Constraining the Equation of State of Asymmetric Nuclear Matter with Collective Flow Measurements

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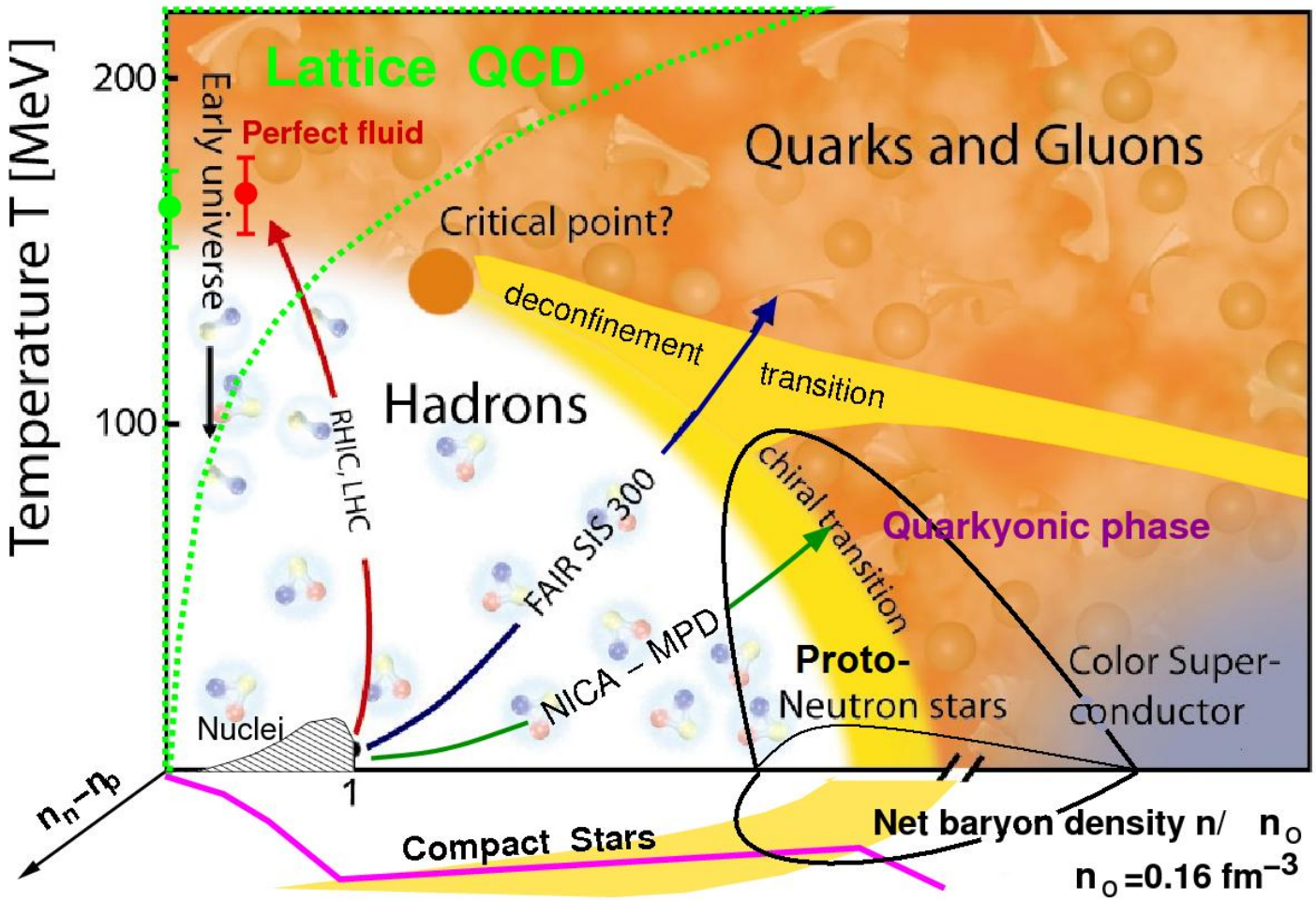
NuSYM11 Workshop,

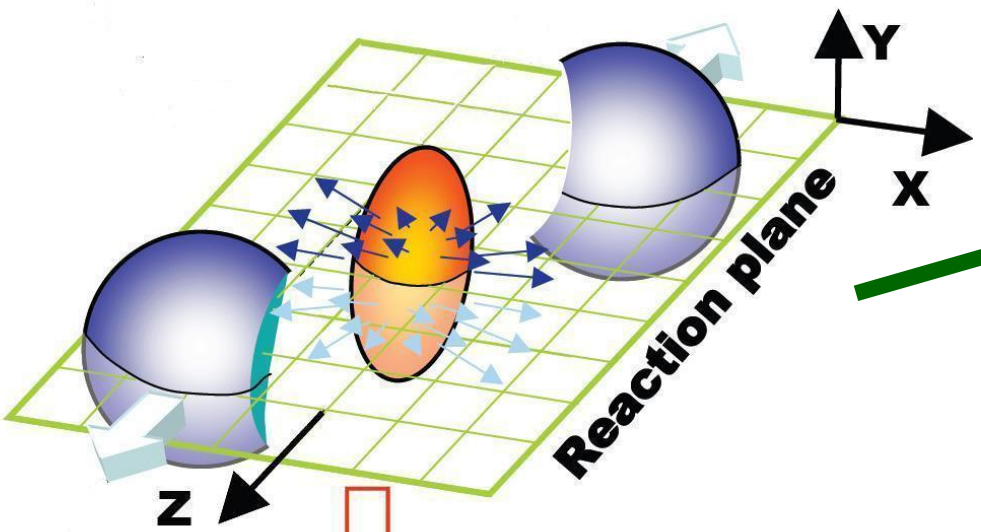
19-21 June 2011, Smith College

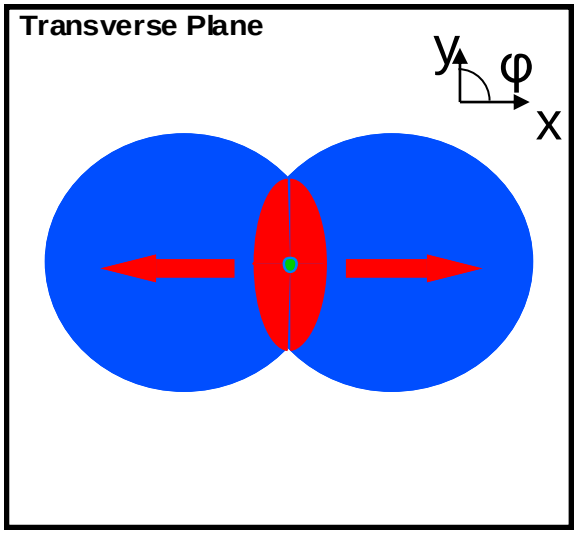
The Phase Diagram of Strongly Interacting Matter

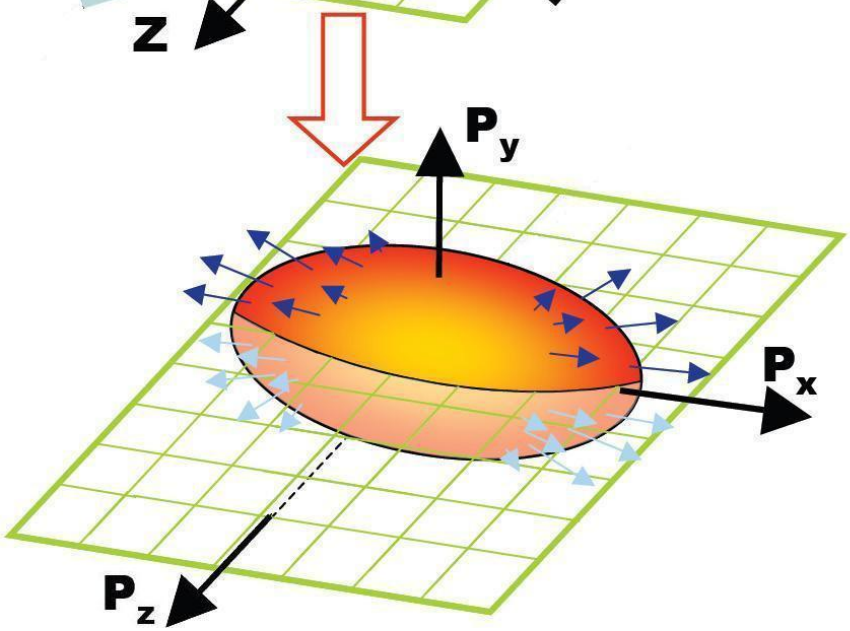


Equation of State (EOS): relationship between Energy, Pressure, Temperature, Density and Isospin Asymmetry of Nuclear Matter

Idealised Picture of Collective Flow







- The dense nuclear overlap is ellipsoidal at the beginning of heavy ion collisions

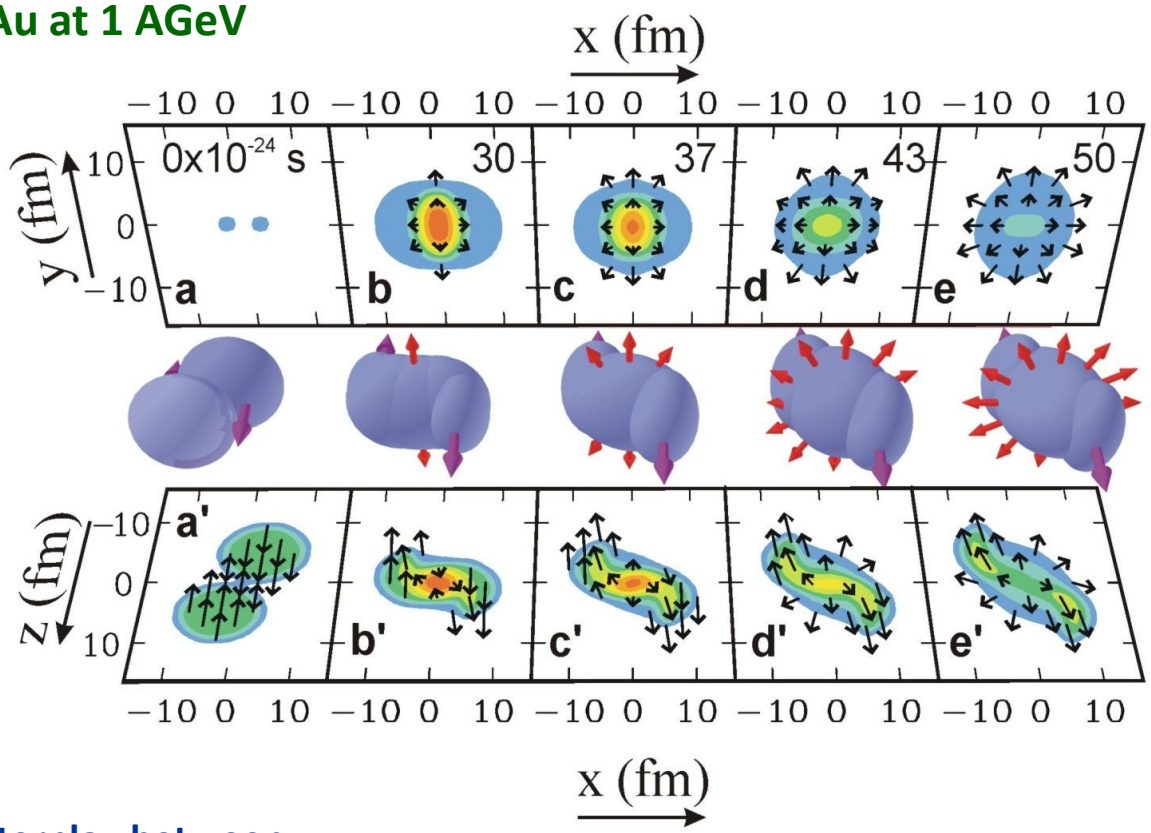
- Pressure gradient is largest in the shortest direction of the ellipsoid

- The initial spatial anisotropy evolves via interactions and density gradients to momentum-space anisotropy

- $\Rightarrow$ **Collective Flow**

Collective Flow in the "Real" World !

Au+Au at 1 AGeV



pressure contours

density contours

P. Danielewicz at el., Science

Interplay between

a) **The collision geometry**
b) **The relative magnitude of the time for development of the transverse expansion**
c) **the passage time for removal of the shadowing of participant hadrons by the projectile and target spectators**

Gives rise to dependence on E, b, pt, y ...

Characterising Collective Flow: Event Plane Method

Fourier expansion of particle azimuthal distribution relative to reaction plane

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left(1+\sum_{n=1} 2v_n \cos(n[\varphi-\Psi_R])\right)$$

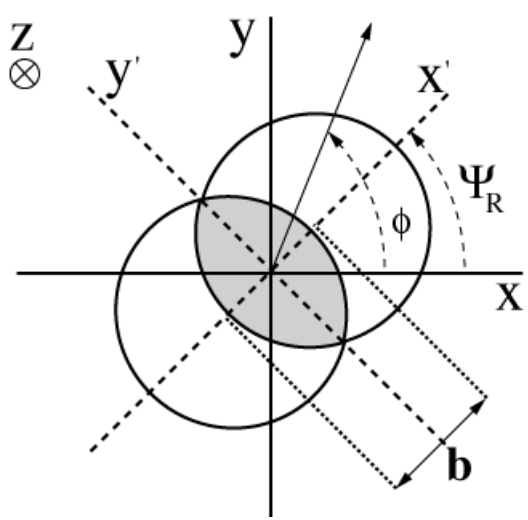
$v_1 = \langle\cos(\phi-\phi_R)\rangle$ **directed flow**

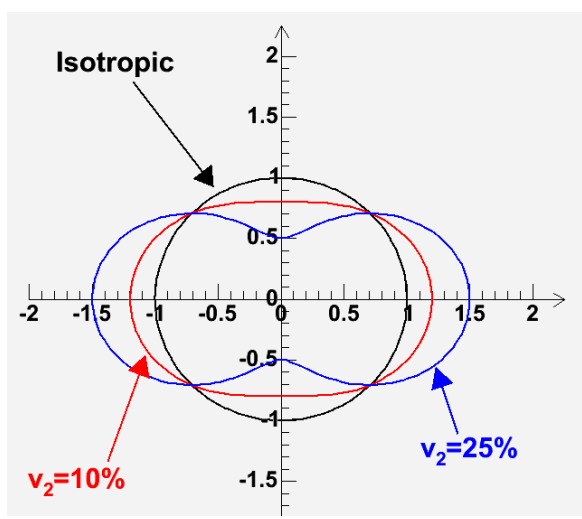
$v_2 = \langle\cos2(\phi-\phi_R)\rangle$ **elliptic flow ($v_2 > 0$ in-plane, $v_2 < 0$ out-of-plane)**

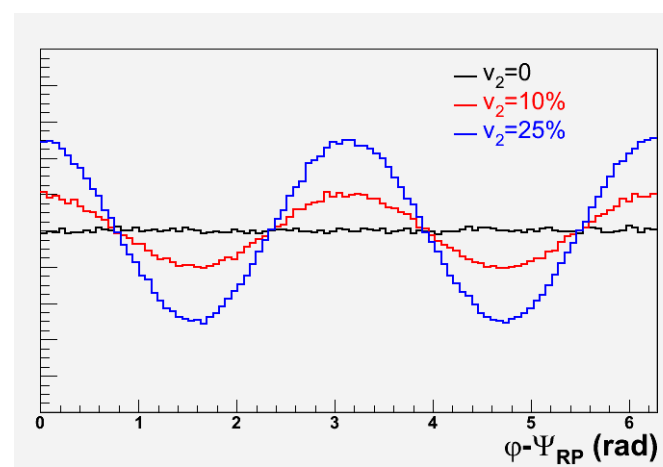
Reaction plane (ϕ_R) unknown. Measure ϕ_E in experiment via Q-vector method.

Can calculate systematically the correction for reaction plane dispersion (fluctuations):

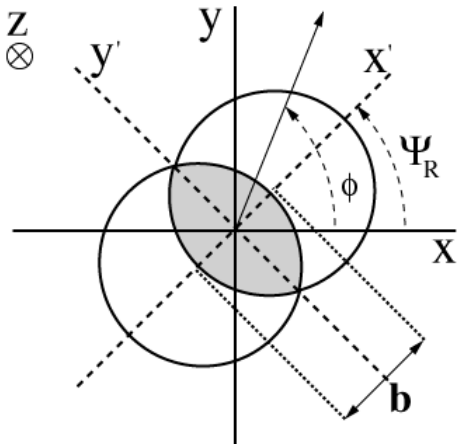
$V_n^{exp} = \langle\cos n(\phi-\phi_E)\rangle = v_n^{corr}\langle\cos n\Delta\phi\rangle$ where $\langle\cos n\Delta\phi\rangle = \langle\cos n(\phi_R-\phi_E)\rangle$





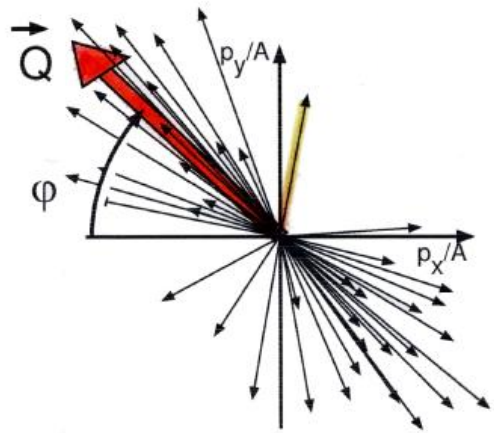


Determination of Reaction Plane and Correction for Dispersion



A. Andronic et al., Nucl. Phys. A 679, 765 (2001).

Experimental Q-vector defines reaction plane ϕ_E event-by-event

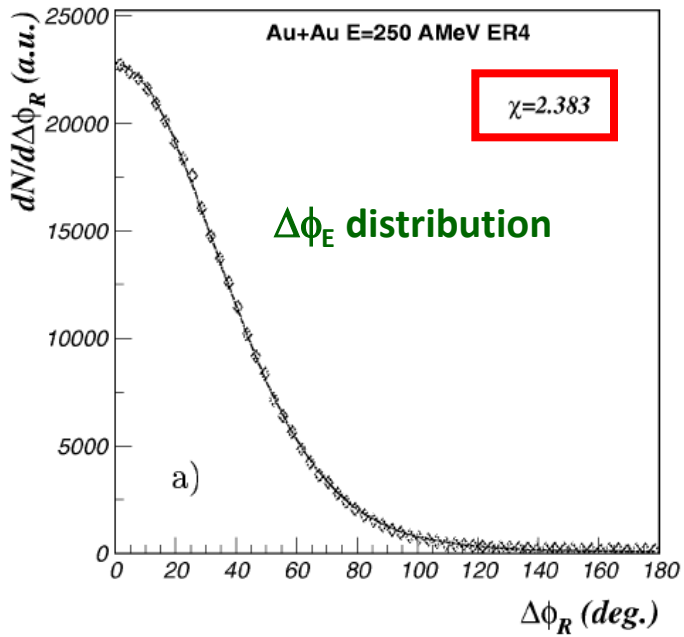


$$\vec{Q} = \sum_{\nu}^{M} p_{\perp}(\vec{\nu})\,\omega(\nu)$$

$$\omega(\nu) = 1 \qquad Y_\nu > Y_{cm}$$

$$\omega(\nu) = -1 \qquad Y_\nu < Y_{cm}$$

P. Danielewicz et al., Phys. Lett. B 157, 146 (1995).



Construct Q for two random sub-events: $\Delta\phi_E = \phi_1 - \phi_2$

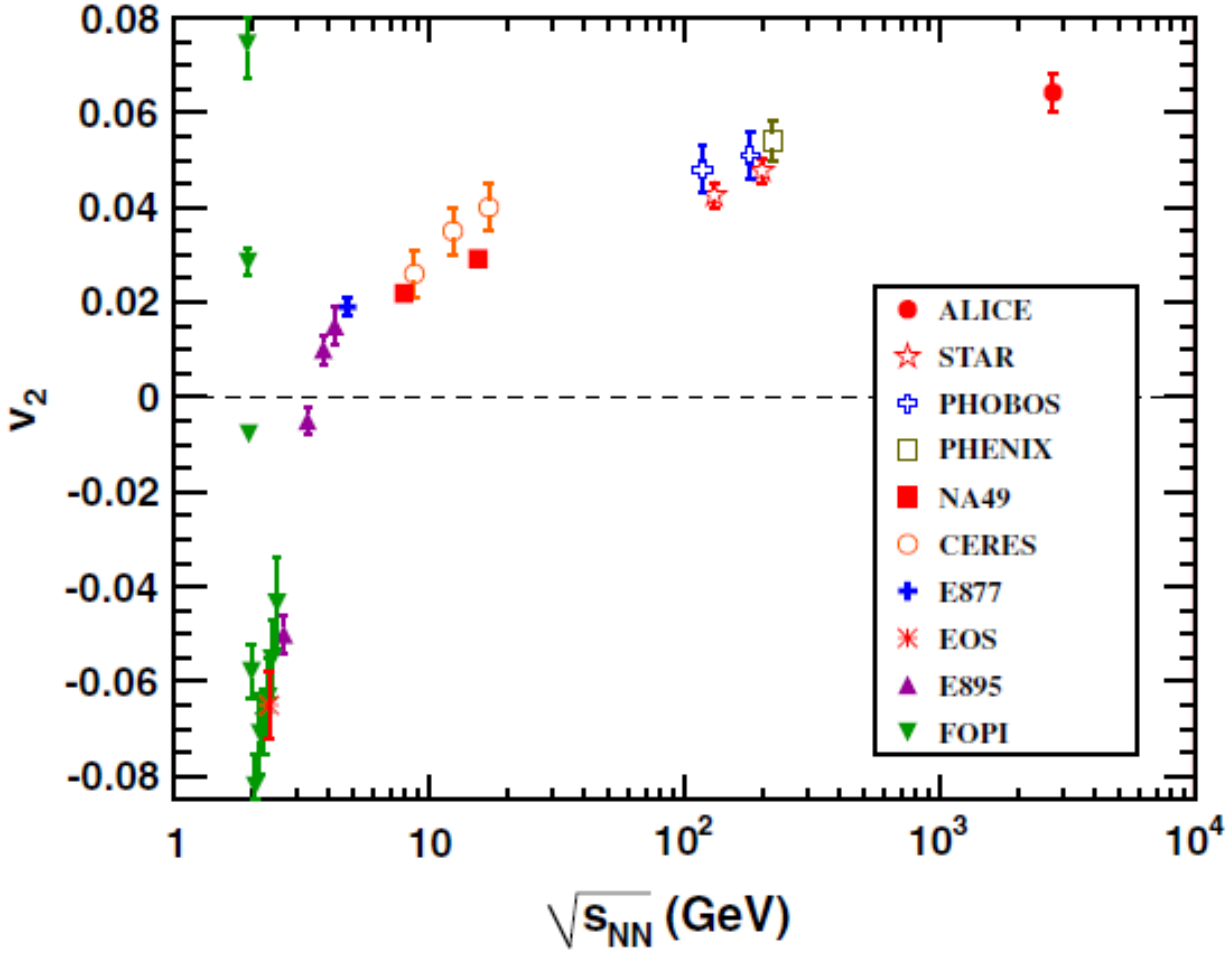
Gaussian model, J.Y. Ollitrault, nucl-ex/9711003

Assumes sub-events are independent, isotropic, equivalent and normally distributed.

$$\frac{dN}{d\Delta\phi_R} = \frac{e^{-\chi^2/2}}{2}\left\{\frac{2}{\pi}(1+\chi^2/2) + z\left[I_0(z) + \mathbf{L}_0(z)\right] + \chi^2/2\left[I_1(z) + \mathbf{L}_1(z)\right]\right\},$$

$$\langle \cos n\Delta\phi \rangle = \frac{\sqrt{\pi}}{2}\chi e^{-\chi^2/2}\left[I_{\frac{n-1}{2}}\left(\frac{\chi^2}{2}\right) + I_{\frac{n+1}{2}}\left(\frac{\chi^2}{2}\right)\right],$$

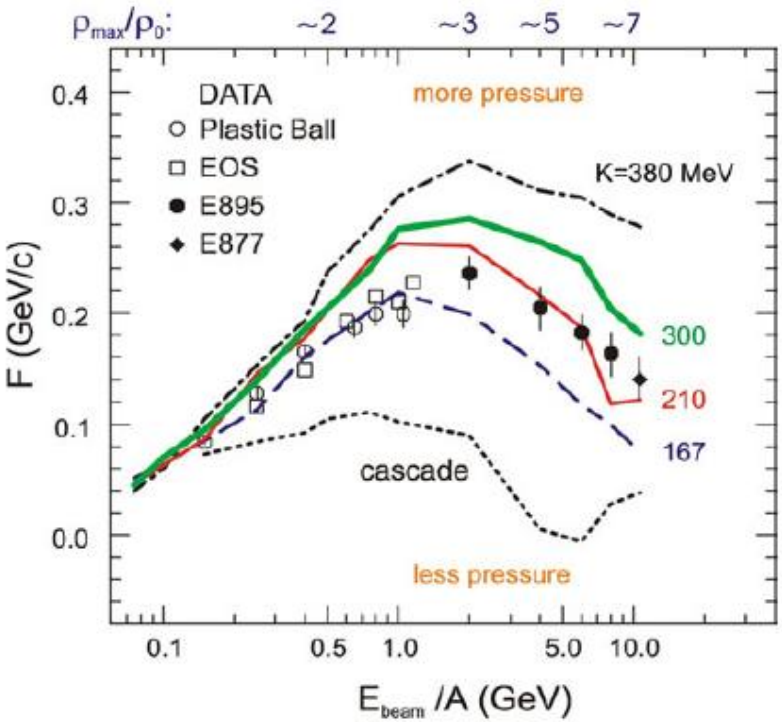
Excitation Function of Integrated Elliptic Flow (v_2)



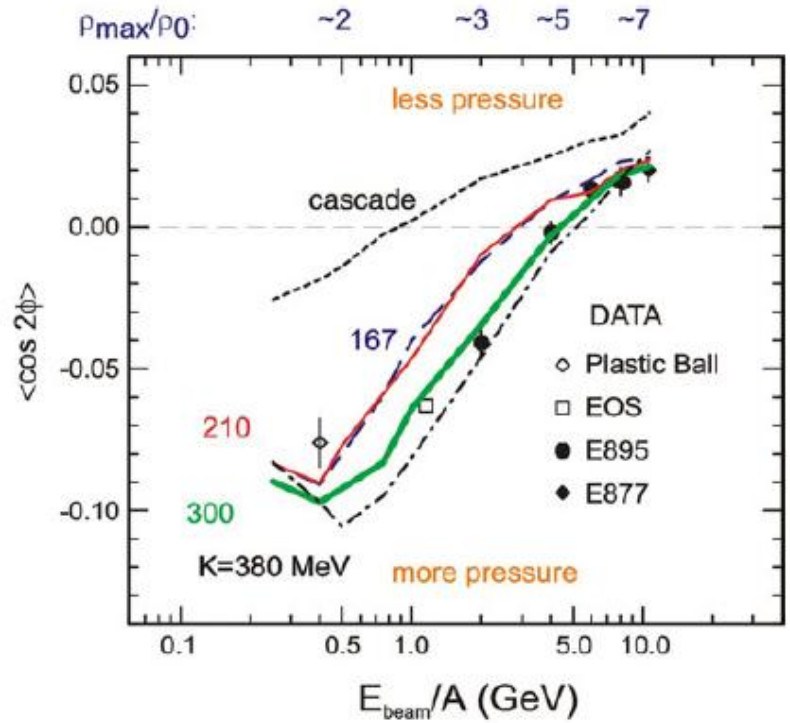
K. Aamodt et al. (ALICE Collaboration), Phys. Rev. Lett. 105 (2010) 252302.

Comparison of Collective Flow to Transport Model Calculations

Directed Flow (v_1)

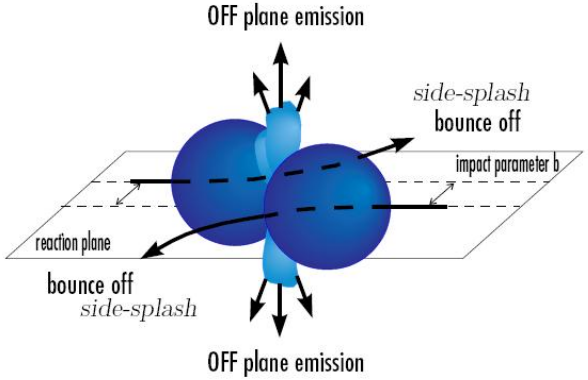


Elliptic Flow (v_2)



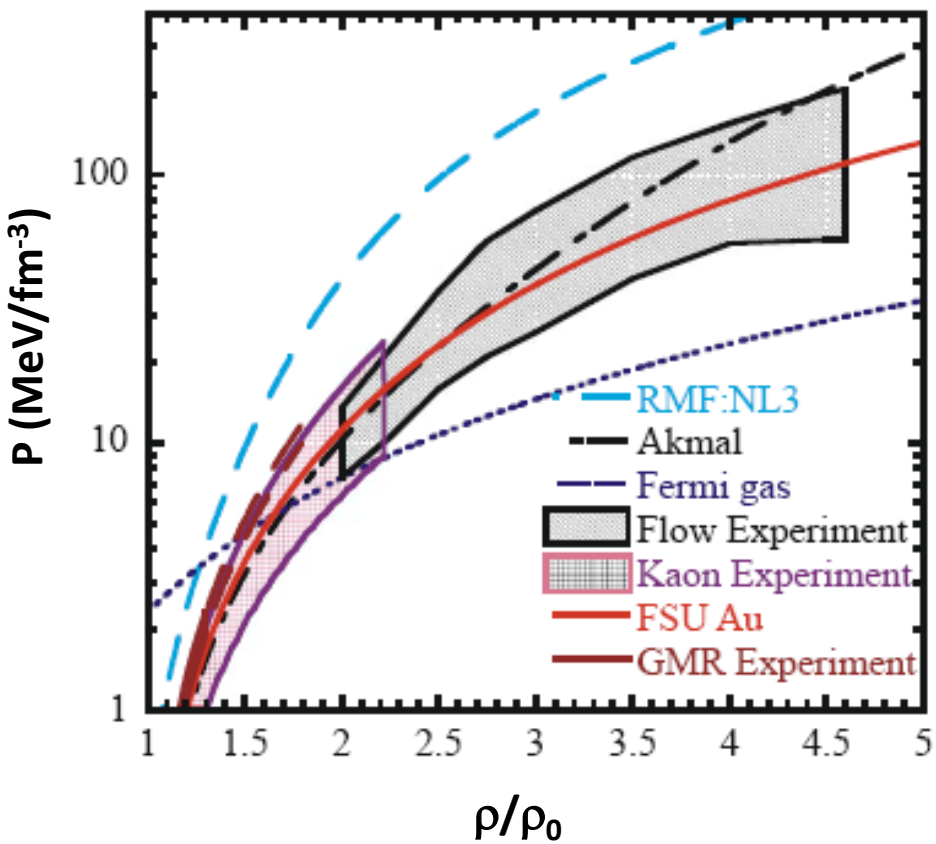
P. Danielewicz et al., Science 298, 1592 (2002).

- BEVALAC and AGS data
  - Comparison to BUU transport model calculations
  - Additional constraints on m* and σ_{nn}



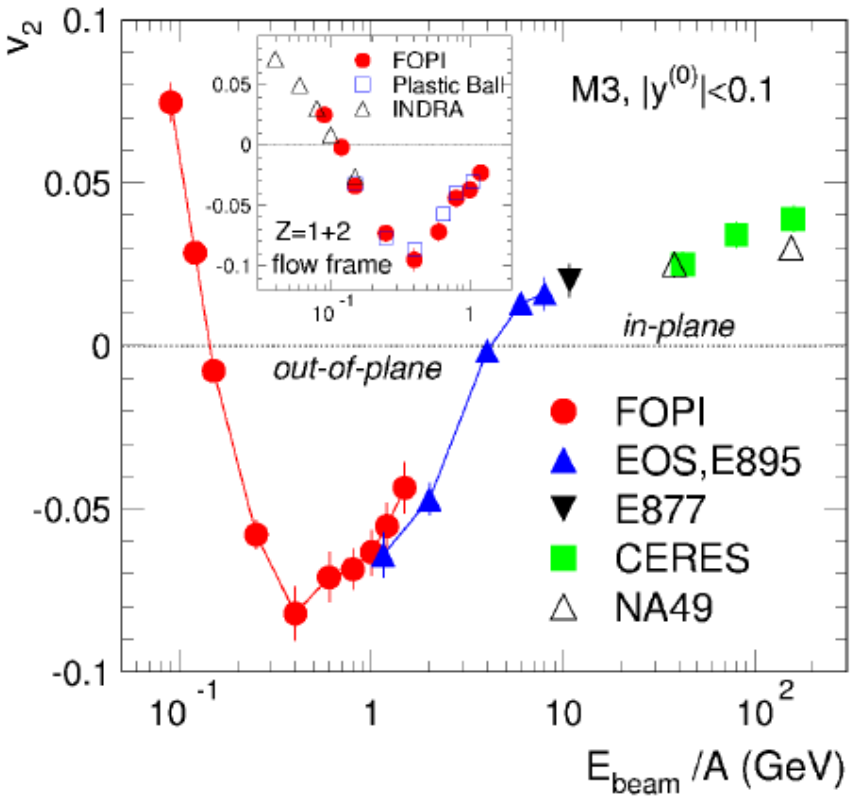
Experimental Constraints on EOS for Nuclear Matter

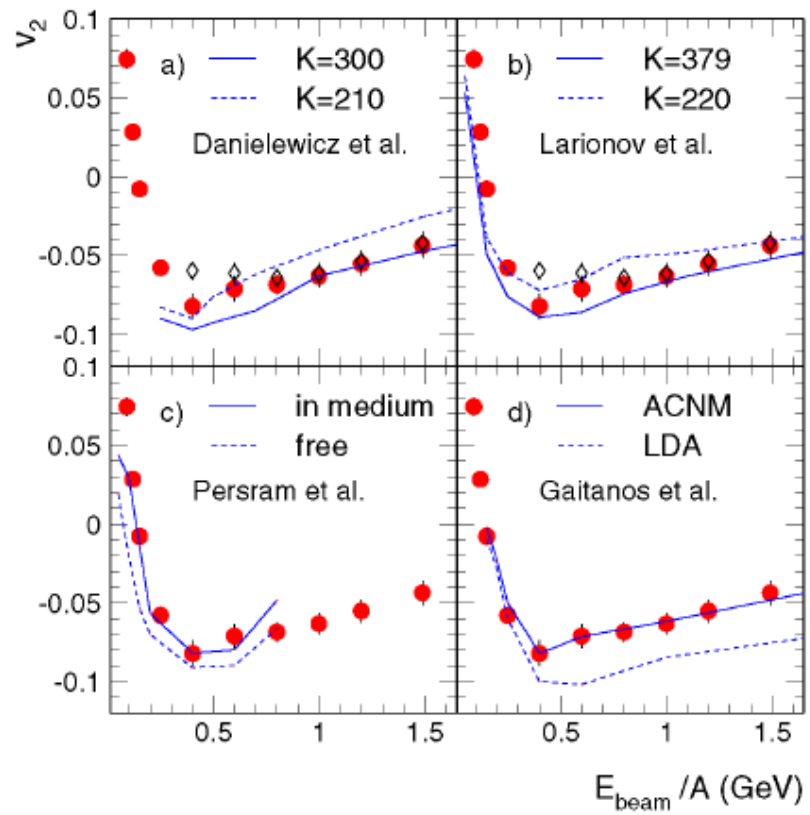
Symmetric



Ch. Hartnack et al., Phys. Rev. Lett. 96 (2006) 012302. P. Danielewicz et al., Science 298 (2002) 1592.

Model Dependence of Elliptic Flow



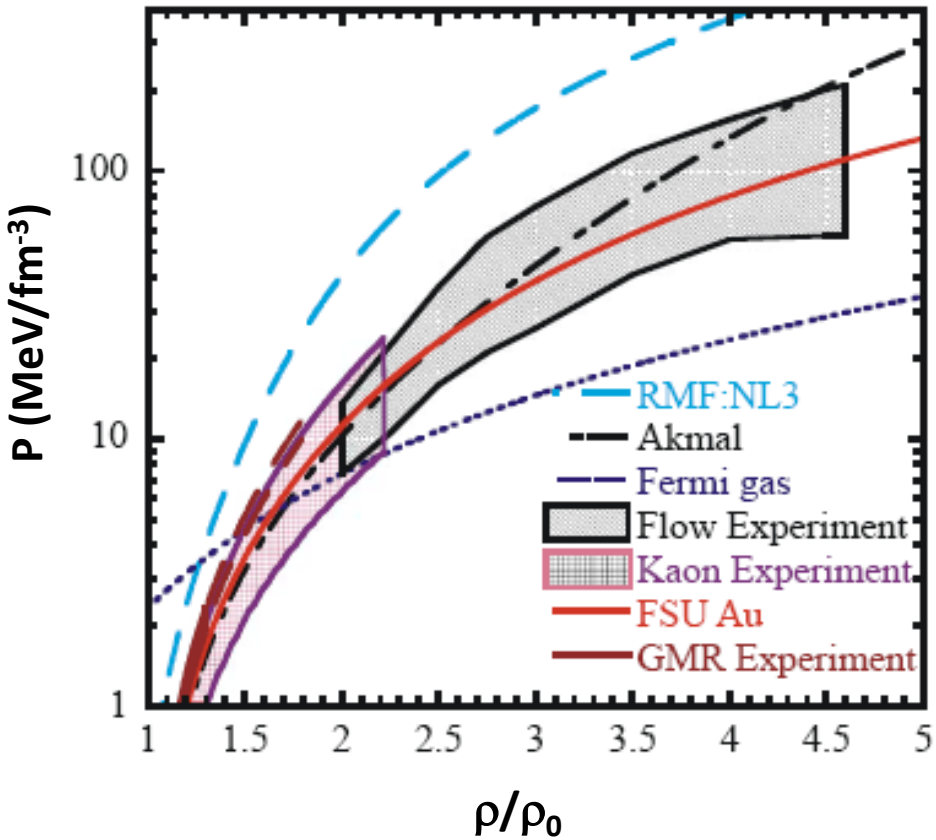


A. Andronic et al, Phys. Lett. B 612, 173 (2005).

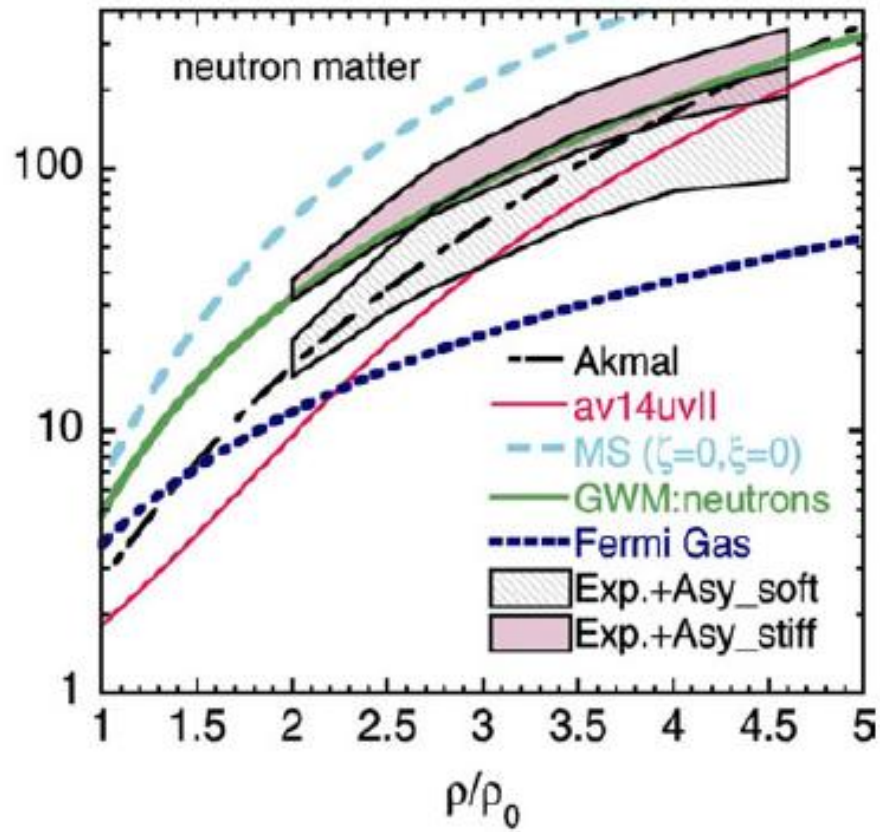
- **Model dependence in determination of equation of state from flow observables**
- **More stringent constraints on the EOS of symmetric nuclear matter should be pursued**

Experimental Constraints on EOS for Nuclear Matter

Symmetric



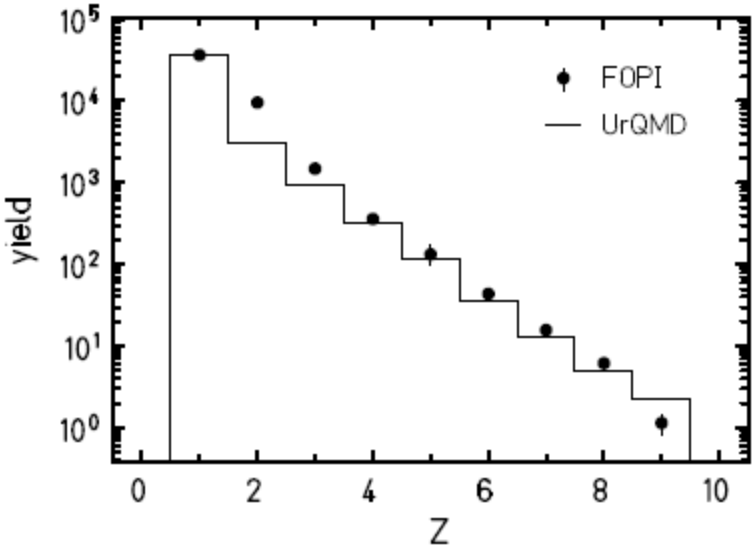
Asymmetric



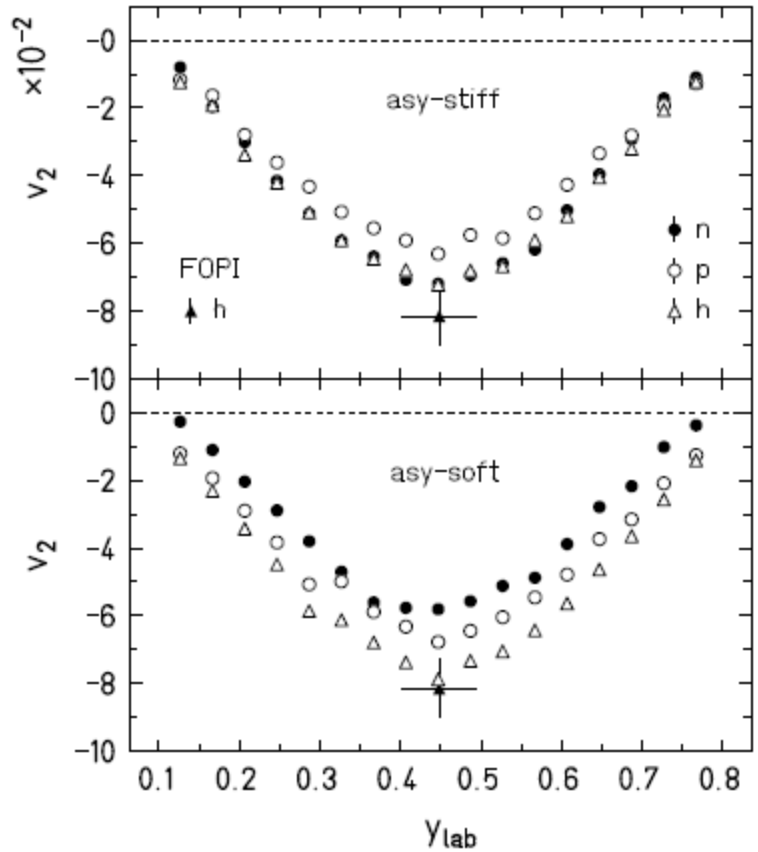
Ch. Hartnack et al., Phys. Rev. Lett. 96 (2006) 012302. P. Danielewicz et al., Science 298 (2002) 1592.

Sensitivity of Elliptic Flow to Symmetry Energy at High Densities

Comparison to FOPI fragment yield data



Sensitivity of v_2 to symmetry energy parametrisation



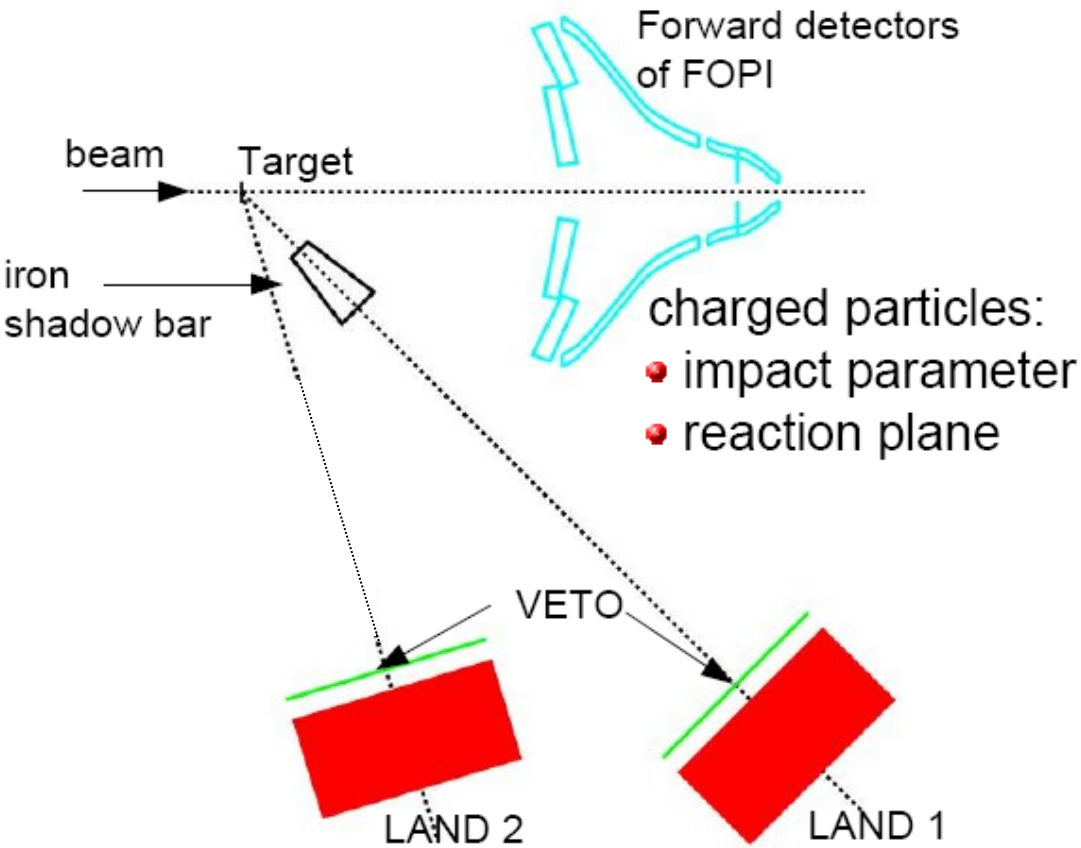
- UrQMD transport model adapted to intermediate energies (Q. Li et al.)
- clustering algorithm (Δr = 3.0 fm; Δp = 275 MeV/c

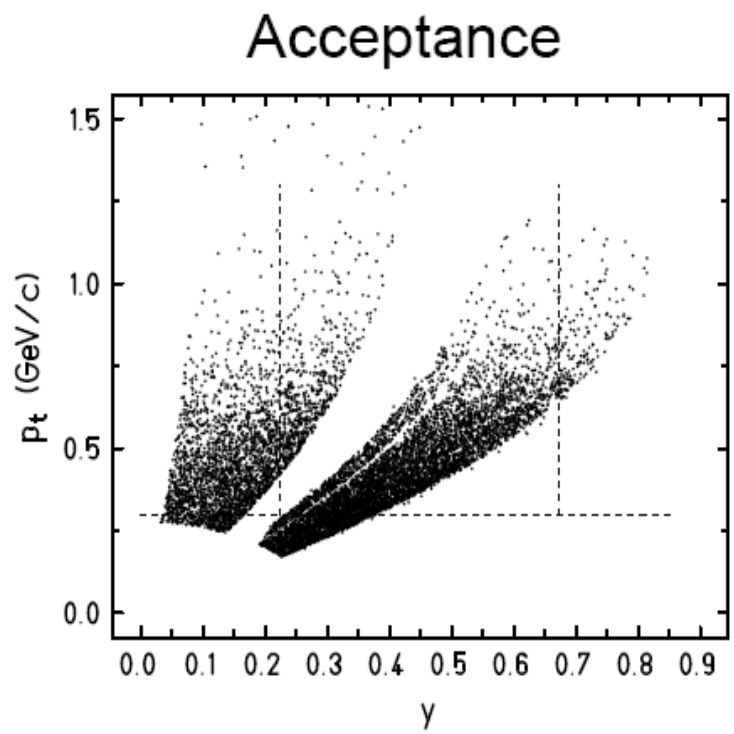
$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
$$= 22MeV.(\rho/\rho_0)^{\gamma} + 12MeV.(\rho/\rho_0)^{2/3}$$

- asy-stiff: γ = 1.5
- asy-soft: γ = 0.5

Measurements of Neutron and Proton Elliptic Flow

- SIS@GSI
- LAND + FOPI forward wall
- Au+Au at 400, 600, 800 AMeV
- Re-analysis of data sets and comparison to UrQMD transport models

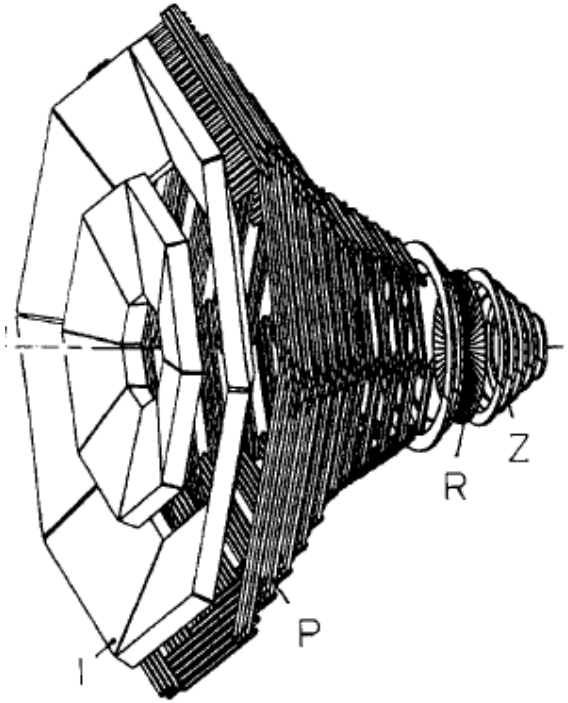




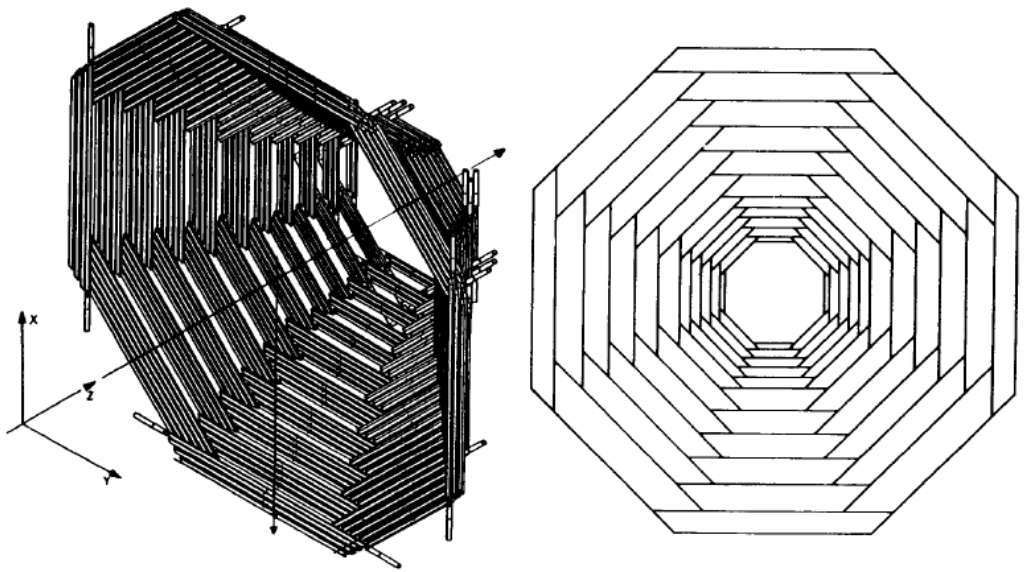
Y. Leifels et al., Phys. Rev. Lett 71, 963 (1993).
D. Lambrecht et al., Z. Phys. A 350, 115 (1994).

FOPI Forward Wall

Forward Wall



Outer Plastic Wall

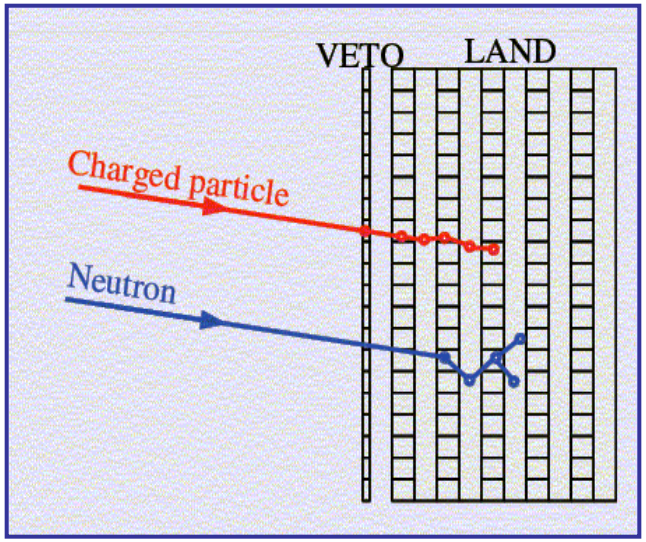


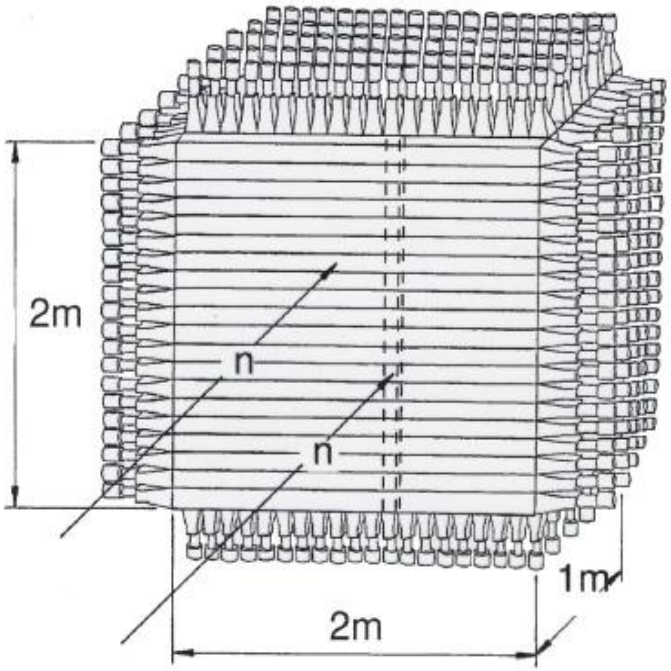
- Highly segmented ΔE-time-of-flight wall
- Full azimuthal angle coverage at polar angles from 1° to 30°
- 764 scintillators, 188 thin ΔE detectors (gas and thin scintillator) in front
- Velocity and Z of fragments determined by ΔE and TOF

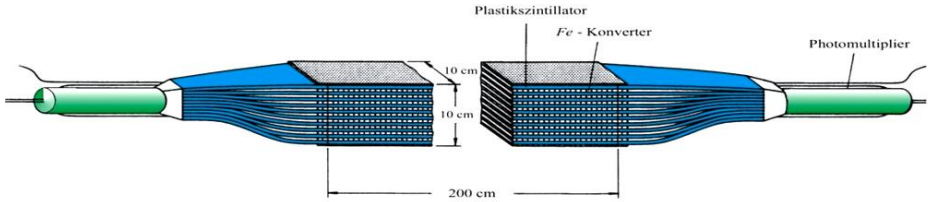
A.Gobbi et al., Nucl. Inst. Meth. A324, 156 (1993).

LAND Neutron Detector

- Plastic scintillator / Fe converter sandwich structure
- Plastic scintillator veto detector in front of LAND
- $\sigma_t < 250$ ps
- $\sigma_{x,y,z} \approx 3$ cm



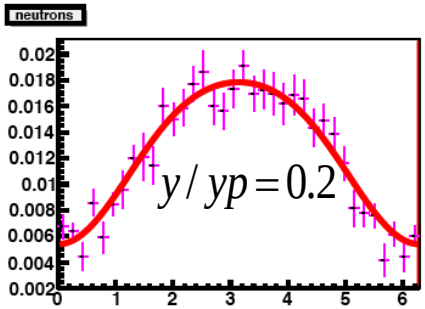




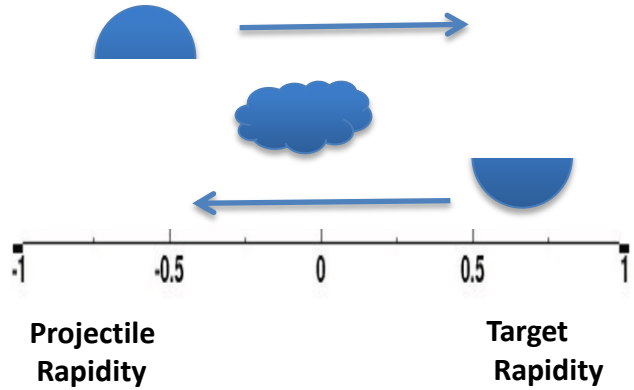
Th. Blaich *et al.*, NIM A 314,136 (1992).

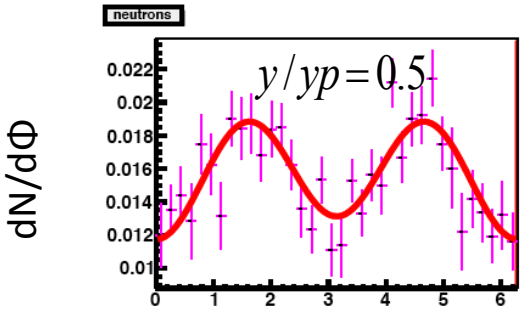
- neutrons and protons in same detector
- reduce errors due to different detector acceptances

Azimuthal Distributions for Au+Au at 400 AMeV

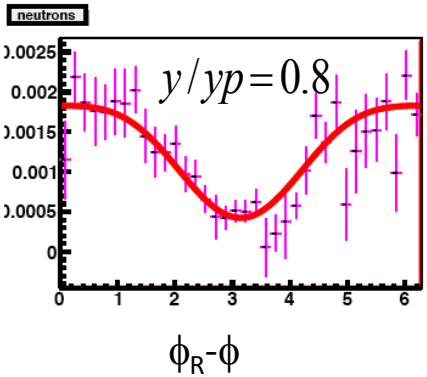


- Target rapidity region
- In-plane flow
- ϕ_R-ϕ = +180°
- v_1 large, v_2 small



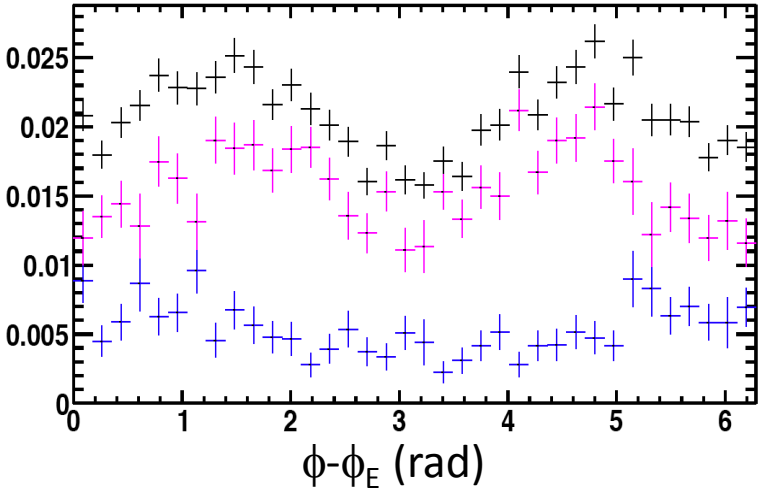


- Mid-rapidity region
- Out-of-plane flow
- ϕ_R-ϕ = 90° and 270°
- v_1 small, v_2 large

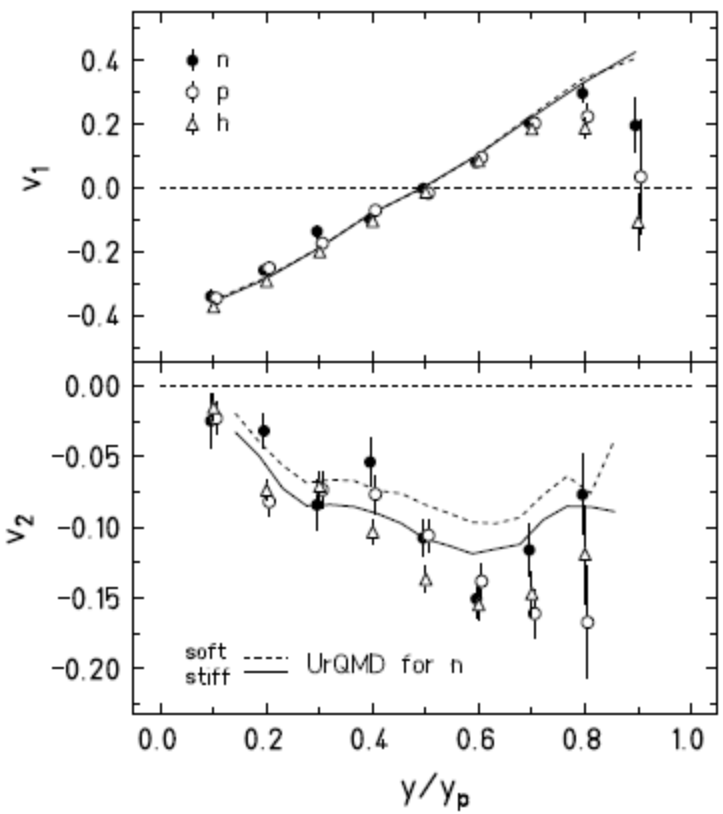


- Projectile rapidity region
- In-plane flow
- ϕ_R-ϕ = -180°
- v_1 large, v_2 small

Background subtraction for neutrons

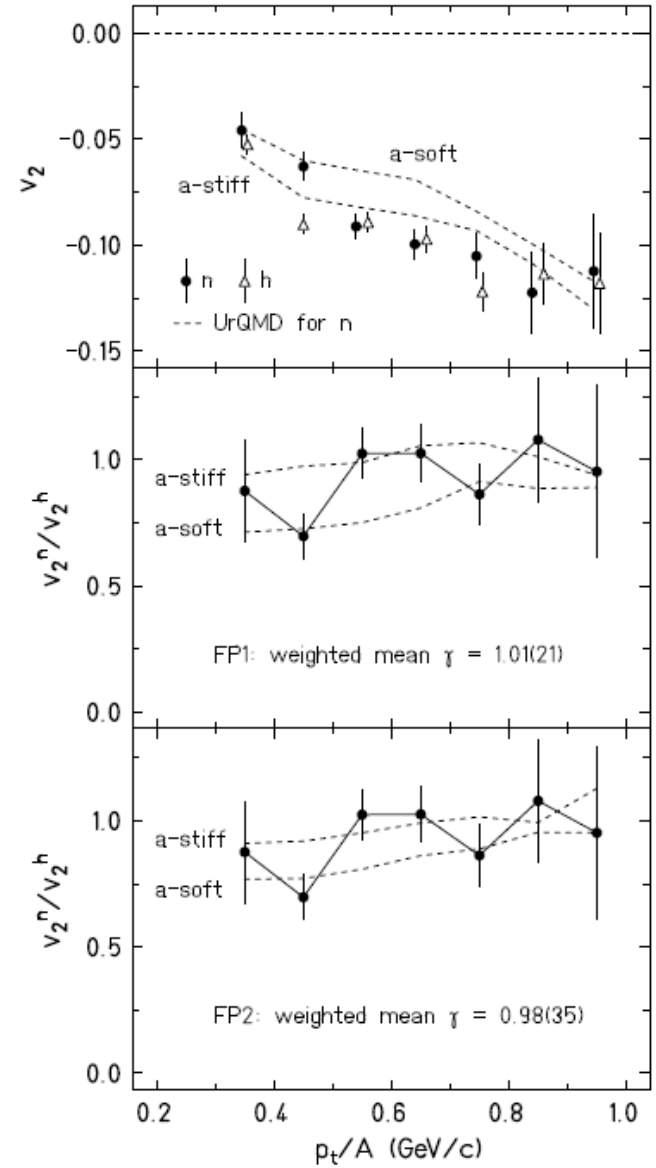


Results at 400 AMeV



- mid-peripheral ($5.5 \leq b \leq 7.5$ fm)
- integrated over $0.3 \leq p_t/A \leq 1.3$ GeV/c

- $\gamma = 0.9 \quad 0.4$
- moderately soft symmetry term
- what does this imply ?

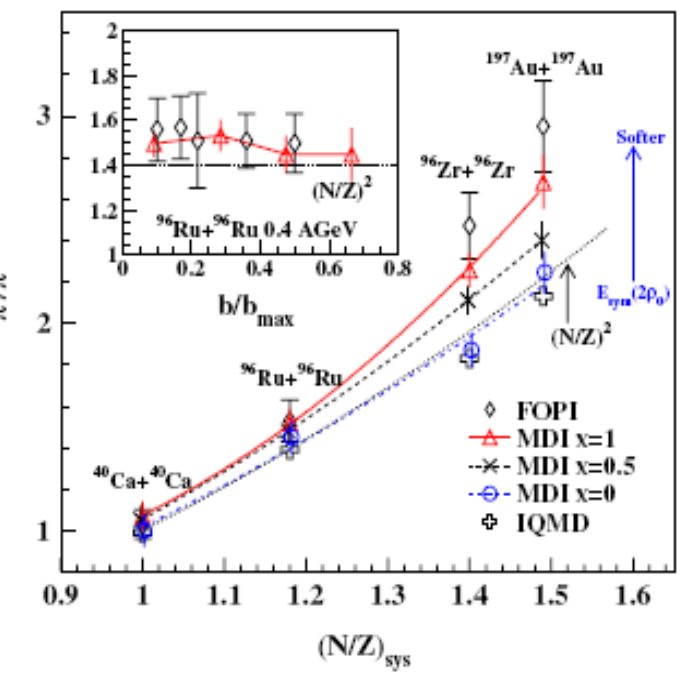


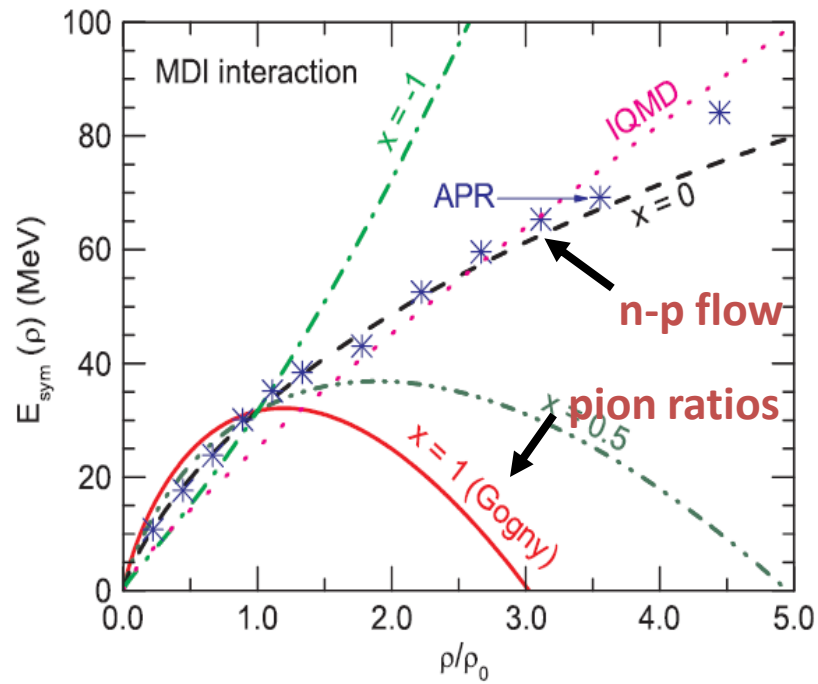
P. Russotto et al., Phys. Lett. B 697 (2011) 471.

- combined central to mid-peripheral
- $0.25 \leq y/y_p \leq 0.75$

Comparison of n-p Elliptic Flow with π^-/π^+ Particle Production

Z. Xiao et al., Phys. Rev. Lett. 102 (2009) 062502.
W. Reisdorf et al., Nucl. Phys. A 781 (2007) 459.





Asy-stiff

Asy-soft

- Comparison of π^-/π^+ ratios measured with FOPI to IBUU04 transport model
  - super-soft symmetry energy (x=1; $\gamma < 0.5$)
- Comparison of neutron-proton elliptic flow data to UrQMD model
  - moderately soft symmetry energy (x=0; $\gamma = 0.9 \pm 0.4$) at $\rho/\rho_0 \sim 2$
- Recent re-analysis of FOPI π-/π+ ratios with ImQMD
  - hard symmetry energy (x=-1; $\gamma = 2$)

Conclusions

- Collective flow can probe EOS of nuclear matter at high densities

- Constraints extracted for *symmetric* nuclear matter
  - Model dependence ...
  - More stringent constraints on symmetric matter should be pursued

- Collective flow can provide constraints on *asymmetric* nuclear matter
  - Neutron-proton elliptic flow
  - First constraints from FOPI-LAND data ^{197}Au+^{197}Au at 400 AMeV
    - γ = 0.9 0.4 (moderately soft)
    - Limited statistics

- Future Work
  - FOPI-LAND data ^{197}Au+^{197}Au at 600, 800 AMeV under analysis
  - New experiment performed at GSI in May 2011
    - ^{197}Au+^{197}Au, ^{96}Ru+^{96}Ru, ^{96}Zr+^{96}Zr at 400AMeV
    - See talks by P. Russotto, S. Santoro (Sunday afternoon)
  - Future prospects at FAIR with R3B
    - See talk by M. Chartier (Sunday afternoon)