Constraining the density dependence of the symmetry energy using the multiplicity and average p_T ratios of charged pions

(arXiv: 1603.00664)

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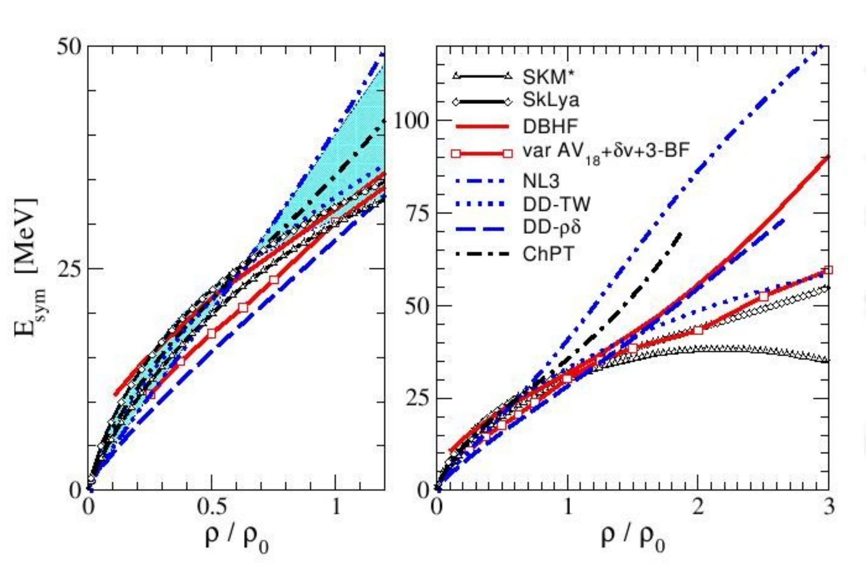
INPC2016
Adelaide, Australia
11-16 September 2016

Symmetry Energy

Equation of State (EoS) of Nuclear Matter:

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

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



C. Fuchs and H. Wolter, EPJA 30, 5 (2006)

Sources of empirical knowledge

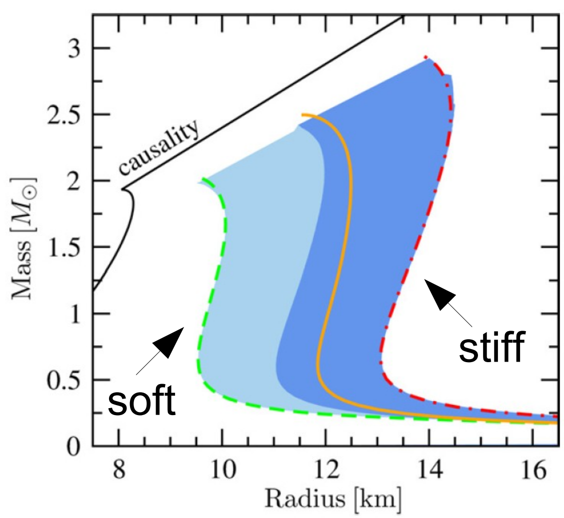
finite nuclei	$\rho/\rho_0 \leq 1$
heavy-ions	$\rho/\rho_0 \leq 3$
neutron stars	$\rho/\rho_0 \leq 10$

Relevance:

- structure of exotic nuclei
- properties of neutron stars (radius, maximum mass)
- astrophysical processes (supernova explosions)

Heavy-ion collisions observables:

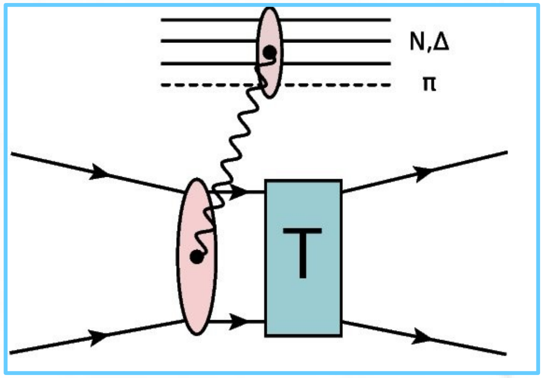
elliptic flow ratios (n/p,n/H), high p_T n/p multiplicity ratios, light cluster emission, pion multiplicity ratios



Hebeler et al., ApJ 773, 11 (2013)

EPJA, vol 50 (2014) – current status

Motivation



Previous work

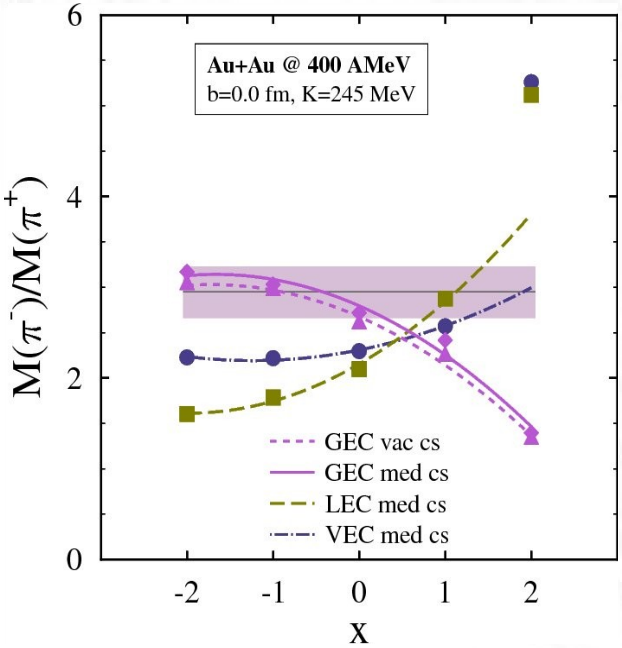
- sizable threshold effects (total energy conservation)
- compatible constraints for asy-EoS possible (wrt elliptic flow)

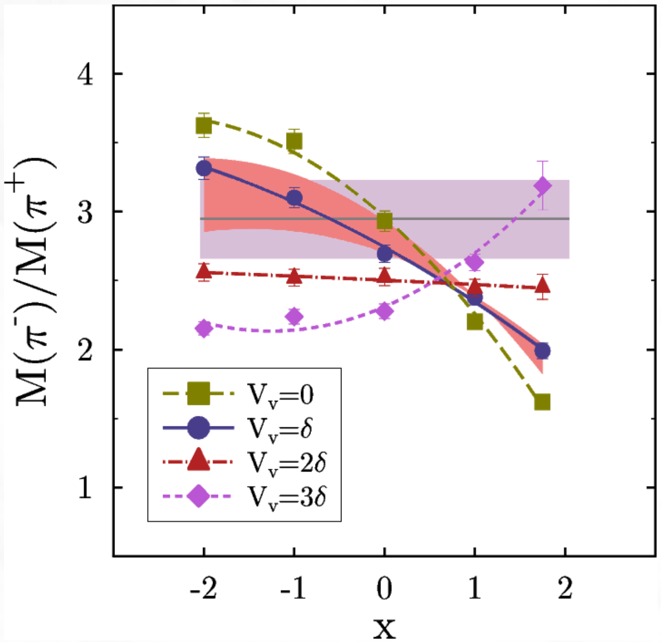
However !

- large impact of the unknown isovector Δ(1232) potential

central Au+Au collisions

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





$$\cancel{\sum_i \sqrt{p_i^2+m_i^2} = const}$$

$$\sum_i \sqrt{p_i^2+m_i^2} + U_i = const$$

for details see: M.D. Cozma, PLB 753, 166 (2016)

see also: G. Ferini et al., PRL 97, 202301 (2006)
T. Song, K.M. Ko, PRC 91, 014901 (2015)

Transport Model

Quantum Molecular Dynamics (TuQMD): HIC 0.1-2.0 GeV/A

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 at IFIN-HH (Bucharest):

- various parametrizations for the EoS: optical potential, symmetry energy PRC 88, 044912 (2013)
- various parametrizations for elastic cross-sections (also in medium ones) PLB 700, 139 (2011)
- threshold effects for baryon resonance & π meson emission/absorption PLB 753, 166 (2016)
- pion optical potential arXiv:1603.00664
- **planned**: 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)

Isospin dependence of EoS

momentum dependent – generalization of the Gogny interaction:

MDI potential

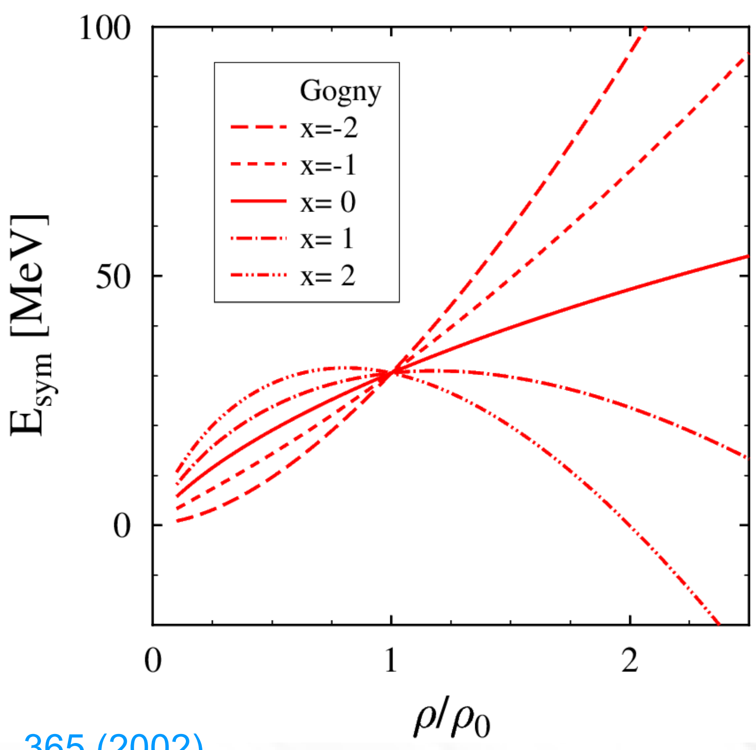
Das, Das Gupta, Gale, Li PRC67, 034611 (2003)

$$\frac{E}{N}(\rho,\beta,x)=\frac{1}{2}A_1 u+\frac{1}{2}A_2(x)u\beta^2+\frac{B}{\sigma+1}(1-x\beta^2)+\frac{1}{u\rho_0^2}\sum_{\tau,\tau'}C_{\tau\tau'}\int\int d^3p\,d^3p'\frac{f_\tau(p,p')f_{\tau'}(p,p')}{1+(\vec{p}-\vec{p}\,')^2/\Lambda^2}$$

$$A_2(x)=A_2^0+\frac{2xB}{\sigma+1}\bar{u}^{\sigma-1} \qquad u=\frac{\rho}{\rho_0}$$

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

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



resonance potential: isovector component unknown

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

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

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

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

$$V_s\equiv\frac{1}{2}(V_n+V_p)$$

$$\delta\equiv\frac{1}{3}(V_n-V_p)$$

$$V_v=\delta$$

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

! In the following: V_v expressed in units of [δ]

Pion optical potential

Sources:

Theoretical models: Effective Hadronic Models

J. Nieves et al., NPA 554, 509; 554 (1993)
M. Doring et al., PRC 77, 024602 (2008)

pion self-energy starting from basic interaction terms πNN, πNΔ, πNN*(1440)

Chiral Perturbation Theory

N. Kaiser et al., PLB 512, 283 (2001)
C. Baru et al., NPA 872, 69 (2011)
W.Weise, Acta. Phys. Pol, B31, 2715 (2000)

Experiment: Pionic Atoms

T. Yamazaki et al., Phys. Rep. 514, 1 (2012)
E. Friedman, A. Gal, Phys. Rep. 452, 89 (2007)

Pion-Nucles Scattering

R. Seki et al, PRC 27, 2799; 2817 (1983)

Ericson-Ericson parametrization (M. Ericson et al. Ann. Phys. 36, 323 (1966))

$$V_{opt}(r)=\frac{2\pi}{\mu}\left[-q(r)+\vec{\nabla}\frac{\alpha(r)}{1+4/3\pi\lambda\alpha(r)}\vec{\nabla}\right]$$

S -wave

P-wave

$$q(r)=\epsilon_1(\overline{b}_0\rho+\overline{b}_1\beta\rho)+\epsilon_2 B_0\rho^2$$

$$\alpha(r)=\epsilon_1^{-1}(c_0\rho+c_1\beta\rho)+\epsilon_2^{-1}(C_0\rho^2+C_1\beta\rho^2)$$

$$\epsilon_1=1+m_\pi/m_N \qquad \epsilon_2=1+2m_\pi/m_N$$

	$\overline{b}_0[m_\pi^{-1}]$	$\overline{b}_1[m_\pi^{-1}]$	Re B_0 $[m_\pi^{-4}]$	Im B_0 $[m_\pi^{-4}]$	λ	c_0 $[m_\pi^{-3}]$	c_0 $[m_\pi^{-3}]$	Re C_0 $[m_\pi^{-6}]$	Im C_0 $[m_\pi^{-6}]$
SM-1	-0.0283	-0.120	0.0	0.042	1	0.223	0.250	0.0	0.10
SM-2	0.030	-0.143	-0.150	0.046	1	0.210	0.180	0.11	0.09
Batty-1	-0.017	-0.130	-0.048	0.0475	1	0.255	0.170	0.0	0.09
Batty-2	-0.023	-0.085	-0.021	0.049	1	0.210	0.089	0.118	0.058
Konijn-2	0.025	-0.094	-0.265	0.0546	1	0.273	0.184	-0.140	0.105

subset from K. Itahashi et al., PRC 62, 025202 (2000)

S-wave pion potential

	$b_0[m_\pi^{-1}]$	$b_1[m_\pi^{-1}]$
Exp	-0.0001±0.0021	-0.0885±0.0021
ChPT	0.0075±0.0031	-0.0861±0.0009
WT	0.0	-0.0790

M. Krell et al. NPB 11, 521 (1969)

double scattering

$$\overline{b_0} = b_0 - \frac{3}{2\pi}(b_0^2+2b_1^2)\left(\frac{3\pi^2}{2}\rho\right)^{\frac{1}{3}}$$

$$b_0 = 0.0 \qquad b_1 = \frac{-m_\pi}{8\pi(1+m_\pi/m_N)f_\pi^2}$$

ChPT

$$f_\pi^2(\rho) = f_\pi^2(0) - \frac{\sigma\rho}{m_\pi^2}$$

W. Weise, NPA 690, 98 (2001)

$$b_1(\rho) = \frac{b_1}{1-\frac{\sigma\rho}{m_\pi^2 f_\pi^2}} \simeq \frac{b_1}{1-2.3\rho}$$

Energy dependence

inferred from exp. pion-nucleus scattering

$$\overline{b_0}^{eff} = \overline{b_0} + \rho^{eff}\, Re\, B_0$$

R. Seki et al., PRC 27, 2799 (1983)
C. Garcia-Recio et al., PRC 40, 1308 (1989)

Free-space & ChPT

R.A. Arndt et al., PRC 74, 045205 (2006)

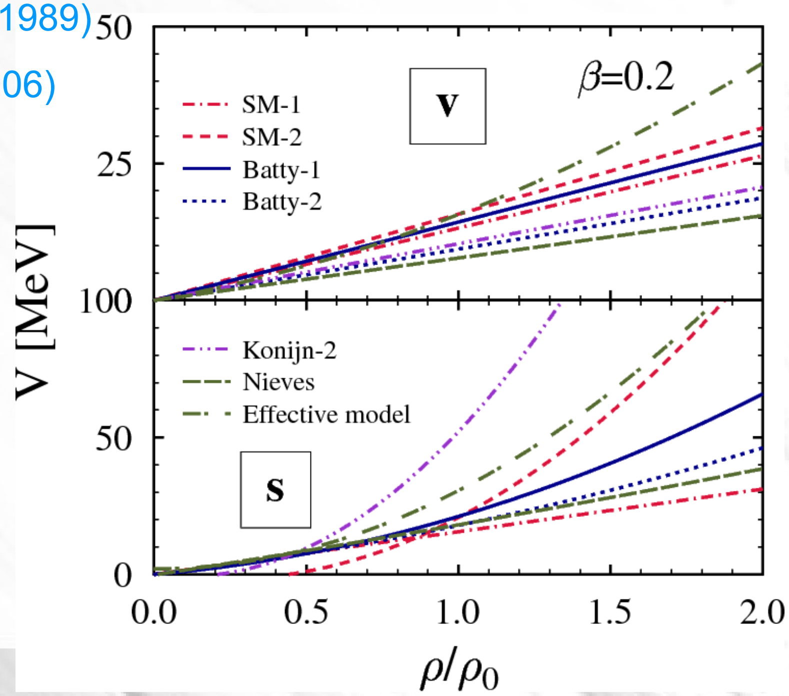
$$\frac{db_0}{d\omega} = -0.00053\, m_\pi^{-1}/\mathrm{MeV} \qquad \frac{db_1}{d\omega} = 0$$

Effective Model

$$b_0(\omega) = -0.010 - 0.00016\,\omega$$

$$\overline{b_1}(\rho) = -0.088\left(1 + \frac{0.6116}{b_1}\frac{\rho}{\rho_0}\right)$$

$$\overline{b_0}(\rho,\omega) = b_0 - \frac{3}{2\pi}(b_0^2+2b_1^2)\left(\frac{3\pi^2}{2}\rho\right)^{\frac{1}{3}}$$



P-wave pion potential

Energy dependence:

-extrapolation of pionic atoms results using a local approximation of the delta-hole model that

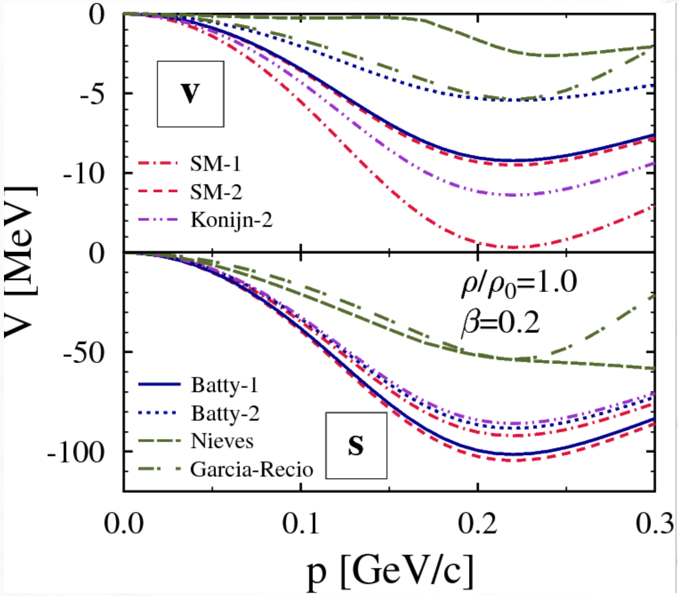
-describes pion-nucleus scattering up to ω=300 MeV

C. Garcia-Recio et al., NPA 526, 685 (1991)

$$f(p^2)=\frac{1-p_{eff}^2/\Lambda_1^2+p_{eff}^4/\Lambda_2^4}{1-p^2/\Lambda_1^2+p^4/\Lambda_2^4}$$

$$\Lambda_1=0.55\,\mathrm{GeV} \qquad \Lambda_2=0.22\,\mathrm{GeV}$$

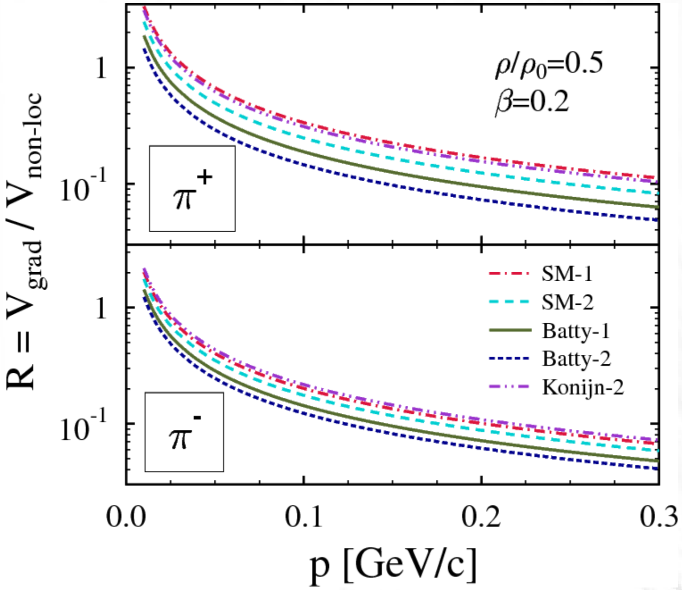
$$p_{eff}=0.05\,\mathrm{GeV}$$



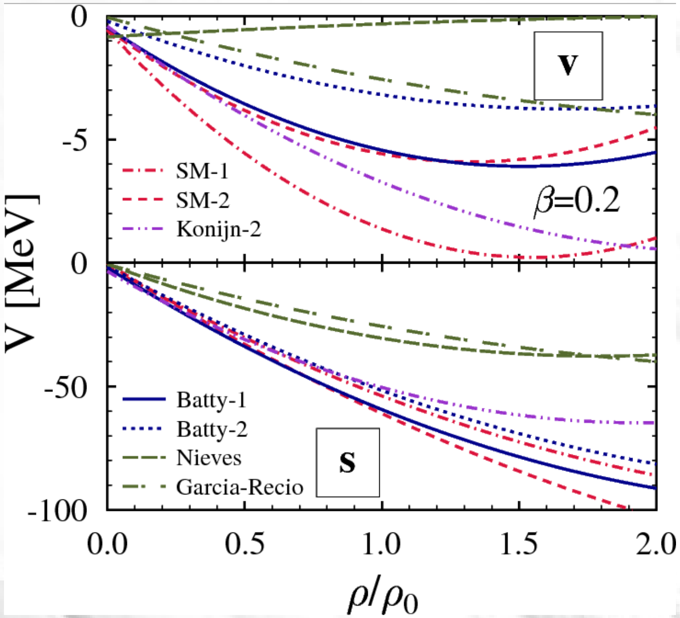
Gradient terms:

$$V_{opt}^P(r)=\frac{2\pi}{\mu}\vec{\nabla}\frac{\alpha(r)}{1+4/3\pi\lambda\alpha(r)}\vec{\nabla}$$

$$\Rightarrow \quad \text{terms} \quad \sim \quad \vec{p}\cdot\vec{\nabla}\rho \qquad \vec{p}\cdot\vec{\nabla}\beta$$



Density dependence

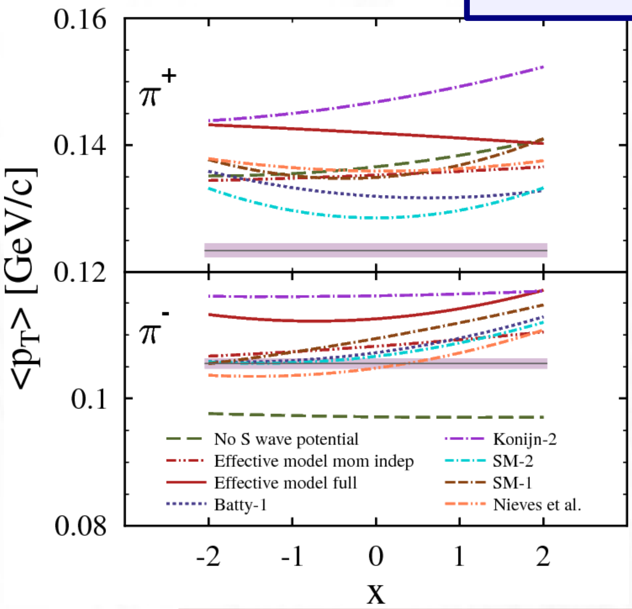


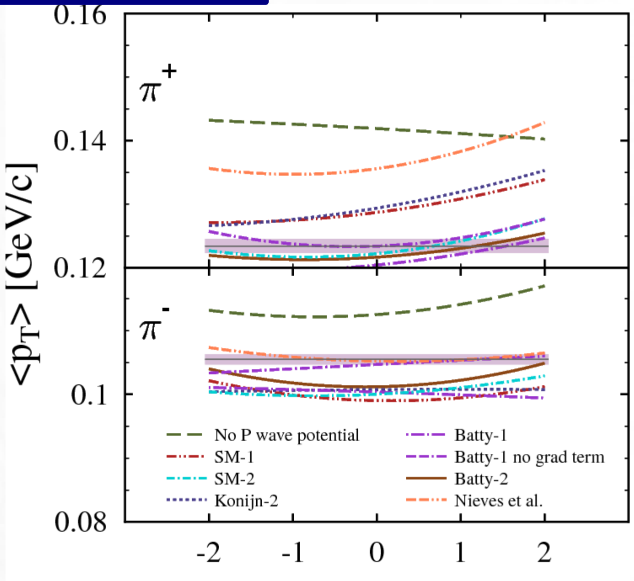
Impact on pion observables

Au+Au@400 MeV/A, 3.35 fm <b<6.0 fm

$|y/y_P|<1.75$
$0<p_T<0.33$ GeV/c

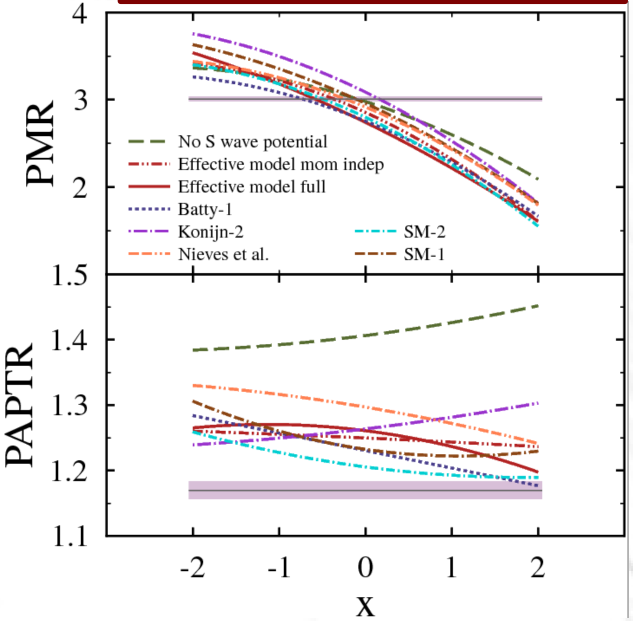
exp data:
W.Reisdorf et al. (FOPI), private communication

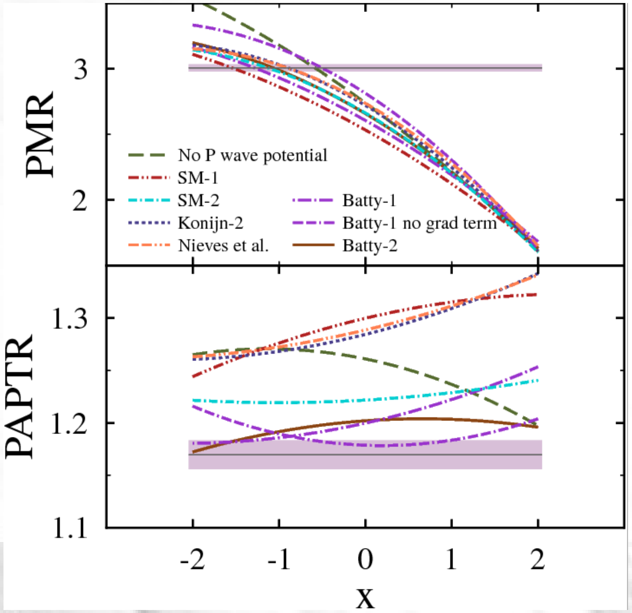




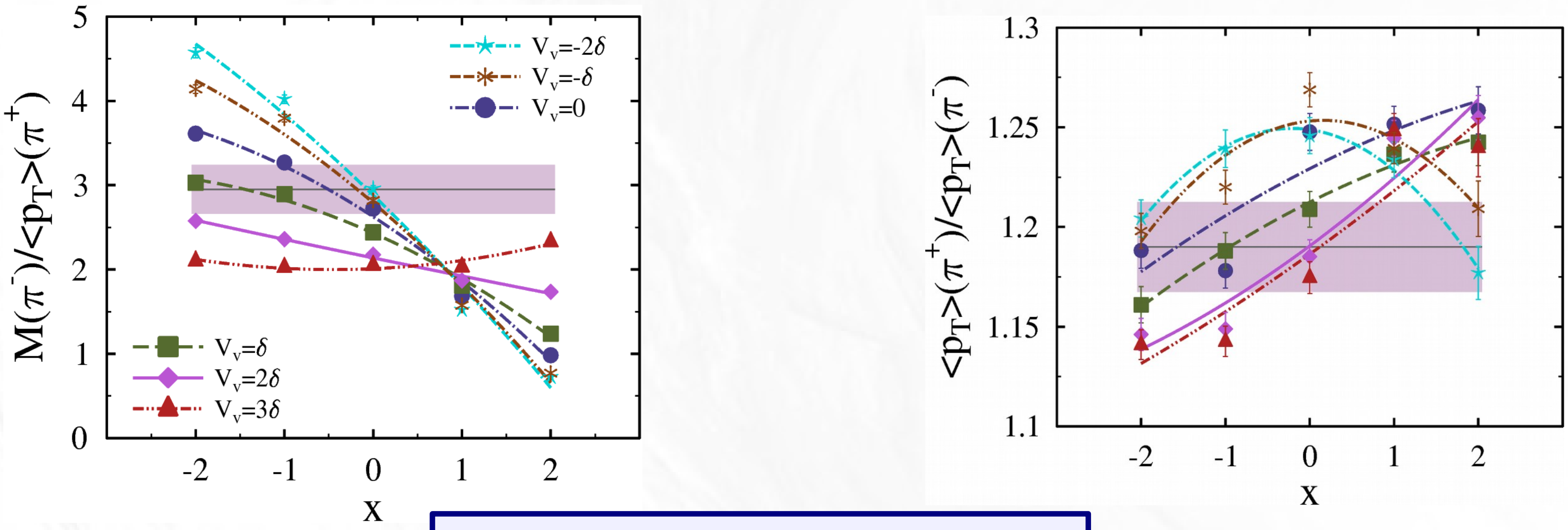
S-wave pion potential

P-wave pion potential



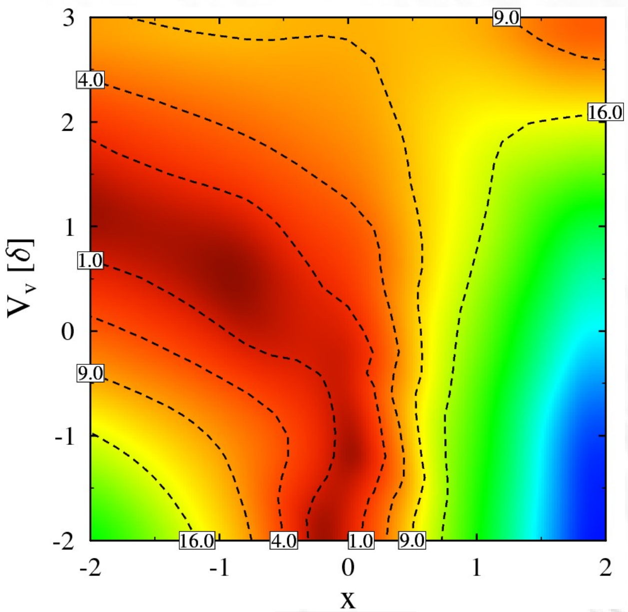


Constraining the symmetry energy



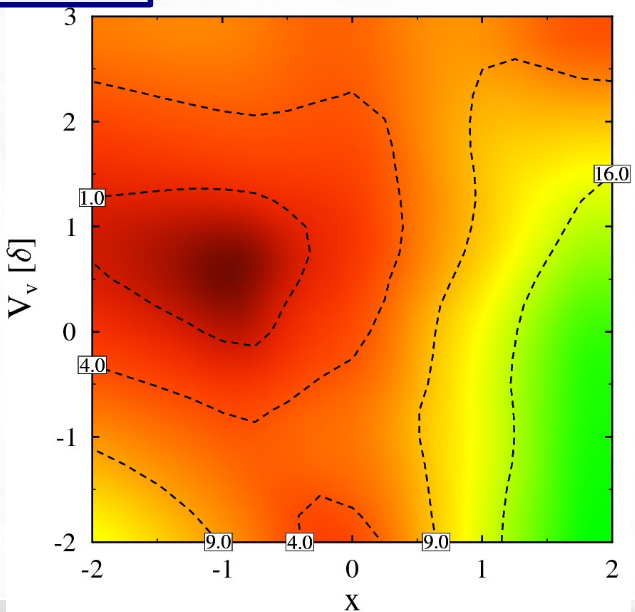
Au+Au@400 MeV/A, b<2.0 fm

W.Reisdorf et al., NPA 781, 459 (2007)



PMR

S - Eff. Model
P - Batty-1



PMR+PAPTR

Model dependence 1

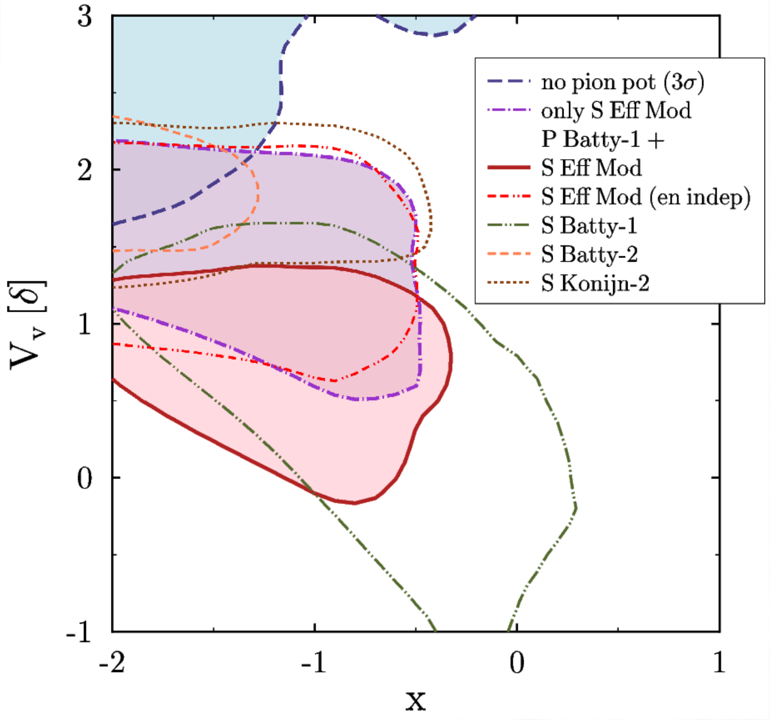
Au+Au@400 MeV/A, b<2.0 fm

W.Reisdorf et al., NPA 781, 459 (2007)

1σ CL contour plots

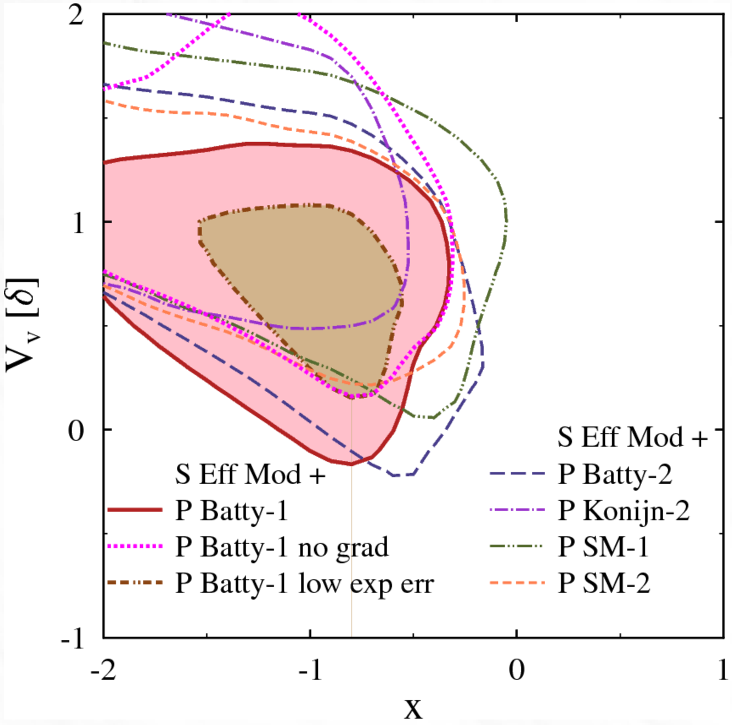
S-wave impact

P-wave: Batty-1



P-wave impact

S-wave: effective model



No pion potential – unable to describe exp. PMR and PAPTR simultaneously

S-wave - energy dependence impacts V_v

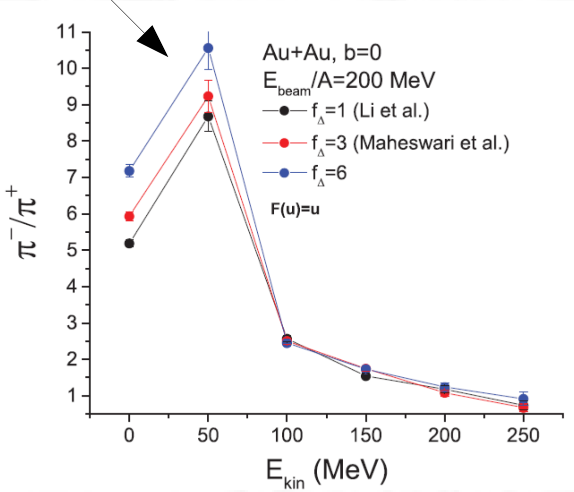
- density dependence – impact both x (60 MeV on L) and V_v

P-wave - moderate impact on both x (25 MeV on L) and V_v

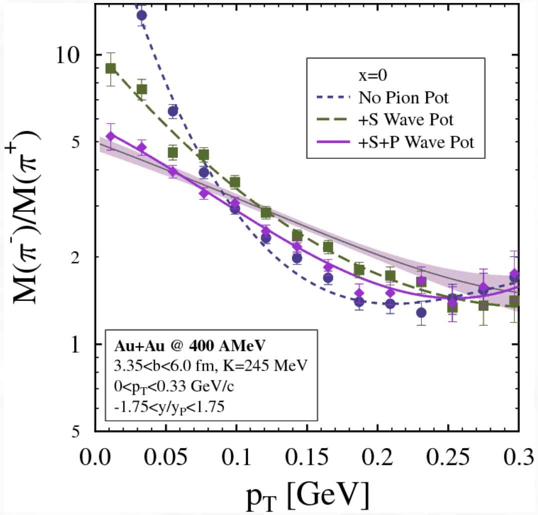
Model dependence 2

claims in the literature: remove pion/Δ(1232) potential by a pion p_T/kinetic energy cut

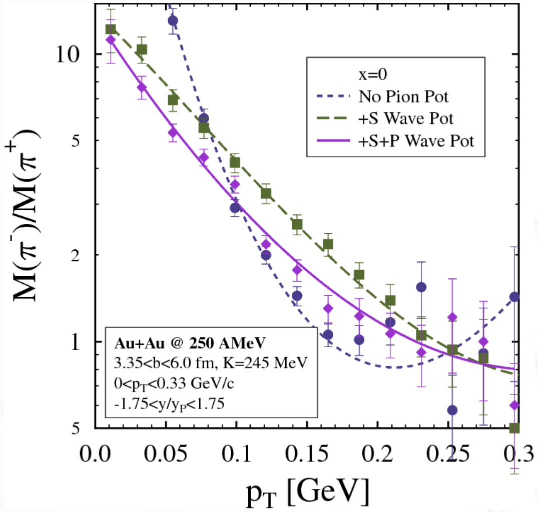
J. Hong, P. Danielewicz, PRC 90, 024605 (2015)
W.-M. Guo et al., PRC 92, 054619 (2015)
B.-A. Li, PRC 92, 034603 (2015)



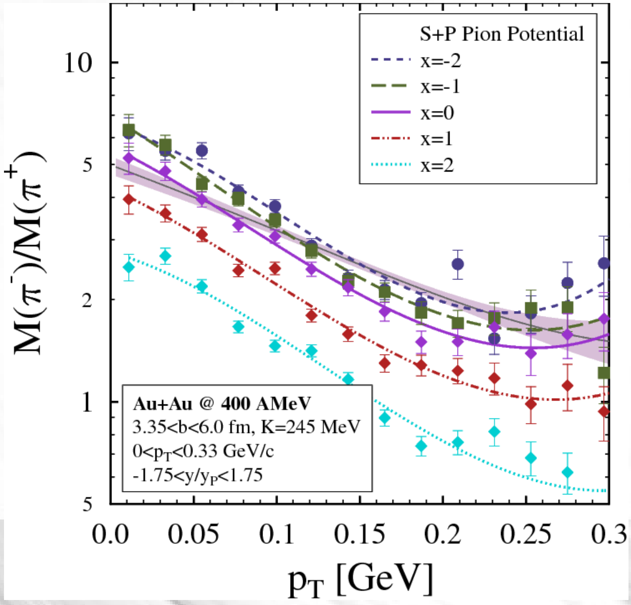
AuAu 400 AMeV



AuAu 250 AMeV



exp data: W.Reisdorf et al. (FOPI), private communication



Conclusion:

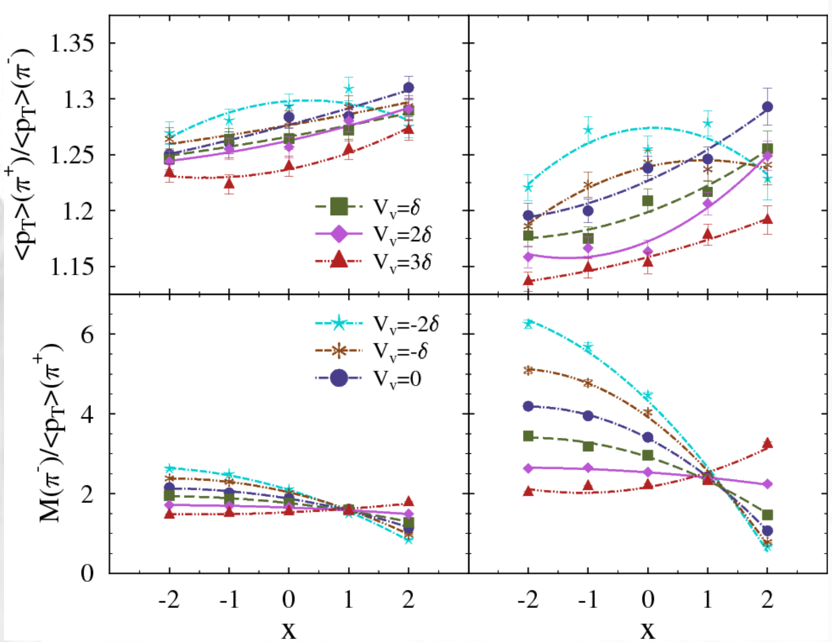
build ratios using low energy pions

advantage: uncertainties in the energy dependence of pion potential suppressed

disadvantage: uncertainties in density dependence of pion potential present

study isospin symmetric HIC

Perspectives



SAMURAI-TPC Collaboration

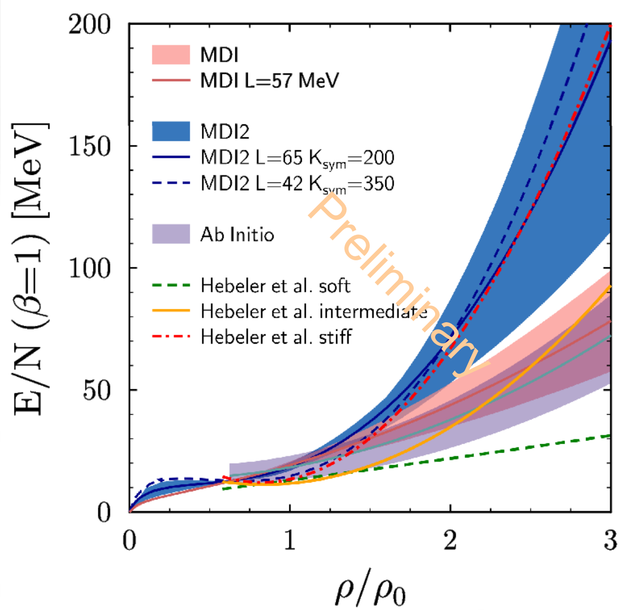
R. Shane et al., NIM A784, 513 (2015)

data taken May-June 2016 @ SPIRIT/RIKEN

^{108}Sn + ^{112}Sn β=0.09
^{124}Sn + ^{112}Sn β=0.15 @ 270 AMeV
^{132}Sn + ^{124}Sn β=0.22

T. Murakami et al.,(2016), presentation at NuSYM16

Modelling: retardation effects not yet included



Longer term goal:

- extract both the slope L and curvature K$_{sym}$ of SE
  preliminary studies on flow observables → feasibility proven
- allow trustworthy extrapolation of SE above 2ρ$_0$ →
  determine NS properties from HICs

L = 65 ±15 MeV
K$_{sym}$= 200 ± 250 MeV
J = 32.3 ± 3.9 MeV

Preliminary results using elliptic flow data
FOPI-LAND: Y. Leifels et al., PRL 71, 963 (1993)
ASYEoS: P. Russotto et al., arXiv:1608. 04332 (2016)

Summary / Conclusions

QMD transport model: – upgraded by including S and P wave pion potential contributions (mean-field propagation, threshold effects)

- allows the study of momentum observables of pions
- average transverse momenta – within 5% of exp values (FOPI)
- moderate impact on PMR (~10%) and PAPTR (~15%)

Constraining the SE: – PMR alone unsuitable (unknown strength of isovector Δ(1232) pot)

- model without pion potential: fails to describe PMR and PAPTR <u>simultaneously</u>
- inclusion S and P wave pion potentials: reasonable SE constraints

Model dependence:

- energy dep of S-wave pot
- gradient terms of P- wave pot : isovector Δ(1232) potential
- density dep of the pion pot impact L : 60 MeV S-wave 20 MeV P-wave
- constraint for SE stiffness: L> 50 MeV (1σ CL)

Perspectives: SAMURAI TPC Collaboration: Sn+Sn 270 MeV/nucleon