Can we experimentally determine the asymmetry energy

by analyzing high energy reactions??

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Why it will be difficult?
Are we ready?
Where should we look?

ESF PESC Exploratory Workshop on High Density Symmetry Energy, Zagreb Oct 09

Nature provides no direct observables for the symmetry energy
theory does not offer much of a guideline (Boa-An)

We can get it only by comparison of transport calculations with experimental results

2 problems:

- is this observable robust (and not contaminated by other little known input quantities)?
  everybody can answer by himself

- what is our systematic error, means:
  is our computer code really a solution of the underlying equation (BUU, QMD) or does the technical implementation create a serious systematic error?
  sequence of workshops in Trento
  next in 2010/11

Why it will be difficult ?

I think the problems are quite different for $\rho \ll \rho_0$ and for $\rho > \rho_0$

$\rho \ll \rho_0$:

Our setup (local Fermi) is adapted to reproduce the fragment pattern as far as it follows Weizsaeckers formula
(Z- distribution, multiplicity)

Failure to reproduce C, α and d : for details quantum effects become important (and we have semi-classical theories)

There are plenty of data of low energy heavy ion collisions (pick up, transfer) which investigate the kinematical regions which we encounter when the fragments separates from the system with low momenta.

They show that details of wavefcts, pairing energies and other Quantum effects became important for the fragment yield

Are our programs apt to deal with these quantum features?
Best we can say: we do not know (but I do not know a transport theory which is good enough to predict isotopic yields).

Why do we want to know the ion detail the symmetry energy (certainly very small) at these densities?

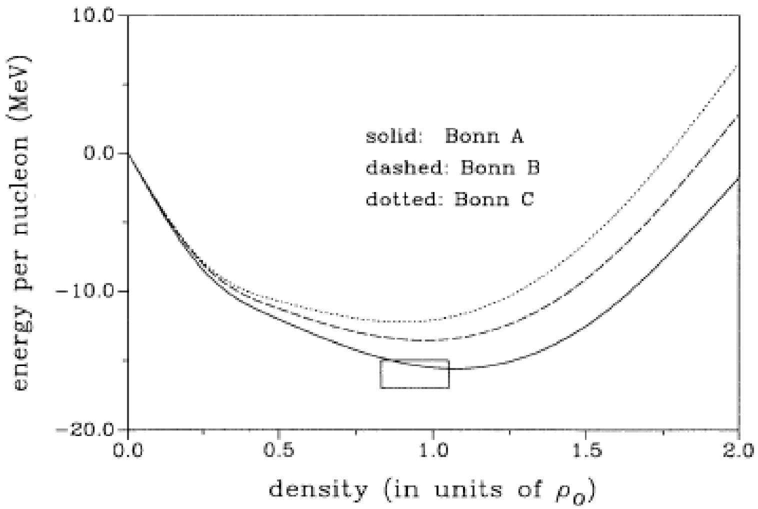
$\rho \geq \rho_0$

The plus:
This interests astrophysicists (supernovae, neutron star)
Symmetry energy larger
Semi-classical models have been successfully applied to data

but

especially there are many pitfalls

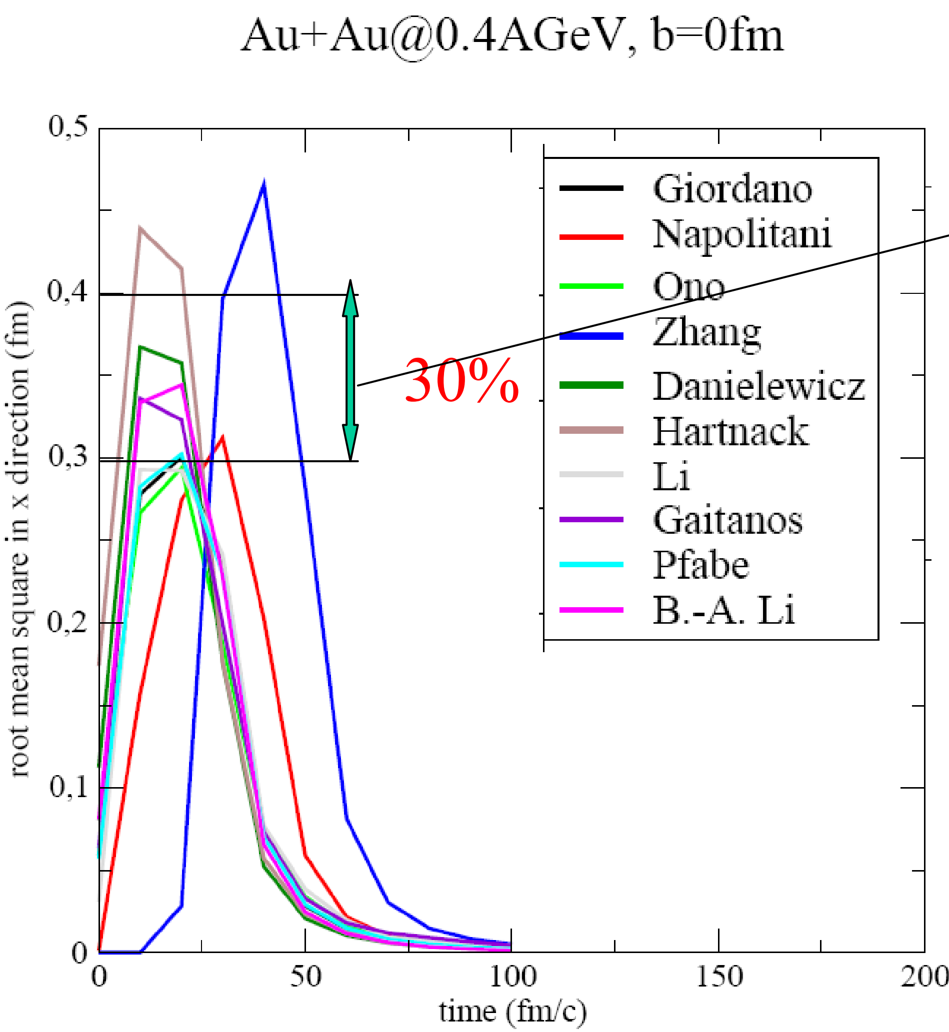
Even the most sophisticated potentials (which fit NN scattering data almost perfectly) give quite different energies/N at finite densities $\rho/\rho_0 > .5$
-> reference point undetermined

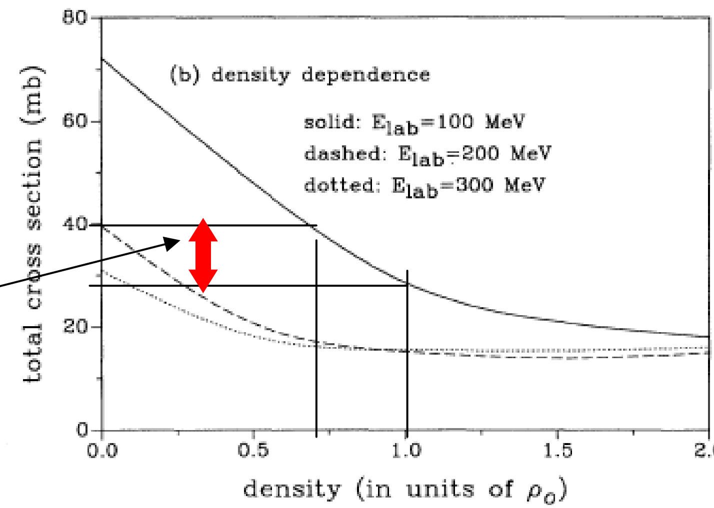


Li&Machleidt

Is there a change to separate bulk and symmetry energy with the small N/Z range available if the uncertainty of the bulk is as large as the symmetry energy?

Problem 1:
nn and np cross sections are strongly density dependent





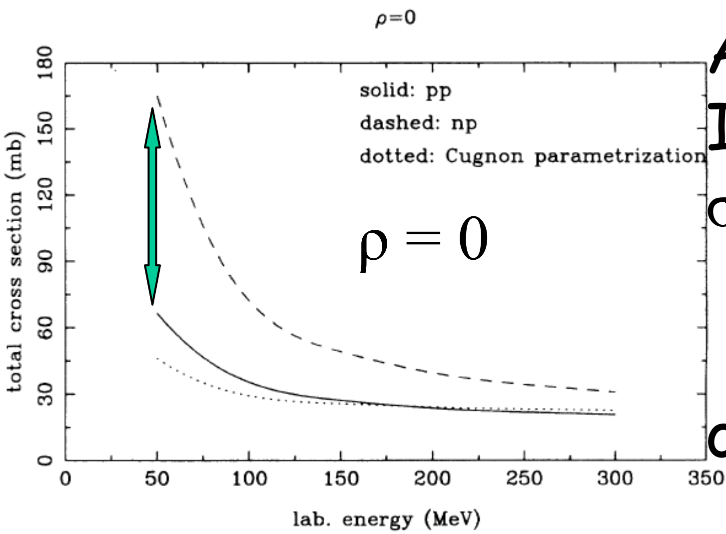
Transversal radius varies by 30% for the same initial condition.

density fluctuation of at least 30% yield cross section fluctuations of at least 10mb or 30%

Problem 2: σ_{np} >> σ_{pp} ↷ hides E_{sym} effects

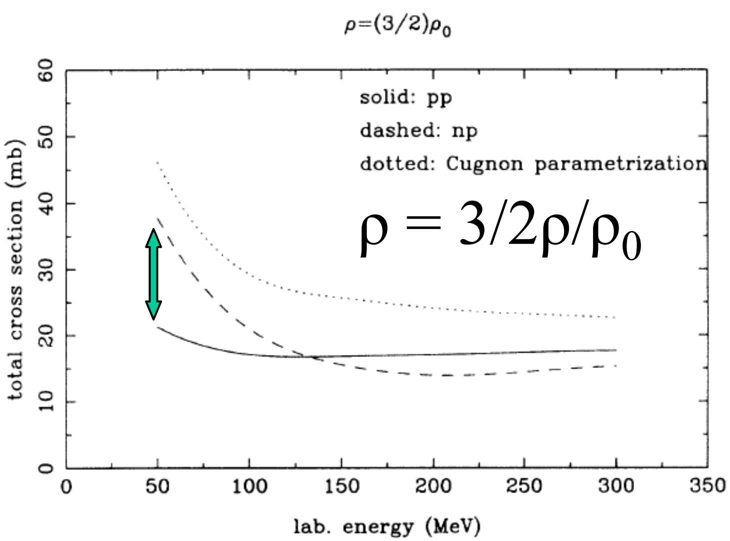
Technical problem (QMD): How to deal with 165 mb

J. Cugnon, T. Mitutani, and J. Vandermeulen, Nucl. Phys. **A352**, 505 (1981).



At 50 AMeV:
If we replace a n by a p
σ_{np} = 165 mb -> σ_{pp} = 65 mb ratio=2.5
at ρ=0

σ_{np} = 38 mb -> σ_{pp} = 22 mb ratio=1.7
at $3/2\ \rho/\rho_0$



Stopping becomes different

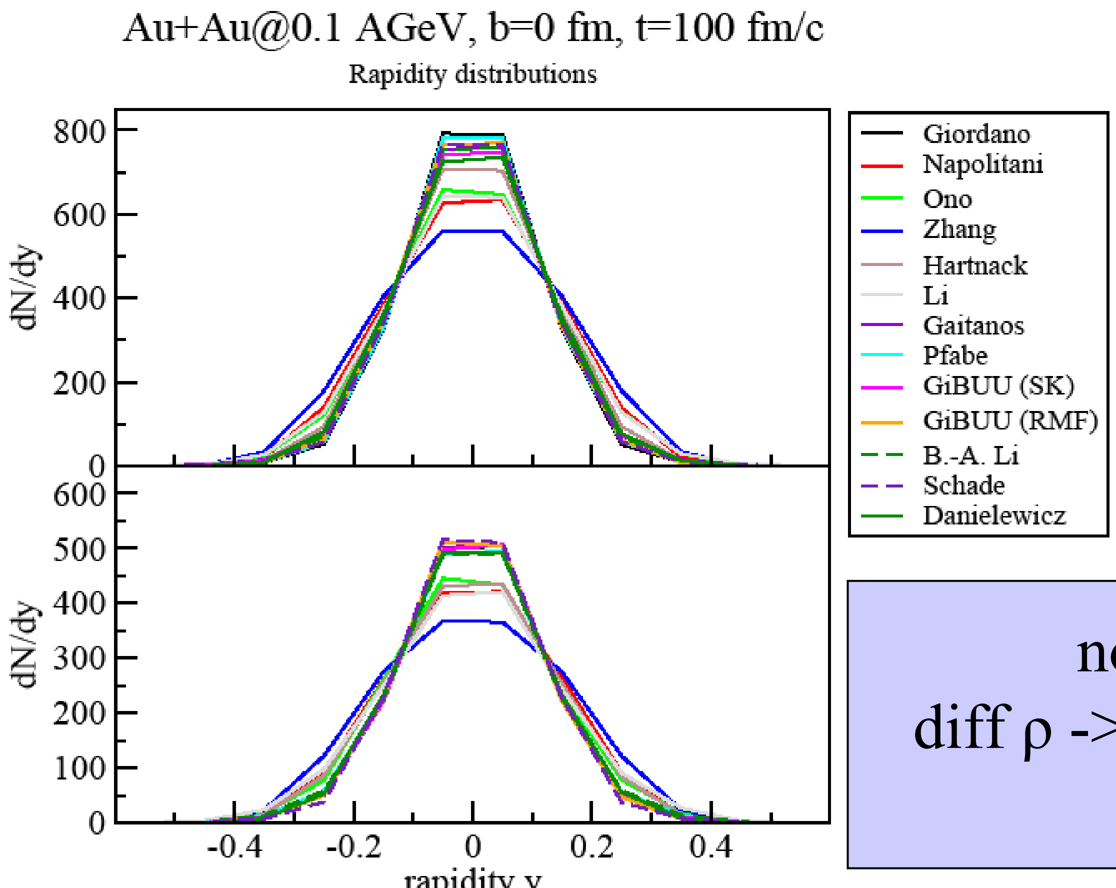
Good idea using ratios of different N/Z for constant A becomes obsolet

Li and Machleidt PRC49,566

Is this change of the cross section not too large to disentangle in our programs effects E_{sym} and σ?

I guess presently we cannot say much about E_{sym} because we do not have the cross sections under control

Hugh differences in stopping, means in central density, means in the cross section

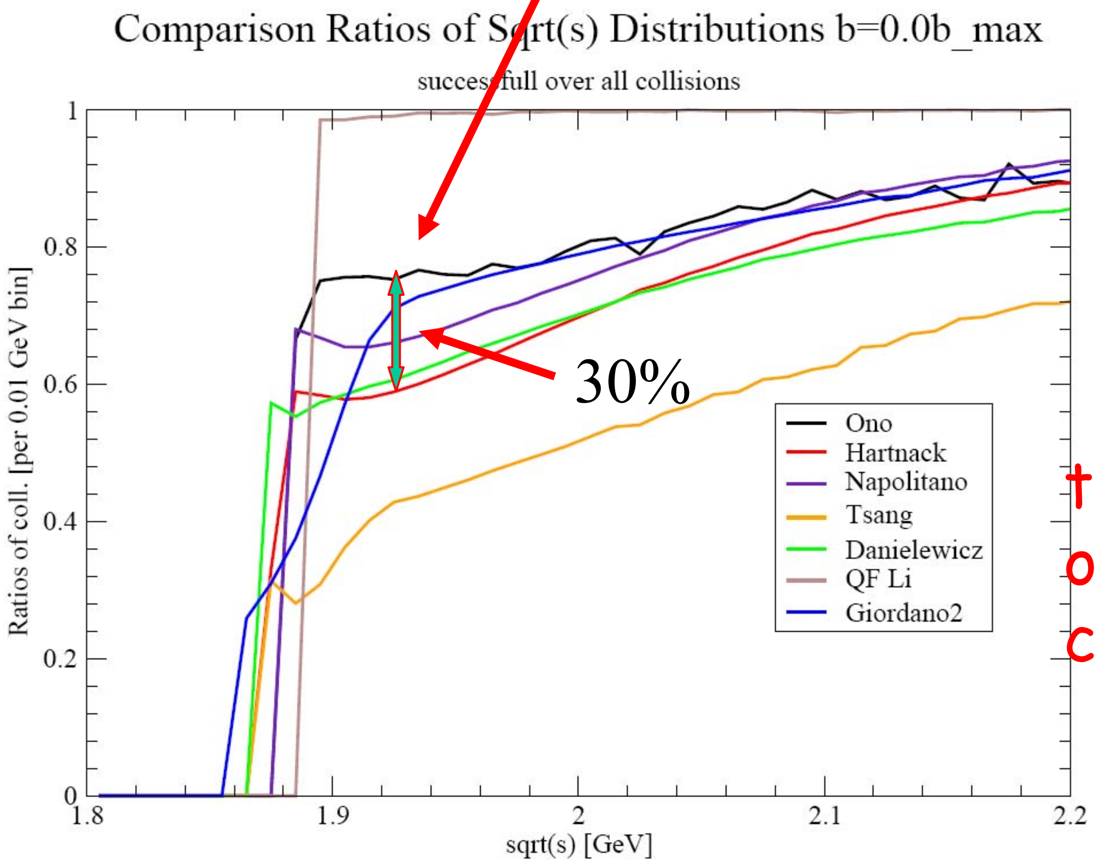


nonlinear:

diff ρ -> diff σ -> diff ρ

This has 3 reasons: - the time evolution of the rms radius is different in different programs
- the Pauli blocking is not under control
- implementation of the cross sections (in the comparison σ=40mb, isotropic)

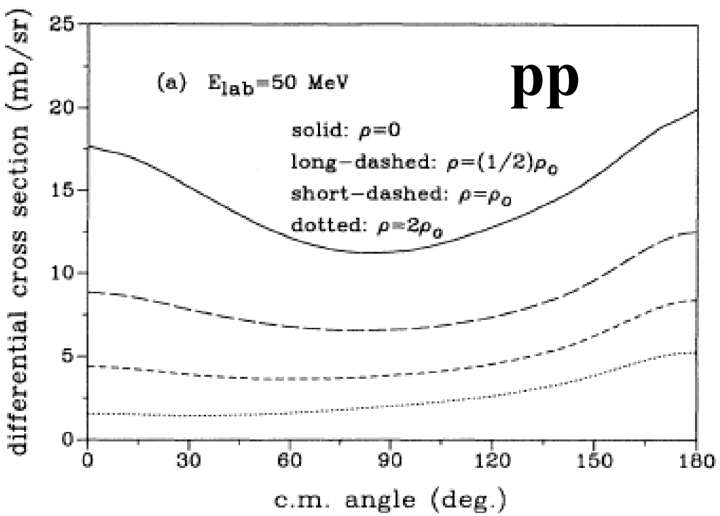
cause syst. errors

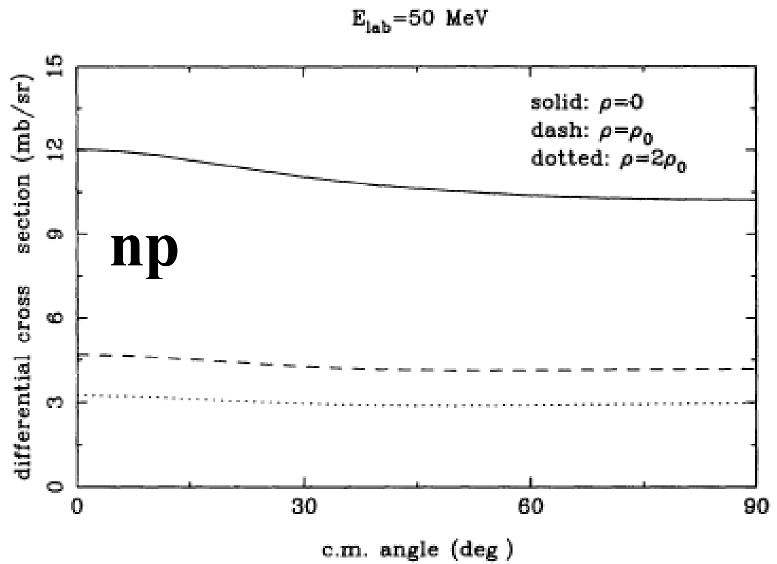


Fraction of Pauli blocking

the systematic error of our Pauli blocking routines changes the σ_{eff} by 30%

Problem 3: Also angular distribution changes





Consequently

Exchange p ⟷ n

At low E_{beam} :

Dramatic change of σ and of $d\sigma/d\Omega$

quite different stopping

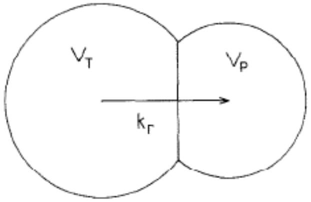
quite different dynamics

Only if these collision effects are under control we can start with the QUANTITATIVE

search for symmetry energy effects

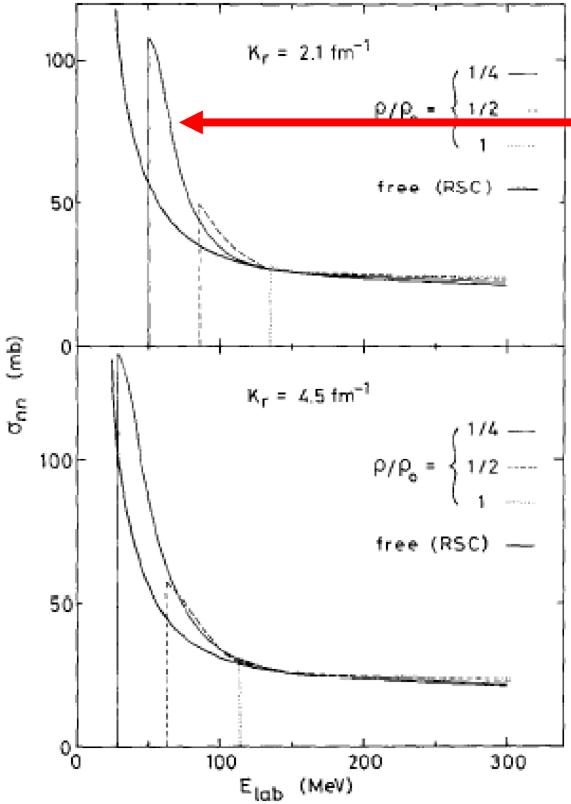
Problem 4: Was makes things worse:

Bohnet et al: σ in matter very different from that in finite nuclei (different Pauli blocking)



σ depends crucially on the local temperature (which phase space is locally occupied)

Bohnet et al. NPA 494,359



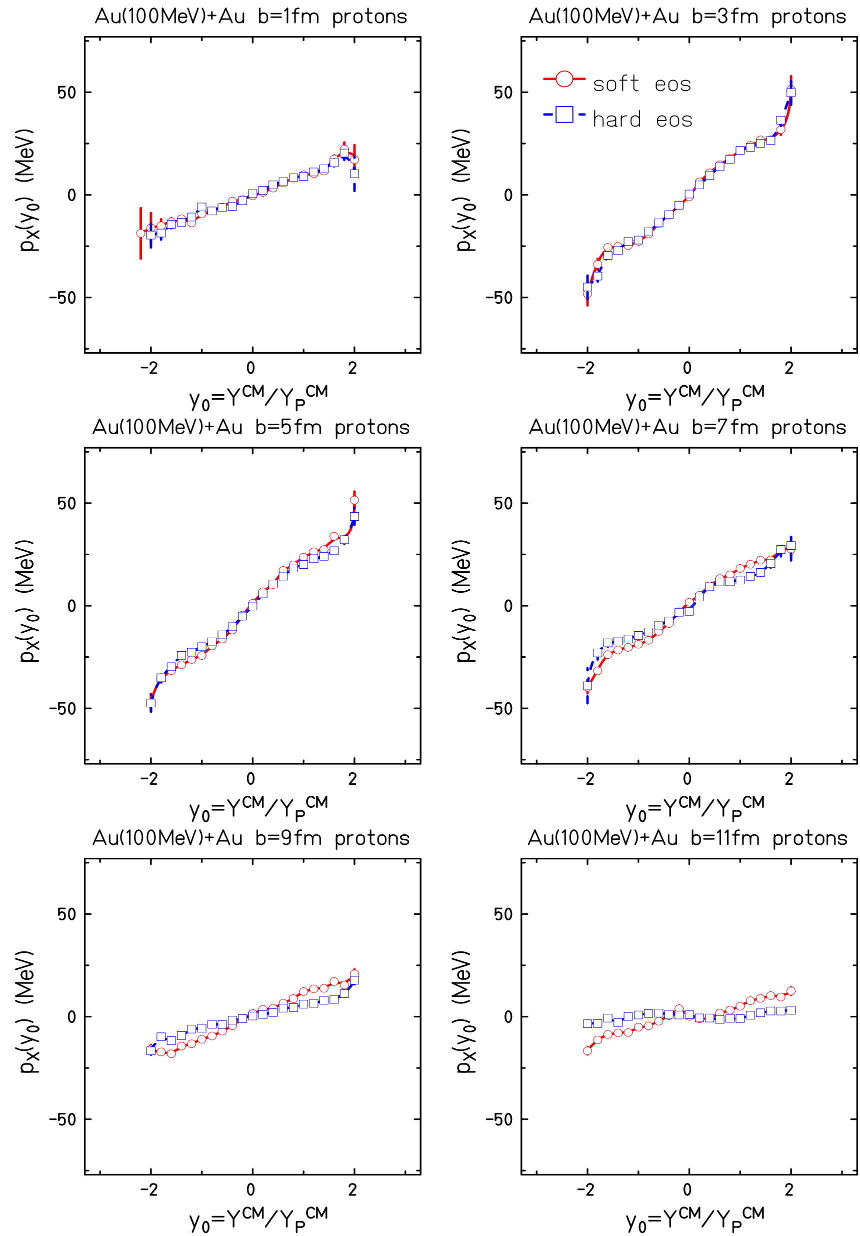
In a nucl. reaction σ even larger than in free space

At high energies $\sigma_{in\ medium}$ -> σ_{free}

This gives hope that for E_{kin} > 400 AMeV the problems 1-4 can get under control and that the systematic error becomes sufficiently small to draw robust conclusions.

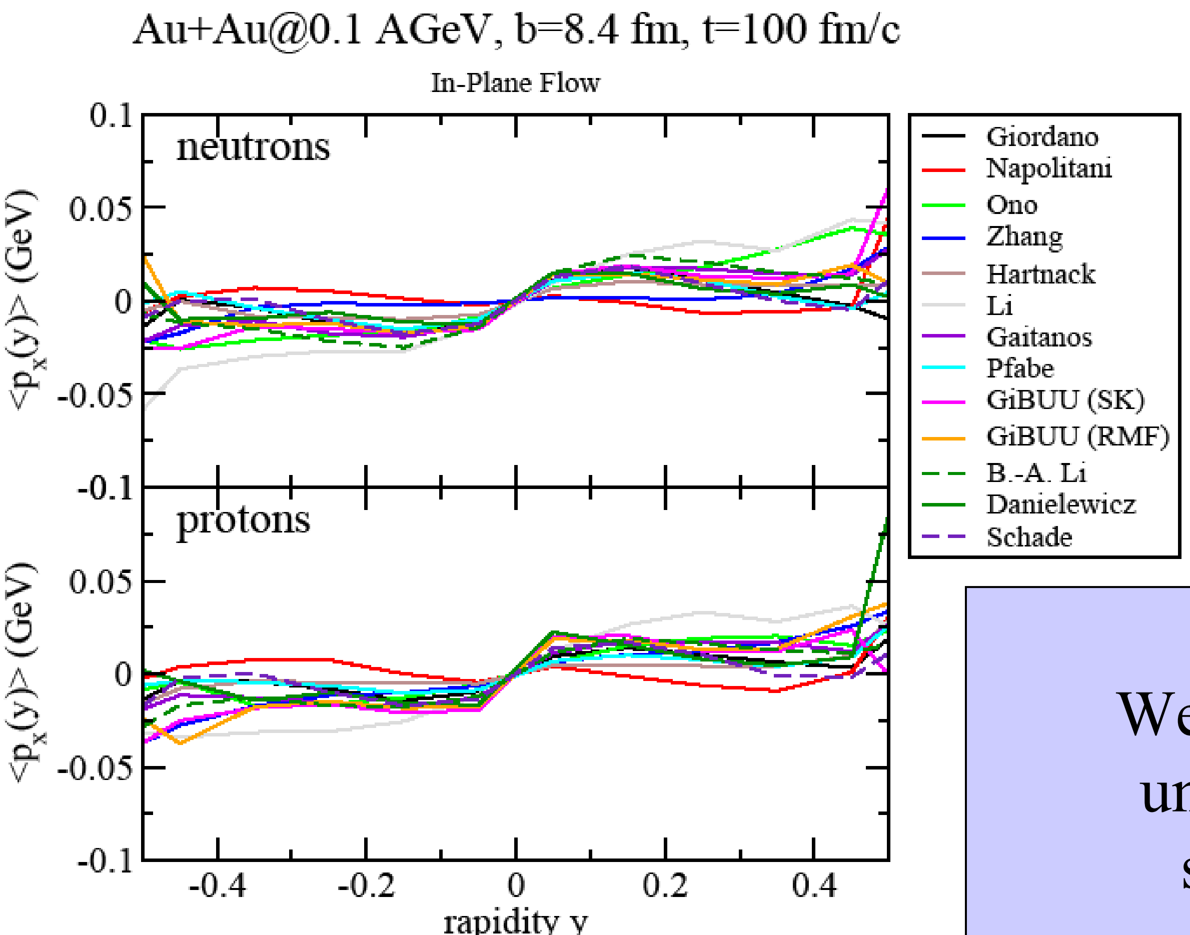
Why to worry?
Because we should not repeat history (in plane flow) :

A couple of years ago
we have been proud to have found
that the in-plane flow depends on
the EOS
and we published papers where
we concluded that the EOS
is soft, hard , semihard



Because everybody compared his results
with diff data using diff cuts we became
not aware that our results are not compatible

The problem was only that
the difference of flow for two EOS in the same program was tiny as compared to the results for the same EOS in different programs

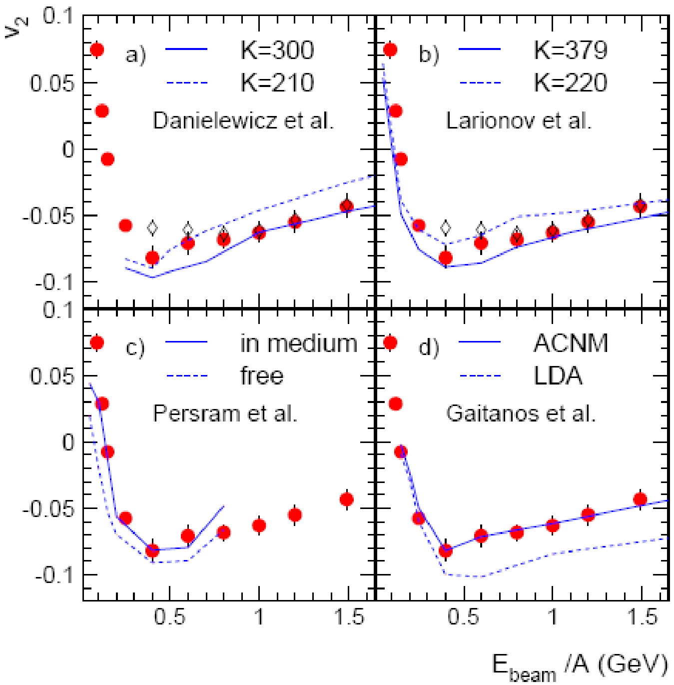


Same initial condition

Same σ

We have completely underestimated our systematic error

What finally motivated experimentalists (Andronic Phys.Lett.B612:173) to compare the programs and to declare their results for inconclusive



Agreement with data is obtained for each approach but for a different EOS a different σ

Conclusion: we have to work hard to get symmetry energies from reactions below 400 AMeV

At higher energies it becames a bit simpler

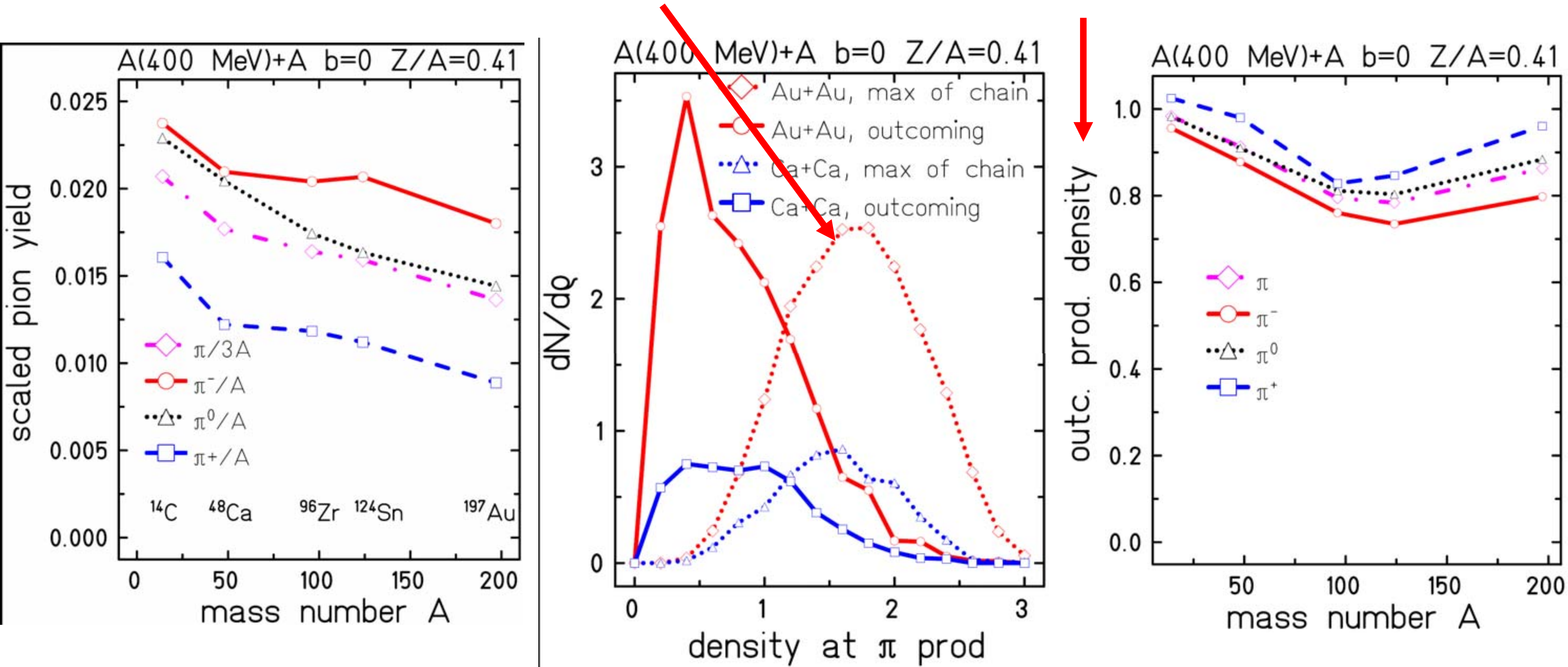
- Reaction fast-> density more under control
- Cross sections becomes similar and less density dependent

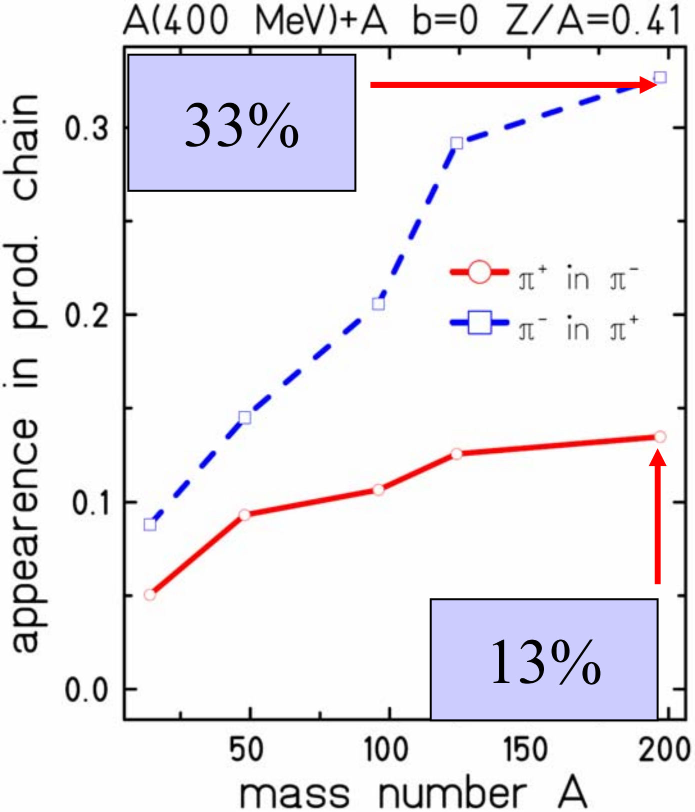
Symmetry sensitve observables at energies > 400 AMeV

1) π's
2) azimuthal distribution of baryons (v_2)

π's are created at many densitites

Observed pions are created at low density ($\rho < .9\ \rho_0$)





Many charge exchange reactions:

$\pi^+ \rightarrow \pi^- \rightarrow \pi^+$

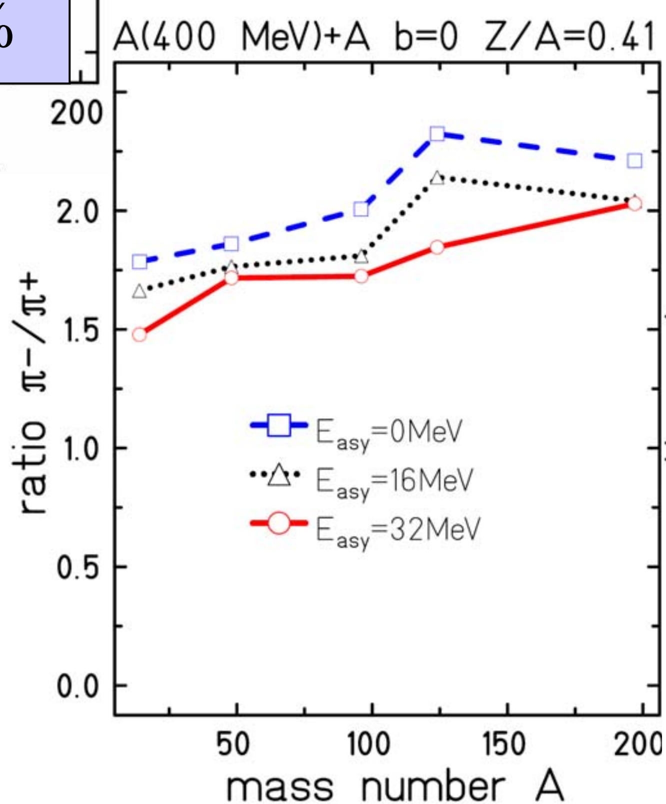
reduces sensitivity

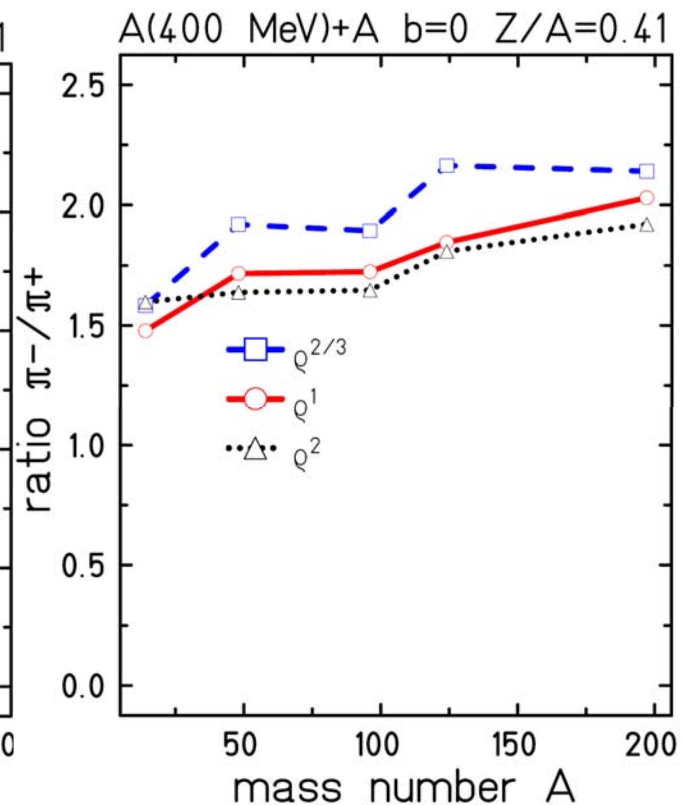
π^- / π^+ ratio

not really sensitive to symmetry energy:

-charge exchange

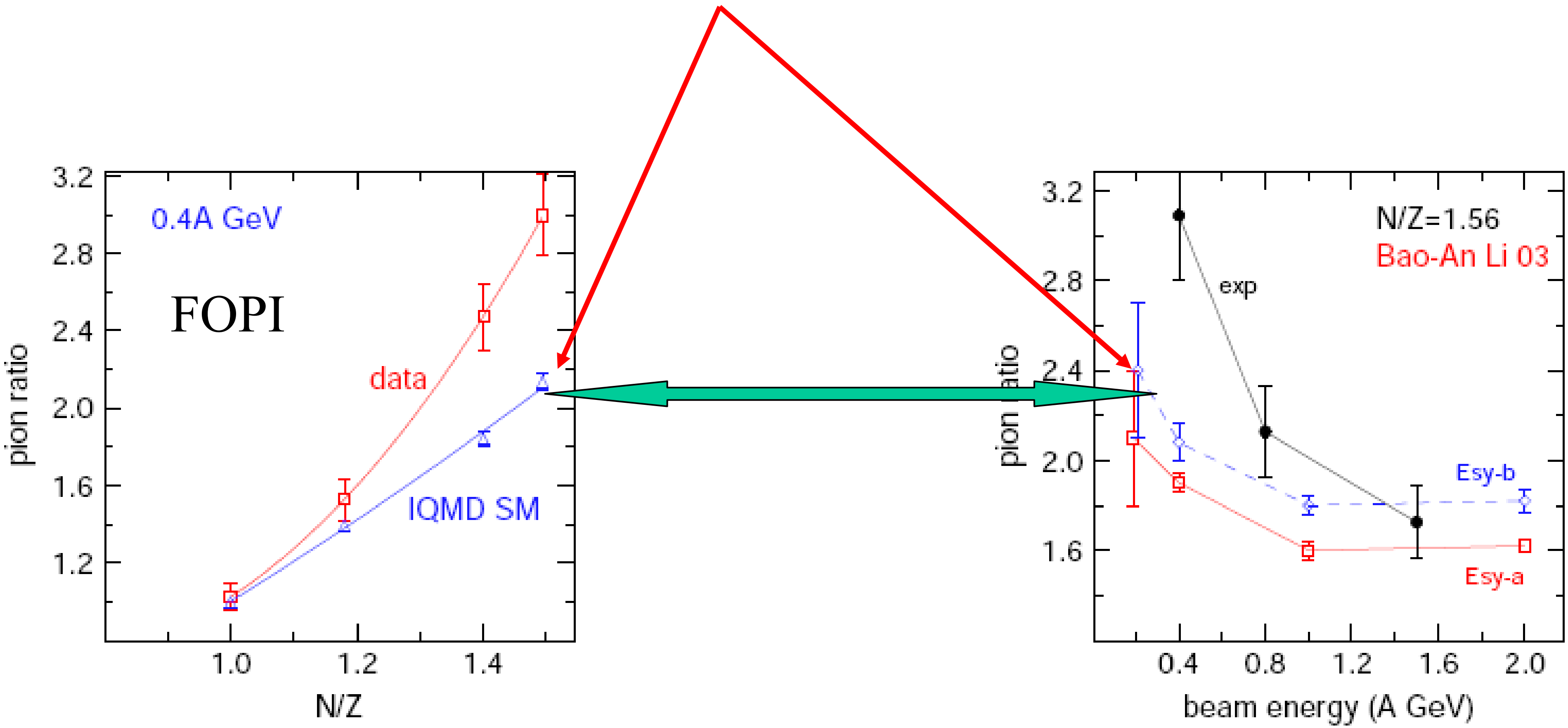
-low density





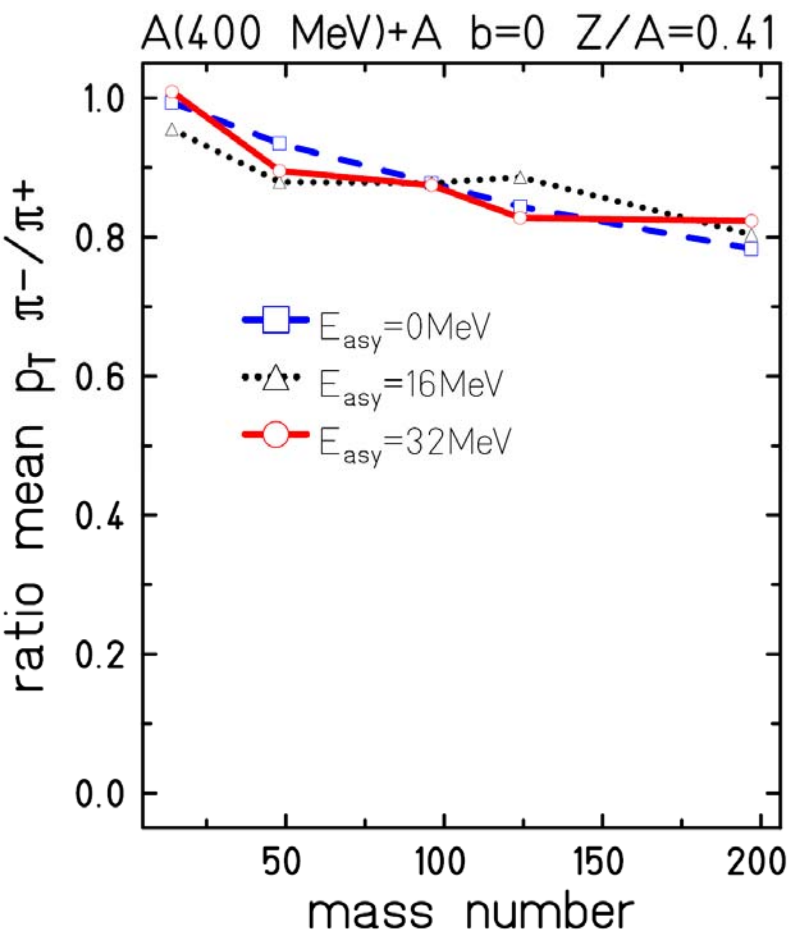
In additon: symmetry energy reduces π^-/π^+ ratio
(less nn collisions -> less π^-)

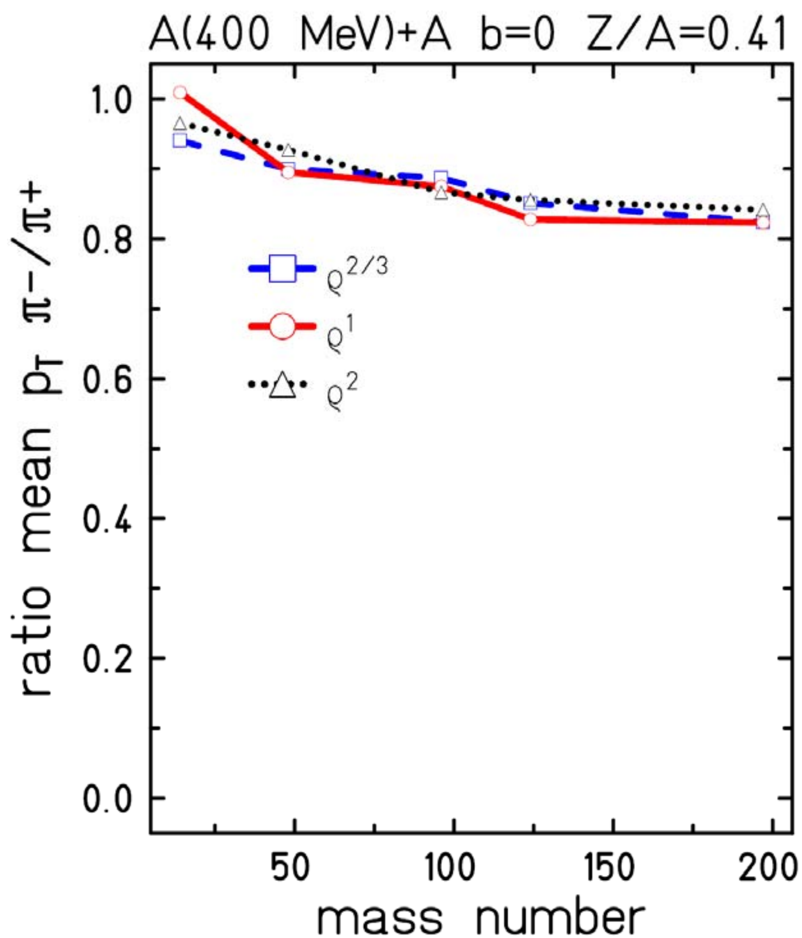
EXPERIMENT REQUIRES A LARGER RATIO
(in medium modification of the Δ ?)
In any case: predicitons of different codes are similar



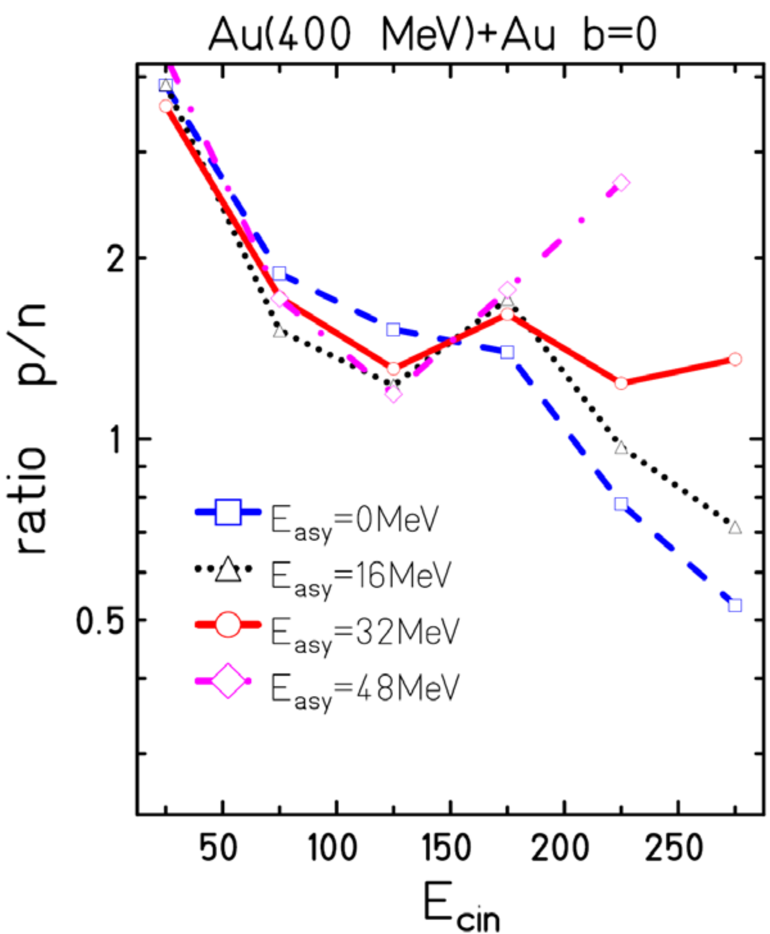
If multiplicity is not dependent on E_{sym} may be other observables like $\langle p_t \rangle$?

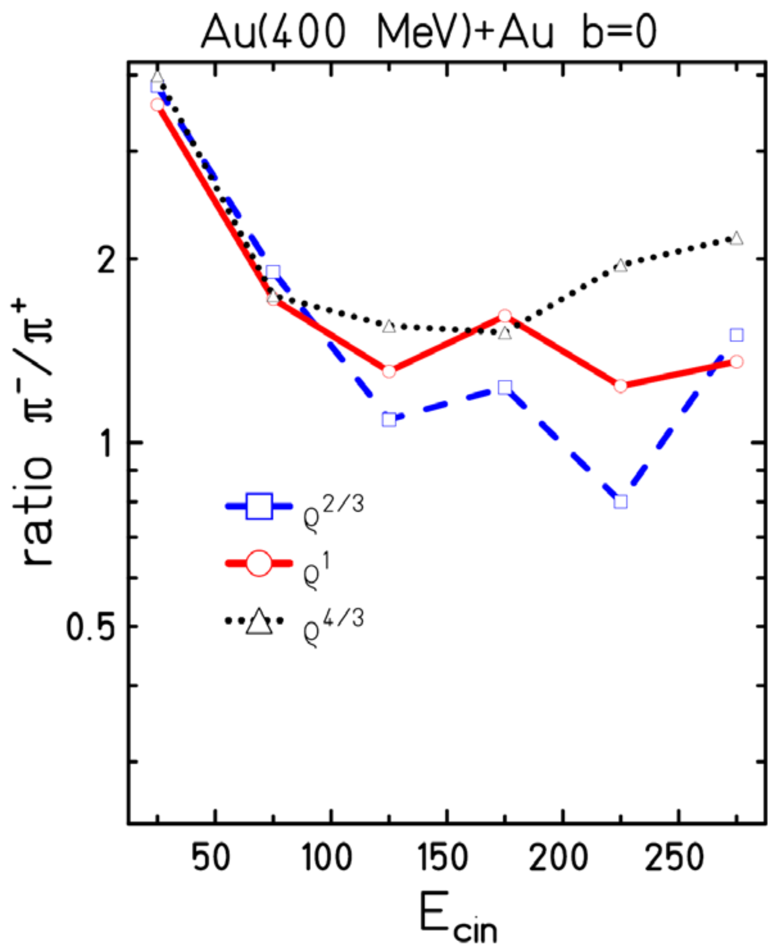
Not really !





And if you look for high momentum π's
(-> early creation)
They seem to be sensitive to the symmetry energy
but difficult to separate E_{asy} and ρ dependence
robust? Dependence on Δ-lifetime and in medium properties has to be checked, large experimental error bars



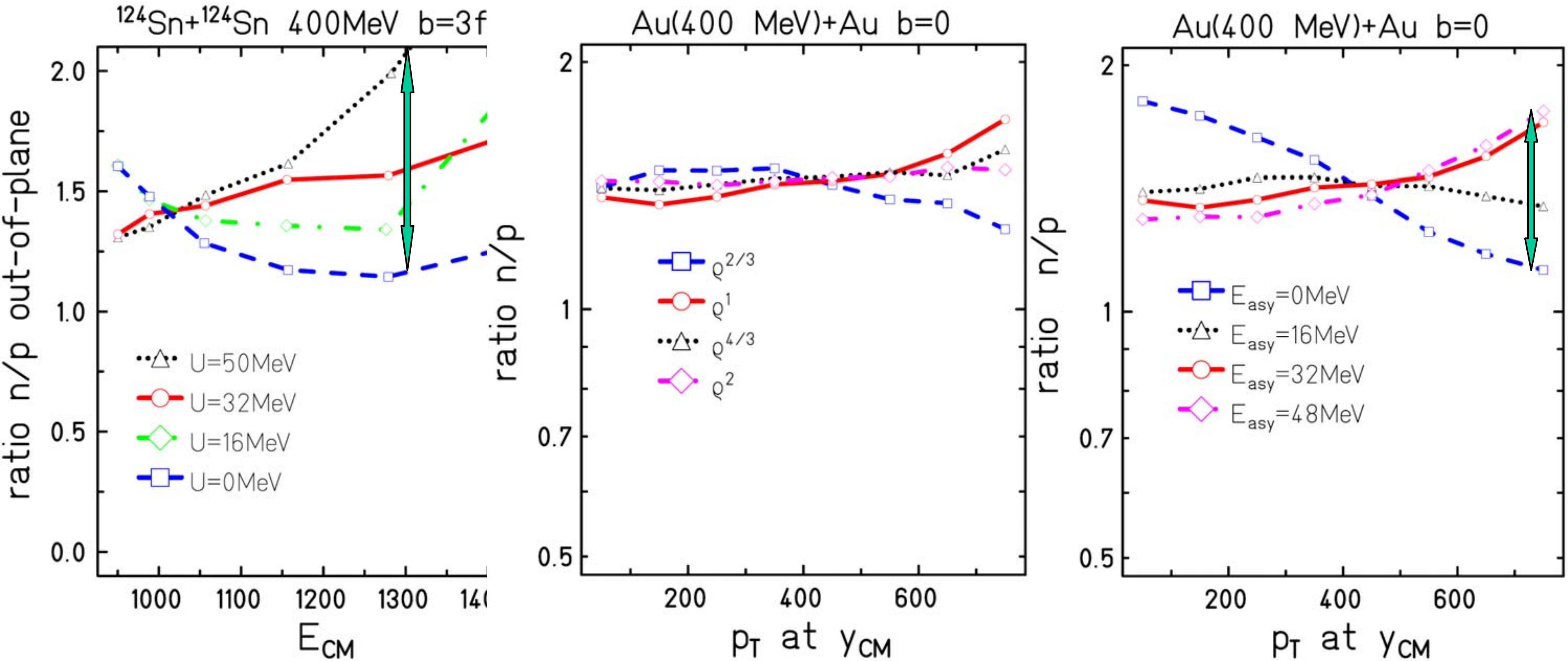


Best candidates for sensitive variables

- v_2 or in-plane/out of plane n/p ratio
- n/p ratio at large transverse momentum

Out of plane
(almost a factor 2)

high pt
(50 %)



Conclusions:

We are not ready to study symmetry energy at E_{beam} <300 AMeV

- nuclear matter calculations show that σ very sensitive to ρ,T, p_{rel}

  ρ and T not sufficiently under control in the codes

  $\sigma_{nuclear\ matter}$ different form $\sigma_{finite\ nuclei}$ (not explored really)

Consequence: each code produces effects but the systematic error is too large for quantitative predictions (-> v_1 and v_2)

At higher energies we can identify several observables which depend on the symmetry energy:

- π^-/π^+ ratio at high π momentum
- out of plane p/n ratio

Whether these variables are robust (do not depend on other little known input (Δ lifetime and width, EOS, fragment formation ...) remains to be seen

This precision is not achieved: densities in the programs differ by (at least 30%)

Trento workshop
Spring 2009

What is IQMD?

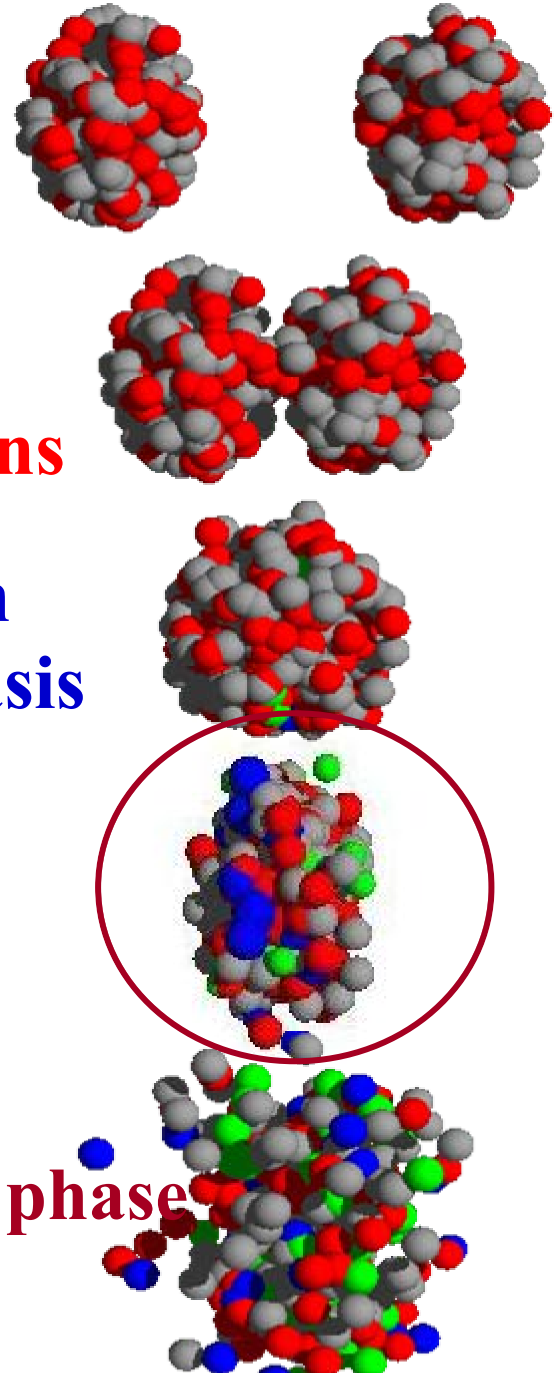
Isospin-Quantum Molecular Dynamics model

- Semiclassical dynamical N-body model with quantum features based on 2- and 3-body interactions

- Microscopic calculation of heavy ion collisions on an event-by-event-basis

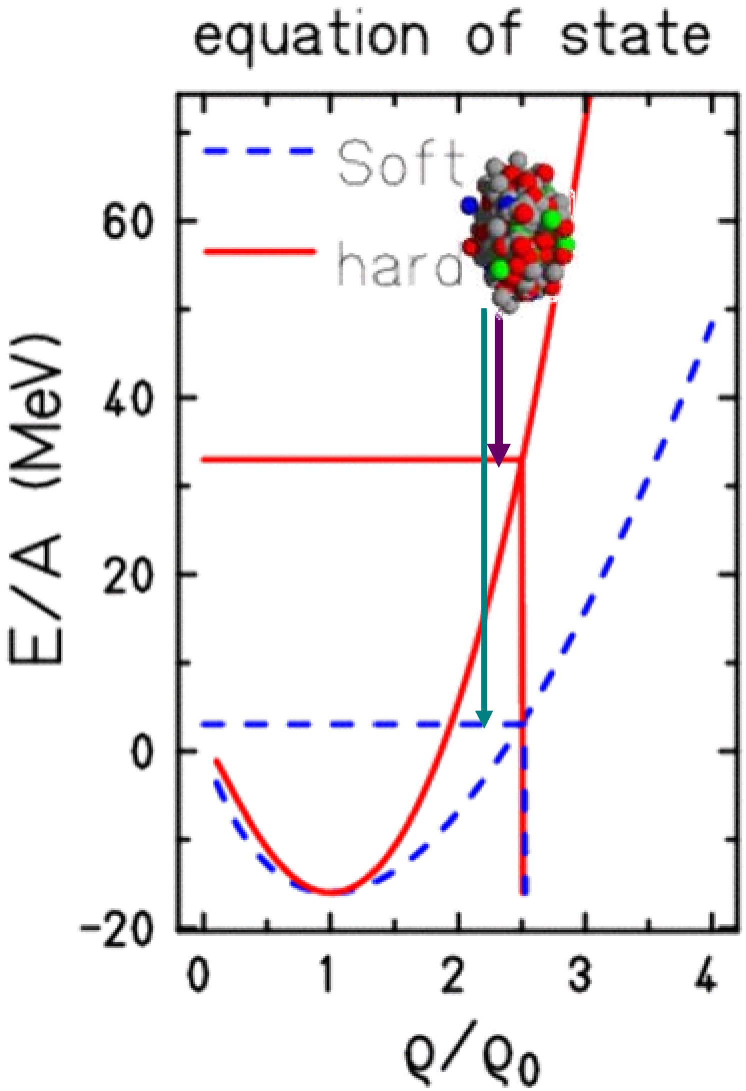
- includes N, Δ, π with isospin d.o.f.

- strange particles treated virtually

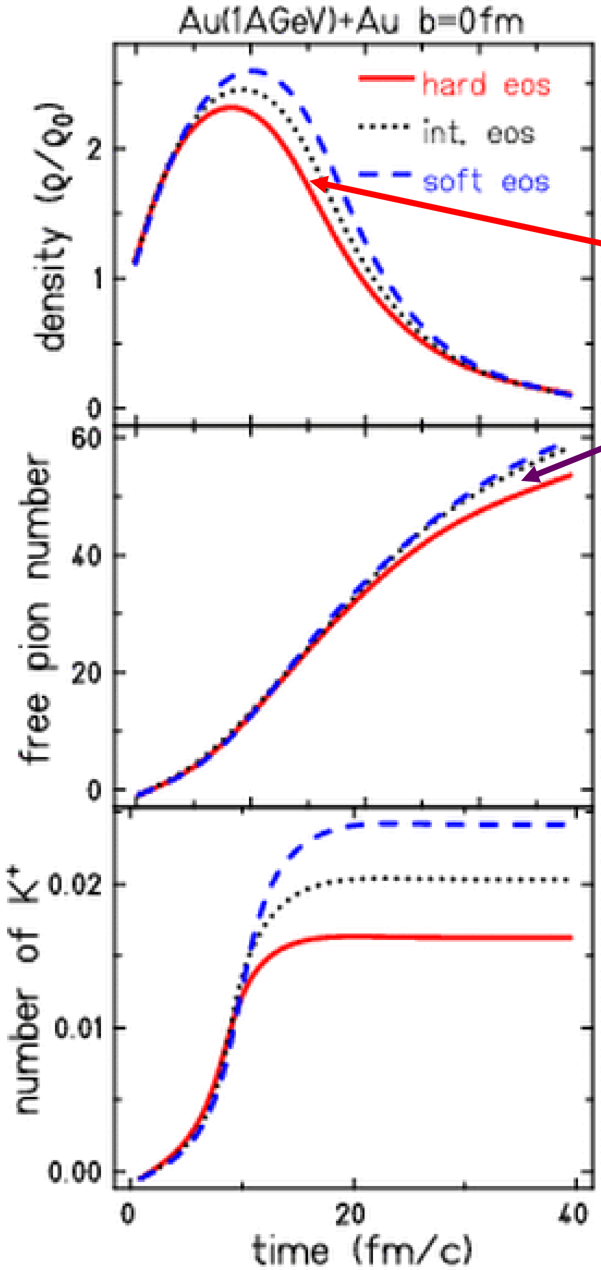


Allows for a « photo » of the high density phase and to to look inside …

The original idea of measuring the eos



- Eos describes the energy needed to compress nuclear matter
- A hard eos requires more energy for a given density than a soft one
- For a given density and a given available energy a soft eos leaves more thermal energy to the system than a hard eos
- R.Stock: This thermal energy could be measured by regarding pion production



At which density should we compare ?

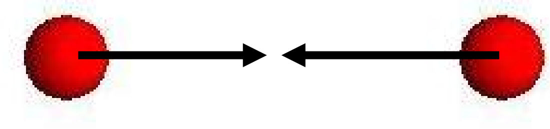
Hard and soft eos reach different maximum densities and the pion numbers are only slightly different.

For a small system the differences in density vanish. The differences in pion yield as well

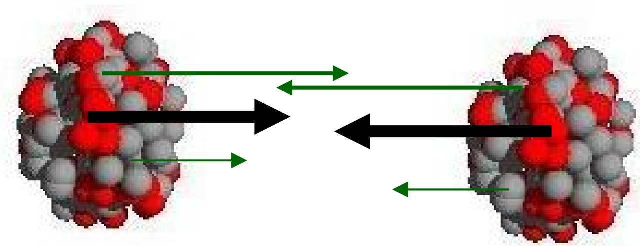
However the kaons show significant differences

Subthreshold kaon production

•Production of kaons at energies below the kinetic threshold for K production in elementary pp collisions



•Fermi momenta may contribute in energy

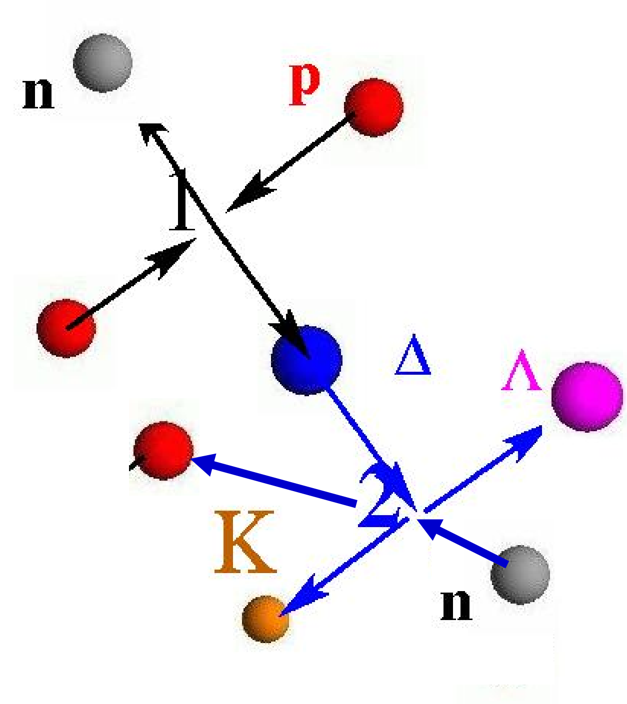


•Multistep processes can cumulate the energy needed for kaon production

•Importance of resonances (especially the Δ) for storing energy

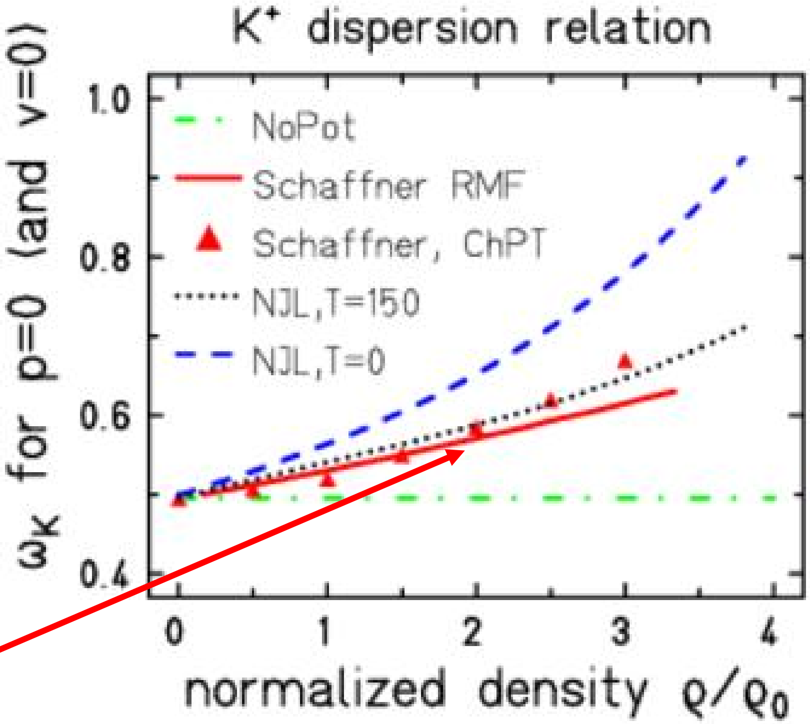
•Short livetime of resonance favors early production at high densities

•Sensitivity to in-medium effects and nuclear equation of state



High density: medium effects

Optical potential: repulsive for K^+, enhances its « mass »



Several parametrizations exist & are implemented

Use of Schaffner-Bielich RMF results as standard

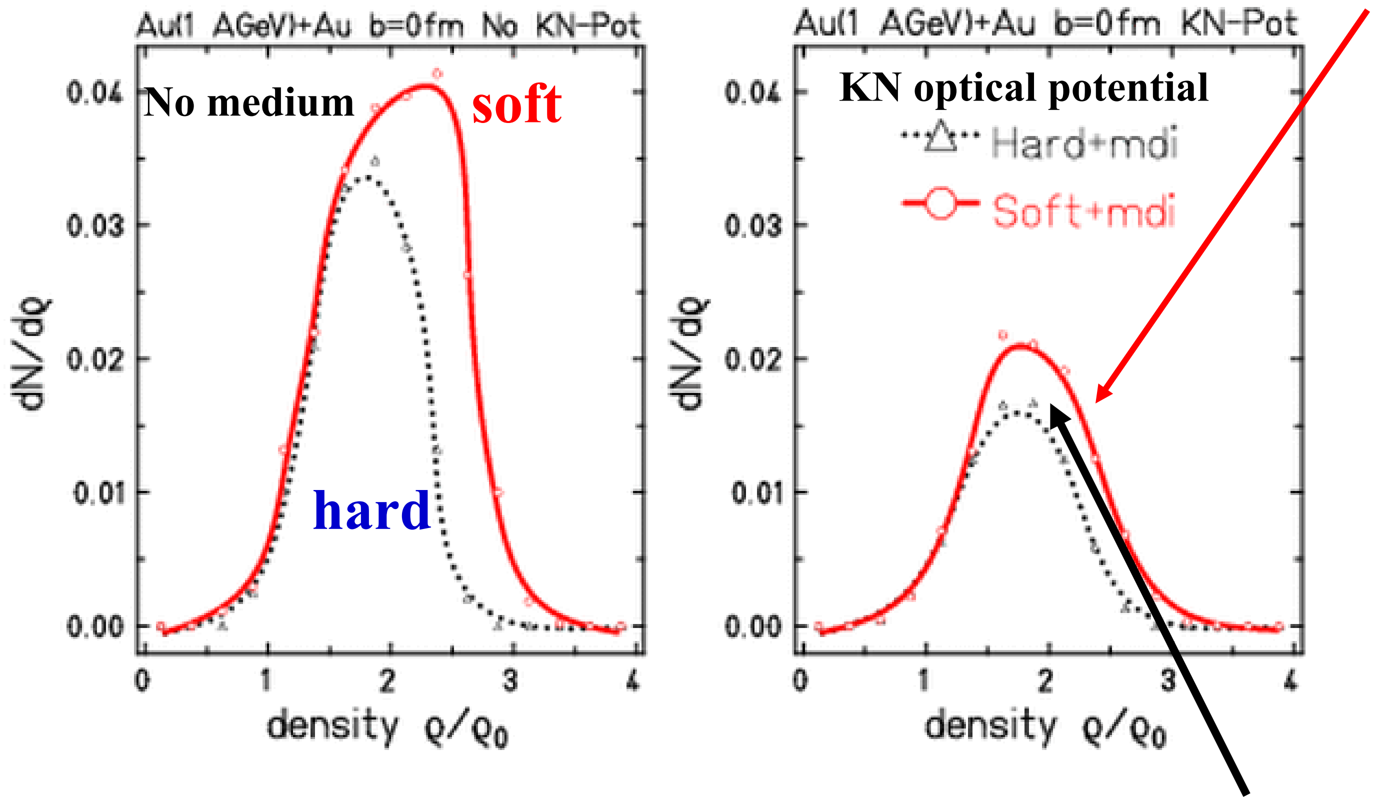
$$U^K_{opt} = \sqrt{(\vec{k} - g_v\vec{\Sigma}_v)^2 + m_K^2 + m_K g_s \Sigma_s} + g_v\Sigma_v^0 - \sqrt{k^2 + m_K^2}$$

Optical potential influences K^+ propagation but changes also the production threshold : penalty at high density

Reduction of the total yield: counter-effect to eos.

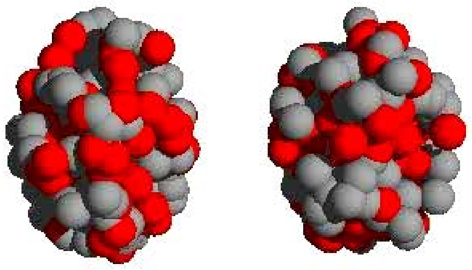
Kaons test high densities

Multistep processes require high densities, but medium effects of kaons penalize the high density production

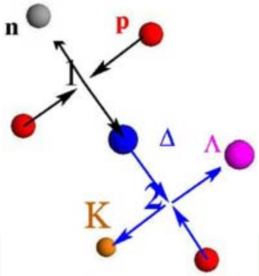


Penalty from KN pot reduces the effect but sensitivity to the eos still survives. However, the absolute yield itself is not conclusif.

Simulation of a collision Au+Au @ 1.5 AGeV b=0 with IQMD



red: protons gray: neutrons green: Deltas blue: pions

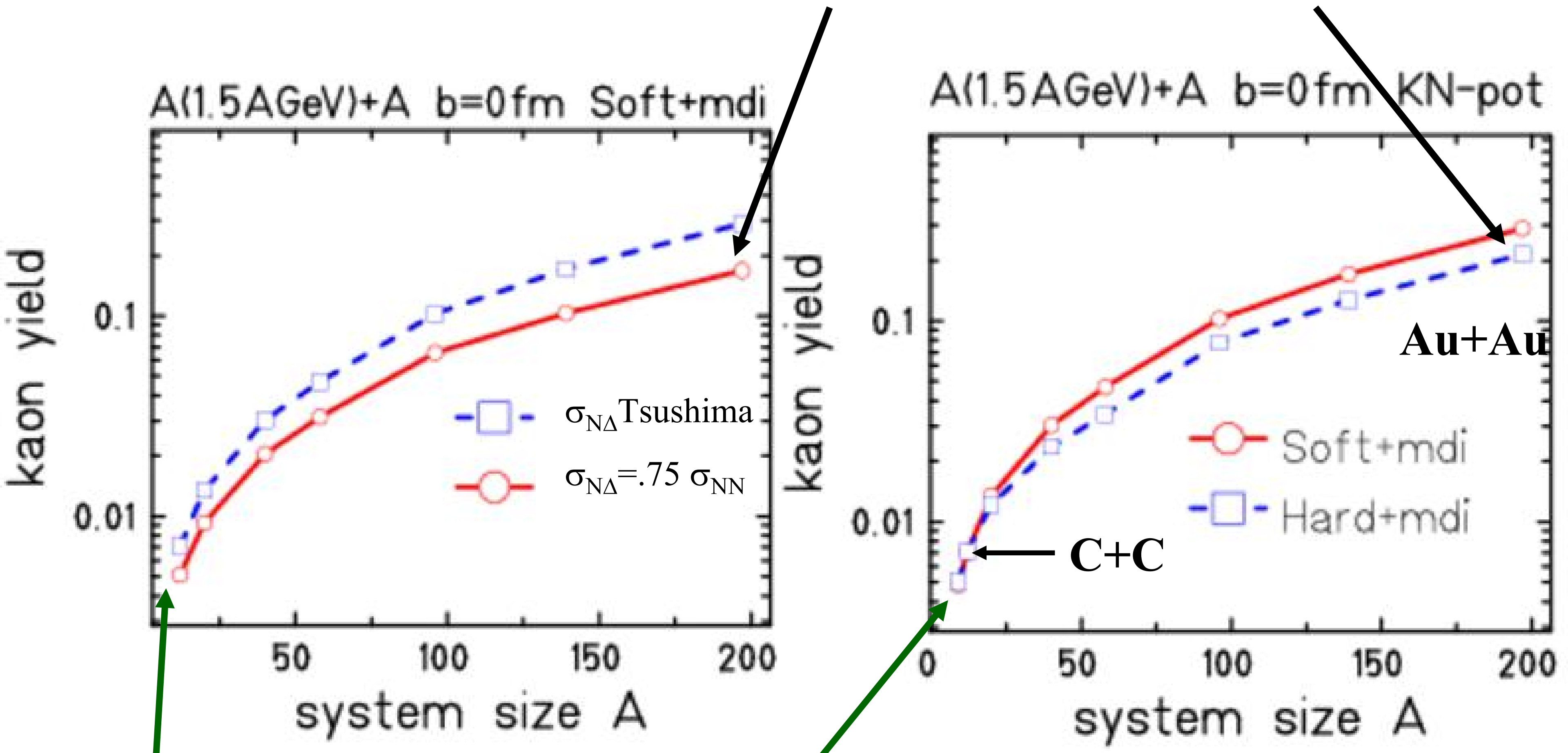


Many combinations are possible - Many channels have to be implemented

$NN \to N\Lambda K^+$	$NN \to N\Sigma K^+$	$NN \to \Delta\Lambda K^+$	$NN \to \Delta\Sigma K^+$
$N\Delta \to N\Lambda K^+$	$N\Delta \to N\Sigma K^+$	$N\Delta \to \Delta\Lambda K^+$	$N\Delta \to \Delta\Sigma K^+$
$\Delta\Delta \to N\Lambda K^+$	$\Delta\Delta \to N\Sigma K^+$	$\Delta\Delta \to \Delta\Lambda K^+$	$\Delta\Delta \to \Delta\Sigma K^+$
$\pi N \to \Lambda K^+$	$\pi N \to \Sigma K^+$	$\pi\Delta \to \Lambda K^+$	$\pi\Delta \to \Sigma K^+$
$NN \to NNK^+K^-$	$N\Delta \to NNK^+K^-$	$N\Delta \to N\Delta K^+K^-$	$\Delta\Delta \to NNK^+K^-$
$\Delta\Delta \to \Delta\Delta K^+K^-$	$\pi N \to NK^+K^-$	$\pi\Delta \to NK^+K^-$	

- **Each channel contains isospin subdivisions**
- **Only few channels (like $pp \to p\Lambda K^+$) are measured by the experiment (even incomplete infos)**
- **Significant incertainties from parametrization of unknown channels or isospin subdivisions**

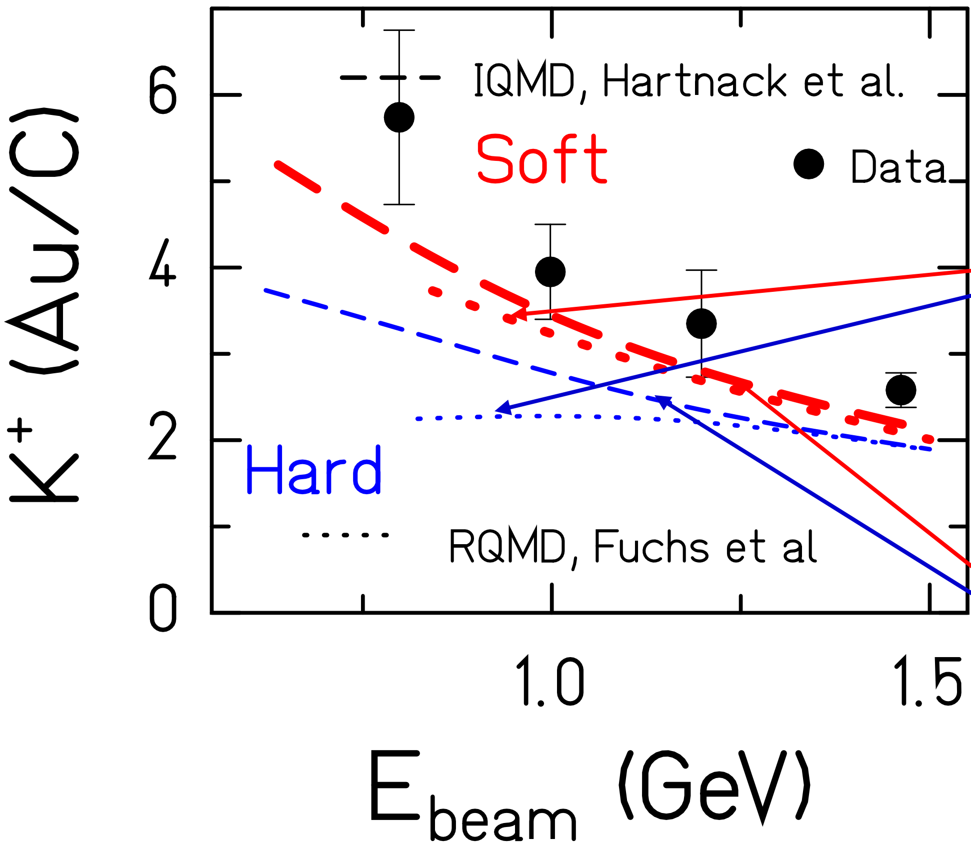
Eos cannot be deduced directly from kaon yields! Incertainties of cross sections larger than eos effect



However, the eos effect vanishes for small A while the cross section effect persists up to small A.

The solution: use ratios Au/C

KaoS data support soft eos



Data: Ch.Sturm et al.

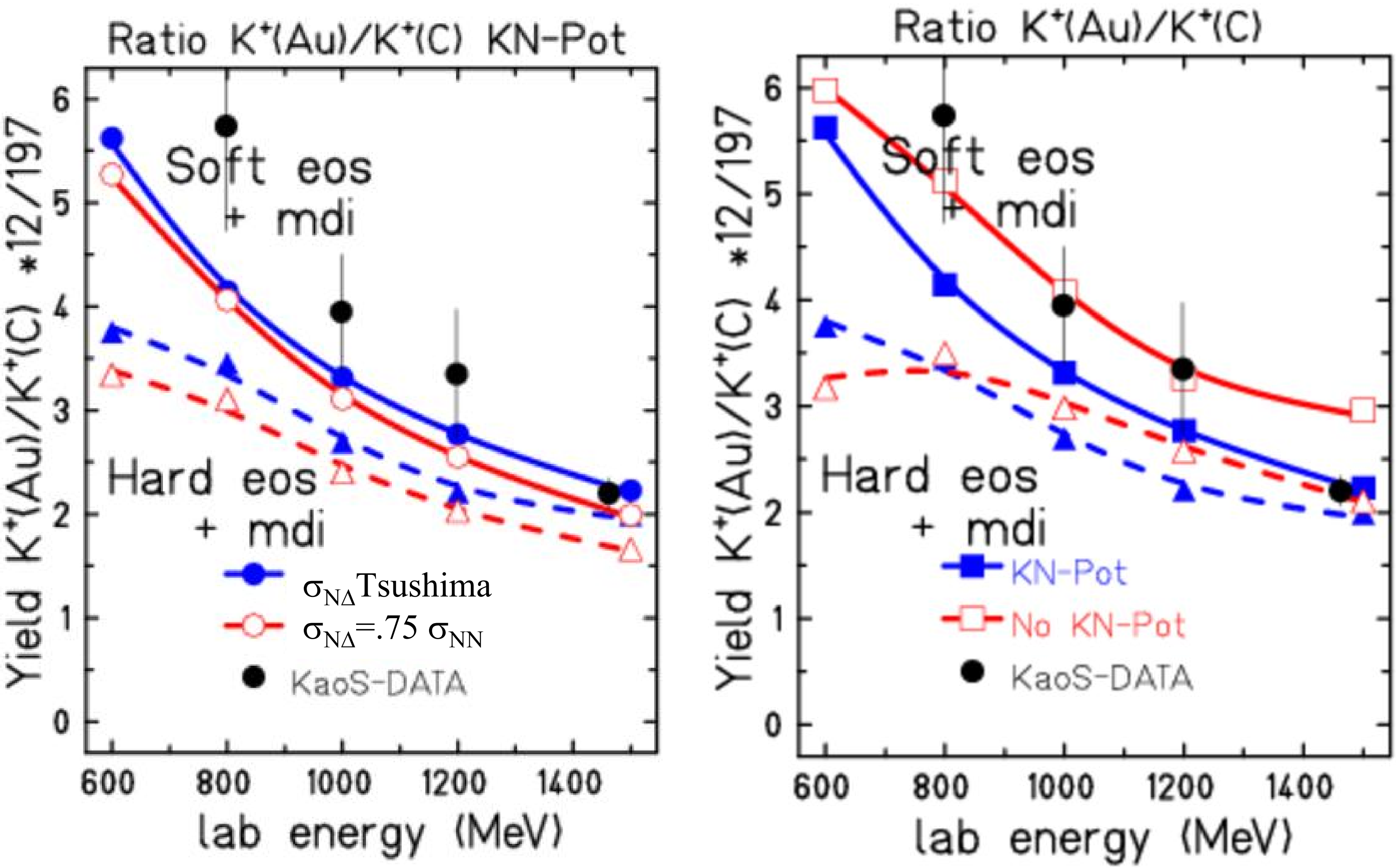
RQMD: Ch. Fuchs

1:0 for soft

IQMD supports this

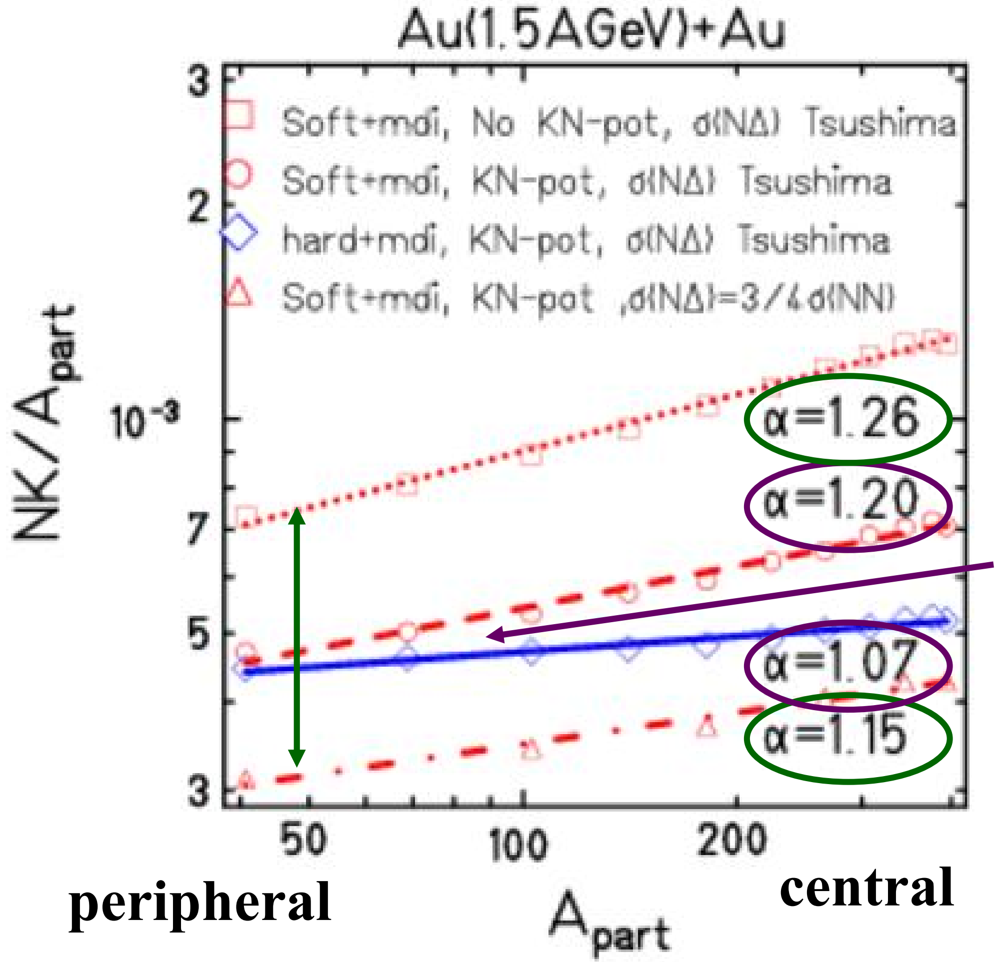
(althouhgh IQMD and RQMD differ in absolute yields)

A observation which is robust



versus effects of production cross sections, KN-potential, less stopping (reduced σ_{NN}) , lifetime of the Δ, …

Au: central versus peripheral

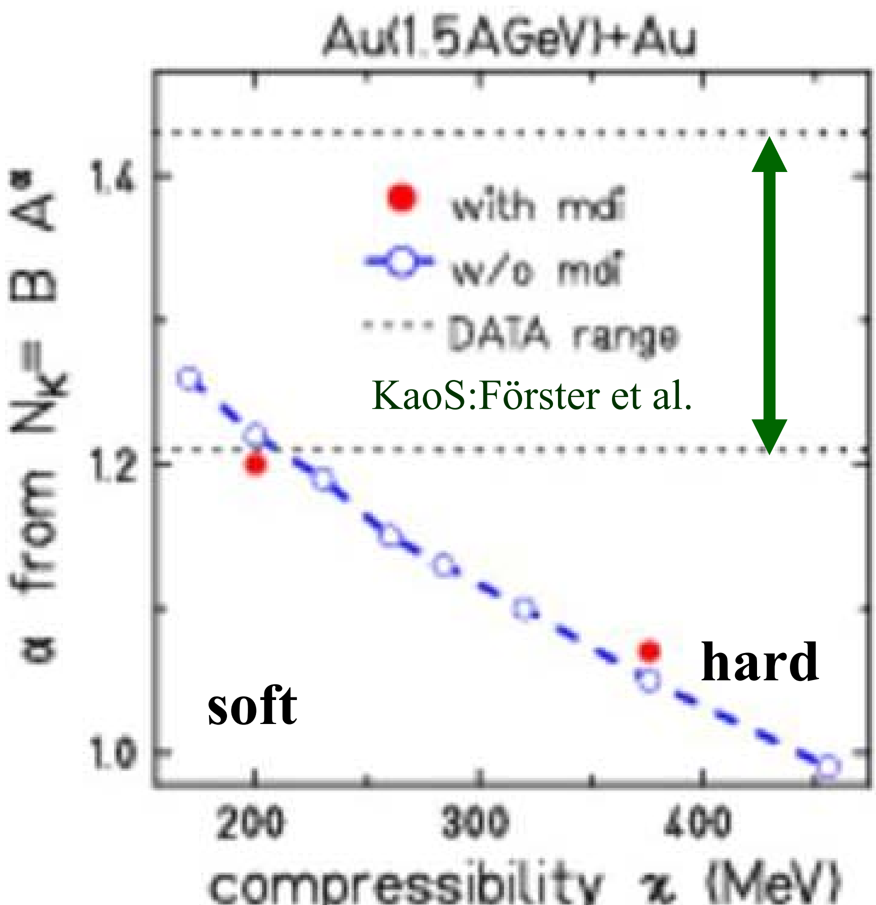


Different cross sections and potential parameters may change the global yield. However, the parameter α for the increase of the kaon yield N with the number A of participating nucleons (raising with centrality)

$$N(K)=N_0\, A^{\alpha}$$

depends on the eos. A soft eos yields higher values than a hard eos.

Determination of the eos from α



The relation between the compression modulus and α is monotonously falling.

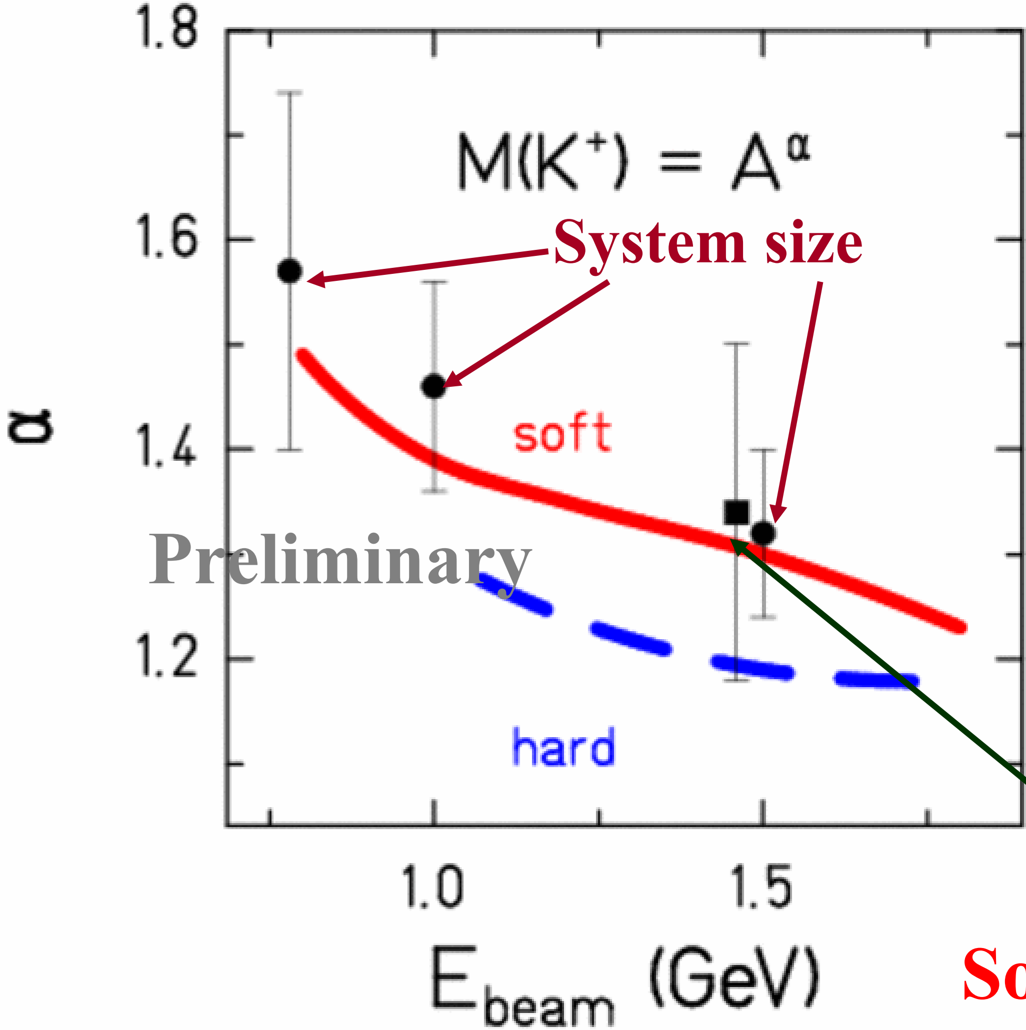
KaoS data (Förster et al.) favor a value below 200 MeV, i.e. a soft eos.

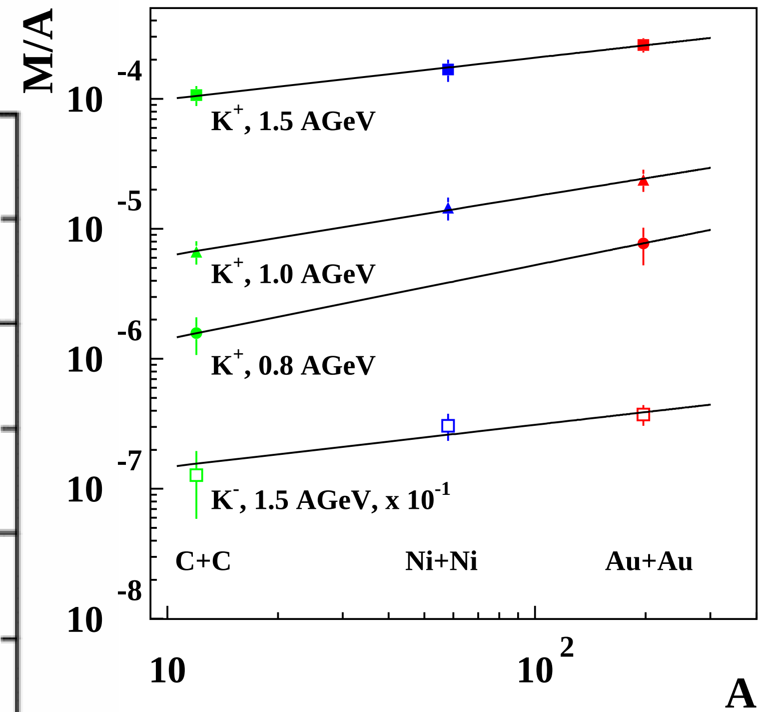
2:0 for soft

PRL 96 (2006) 012302

Energy dependence of the system size systematics

Similar method, now using system size A of inclusive events





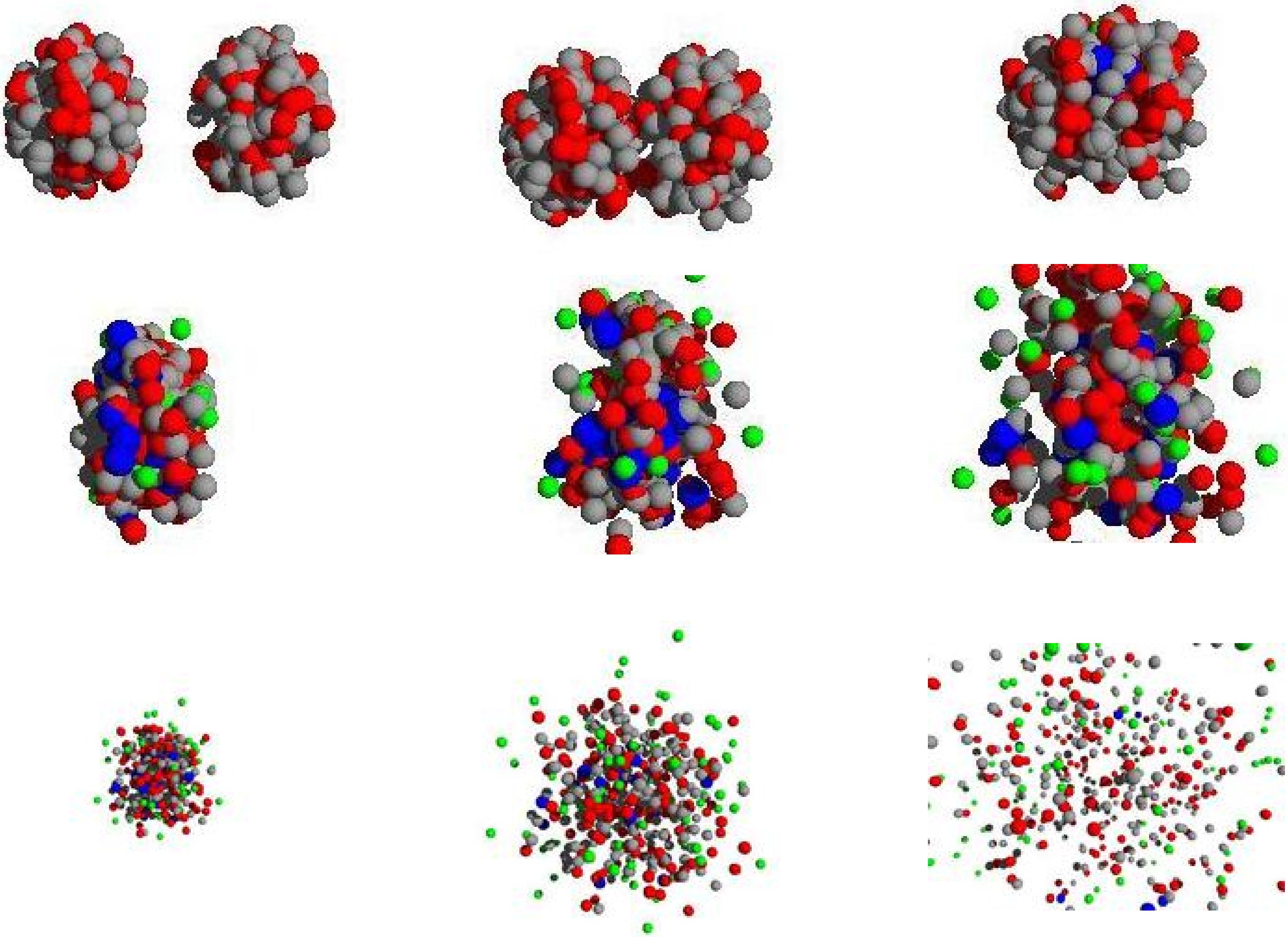
A_{part} in Au+Au agrees with that

3:0 for soft

Soft eos confirmed

Conclusion

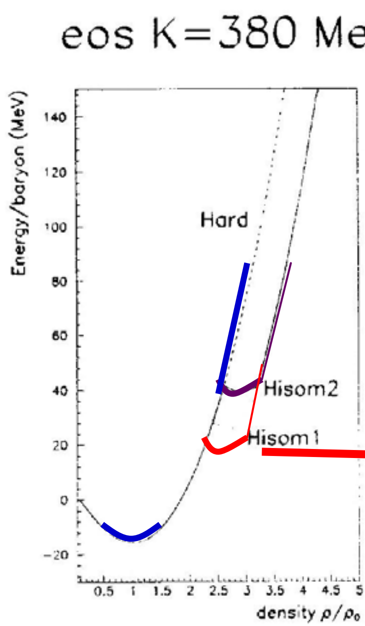
- In a range up to 1.5 AGeV the kaon data from KaoS (and FOPI) are consistent with a soft equation of state (K~200 MeV)
  - Au/C ratios at different energies
  - Scaling law on participant numbers
  - Scaling law on system size at different energies
- These findings are consistent with results of the analysis of FOPI-data on nucleonic flow, squeeze, …
- The kaon excitation function of KaoS gives no rise for the existence of density isomers up to $3\rho_0$. The exitation function of E895 seems to prolong this statement to even higher densities.

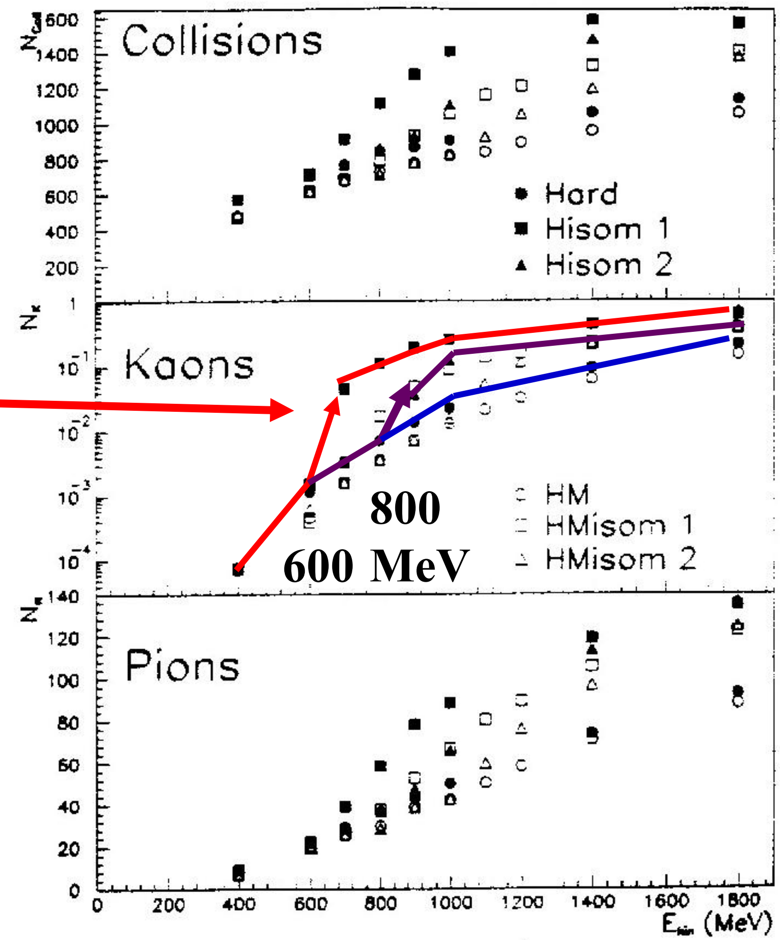


Kaons and density isomers

- Could reveal density isomers by a sudden rise in the excitation function of kaons - KaoS might measure it

A 2nd minimum would yield a sudden factor of 10 in the kaon yield





24 PHYSICAL REVIEW LETTERS

Subthreshold Kaons Would Reveal Density Isomers

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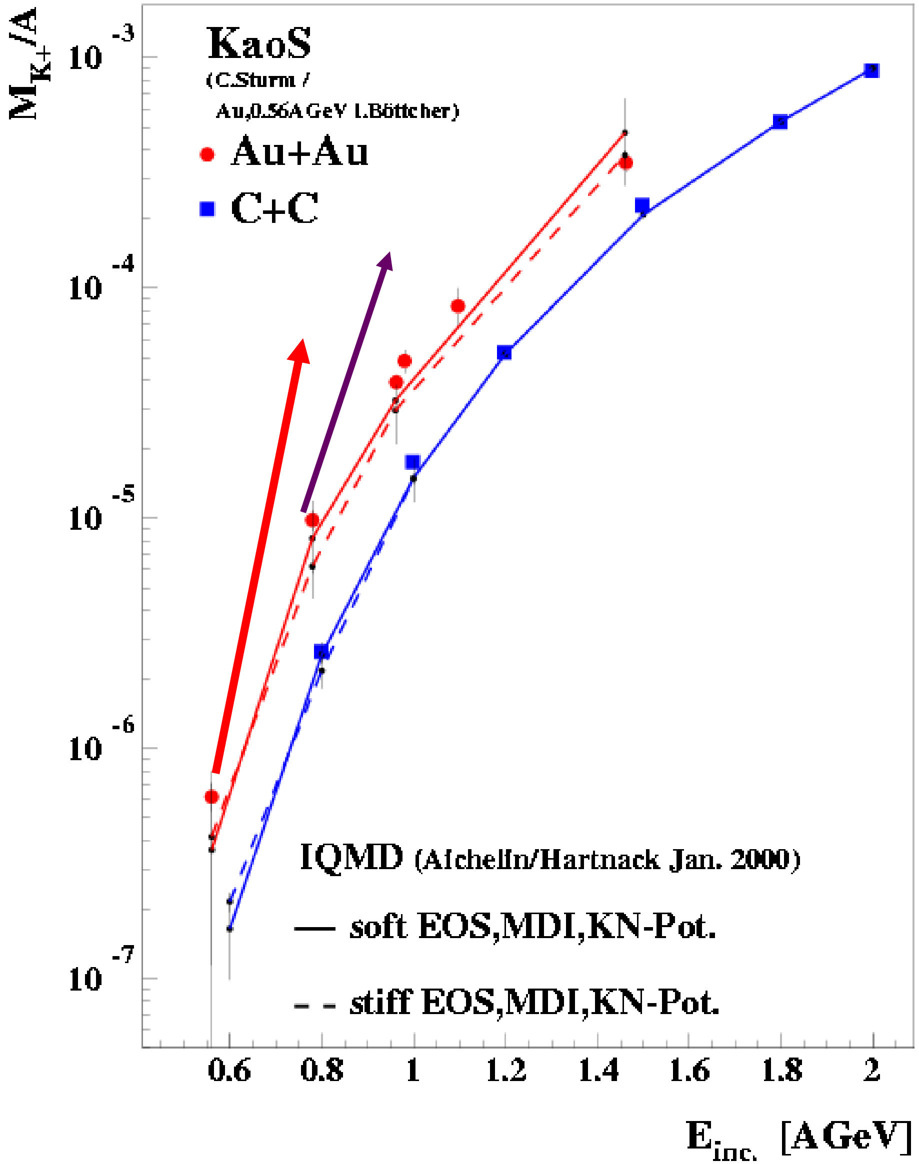
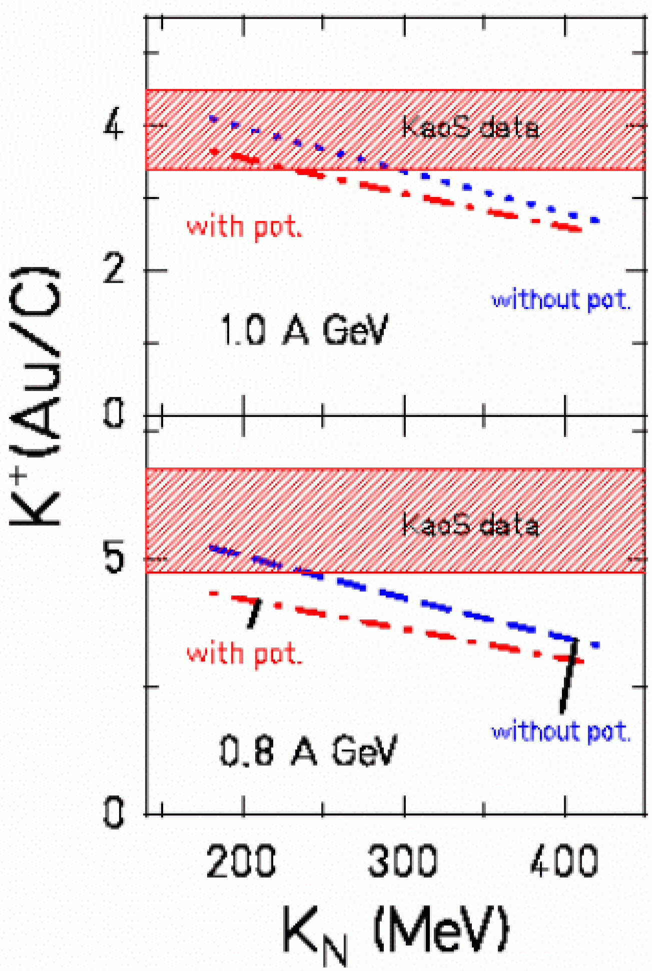


KaoS DATA: no isomer up to $3\rho_0$

A density isomer would have needed the strong raise indicated by the arrows.

IQMD calculations using a KN optical potential and a soft eos are consistent with KaoS data on Au+Au and C+C of Sturm et al.

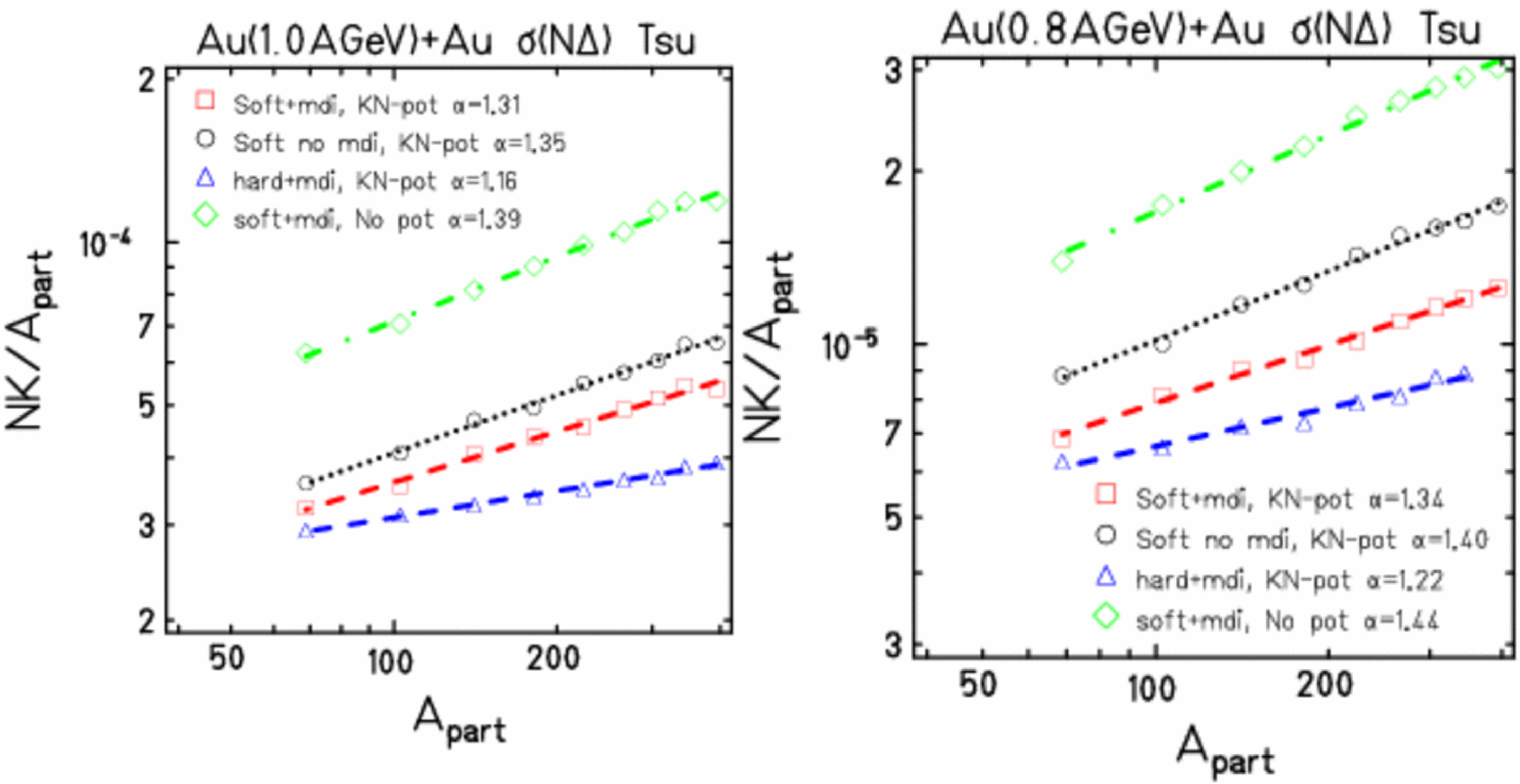
Analysis at lower beam energy



A soft equation of state is favoured.

Acceptation range for K.

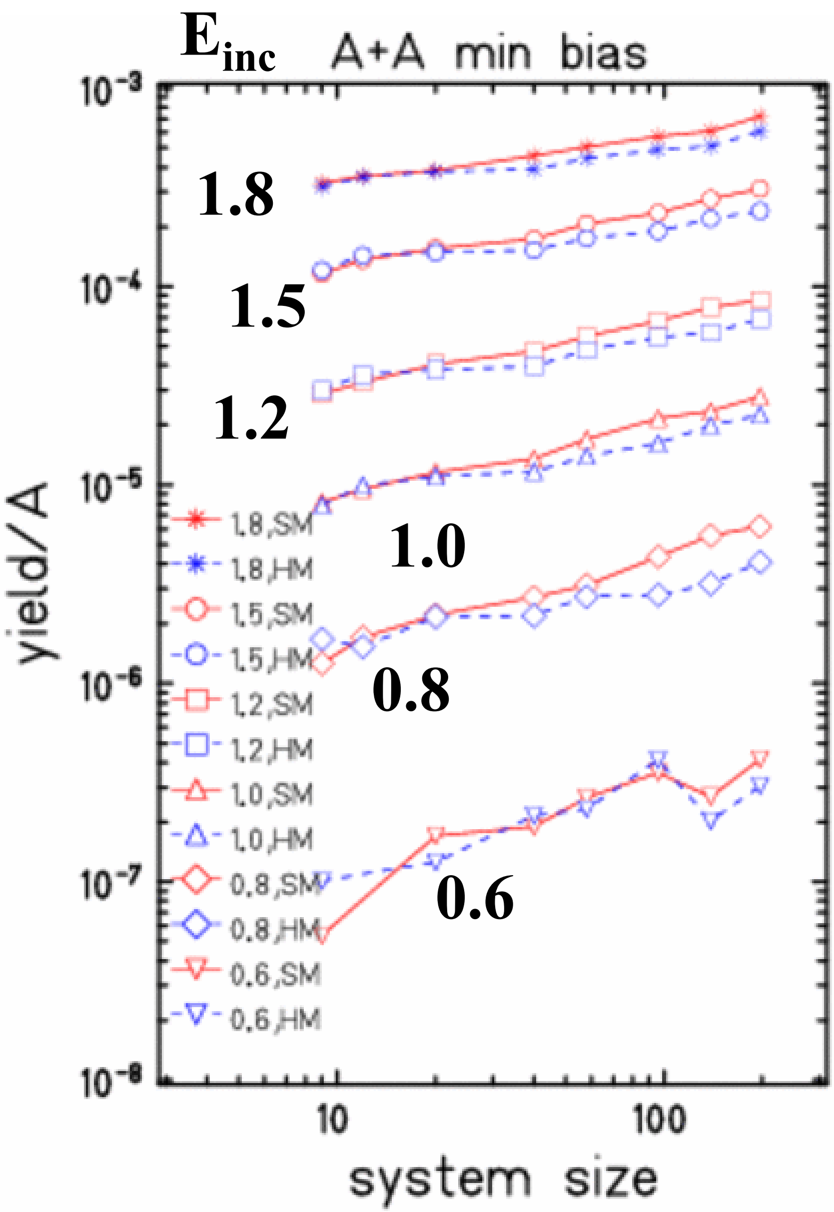
Going down in beam energy



A soft eos yields $\alpha \approx 1.4$ at E=0.8 AGeV, a hard eos yields $\alpha \approx 1.2$

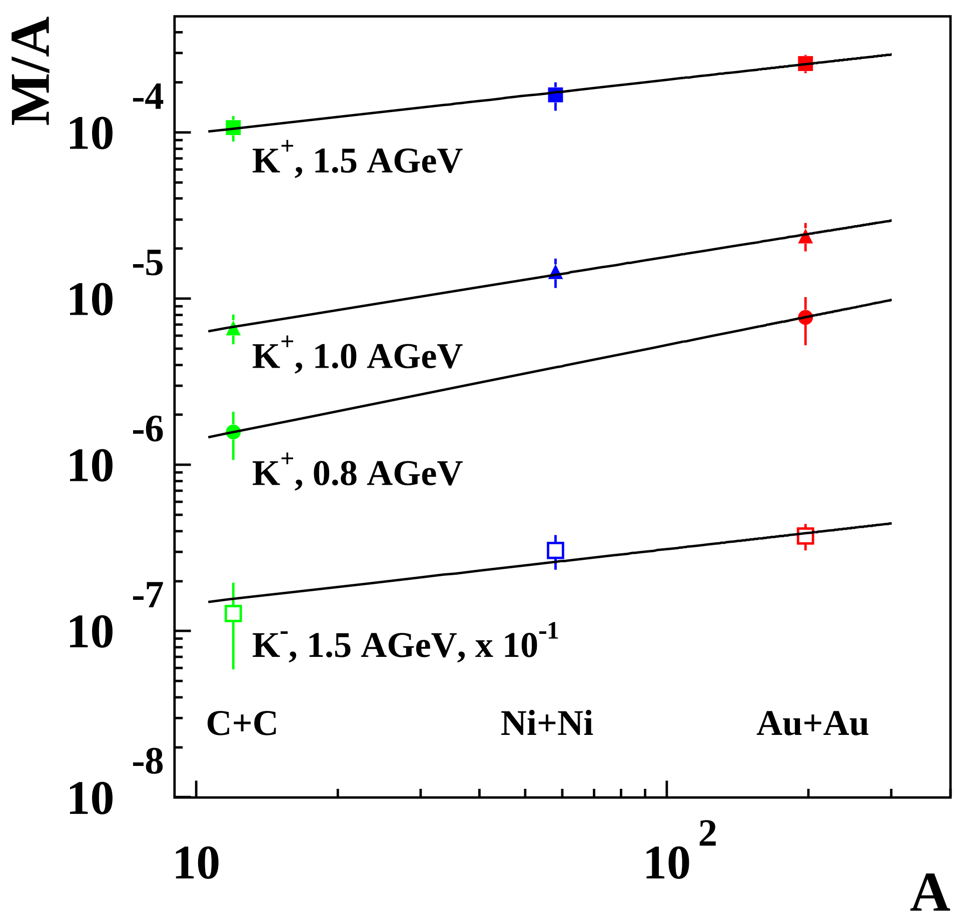
Limits for lower E: no asymptotic yield for peripheral collisions

System size dependence



A soft eos obtains higher kaon yields for heavy systems

KaoS: PRC in preparation



Definition of the potentials

$$
\begin{aligned}
V^{ij} &= G^{ij} + V^{ij}_{\text{Coul}} \\
&= V^{ij}_{\text{Skyrme}} + V^{ij}_{\text{Yuk}} + V^{ij}_{\text{mdi}} + V^{ij}_{\text{Coul}} + V^{ij}_{sym} \\
&= t_1\delta(\vec{x}_i - \vec{x}_j) + t_2\delta(\vec{x}_i - \vec{x}_j)\rho^{\gamma-1}(\vec{x}_i) + t_3\frac{\exp\{-|\vec{x}_i - \vec{x}_j|/\mu\}}{|\vec{x}_i - \vec{x}_j|/\mu} + \\
& t_4 \ln^2(1 + t_5(\vec{p}_i - \vec{p}_j)^2)\delta(\vec{x}_i - \vec{x}_j) + \frac{Z_i Z_j e^2}{|\vec{x}_i - \vec{x}_j|} + \\
& t_6 \frac{1}{\varrho_0} T_3^i T_3^j \delta(\vec{r}_i - \vec{r}_j)
\end{aligned}
$$

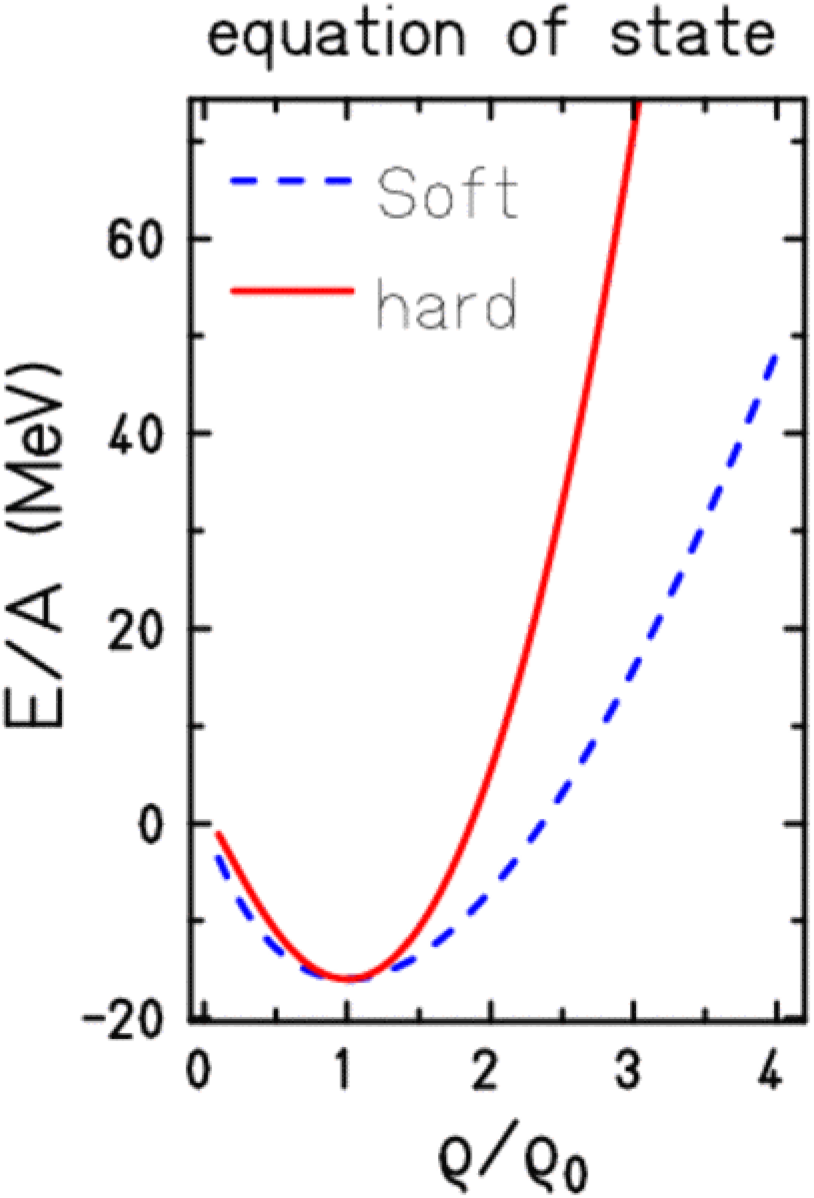
2 and 3 body interactions (no equilibrium required)

Bethe Weizsaecker –mass formula:

Volume term +Surface term +Coulomb term +symmetry term

(with eos) **(+pairing term not included)**

The static part (our « eos »)



$$U = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma}$$

3 parameters, 2 ground state condit.

1 remaining d.o.f.: compression mod.

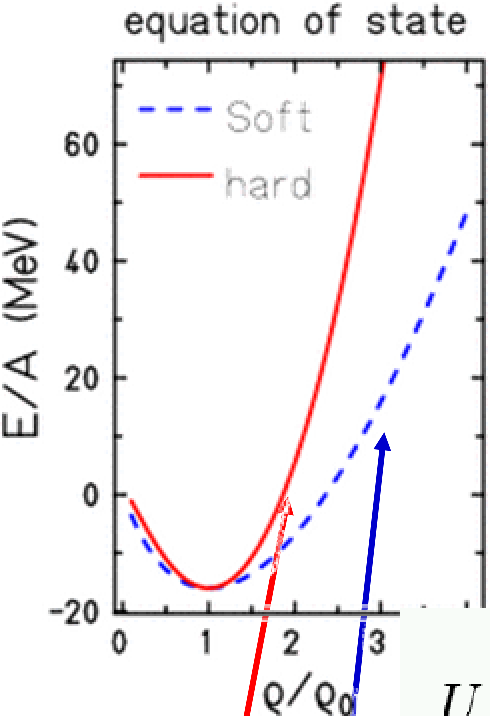
Artificial link between curverture at ground state and high density behaviour.

Compression modulus K>170 MeV

Problems of causality for high densities ρ> 5-7 ρ_0

Caution when extrapolating to high densities

The eos in IQMD



after the convolution of the Skyrme type potentials supplemented by momentum dependent interactions (mdi) for infinite saturated nuclear matter at equilibrium

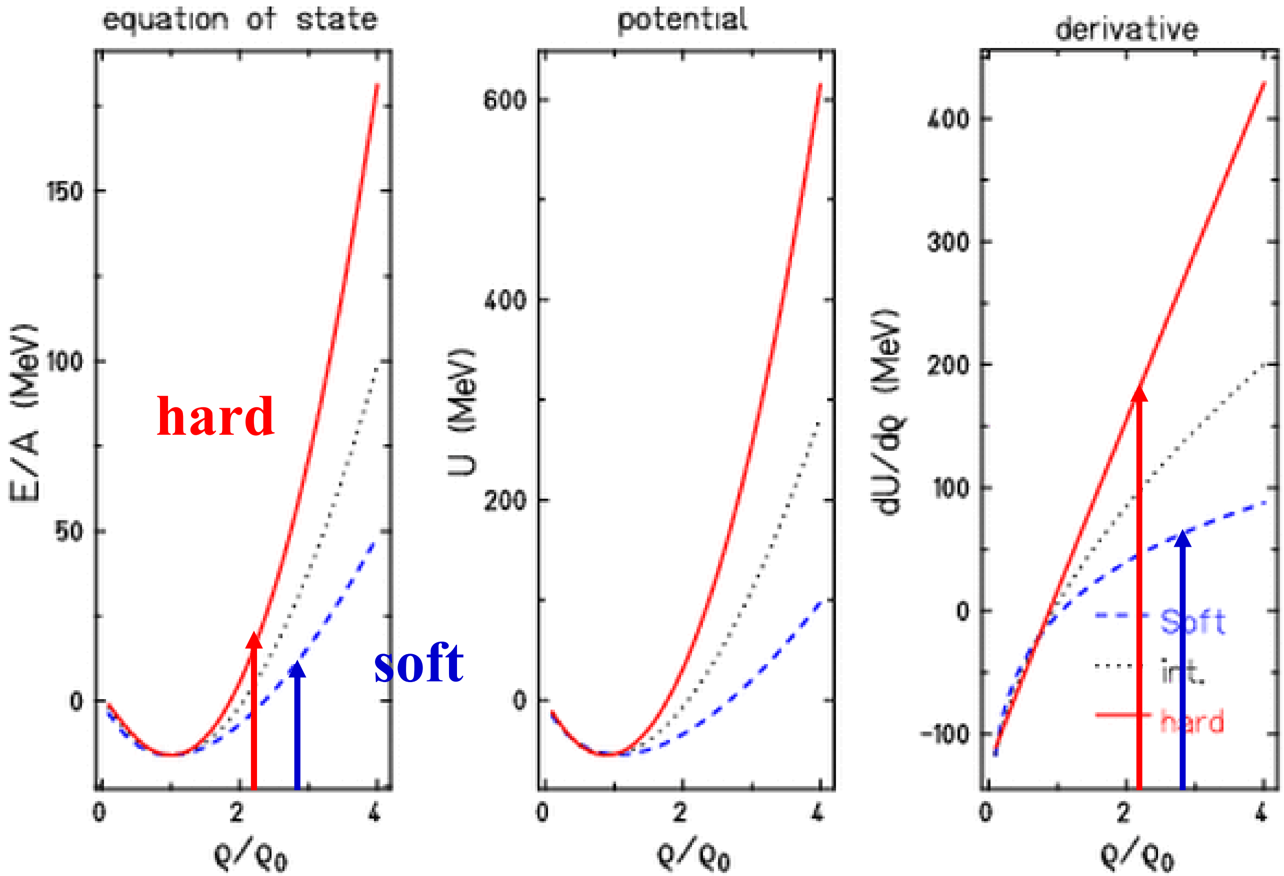
$$U = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma} + \delta \cdot \ln^2\left(\varepsilon \cdot (\Delta\vec{p})^2 + 1\right) \cdot \left(\frac{\rho_{int}}{\rho_0}\right)$$

soft — S, SM

hard — H, HM

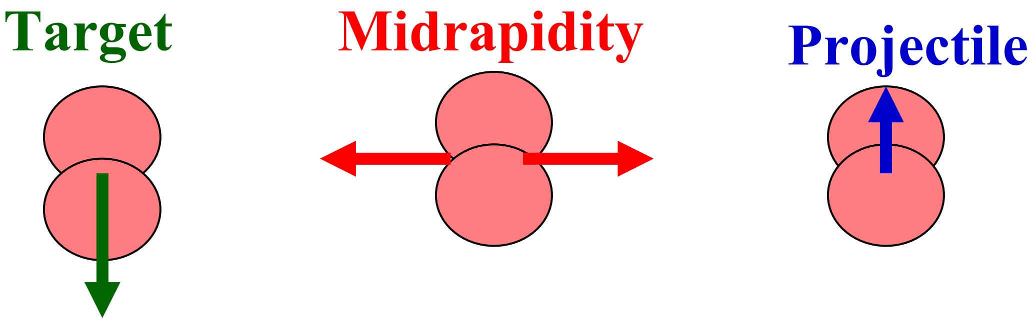
	α (MeV)	β (MeV)	γ	δ (MeV)	$\varepsilon\ \left(\frac{c^2}{\mathrm{GeV}^2}\right)$	κ (MeV)
S	-356	303	1.17	—	—	200
SM	-390	320	1.14	1.57	500	200
H	-124	71	2.00	—	—	376
HM	-130	59	2.09	1.57	500	376
INT	-157	103	1.58	—	—	284
VH	-110	56	2.40	—	—	456

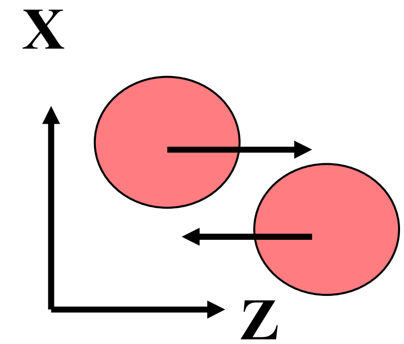
Different densities and different pressure



Next idea on eos: do not use the compressional energy but the repulsion of the potential **Nucleonic flow**

In-plane flow, Squeeze, pion flow



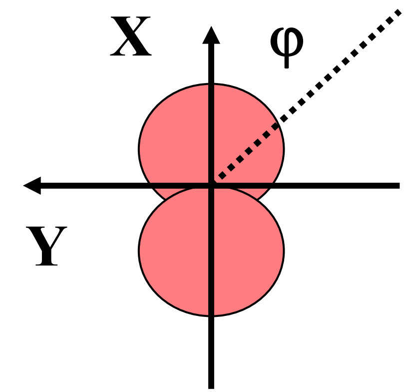


Test of density gradient and geometry

Transverse flow dominated by «cold » matter

Dense matter tends towards isotropy

Pion flow: test on resonance matter



Comparison of Plasticball squeeze favors soft eos+mdi

For recent analysis on FOPI data see the contributions of Willi Reisdorf and Anton Andronic