Constraining the nuclear matter equation of state around twice saturation density

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[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

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- Introduction.
- Analysis and results.
- Simulations: the scenario.
- Summary and discussion.

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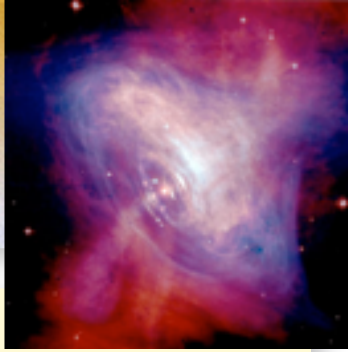
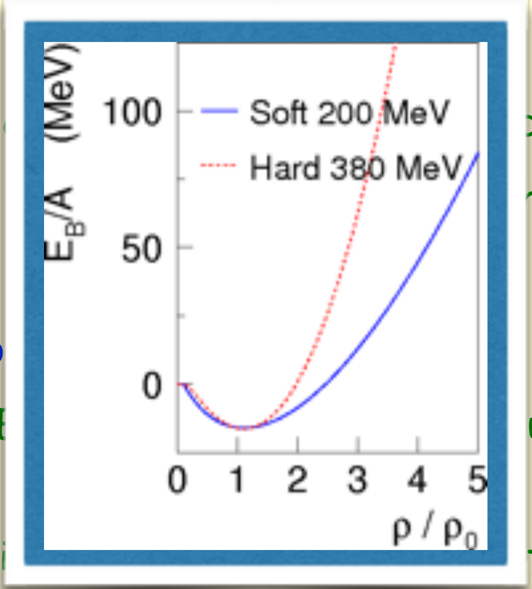
Introduction



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



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  - precise model-independent radii,
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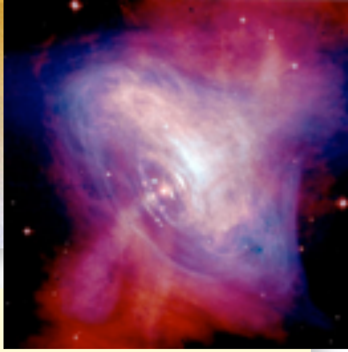

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- The equation of state (EOS) of nuclear matter:
    - of fundamental interest
    - object of intense theoretical efforts since several decades
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        - compact stars [1]
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- The calculation of the nuclear EOS from first principles, such as very recently attempted in [3], is a very complex task.
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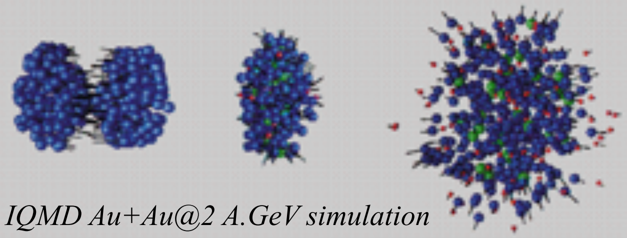
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- Alternative method: in earth laboratories, heavy ion collisions over a wide range of incident energies, system sizes and compositions.

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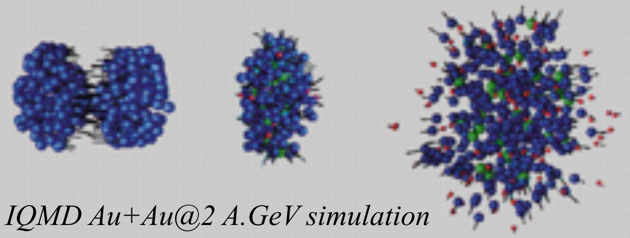

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Flows at high density in heavy-ion collisions

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

Y = rapidity

p_t = transverse momentum

Φ_R = reaction plane azimuthal angle

V_1 = 'side/directed flow', $\cos(\Phi-\Phi_R)$ mode

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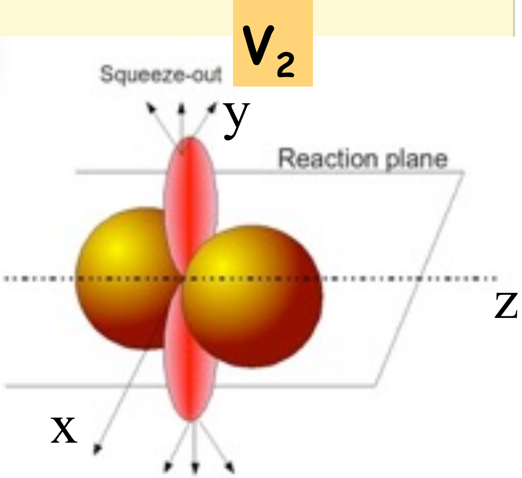

'Elliptic flow': $\cos(2(\Phi-\Phi_R))$ mode, competition between 'in-plane' ($V_2>0$) and 'out-of-plane' ejection ($V_2<0$).

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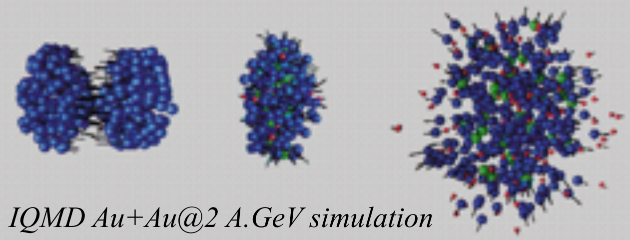

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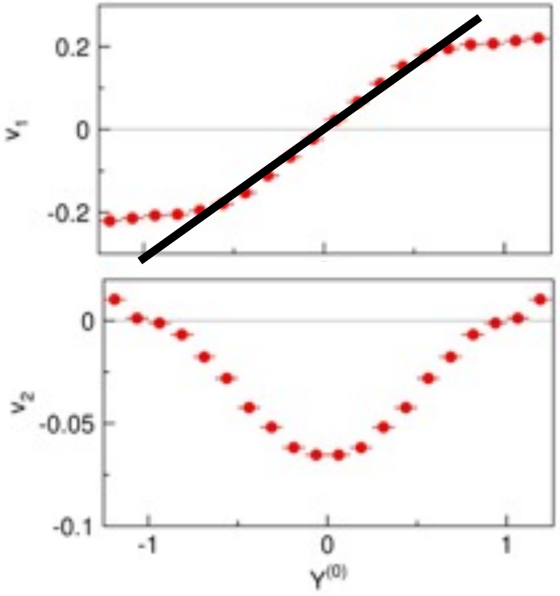

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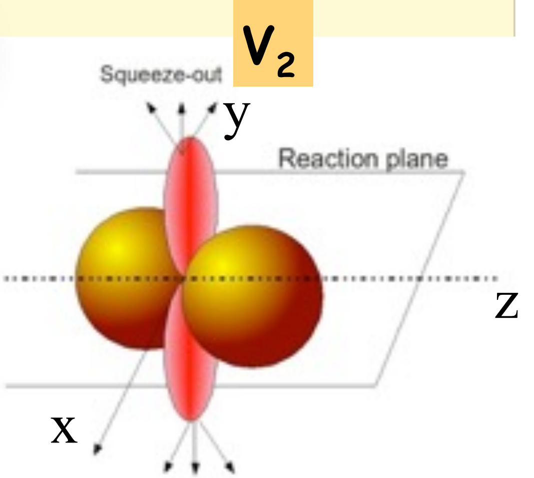

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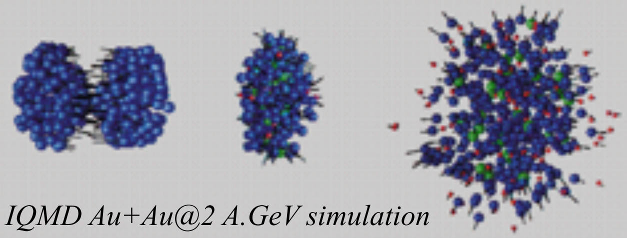

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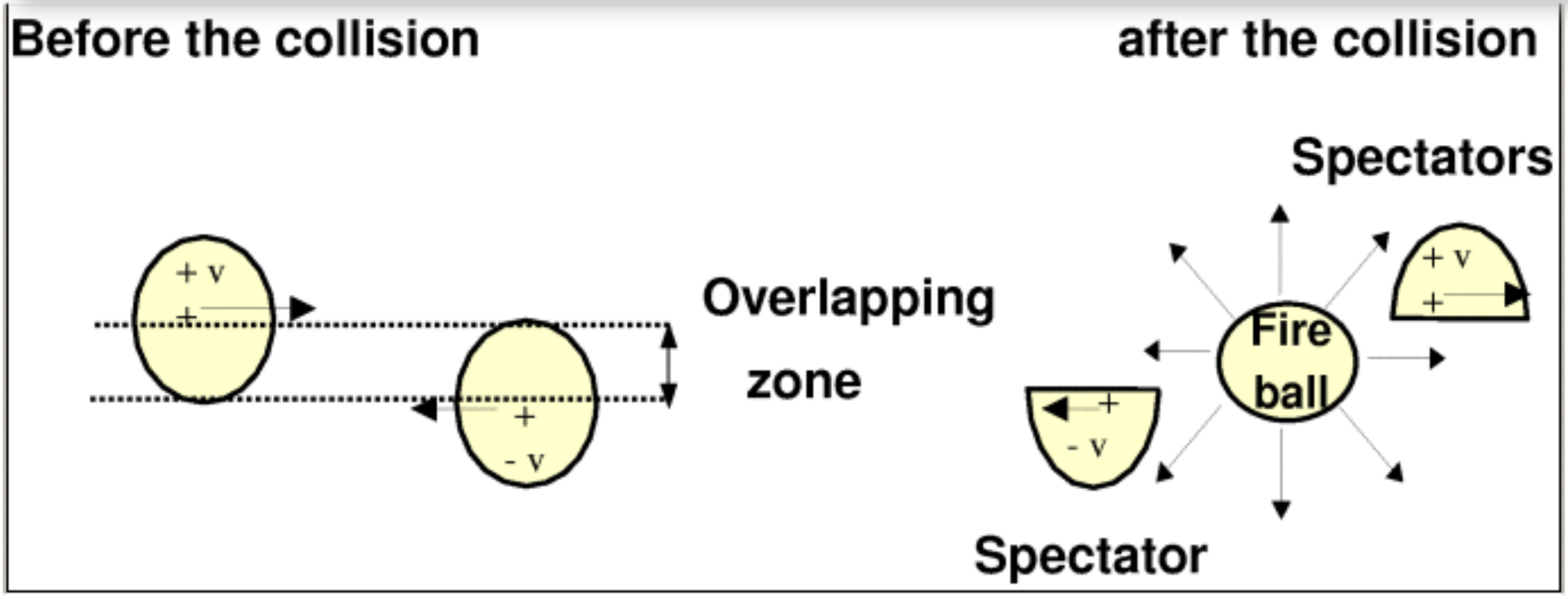

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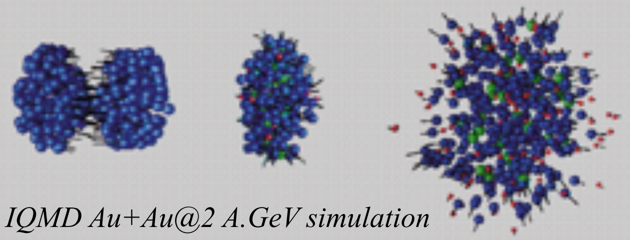

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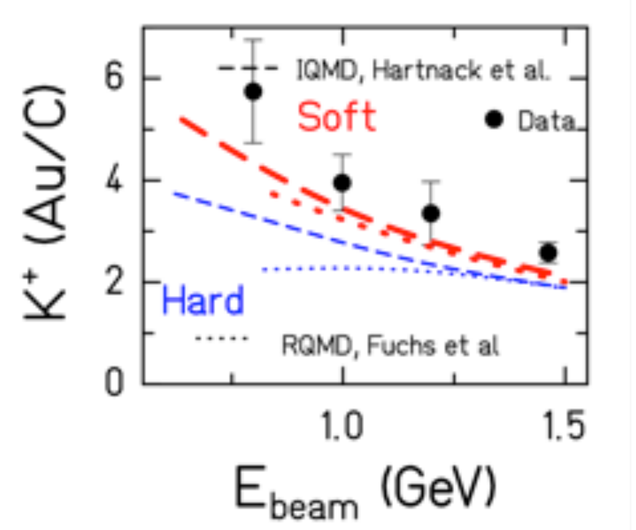

Data: C. Sturm et al., PRL 86 (2001) 39

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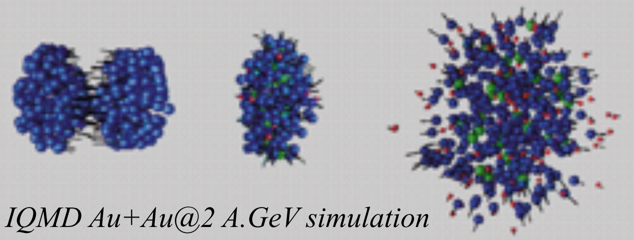
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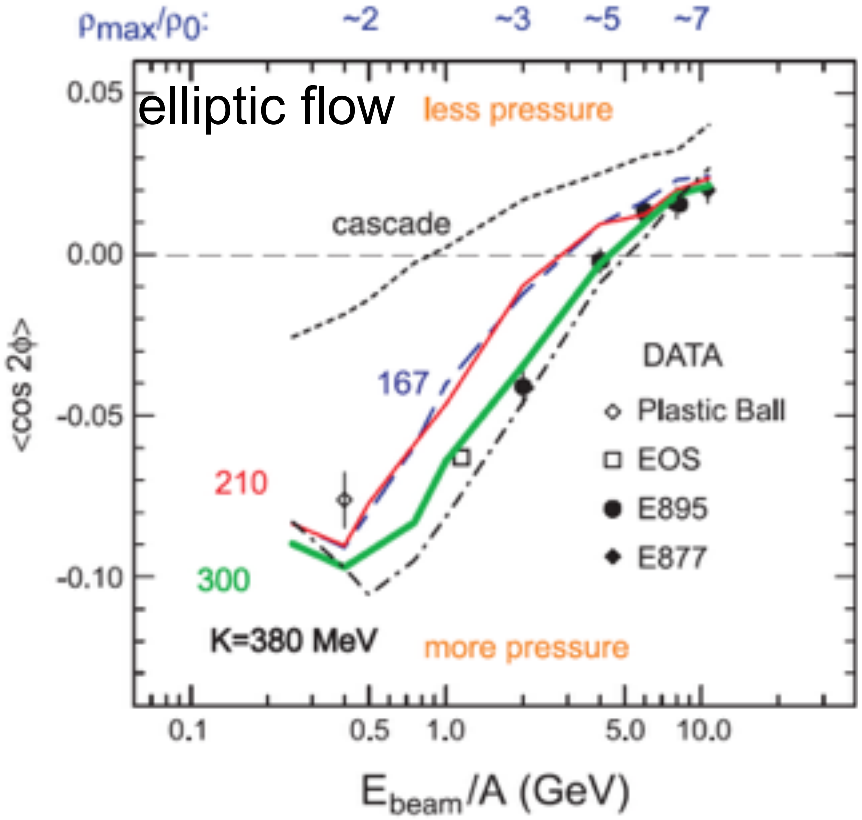
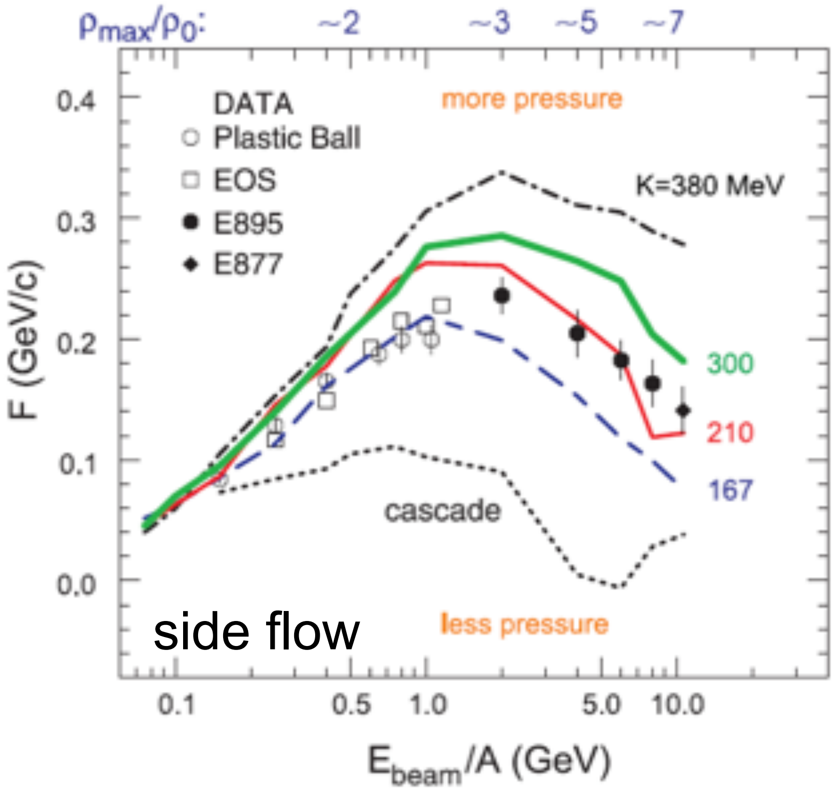
    - kaons rare at E_{beam}=0.8 A.GeV (max. sensitivity to the EOS).
    - all 'bulk' observables (multiplicities, clusterisation, stopping, flow) under control in the transport model ?
  - EoS (1996), Au+Au @ 0.25 to 1.15 A.GeV, radial & sideward flow, squeeze-out versus QMD -> no strong sensitivity on the nuclear incompressibility K_0.
  - FOPI (2005), Au+Au @ 0.09-1.5 A.GeV, Z=1 elliptic flow, versus 4 different transport codes -> 'no strong constraint on the EOS can be derived at this stage'.
  - BEVALAC & AGS accelerators, proton flows versus transport theories -> K_0 = 167-200 MeV (soft) from V_1, K_0 = 300 MeV (semi-stiff) from V_2 -> contradictions.

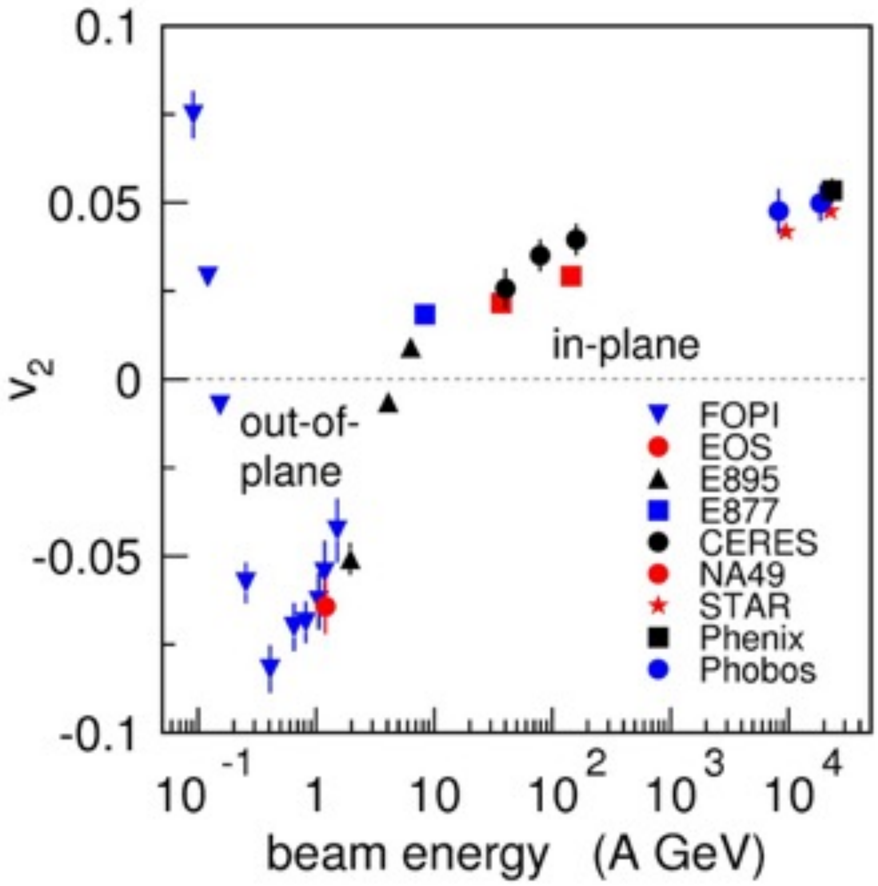
Elliptic flow and the nuclear matter EOS





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

Beam energy dependence of the 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

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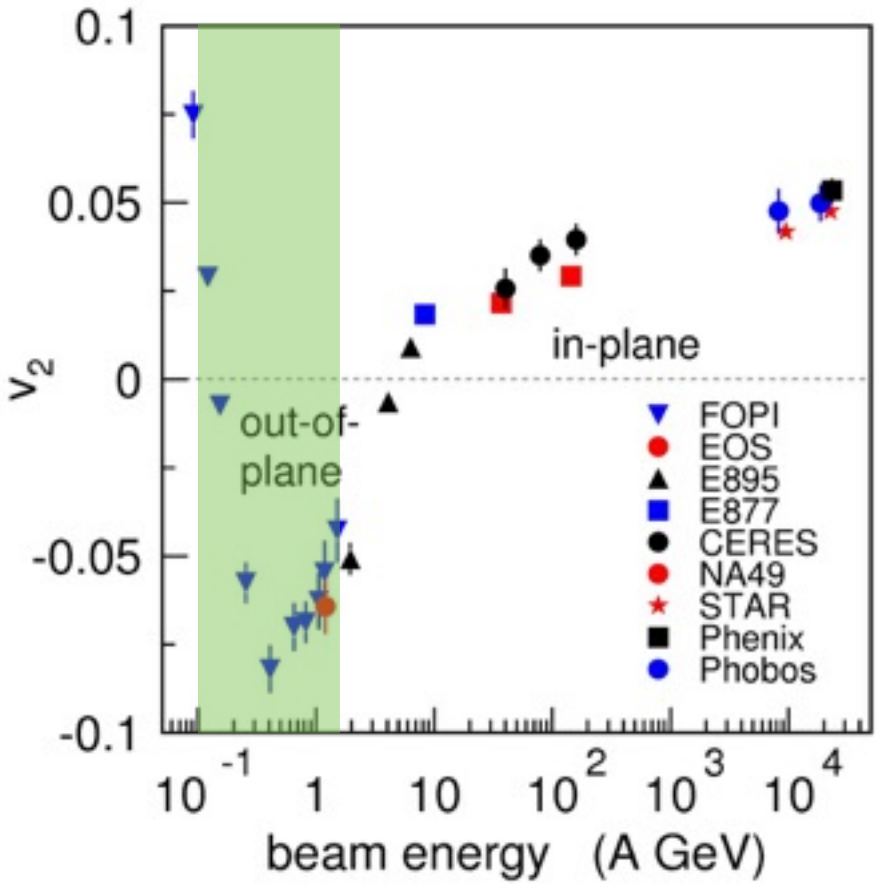

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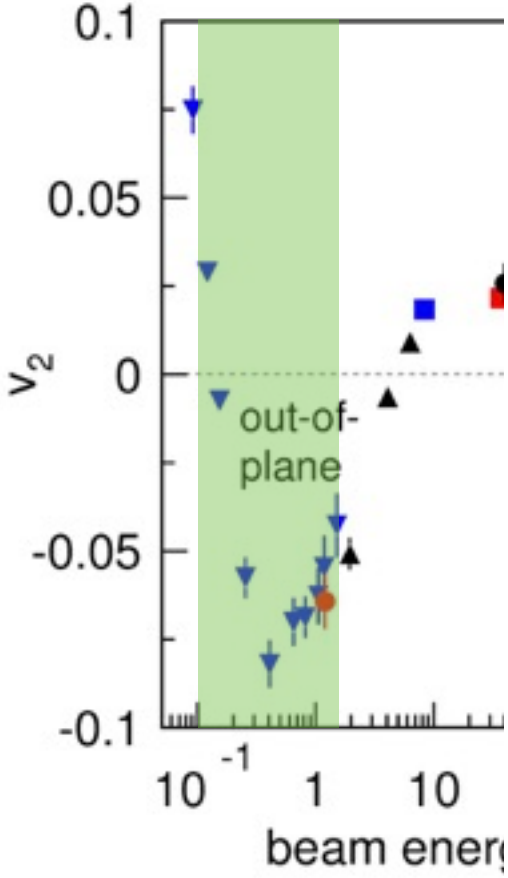
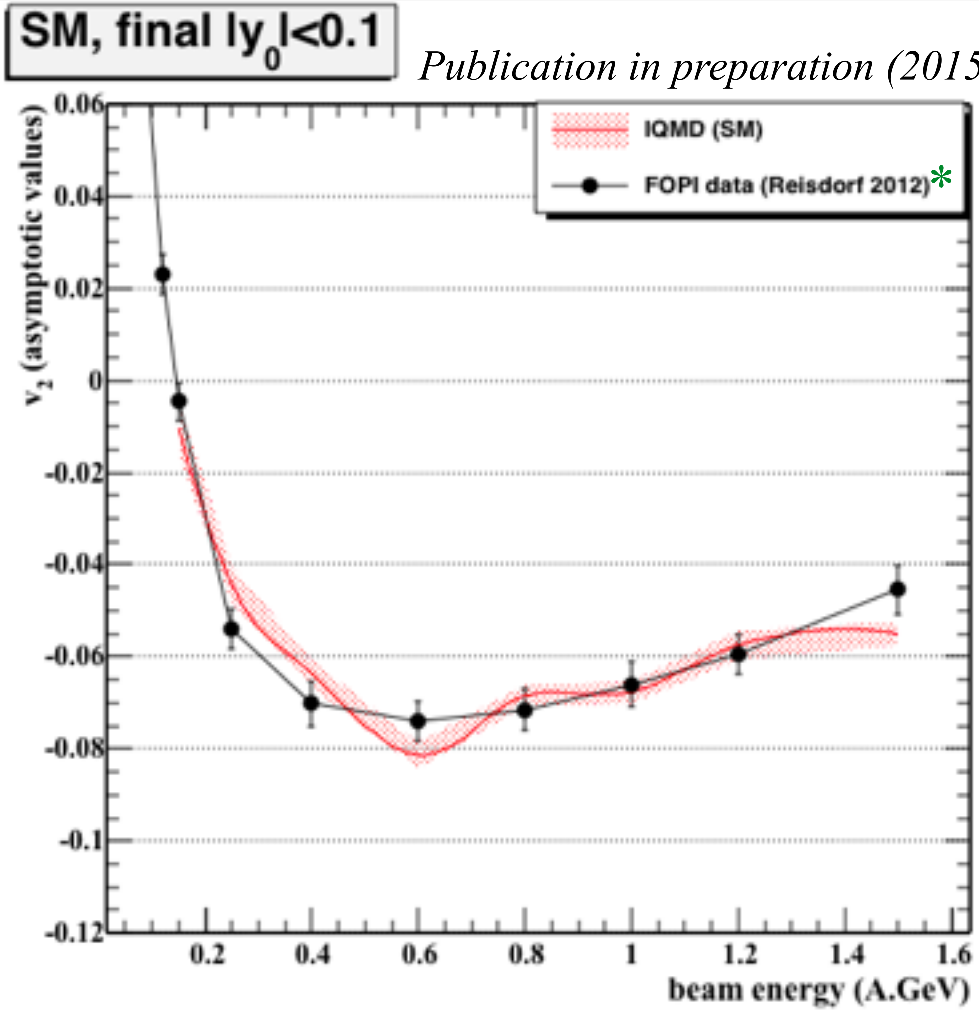




Publication in preparation (2015)

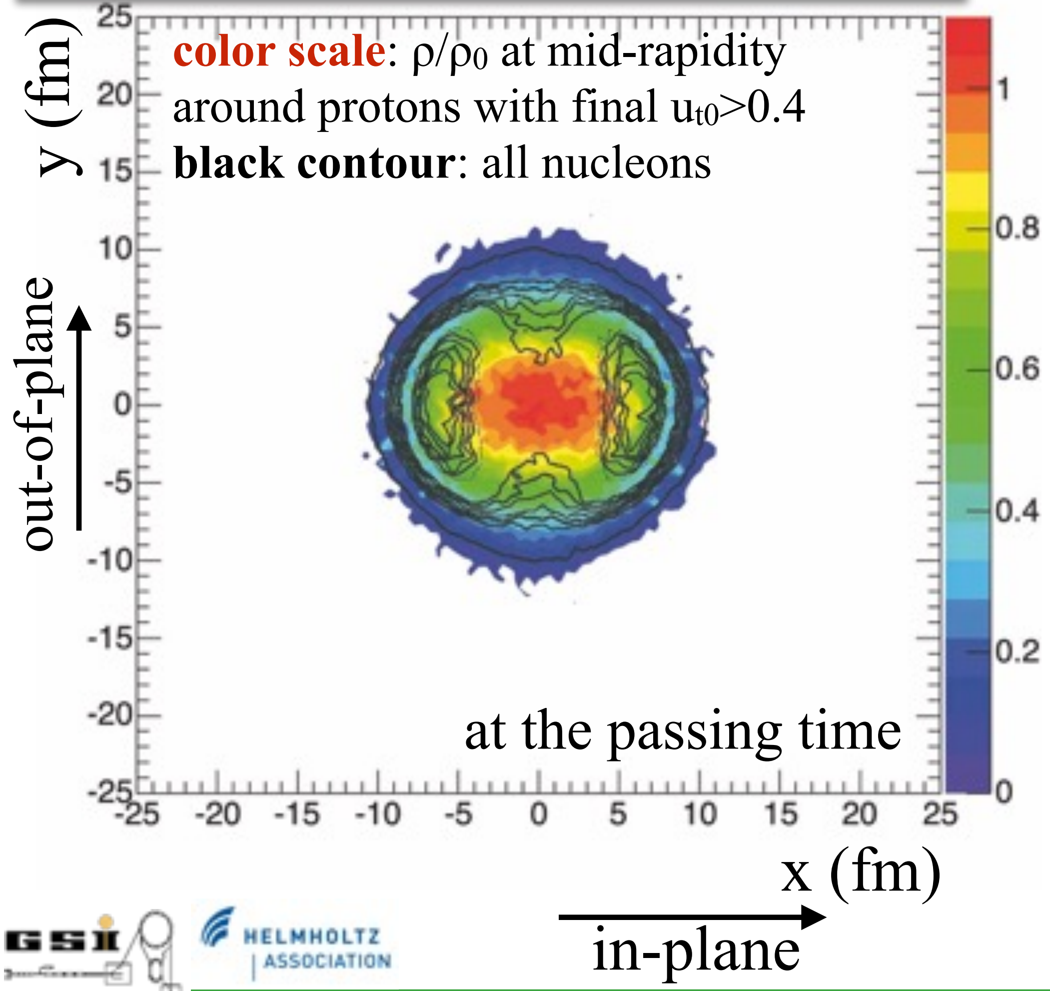
ression

field of

*: *FOPI data: Reisdorf et al, Nuclear Physics A 876 (2012) 1–60*

Origin of the negative elliptic flow

IQMD (SM) Au+Au @ 1.5 A.GeV, b=6 fm



color scale: ρ/ρ_0 at mid-rapidity around protons with final u_{t0}>0.4

black contour: all nucleons

at the passing time

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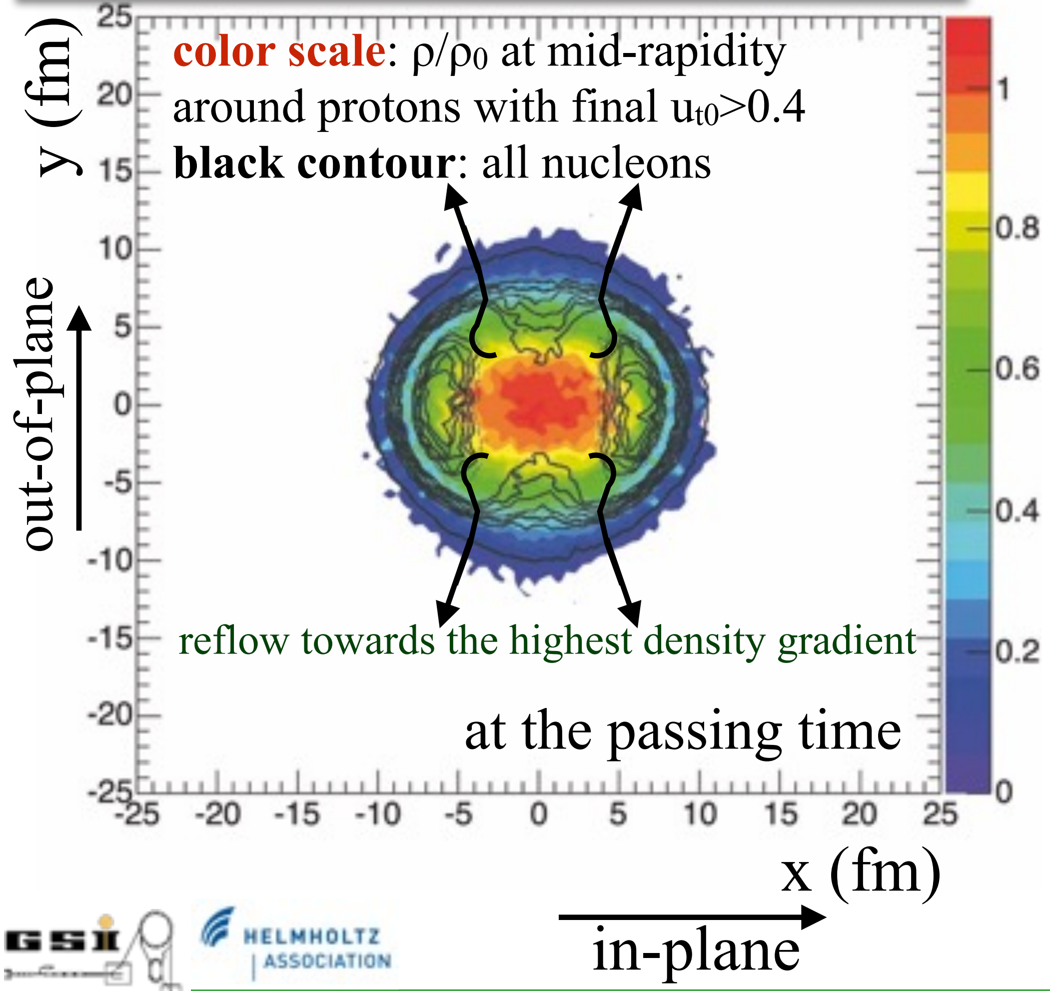

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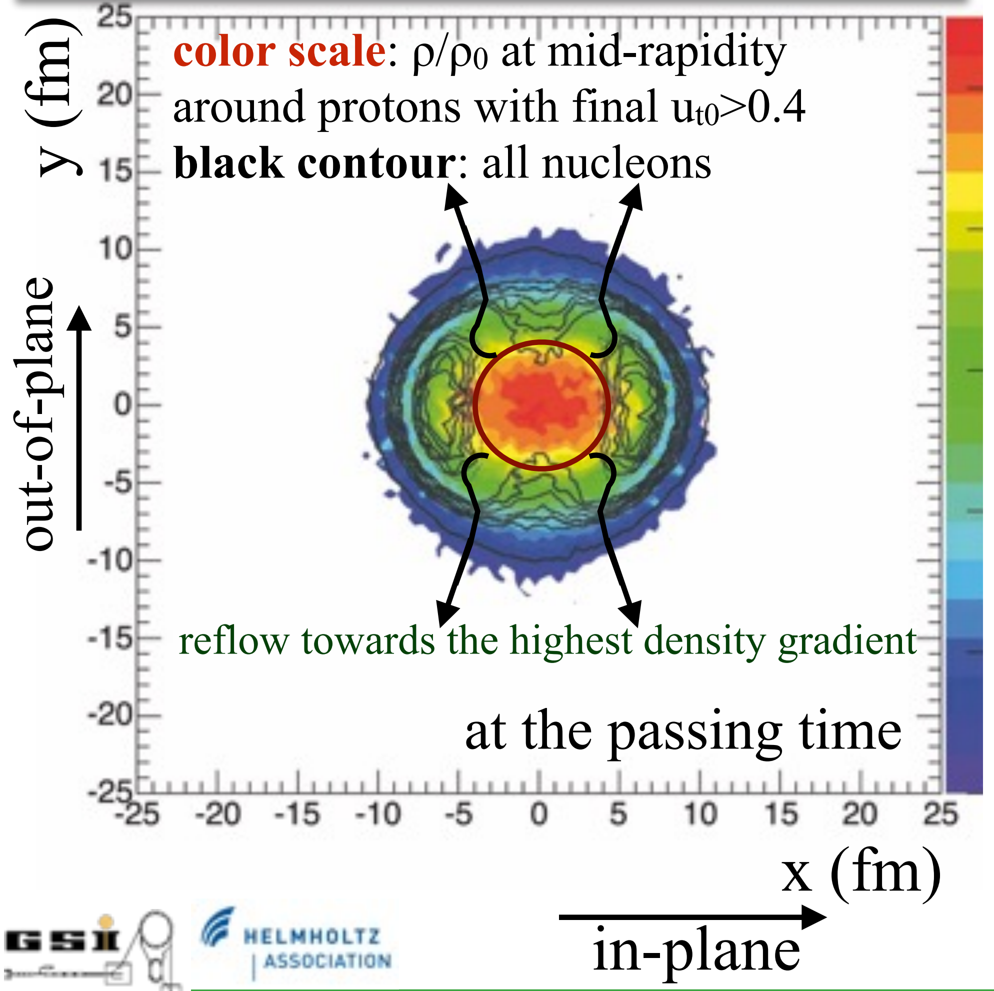

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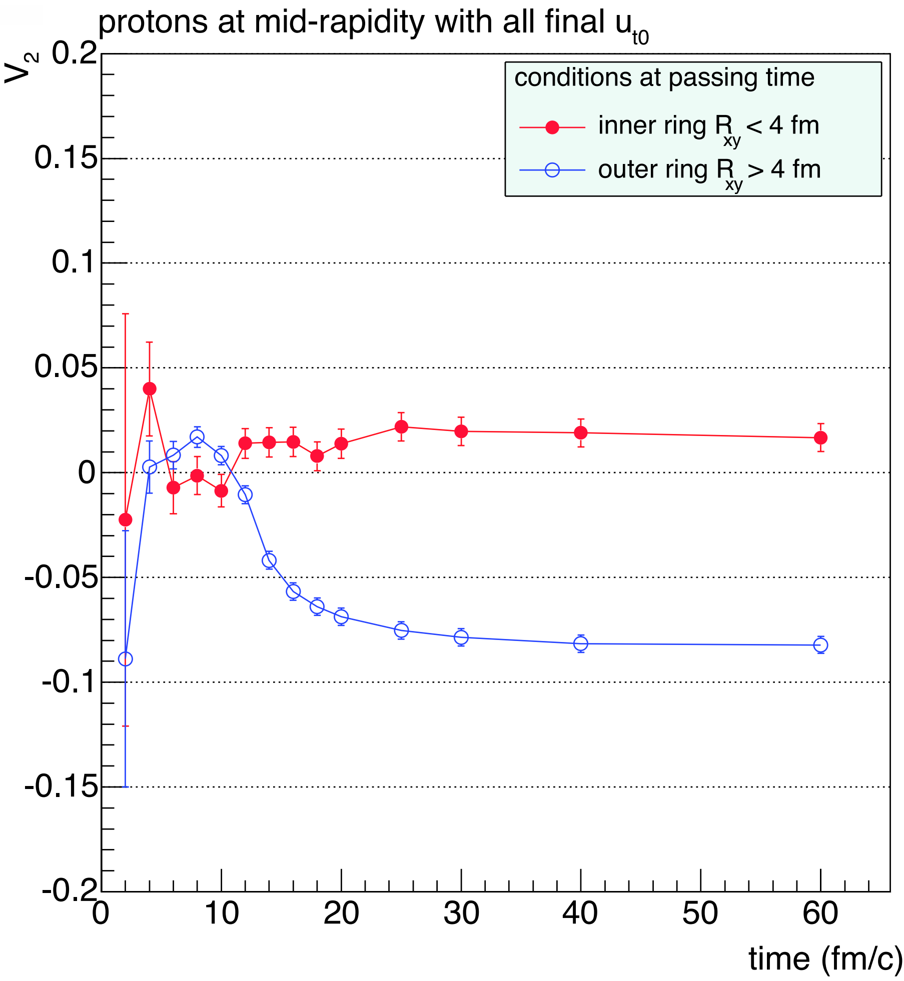

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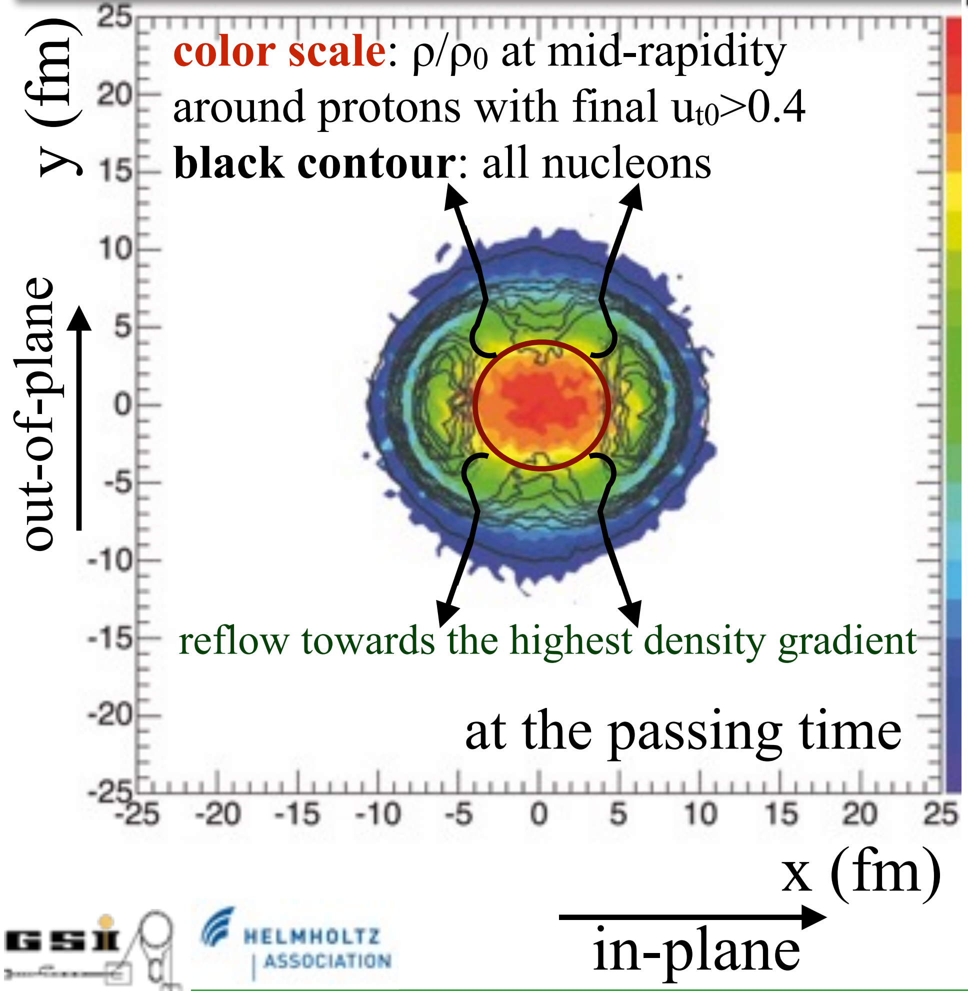

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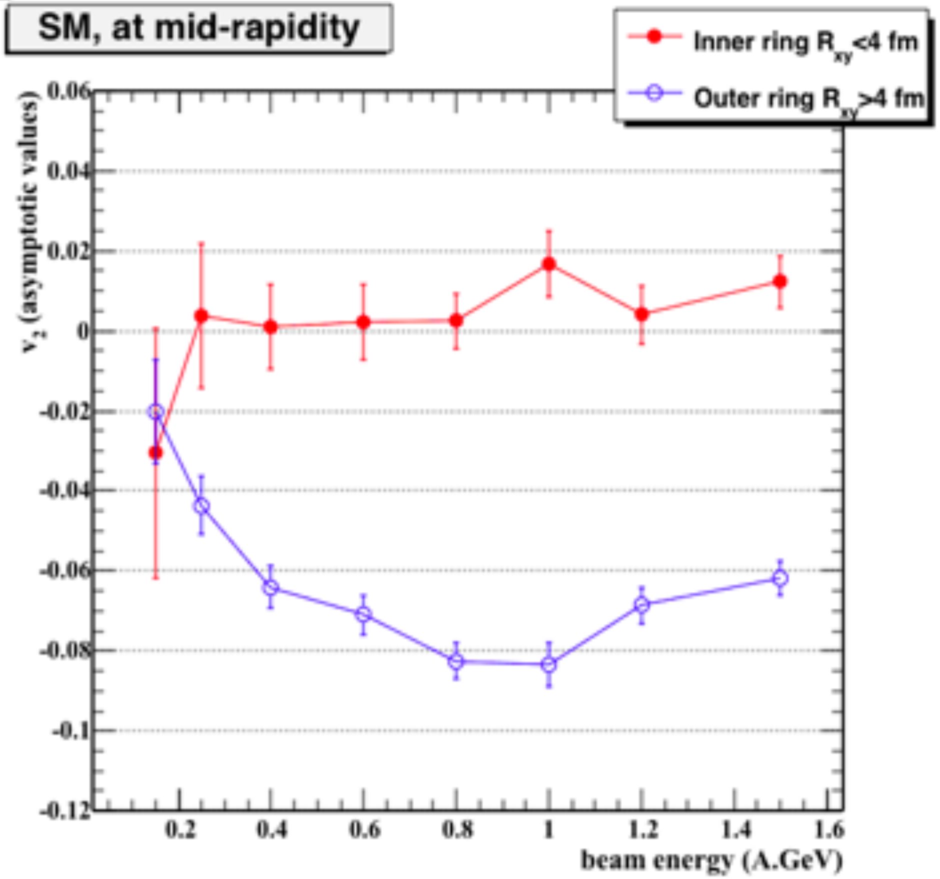

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Introduction

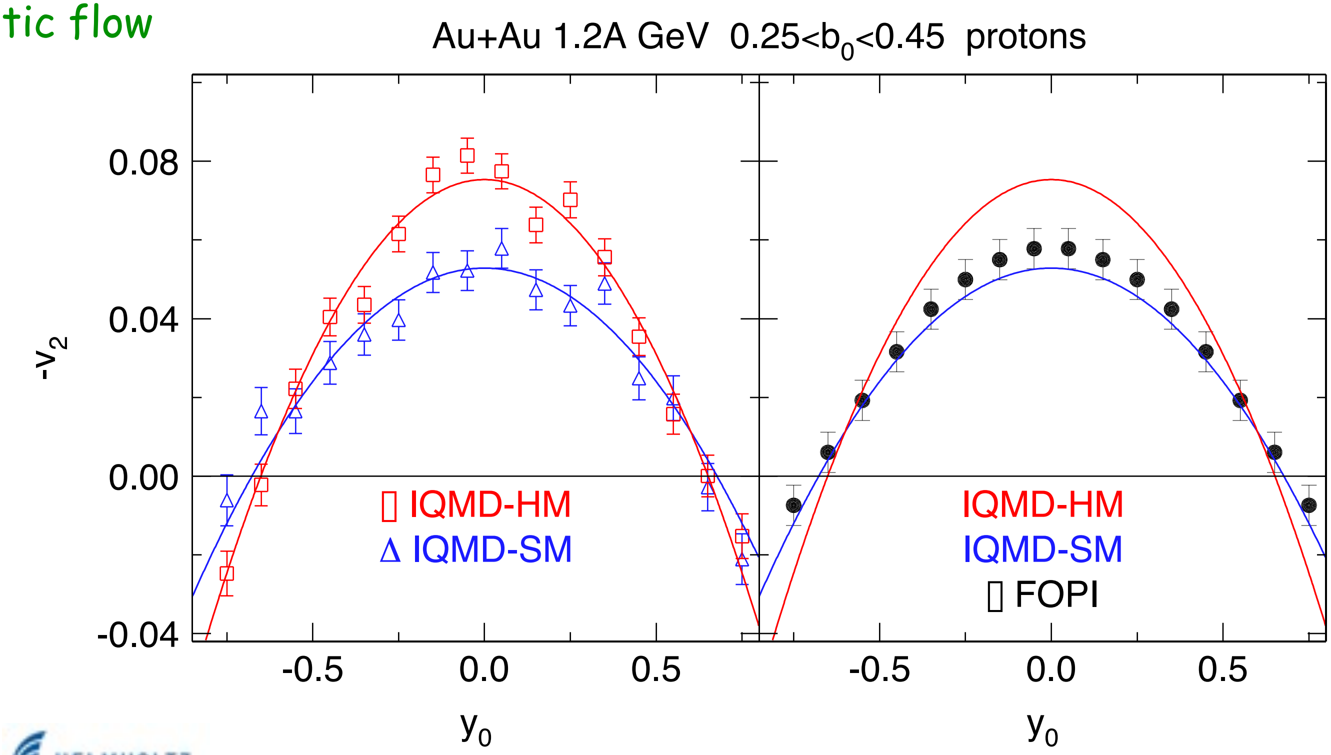
- Present work: improve the situation in the 1 A.GeV regime, from extensive flow data published recently by the FOPI Collaboration (Au+Au @ 0.4-1.5 A.GeV) [4]
  ➜ close look at the elliptic flow data with improvements:
  - 1) not only protons: d, t, ^{3}He ^{4}He having larger flow signals than single 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.

Analysis and results

After Andronic et al., Phys. Rev. C67 (2003) 034907, only the m.d.i. can account for the experimental directed flow => we restrict this study to SM and HM.

Elliptic flow



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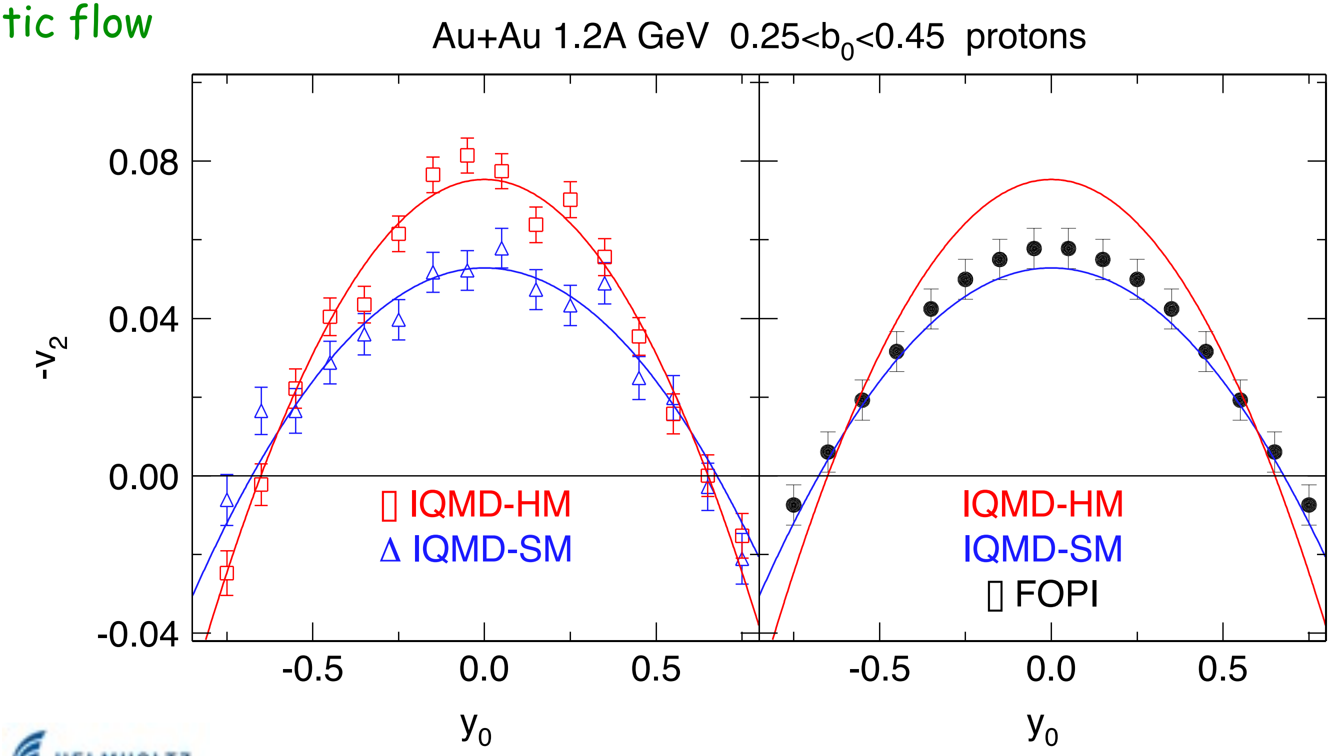

K_0 =
380 MeV (‘stiff’)
200 MeV (‘soft’)

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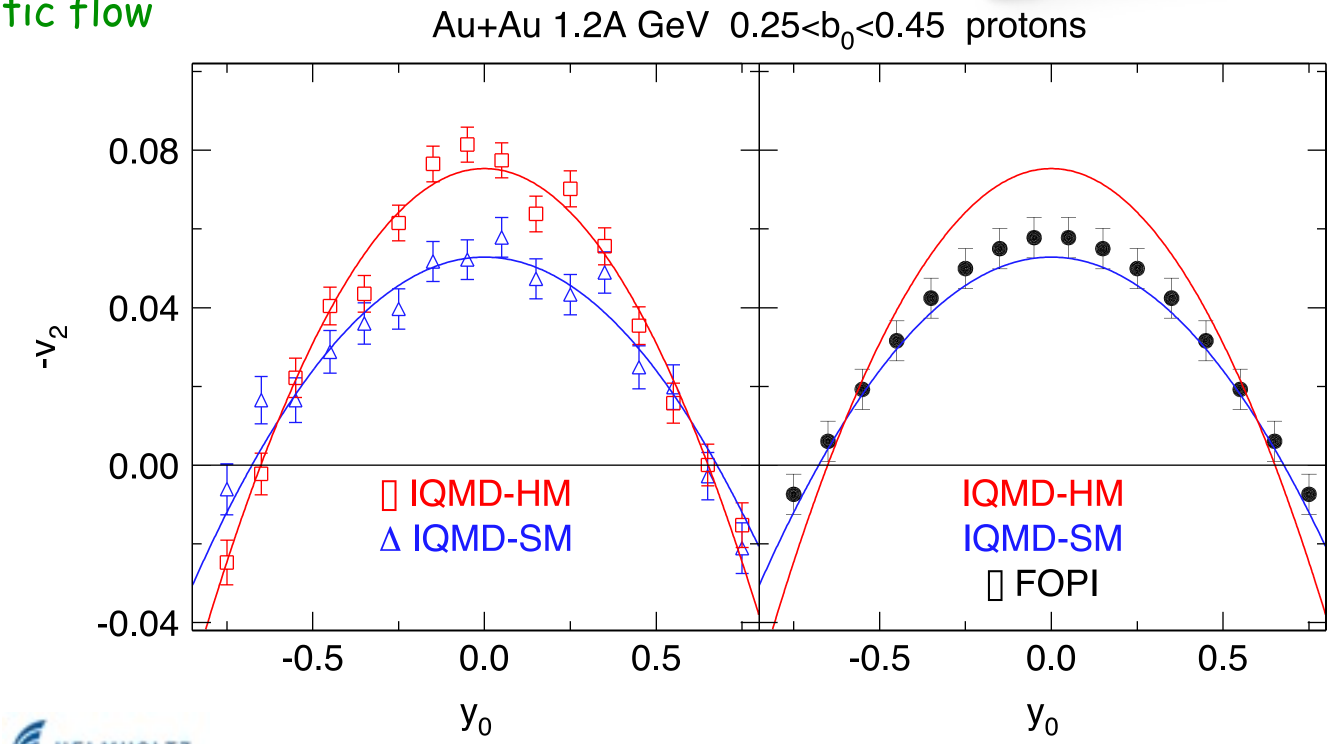
Complete shape of $v_2(y_0)$: a new observable:
$v_{2n} = |v_{20}| + |v_{22}|$,
from fit
$v_2(y_0) = v_{20} + v_{22} \cdot y_0^2$

Elliptic flow



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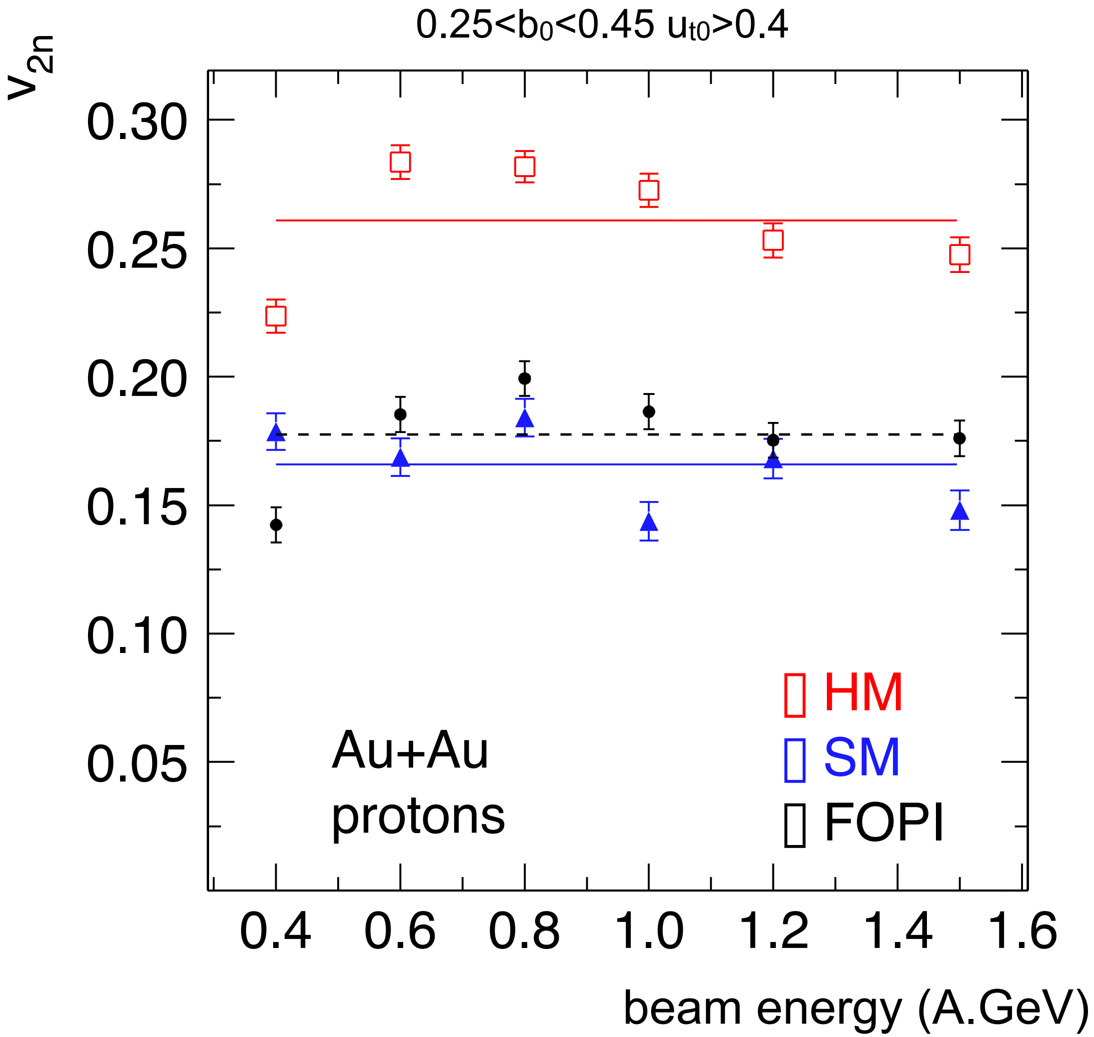
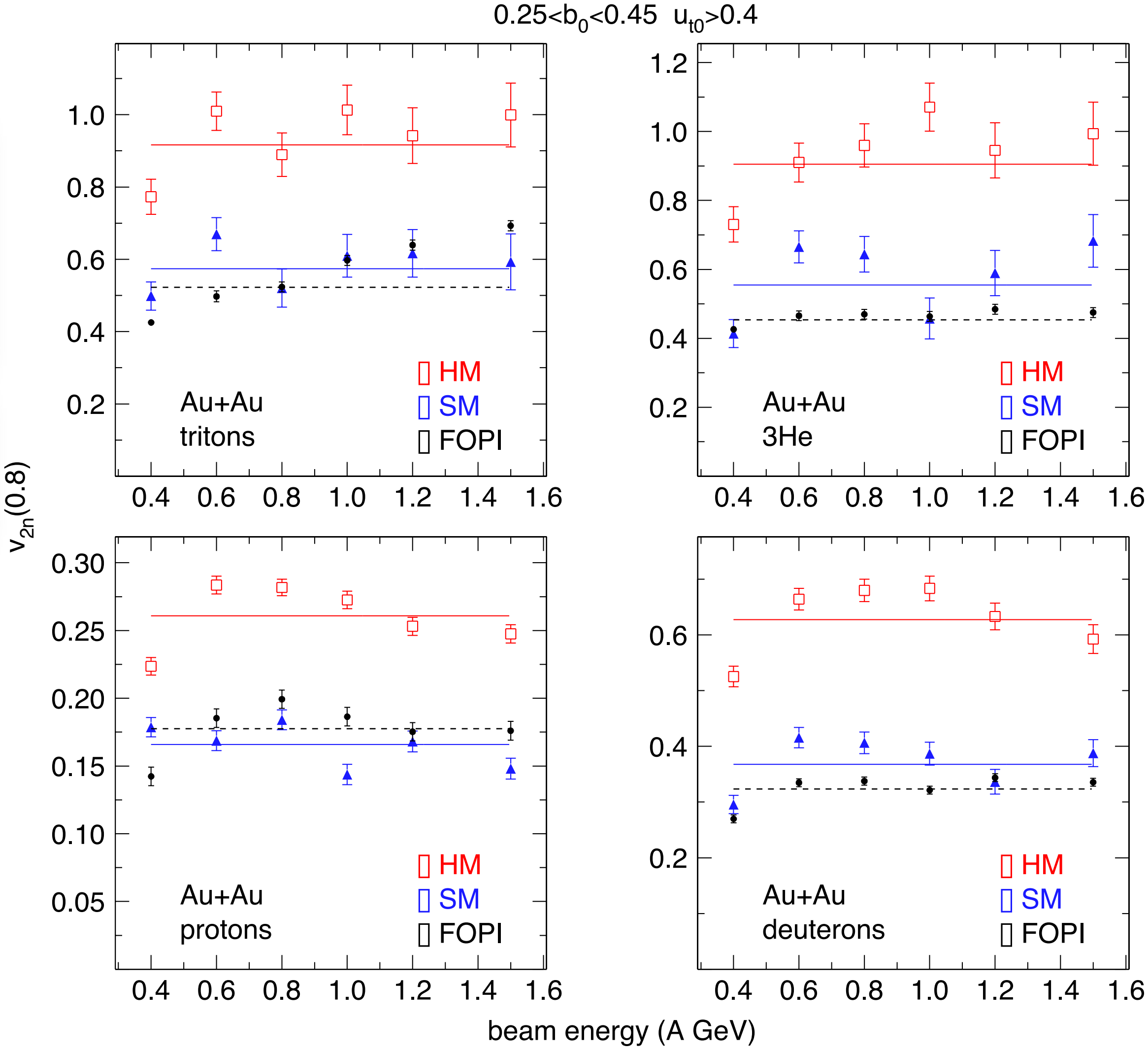
➜ $v_{2n}(E_{beam})$ varies by a factor ≈1.6, >> measured uncertainty (≈1.1)



Analysis and results

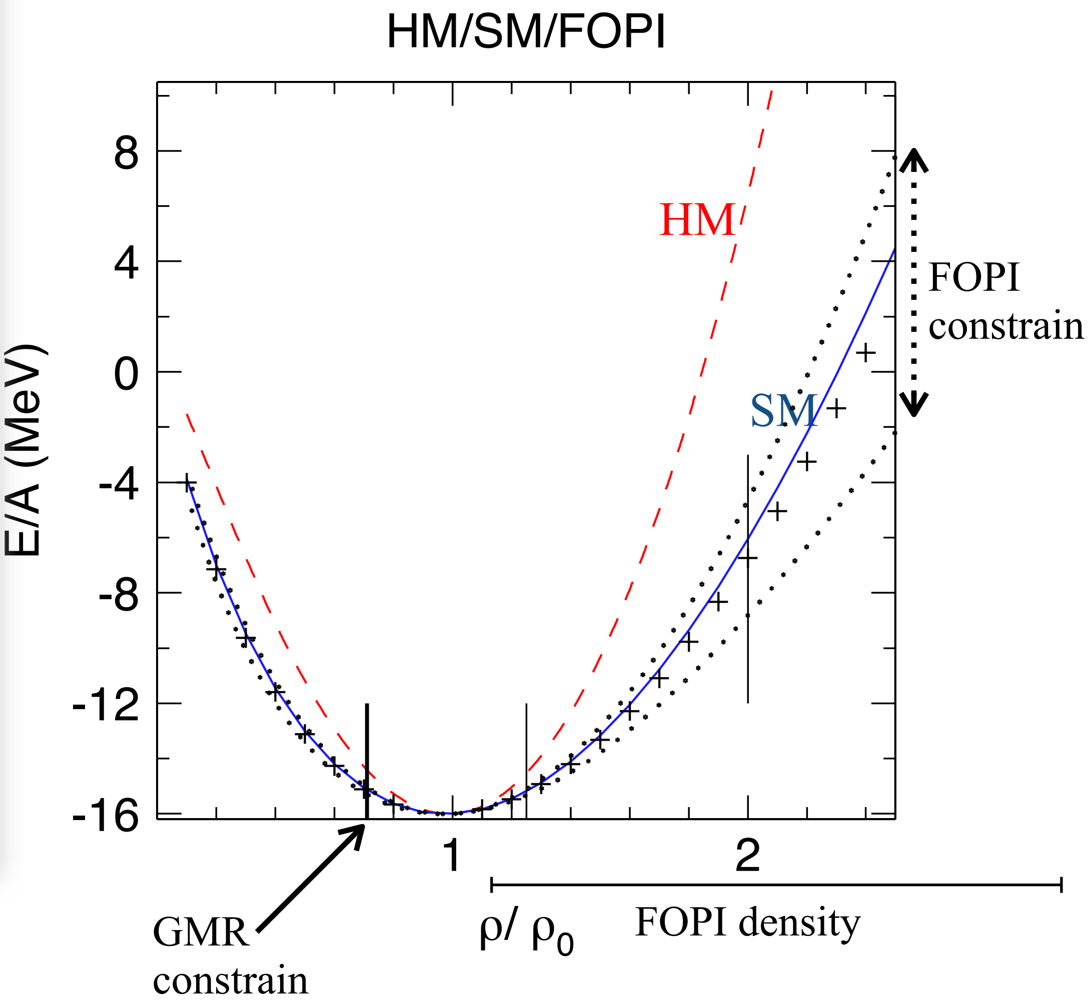
➜ $v_{2n}(E_{beam})$ varies by a factor ≈1.6, >> measured uncertainty (≈1.1)

➜ clearly favors a 'soft' EOS : K_0 = 190 +/- 30 MeV



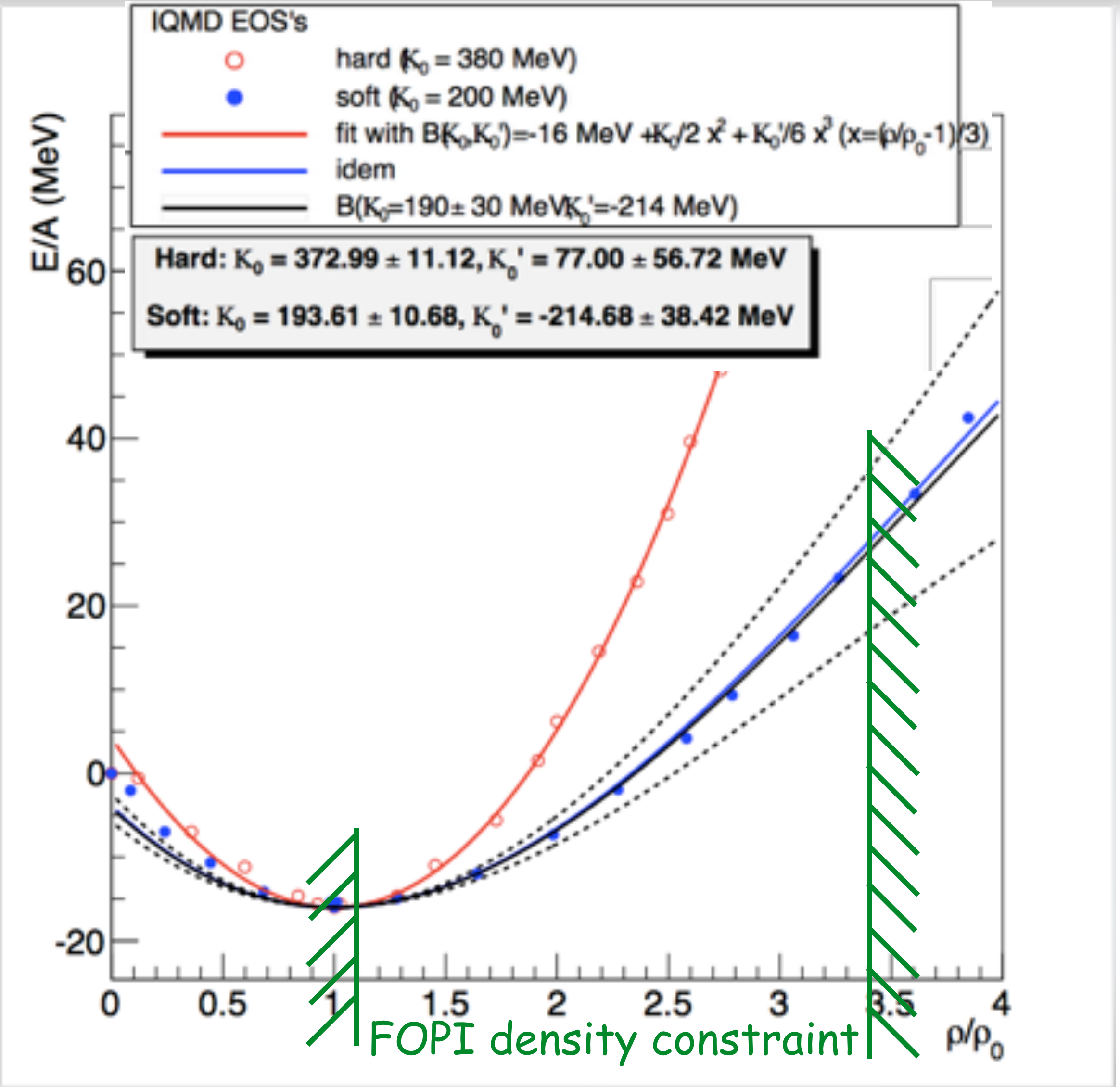
Analysis and results

- 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.



Analysis and results

NB: the qualified EOS has a non quadratic behavior : not only an incompressibility **$K_0 = 190 \pm 30$ MeV**, but a skewness **$K_0' = -214 \pm 38$ MeV**



Deducing the probed density

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=> at which time V_2 develops, and which conditions influence it the most.

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IQMD transport model[5,6] various phenomenological EOS's:

- 'stiff' = HM (+ momentum dependent), K_0 = 380 MeV
- 'soft' = SM (+ momentum dependent), K_0 = 200 MeV.

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

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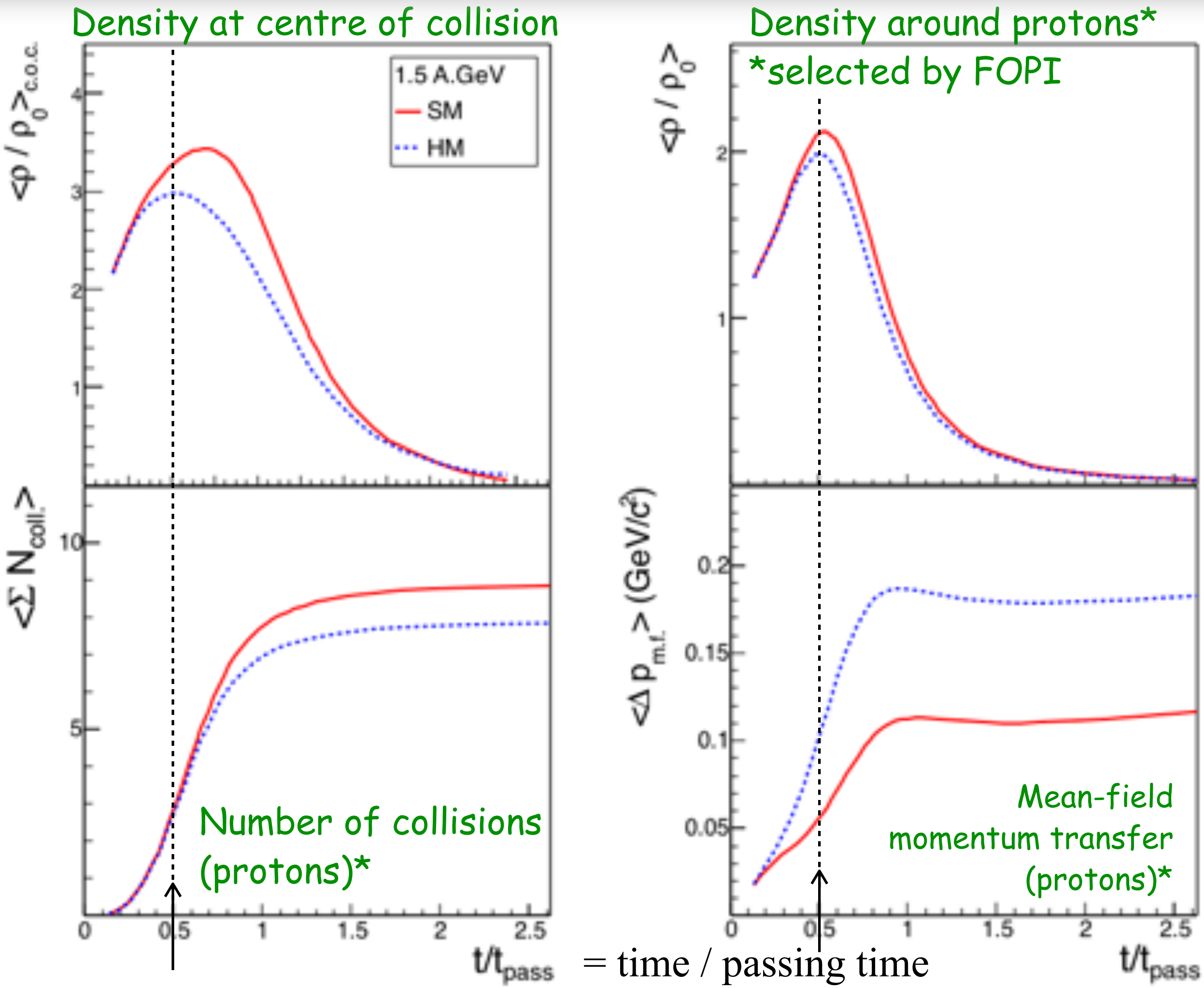
Density at centre of collision

Density around protons*

*selected by FOPI

Number of collisions (protons)*

Mean-field momentum transfer (protons)*

t/t_pass = time / passing time

full target-projectile overlap

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Tested: a high density cut-off in the EOS => no elliptic flow.

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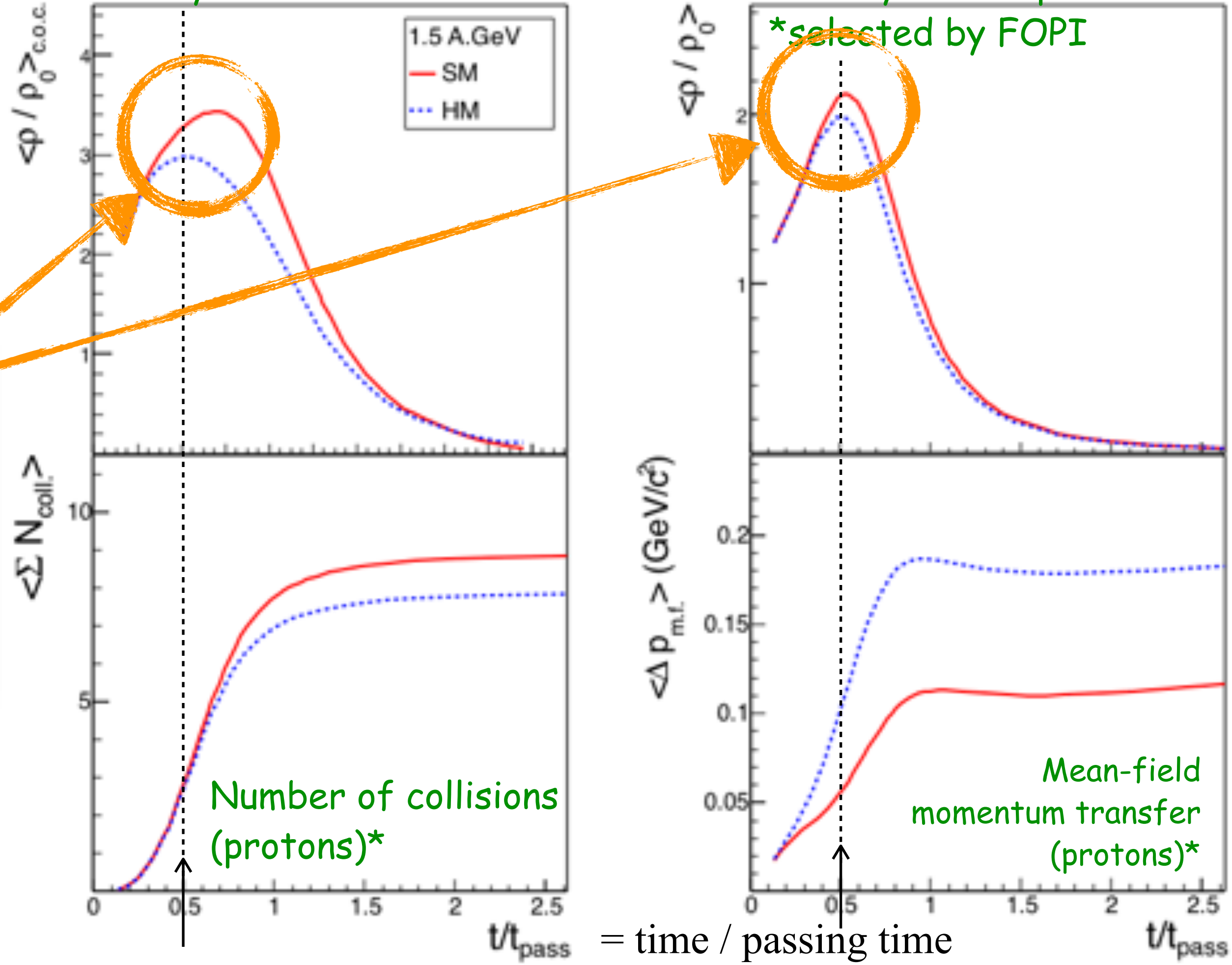

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The (flow) dynamics develops up to later times, hence lower densities.

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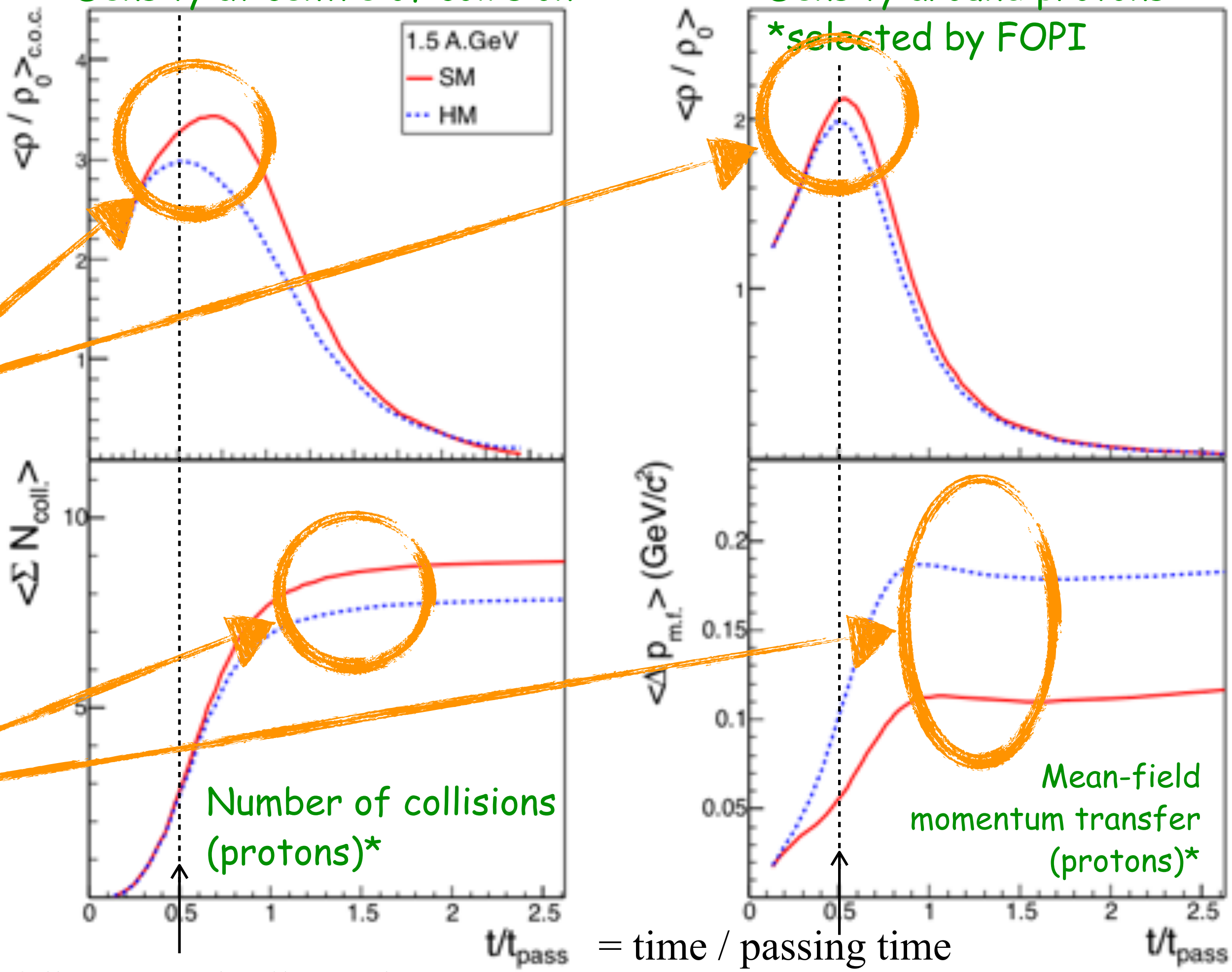

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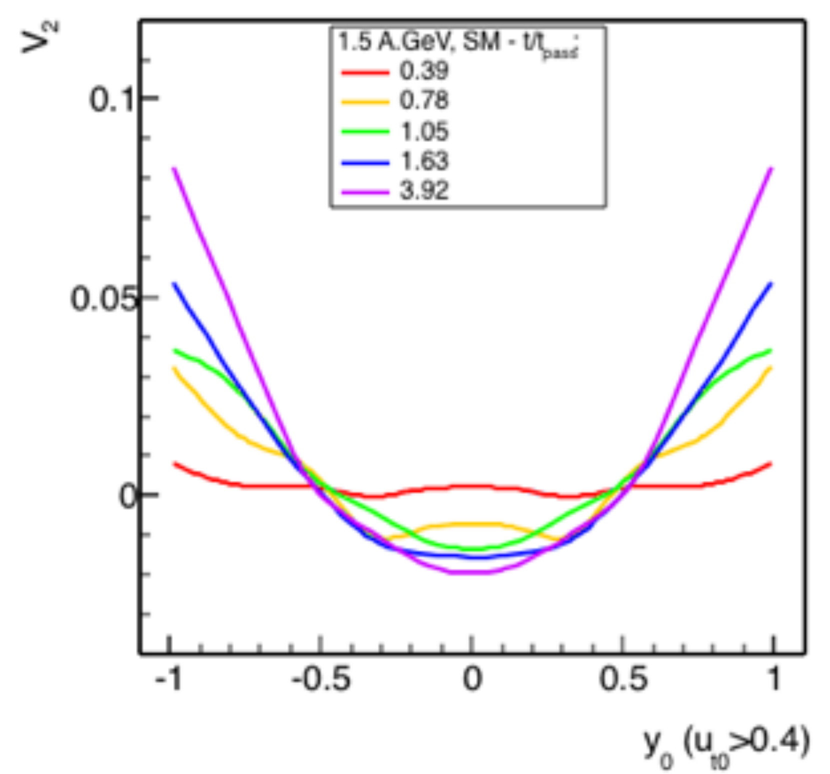
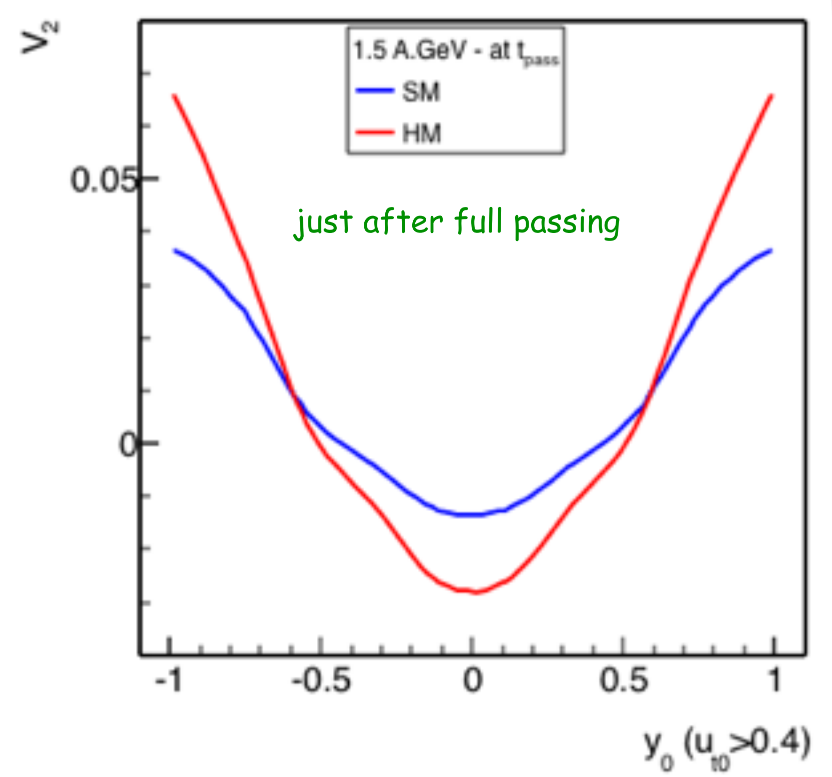
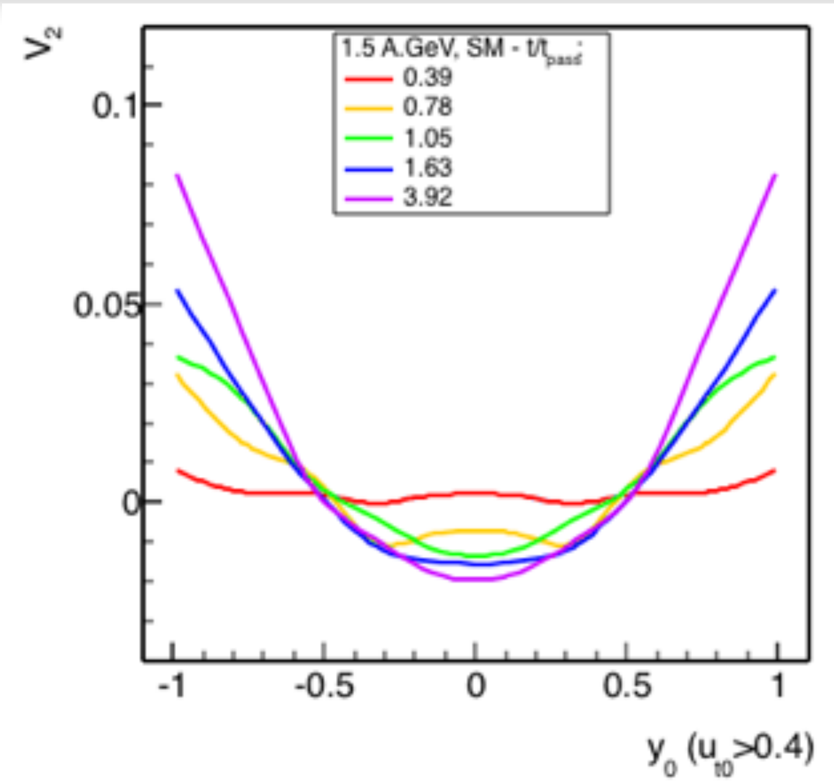
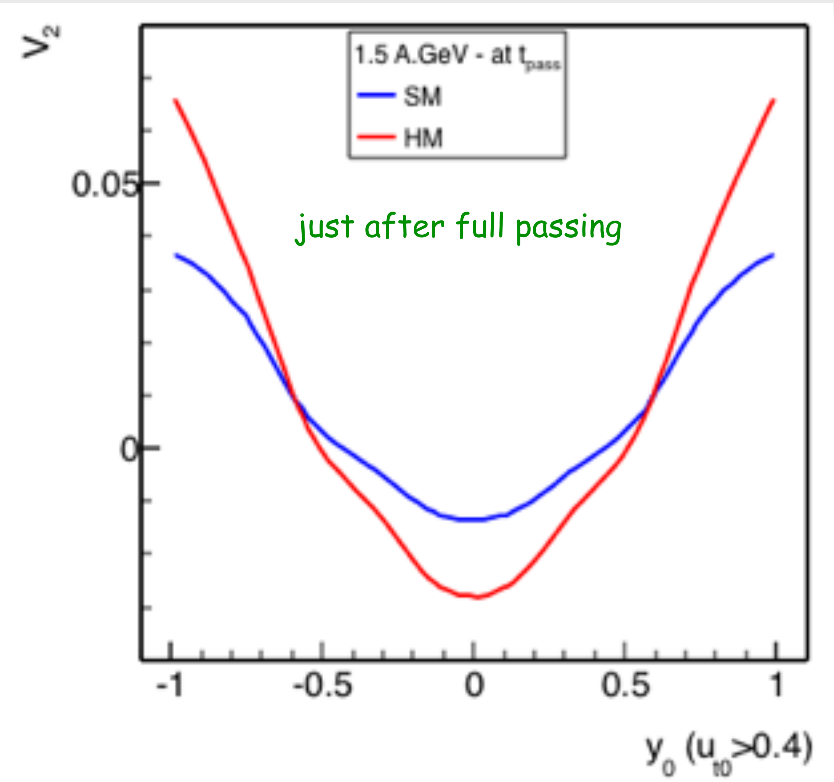




just after full passing

Simulations: the scenario





just after full passing

- The elliptic flow at mid-rapidity develops fast: already stabilised at the passing time.
- At t_{pass}, the elliptic flow, in its rapidity dependance, depends already strongly on the EOS.
- The elliptic flow around the spectators (|y0| close to 1) stabilises twice slower.

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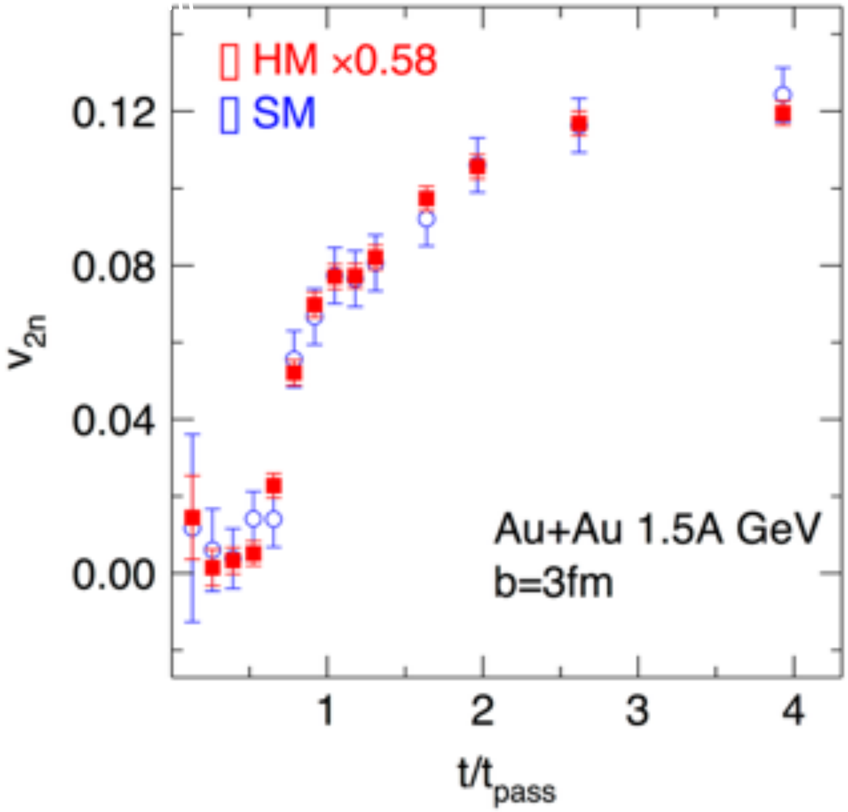

- The shape of its rapidity dependance shows a universality with the EOS's (through scaling).

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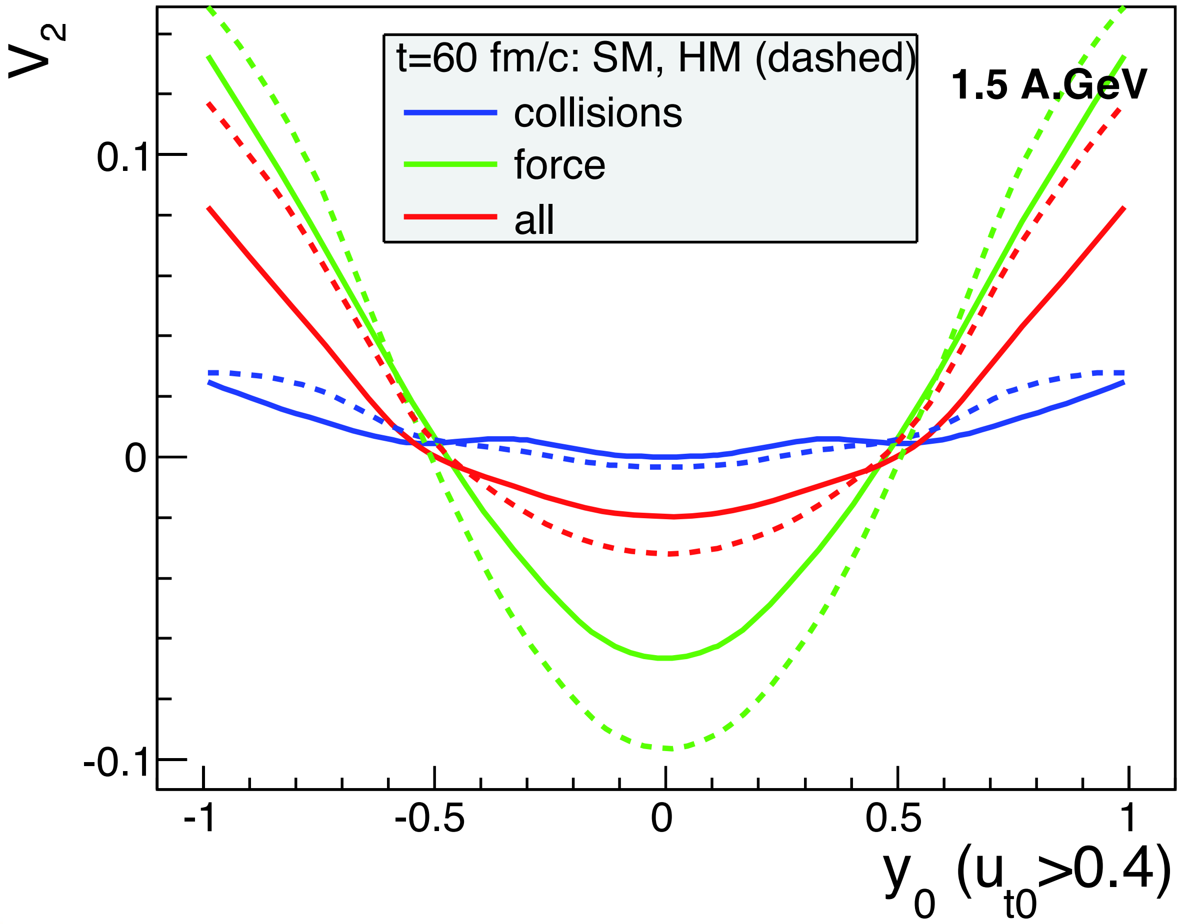
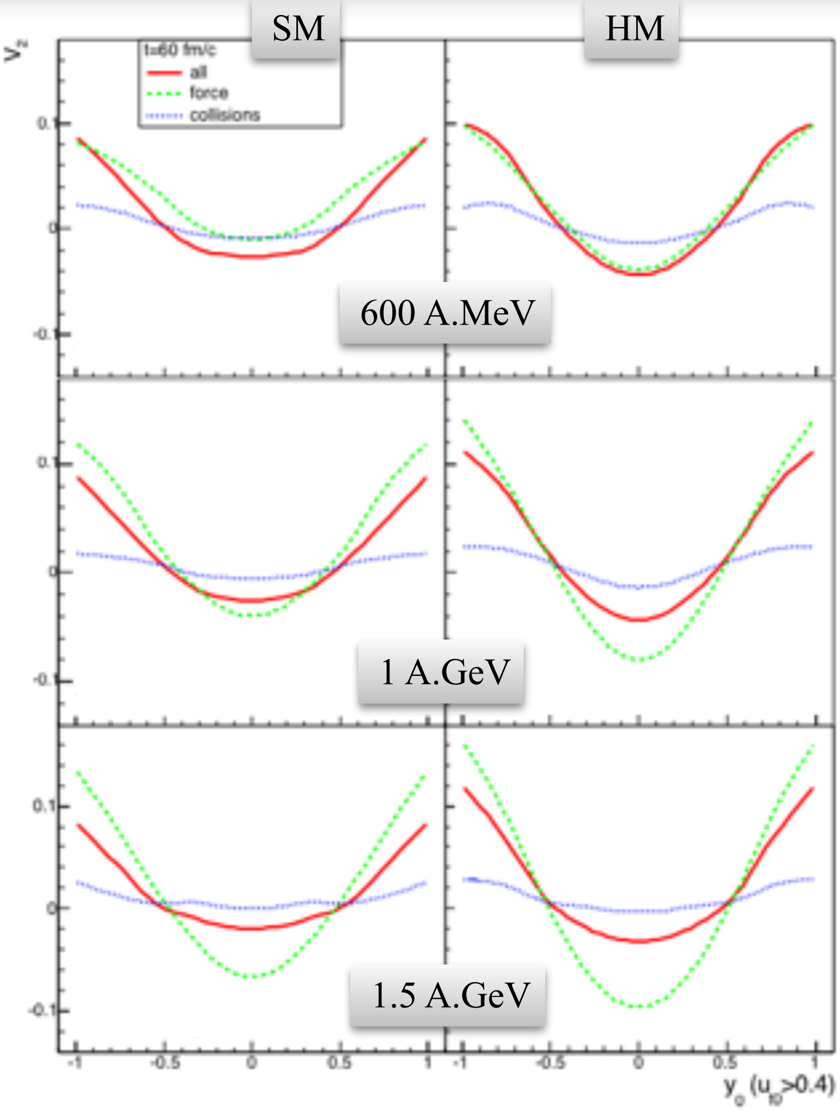


Simulations: the scenario

- The elliptic flow in strength and shape is mostly influenced by the force of the mean field (hence EOS).
- A 'mean' density characterising the development of the elliptic flow can be built from the mean value weighted by this force up to around the passing time.



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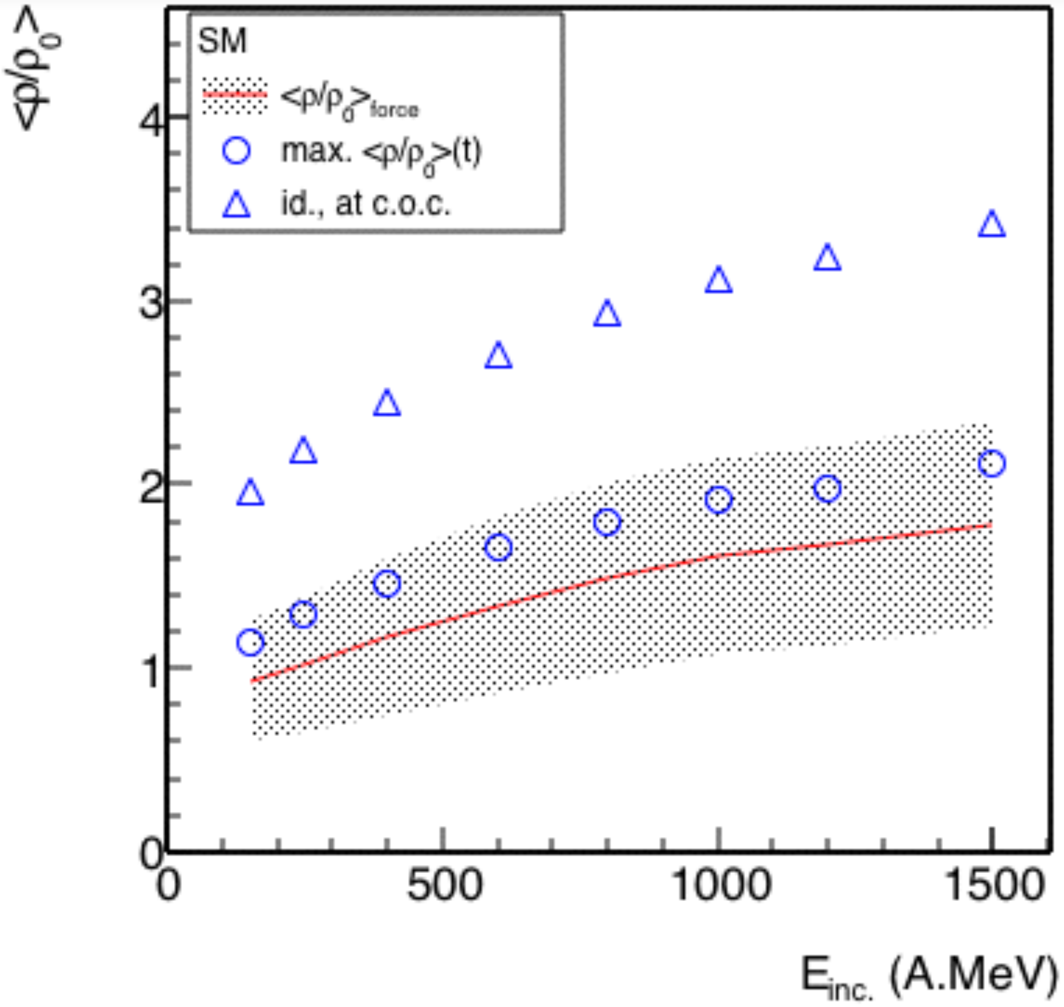

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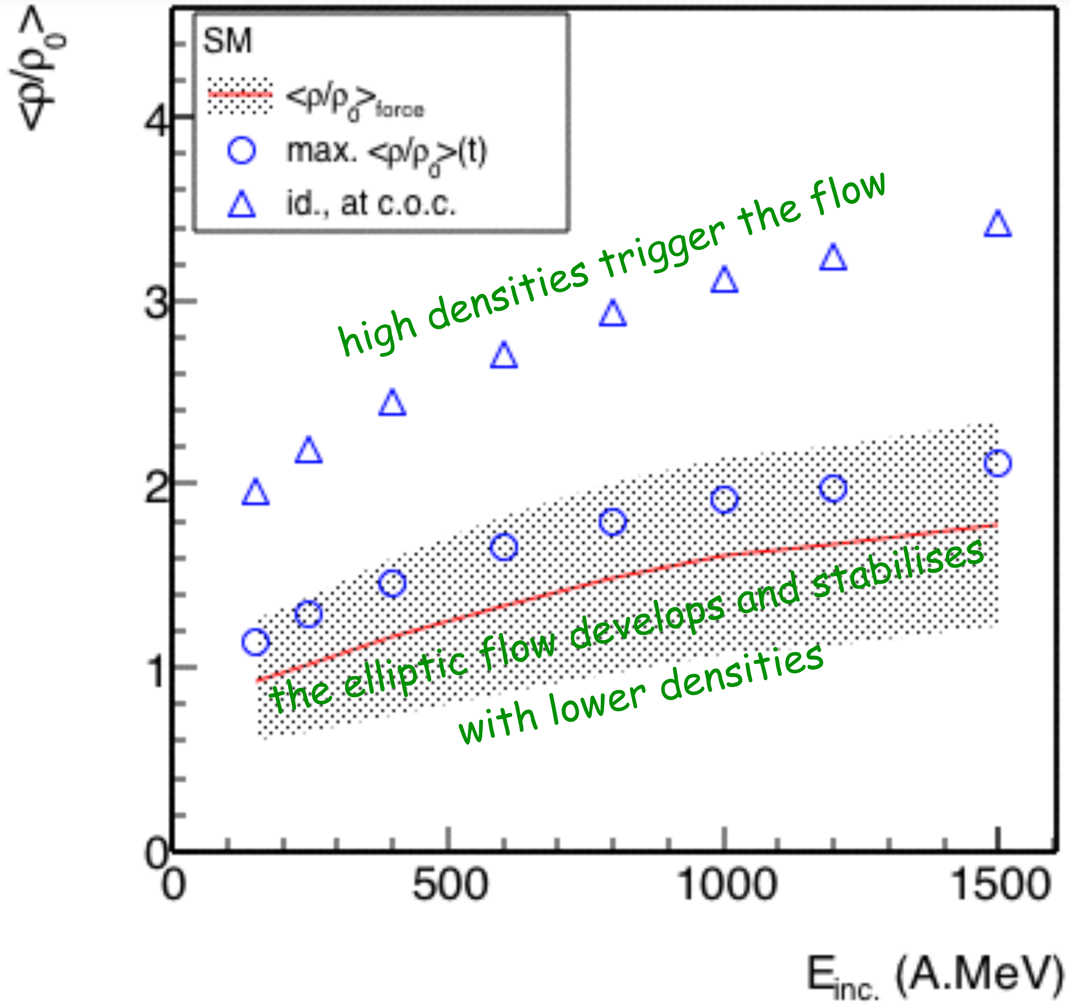

- In the QMD model, the EOS must be correct over a broad range of densities in order to predict the observed elliptic flow.
- The density range, relevant to the EOS evidenced by the FOPI Collaboration, spans in the range $\rho \simeq (1 - 3)\,\rho_0$.

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- Pion yields: differ only by about 10% between HM and SM options, imply high experimental accuracy and better transport model predictions (elementary pion cross sections not precisely known).

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Thank you for your attention!

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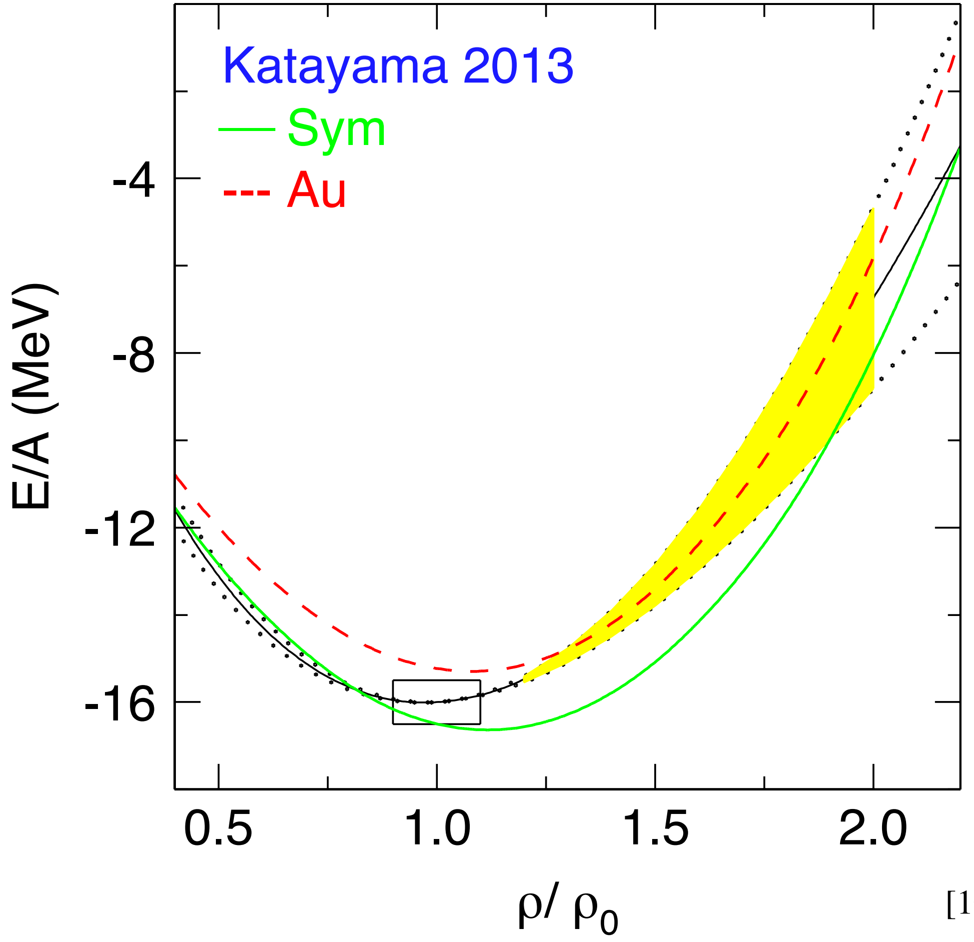
Comparison to microscopic calculations

(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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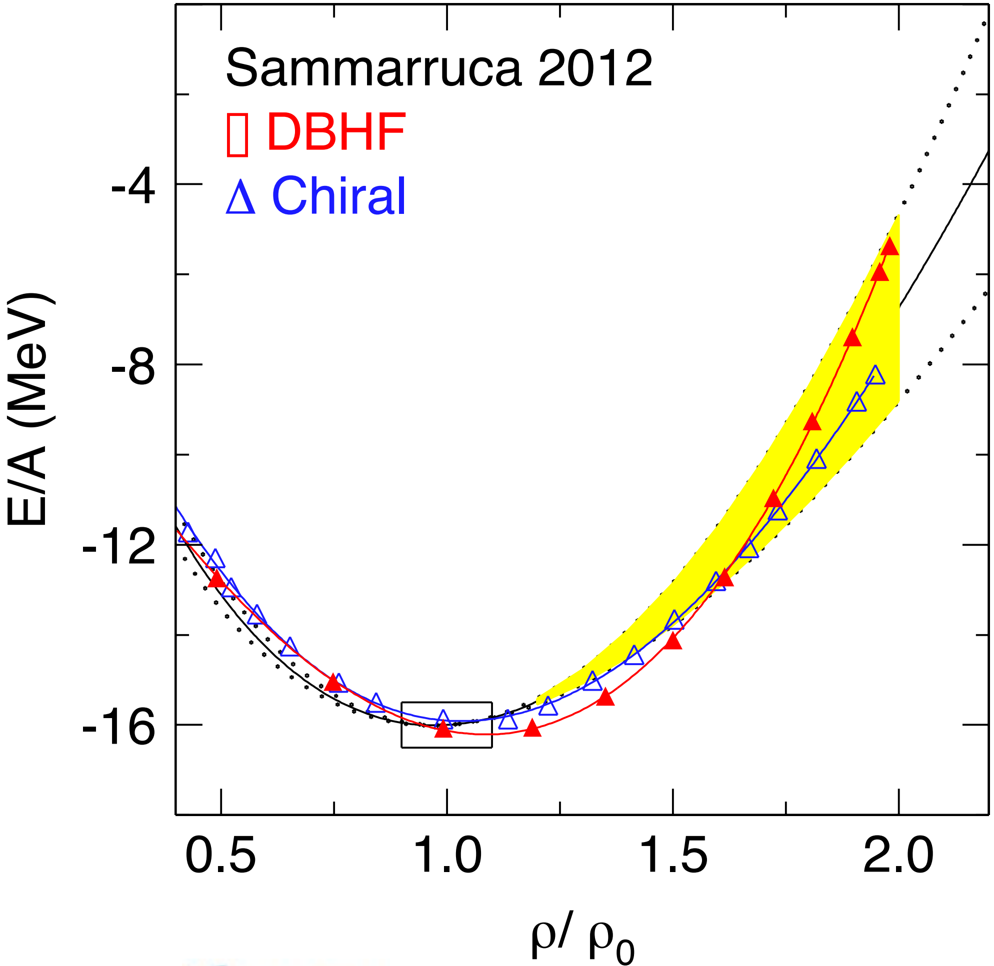

2 symmetric nuclear matter EOS's from [12]:

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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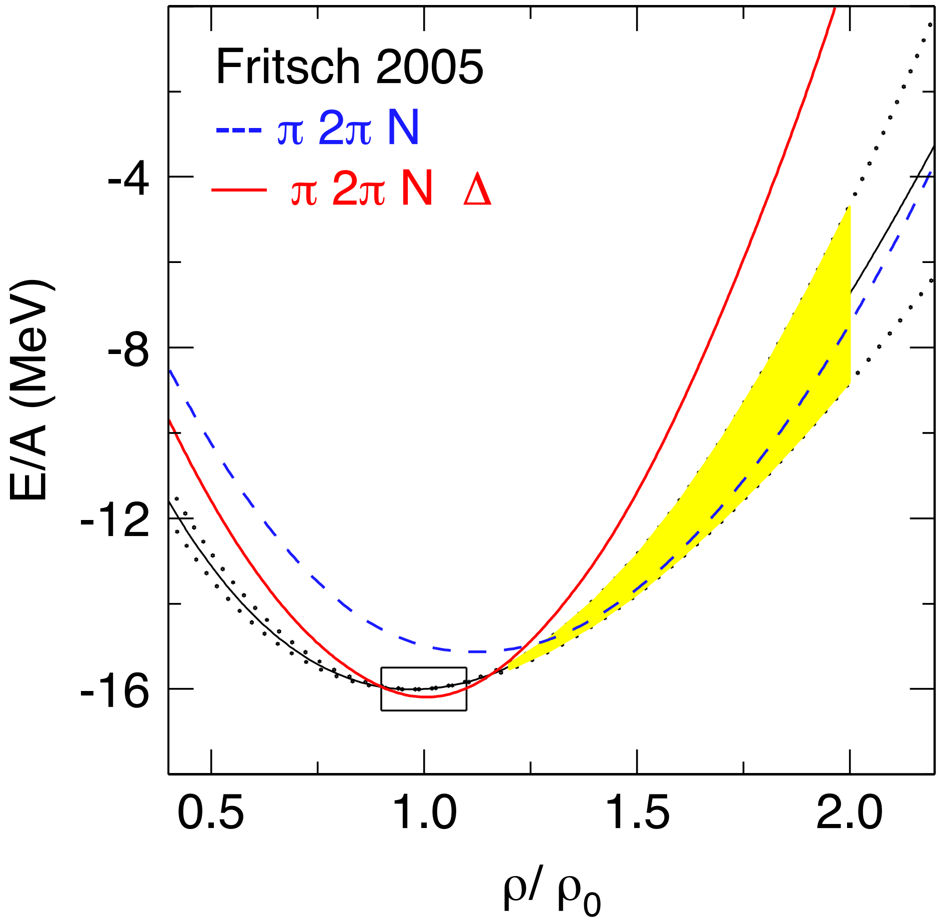

Using the chiral approach[13]: 2 rather different EOS's including or not virtual Δ excitations.

- » 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.