The π^-/π^+ multiplicity ratio in heavy-ion collisions and the conservation of energy

Dan Cozma

IFIN-HH
Magurele-Bucharest, Romania

dan.cozma@theory.nipne.ro

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Symmetry Energy

EoS of Asymmetric Nuclear Matter

$$E(\rho,\beta)=E(\rho,\beta=0)+S(\rho)\beta^2 \quad \beta=\frac{\rho_n-\rho_p}{\rho}$$

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

Theoretical estimates of L and K

B.A. Li *et al.* Int.J.Mod.Phys. E7, 147 (1998)

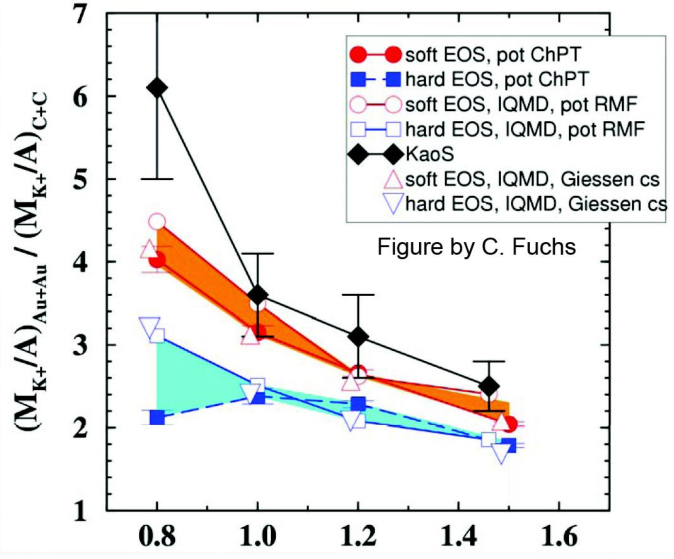
Force	Paris	SKM*	SI′	SIII	DHF (b)	DHF (e)
L	68.8	45.78	35.34	9.91	132	138
K_{sym}	37.56	-155.9	-259.1	-393.7	466	276

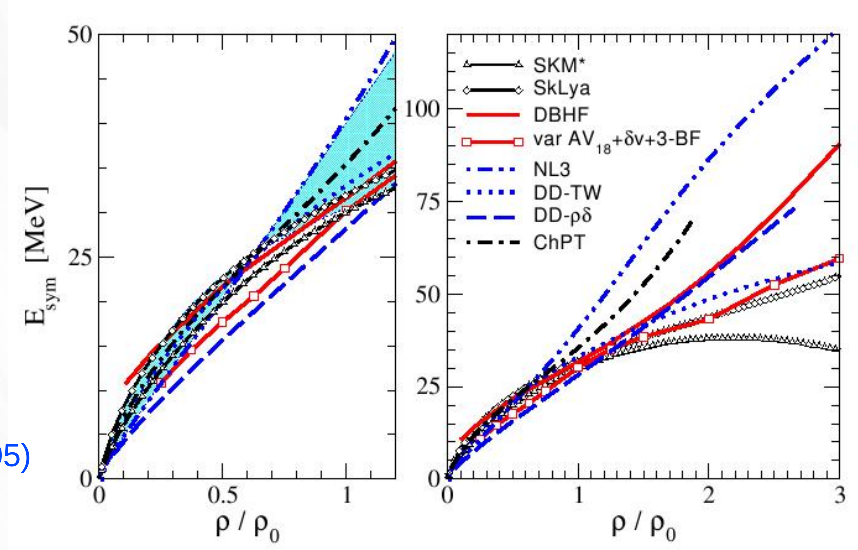
Experiment

isospin diffusion/neutron skin thickness of Pb: $L_{sym} \simeq 65$ MeV B.A. Li *et al.* PRC 72,064611 (2005)

giant monopole resonances:
K_{sym} -566 +/- 1350 MeV; 34 +/- 159 MeV
S. Shlomo *et al.* PRC 47, 529 (1993)

C. Fuchs *et al.* PRL 86, 1974 (2001)





See also: M.B. Tsang *et al.* PRC86, 015803 (2012)

Transport Model

Quantum Molecular Dynamics (TuQMD):

Monte Carlo cascade + Mean field + Pauli-blocking+ in medium cross section

all 4$\ast$ resonances below 2 GeV - 10 Δ^* and 11 N^*

baryon-baryon collisions:

all elastic channels

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

pion-absorption ⇋ resonance-decay channels: $\Delta \leftrightarrow N\pi$, $\Delta^* \leftrightarrow \Delta\pi$, $N^* \leftrightarrow N\pi$

meson production/absorption: η(547), ρ(770), ω(782), η'(958), f_0(980), a_0(980), Φ(1020)

previously applied to study:

-dilepton emission in HIC: K.Shekter, PRC 68, 014904 (2003);D. Cozma, PLB640,170 (2006); E.Santini PRC78,03410 (2008)
-EoS of symmetric nuclear matter: C. Fuchs, PRL 86, 1974 (2001); Z.Wang NPA 645, 177 (1999)
-In-medium effects and HIC dynamics: C. Fuchs, NPA 626,987 (1997); U. Maheswari NPA 628,669 (1998)

upgrades implemented in Bucharest:

-various parametrizations for the EoS: optical potential, symmetry energy(powerlaw, Gogny)
-threshold effects for baryon resonance reaction emission absorption, π emission/absorption
-clusterization algorithms (MST, SACA): not up to the task yet
-**planned**: in-medium pion potential, account for threshold effects for reactions involving strangeness degrees of freedom

Isospin dependence of EoS

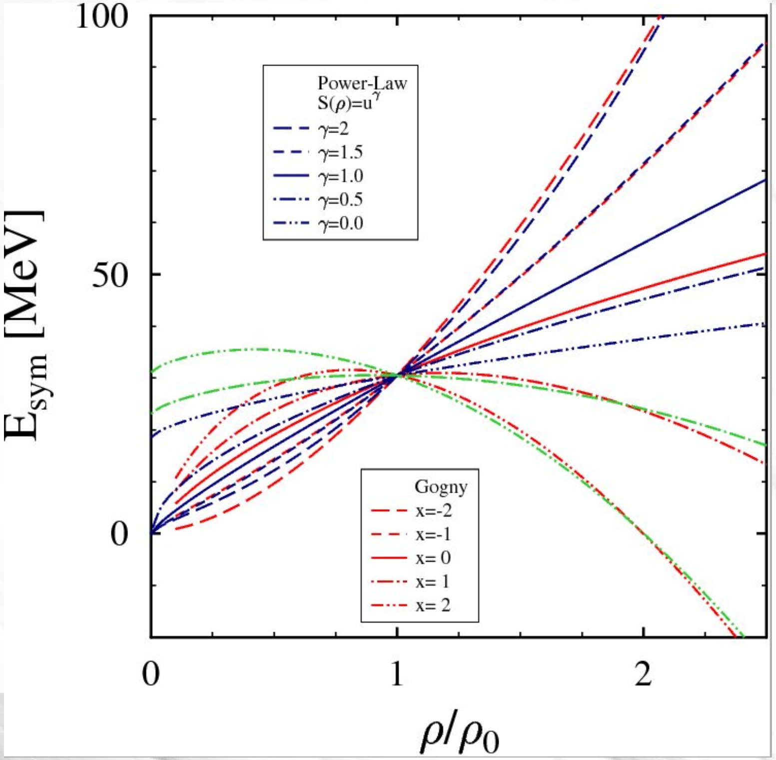
a) momentum dependent – generalization of the Gogny interaction:

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



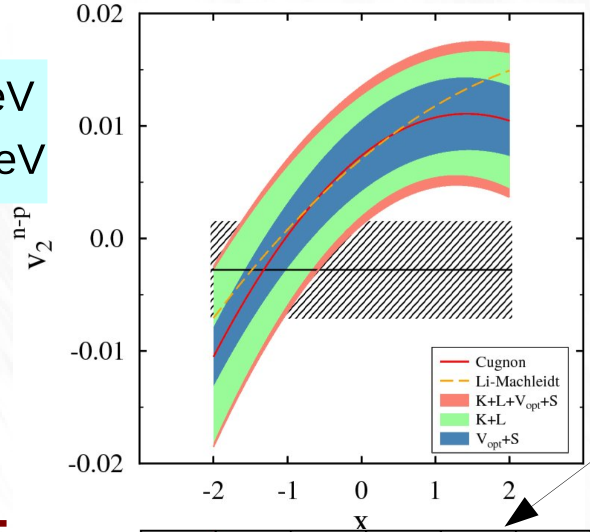
b) momentum dependent – power law

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

Constraints using elliptic flow

flow difference:

$L_{sym} = 129^{+46}_{-80}$ MeV
$K_{sym} = 272^{+291}_{-508}$ MeV



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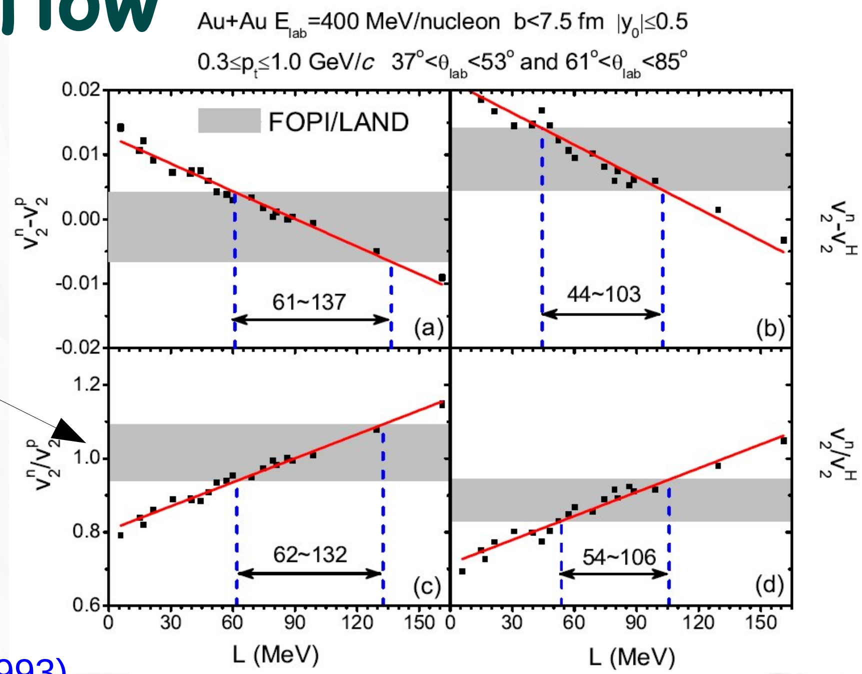
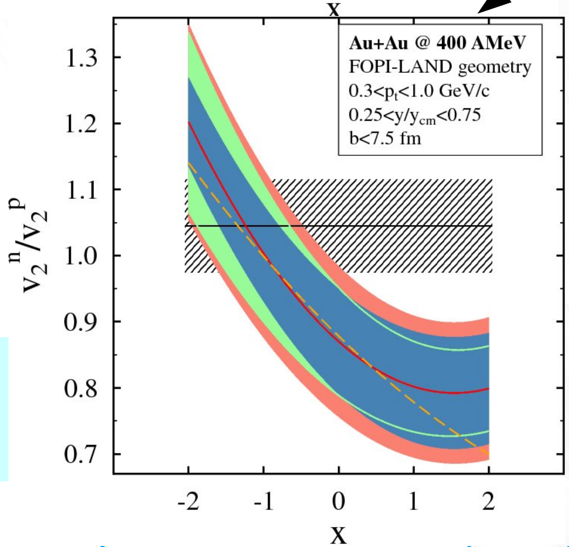


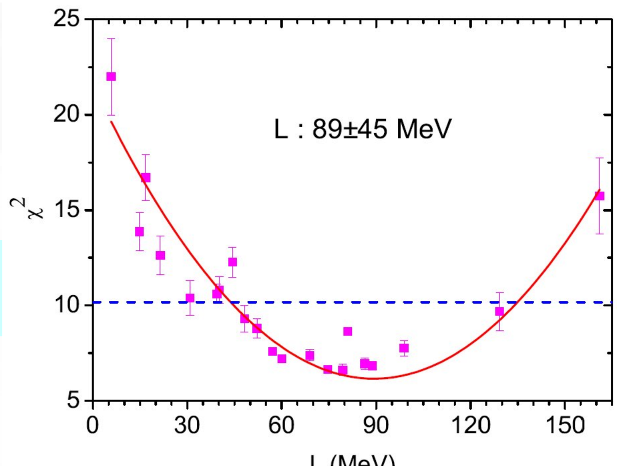
flow ratio:



Y.Leifels et al.,
PRL 71, 963 (1993)

$L_{sym} = 118^{+45}_{-57}$ MeV
$K_{sym} = 199^{+291}_{-362}$ MeV

$L_{sym} = 89 \pm 45$ MeV



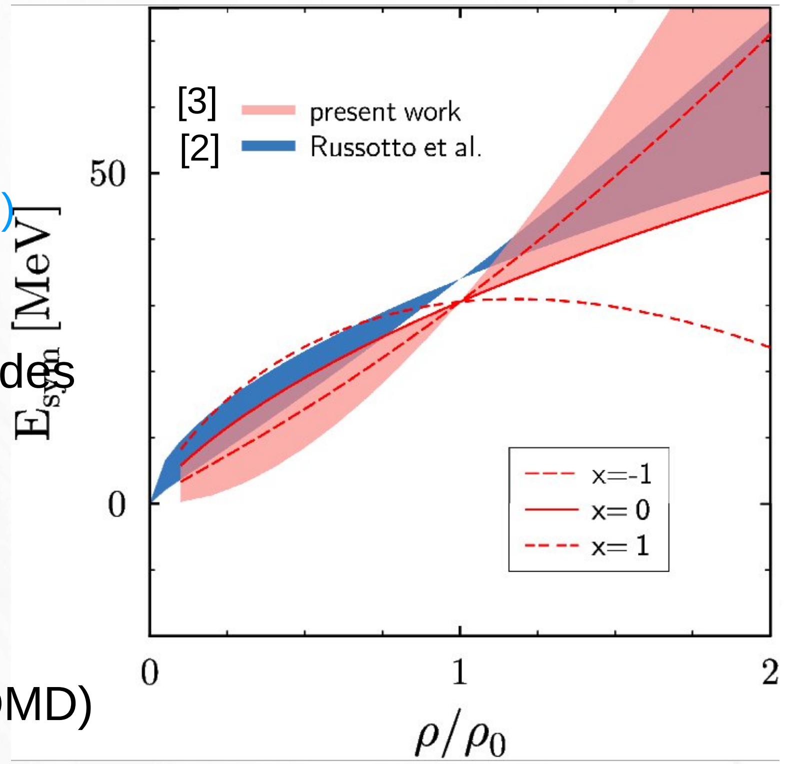
M.D. Cozma et al. PRC 88, 044912 (2013)

Y. Wang et al. ArXiv: 1403.7041(2014)

Density dependence of SE

studies presented in

[1] M.D. Cozma, PLB 700, 139 (2011)
[2] P. Russotto *et al.*, PLB 697, 471 (2011)
[3] M.D. Cozma *et al.*, PRC 88, 044912(2013)
[4] W.-M. Guo *et al.*, PLB 726, 211 (2013)
[5] Y. Wang *et al.*, ArXiv: 1403.7041(2014)



-**Independently developed** transport codes and upgrades
QMD – Tuebingen/ upgraded in Bucharest
UrQMD – Frankfurt/ upgraded Q.Li et al. Huzhou
IBUU – G.-C. Yong et al. (IMP, Lanzhou, China)

-**different parametrizations** of the symmetry energy
- momentum dependent (QMD/IBUU) /
momentum independent, Skyrme interactions (UrQMD)

-inclusion of **in-medium effects**
-in medium NN cross-section (QMD,IBUU,UrQMD)

-**thorough study** of various model parameters:
- width of nucleon wave-function (L)
- compressibility modulus of nuclear matter (K)
- impact of optical potential

similar result

[2,3] $L_{sym}=106\pm46$ MeV
$K_{sym}=127\pm290$ MeV

[5] $L_{sym}=89\pm45$ MeV

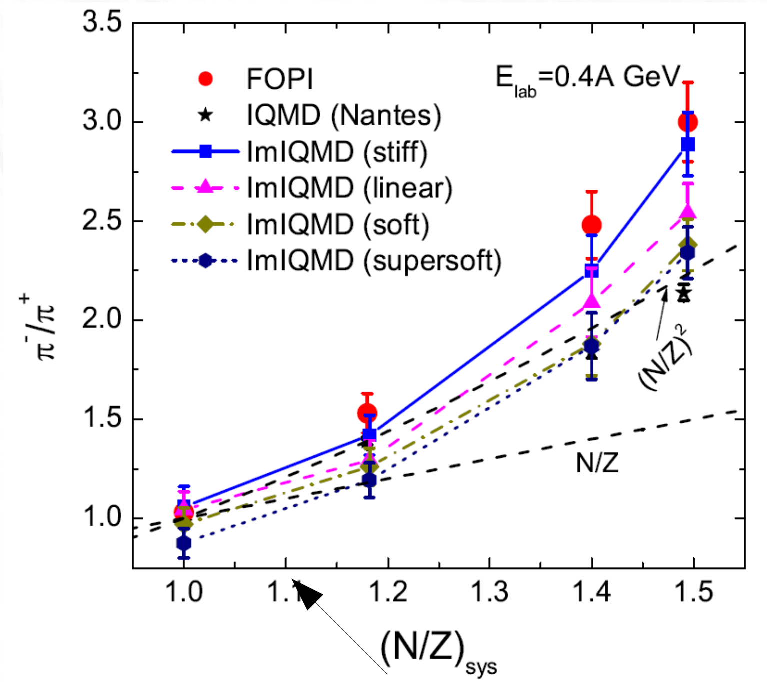
Pion ratios

Isobar model (no symmetry potential)

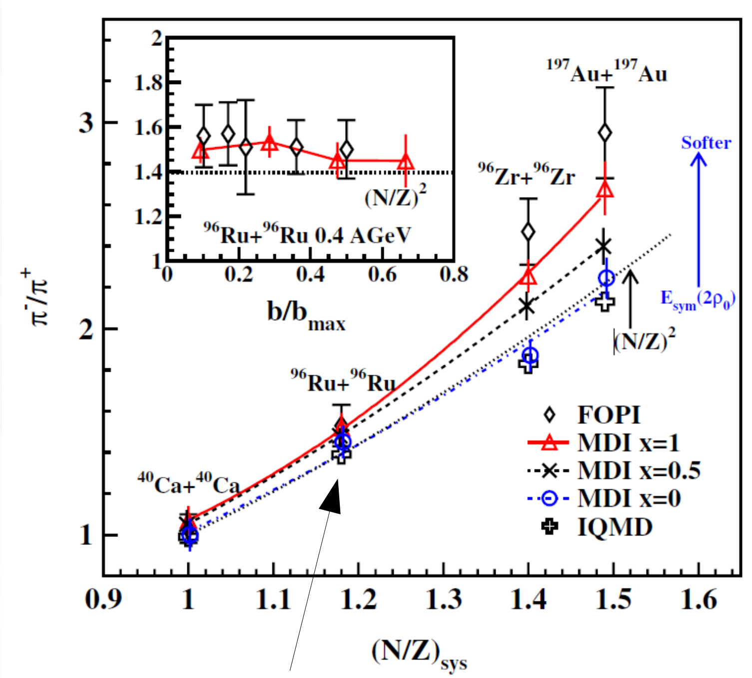
$$\pi^-/\pi^+=(5N^2+NZ)/(5Z^2+NZ)$$

Z.-Q. Feng et al., PLB 683, 140 (2010)

Z.Xiao et al. PRL 102,062502 (2009)



IQMD



IBUU

Boltzmann-Langevin aproach - super-soft W.-J. Xie et al., PLB 718, 1510 (2013)

pBUU – no sensitivity to stiffness of SE J. Hong et al. ArXiv: 1307.7654 [nucl-th]

TuQMD – super-soft scenario favored (opposite to elliptic flow constraint)

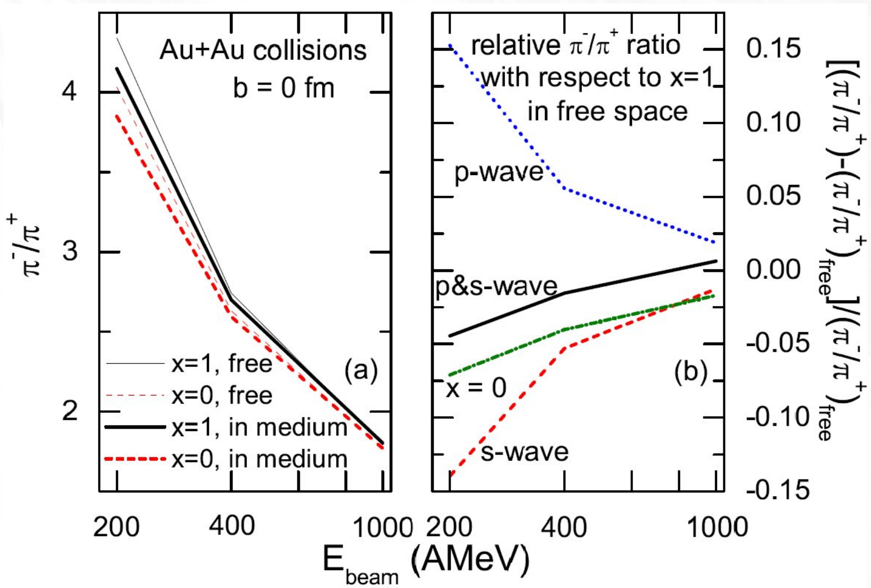
Medium Effects

-pion production threshold in asymmetric & hot nuclear matter

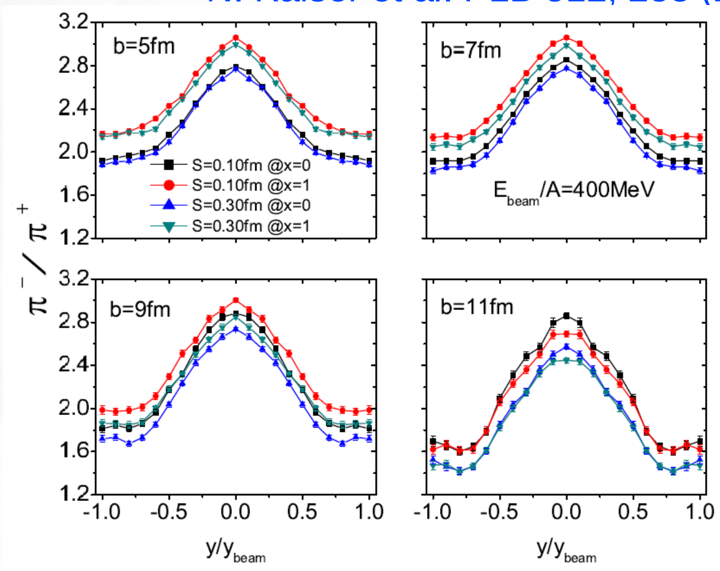
C.L. Korpa et al. PLB 446, 15 (1999)

-charge dependent pion mass shift driven by S wave πN interaction (ChPT)

N. Kaiser et al. PLB 512, 283 (2001)



J. Xu et al. PRC 87, 067601 (2013)



G.-F. Wei et al. ArXiv: 1309.7717

Pitfalls: - S wave pion potential needed to explain pionic atoms 2x more repulsive

- isospin breaking effects in the Δ(1232) mass/decay widths

Energy conservation (in-medium)

$$\sqrt{p_1^2+m_1^2}+U(p_1)+\sqrt{p_2^2+m_2^2}+U(p_2)=\sqrt{p'^2_1+m'^2_1}+U(p'_1)+\sqrt{p'^2_2+m'^2_2}+U(p'_2)$$

- rarely considered in transport models below 1 AGeV, with a few exceptions:
  G. Ferini et al. PRL 97, 202301 (2006), C.Fuchs et al. PRC 55, 411 (1997), T.Song et al. ArXiv:1403.7363 (2014)
- Ansatz for the isospin 3/2 resonance potential motivated by decay channel – see also S.A. Bass et al., PRC 51, 3343 (1995)
- imposed in the CM of the colliding nuclei (not in Eckart frame)
- reactions: NN↔NR, R↔Nπ (R↔Nππ not corrected)

$$U(\Delta^{++})=U^p$$
$$U(\Delta^{+})=\frac{2}{3}U^p+\frac{1}{3}U^n$$
$$U(\Delta^{0})=\frac{1}{3}U^p+\frac{2}{3}U^n$$
$$U(\Delta^{-})=U^n$$

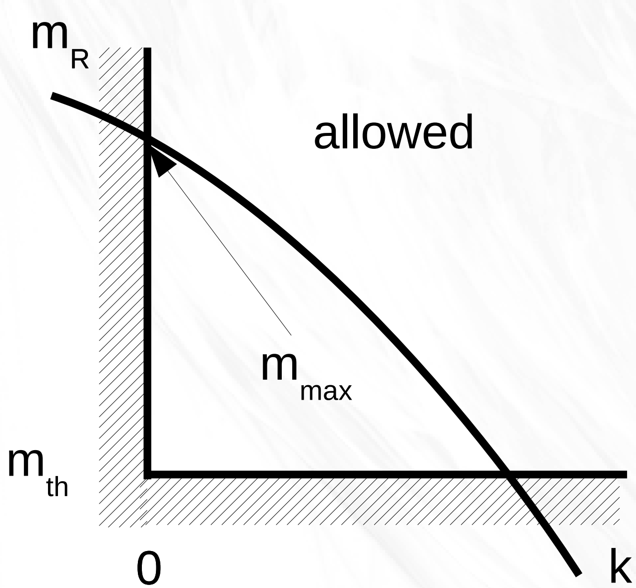
Reaction	$\Delta U=U^f-U^i$	Effect
nn → pΔ^-	$U^p-U^n<0$	more π^-
nn → nΔ^0	$1/3(U^p-U^n)<0$	more π^-, π^0
np → pΔ^0	$1/3(U^p-U^n)<0$	more π^-, π^0
np → nΔ^+	$1/3(U^n-U^p)>0$	less π^+, π^0
pp → pΔ^+	$1/3(U^n-U^p)>0$	less π^+, π^0
pp → nΔ^{++}	$U^n-U^p>0$	less π^+

Approximations

final state phase space in NN->NR

VEC

$$\sqrt{s} = \sqrt{m_N^2 + k^2} + \sqrt{m_R^2 + k^2}$$



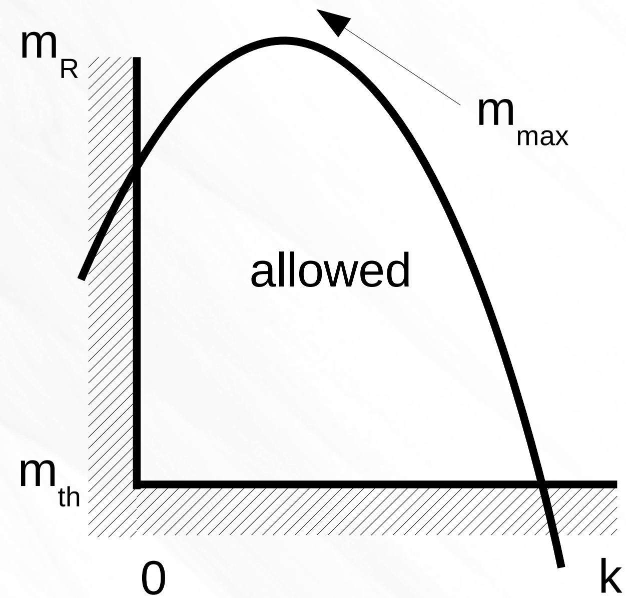
$m_{th} \leqslant m_R \leqslant m_{max}$

$0 \leqslant \theta \leqslant \pi$

$0 \leqslant \Phi \leqslant 2\pi$ consistent with $\frac{d\sigma}{d\Omega}$

LEC, GEC

$$\sqrt{\tilde{s}} = \sqrt{m_N^2 + k^2} + V_N(p_N) + \sqrt{m_R^2 + k^2} + V_R(p_R)$$



$m_{th} \leqslant m_R \leqslant m_{max}$ → $m_{th} \leqslant m_R \leqslant m_R(k=0)$

$\theta_{min} \leqslant \theta \leqslant \theta_{max}$

$\Phi_{min} \leqslant \Phi \leqslant \Phi_{max}$

} approximate to vacuum case

Different "scenarios"

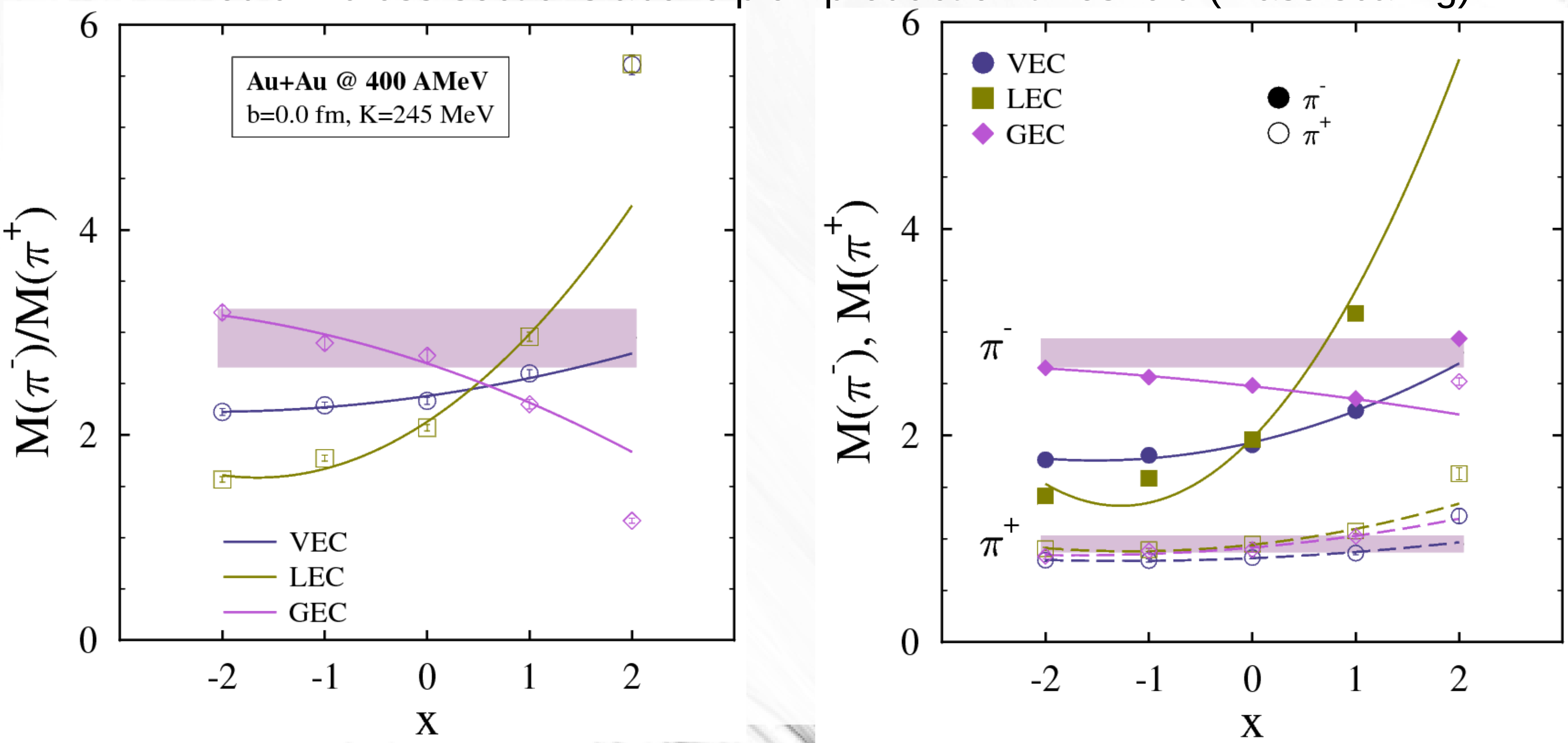
T. Song, C.M. Ko arXiv:1403.7363 (similar)

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 above pion production threshold (mass scaling)



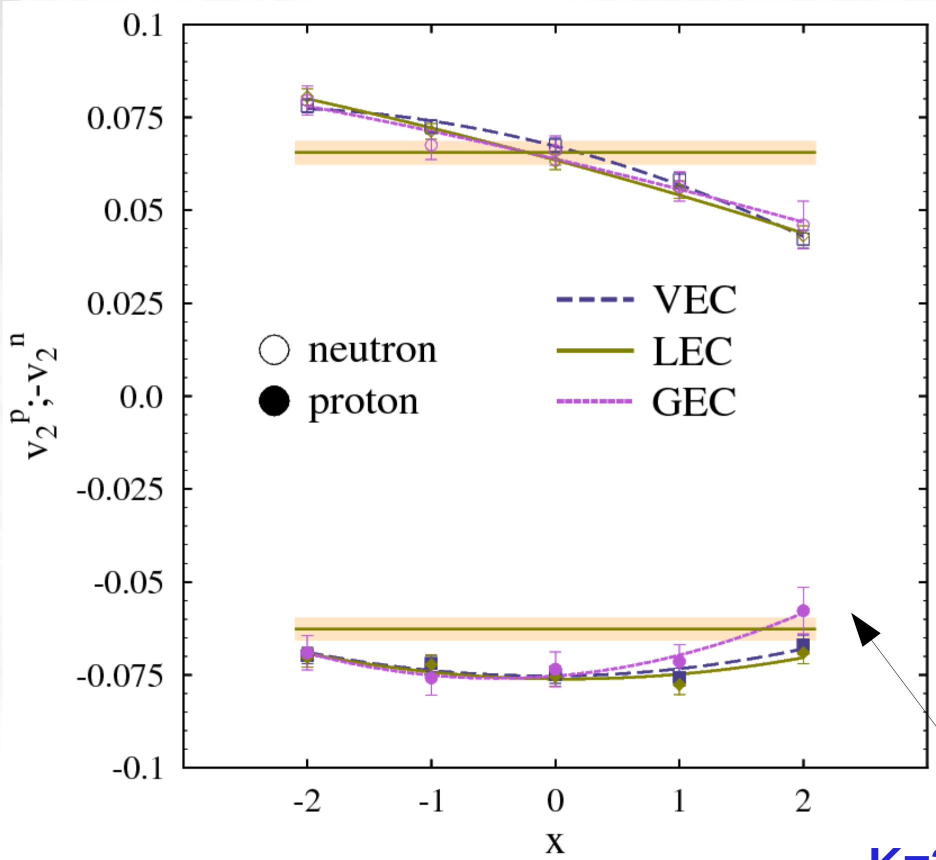
Experimental data: W. Reisdorf et al. (FOPI) NPA 848, 366 (2010)

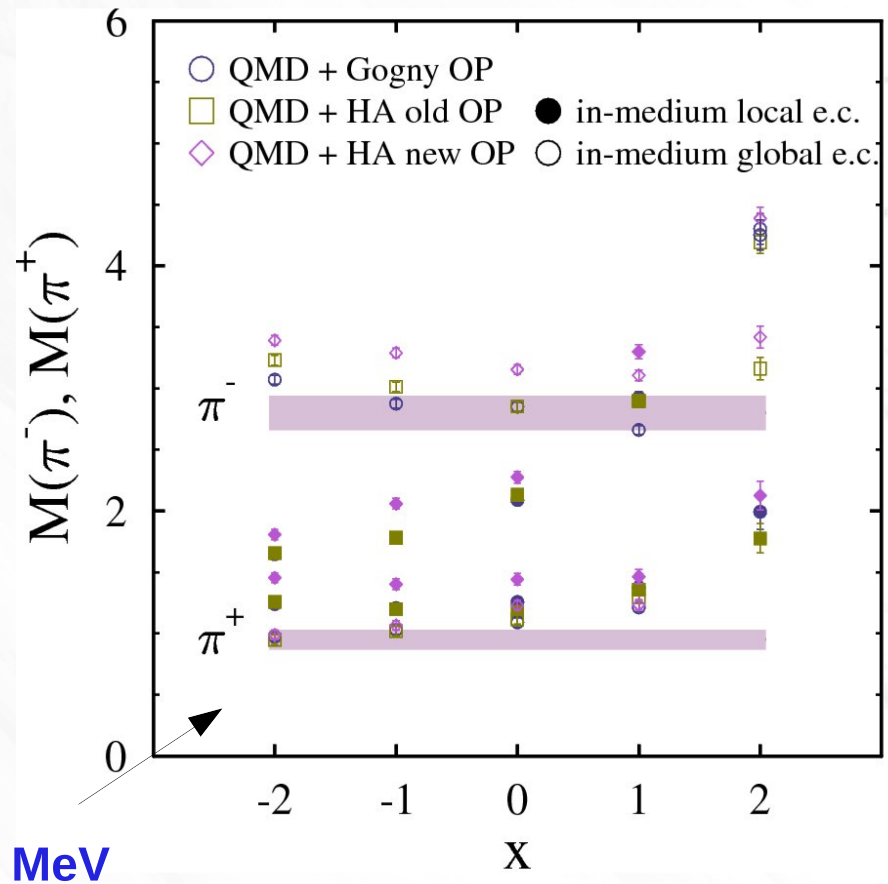
Arguments for in-medium cross-sections

-vacuum cross-section – difficult to describe exp. FOPI-LAND v_2 and FOPI π data

-detailed analysis of FOPI light particle flow data: K=230±30 MeV

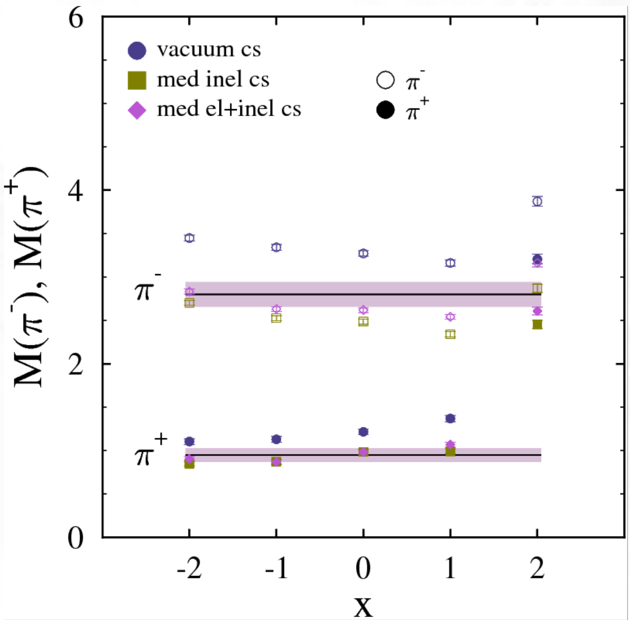
Y.Wang et al., PRC 89, 034606 (2014)



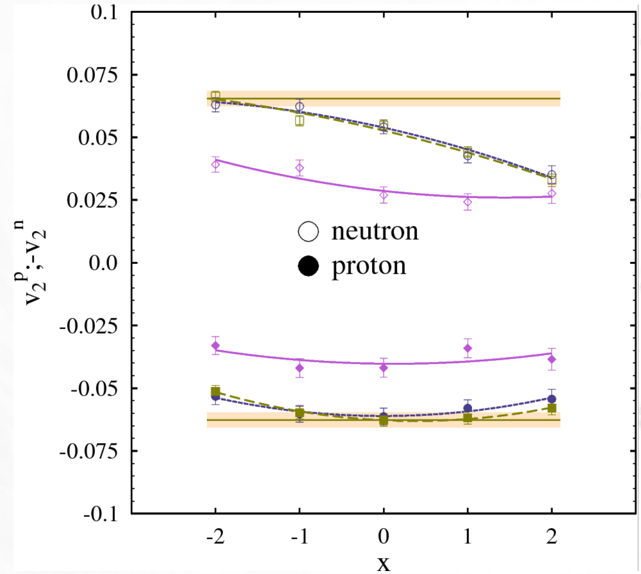


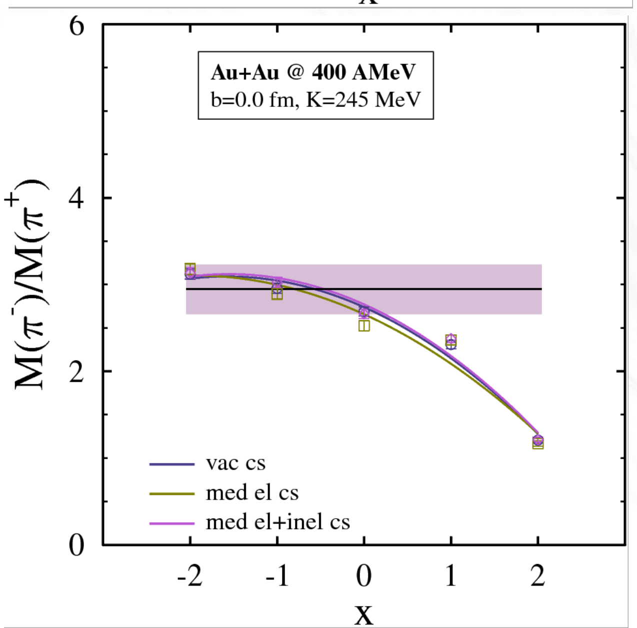
K=300 MeV

Pion ratio vs Elliptic Flow



consistency
between
pion ratio and
elliptic flow
constraints **can**
be achieved

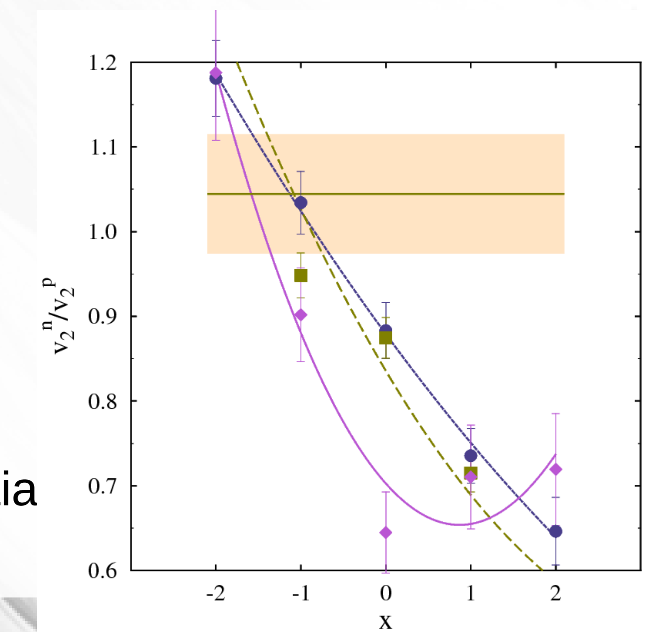




conservation
of the total energy
of the system

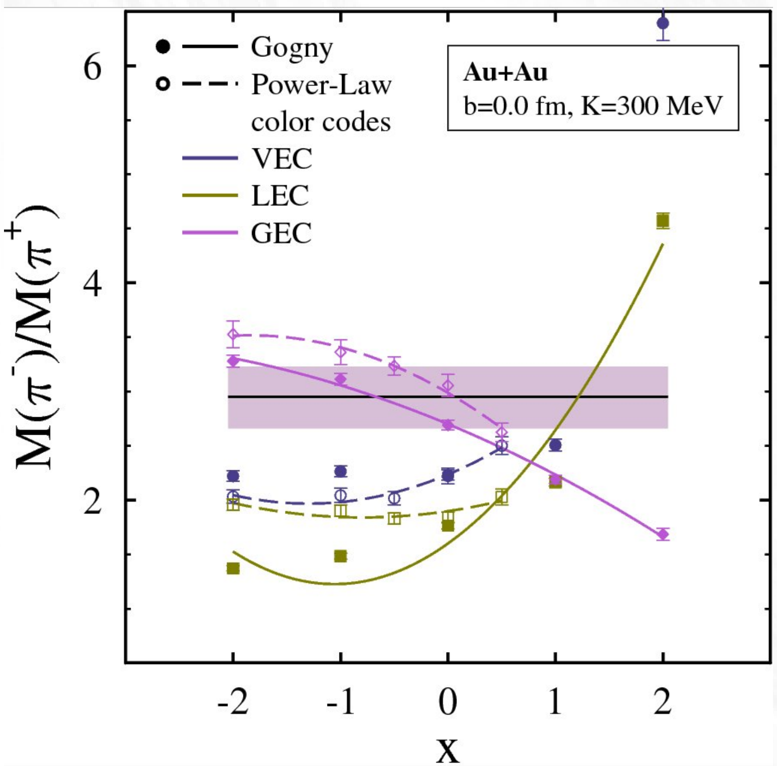
+

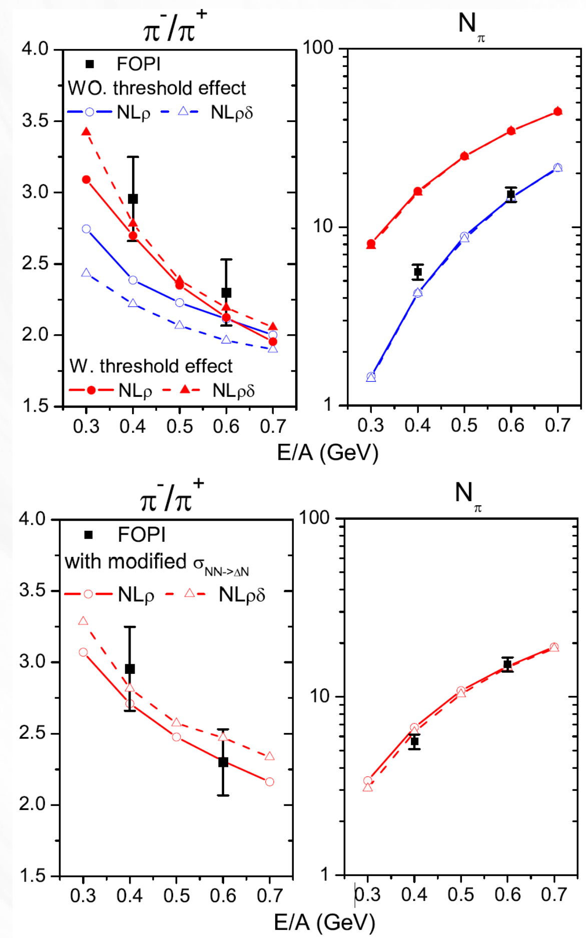
finer details:
medium modified
cross-sections,
delta isobar potentia



Comparison with RVUU

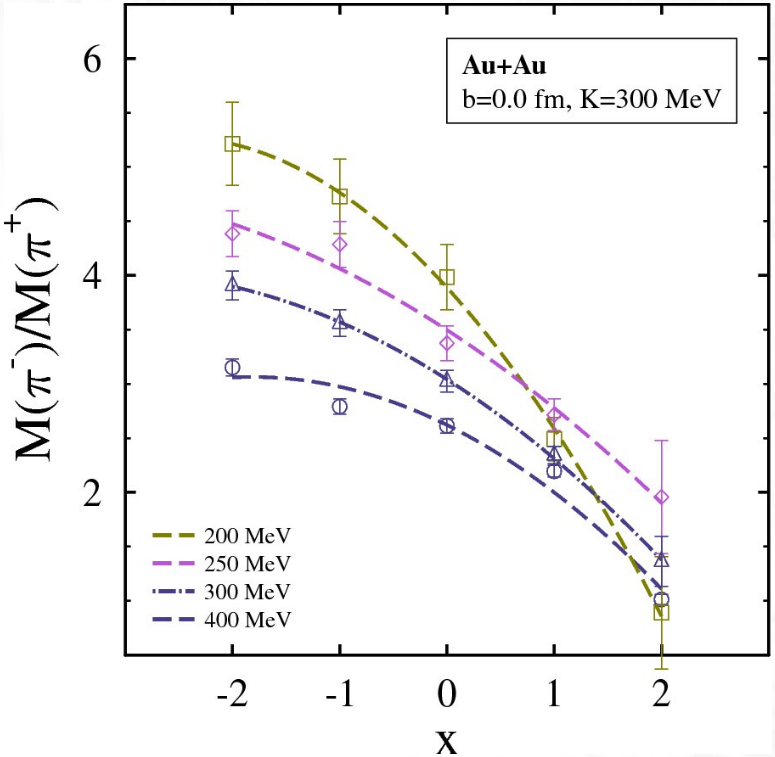
- recent similar calculation (LEC): T. Song, C.M. Ko arXiv:1403.7363
- QMD: impact of neutron-proton effective mass splitting

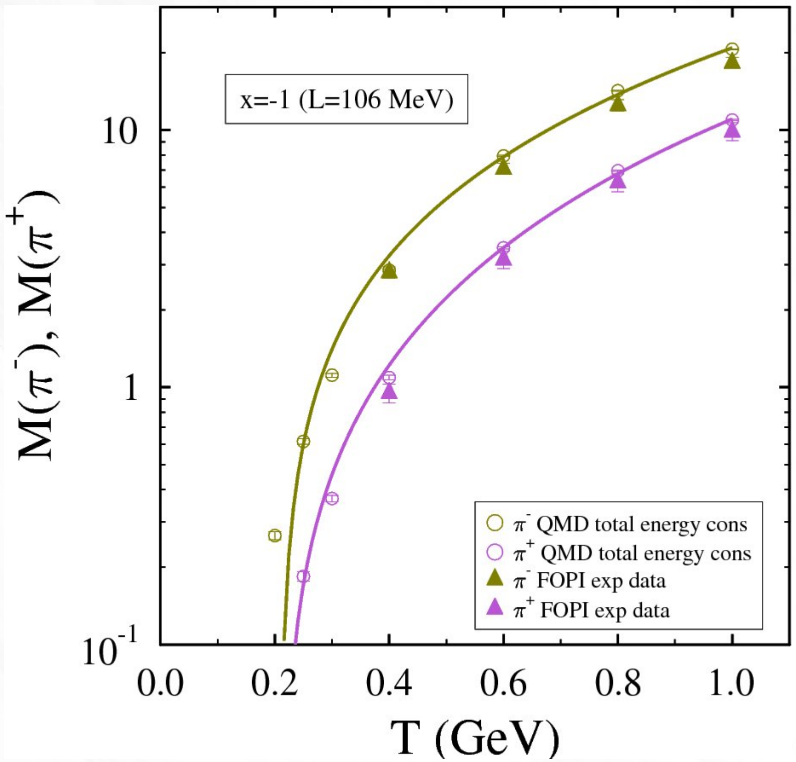




Energy dependence

Samurai (TPC+Nebula Collaboration)
-<u>pion production</u>, flow (including neutrons)
-energies 285-350 MeV
$^{132}Sn+^{124}Sn$, $^{105}Sn+^{112}Sn$





Impact of the Δ(1232) potential

Phenomenology – inclusive electron nucleus scattering (He,C,Fe) attractive

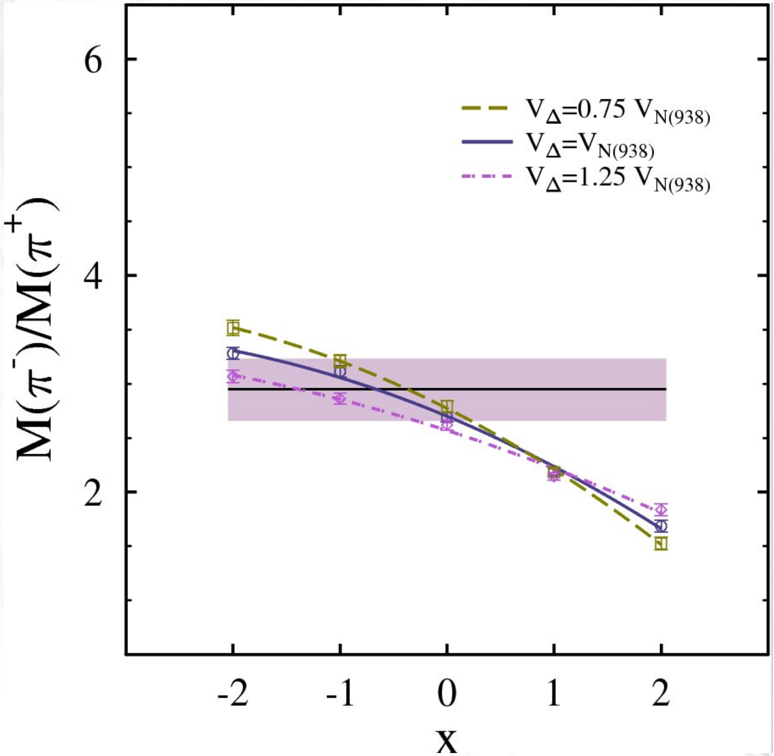
- Δ-nucleus potential deeper than the nucleon-nucleus potential

O'Connel, Sealock PRC 42, 2290 (1990)

Ab initio calculations – Argonne v_{28} interaction => repulsive Δ potential

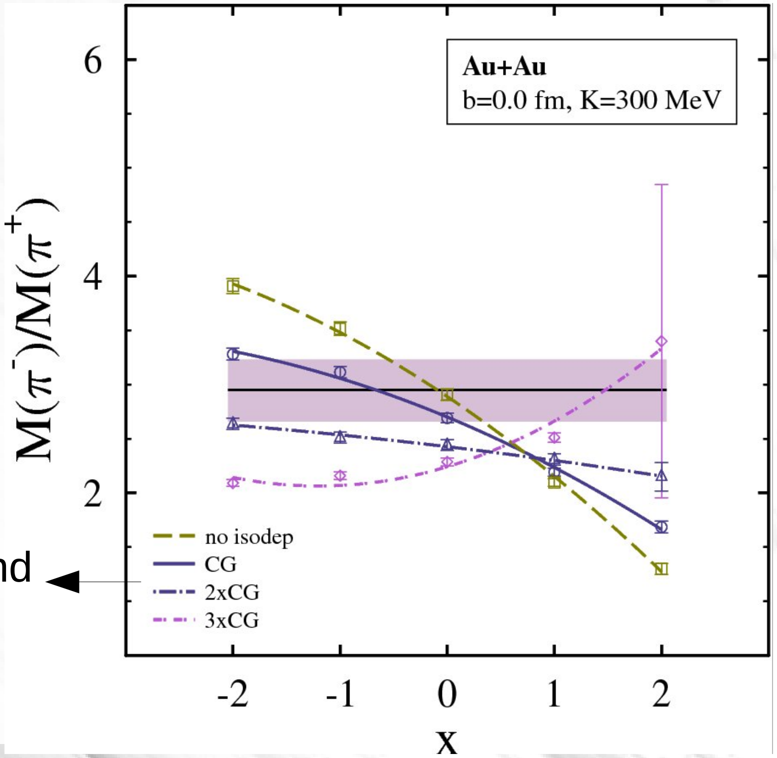
Baldo, Ferreira NPA 569, 645 (1994) - 3D reduction of Bethe-Salpeter equation similar

Malfliet, de Jong PRC 46, 2567 (1992) - strong dominant repulsive contribution from T=2 sector



$$U(\Delta^{++}) = U^p$$
$$U(\Delta^{+}) = \frac{2}{3}U^p + \frac{1}{3}U^n$$
$$U(\Delta^{0}) = \frac{1}{3}U^p + \frac{2}{3}U^n$$
$$U(\Delta^{-}) = U^n$$

centered around $1/2(U^n+U^p)$



Conclusions

Conservation of Energy: important impact on pion multiplicities in heavy-ion collisions at few hundred MeV impact energy

pi-/pi+: - confirmed as sensitive to the stiffness of asy-EoS
- increased sensitivity below production threshold

However:
- isovector part of the in-medium Δ potential has a large/decisive impact
- the pion potential has yet to be taken into account
- precise density/asymmetry dependence of elastic/inelastic channels cross-sections important

Good news: -consistency between pion ratio and elliptic flow constraints can be achieved
-past approximations (VEC) and even LEC seem unrealistic

Perspectives: - effort on the theoretical side: in-medium baryon potentials
in-medium modification of cross-sections
- extend the study to strangeness d.o.f.

experimental side: -higher accuracy elliptic flow data
-pion multiplicity and spectra below production threshold

Worst case scenario: test of our understanding of hadronic interaction in the few hundred MeV energy domain