Directed and Elliptic flow in 0.25-8.0 A GeV Au+Au Collisions

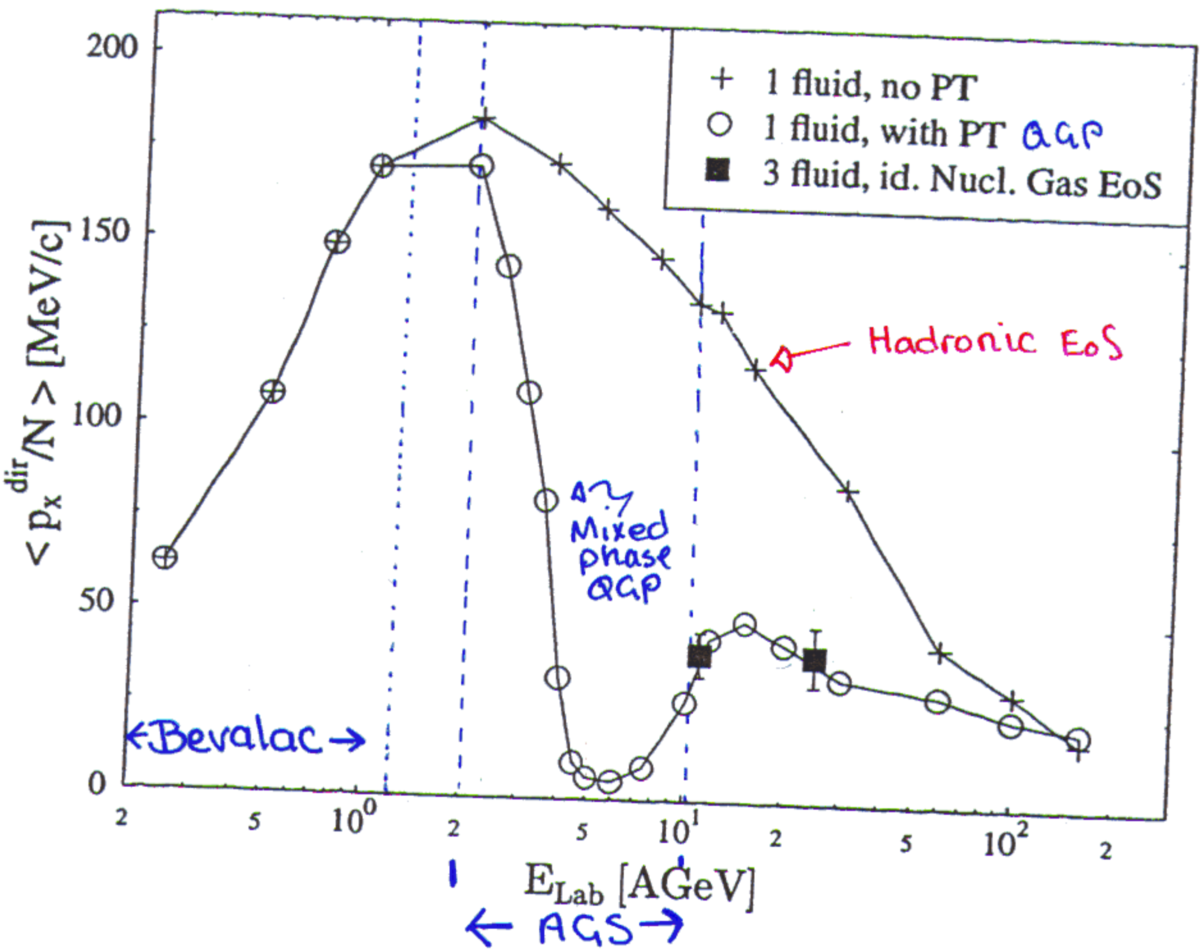
- Data from EOS Collaboration 0.25-1.15 A GeV
- Latest from the E895 Collaboration 2-8 A GeV

- Both experiments used the same TPC detector at the Bavalac and the AGS
  - TPC Provides 3D tracking over a substantial fraction of 4π
  - Particle identification via dE/dx measurement

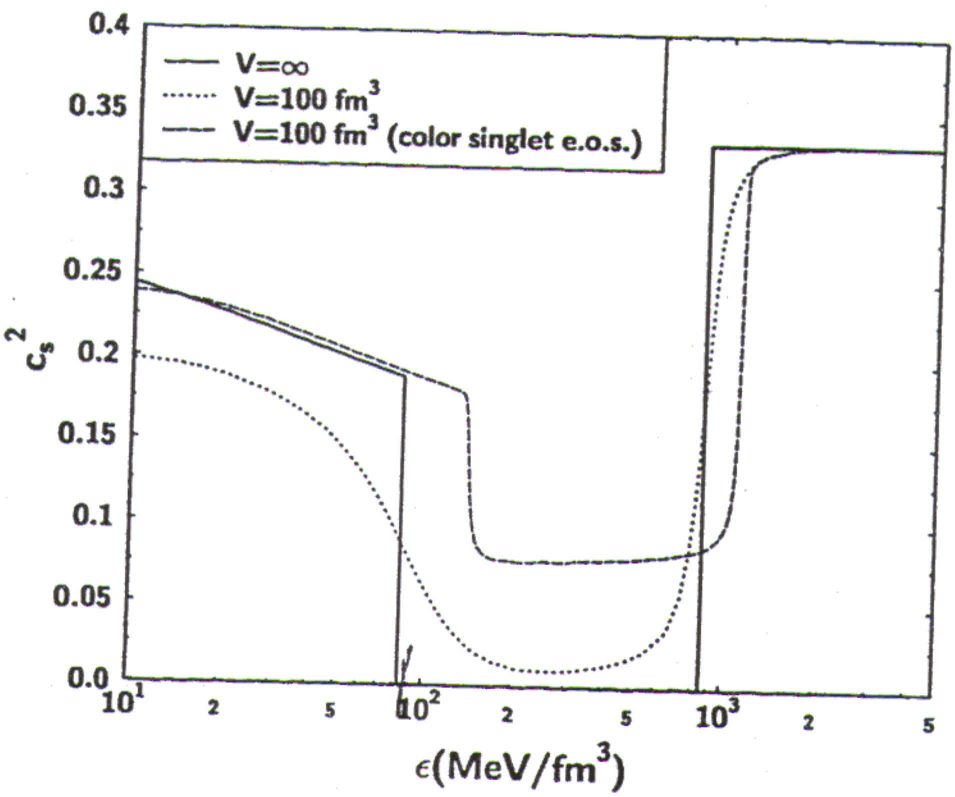
Summary

- Detailed excitation functions spanning two decade in beam energy
- Proton directed flow peaks ~ 2 A GeV and decreases smoothly at higher energies
- Elliptic flow (squeeze-out) develops rapidly at low at energies < 0.6 A GeV, Corner on Plateau at 2 A GeV, vanishes ~ 4 A GeV, and transition to in-plane > 6 A GeV
- K0s exhibit anti-flow and squeeze-out at 6 A GeV
- Good time to speculate, next speaker ……

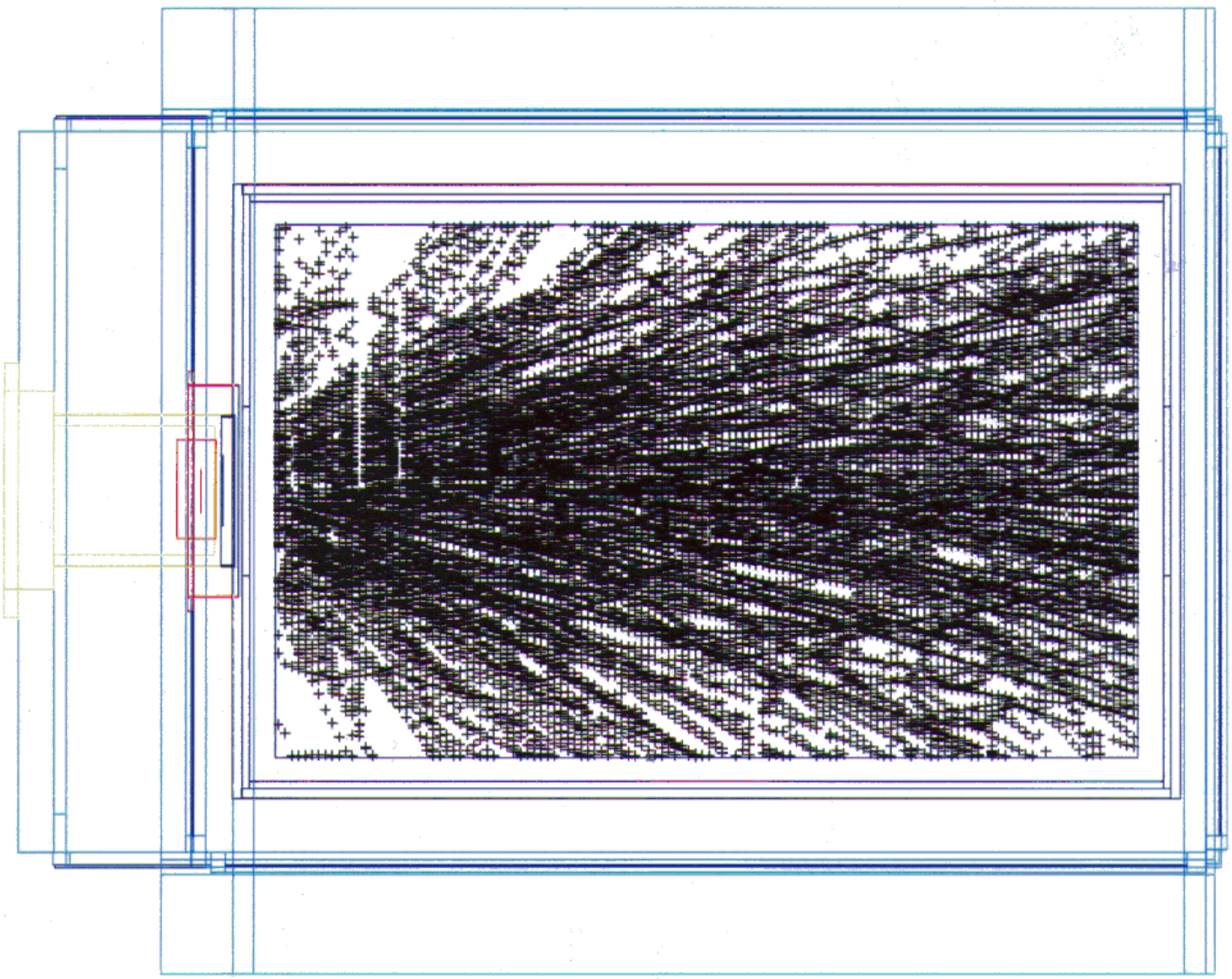
The Famous Rischke Plot
1D Hydrodynamics

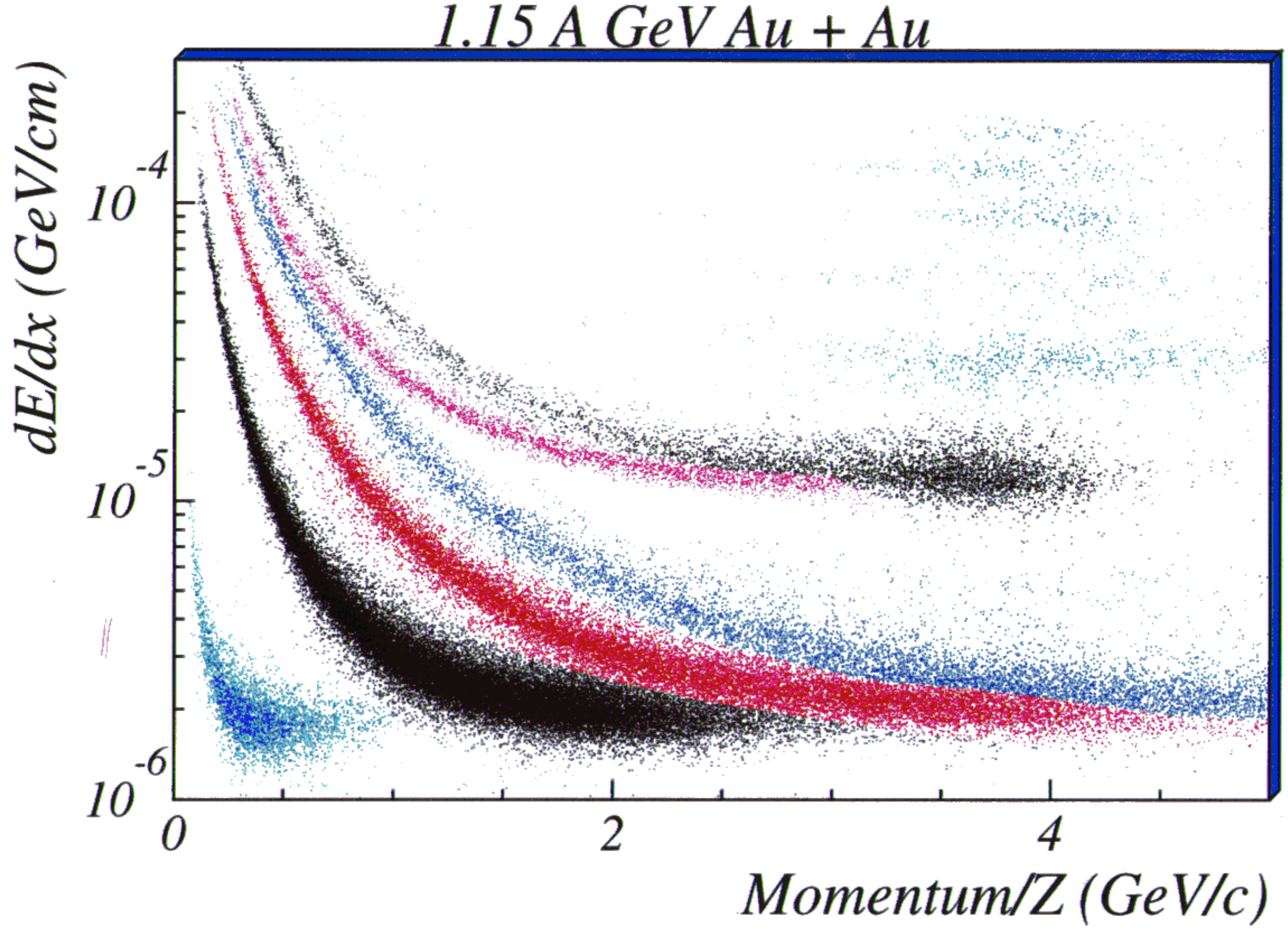


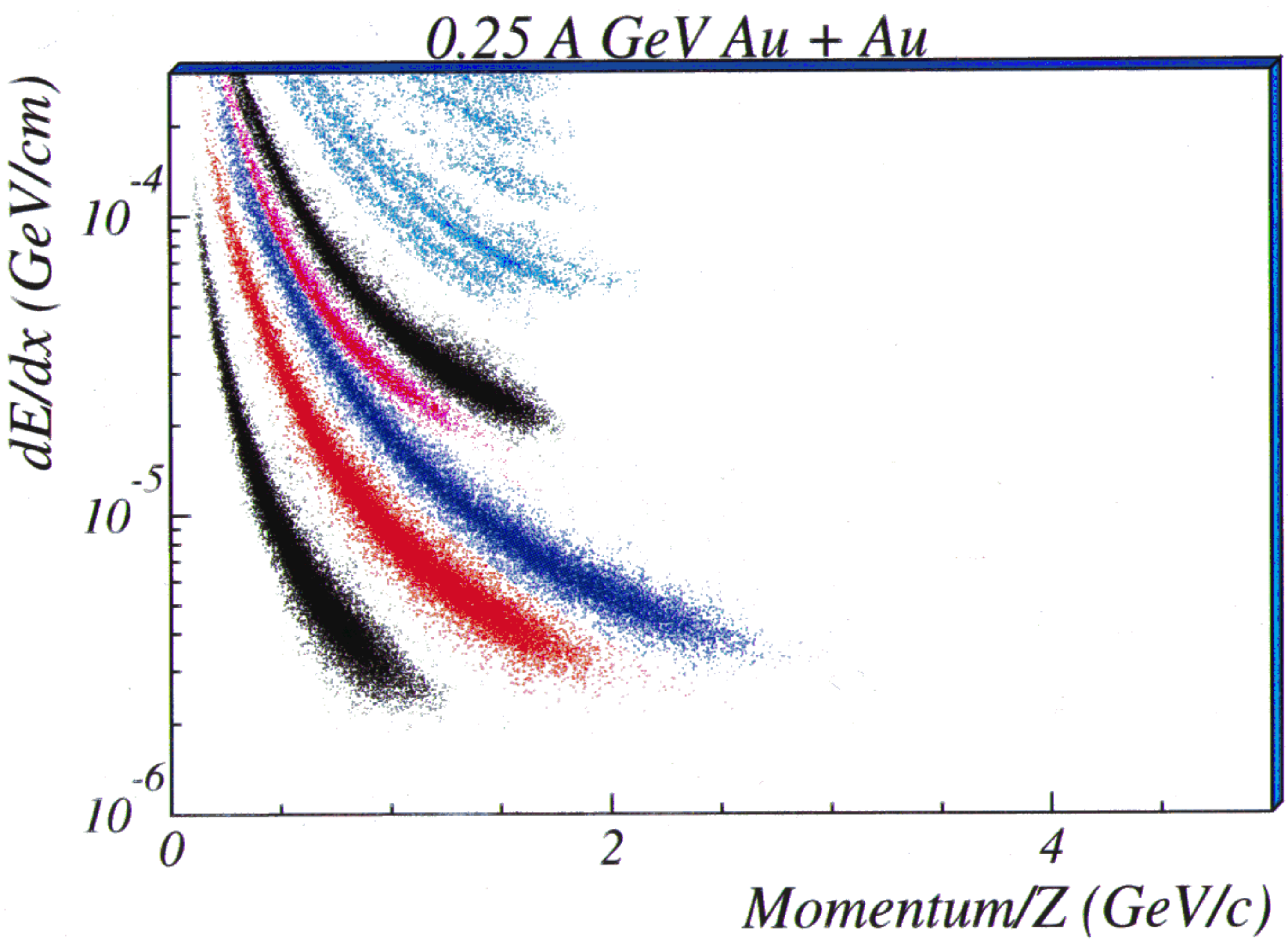
- Only a qualitative signal
- 3D hydro reduces magnitude of effect
- Finite size affects C_s, velocity of sound varies smoothly → does not go to zero
- Minimum can be anywhere. Bo An Li puts it between 6 – 30 GeV



C_s in finite volume. C. Spieles, H. Stöcker, C. Greiner Phys Rev C57, 908 (1998)




1.15 A GeV Au + Au
dE/dx (GeV/cm)
10^-4
10^-5
10^-6
0
2
4
Momentum/Z (GeV/c)


0.25 A GeV Au + Au
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10^-4
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0
2
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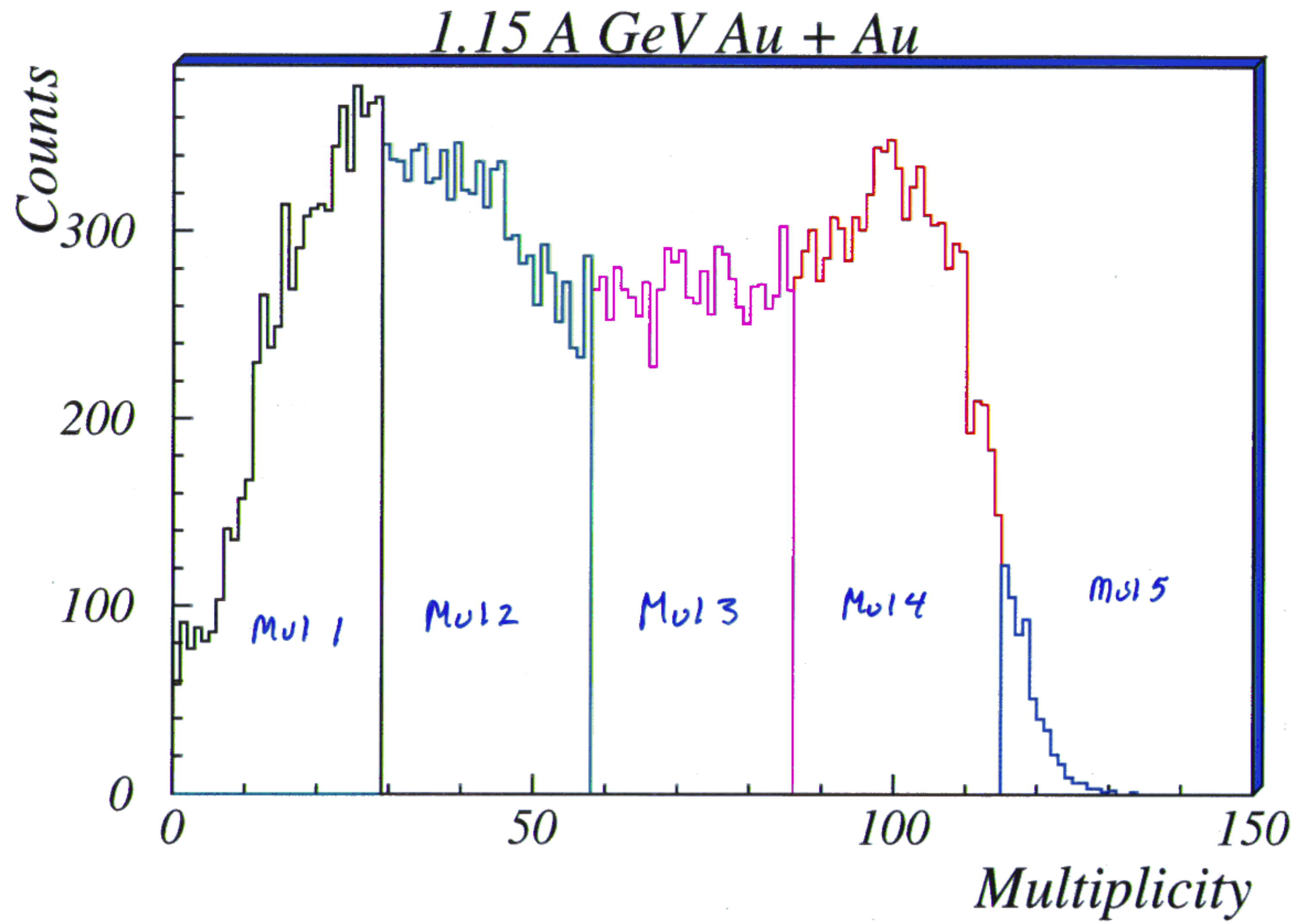
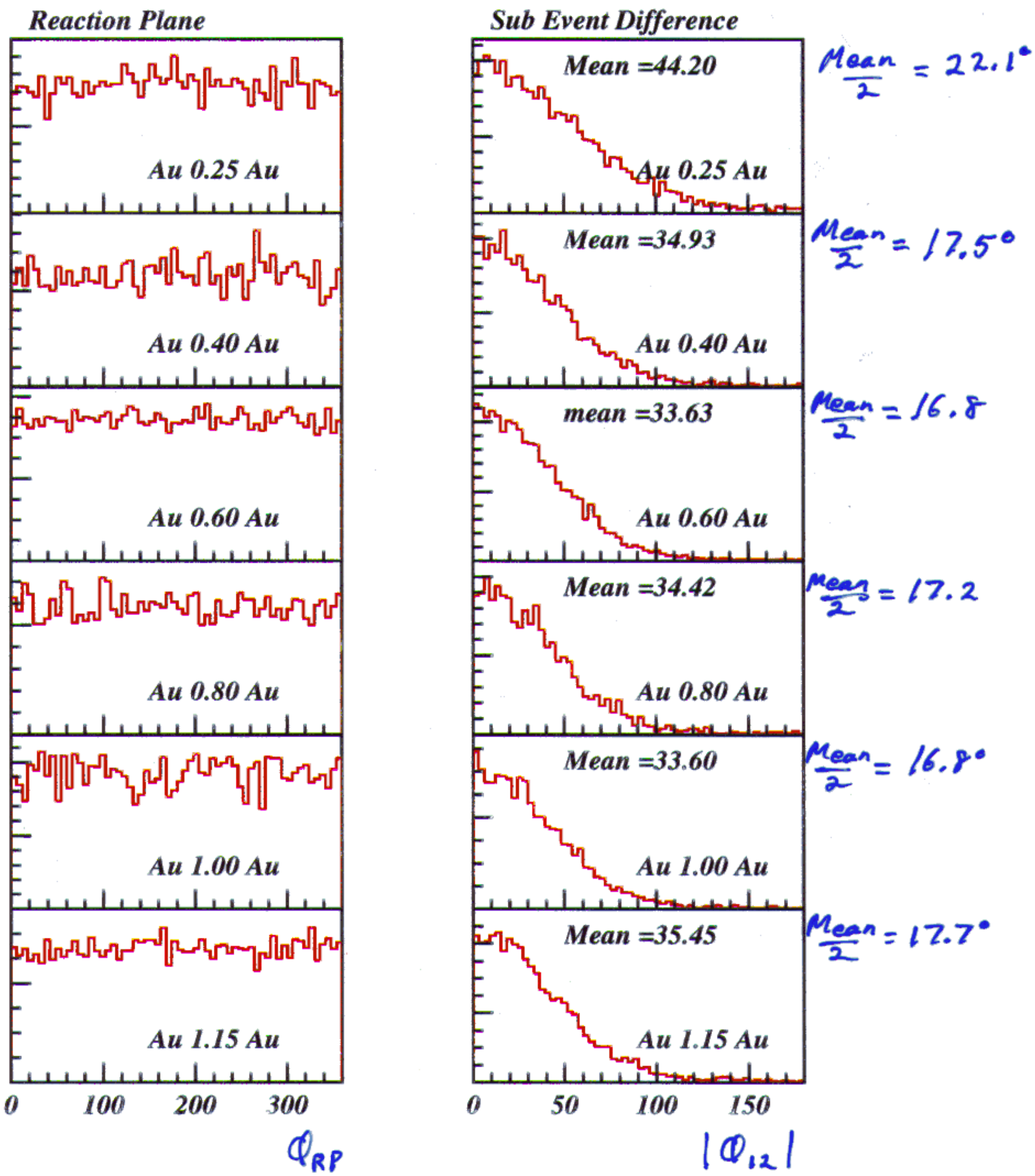
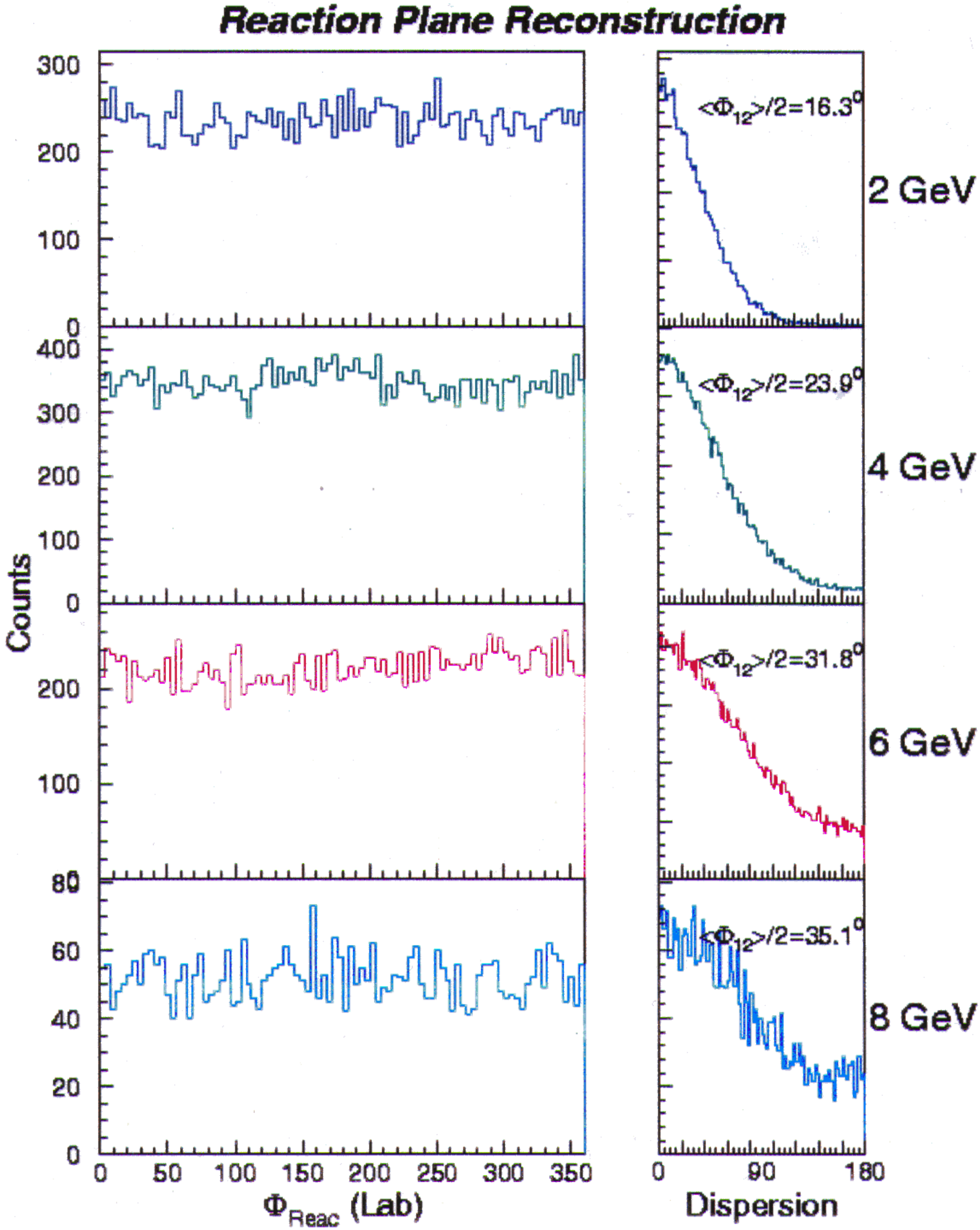
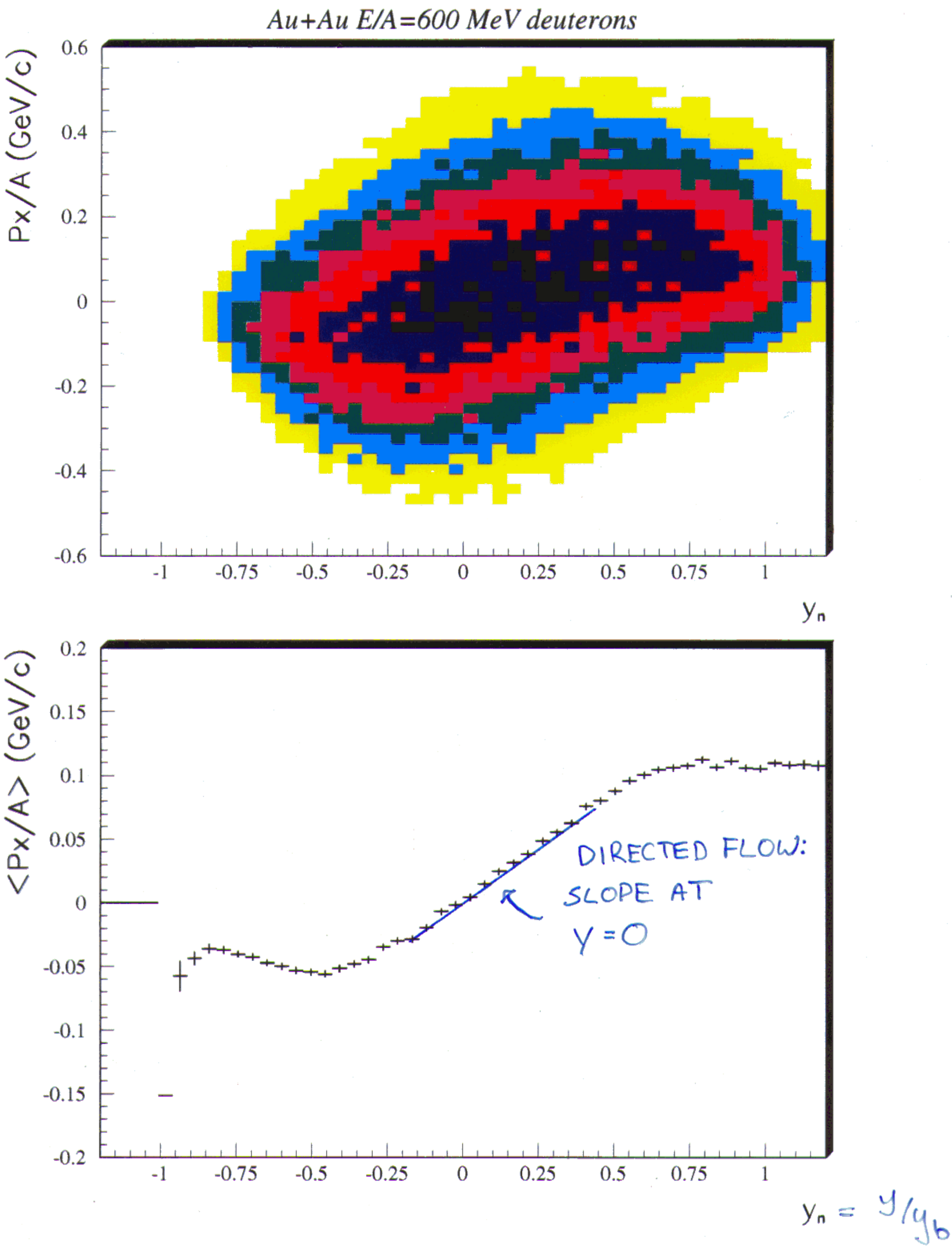

1.15 A GeV Au + Au
Counts
0
100
200
300
0
50
100
150
Multiplicity
Mul 1
Mul 2
Mul 3
Mul 4
Mul 5

LBL EOS Acceptance

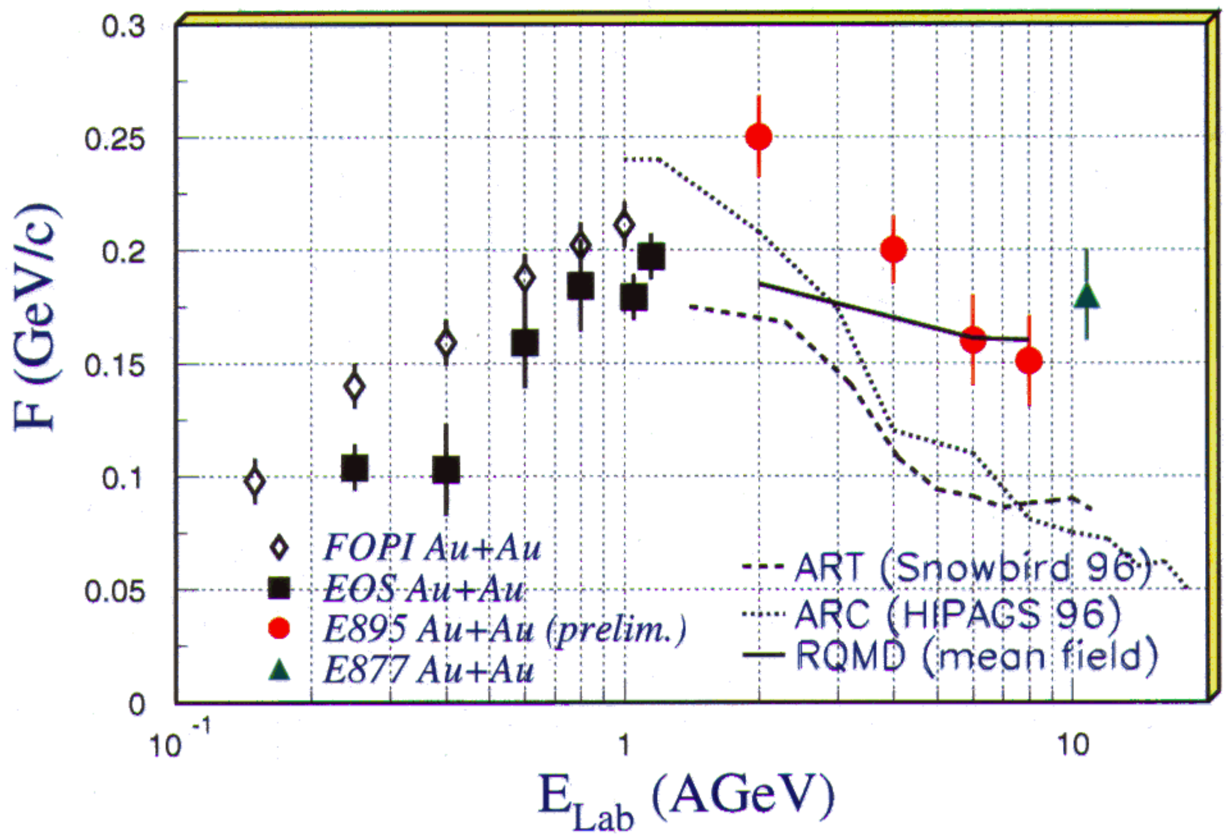




Reaction Plane Reconstruction
Counts
300
200
100
0
400
300
200
100
0
200
100
80
60
40
20
0
0
50
100
150
200
250
300
350
Φ_{Reac} (Lab)
$<\Phi_{12}>/2=16.3^o$
$<\Phi_{12}>/2=23.9^o$
$<\Phi_{12}>/2=31.8^o$
$<\Phi_{12}>/2=35.1^o$
0
90
180
Dispersion
2 GeV
4 GeV
6 GeV
8 GeV

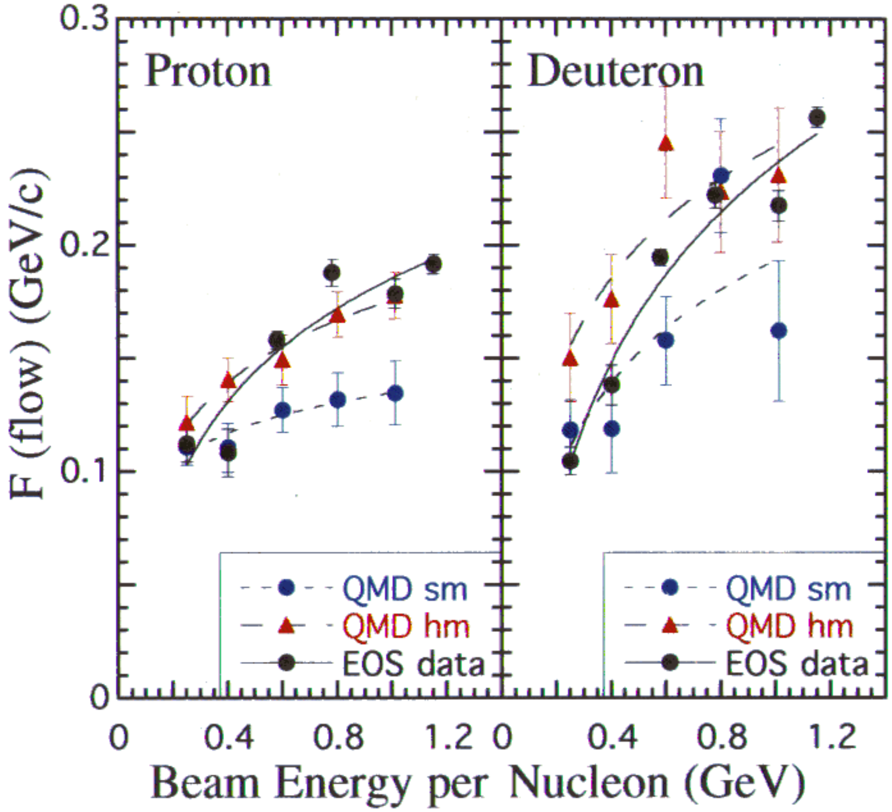

Au+Au E/A=600 MeV deuterons
Px/A (GeV/c)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
y_n
<Px/A> (GeV/c)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
DIRECTED FLOW:
SLOPE AT
Y = 0
$y_n = y/y_b$

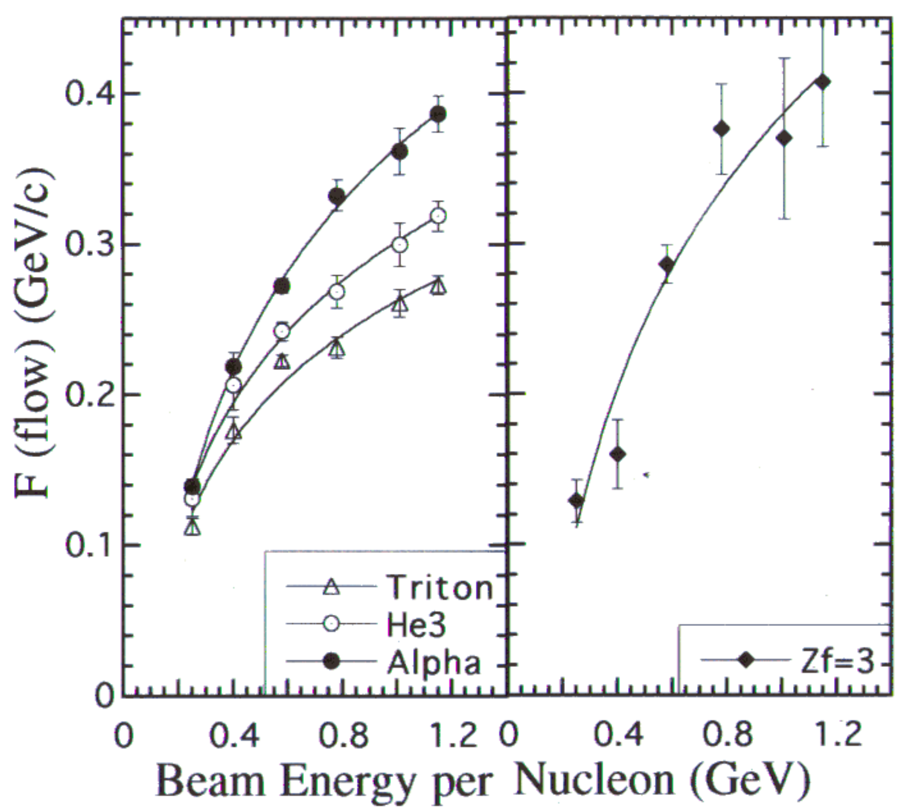
Flow excitation function



M. Partlan and EOS

Flow measured as function of Mass and Energy





Representations of Elliptic Flow

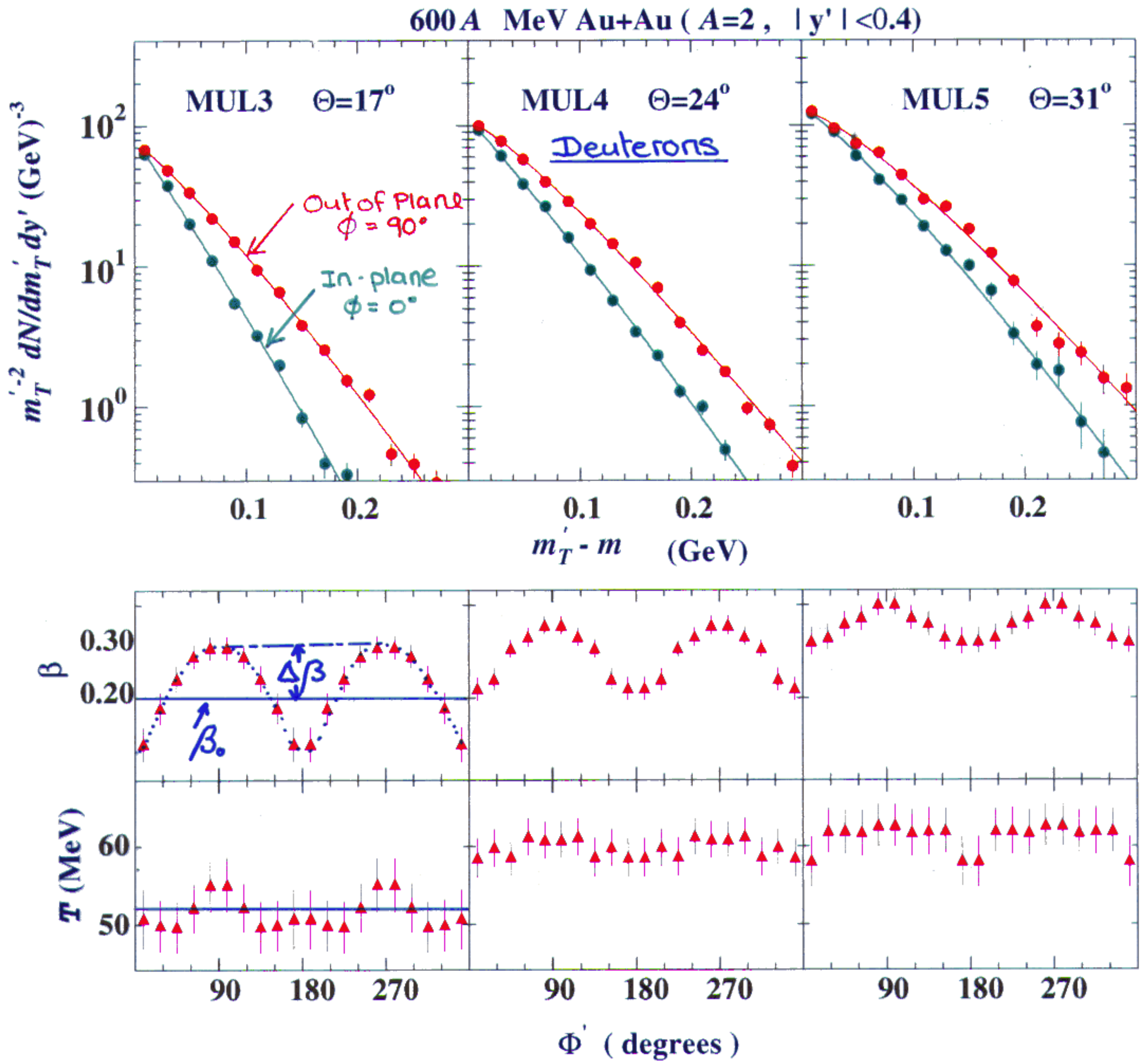
Early Analyses used the Number Ratio R
R is a function of transverse momentum Pt

Latest Methods

- Velocity Modulation
- One parameter describes Pt dependence

- Fourier Expansion of the Azimuthal Angular Distribution
- Quite Popular

Expansion Velocity Modulation

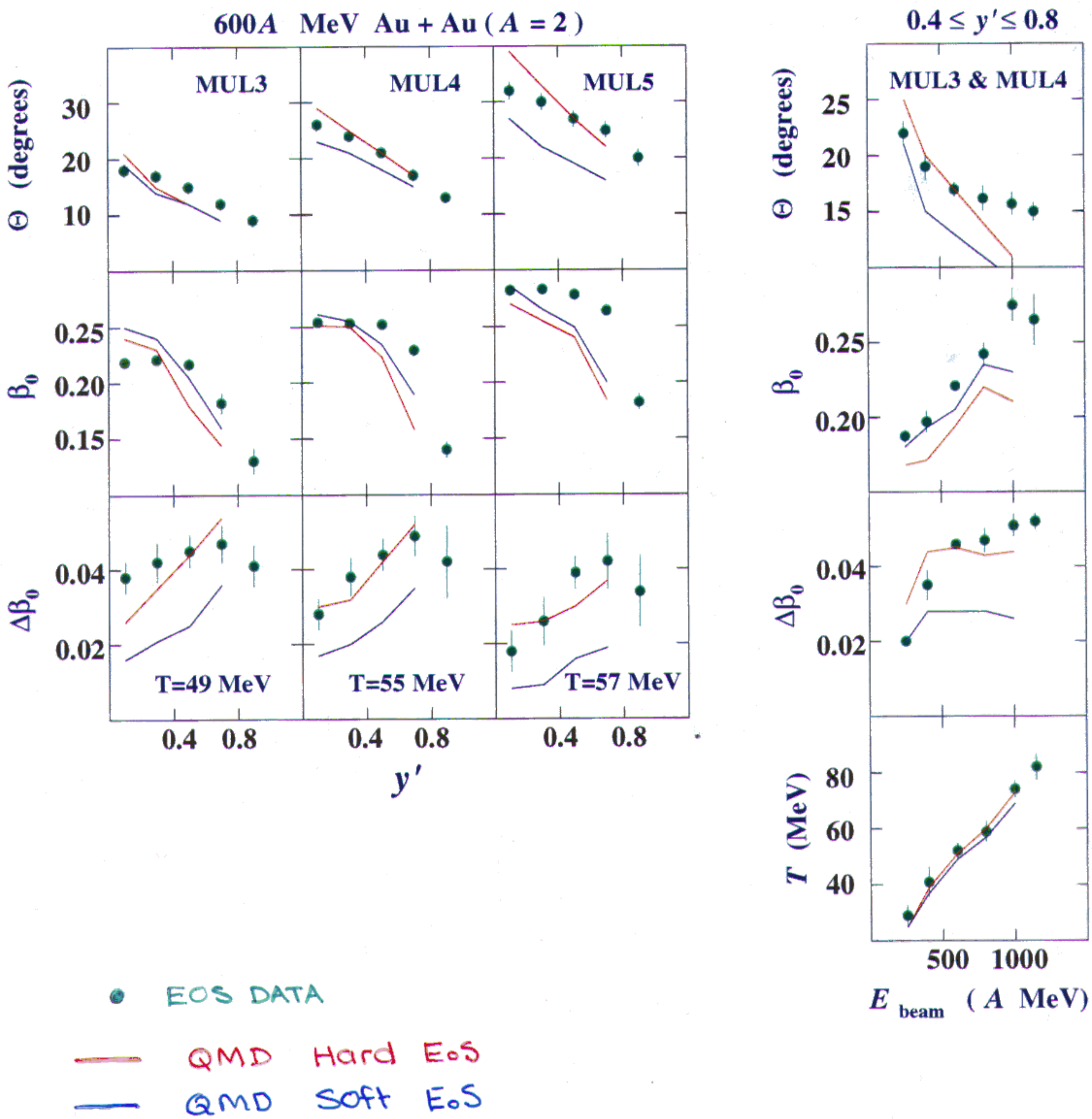


$$\beta(\Phi') = \beta_0 - \Delta\beta \cos 2\Phi'$$

β is the expansion velocity

$$\frac{dN}{m_\perp^2 dm_\perp dy} = N_0 \cosh y \left[\frac{\sinh\alpha}{\alpha}(\gamma + T_r) - T_r \cosh\alpha\right] \exp\left(-\frac{\gamma}{T_r}\right)$$

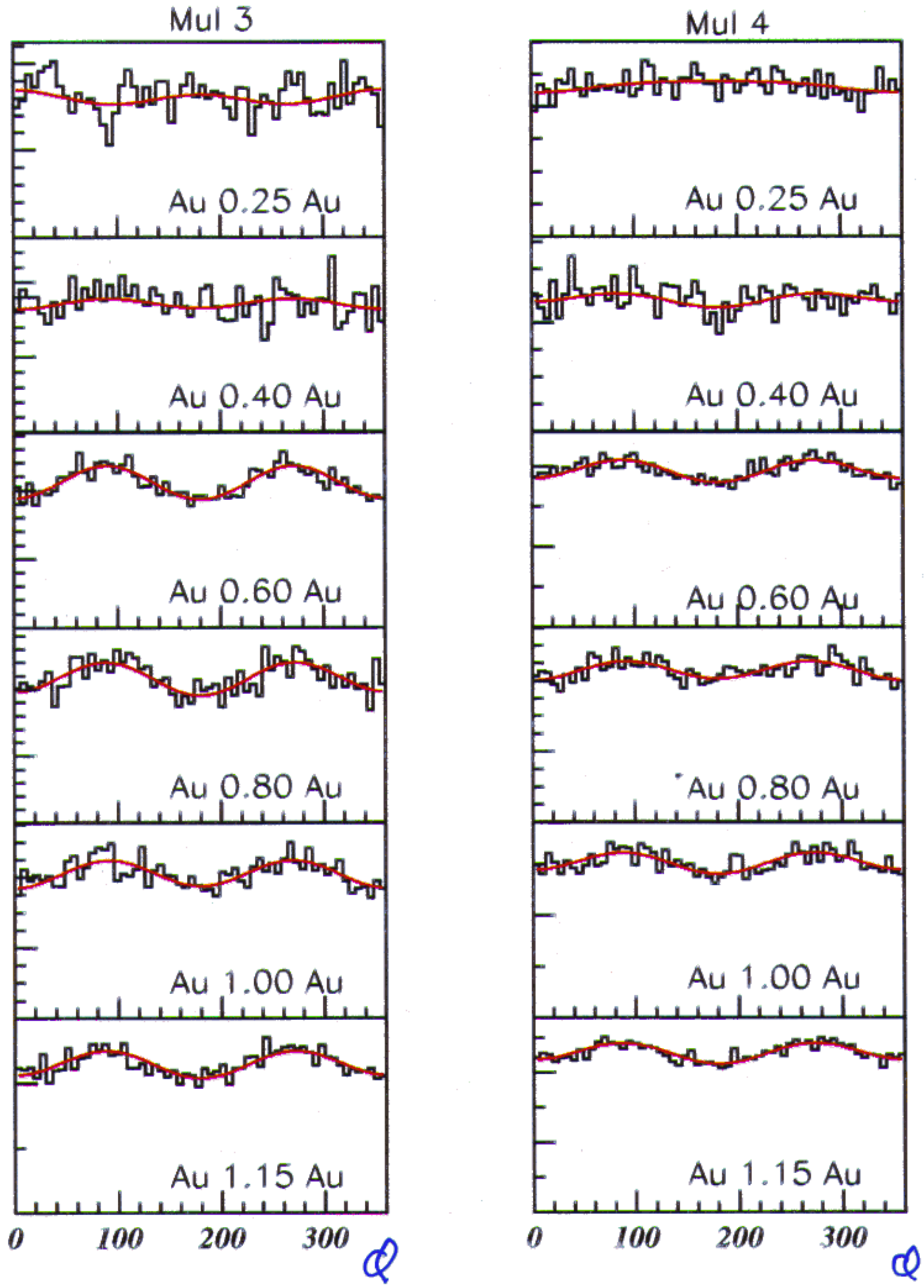
Siemans + Rasmussen 79

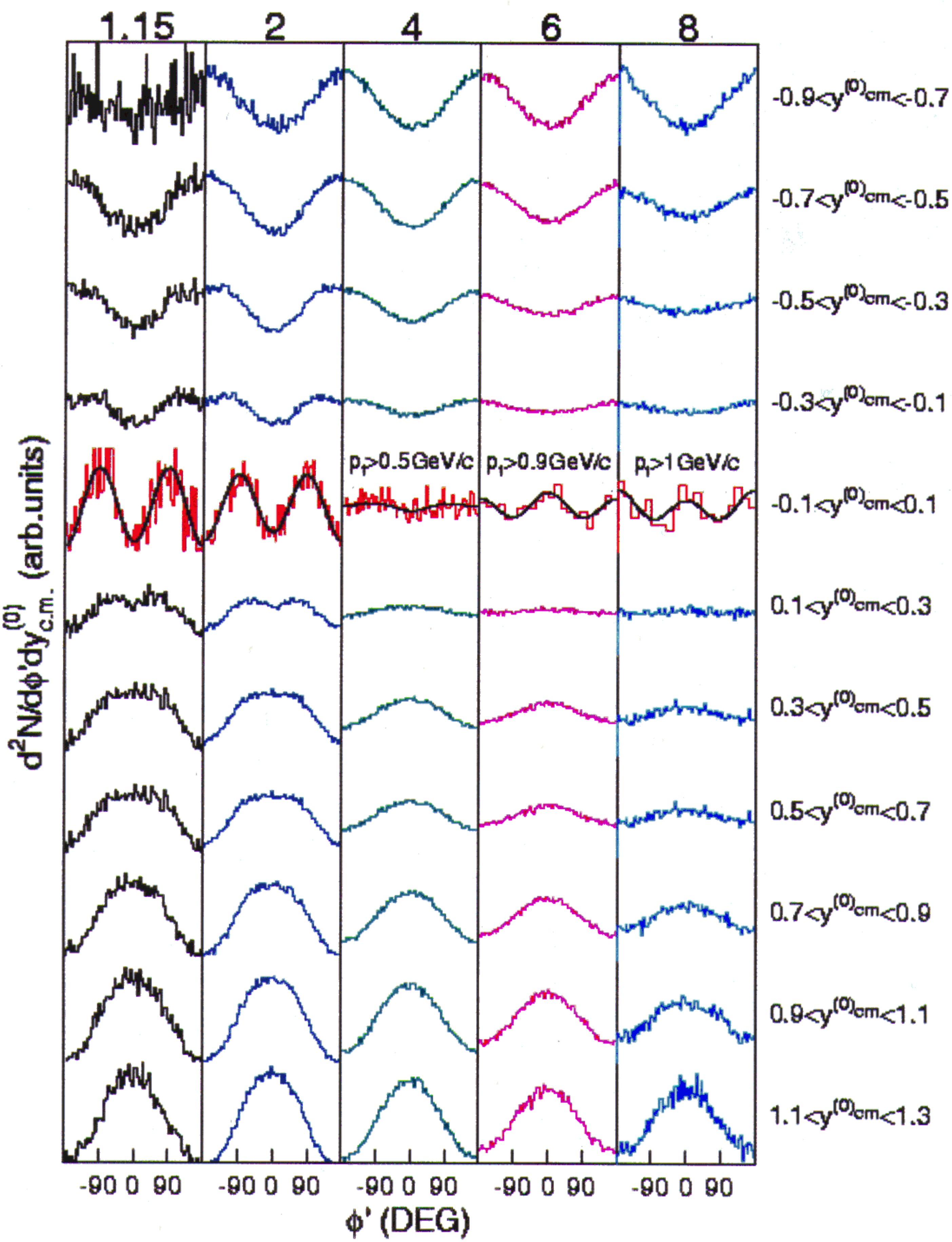

600A MeV Au + Au (A = 2)
MUL3
MUL4
MUL5
Θ (degrees)
30
20
10
β0
0.25
0.20
0.15
Δβ0
0.04
0.02
T=49 MeV
T=55 MeV
T=57 MeV
0.4
0.8
y′
0.4 ≤ y′ ≤ 0.8
MUL3 & MUL4
25
15
T (MeV)
80
60
40
500
1000
E beam (A MeV)
EOS DATA
QMD Hard EoS
QMD Soft EoS

Fourier Analysis

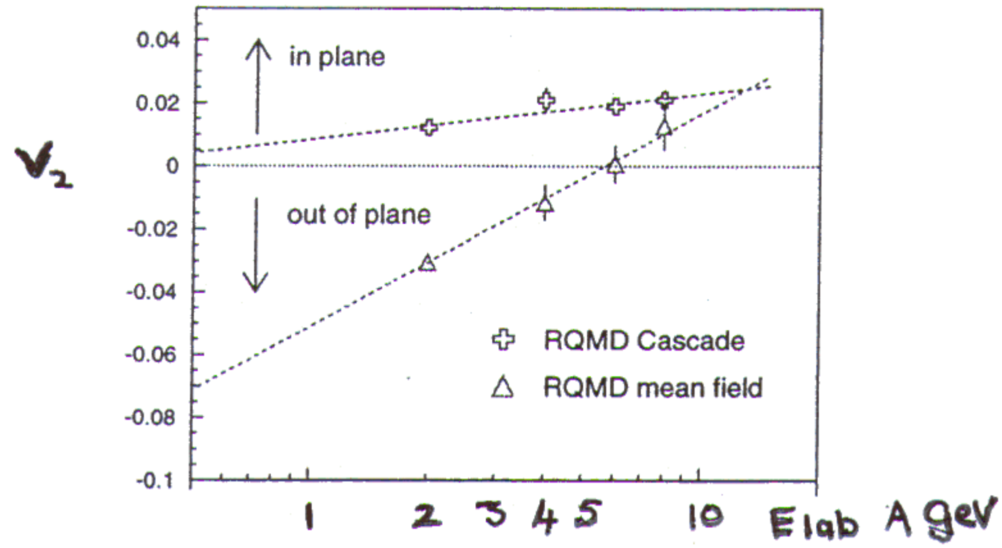
- Fit $dN/d\Phi \sim 1+2v_1*\cos(\Phi) + 2v_2*\cos(2\phi)$
- $v_2 = \langle \cos(2\Phi) \rangle$, Φ wrt reaction plane
- $v_2 < 0$ Squeeze-out, $v_2 > 0$ In-plane
- v_2 corrected for dispersion
  - Poskanzer & Voloshin, Ollitraut

Protons at Mid-Rapidity

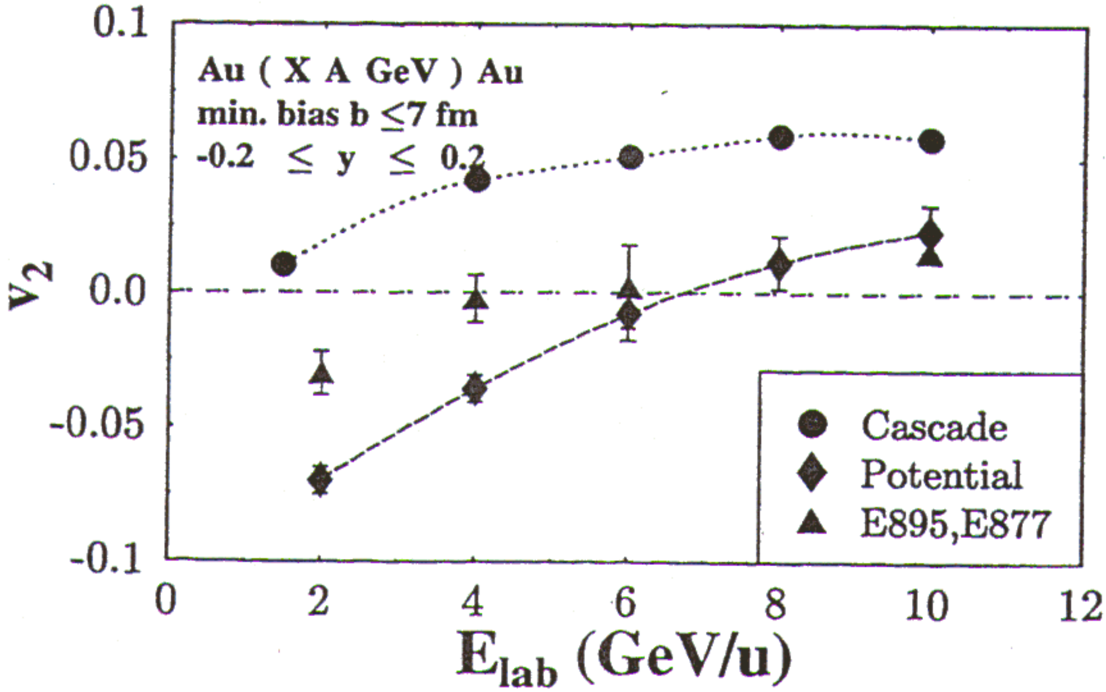



1.15
2
4
6
8
-0.9<y(0)cm<-0.7
-0.7<y(0)cm<-0.5
-0.5<y(0)cm<-0.3
-0.3<y(0)cm<-0.1
-0.1<y(0)cm<0.1
0.1<y(0)cm<0.3
0.3<y(0)cm<0.5
0.5<y(0)cm<0.7
0.7<y(0)cm<0.9
0.9<y(0)cm<1.1
1.1<y(0)cm<1.3
pt>0.5GeV/c
pt>0.9GeV/c
pt>1GeV/c
d2N/dφ'dy(0)c.m. (arb.units)
-90 0 90
φ' (DEG)

Au+Au 3fm<b<fm6



uRQMD



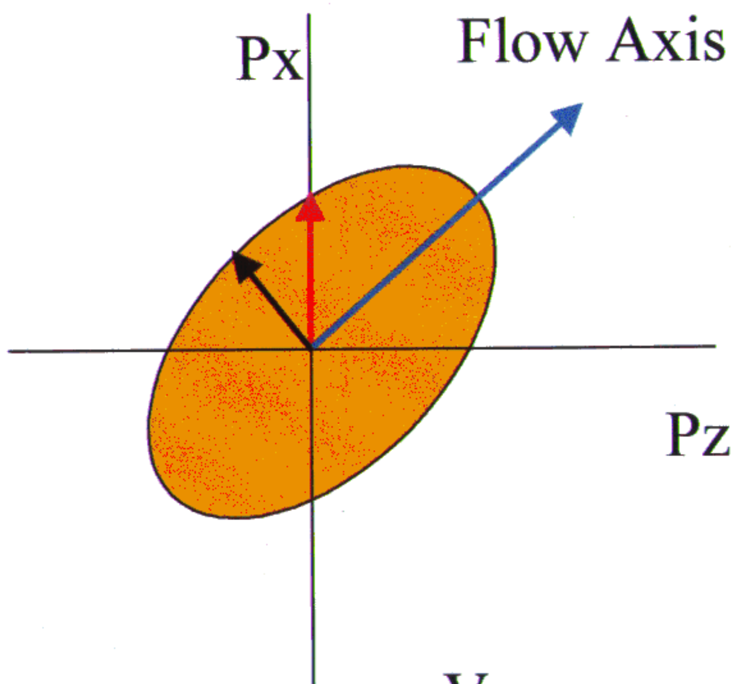
uRQMD Definition of V_2 ?

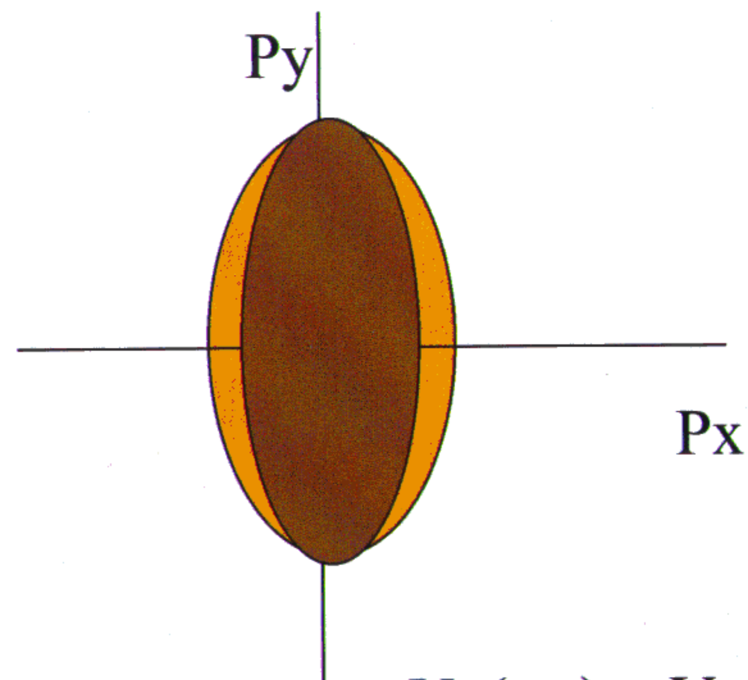
if $V_2^{uRQMD} = 2 V_2^{exp}$

Potential gives better agreement.

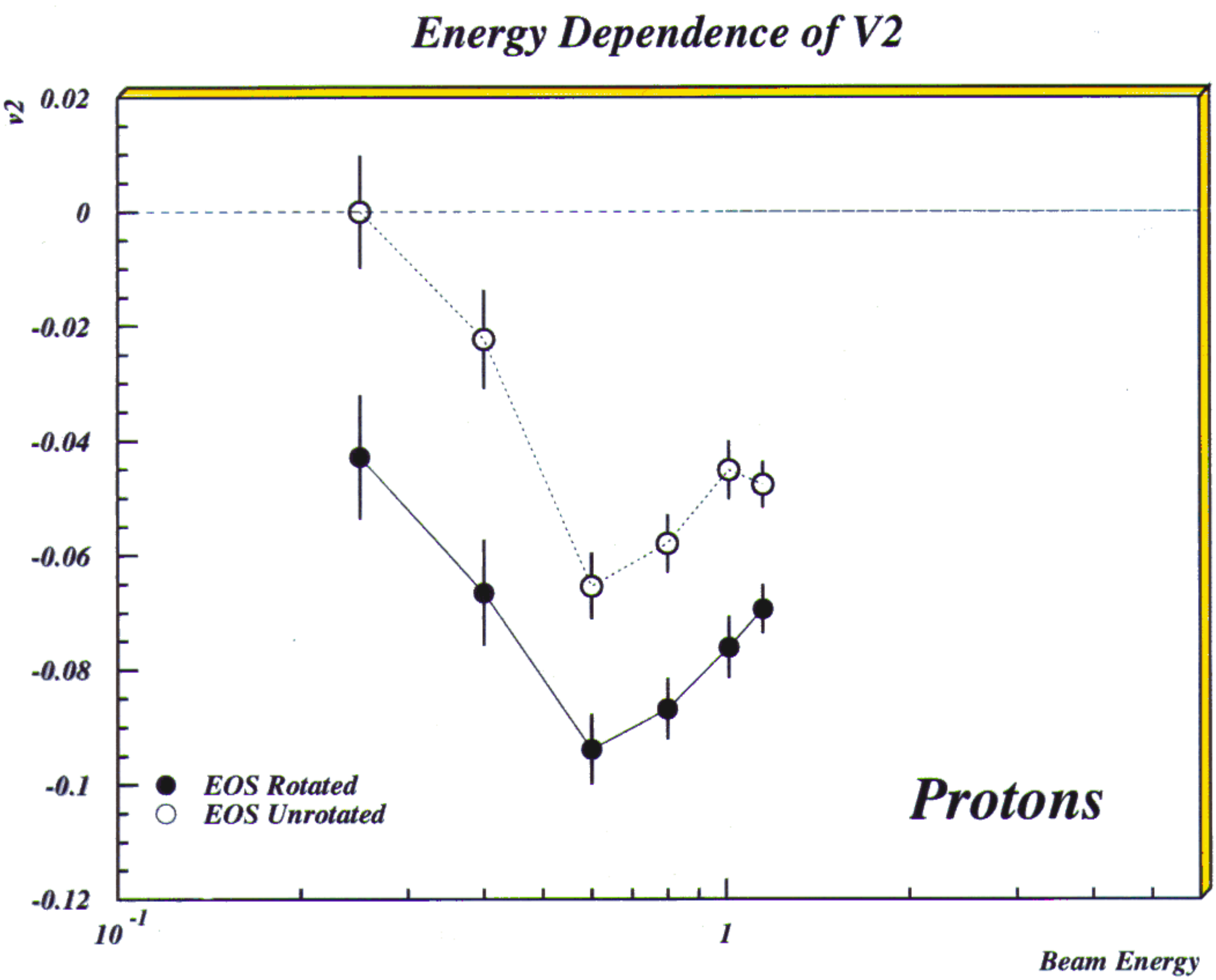
S. Bass et al 98

Rotation into flow frame increases V_2





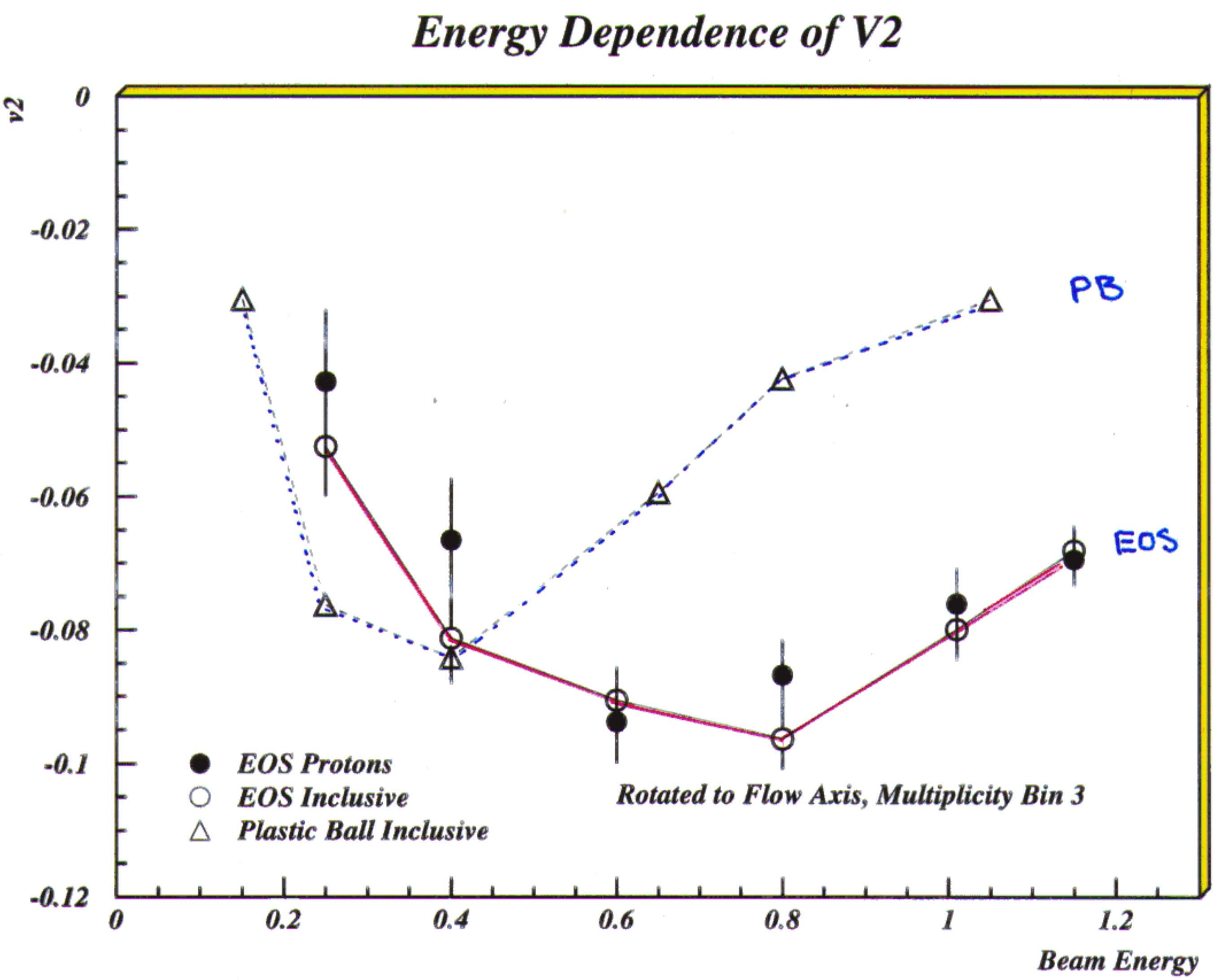
PRELIMINARY EOS DATA



Rotation applied event by event

not dispersion corrected

dispersion, direct comparison with plastic ball



PLASTIC BALL MEASURES $R \equiv \frac{1 - 2V_2}{1 + 2V_2}$

$\therefore \quad V_2 = \frac{1 - R}{2(1 + R)}$

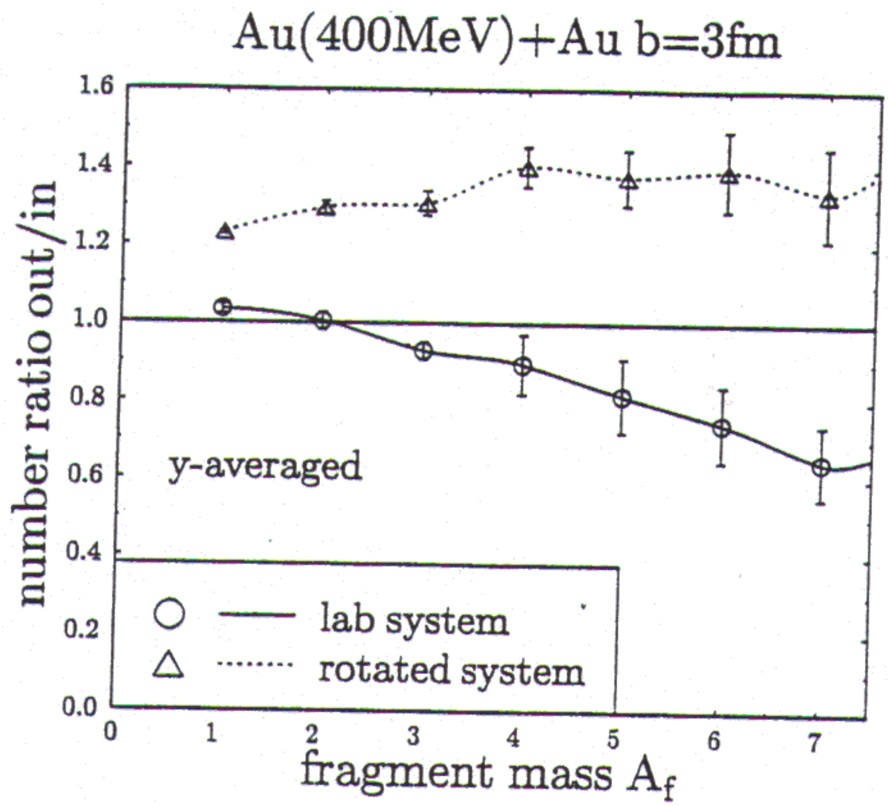
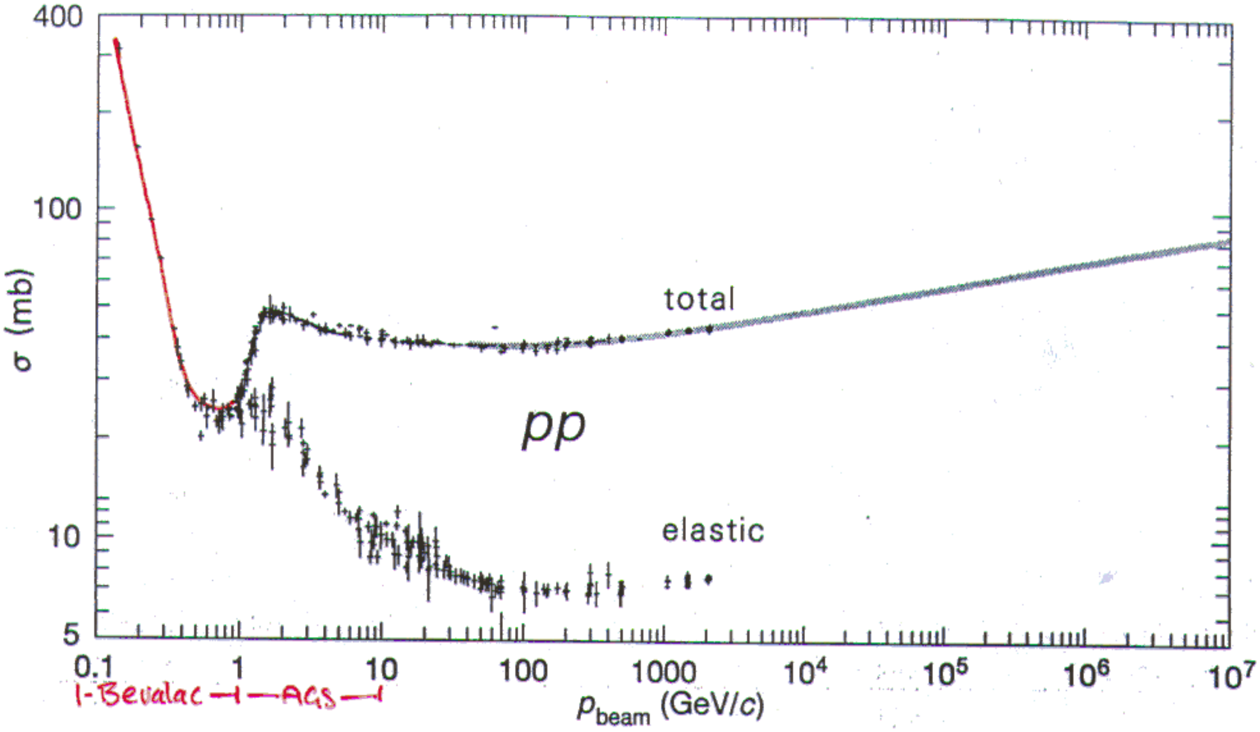
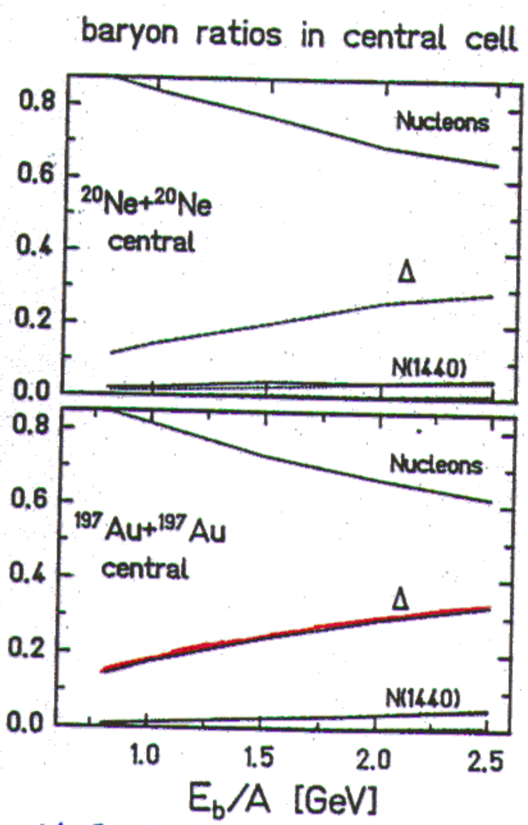


Figure 3: Comparison of the out-of-plane to in-plane ratio of fragments from all rapidities taken in the lab system and in the rotated system.

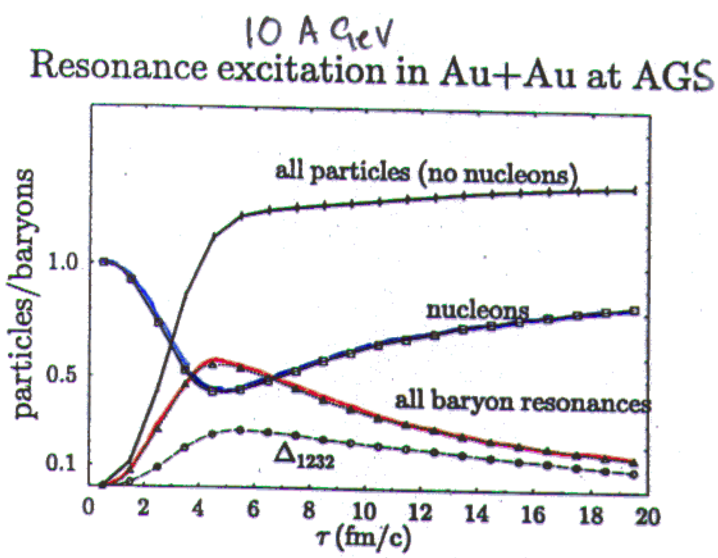
$$\text{Number Ratio} = R_N = \left. \frac{\frac{dN}{d\varphi}(\varphi = 90^\circ) + \frac{dN}{d\varphi}(\varphi = 270^\circ)}{\frac{dN}{d\varphi}(\varphi = 0^\circ) + \frac{dN}{d\varphi}(\varphi = 180^\circ)} \right|_{Y = Y_{cm}}$$

C. Hartnack, IQMD





W. Ehehalt et al PRC 47 (1993) 2467



Nucl. Phys A 566 (1994) 15c
M. Hoffmann et al

Kaons in Dense Matter

Probe In-Medium Modifications

Potential = scalar (attractive) + Vector part

- Kaon Mass Changes with increasing nuclear density
- Affects the yields

- Kaons and Anti kaons propagate differently
- Affect Directed flow
- Azimuthal emission pattern

Rationale

- Directed and Elliptic flow built-up in very early stages of the collision
- Sensitive to the pressure (baryon density) and hence Equation of State (EoS)
- Hot Topic: Probing the softest point in EOS
  - Does it exist ?
  - If so what causes it ? Resonance Matter, QGP, other ?