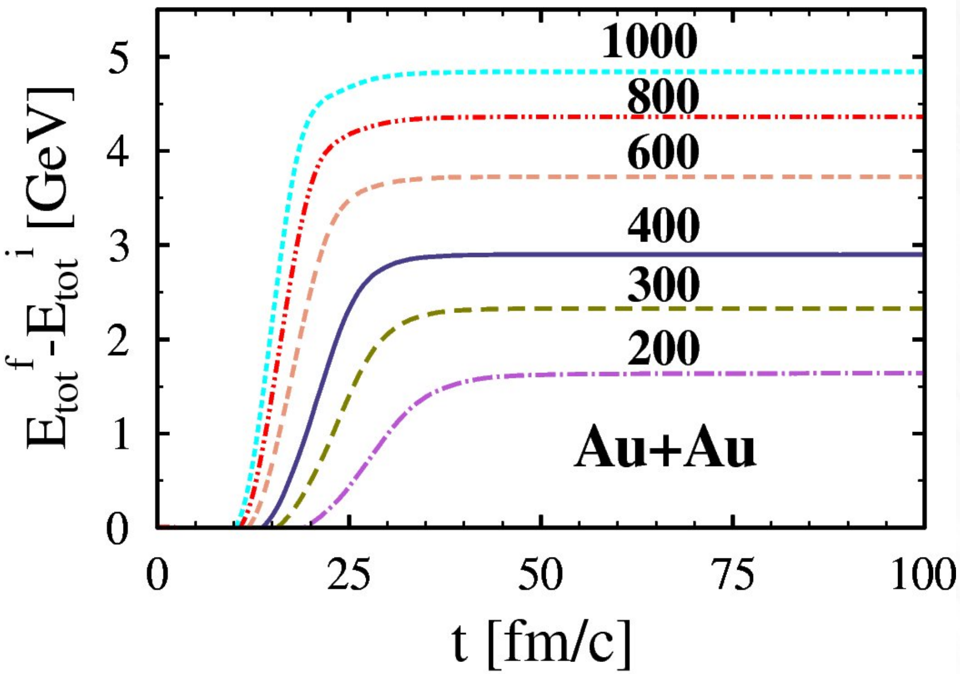
Energy Conservation

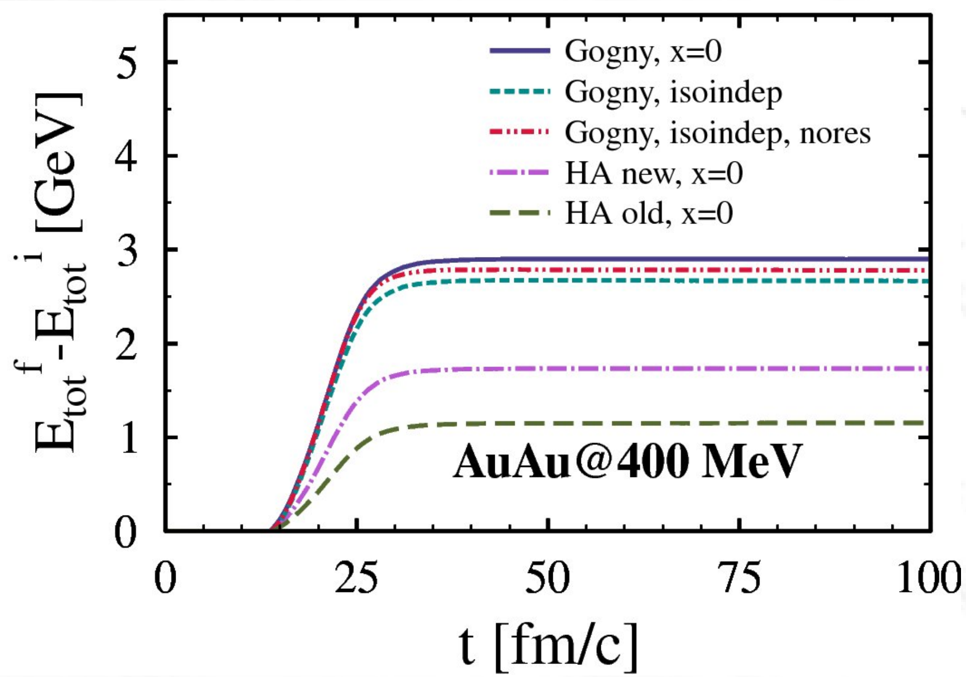
80's transport models – total energy conserved (potentials dependent only on density)

Collective phenomena – momentum dependence of opt.pot.
Isospin effects – isospin asymmetry dependence

Violation of total energy conservation

Determination of final state kinematics of 2-body collisions neglects medium effects





Gogny: Das, Das Gupta, Gale, Li PRC67, 034611 (2003)
HA: Hartnack, Aichelin, PRC 49, 2901 (1994)

Approximations

Elastic scattering:

$$\sqrt{s_f} \approx \sqrt{s_i}$$
$$\sqrt{s^*} = 0.5(\sqrt{s_f} + \sqrt{s_i})$$

Resonance excitation:

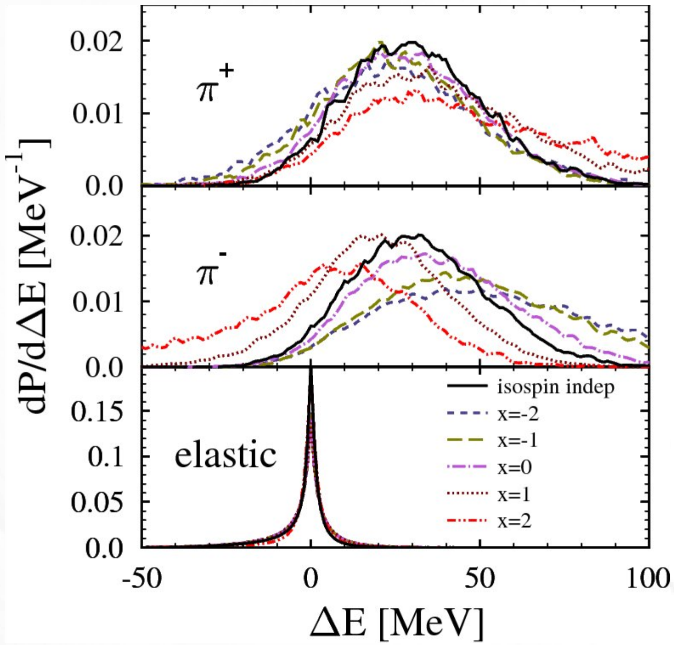
$$\sqrt{s_f} - \sqrt{s_i} \approx 25\,\mathrm{MeV}$$
$$\sqrt{s^*} = \sqrt{s_f}$$

Resonance absorption: detailed balance

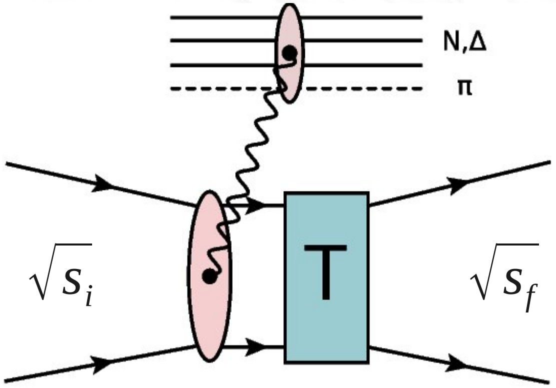
P. Danielewicz et al., NPA 533, 712 (1992)

$$\frac{d\sigma^{NR\to NN}}{d\Omega} = \frac{1}{4}\frac{m_R p_{NN}^2}{p_{NR}}\frac{d\sigma^{NN\to NR}}{d\Omega} \times \left[\frac{1}{2\pi}\int_{m_N+m_\pi}^{\sqrt{s_i}-m_N} dM\, M\, p'_{NR} A_R(M)\right]^{-1}$$

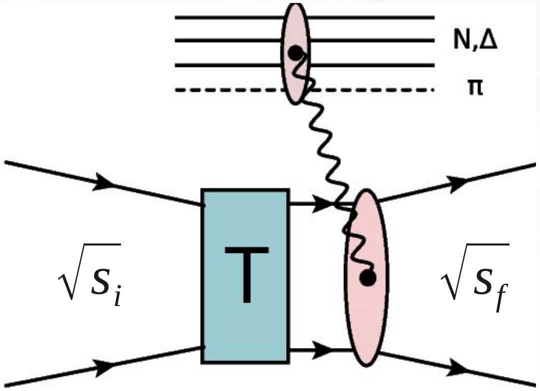
$$\sqrt{s_i} \rightarrow p_{NR}, \quad \sqrt{s_f} \rightarrow p_{NN}$$



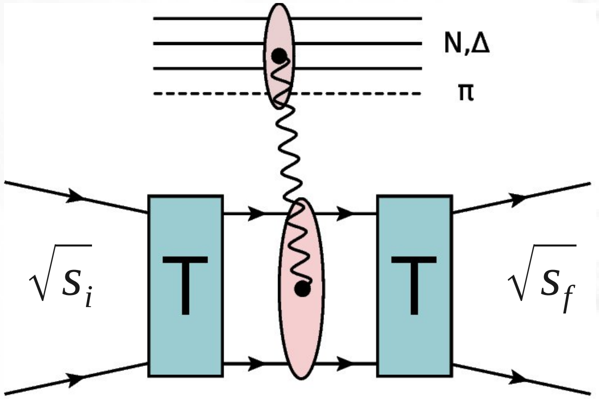
$$\Delta E = \sqrt{s_f} - \sqrt{s_i}$$



initial



final state



rescattering

Different "scenarios"

$$\sum_i \sqrt{p_i^2+m_i^2}+U(p_i)=\sum_j \sqrt{p'^2_j+m'^2_j}+U(p'_j)$$

T. Song, C.M. Ko PRC 91, 014901 (2015)
G. Ferini et al. PRL 97, 202301 (2006)
S. Teis et al. Z.Phys. A356, 421 (1997)
C.Fuchs et al. PRC 55, 411 (1997)

VEC – vacuum energy conservation constraint

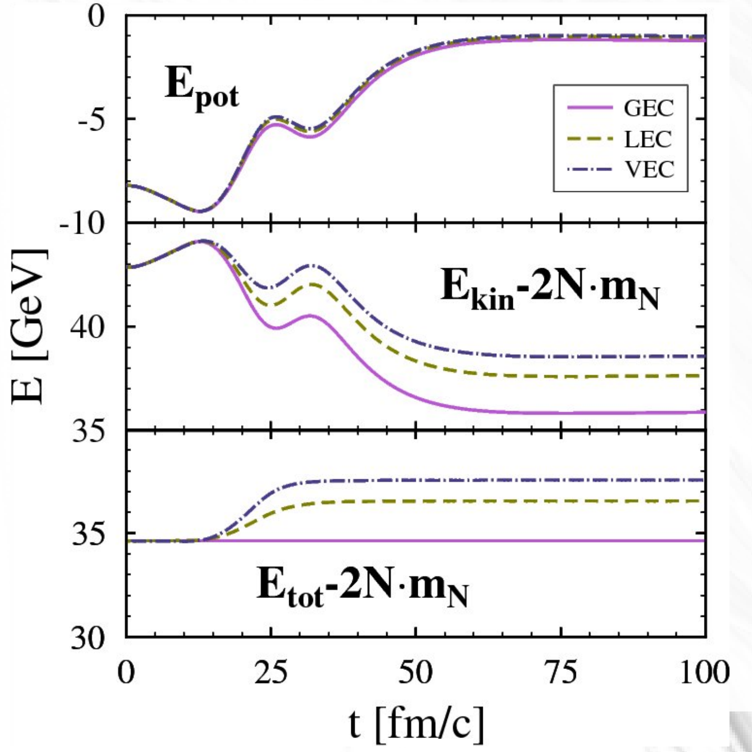
LEC - "local" energy conservation – limited impact on multiplicities and ratios

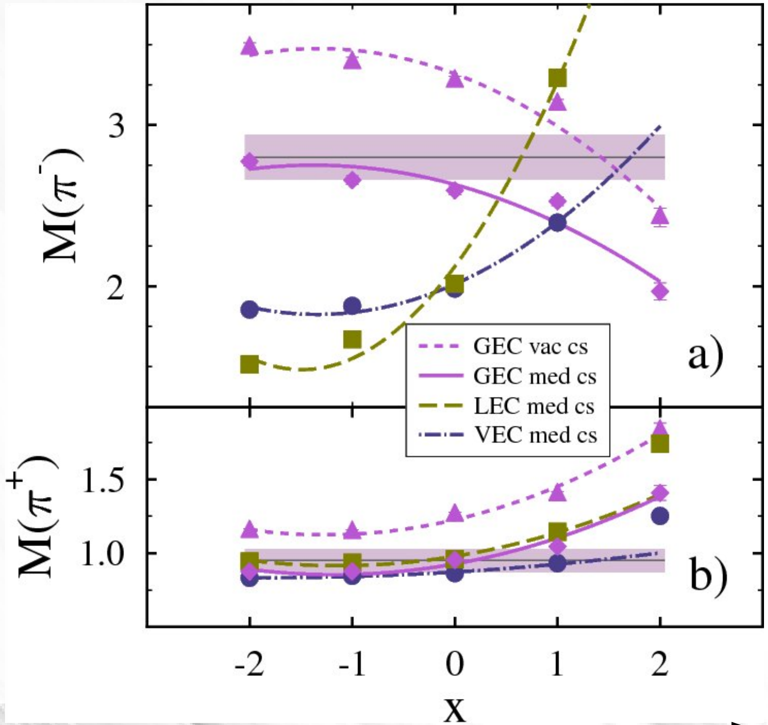
GEC- "global" energy conservation – conserve energy of the entire system

-in-medium cross-sections for the inelastic channels

$$\sigma^{*(12\rightarrow 23)}=\left[\frac{m_1^* m_2^* m_3^* m_4^*}{m_1 m_2 m_3 m_4}\right]^{1/2}\sigma^{(12\rightarrow 34)}$$

AuAu@400 MeV, b=0 fm



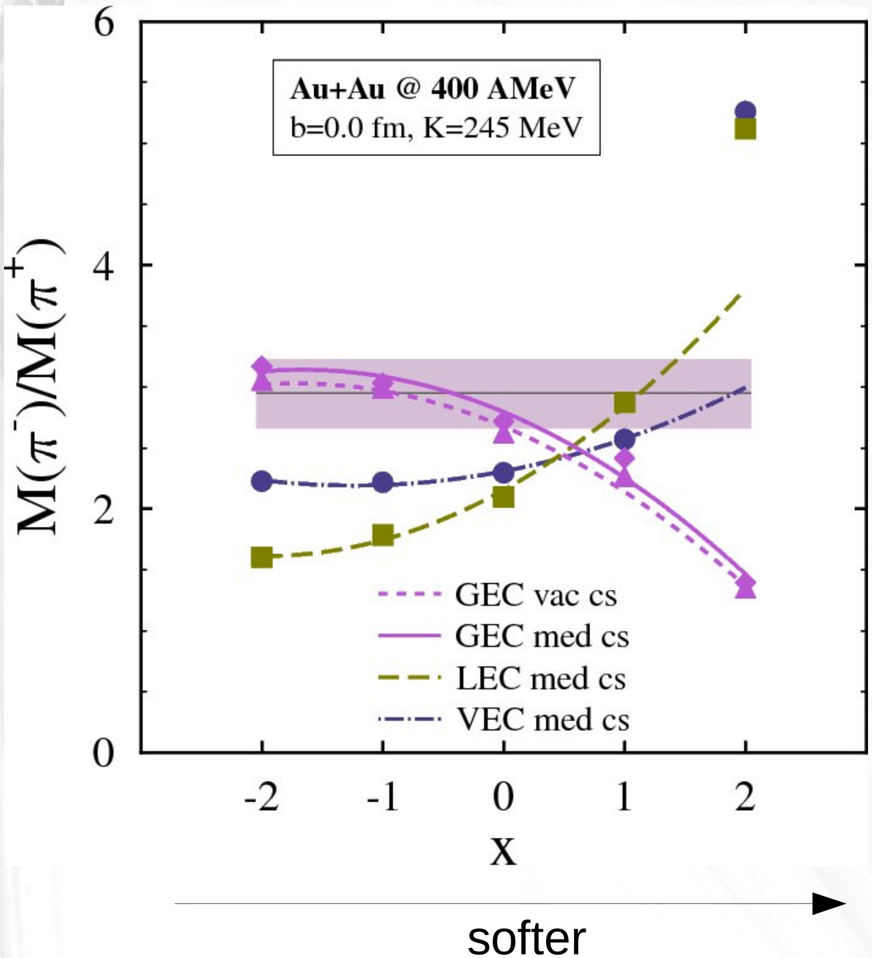


softer

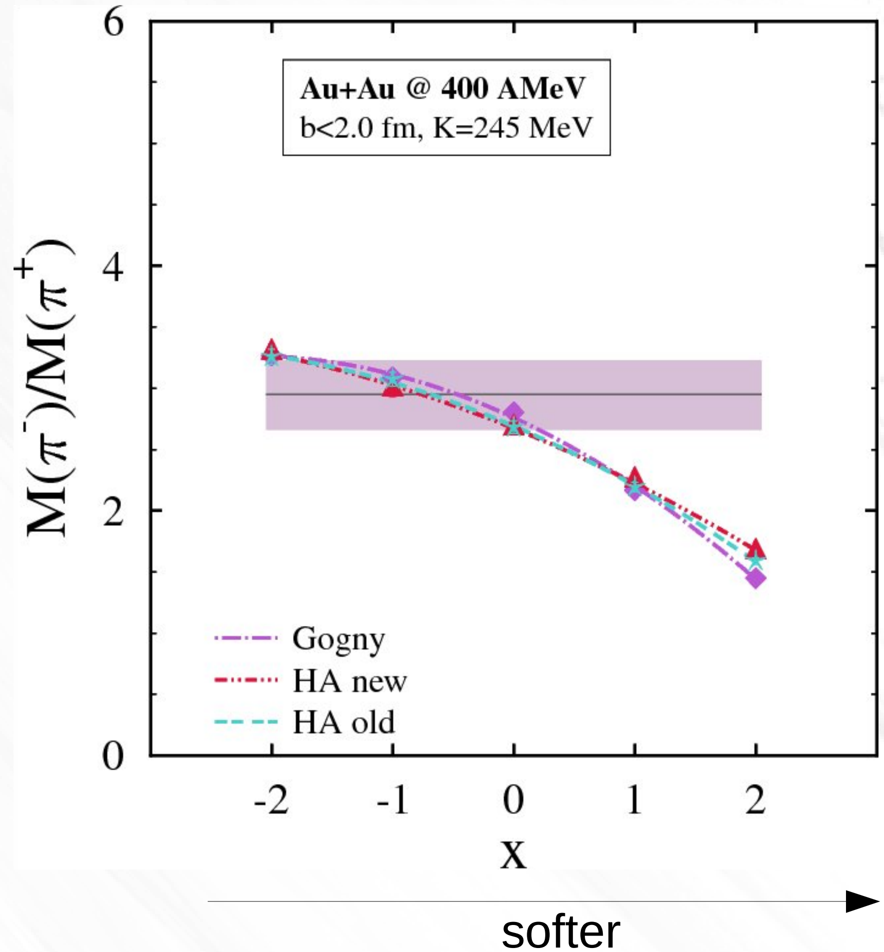
Experimental data: W. Reisdorf et al. (FOPI) NPA 848, 366 (2010)

Multiplicity Ratio

Energy Conservation Scenario



Optical Potential Dependence



Pion S wave potential

Microsopical approaches: Hadronic Models J.Nieves et al., NPA 554, 509 (1993)

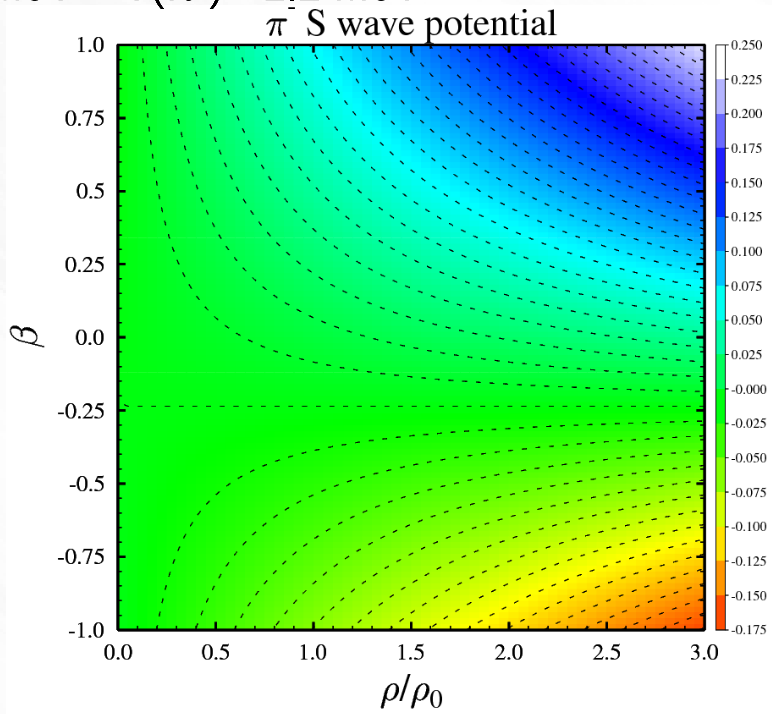
V(π⁻)=26.3 MeV V(π⁰)=16.2 MeV V(π⁺)=6.2 MeV

M.Doring et al, PRC 77, 024602 (2008)

can accomodate repulsion needed by phenomelogical fits; large theoretical uncertainties

ChPT: two loop approximation N. Kaiser et al. PLB 512, 283 (2001)

V(π⁻)=13.8 MeV V(π⁰)=6.1 MeV V(π⁺)=-1.2 MeV



Parametrization:

$$V_S(r) = -4\pi[b(r) + \epsilon_2 B_0 \rho^2(r)]$$
$$b(r) = \epsilon_1[b_0\rho(r) + b_1(\rho_n(r) - \rho_p(r))]$$

$$\epsilon_1 = \frac{1}{2\mu} + \frac{1}{2M} \qquad \epsilon_1 = \frac{1}{2\mu} + \frac{1}{4M}$$

$$b_0 = 0.0283\, m_\pi^{-1} \qquad b_1 = -0.120\, m_\pi^{-1}$$

$$B_0 = 0.042\, i\, m_\pi^{-4}$$

R. Seki, K. Masutani, PRC 27, 2799 (1983)

V(π⁻)=28.8 MeV V(π⁰)=15.6 MeV V(π⁺)=2.4 MeV

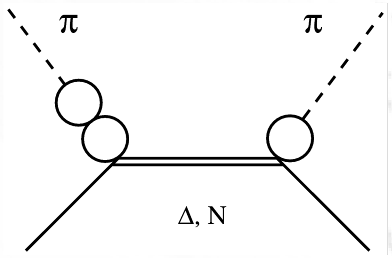
(at $\rho=\rho_0$, β=0.20)

Pion P wave potential

Three level model (3LM): allows analytical calculation (self-energies)

M.Urban et al.
NPA 641, 433 (1988)

Approximations: only Δ and non-resonant scattering
perform a non-relativistic reduction
pion momentum larger than Fermi momentum



$$\Pi(k)=\frac{\Pi_{Nh}+\Pi_{\Delta h}-(g_{11}-2g_{12}+g_{22})\Pi_{Nh}\Pi_{\Delta h}}{1-g_{11}\Pi_{Nh}-g_{22}\Pi_{\Delta h}+(g_{11}g_{22}-g_{12}^2)\Pi_{Nh}\Pi_{\Delta h}}$$

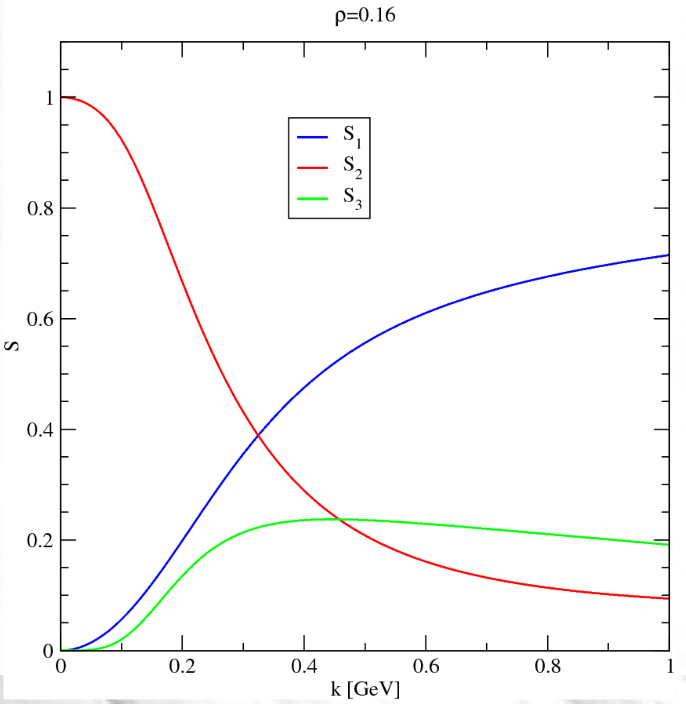
$$\Delta_\pi(k)=\frac{1}{k^2-m_\pi^2-\vec{k}^2\Pi(k)}$$

$$\Delta_\pi(k)\overset{3LM}{=}\frac{S_1(\vec{k})}{k_0^2-\omega_1^2(\vec{k})}+\frac{S_2(\vec{k})}{k_0^2-\omega_2^2(\vec{k})}+\frac{S_3(\vec{k})}{k_0^2-\omega_3^2(\vec{k})}$$

Effective dispersion relation:

$$\omega_{eff}(\vec{k})=S_1(\vec{k})\omega_1(\vec{k})+S_2(\vec{k})\omega_2(\vec{k})+S_3(\vec{k})\omega_3(\vec{k})$$

W. Ehehalt et al., PLB 298, 31 (1993)
C. Fuchs et al., PRC 55, 411 (1997)



Effective potential:

$$V_\pi^{eff}=\omega^{eff}-\sqrt{m_\pi^2+\vec{k}^2}$$

Pion Potential

P wave (continued)

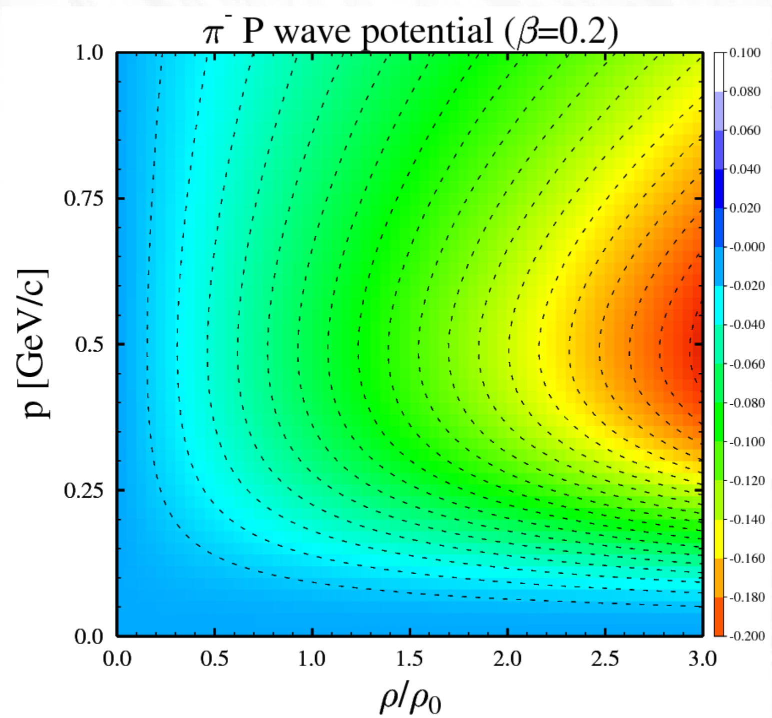
Parametrization:

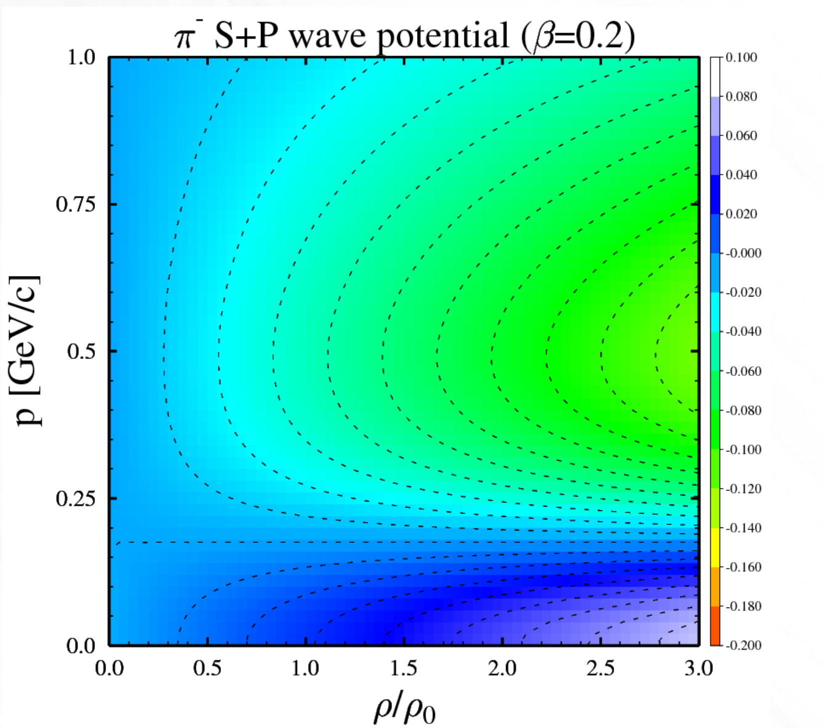
$$V(\pi^- ;u,\beta,k)=\frac{k^2}{1+k^2/\Lambda_1^2+k^4/\Lambda_2^4}(b_{11}u+b_{21}u\beta)$$

$$\Lambda_1=2.138\mathrm{m}_\pi \qquad \Lambda_2=3.551\mathrm{m}_\pi$$

$$b_{11}=-0.180\mathrm{m}_\pi^{-1} \qquad b_{21}=0.011\mathrm{m}_\pi^{-1}$$

fitted in the region: 0 < u < 3.0; -0.5 < β < 0.5; 0.0 GeV/c < k < 0.75 GeV/c





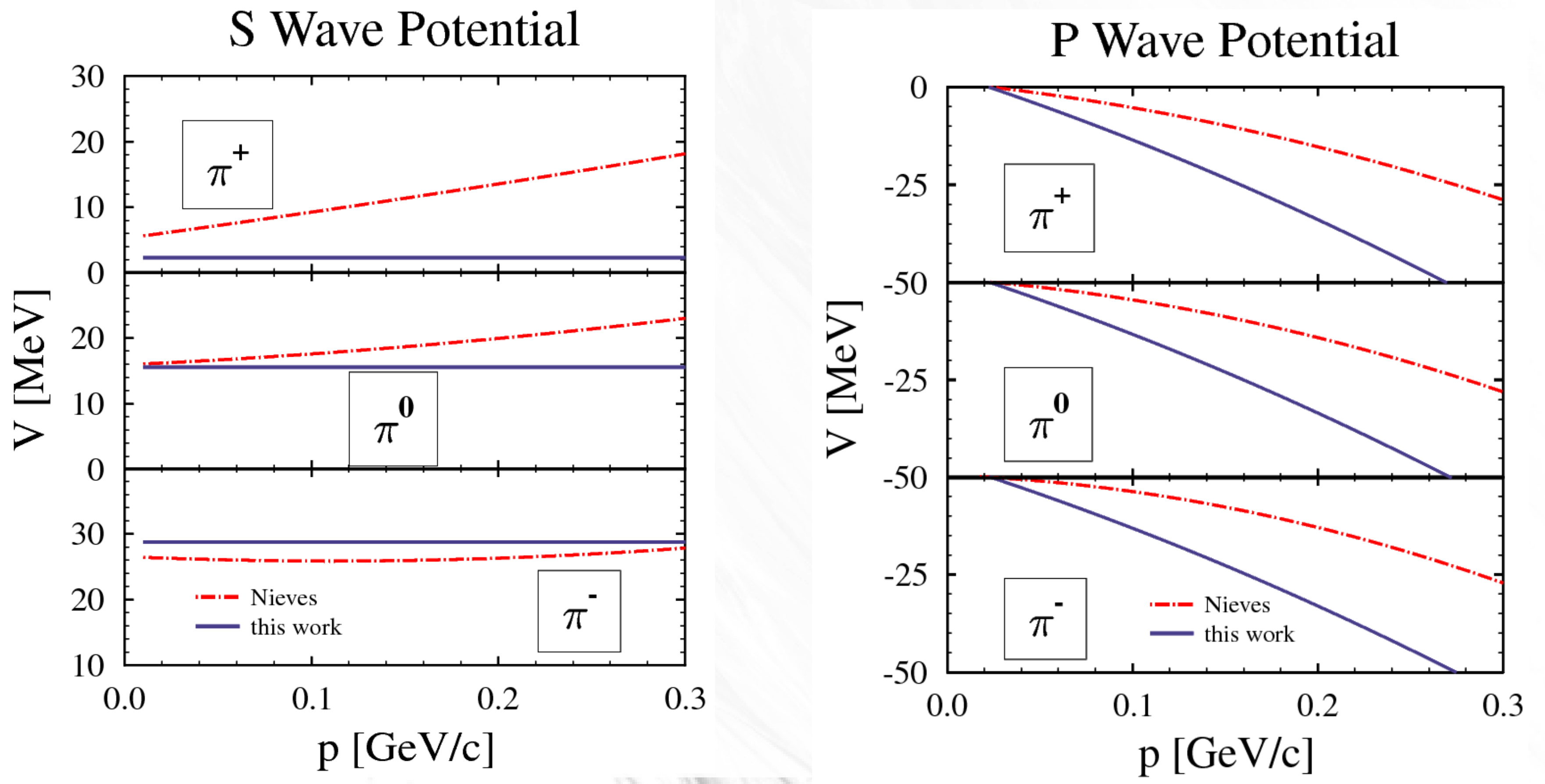
Comparison with Nieves et al.

(at saturation density)

J.Nieves et al., NPA 554, 509 (1993)

3-level P wave potential – cold nuclear matter at equilibrium – likely to overestimate πN correlations

W. Ehehalt et al. PLB 289, 31 (1993)
G.E. Brown et al. NPA 535, 701 (1991)

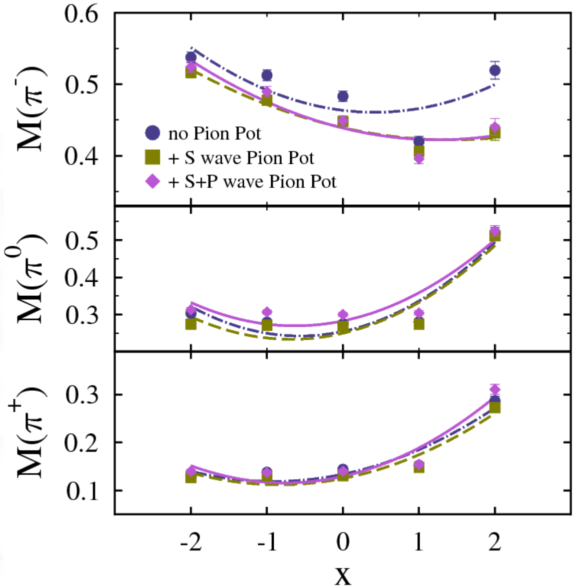


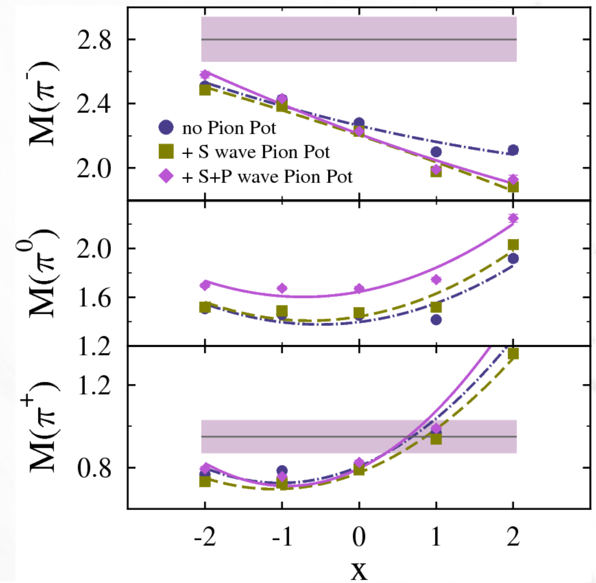
Multiplicities & Ratio

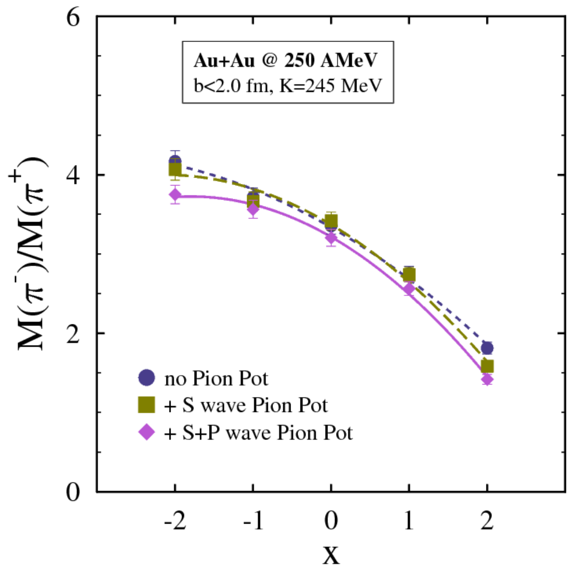
central collisions (b<2.0 fm)

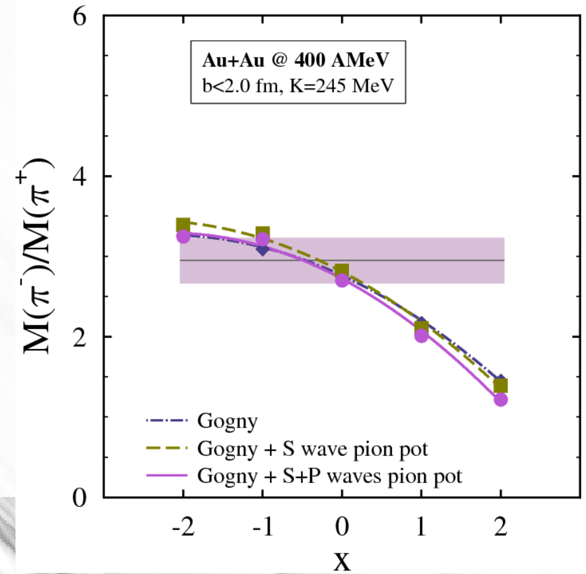
250 AMeV

400 AMeV





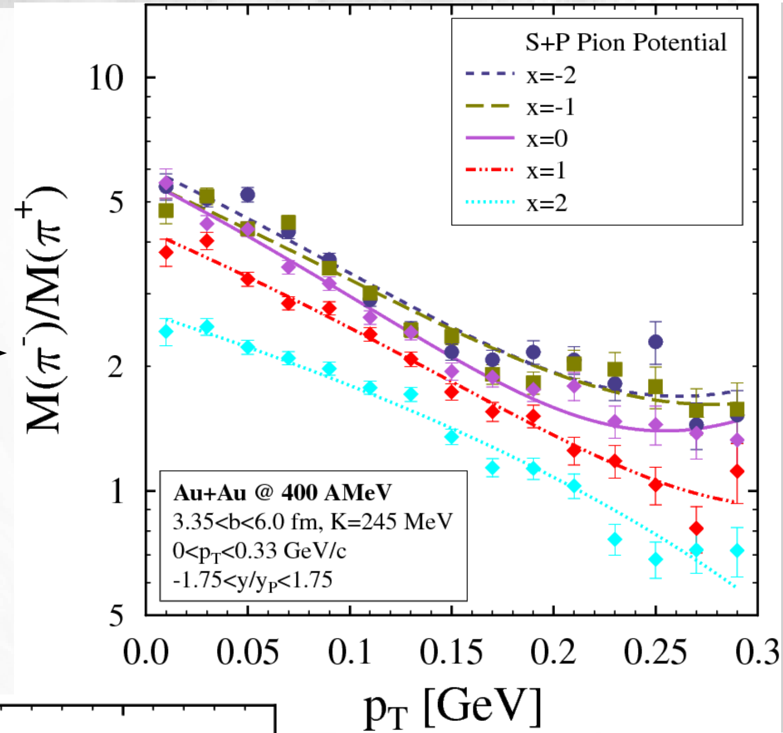




P_T Multiplicity Spectra

mid-central 3.35 fm<b<6.0 fm

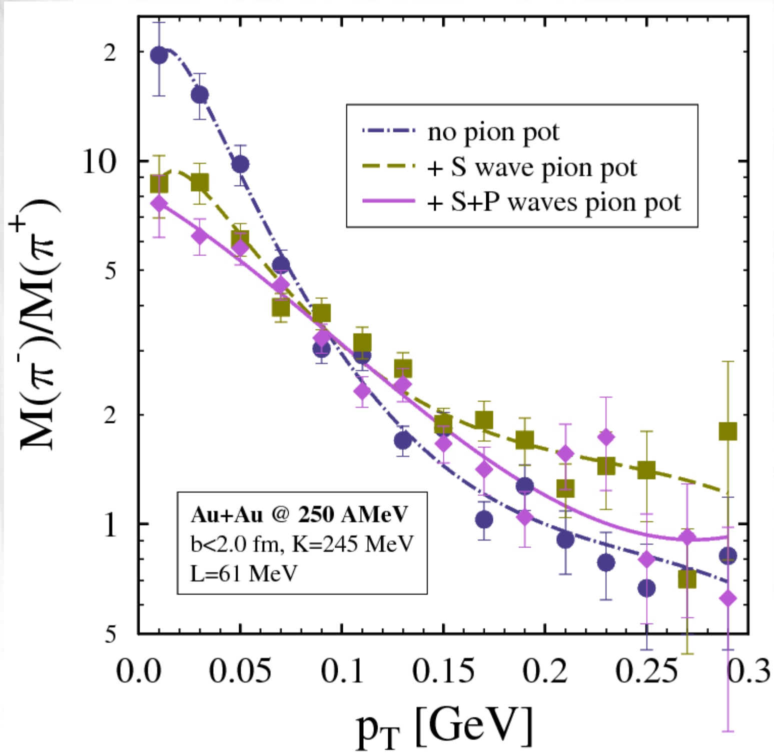
400 AMeV

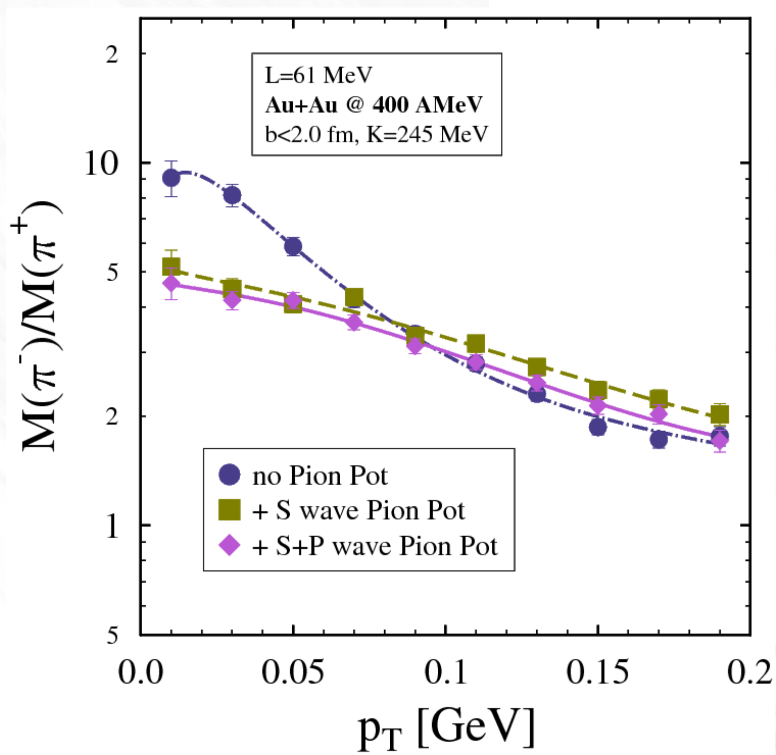


250 AMeV

central b<2.0 fm

central b<2.0 fm

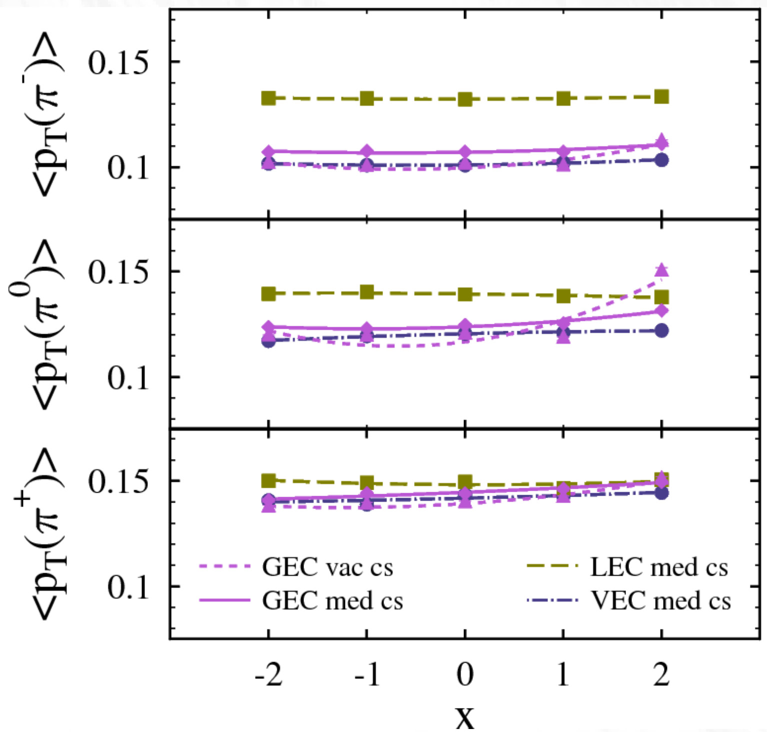


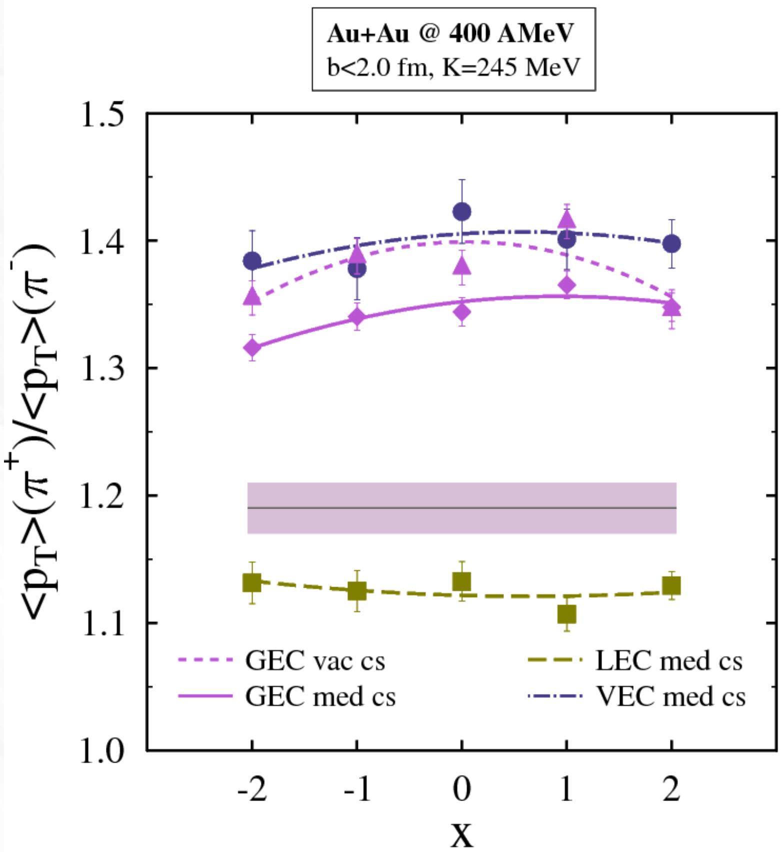


Transverse momentum: <p$_T$>

Impact of: energy conservation scenario
in-medium cross-sections

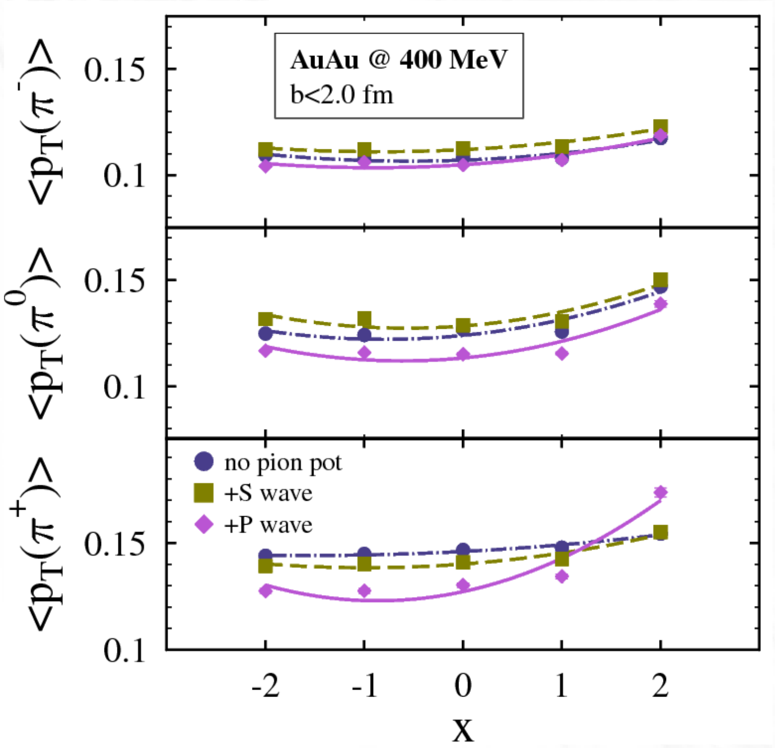
pion – wave function width half of that of the nucleon

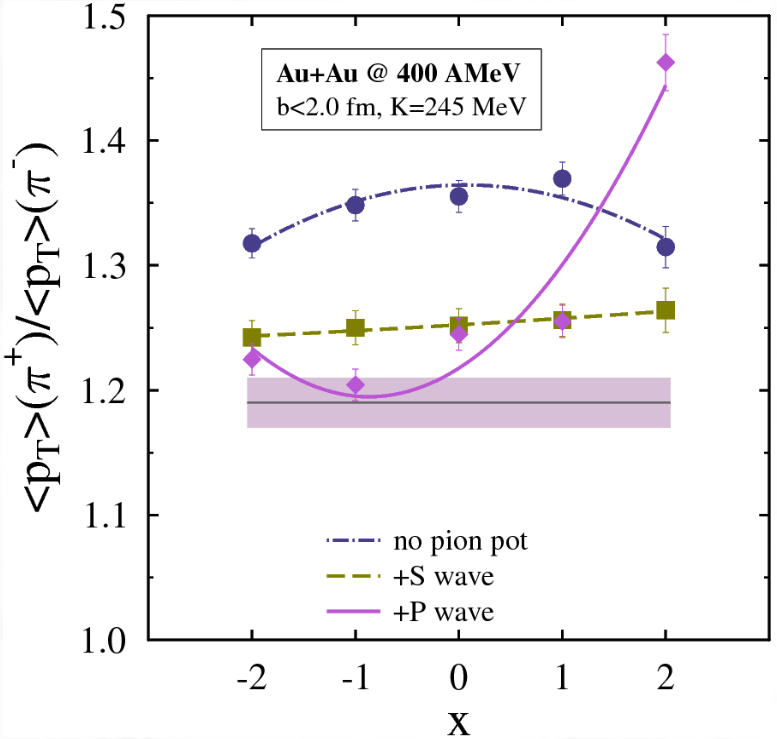




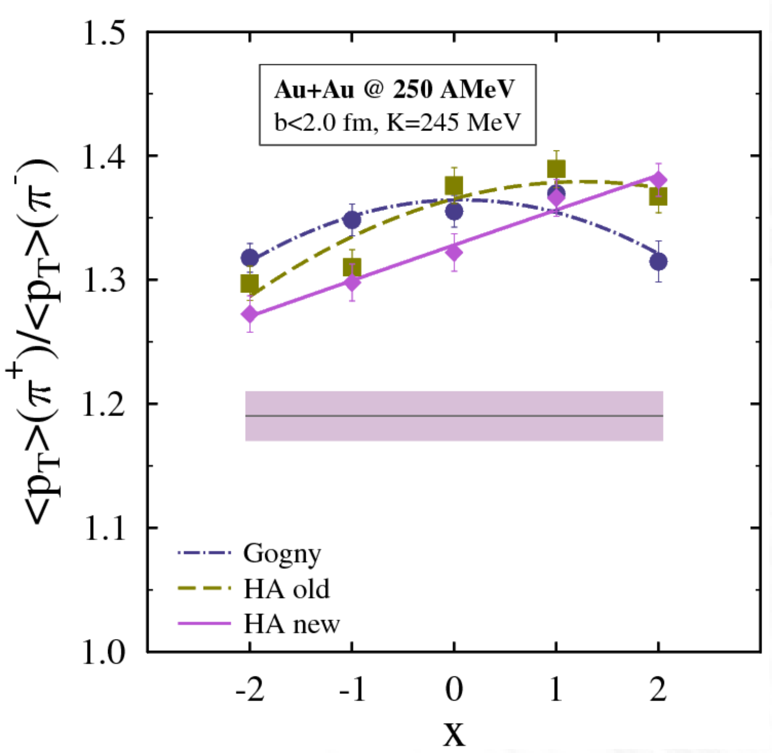
Experimental data (FOPI): W.Reisdorf et al. NPA 781, 459 (2007)

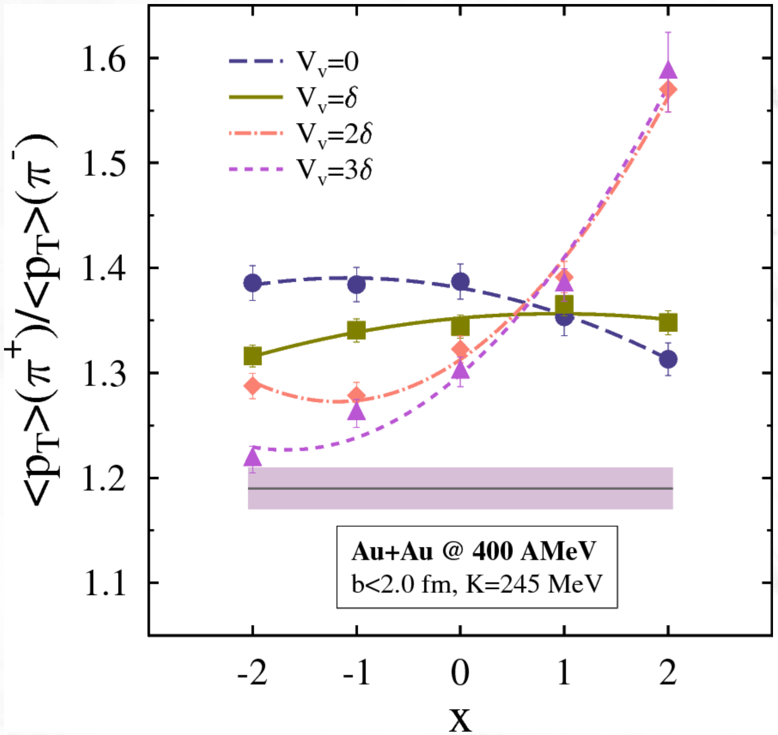
Impact of the Pion Potential





Optical/Delta Potential Dependence





softer

Constraints for symmetry energy

$$V(\Delta^{++}) = V_s + \frac{3}{2} V_v$$

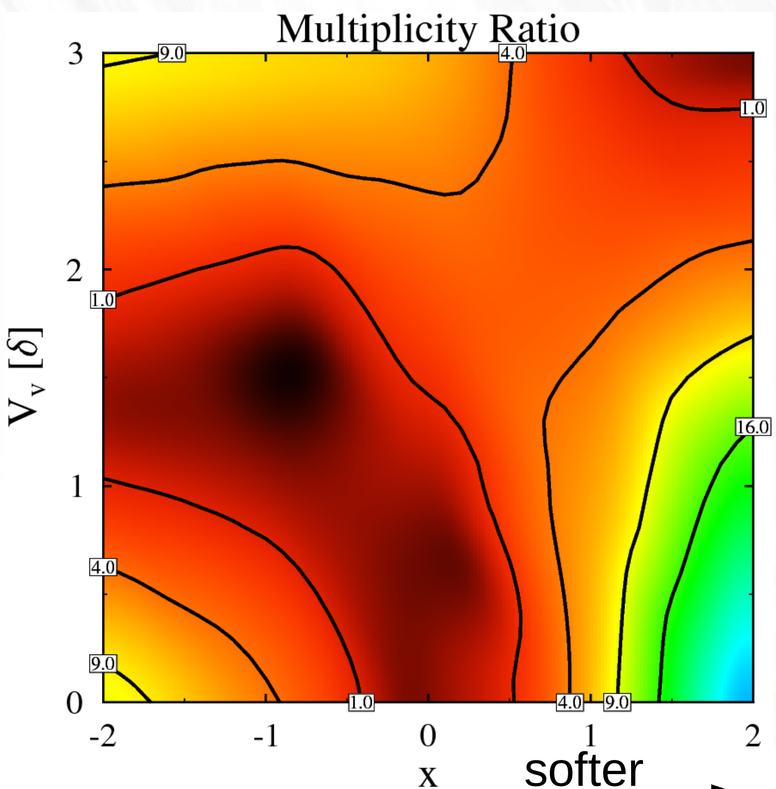
$$V(\Delta^{+}) = V_s + \frac{1}{2} V_v \qquad V_s = \frac{1}{2}(V_n + V_p)$$

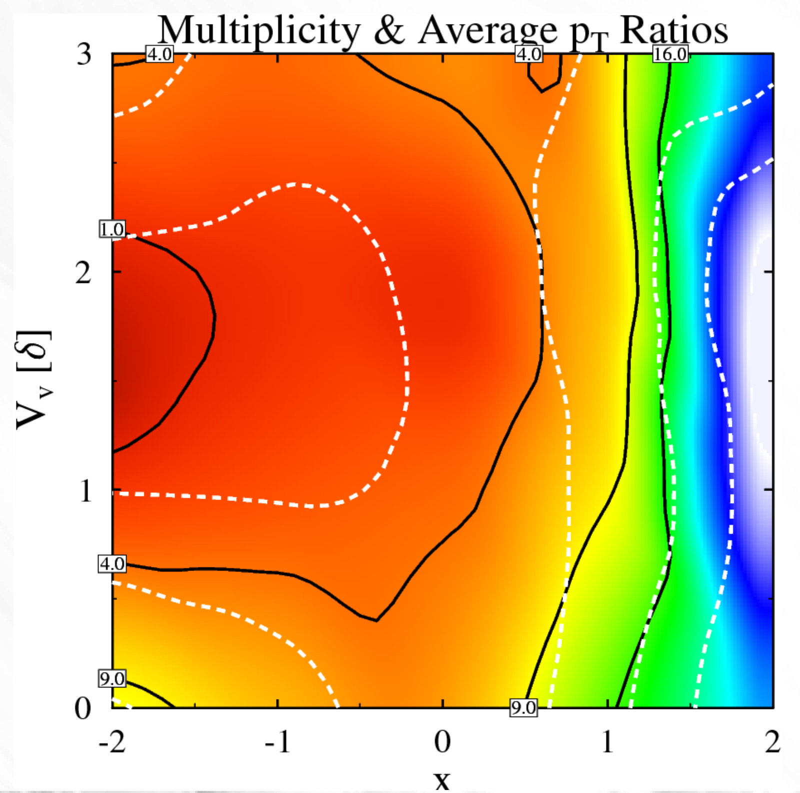
$$V(\Delta^{0}) = V_s - \frac{1}{2} V_v \qquad \delta = \frac{1}{3}(V_n - V_p)$$

$$V(\Delta^{-}) = V_s - \frac{3}{2} V_v$$

Lower limits for L:

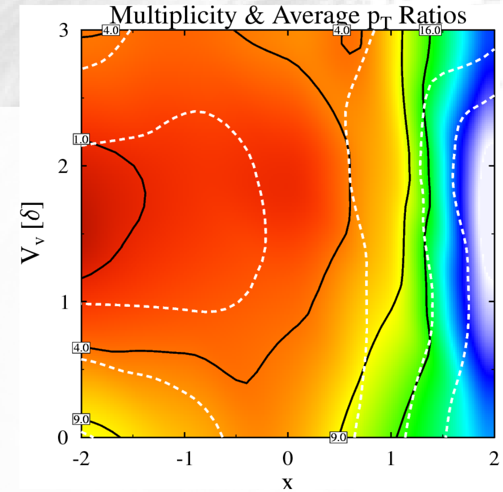
$$L \geq 10\,\mathrm{MeV} \quad (3\sigma)$$
$$L \geq 30\,\mathrm{MeV} \quad (2\sigma)$$





Nucleon Optical Potentias:

Gogny: Das, Das Gupta, Gale, Li PRC67, 034611 (2003)
HA: Hartnack, Aichelin, PRC 49, 2901 (1994)



Conclusions

To be able to constrain SE from pion observables in HIC:

- enlarge the list of observable included in the fit (+pion $\langle p_T \rangle$ ratios)
- include pion optical potential

Impact of pion optical potential:

- multiplicity ratios – small
- p_T multiplicity spectra – important reduction/enhancement at low/high p_T (factor of 2 at 250 AMeV)
- $\langle p_T \rangle$ - both S and P wave contributions are important
- $\langle p_T \rangle$ ratios – S wave has an important impact

Average p_T ratios:

- important impact from in-medium effects on cross-sections, in-medium delta potential, nucleon optical potential, pion potential
- large differences between the VEC, LEC and GEC scenarios

Constraint for SE: a lower limit on L can be extracted from comparison with FOPI data

$$L \geq 10\,\text{MeV} \quad (3\sigma) \qquad L \geq 30\,\text{MeV} \quad (2\sigma)$$

To do list:
- impact of in-medium cross-sections
- energy dependence of S wave pion potential
- model dependence due to nucleon optical potential
- include in the constraint the individual $\langle p_T \rangle$ rather than their ratio