Impact of the In-Medium Conservation of Energy on the π^-/π^+ Multiplicity Ratio

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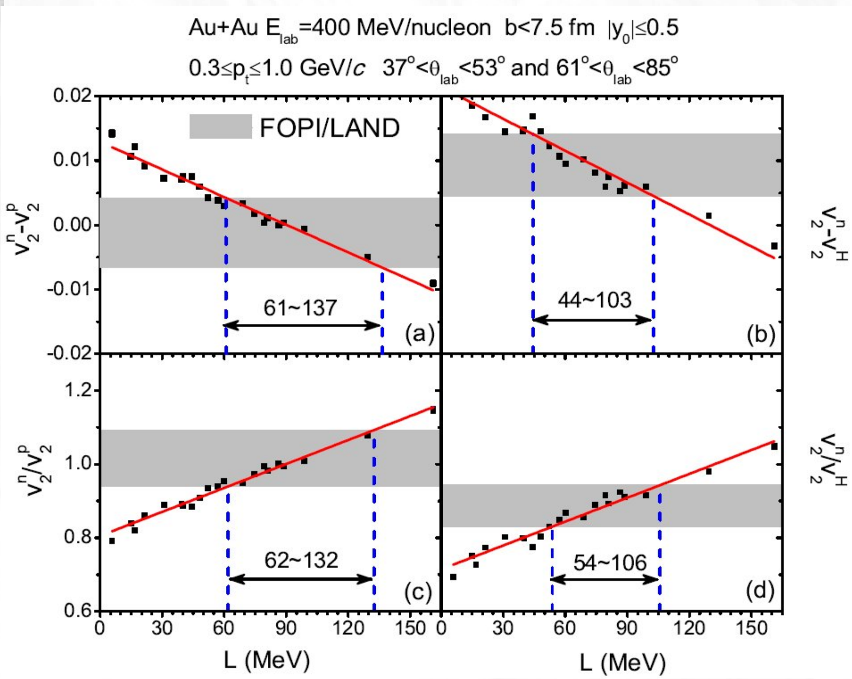
Elliptic Flow vs. Pion ratios

$$\frac{dN}{d\phi} \sim 1 + 2 v_1 \cos\phi + 2 v_2 \cos 2\phi$$

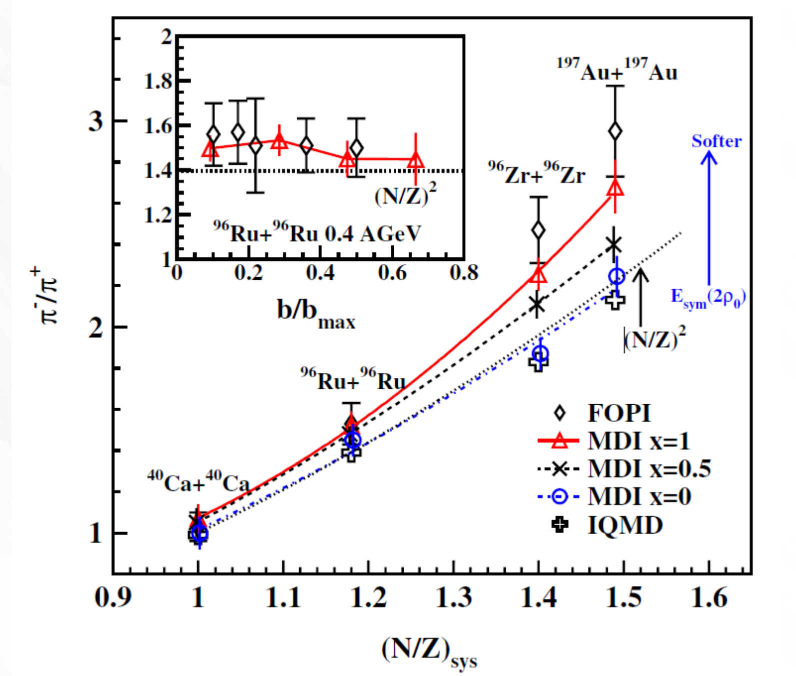
UrQMD - Y. Wang et al. PRC 89, 044603 (2014)



Isobar model (no symmetry potential)

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

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



TuQMD - linear/moderately stiff
M.D. Cozma et al. PRC 88, 044912 (2013)
UrQMD – linear
P. Russotto et.al PLB 697, 491 (2011)
IBUU - linear/moderately stiff
G.-C. Yong private communication

ImQMD – stiff
Z.-Q. Feng et al., PLB 683, 140 (2010)
Boltzmann-Langevin – super-soft
W.-J. Xie et al., PLB 718, 1510 (2013)
TuQMD (VEC) – super-soft
M.D. Cozma (arXiv:1409.3110)
pBUU – no sensitivity to SE
J. Hong et al. PRC 90, 024605 (2014)

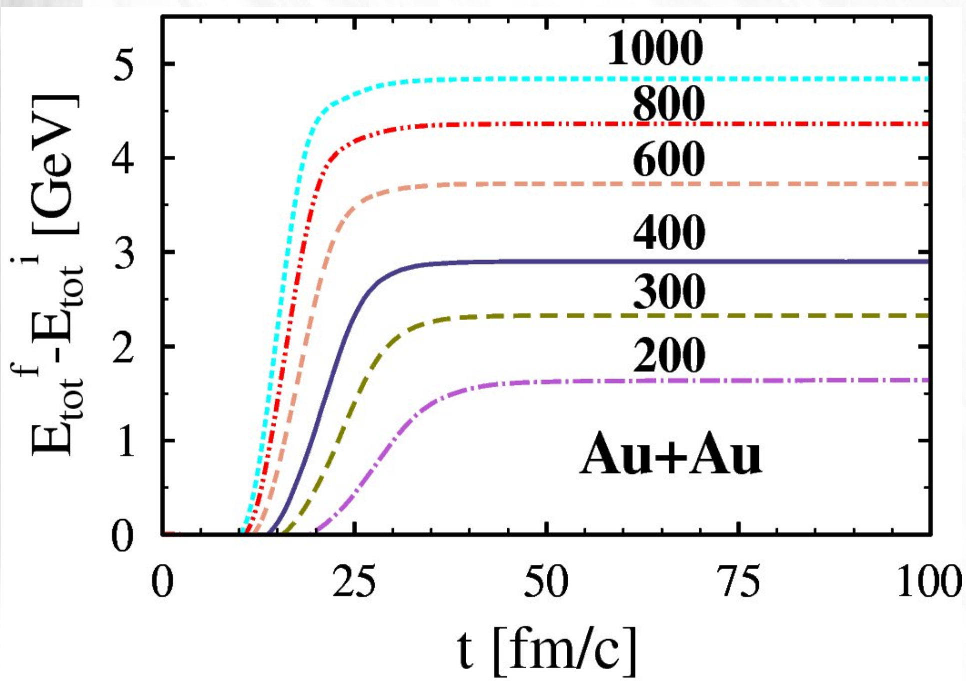
Energy Conservation -The Smoking Gun

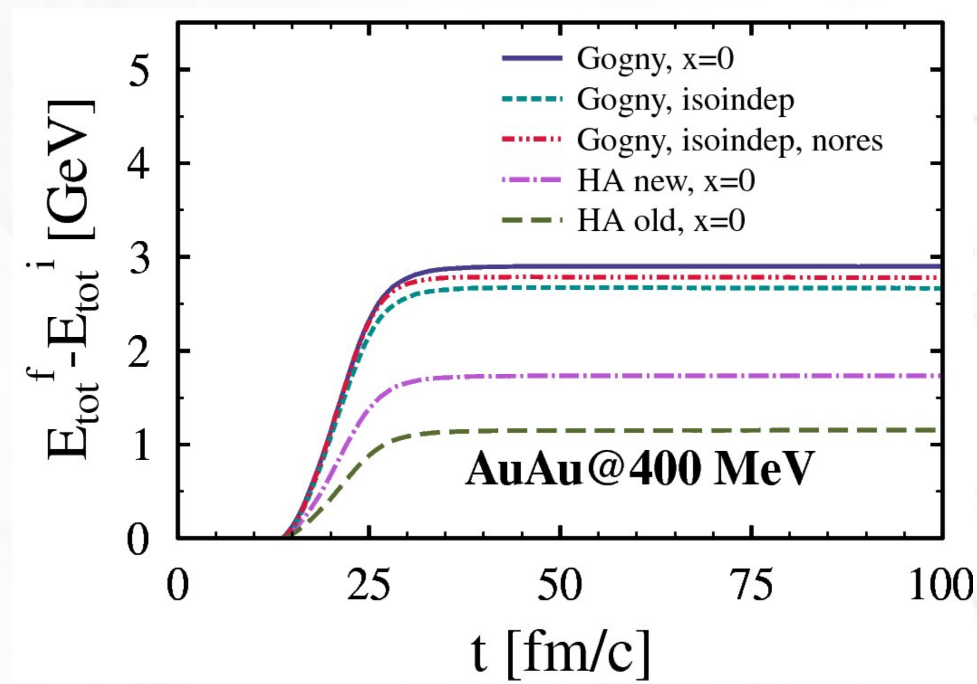
80's transport models – total energy conserved (potentials dependent only on density)

Collective phenomena – momentum dependence
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)

Transport Model

Quantum Molecular Dynamics (TuQMD):

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

all 4∗ 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: $\eta(547)$, $\rho(770)$, $\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\Phi(1020)$

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)

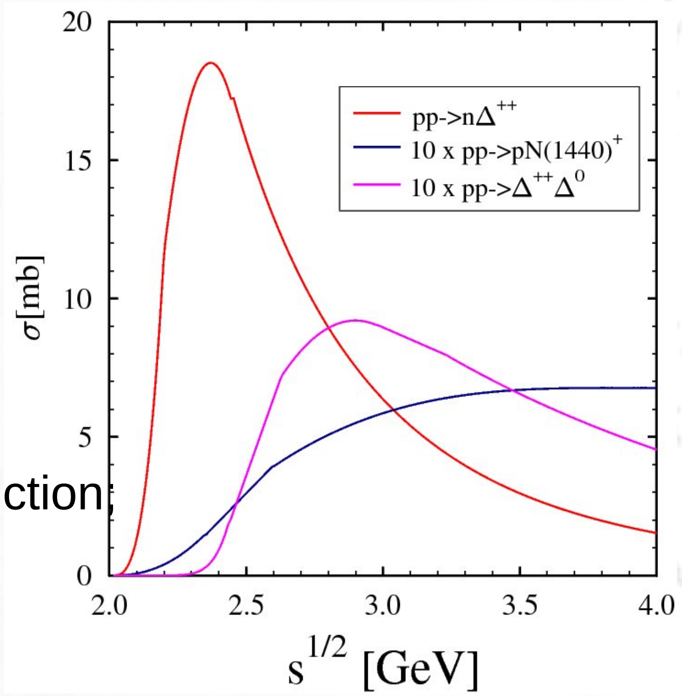
upgrades implemented in Bucharest:

- -various parametrizations for the EoS: optical potential, symmetry energy(power-law, Gogny)
- -threshold effects for baryon resonance reaction emission absorption, π emission/absorption
- -in-medium pion potential
- -clusterization algorithms (MST, SACA): promising preliminary results
- -**planned**:account for threshold effects for reactions involving strangeness degrees of freedom

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

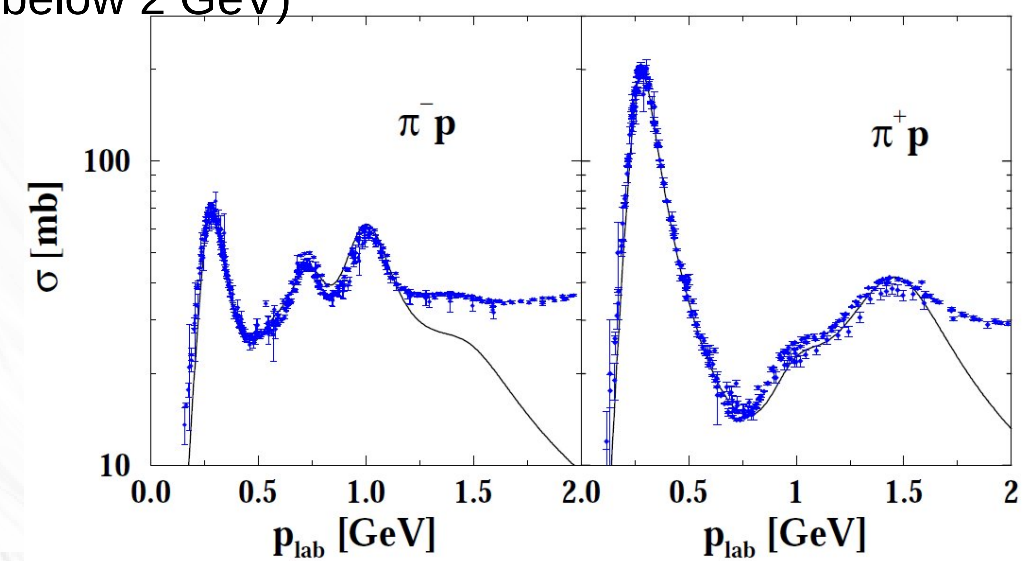
$V+B \rightarrow \pi+B', \pi+\pi+B'$

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

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

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

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



Isospin dependence of EoS

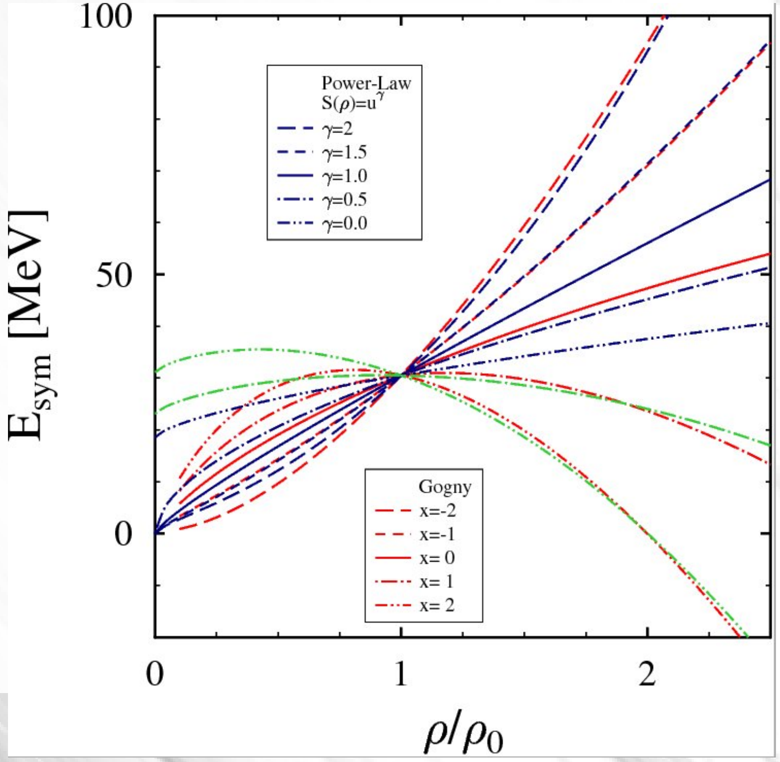
a) momentum dependent – generalization of the Gogny interaction:

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	-31	-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 (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, C.M. Ko PRC 91, 014901 (2015)
- 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 the Eckart frame)
- reactions: NN↔NR, R↔Nπ (R↔Nππ not corrected)

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

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

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

Elastic scattering:

$$\sqrt{s_f} \approx \sqrt{s_i}$$

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

Resonance excitation:

$$\sqrt{s_f} - \sqrt{s_i} \approx 25\,\mathrm{MeV}$$

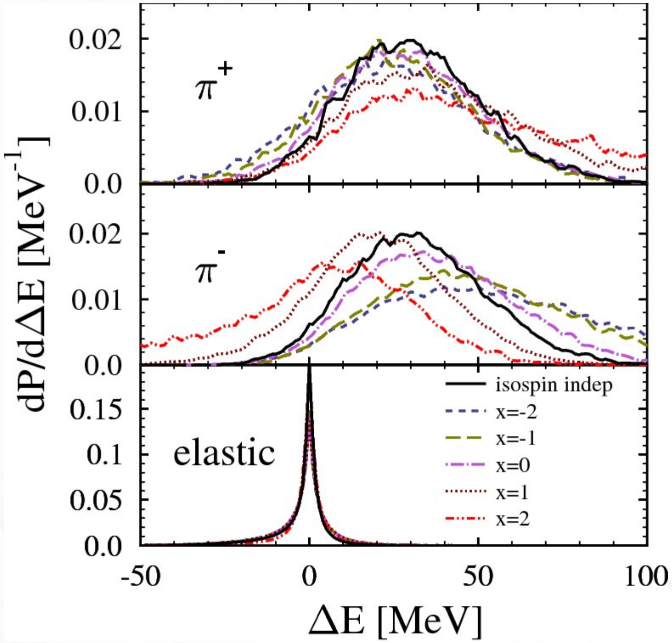
$$\sqrt{s^*} = \sqrt{s_f}$$

Resonance absorption: detailed balance

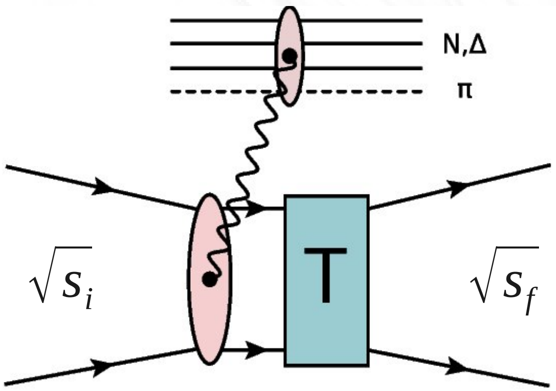
P. Danielewicz et al., NPA 533, 712 (1992)

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

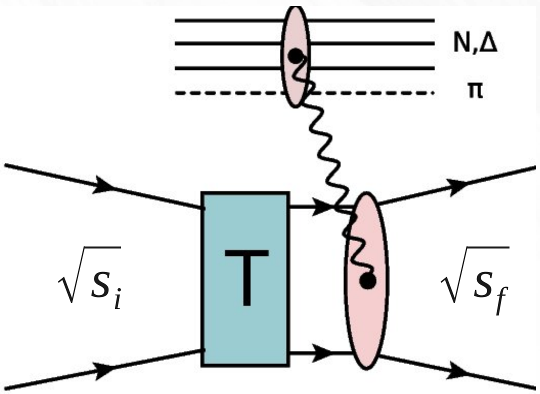
$$\sqrt{s_i} \to p_{NR}, \quad \sqrt{s_f} \to p_{NN}$$



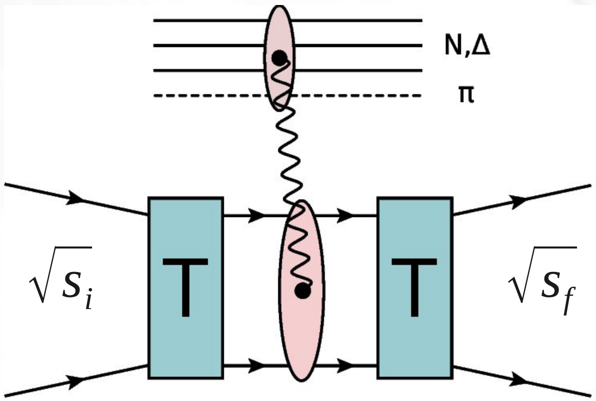
$$\Delta E = \sqrt{s_f} - \sqrt{s_i}$$



initial



final state



rescattering

Different “scenarios”

T. Song, C.M. Ko PRC 91, 014901 (2015)

(similar)

VEC – vacuum energy conservation constraint

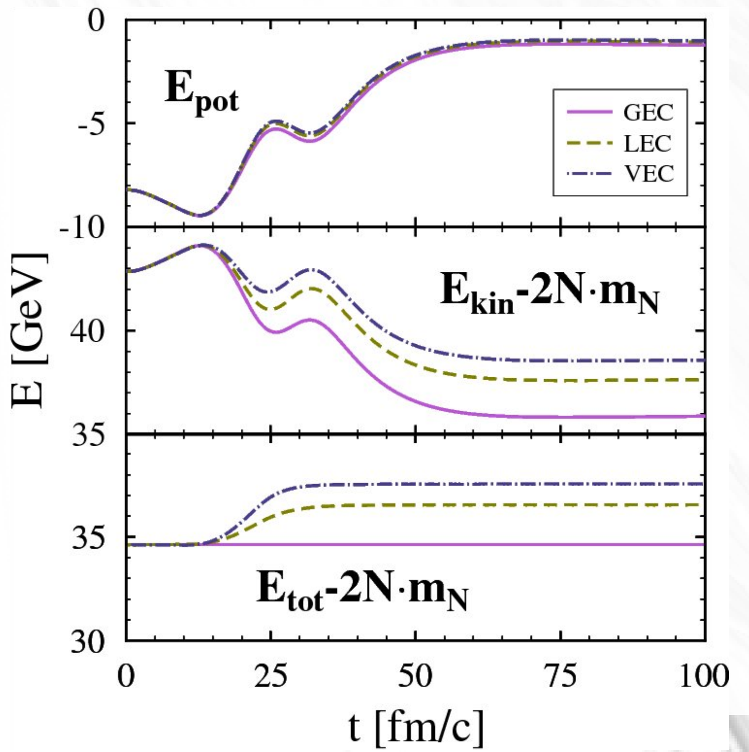
LEC - “local” energy conservation – limited impact on multiplicities and ratios

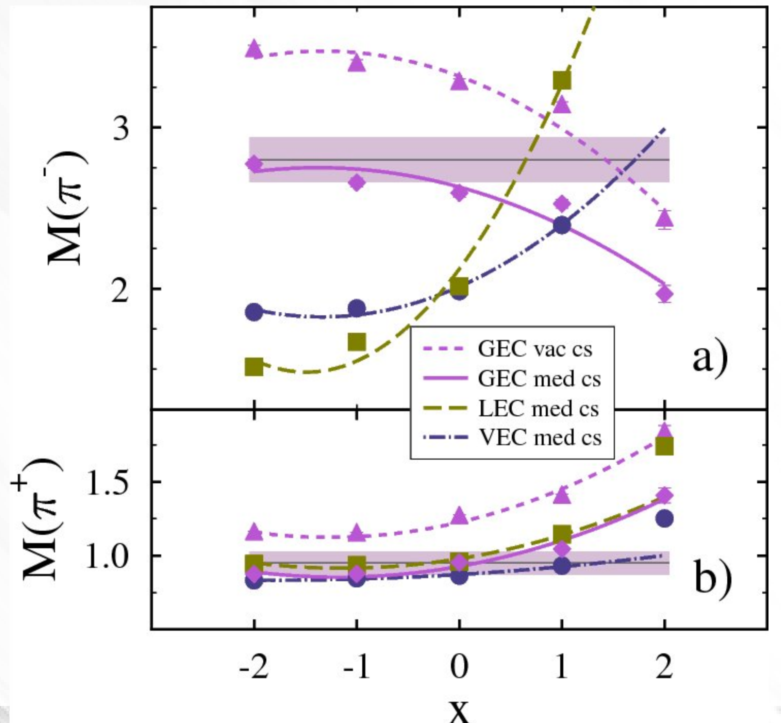
GEC- “global” energy conservation – conserve energy of the entire system

-in-medium cross-sections 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





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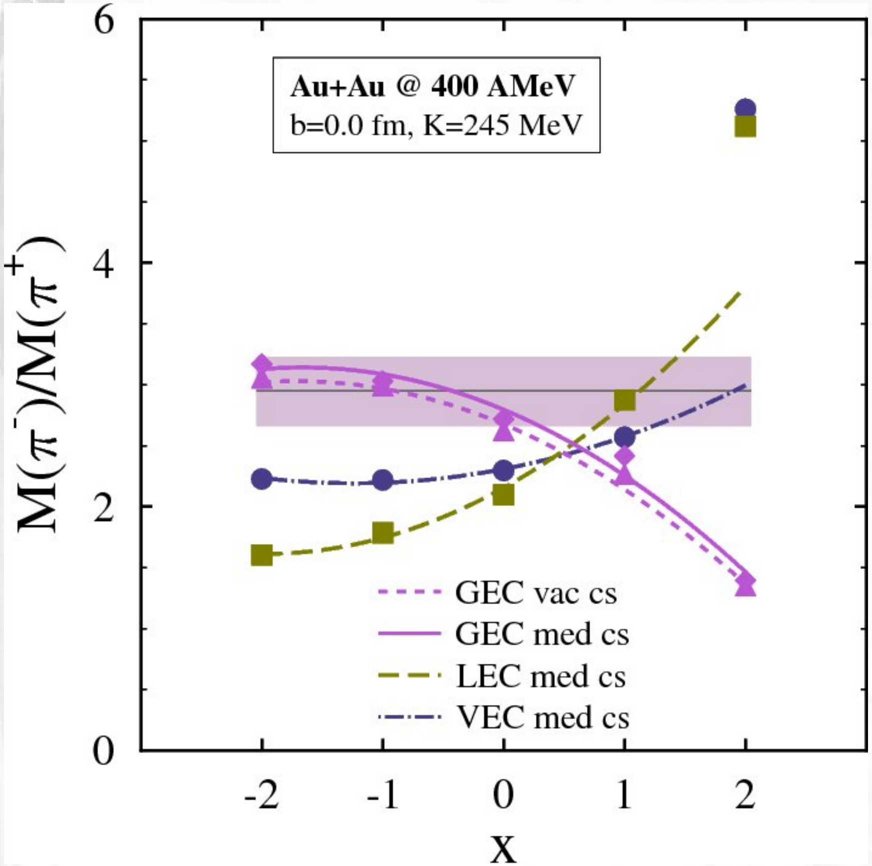
Experimental data: W. Reisdorf et al. (FOPI) NPA 848, 366 (2010)

Multiplicity Ratio

Energy Conservation Scenario



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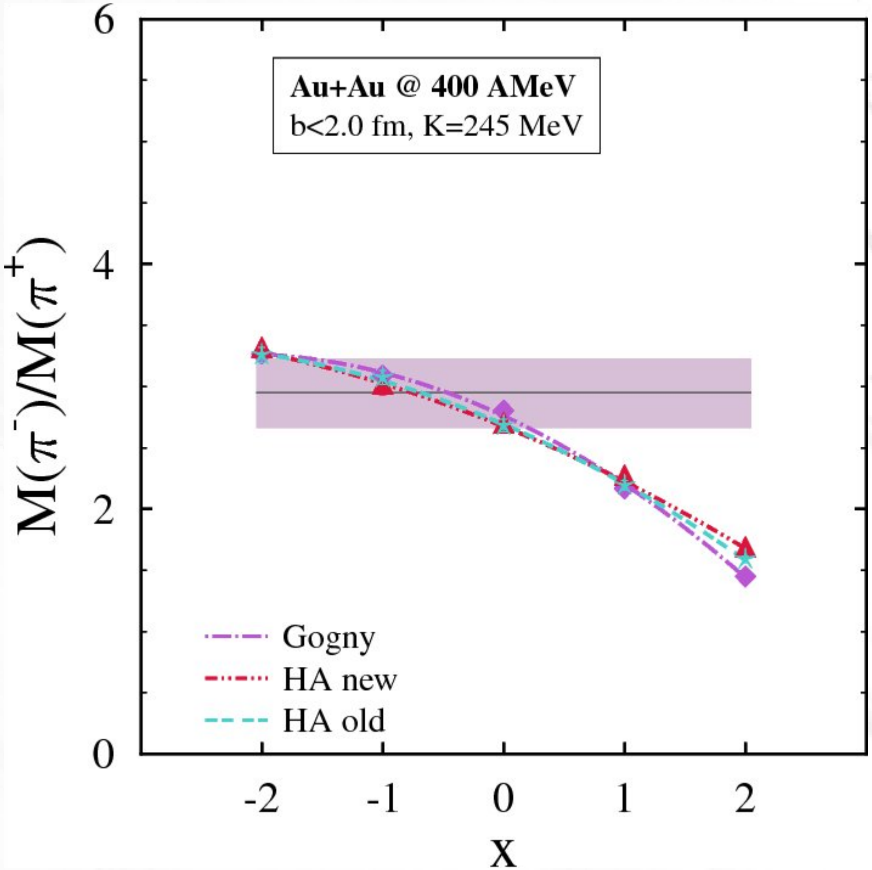
Optical Potential Dependence



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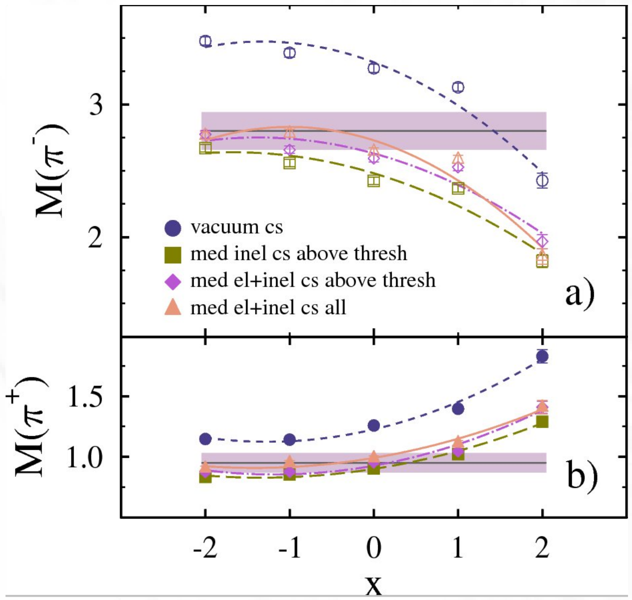
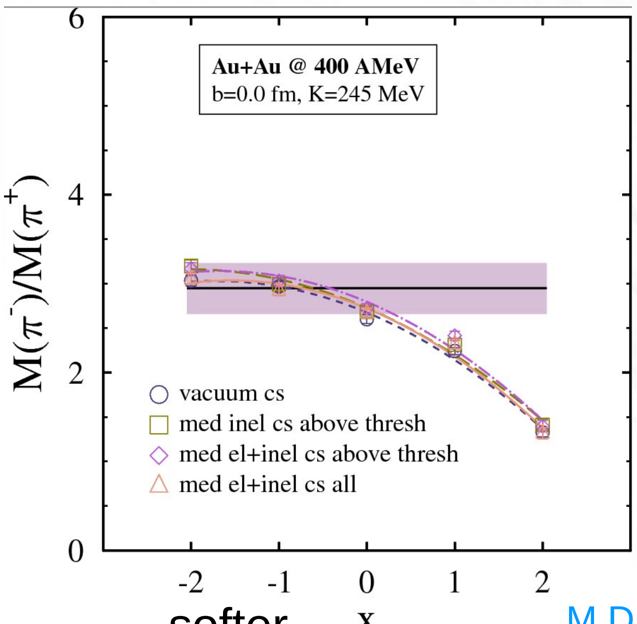
Pion ratio vs Elliptic Flow





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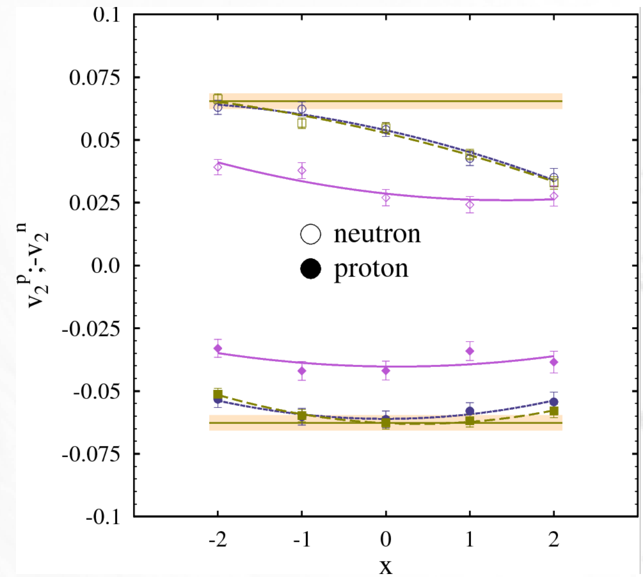
consistency between pion ratio and elliptic flow constraints **can** be achieved

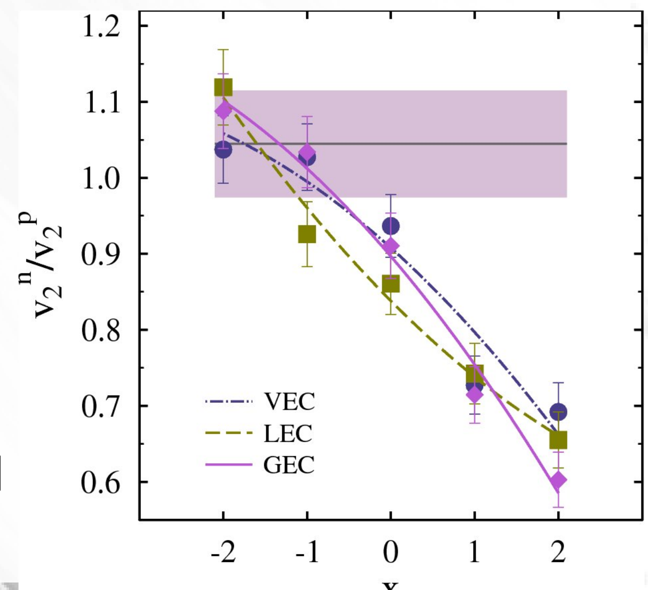
⇕

conservation of the total energy of the system

+

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





softer

M.D. Cozma arXiv:1409.3110 (2014)

Impact of the Δ(1232) potential

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

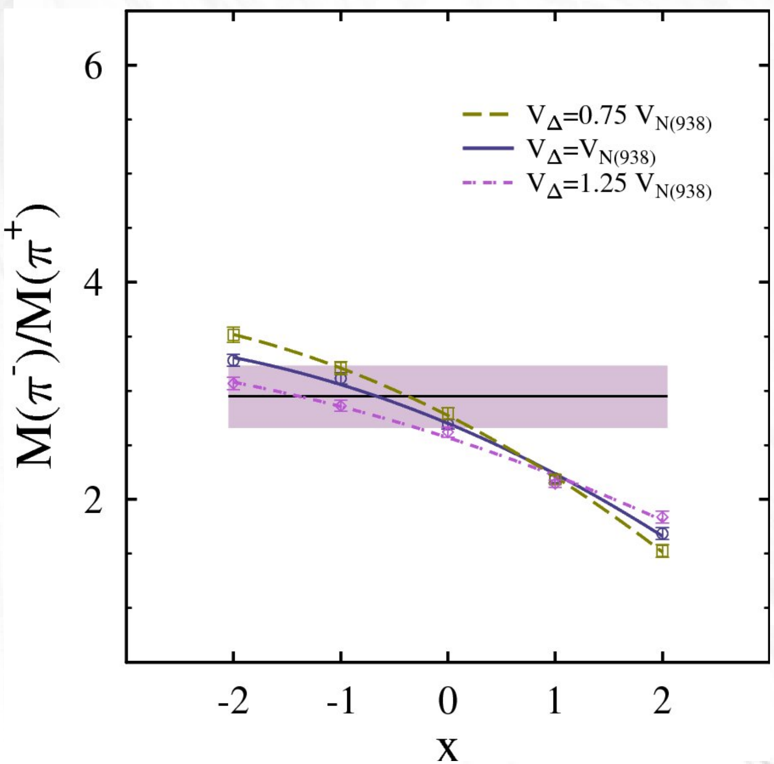
- Δ-nucleus potential deeper than the nucleon-nucleus potential

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

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

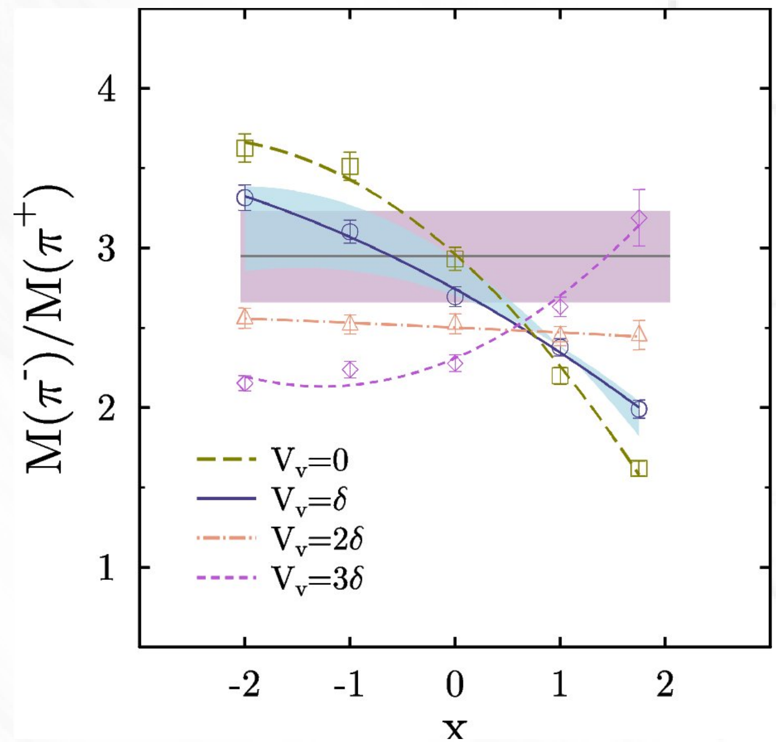
- 3D reduction of Bethe-Salpeter equation similar (DB)
- strong dominant repulsive contribution from T=2 sector

Baldo, Ferreira NPA 569, 645 (1994)
Malfliet, de Jong PRC 46, 2567 (1992)



$$V(\Delta^{++}) = V_s + \frac{3}{2} V_v$$
$$V(\Delta^{+}) = V_s + \frac{1}{2} V_v$$
$$V(\Delta^{0}) = V_s - \frac{1}{2} V_v$$
$$V(\Delta^{-}) = V_s - \frac{3}{2} V_v$$

$$V_s = \frac{1}{2}(V_n + V_p)$$
$$\delta = \frac{1}{3}(V_n - V_p)$$



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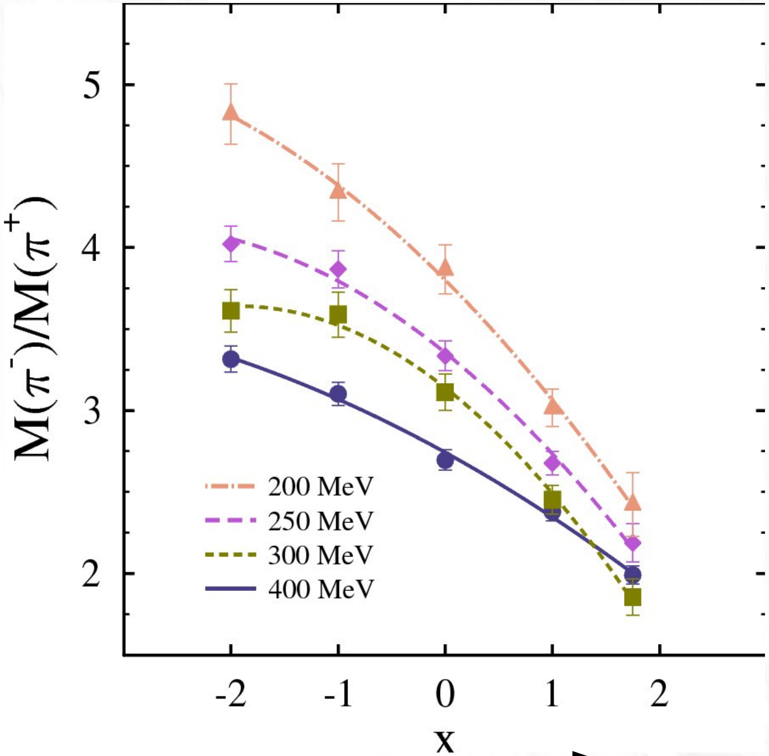
M.D. Cozma arXiv:1409.3110 (2014)

Energy dependence

close or below threshold

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



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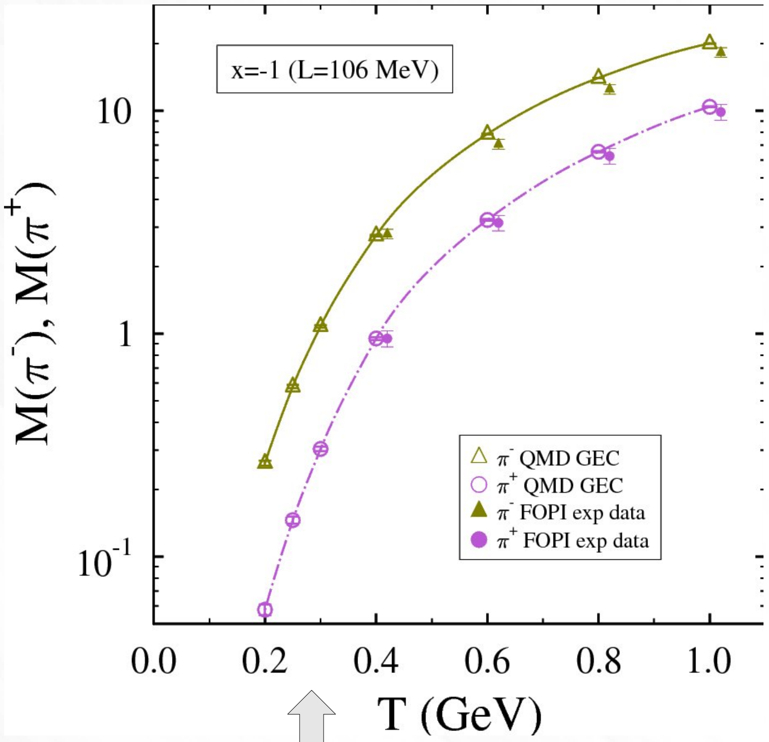
M.D. Cozma arXiv:1409.3110 (2014)



above threshold (FOPI/GSI)

Conclusions

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

π^-/π^+: - confirmed as sensitive to the stiffness of asy-EoS
- increased sensitivity below production threshold
- dependence on in-medium cross-sections and optical potential choice is modest

However:
- isovector part of the in-medium Δ potential has a large/decisive impact

Good news: -consistency between pion ratio and elliptic flow constraints can be achieved (GEC scenario only!)

Differences between different models – most likely due to different choices for the isovector Δ(1232) and pion potentials

To do list: - retardation and relativistic corrections
- in-medium baryon potentials (particularly Δ(1232))
- pion potentials (recently included)

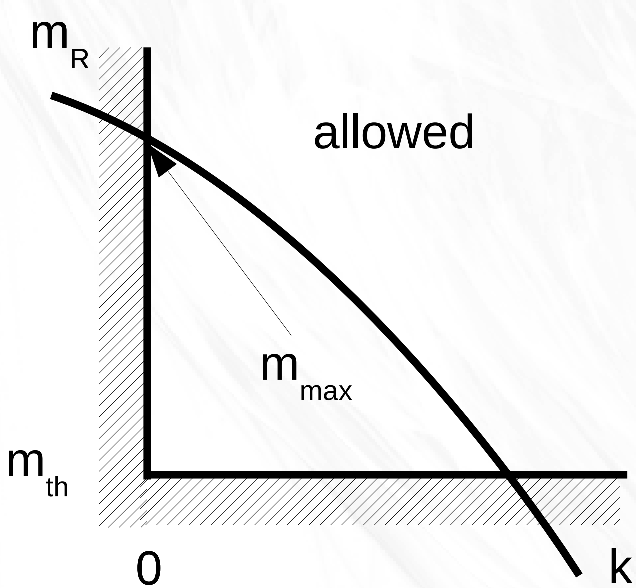
Worst case scenario: test of our understanding of hadronic interaction in the few hundred MeV energy domain

Approximations

final state phase space in NN->NR

VEC

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



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

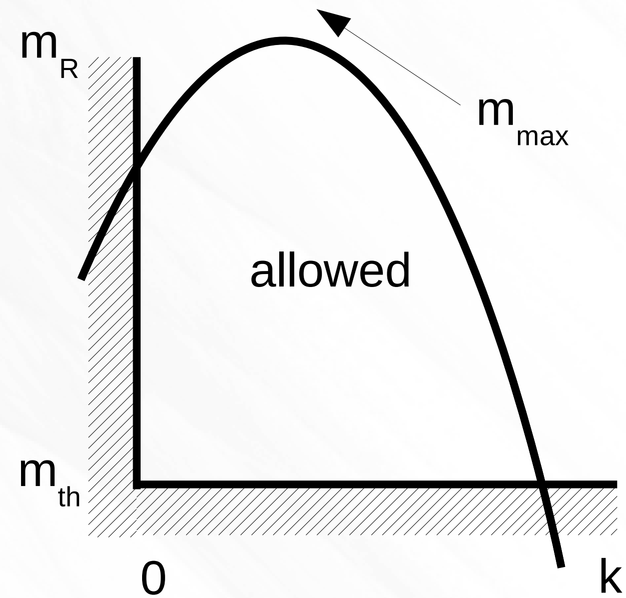
$$0\leqslant\theta\leqslant\pi$$

$$0\leqslant\Phi\leqslant 2\pi$$

consistent with $\frac{d\sigma}{d\Omega}$

LEC, GEC

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



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

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

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

approximate to vacuum case