Constraining the nuclear matter equation of state using the elliptic flow of light clusters

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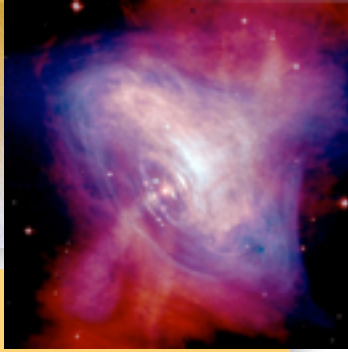
- Constraining the stiffness of the EOS with the elliptic flow.
- A clusterisation approach…
- Towards the determination of the stiffness of the asymmetry energy.
- Summary and discussion.

Introduction



NGC 1952, Crab Nebula pulsar neutron star imaged by the NASA/ESA Hubble Space Telescope

- The equation of state (EOS) of nuclear matter:
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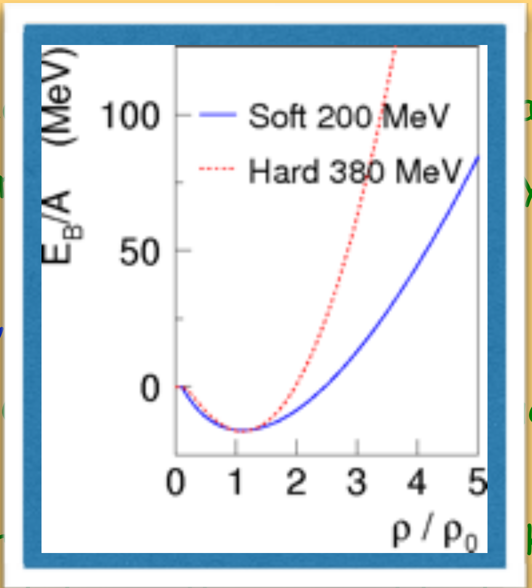
  - object of intense theoretic ... ades
  - an important ingredient in n ... ysical phenomena such as:
    - compact stars [1]
    - core collapse supernov



- The calculation of the nuclear E ... ch as very recently attempted in [3], is a very complex task.
- Nuclear physics based on empir ... he most 'fundamental' theory of nuclear forces requires a confrontation with empirical facts.
- 1st method, from astrophysicists: from 'neutron' star masses and radii. But missing:
  - precise model-independent radii,
  - composition of the matter in the center of the stars.

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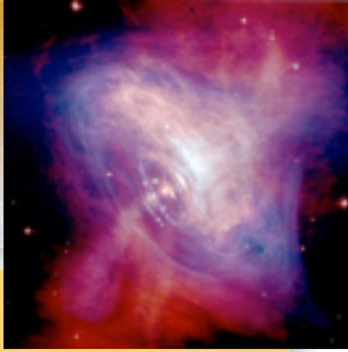

NGC 1952, Crab Nebula pulsar neutron star imaged by the NASA/ESA Hubble Space Telescope

- The equation of state (EOS) of nuclear matter:
  - of fundamental interest
  - object of intense theoretical efforts since several decades
  - an important ingredient in modeling fascinating astrophysical phenomena such as:
    - compact stars [1]
    - core collapse supernovae[2]
- The calculation of the nuclear EOS from first principles, such as very recently attempted in [3], is a very complex task.
- Nuclear physics based on empirical observations => even the most 'fundamental' theory of nuclear forces requires a confrontation with empirical facts.
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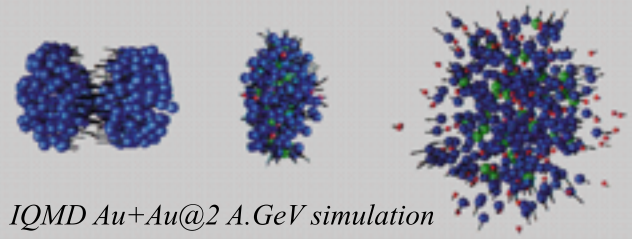

IQMD Au+Au@2 A.GeV simulation

- Alternative method: in earth laboratories, heavy ion collisions over a wide range of incident energies, system sizes and compositions.
  - limited to E_{beam}<10 A.GeV ⬅ some kind of a clock is available (sound velocity versus participant-spectator interaction).

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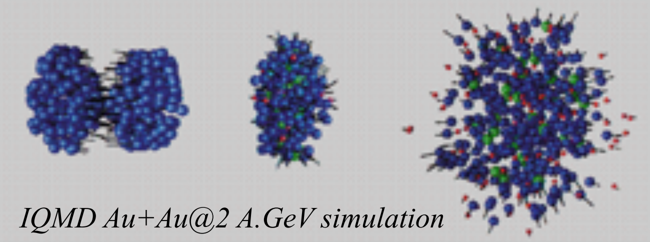

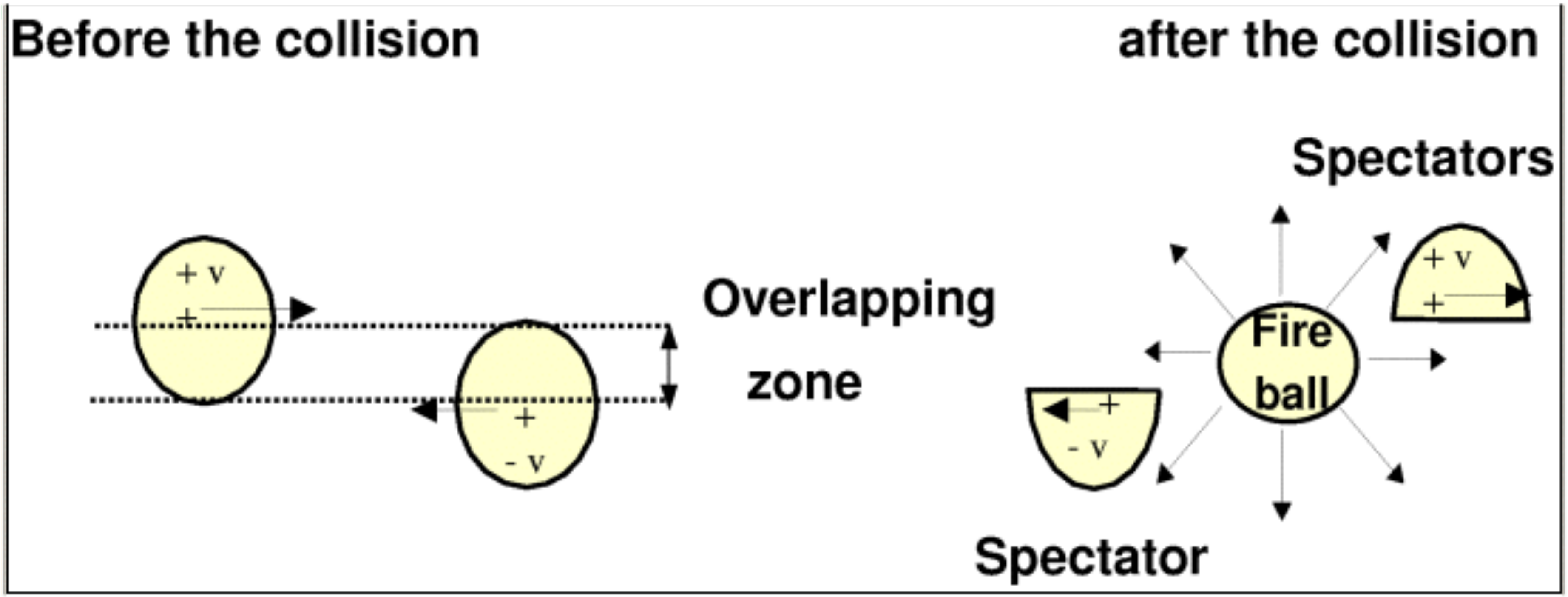

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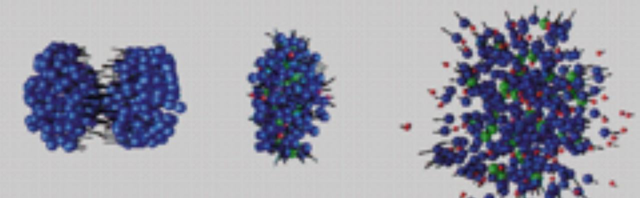
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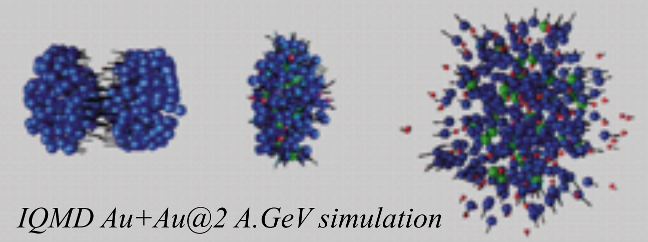


Flows at high density in heavy-ion collisions

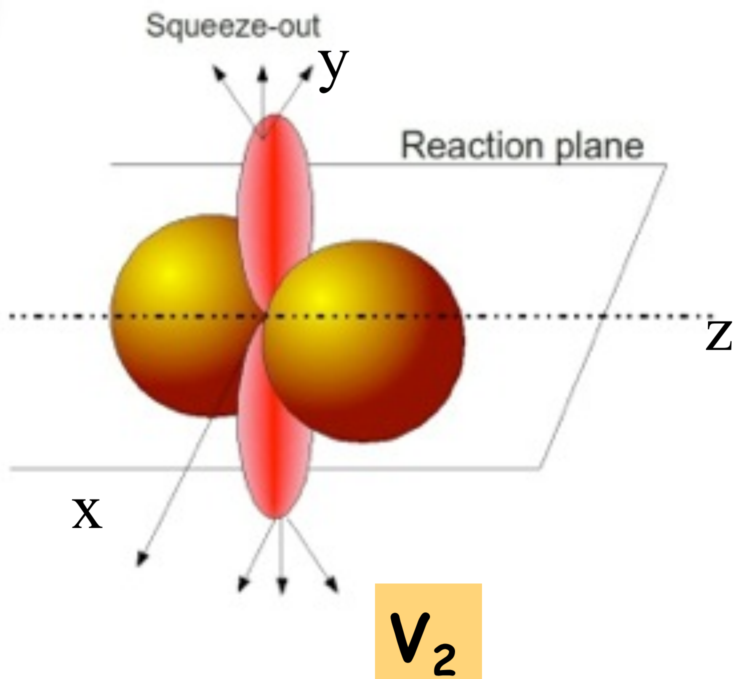
$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

Y = rapidity
p_t = transverse momentum
Φ_R = reaction plane azimuthal angle

V_1 = 'side/directed flow', $\langle p_x/p_t^2\rangle$

$$V_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$

'Elliptic flow': $\cos(2(\Phi-\Phi_R))$ mode,
competition between 'in-plane' ($V_2>0$) and
'out-of-plane' ejection ($V_2<0$).



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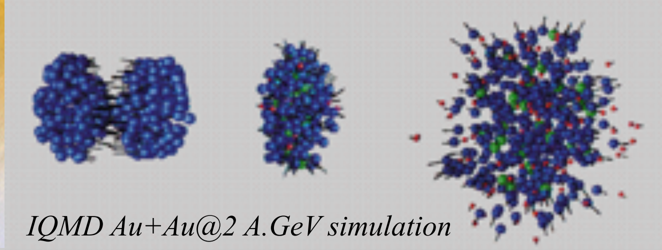

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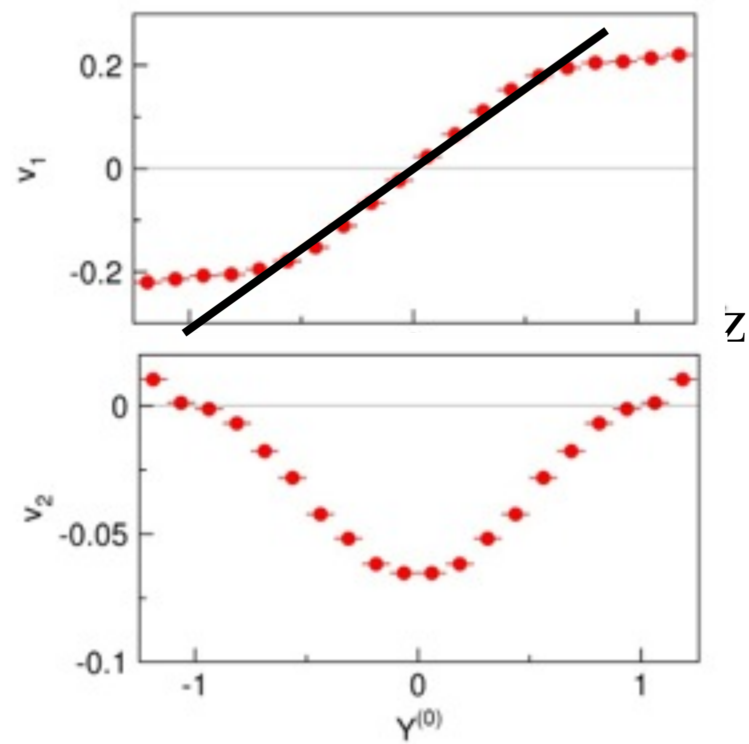

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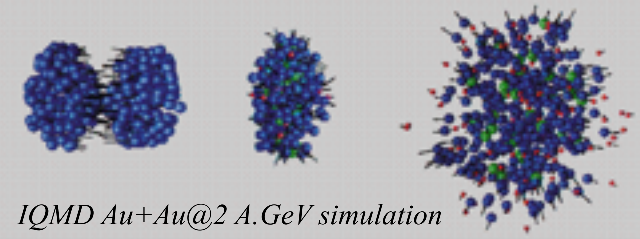

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Constraining the stiffness of the EOS with the elliptic flow.

- Present work: improve the situation in the 1 A.GeV regime, from extensive flow data published recently by the FOPI Collaboration (Au+Au @ 0.4-1.5 A.GeV) [4]

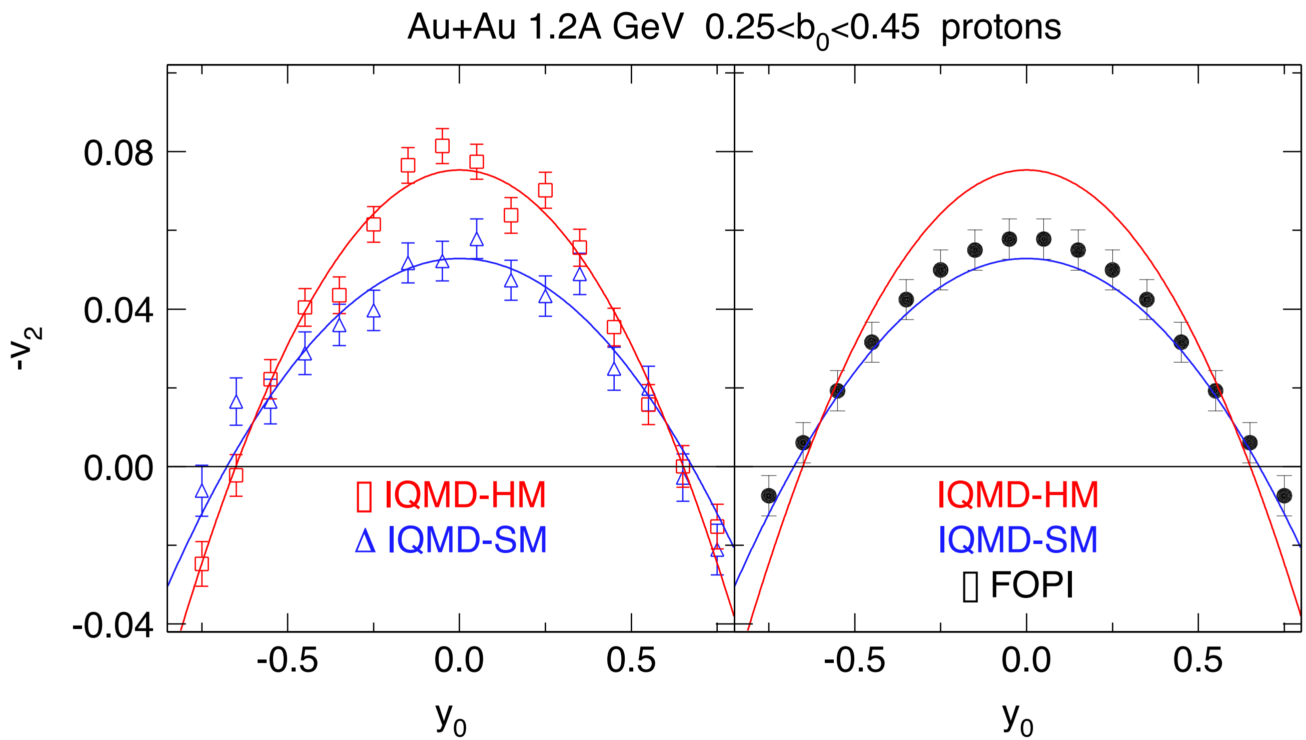
  → close look at the elliptic flow data with improvements:

  - 1) not only protons: d, t, ^{3}He ^{4}He having larger flow signals than single nucleons.
  - 2) not only mid-rapidity data: 80% of the target- projectile rapidity gap.

[4] W. Reisdorf, et al. (FOPI Collaboration), Nucl. Phys. A 876 (2012) 1.

Constraining the stiffness of the EOS with the elliptic flow.

Elliptic flow

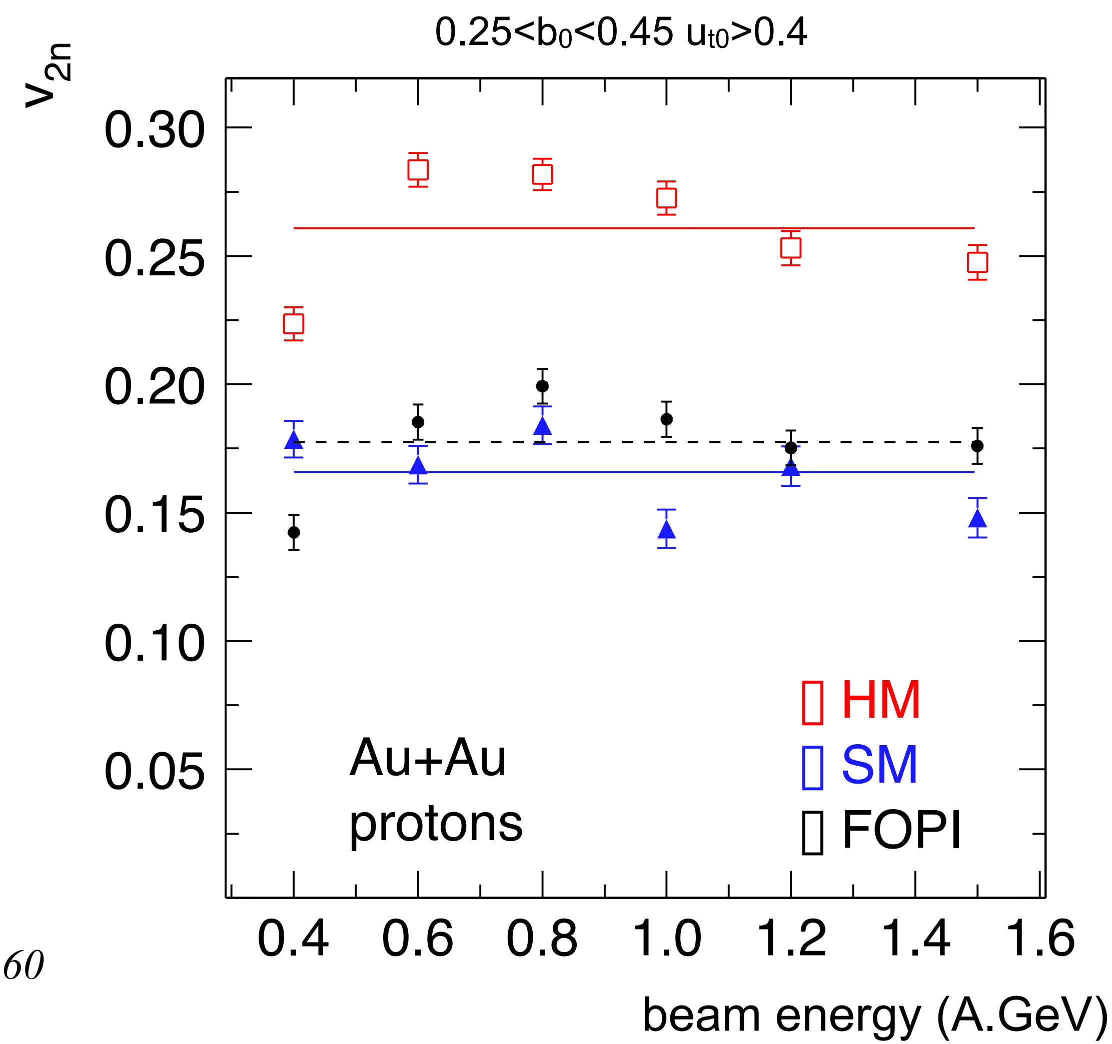


IQMD: J. Aichelin, Phys. Rep. 202 (1991) 233.
C. Hartnack, et al., Eur. Phys. J. A 1 (1998) 151.

Constraining the stiffness of the EOS with the elliptic flow.

Complete shape of $v_2(y_0)$:
a new observable:
$v_{2n} = |v_{20}| + |v_{22}|$,
from fit
$v_2(y_0) = v_{20} + v_{22} . y_0$

➜ $v_{2n}(E_{beam})$ varies by a factor ≈1.6, >> measured uncertainty (≈1.1)
➜ clearly favors a 'soft' EOS.



FOPI Collaboration / NPA 876 (2012) 1-60

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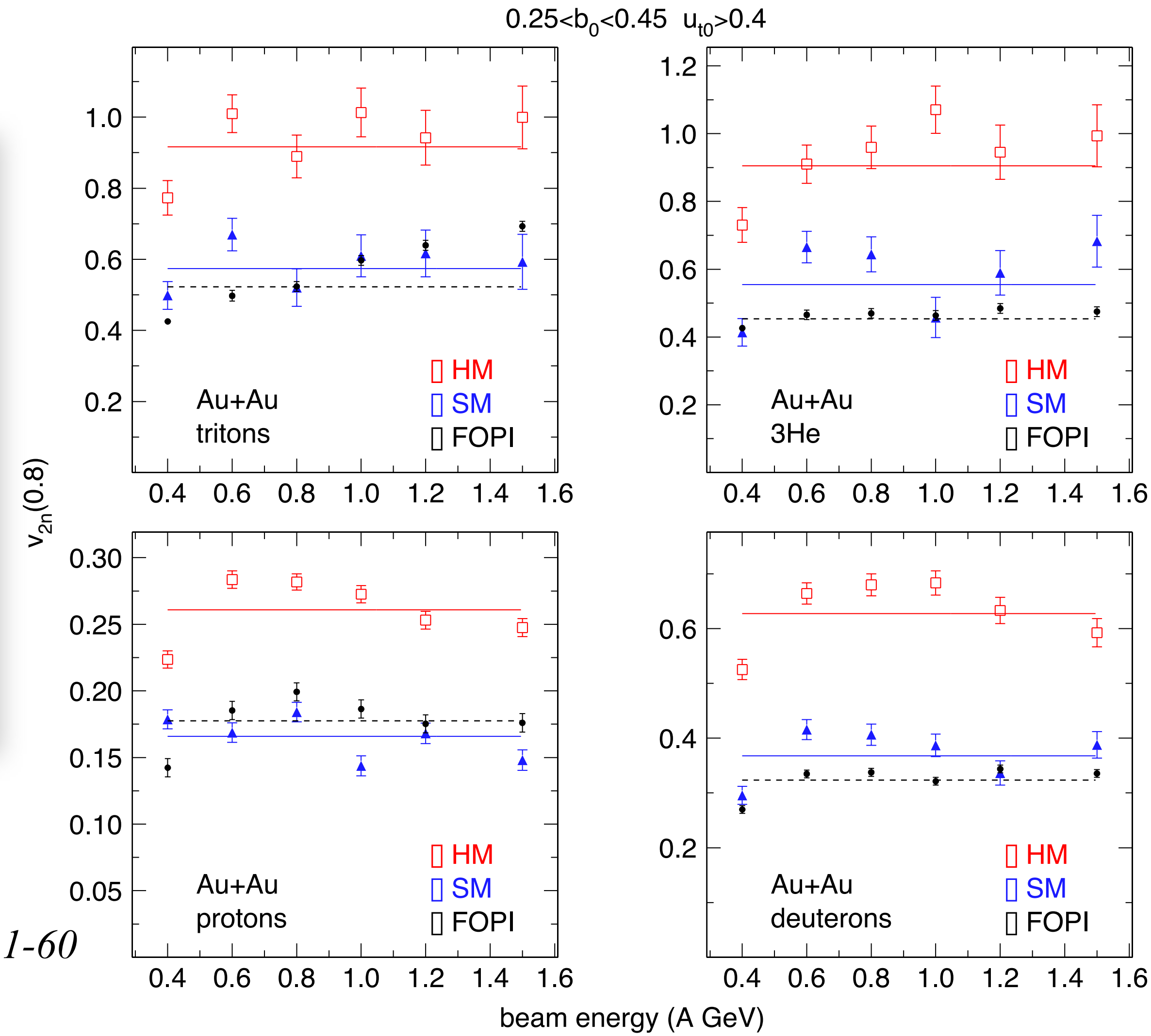

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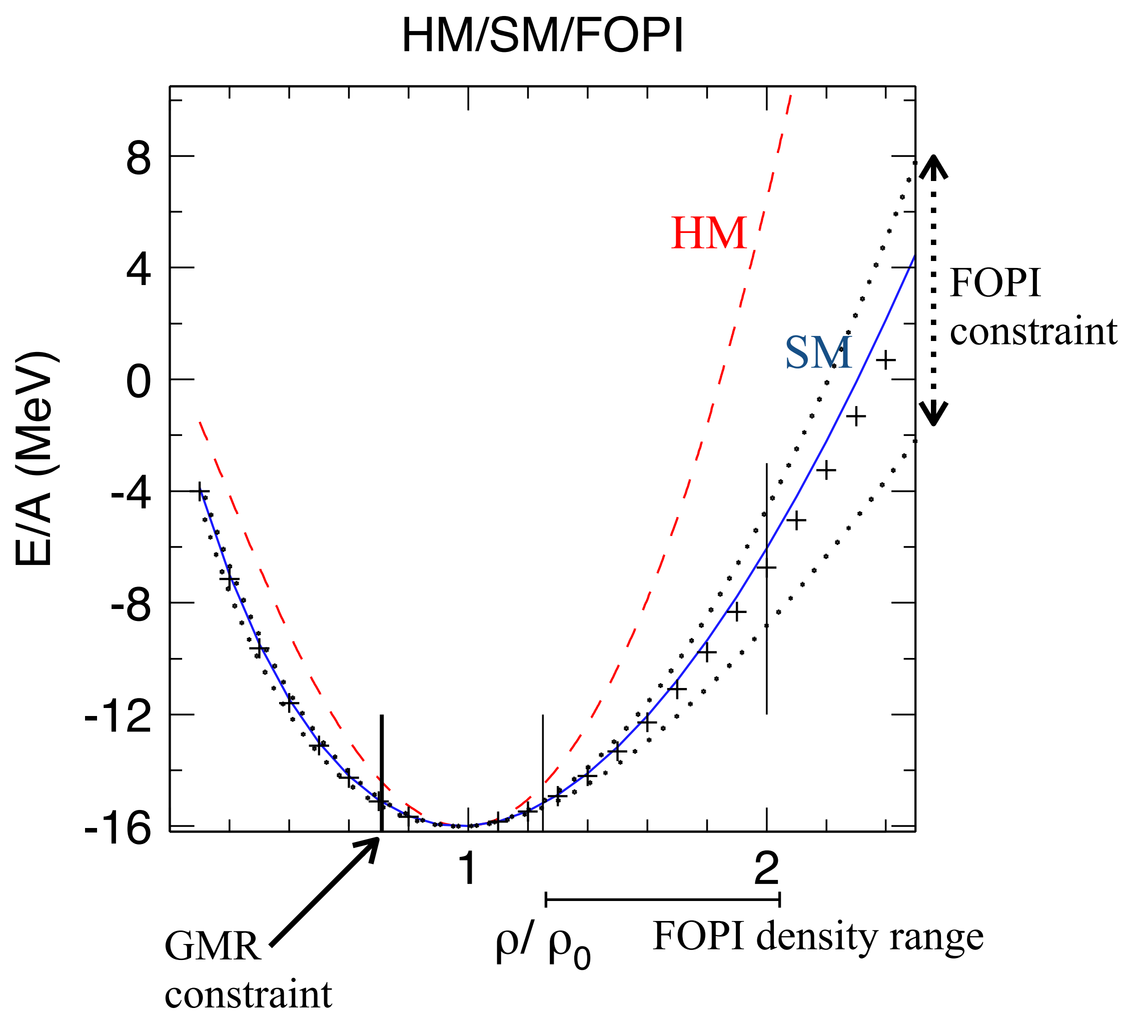
Constraining the stiffness of the EOS with the elliptic flow.

- Phenomenological EOS HM and SM include the saturation point at $\rho/\rho_0 = 1$, $E/A = -16$ MeV by construction.
- ➜ fixes the absolute position of the curves:
- the heavy ion data are only sensitive to the shape, i.e. the pressure (derivative).
- ➜ a stiff EOS, characterised by $K_0 = 380$ MeV is not in agreement with the flow data in the incident energy range 0.4 - 1.5 A.GeV.



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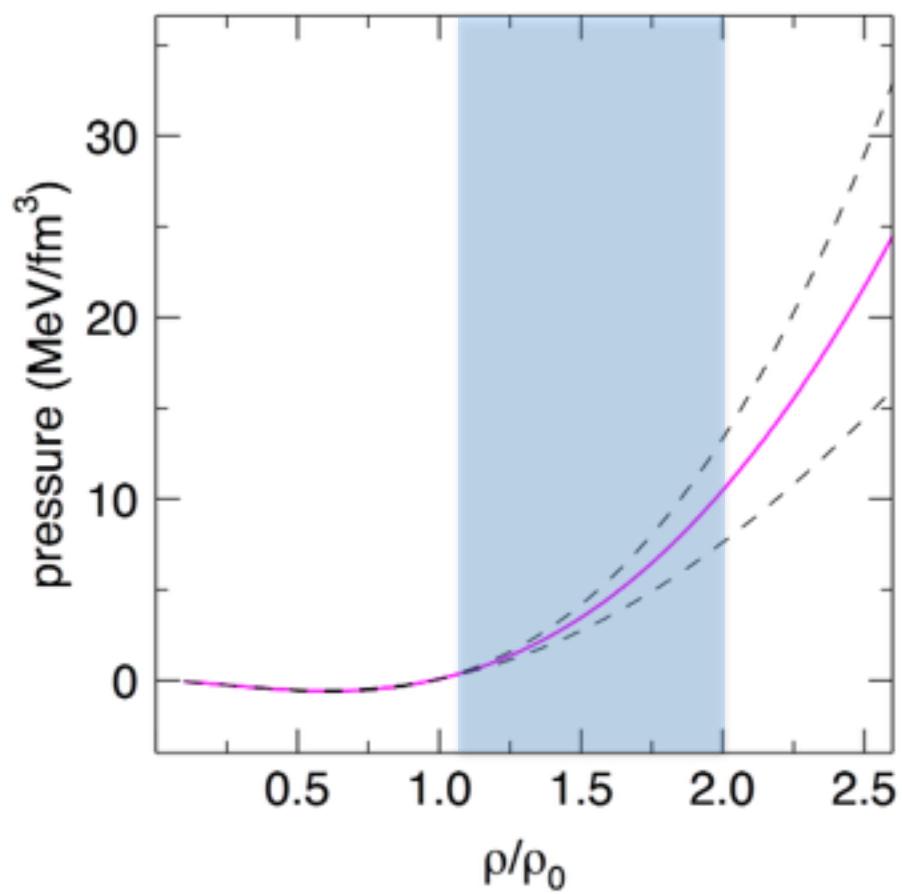

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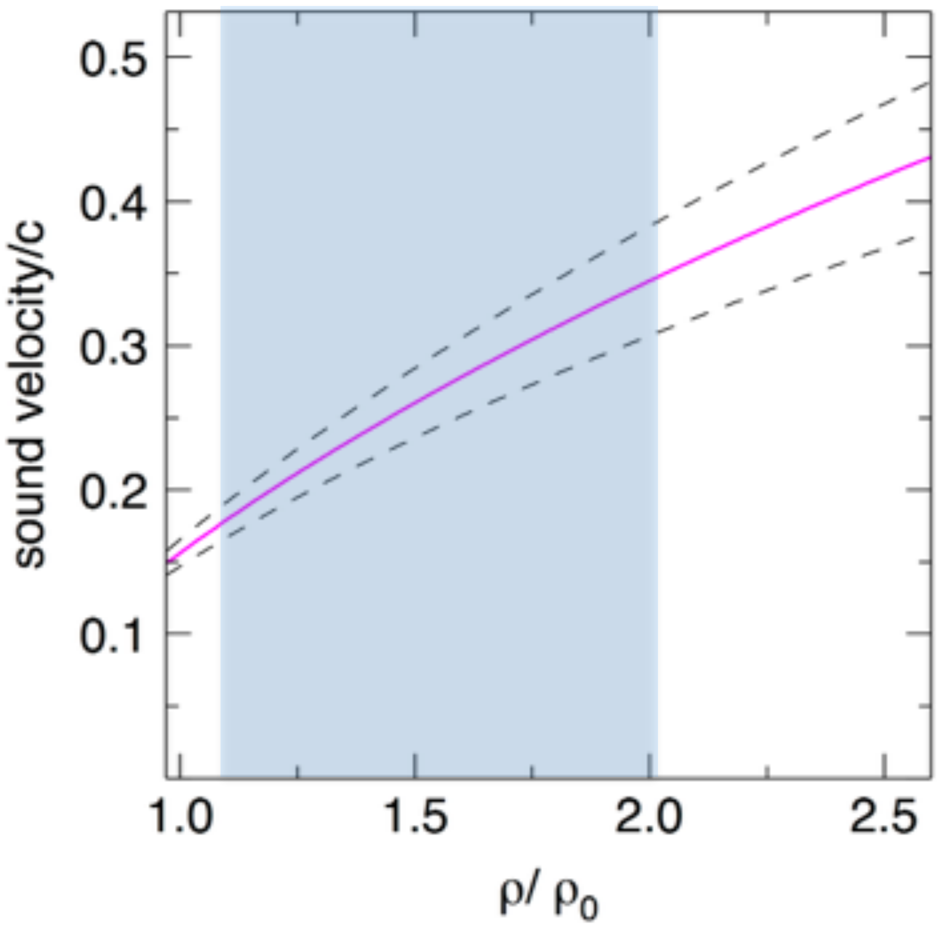
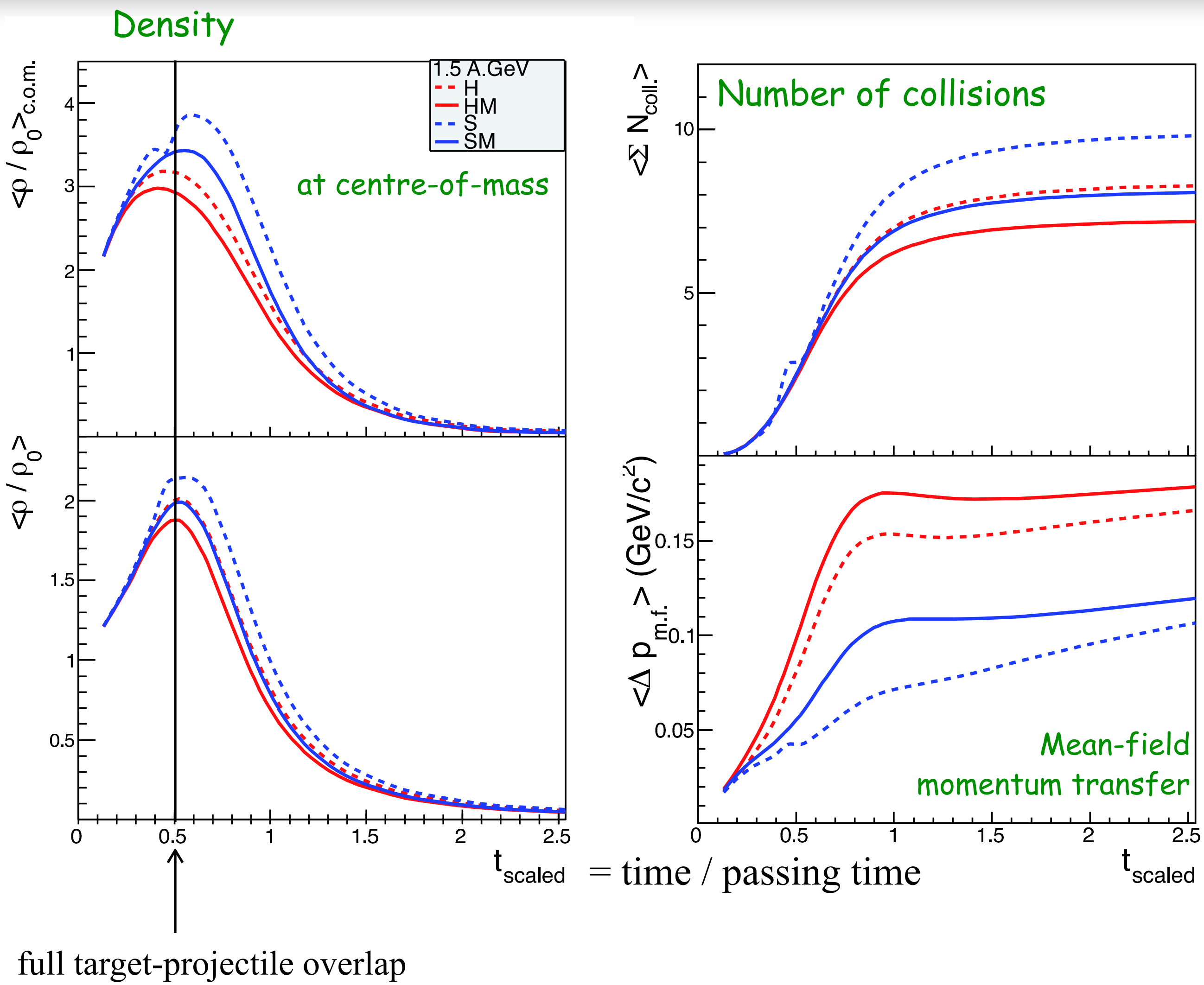


Which density has been probed?

Purpose = characterise which 'typical' densities where probed in the FOPI experiments
=> at which time V_2 develops, and which conditions influence it the most.

IQMD transport model[5,6]
various phenomenological EOS's:
- 'stiff' = H & HM (+ momentum dependent), K_0 = 380 MeV
- 'soft' = S & SM (+momentum dependent), K_0 = 200 MeV.

Here: protons in Au+Au at 1.5 A.GeV, b=3 fm



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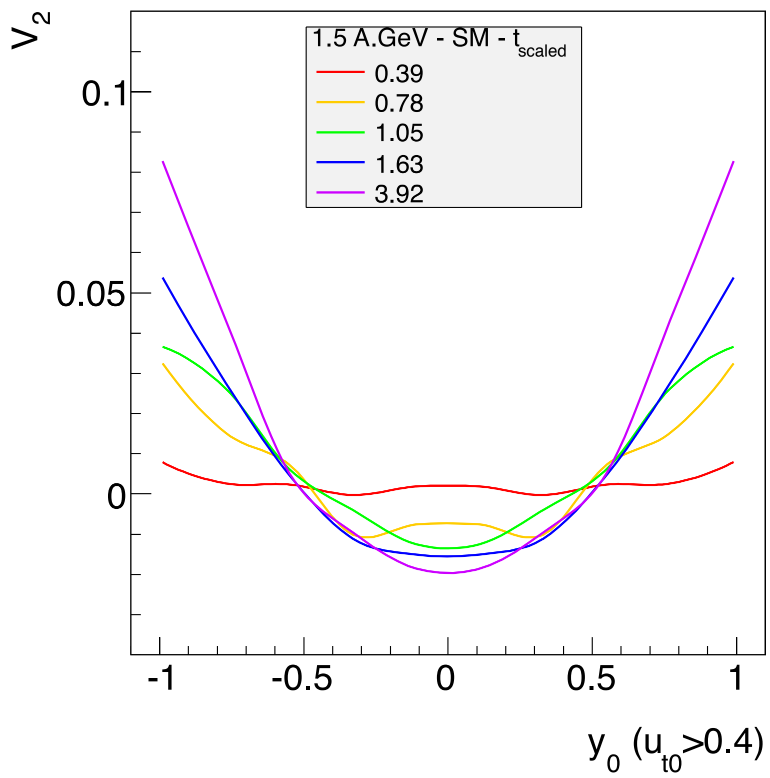
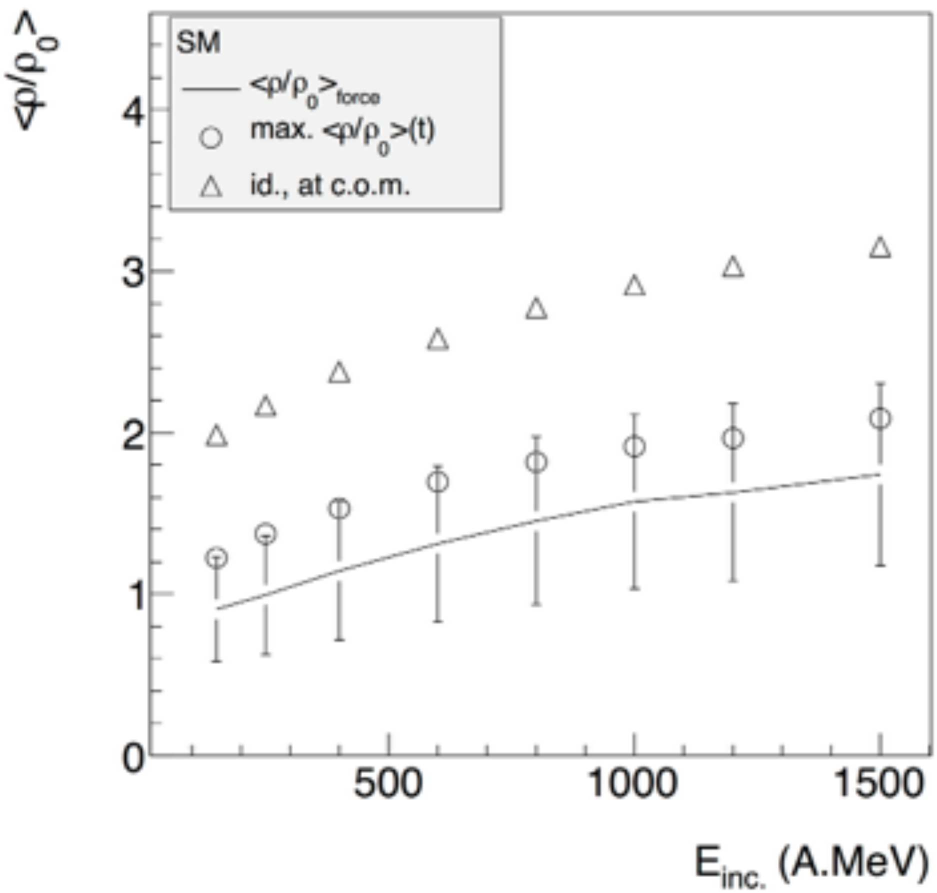


- The elliptic flow in his final dependence with rapidity develops fast: during the passing time.

- The elliptic flow in strength and shape is mostly influenced by the force of the mean field
- The 'typical' density of the 'measured' EOS can be built from the mean value weighted by this force up to the passing time.

Simulations: the scenario



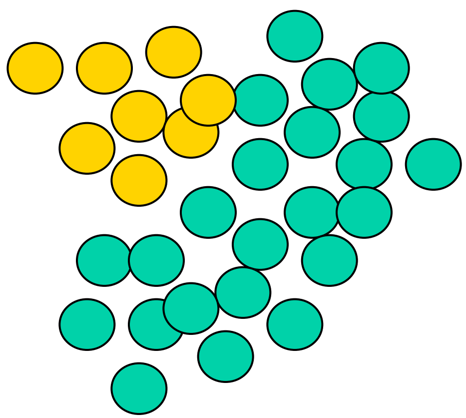
- The density range, relevant to the EOS evidenced by the FOPI Collaboration, spans in the range $\rho = (1.25 - 2.0)\ \rho_0$.

SACA: a clusterisation approach…

* Simulated Annealing Procedure: PLB301:328,1993; later called SACA.
* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390
* 2010 version: publication in progress…

2 steps:

1) Pre-select good «candidates» for fragments according to proximity criteria: real space coalescence = Minimum Spanning Tree (MST) procedure.



$E=E^1_{kin}+E^2_{kin}+V^1+V^2$

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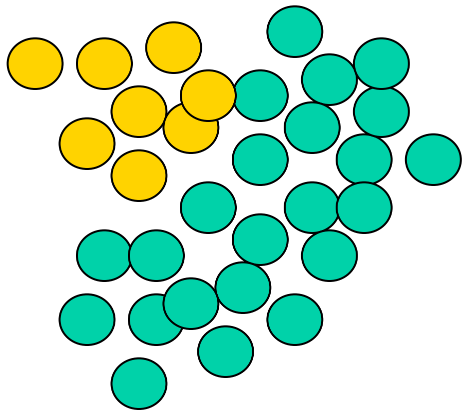
2) Take randomly 1 nucleon out of one fragment



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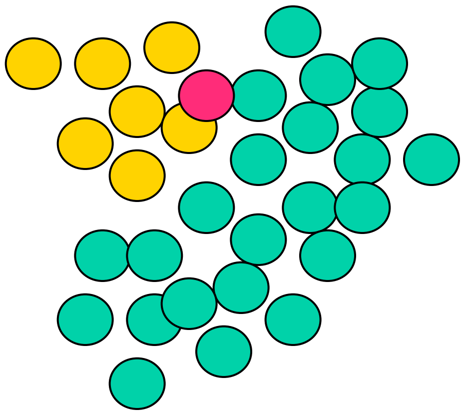

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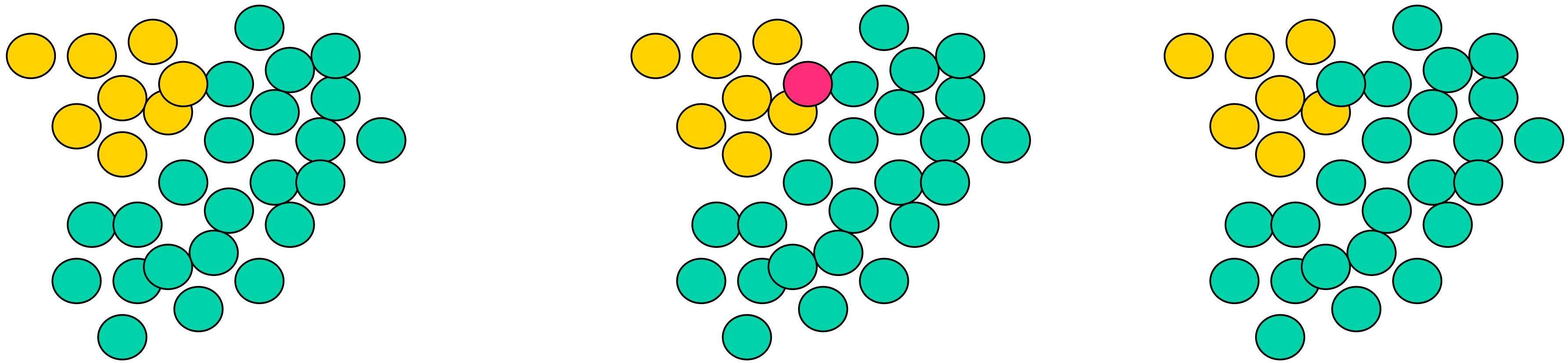

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$E'=E^{1'}_{kin}+E^{2'}_{kin}+V^{1'}+V^{2'}$

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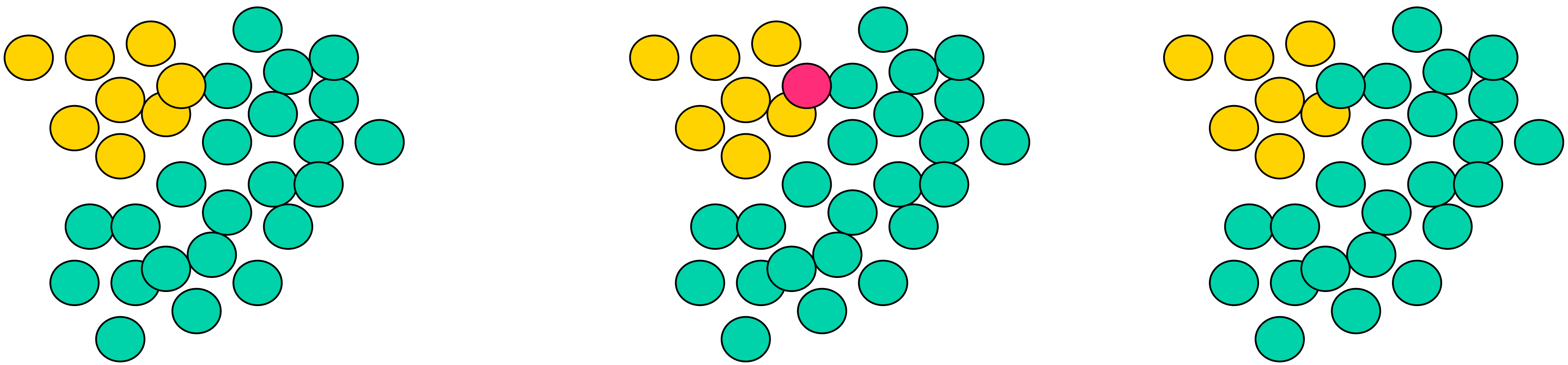

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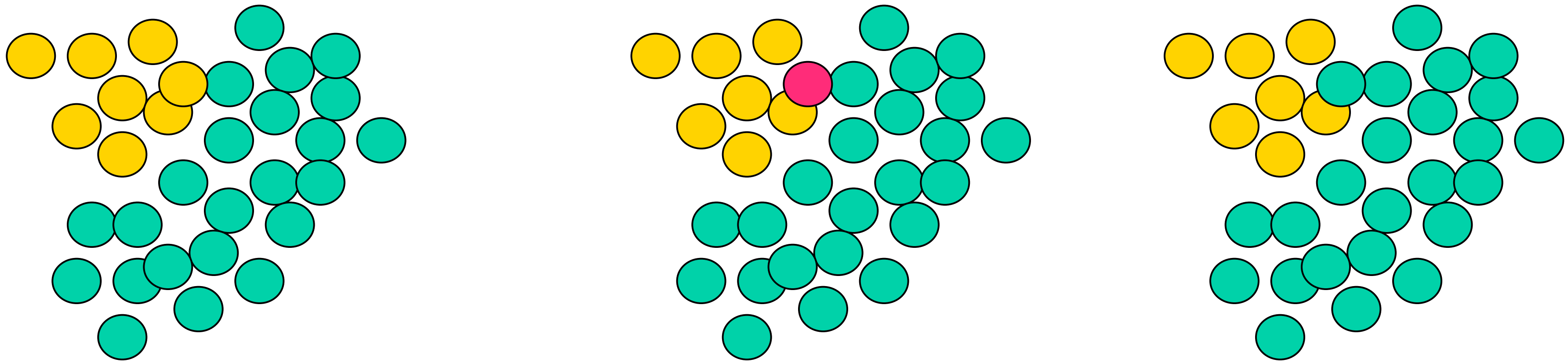

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If $E' > E$ take the old with a probability depending on $E'-E$

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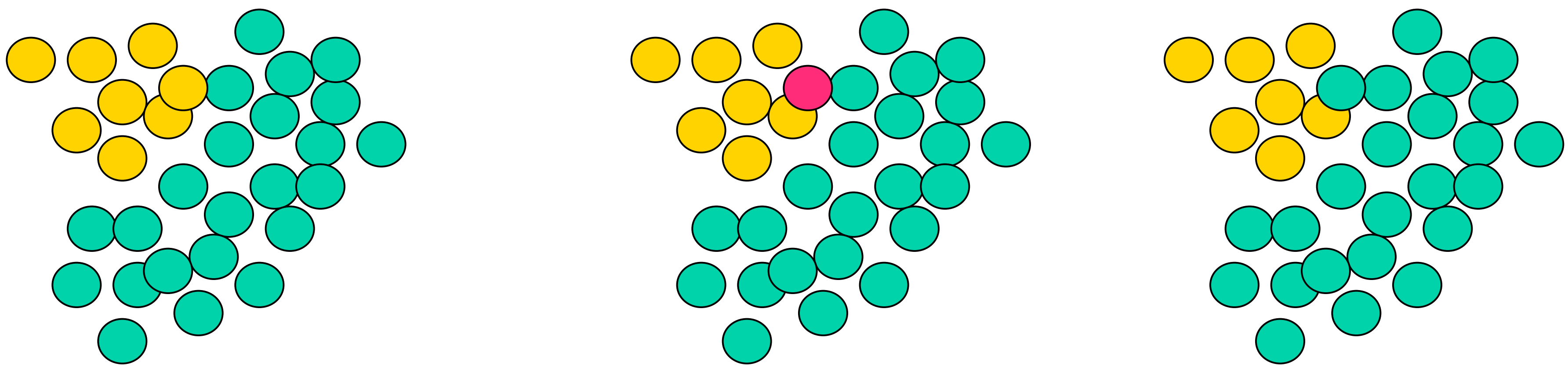

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Repeat this procedure very many times...

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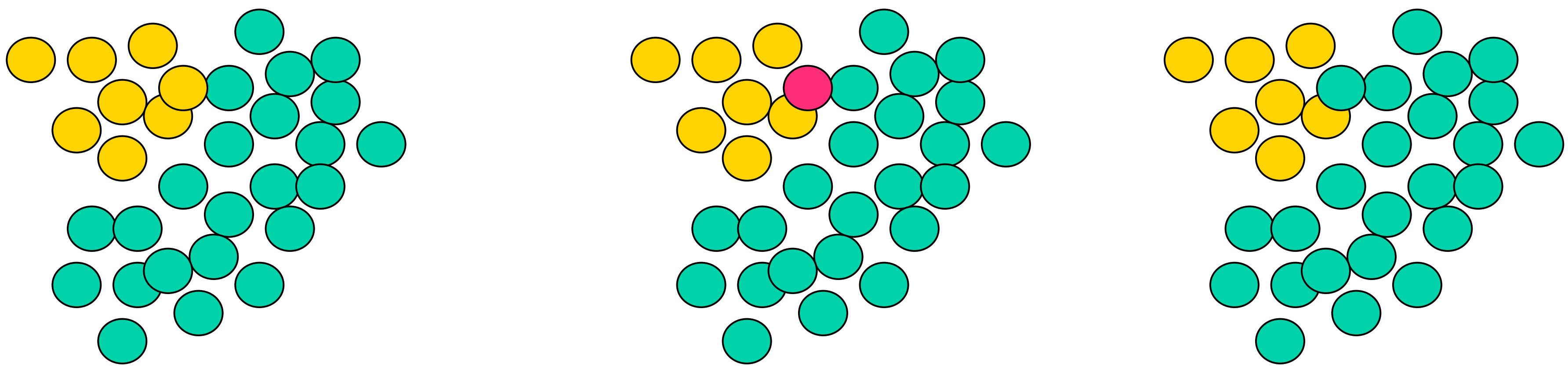

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Repeat this procedure very many times...

It leads automatically to the most bound configuration.

SACA: a clusterisation approach…

Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei)

② Surface effect correction: Yukawa term.

③ Asymmetry energy : 23.3 MeV.$(\langle\rho'_B\rangle)^{(\gamma_{ASY}-1)}.(\langle\rho'_n\rangle-\langle\rho'_p\rangle)^2/\langle\rho'_B\rangle$

④ Extra « structure » energy (N,Z,ρ) = $B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$

⑤ ^{3}He+n recombination.

⑥ Secondary decay: GEMINI.

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➲ Remarks:

- Advantage of SACA : the fragment partitions can reflect the early dynamical conditions (Coulomb, density, flow details, strangeness…). Fragment partitions already determined at the passing time of the colliding system.
- In the framework of QMD, HSD, $\langle\rho_{clusters}\rangle < 0.5.\ \rho_0 \Rightarrow$ isotope yields of SACA with E_{asy} probe it at sub-saturation densities

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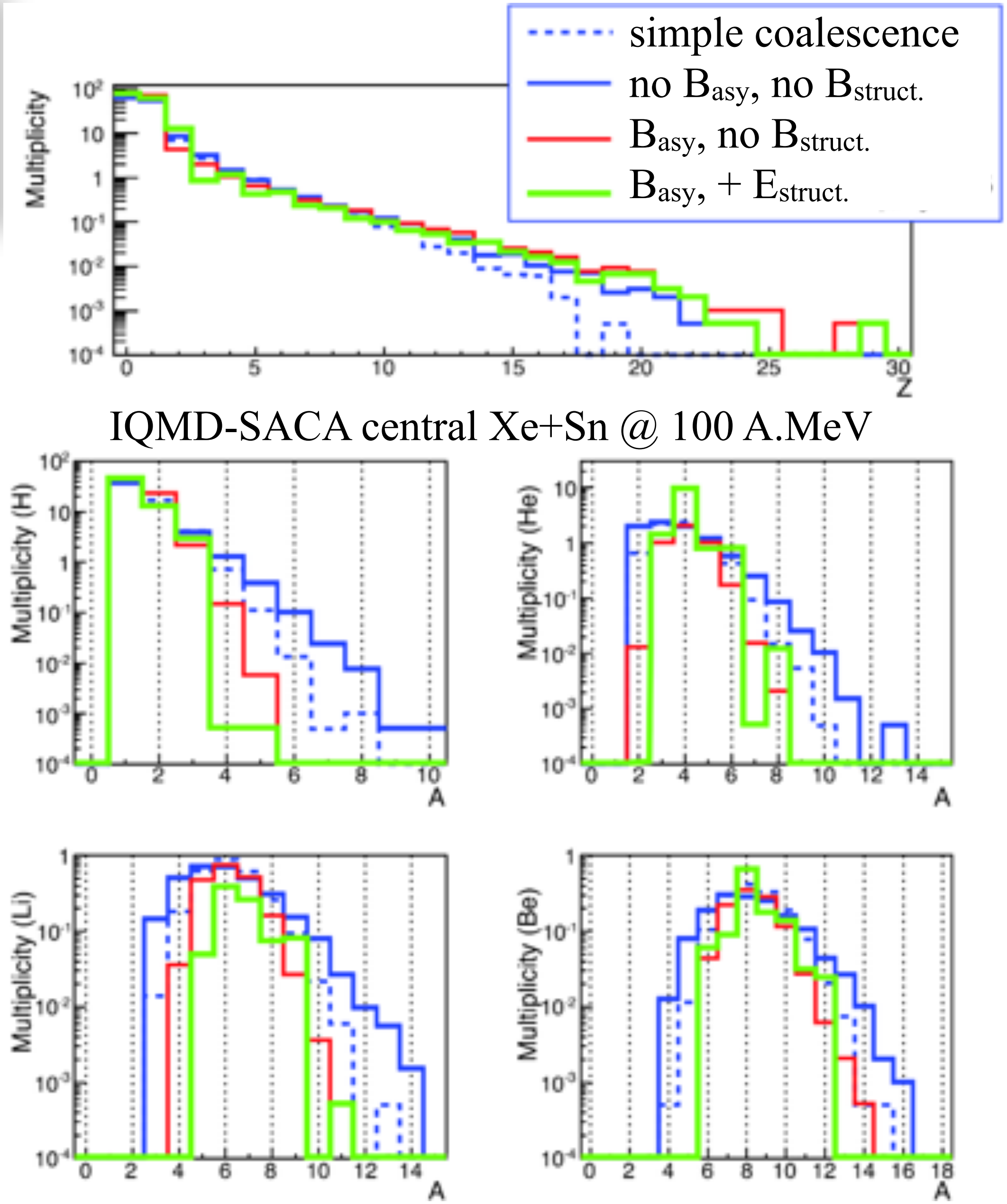

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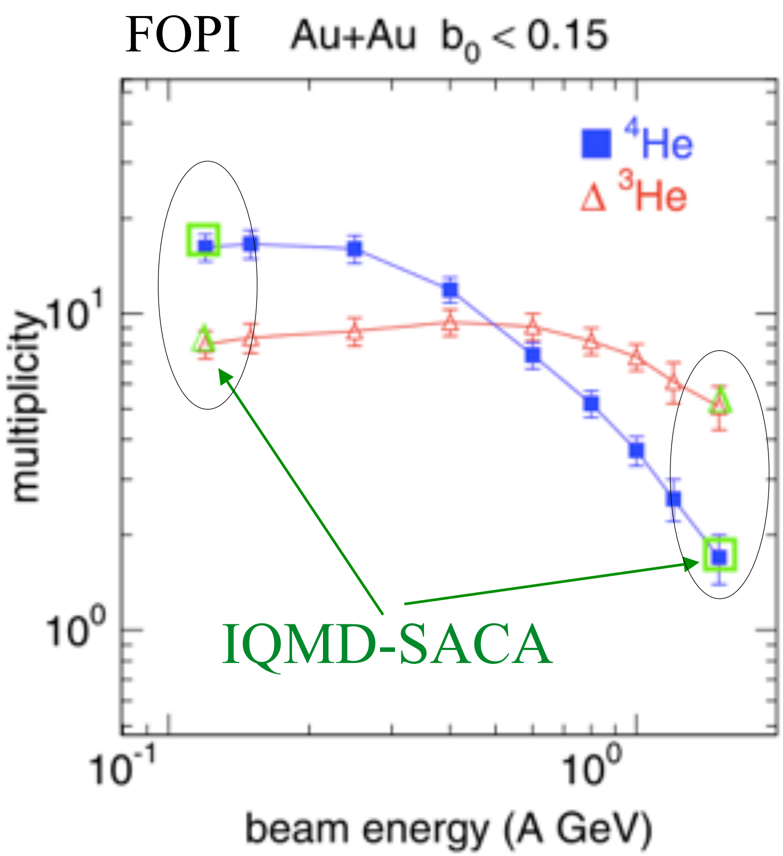
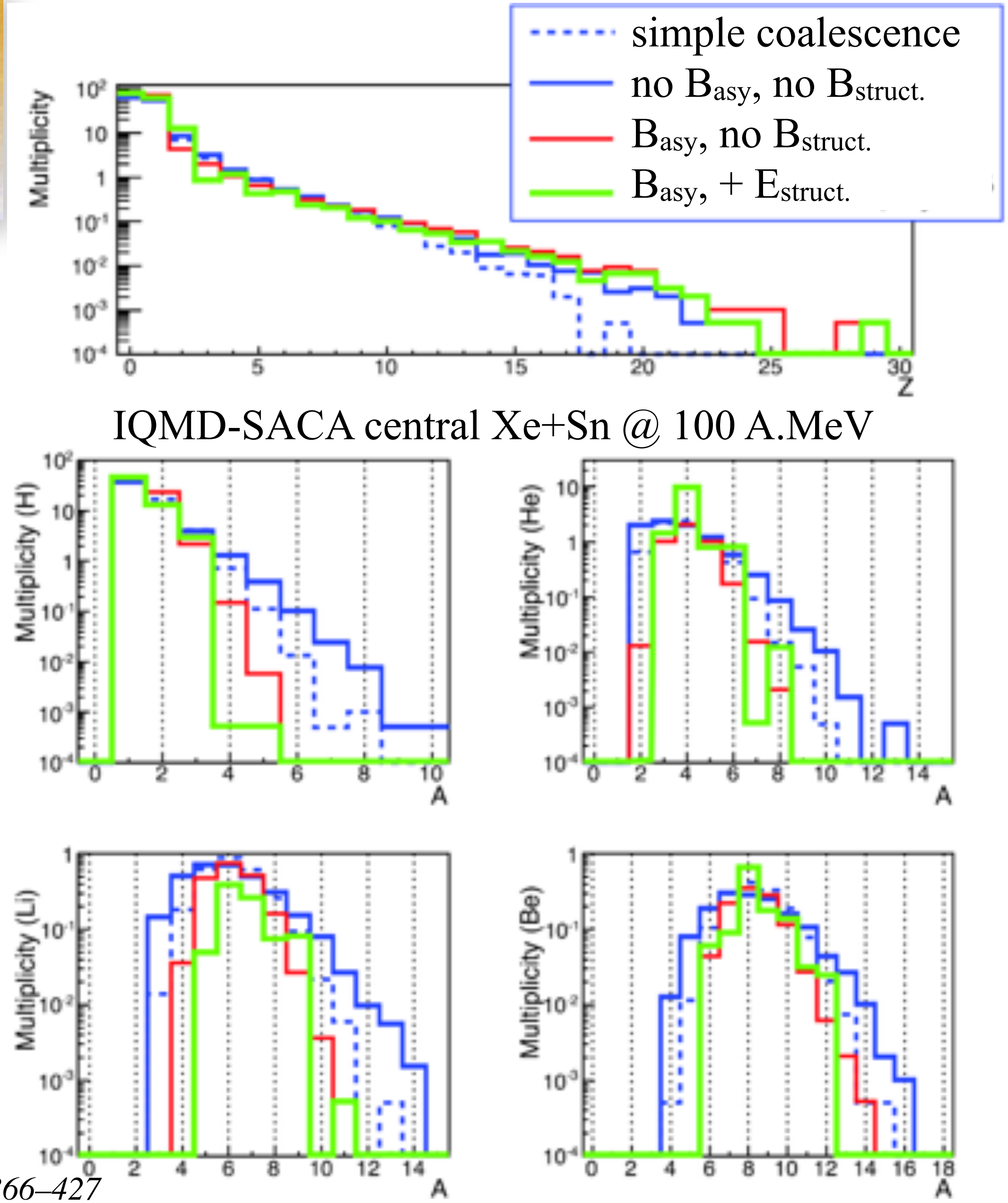


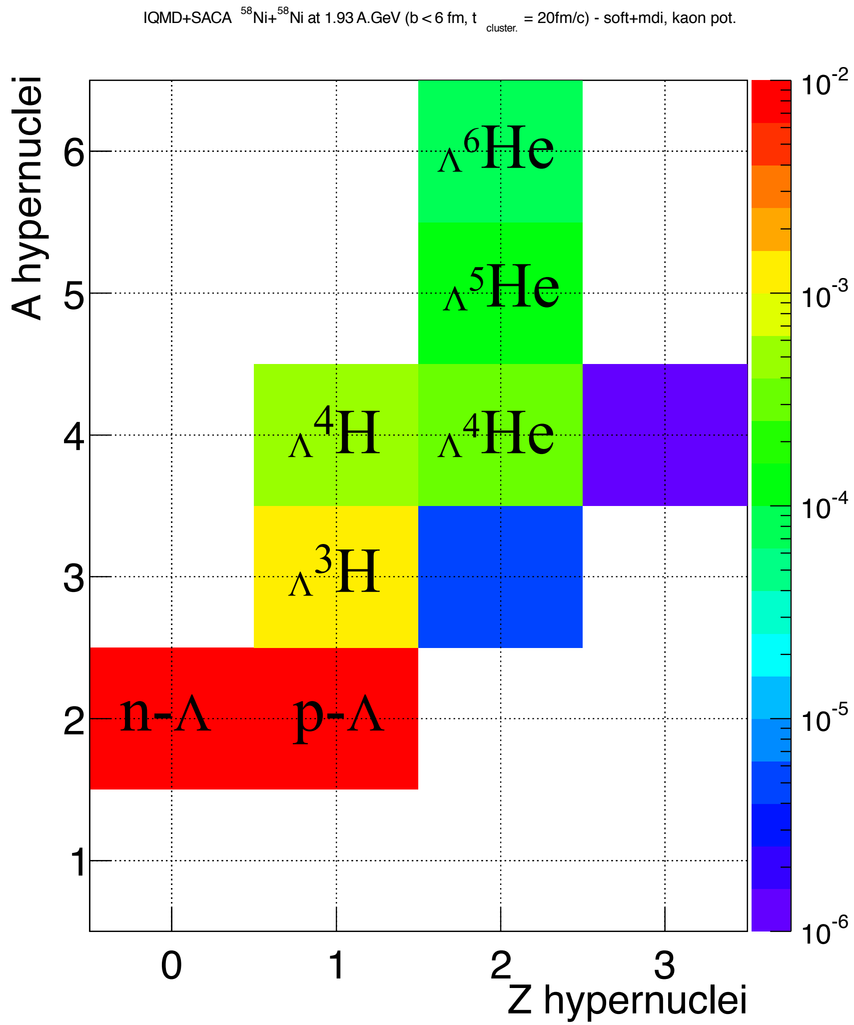


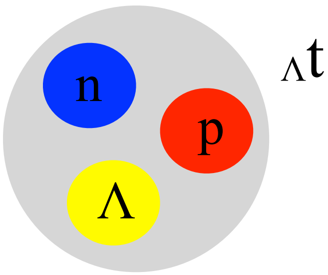
W. Reisdorf and the FOPI Collaboration NPA 848 (2010) 366–427

Another application of SACA : hypernuclei production

IQMD+SACA
$^{58}Ni+^{58}Ni$
at
1.91 A.GeV
(b < 6 fm) -
$t_{cluster.}$=20 fm/c

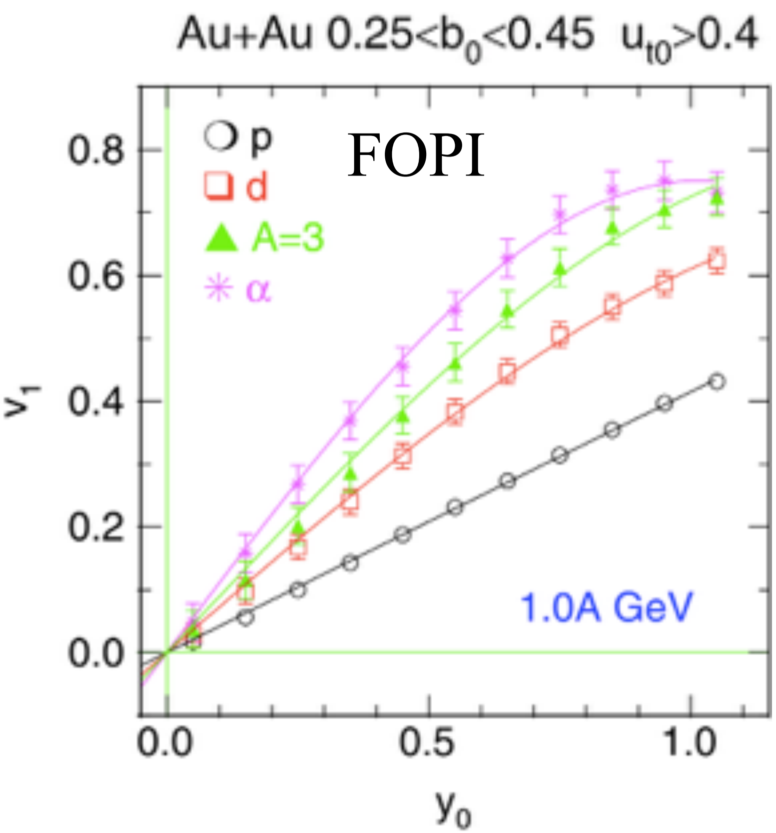
Soft EOS
with m.d.i.
with Kaon pot.

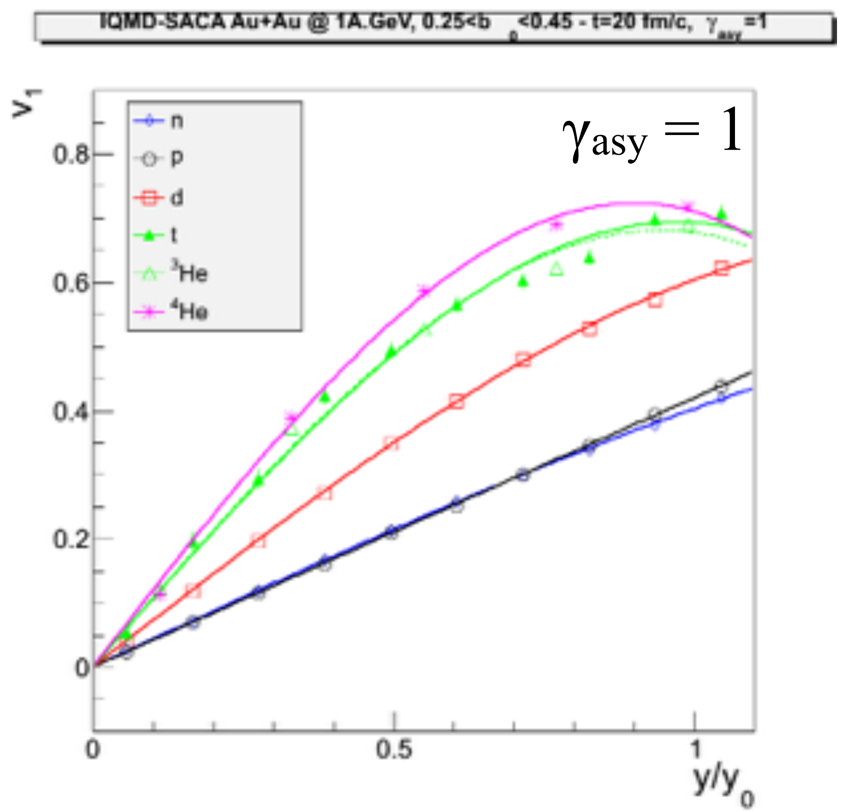




Towards the determination of the stiffness of the asymmetry energy.

Directed flow





FOPI Collaboration / NPA 876 (2012) 1-60

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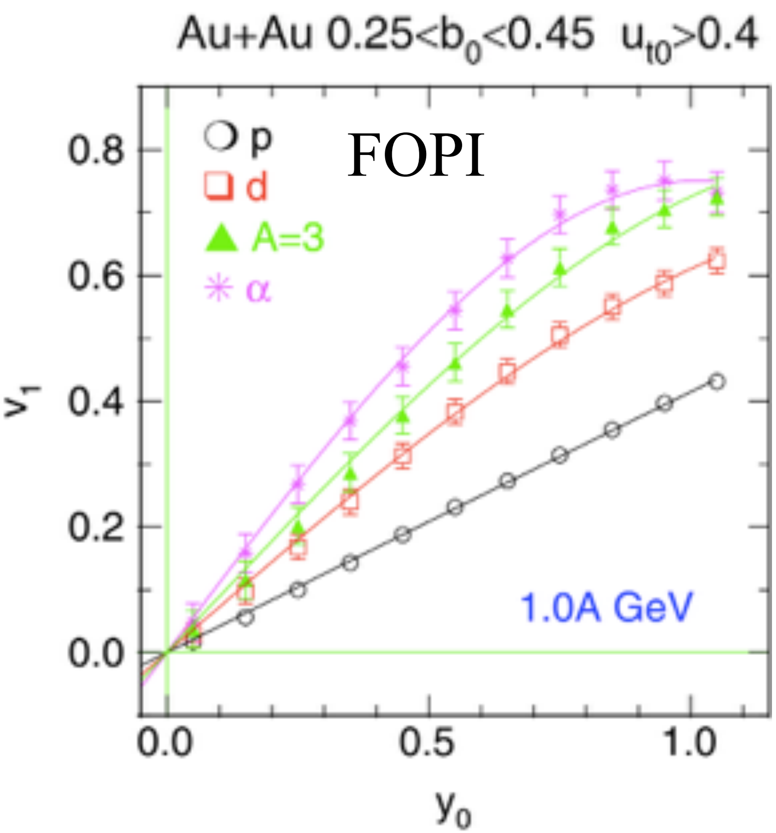

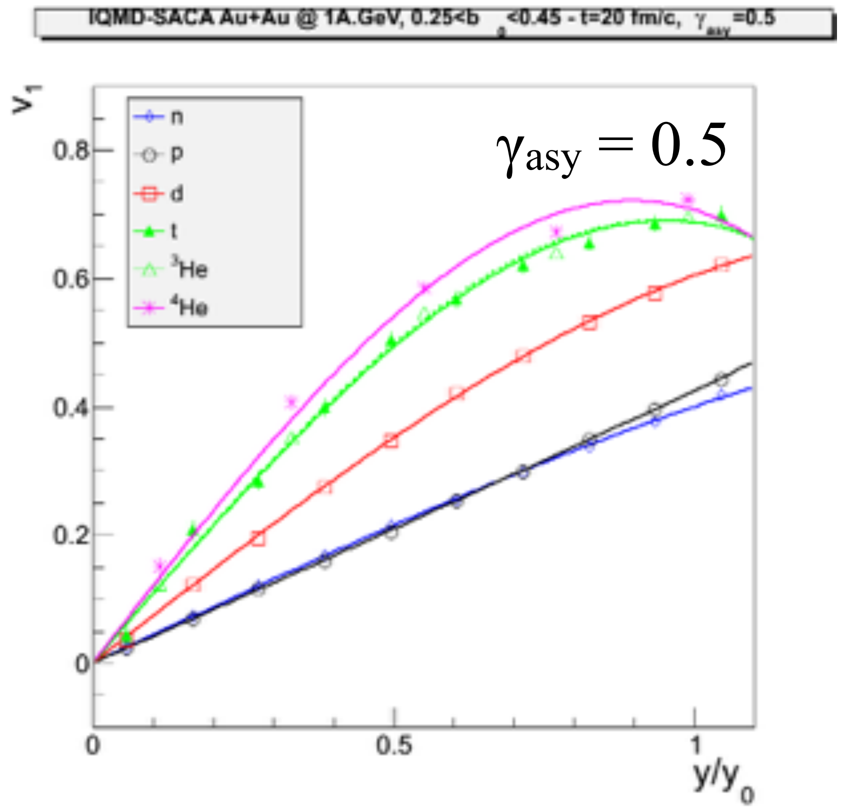

FOPI Collaboration / NPA 876 (2012) 1-60

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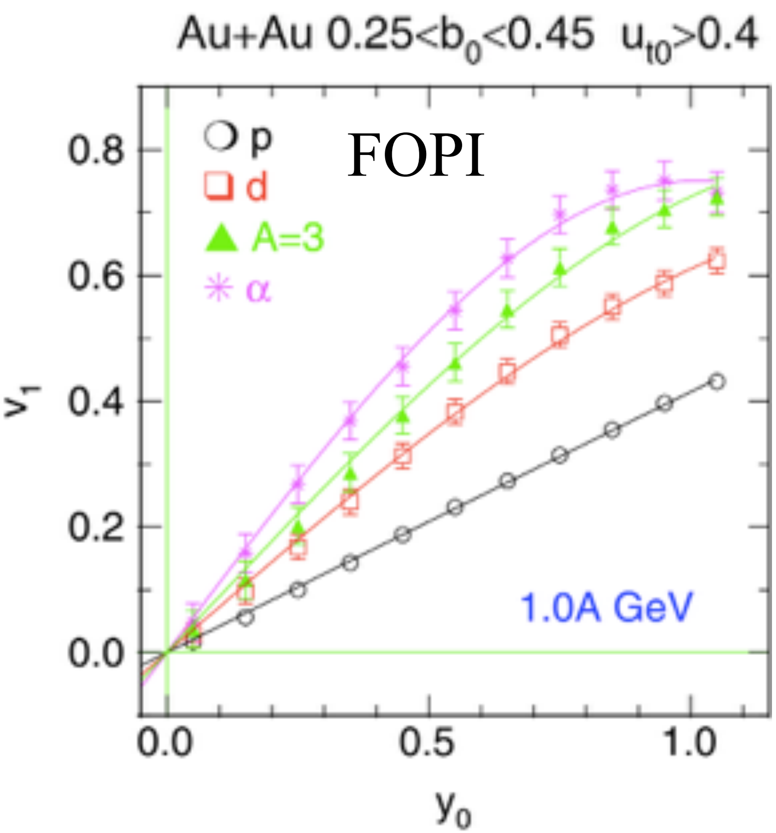
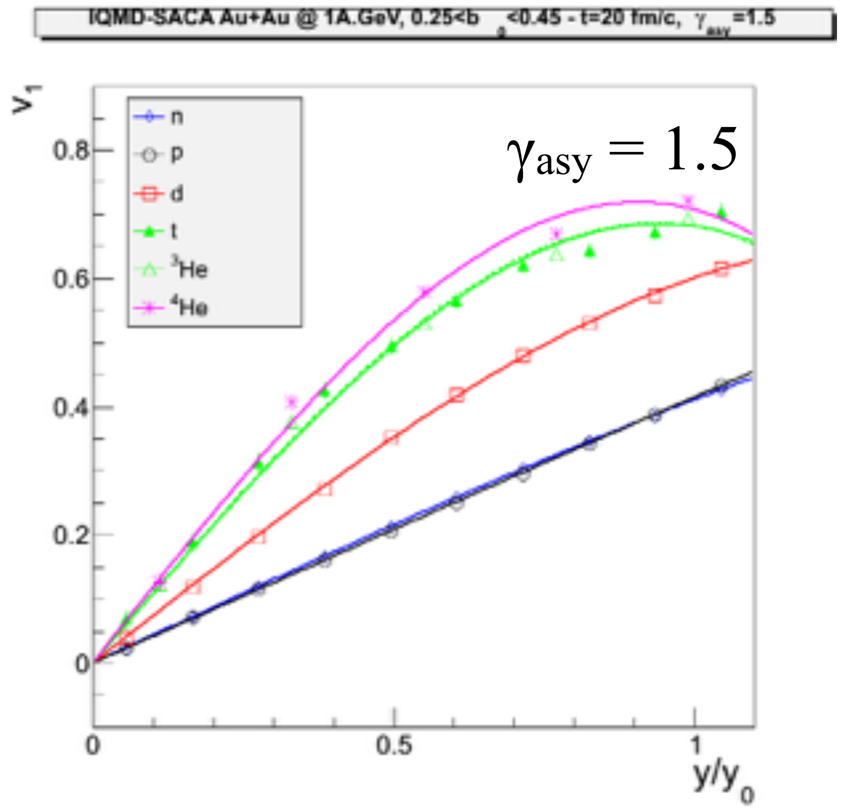


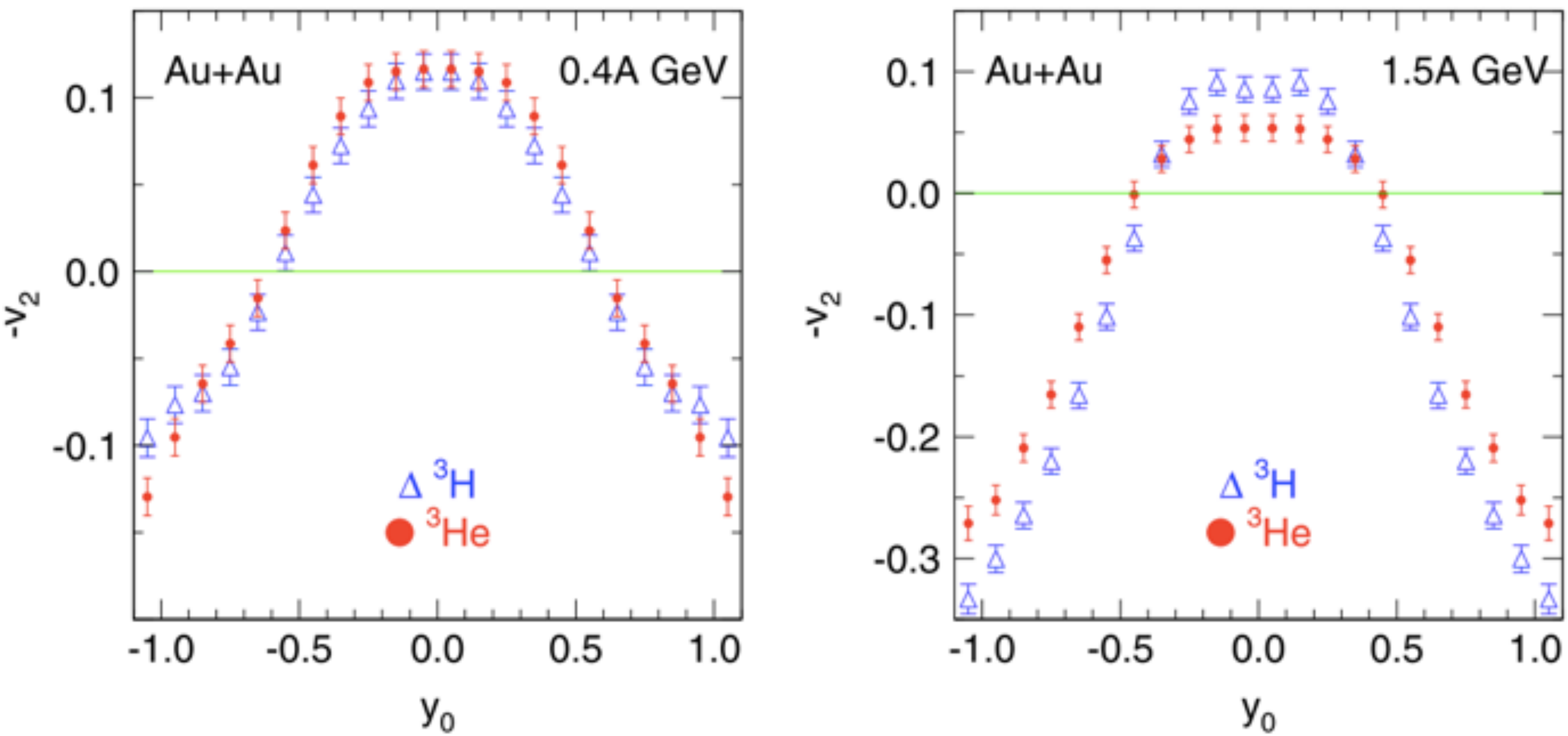


FOPI Collaboration / NPA 876 (2012) 1-60

Towards the determination of the stiffness of the asymmetry energy.

Elliptic flow

Au+Au ut0>0.4 *FOPI Collaboration / NPA 876 (2012) 1-60*



$\gamma_{asy} = 1$

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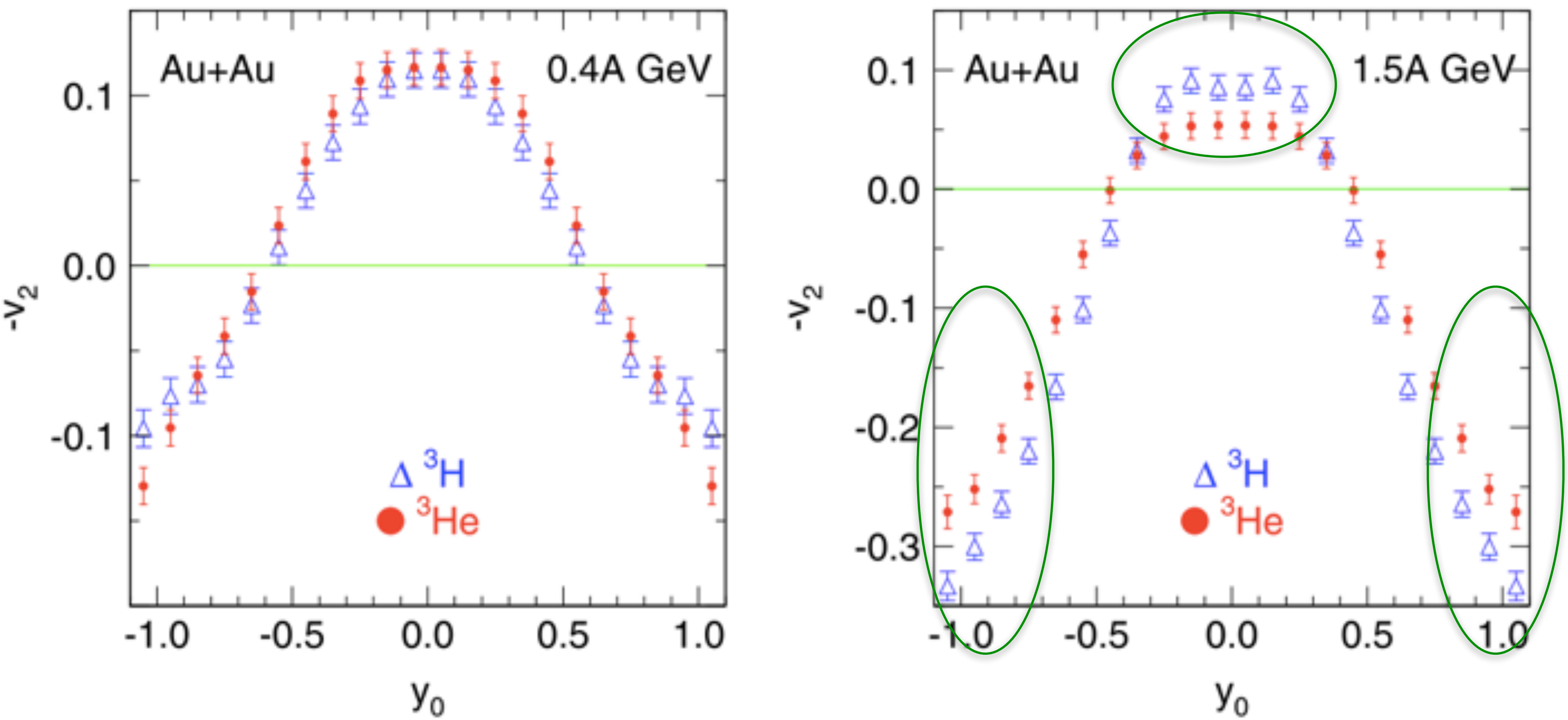
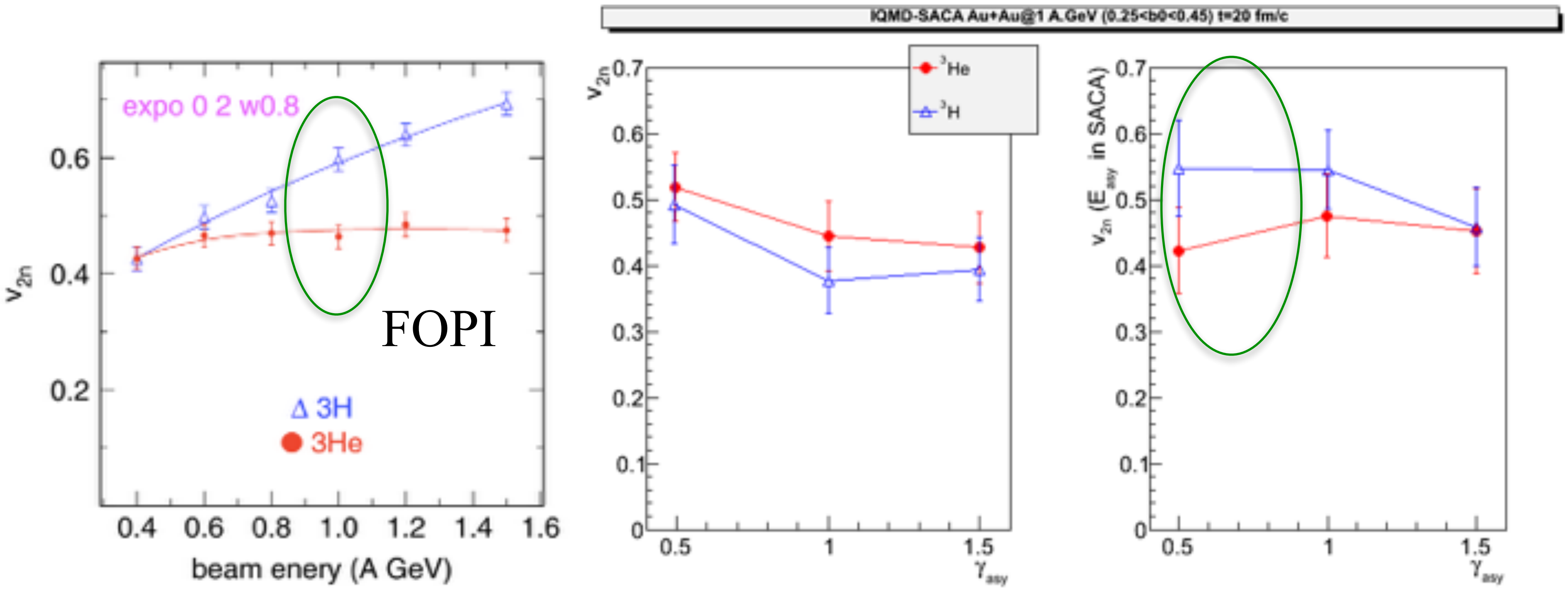


The differences in t/^{3}He elliptic flow increases with energy $\gamma_{asy} = 1$

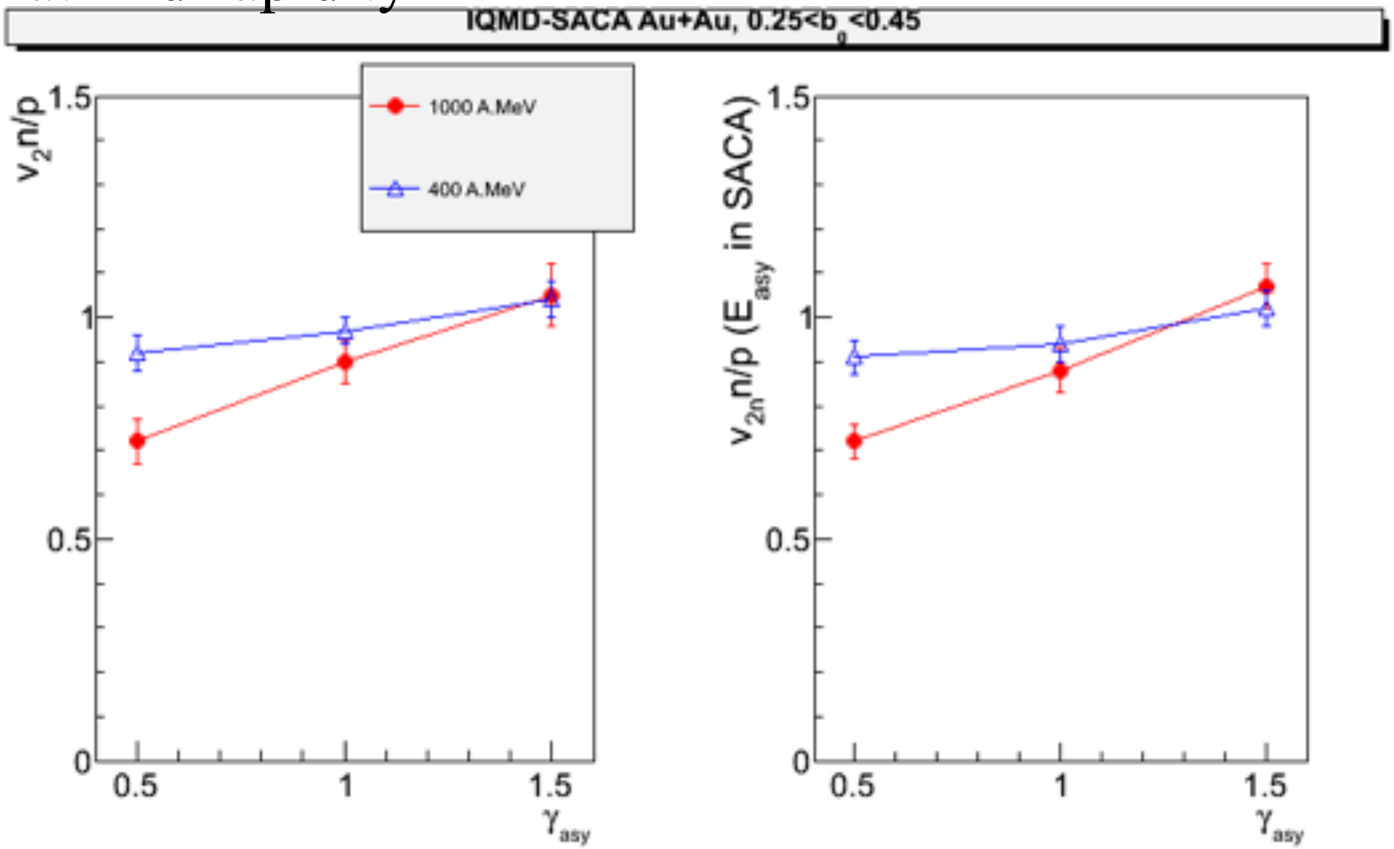
Towards the determination of the stiffness of the asymmetry energy.



PRELIMINARY

Towards the determination of the stiffness of the asymmetry energy.

at mid-rapidity



The higher the bombarding energy, the stronger the sensitivity.

Summary and discussion

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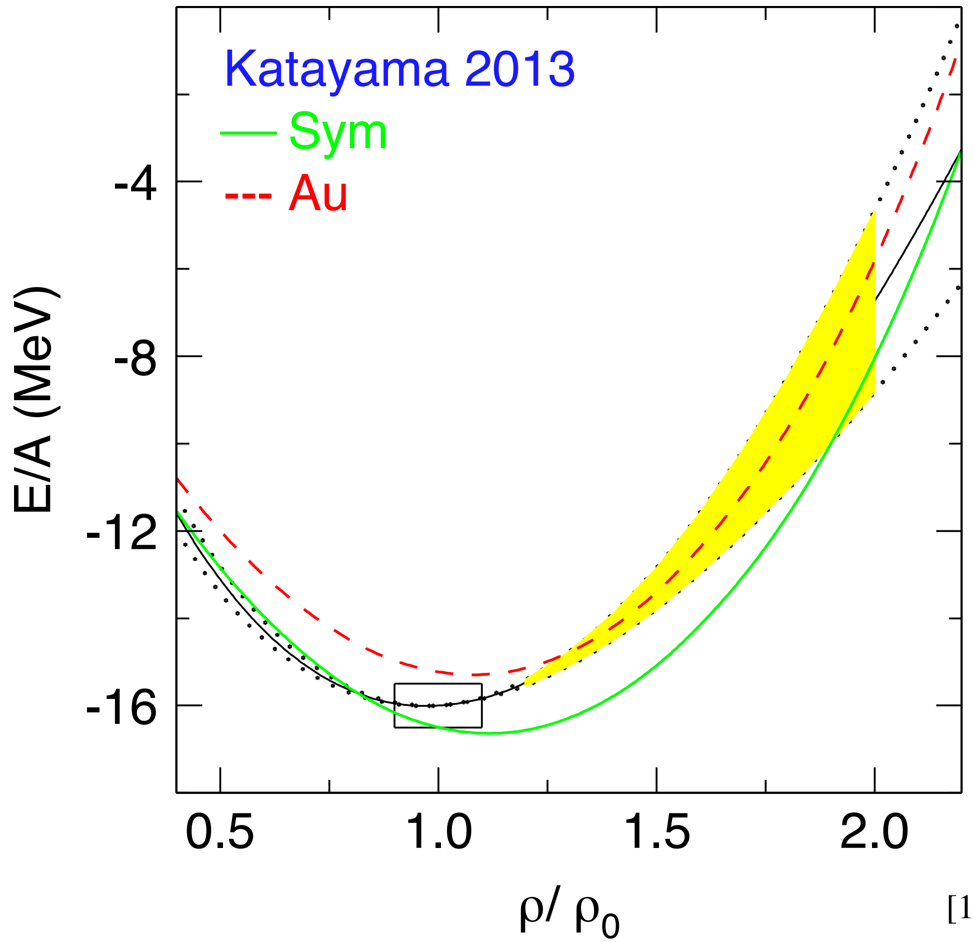
➲ See AsyEOS experiment: ongoing analysis,

forthcoming talks by P. Russotto and J. Brzychczyk.

Comparison to microscopic calculations

(three representative microscopic calculations compared with our new constraints)



Dirac-Brueckner-Hatree-Fock (DBHF) calculation[10] using the Bonn A[11] nucleon-nucleon potential

[10] R. Brockmann, R. Machleidt, Phys. Rev. C 42 (1990) 1965.

[11] T. Katayama, K. Saito, Phys. Rev. C 88 (2013) 035805.

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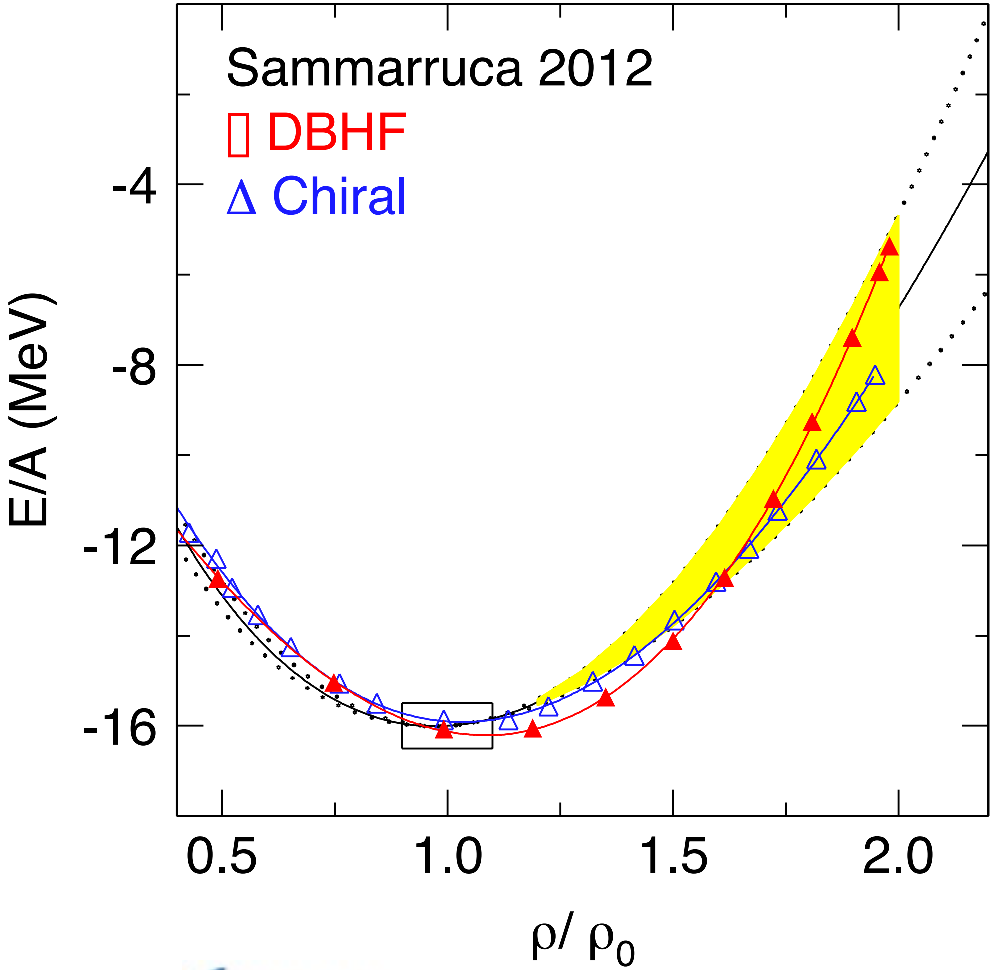

2 symmetric nuclear matter EOS's from [12]:

1) 'DBHF' = meson theoretic potential together with the DBHF method

2) 'Chiral'= use of effective field theory (EFT) with density dependent interactions derived from leading order chiral three-nucleon forces.

[12] P. Danielewicz, G. Odyniec, Phys. Lett. B 157 (1985) 168.

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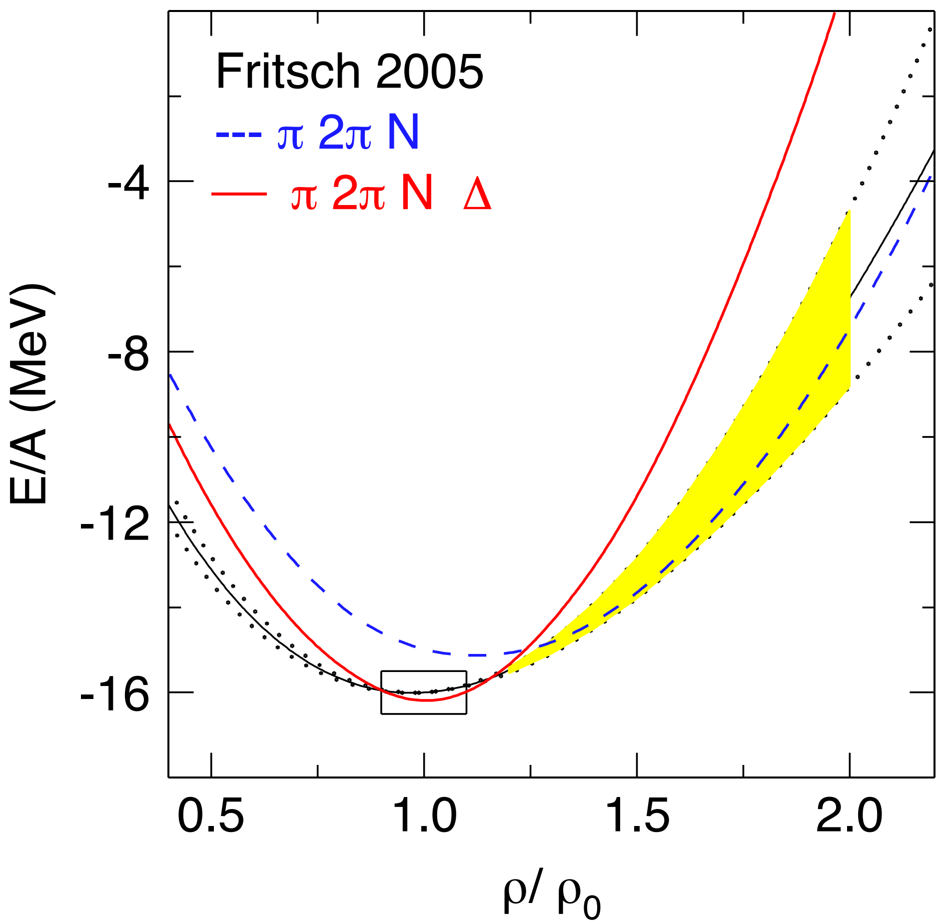
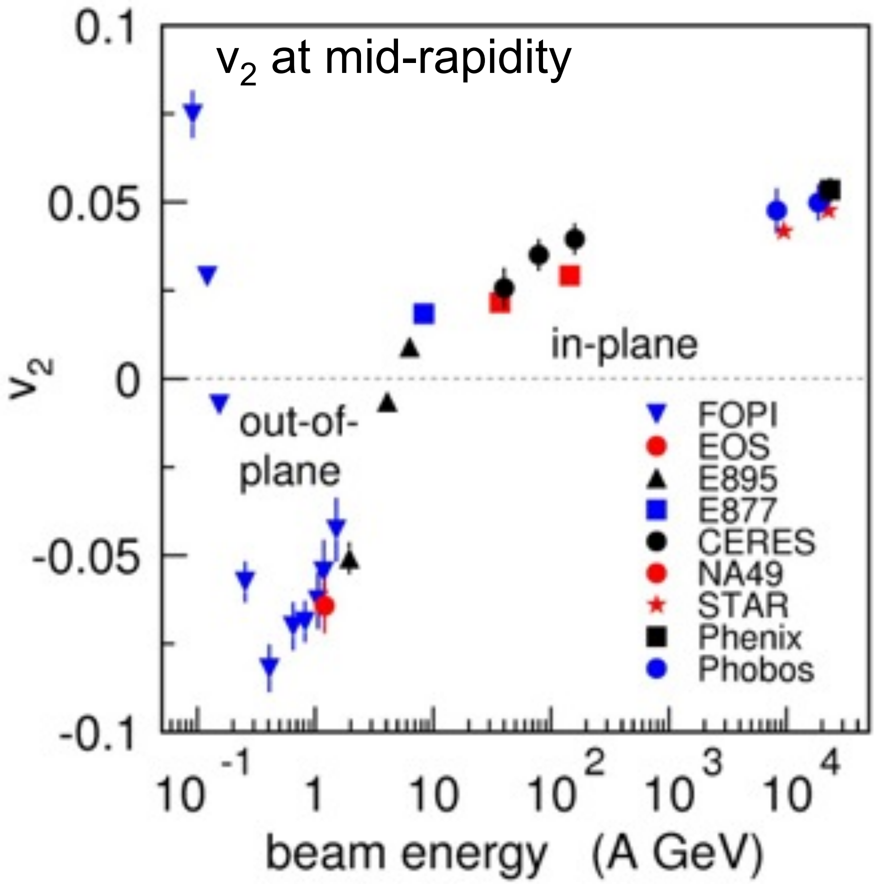


Using the chiral approach[13]: 2 rather different EOS's including or not virtual Δ excitations.

- » the virtual Δ-excitations help locate the EOS at the right horizontal place around ρ = 0.16 fm−3.
- » the Δ leads to a rather marked stiffening of the EOS (K0 = 304 MeV)
- » because 'cold' EOS ?
- » finite temperature in the reaction => the Δ are real rather than virtual. The theoretical 'Δ stiffness' could then be a dispersion effect rapidly changing with temperature.

[13] S. Fritsch, N. Kaiser, W. Weise, Nucl. Phys. A 750 (2005) 259.

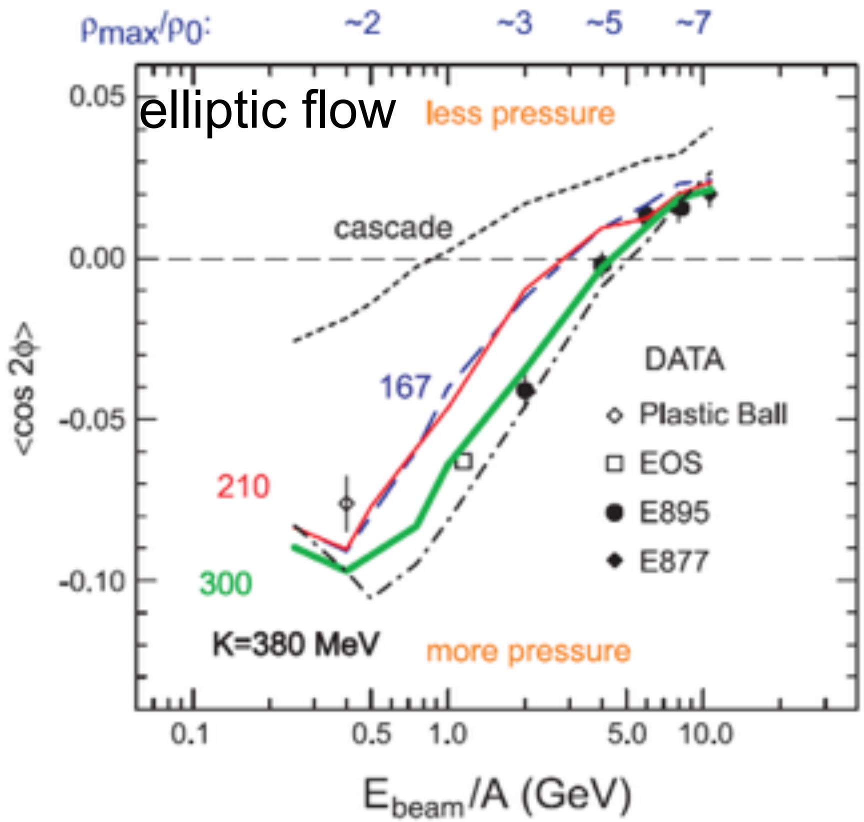
Beam energy dependence of elliptic flow



elliptic flow

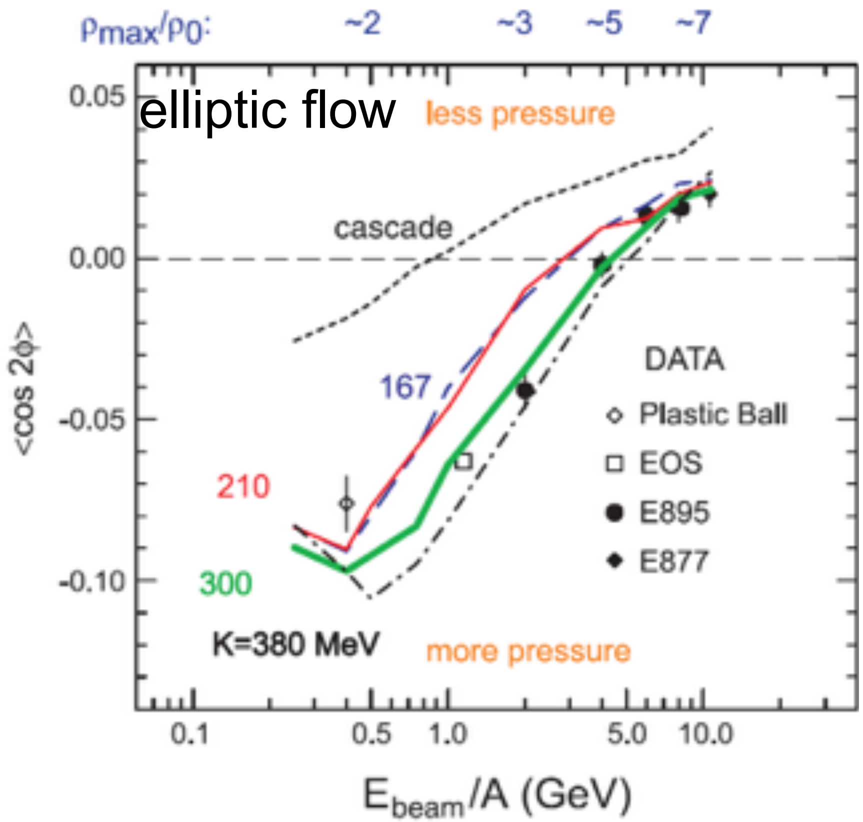
- ➢ pressure gradient of compression zone
- ➢ shadowing of spectators
- ➢ at low energies
  - – attraction due to mean field of nucleons
- ➢ at high energies
  - – lacking shadowing of spectators

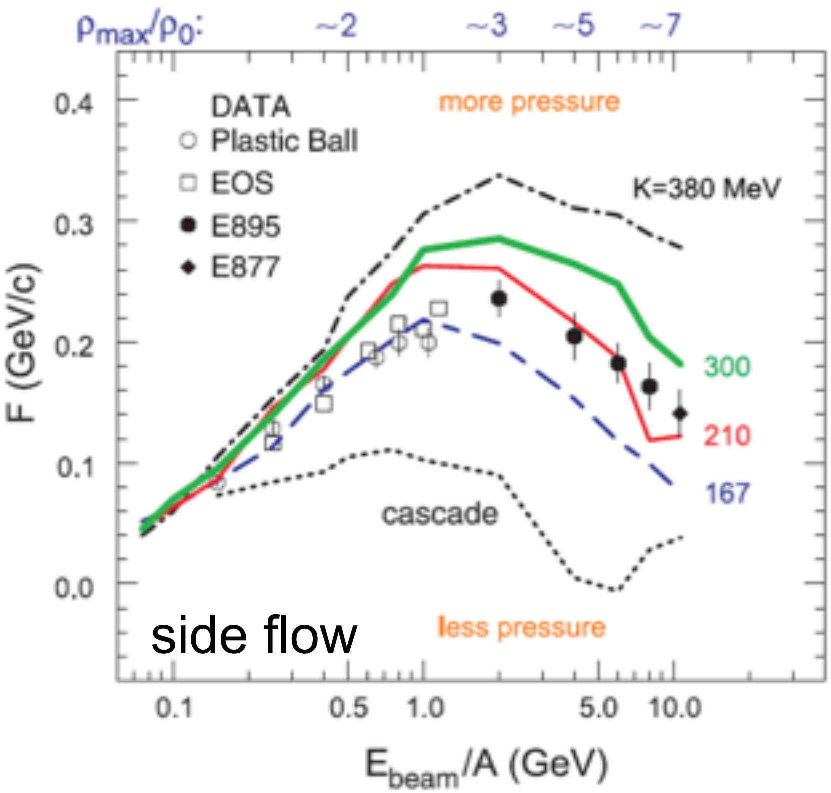
Elliptic flow and the nuclear matter EOS



P. Danielewicz et al.
Science 298, 1592 (2002)

Elliptic flow and the nuclear matter EOS





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