# ANALYSIS OF NEUTRON AND HYDROGEN FLOW IN Au+Au COLLISIONS AT 400 AND 600.A.MeV


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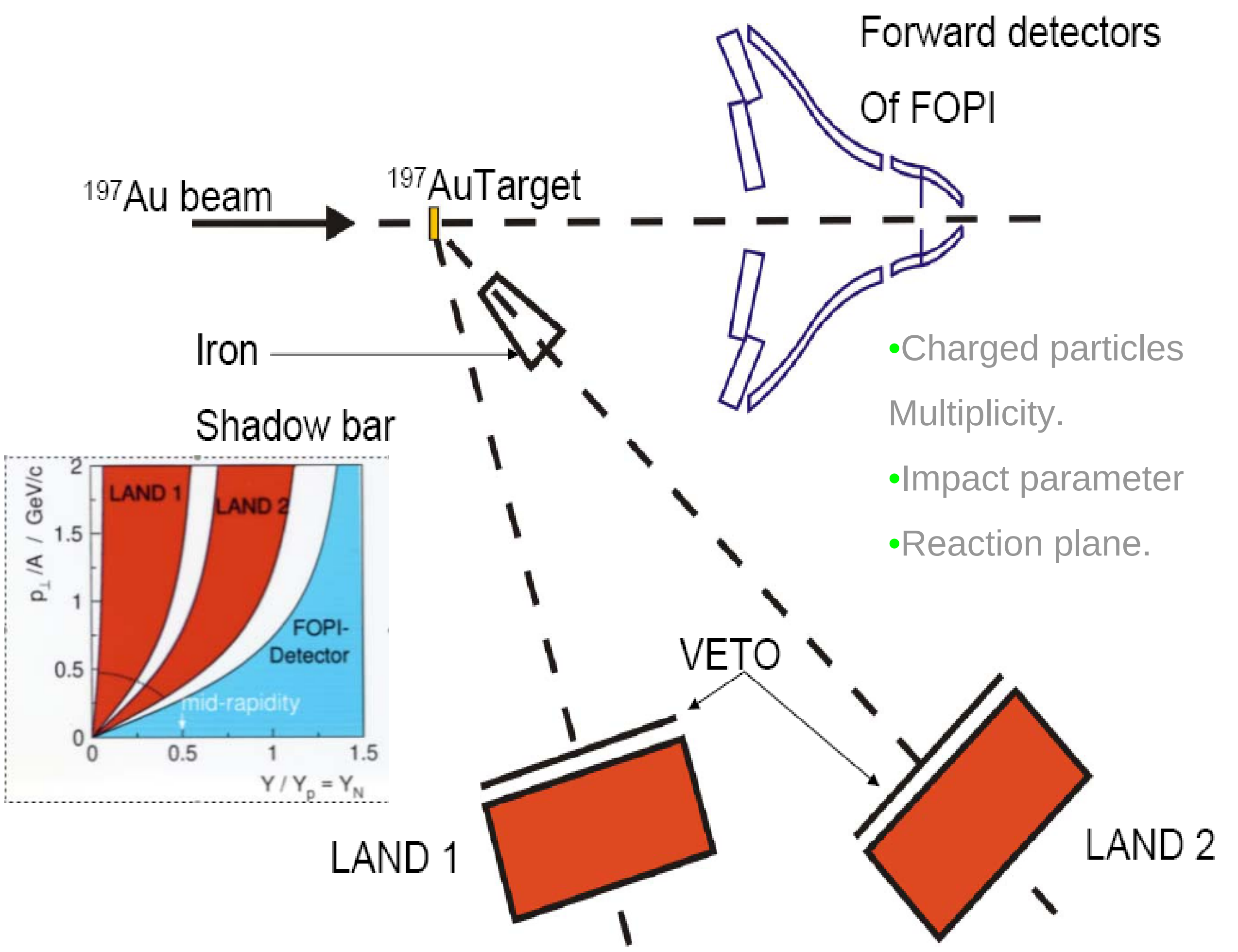
# Neutron-Proton Collective Flow Experiment at GSI

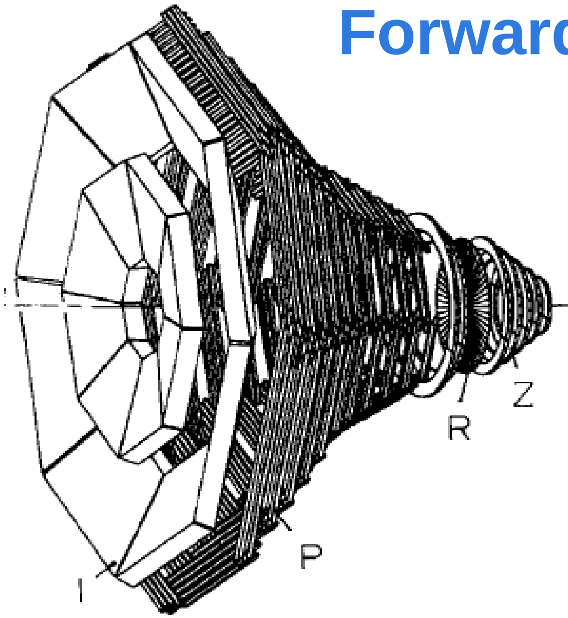
## $^{197}$Au+$^{197}$Au @ 400, 600 and 800.A.MeV



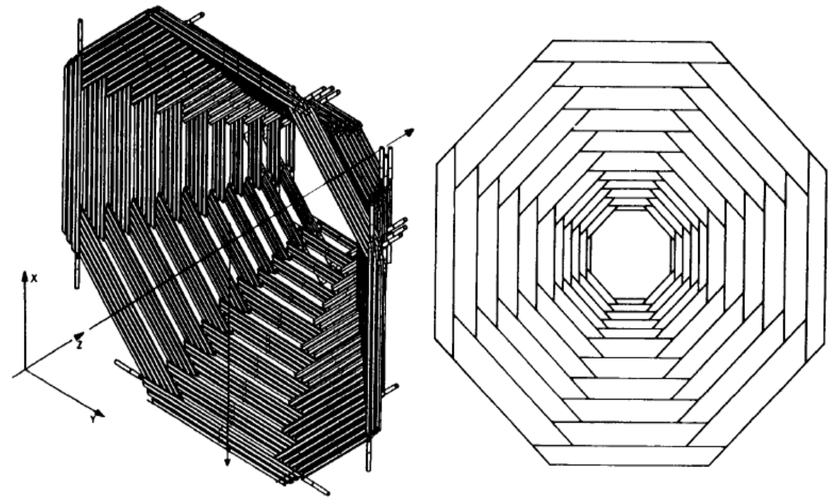

- Few existing measurements of neutron flow – this is most comprehensive
- Novel experiment as **both** neutrons and protons were measured using same detector: **LAND**

# Reaction-Plane Detector: FOPI Forward Wall

## Forward Wall




## Outer Plastic Wall

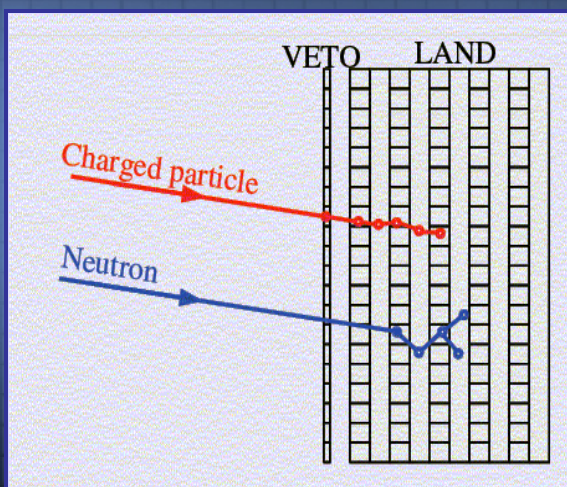


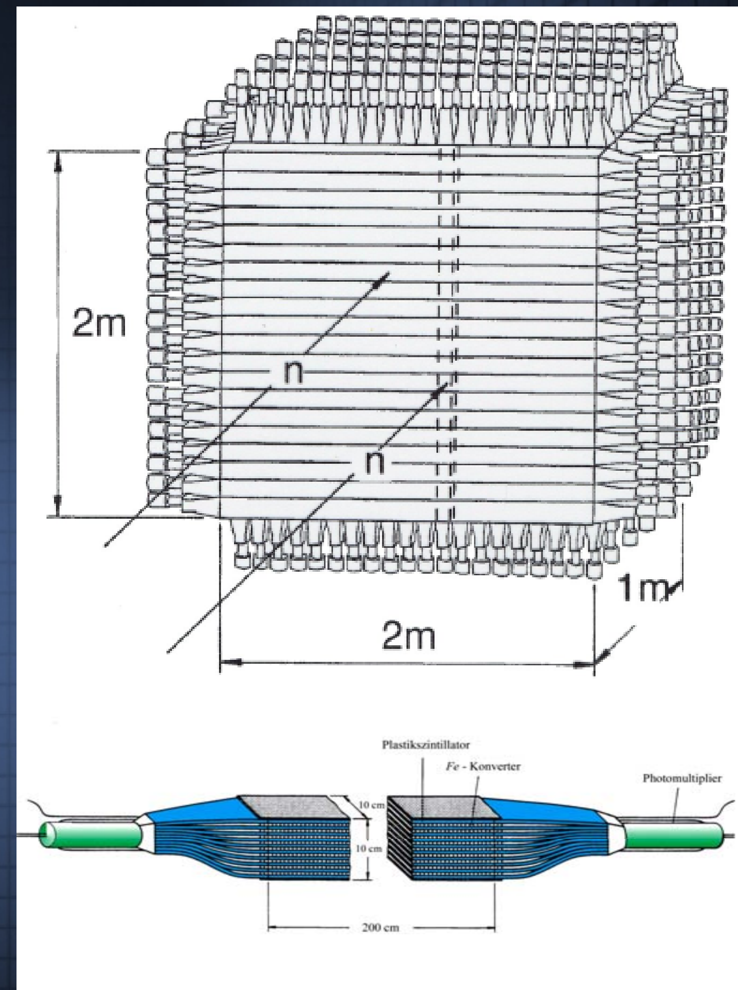
A.Gobbi et al., Nucl. Inst. Meth. A324, 156 (1993).

- 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

# Neutron And Proton Detector: LAND

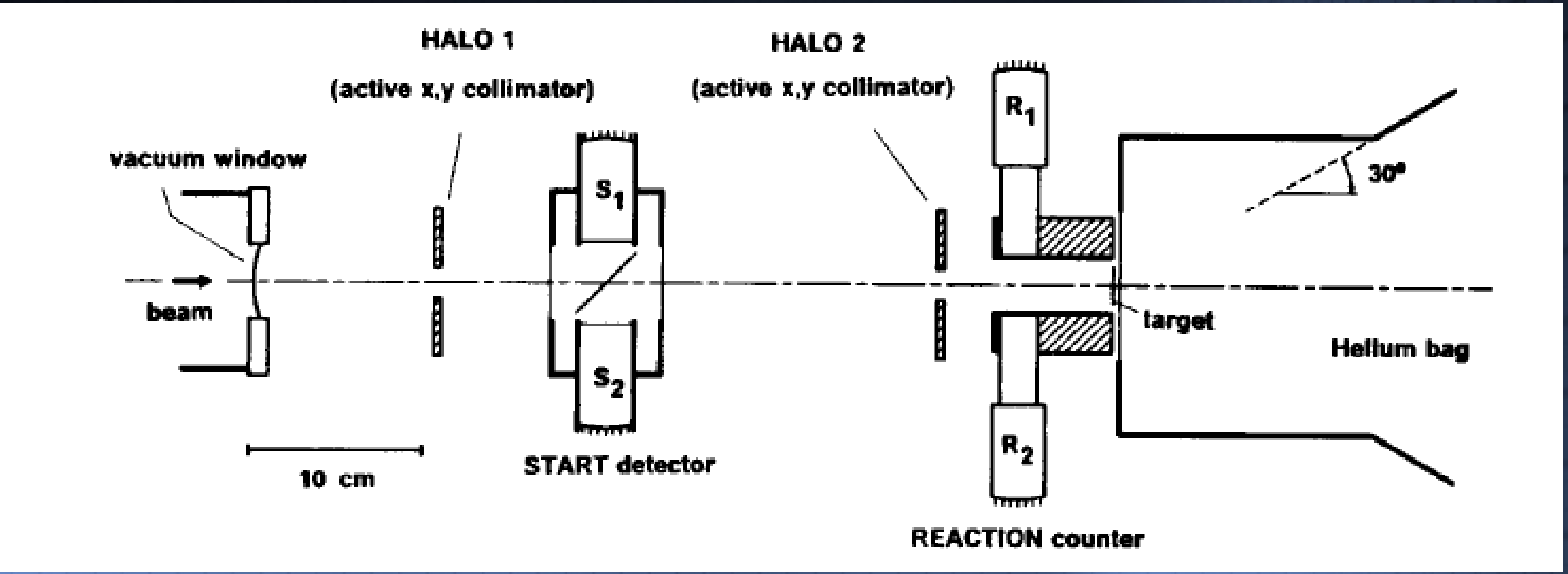
- Plastic scintillator / Fe converter sandwich structure
- Plastic scintillator veto detector in front of LAND
- $\sigma_t < 250$ ps
- $\sigma_{x,y,z} \approx 3$ cm




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

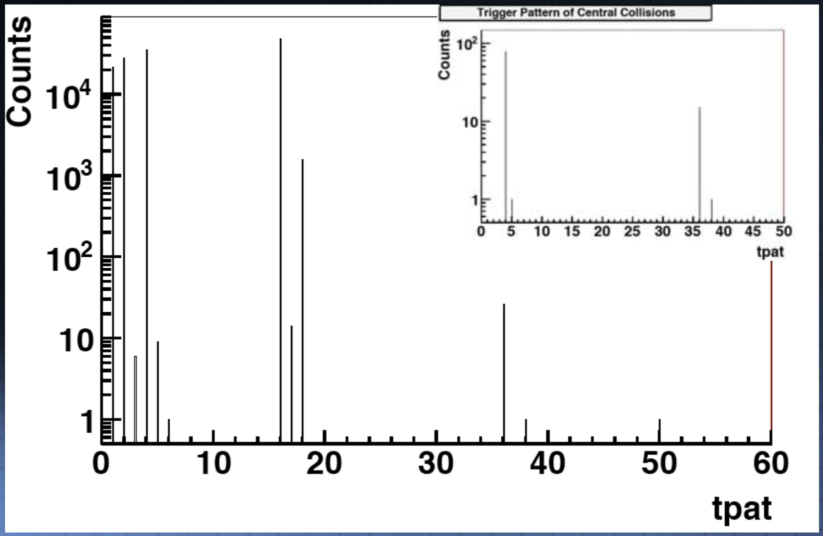
# Target Region Detector Configuration



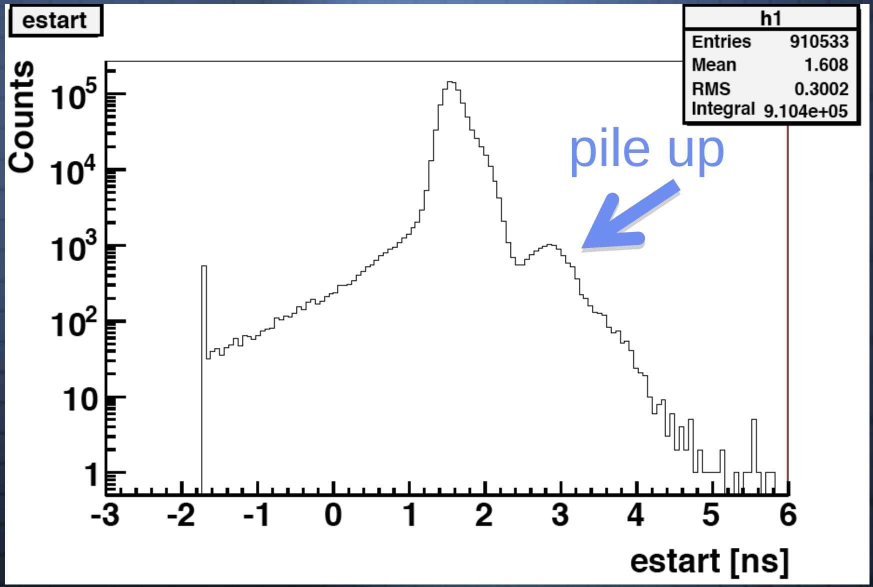

- To produce central collision trigger (tpat=4):
  - START detector ($S_1$ and $S_2$) to fire but NOT HALO2.
  - Reaction Counter ≥1.
  - Spill gate trigger to fire.
  - Central collision multiplicity signal from FOPI forward plastic wall.

$$(t,e_{Start}) = S_2 - S_1$$

# Event Selection

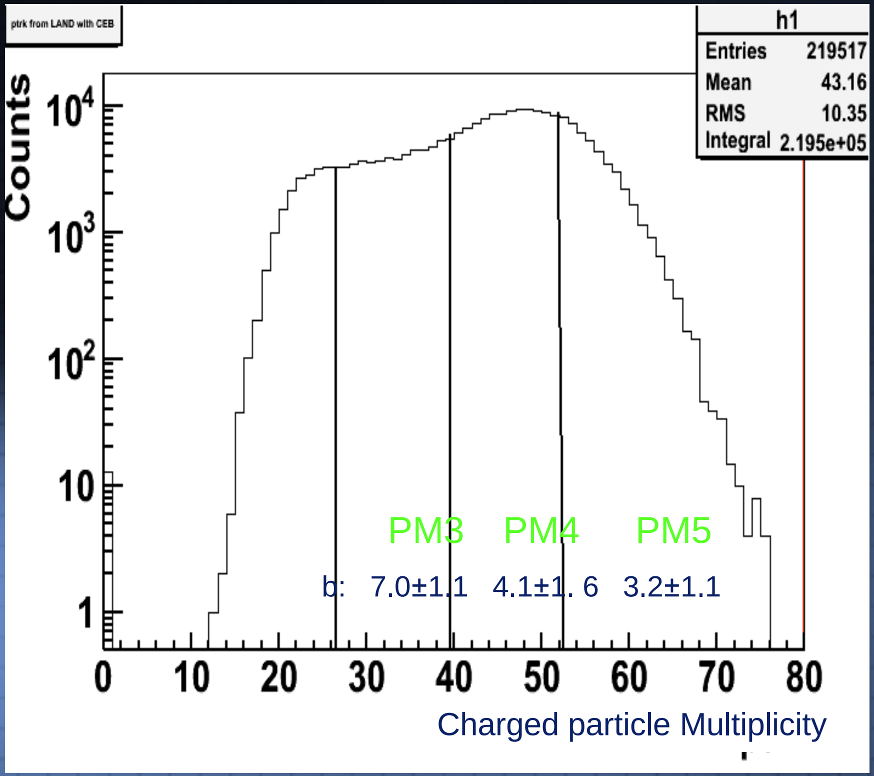


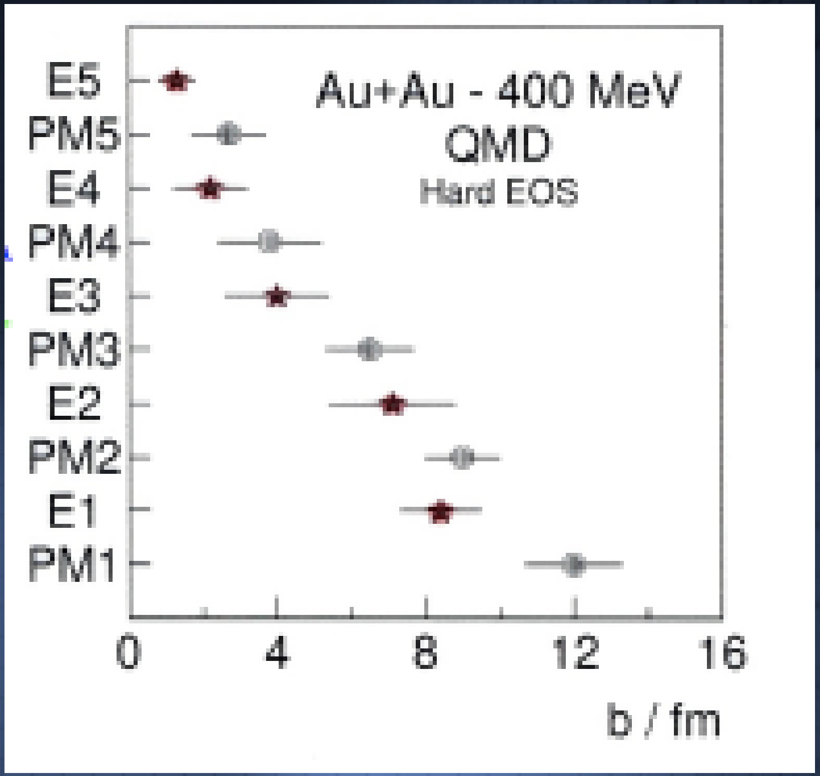

- Trigger pattern.
- Many different triggers used
- Tpat=4 provides selection of central collisions.




- To remove double hit events, a gate on the start detector has been applied.
- Removing events where two particles are detected within the same time interval.

# Impact Parameter Selection



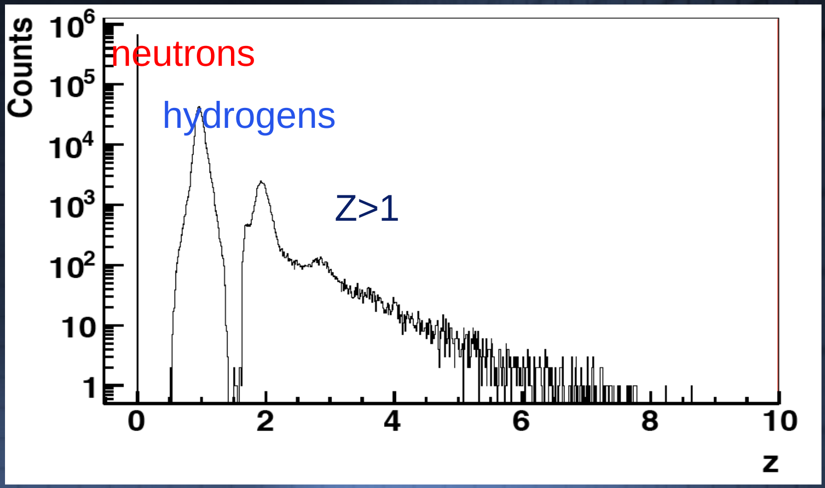

Y. Leifels thesis

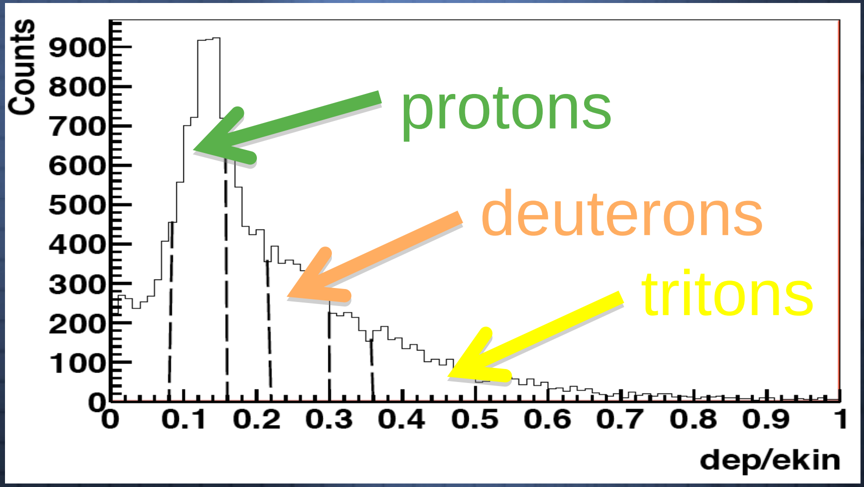
# Particle ID In LAND

- z identification via the veto wall of LAND.
- Mass identification via Energy deposited in LAND ➡ particle ID via:

$$E_{deposited} \Big/ (\gamma - 1) \equiv dep \Big/ ekin$$

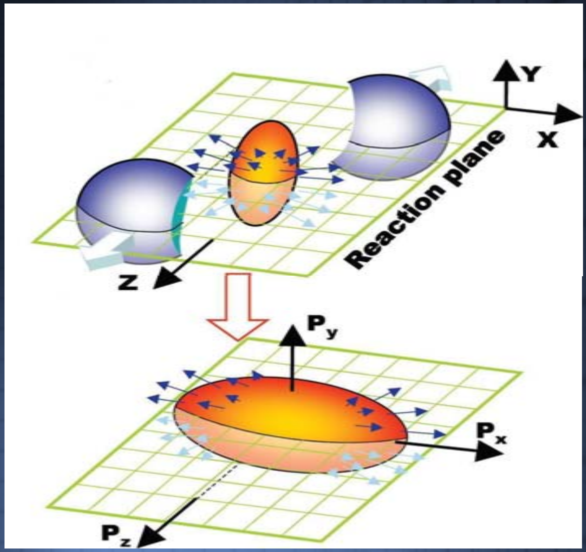
- well established method (simulations, measurements)
- p,d,t identified via 1-D cuts.
- More sophisticated method, but does improve the analysis is to fit the distribution with a series of mathematical functions.



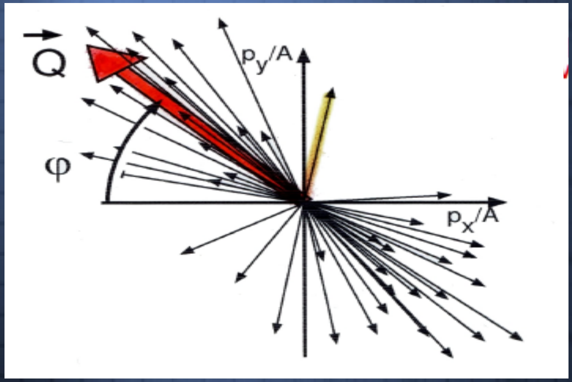



# Event Plane Method of Flow Analysis

- Non-central HICs create a hot and dense region at mid-rapidity which is non-spherical.
- Pressure gradients translate this anisotropy from co-ordinate space momentum space (pressure largest in the x-direction → $p_x$ larger than $p_y$)
- Results in the particle azimuthal distributions measured in the detectors being anisotropic w.r.t. the reaction-plane.
- This azimuth anisotropy can be described via a Fourier expansion:

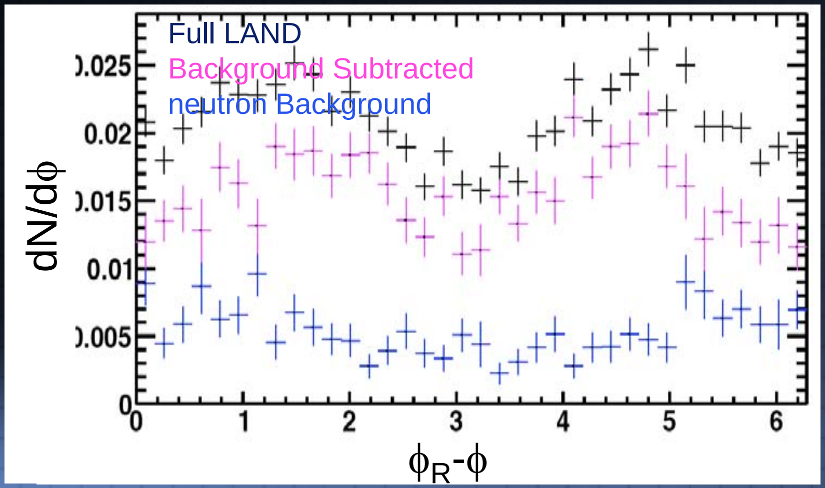



$$\frac{dN}{d(\varphi_R-\varphi)} = \frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1} v_n \cos n(\varphi_R-\varphi)\right)$$

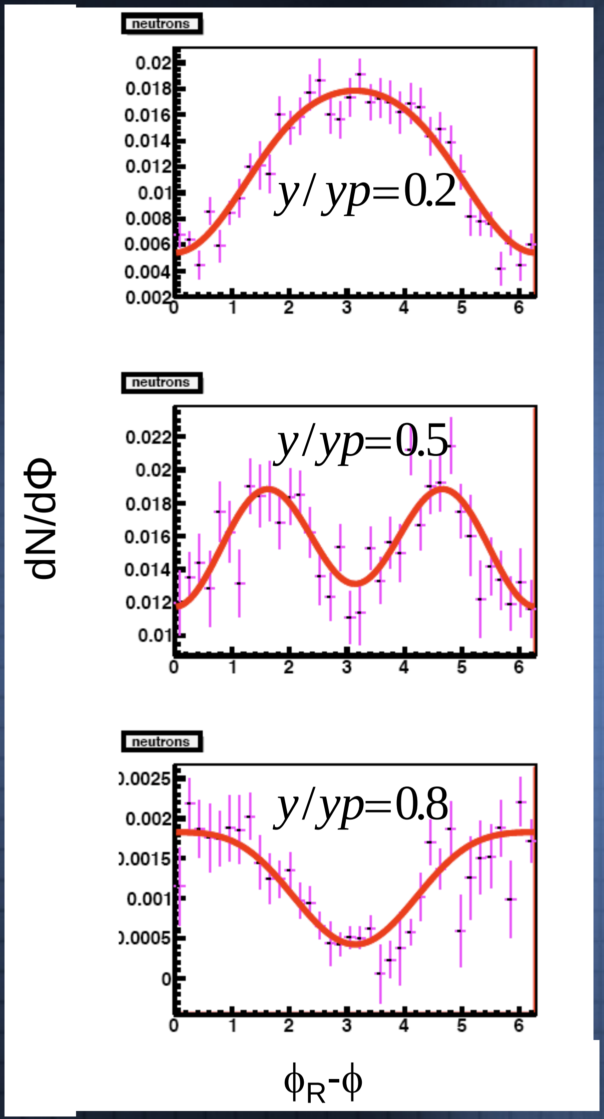



  - $V_1$: directed flow (in-plane)
  - $V_2$: elliptic flow(out-of-plane)
- Reaction plane angle $\phi_R$ constructed event-by-event using Q-vector method (average transverse momentum of emitted particles)

# Experimental Results: Au+Au@400.A.MeV




- Reaction plane measured in FOPI forward wall
- Proton and neutrons measured in LAND
- Background subtraction for neutrons
- Azimuthal distributions fitted with Fourier expansion
    - $dN/d\phi \sim 1 + 2[v_1\cos(\phi-\phi_R) + v_2\cos2(\phi-\phi_R)]$
    - $v_1$ and $v_2$ extracted




- Target rapidity region
- In-plane flow
- $\phi_R$-$\phi$ = +180°
- $v_1$ large, $v_2$ small

- Mid-rapidity region
- Out-of-plane flow
- $\phi_R$-$\phi$ = 90° and 270°
- $v_1$ small, $v_2$ large

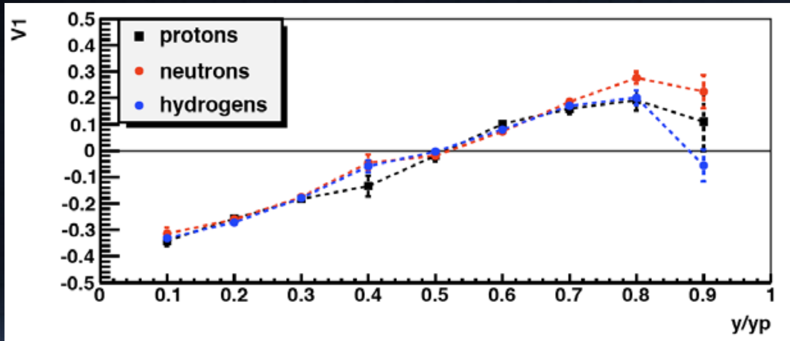
- Projectile rapidity region
- In-plane flow
- $\phi_R$-$\phi$ = -180°
- $v_1$ large, $v_2$ small

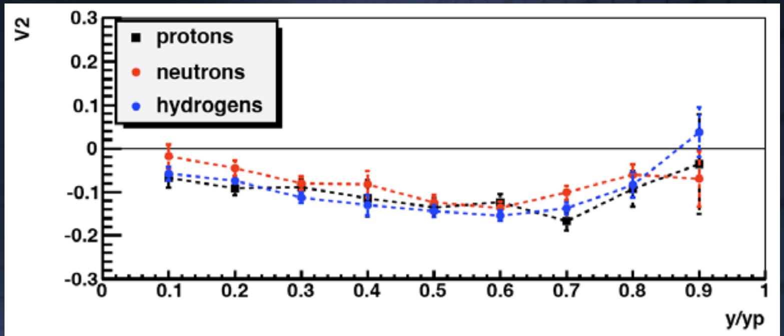
# Experimental Results: Au+Au@400.A.MeV

## $V_1$ Directed Flow

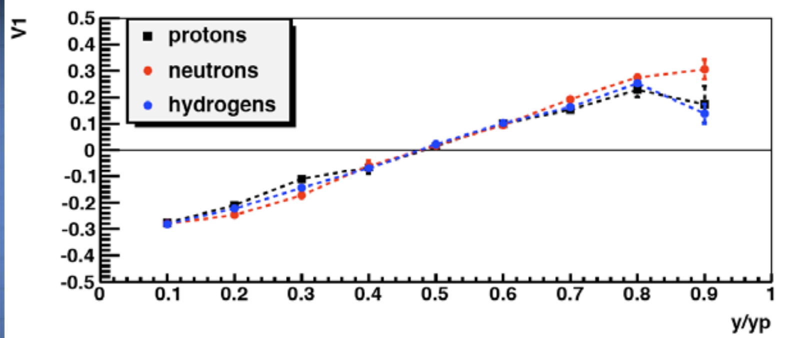
## $V_2$ Elliptic Flow

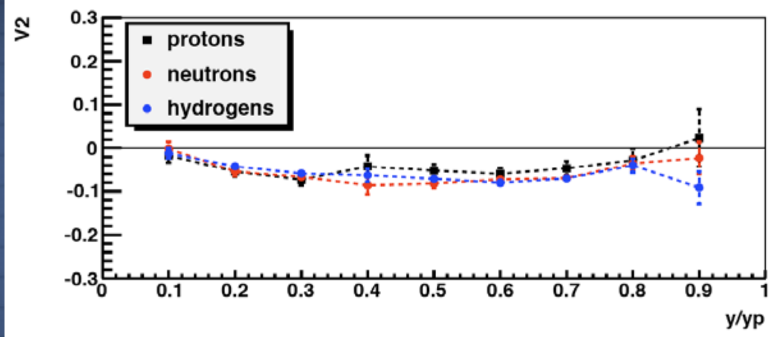
PM3 Bin



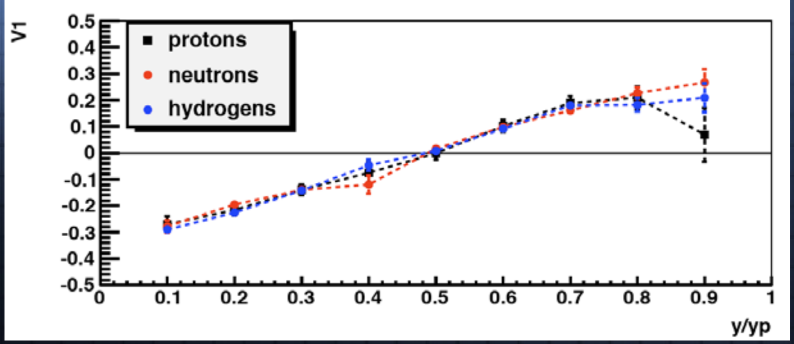



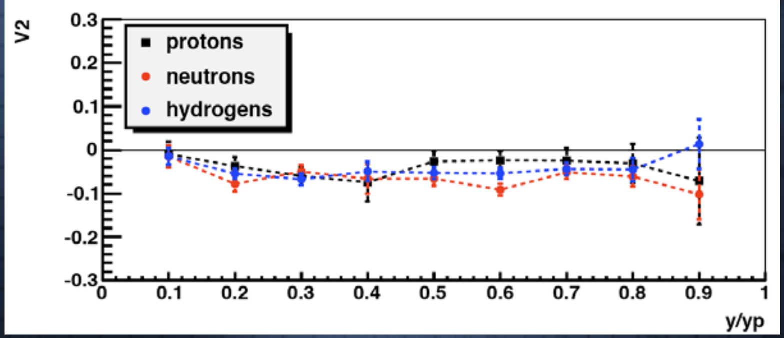

PM4 Bin



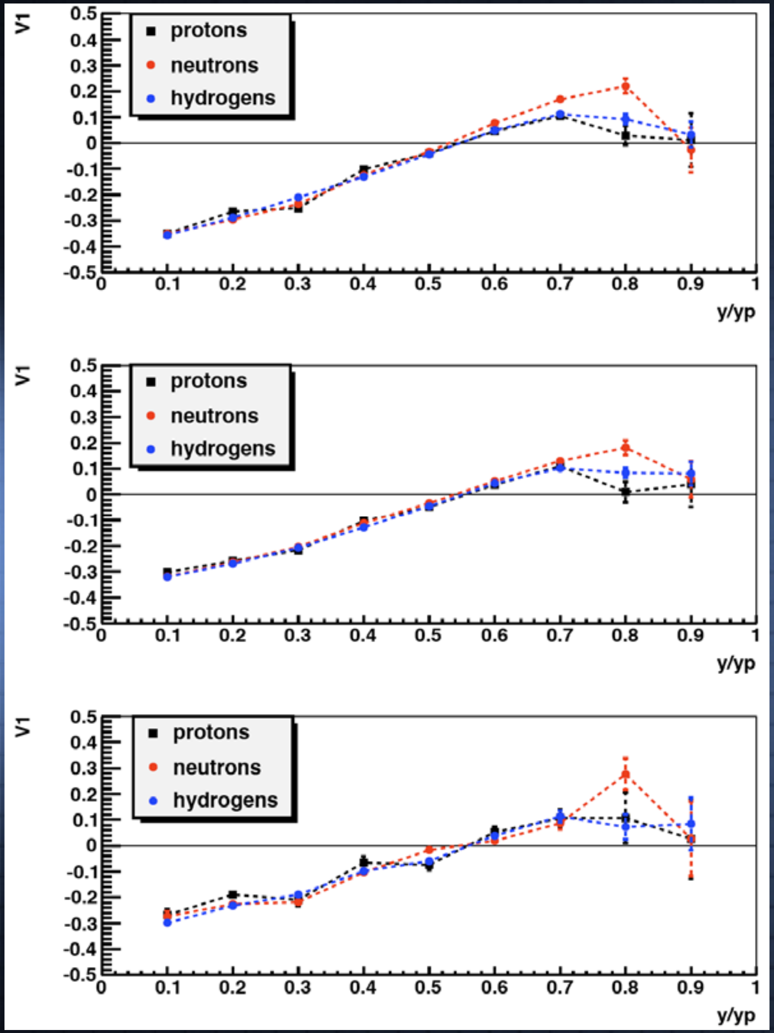

PM5 Bin



# Experimental Results: Au+Au@600.A.MeV

## $V_1$ Directed Flow

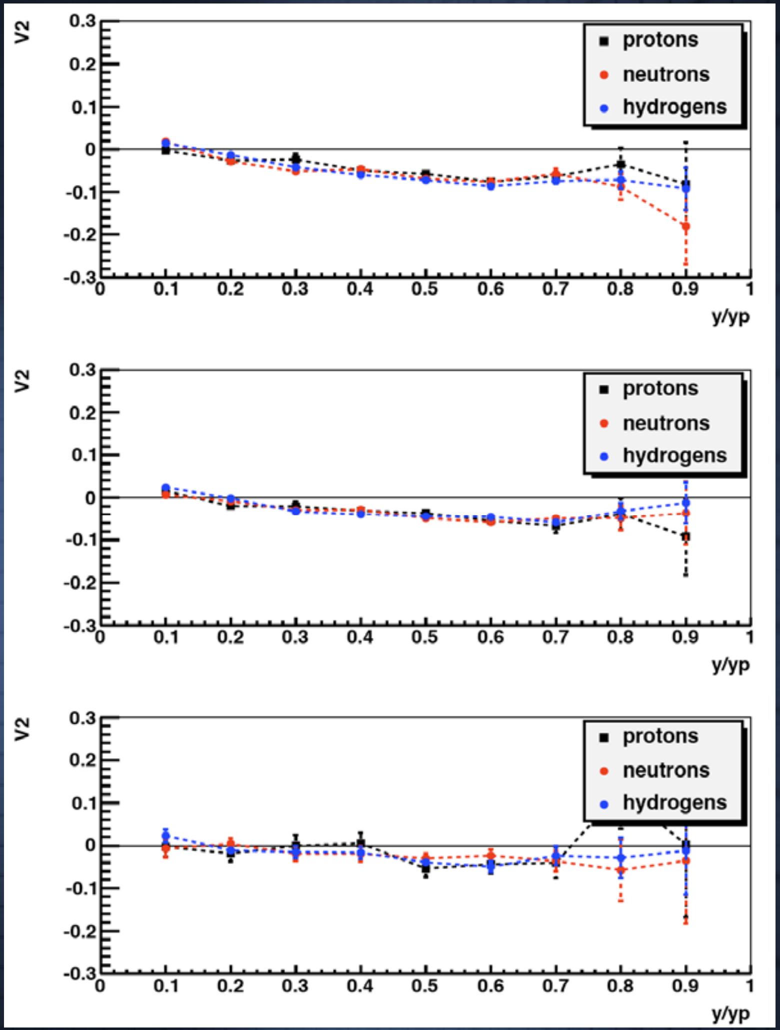



PM3 Bin

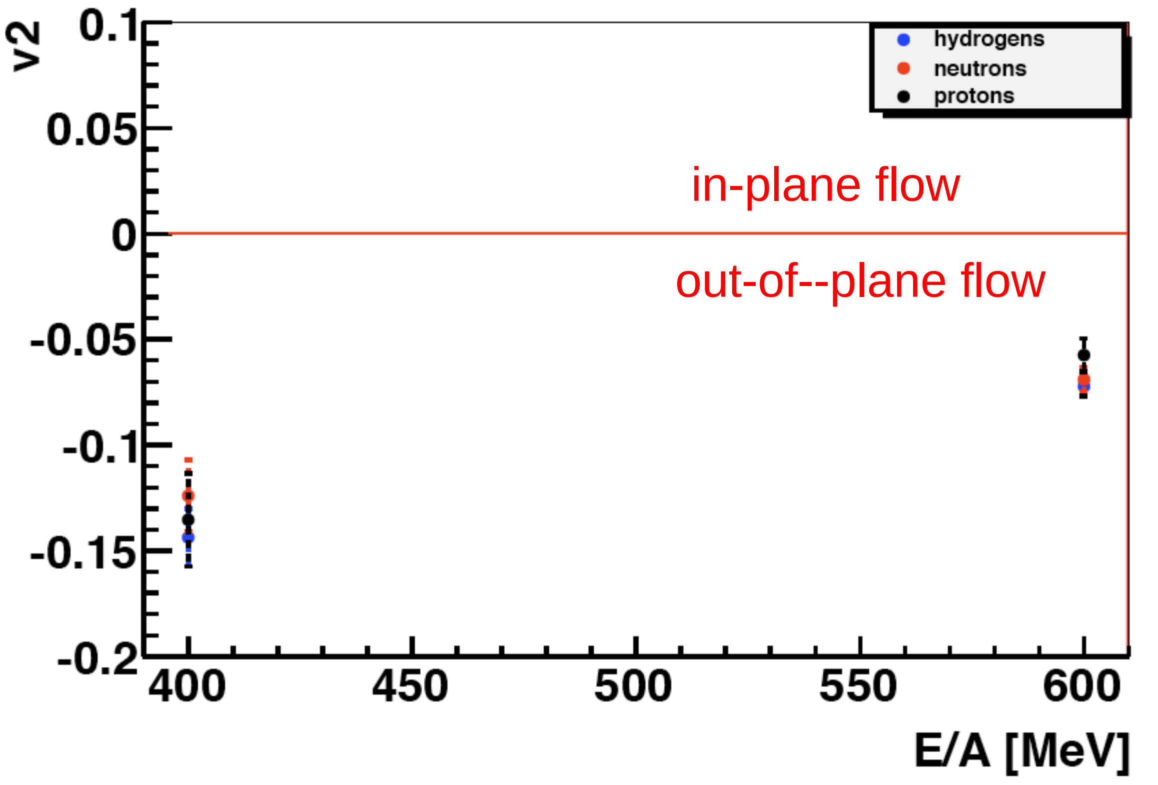
PM4 Bin

PM5 Bin

## $V_2$ Elliptic Flow



# Integrated $V_2$ Excitation Function



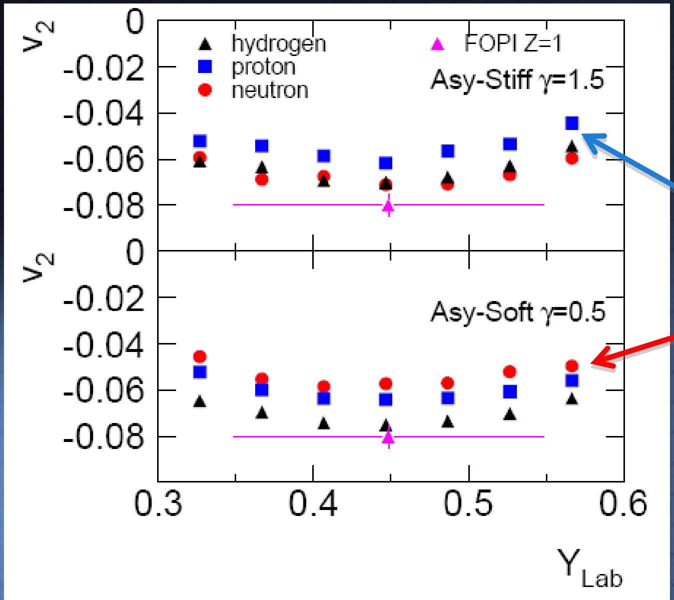

- Differential elliptic flow integrated over mid-rapidity ($y/y_p$=0.5) and over all pT.
- Trend is in agreement with findings of flow systematics. A. Andronic et.al.

Eur. Phys. J. A 30, 31{46 (2006)

- Maximum $v_2$ at 400.A.MeV

# Interpretation of Results: Au+Au@400.A.MeV

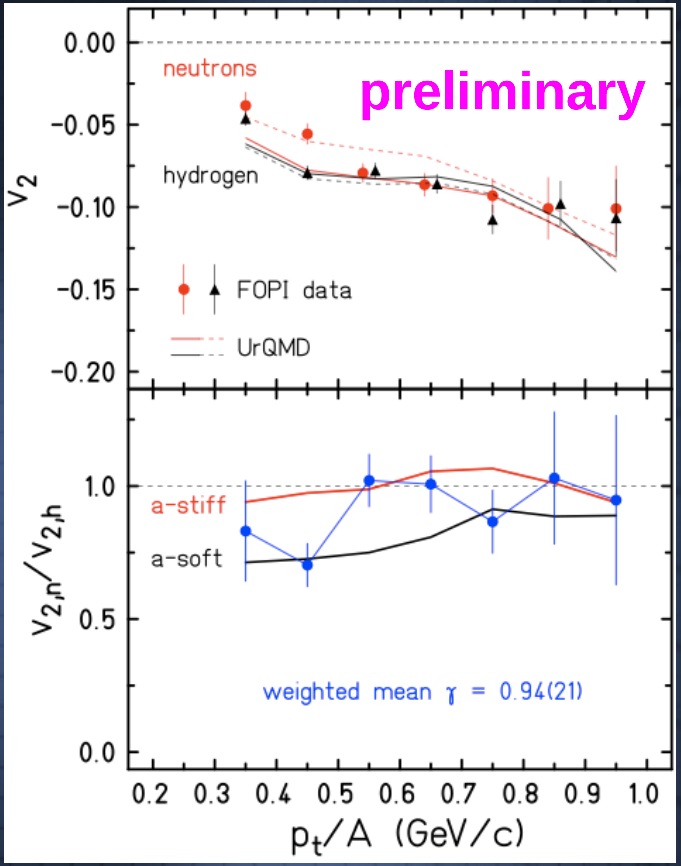
## UrQMD calculations




P. Russotto and Q. Li

np inversion

## Comparison with data

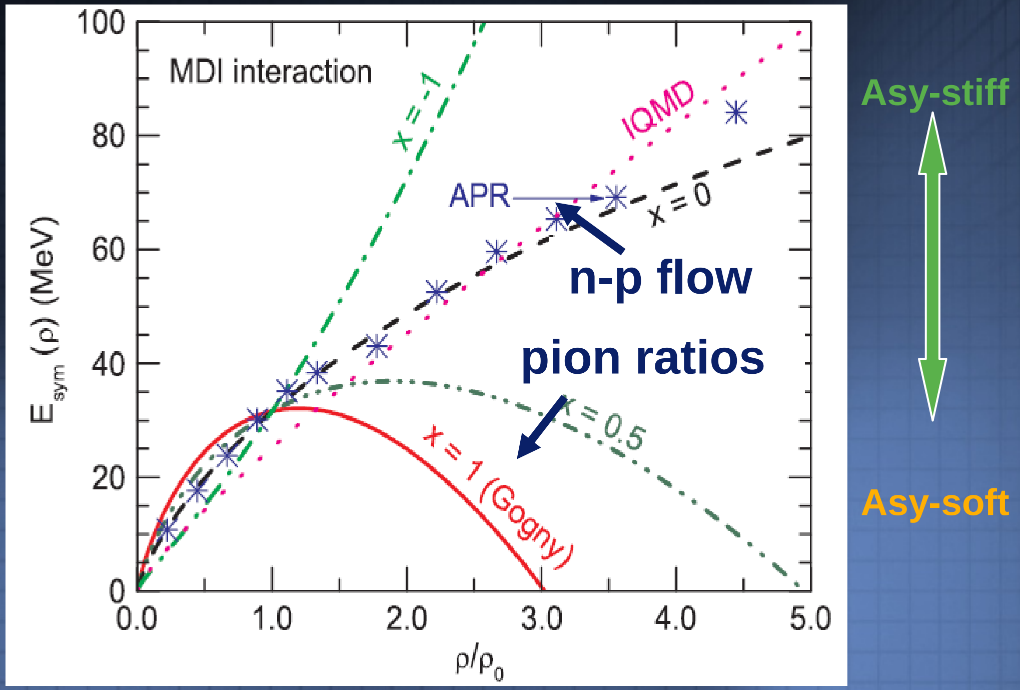



UrQMD transport model calculations:

- symmetry energy parametrised by $F(u) = u^{\gamma}$, where $\gamma = 1.5$ is asy-stiff and $\gamma = 0.5$ is asy-soft
- inversion of neutron and hydrogen elliptic flow between stiff and soft symmetry energy

- experiment gives $\gamma = 0.86 \pm 0.21$

# Comparison of Neutron-Proton Elliptic Flow Results with $\pi^-/\pi^+$ Measurements




- Comparison of $\pi^-/\pi^+$ 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; $\gamma$ = 0.86 (21)) at $\rho/\rho_0 \sim 2$
- Conflicting results !!! Need new experiments …

# Summary

- Measurements of neutron-proton elliptic flow can provide constraints on the behaviour of the nuclear EOS at high densities.
- Comparison of experimental neutron-proton elliptic flow in Au+Au at 400 A.MeV to UrQMD calculations suggests a moderately soft symmetry energy.
- In conflict with recent results from $\pi^-/\pi^+$ ratios.
- Analysis of neutron-proton elliptic flow in Au+Au at 600 and 800 A.MeV in progress
- Alternatives to the event-plane method are in progress e.g. LYZ.

# Collaborators

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and the ASYEOS Collaboration.