Collective flow measurements:
Selected results from low and high energies

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"REPETITION IS GOOD"
N. XU

Progression of flow studies

- establishment of flow phenomena
- characterization/disentanglement
- systematics (information-rich)
- extraction of physics (models)

Where are we in low/high energy studies?

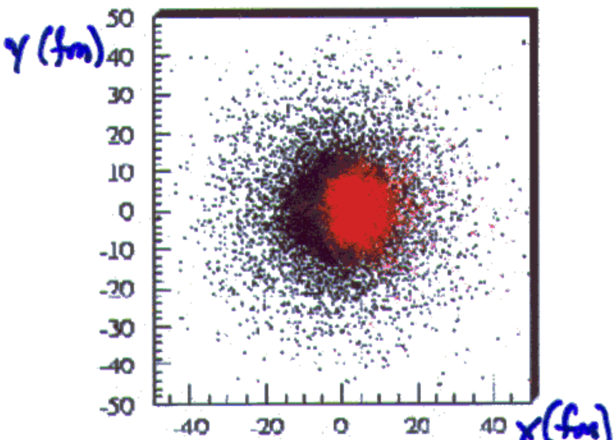
With randomizing "thermal" motion, flow velocity field determines d^3N/dp^3

RHIC Winter Workshop
LBNL Jan 98

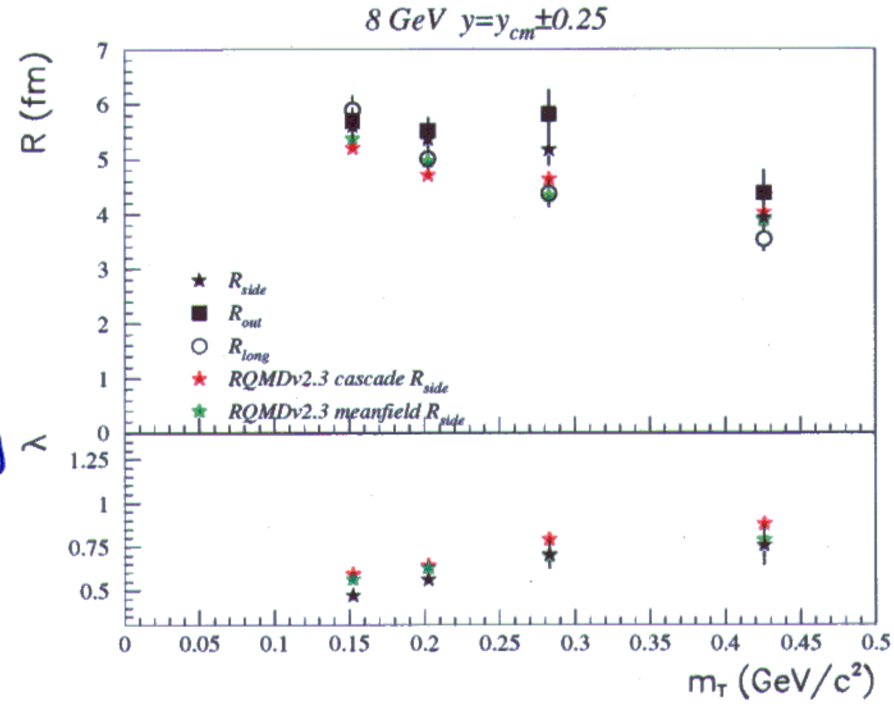
Interferometry (HBT) studies

x-p correlations reduce viewable source

RQMD 8GeV Au+Au



Meanfield- Px>300 MeV/c



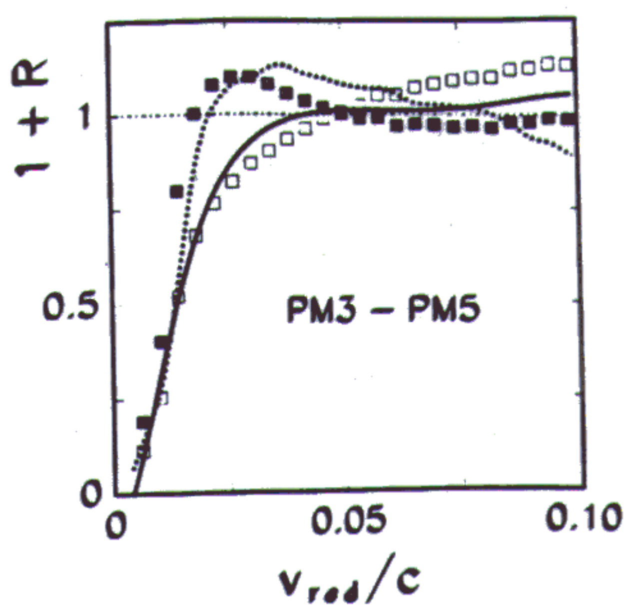
Lisa *et al* (E895) to be published

event-to-event variation in directed flow direction induces additional correlation in Q for "real" pairs

IMF - IMF CORRELATION AT SIS (Au+Au)

■ RAW MEASURED C.F. (STRANGE SHAPE!)

□ C.F. ACCOUNTING FOR DIRECTED FLOW



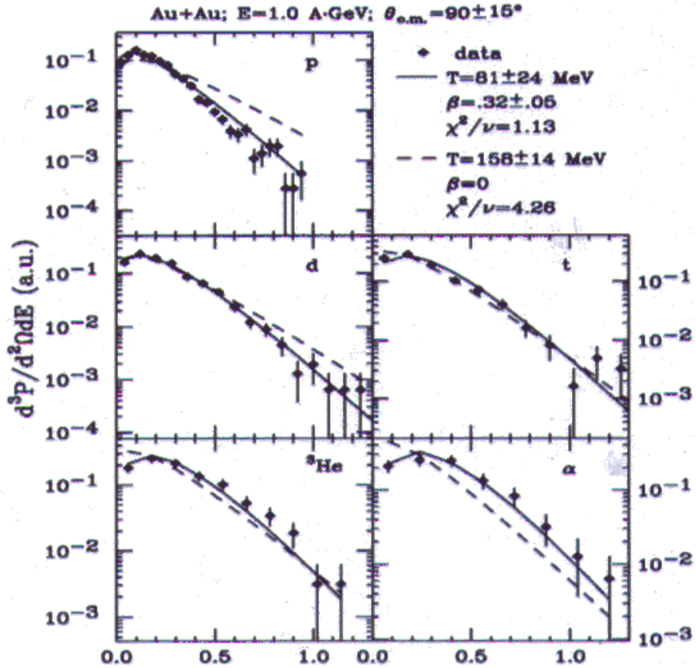
Kämpfer et al PRC R955 (93) (FOPI)

Radial (transverse isotropic) flow

Spectra naturally described by (nearly) common flow velocity and thermal motion

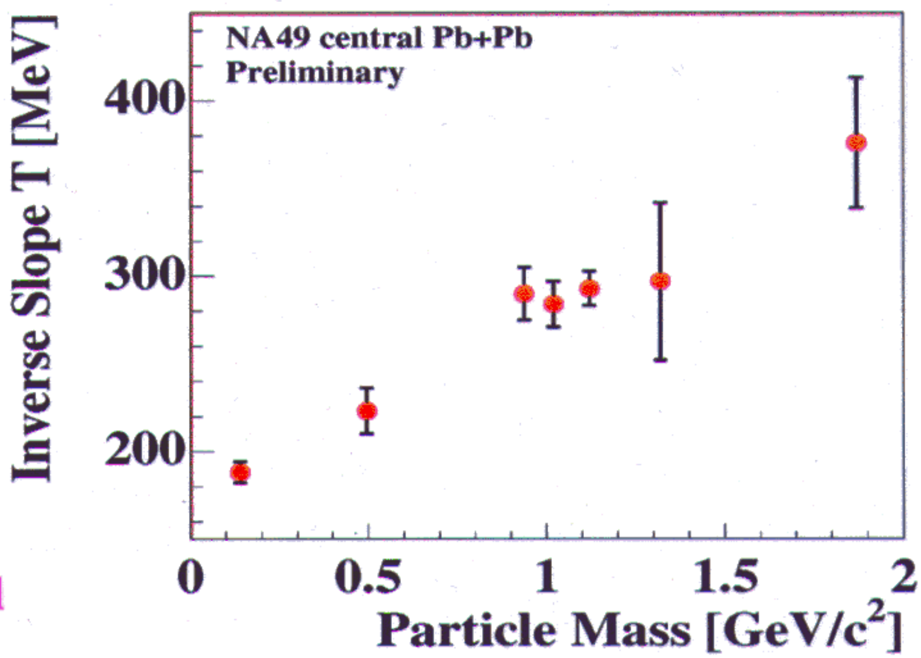
Increasing mass → increasing <p_T> (or T_B)

1 AGeV Au+Au



Lisa *et al* (EOS), PRL **75**, 2662 (1995)

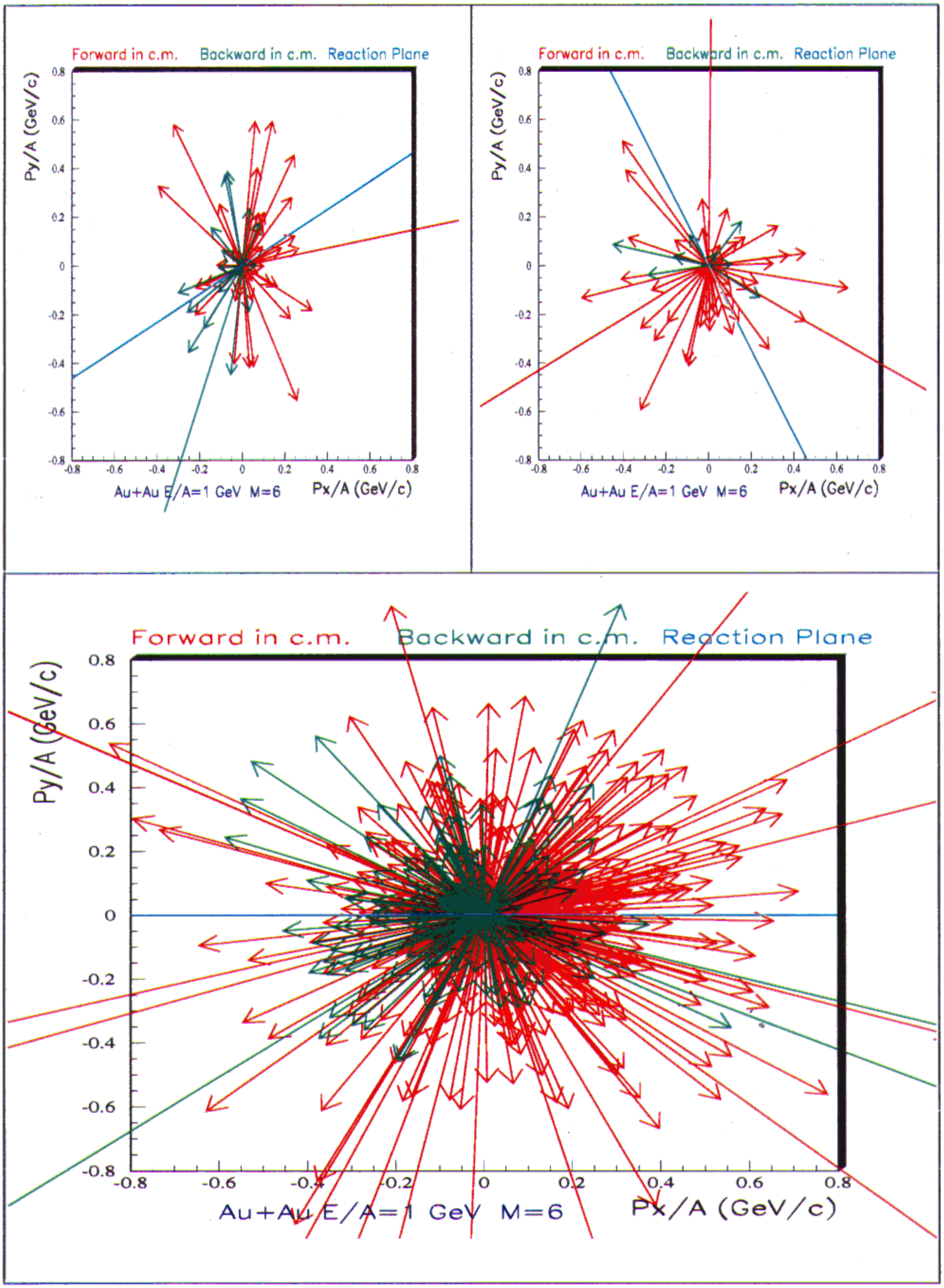
158 AGeV Pb+Pb



G. Roland *et al* (NA49), NPA **638**, 91c (1998)

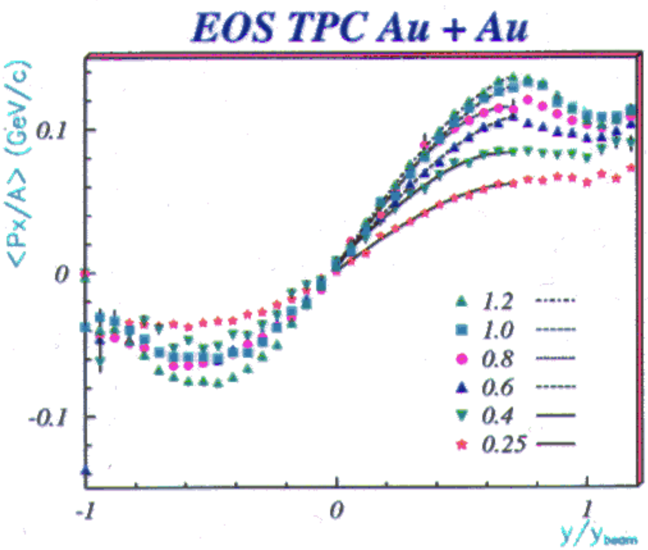
~ 50% transverse kinetic energy in radial flow → crucial for any global thermochemical analysis

EVENTWISE SIDEWARD FLOW AT 1 AGeV

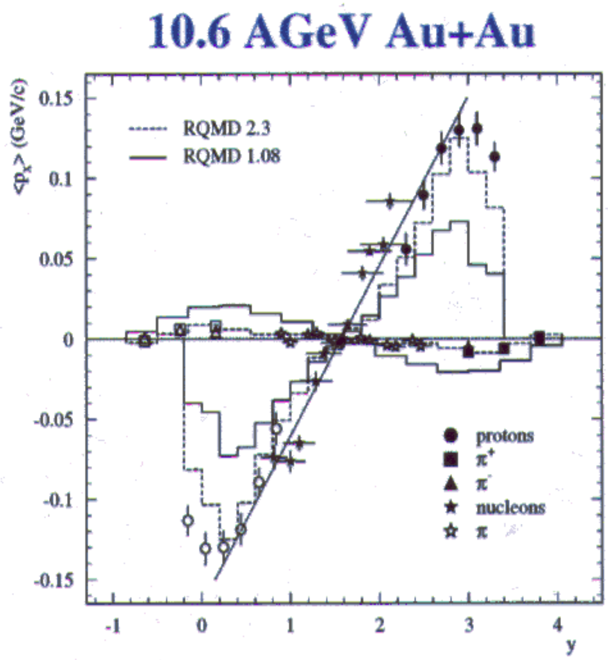


(EOS)

Sidewards directed flow



Partlan *et al* (EOS) PRL **75**, 2100 (1995)



Barrette *et al* (E877) PRC **56** 3254 (1997)

$$F_y = \left.\frac{d\langle p_x\rangle}{dy}\right|_{y_{c.m.}}$$

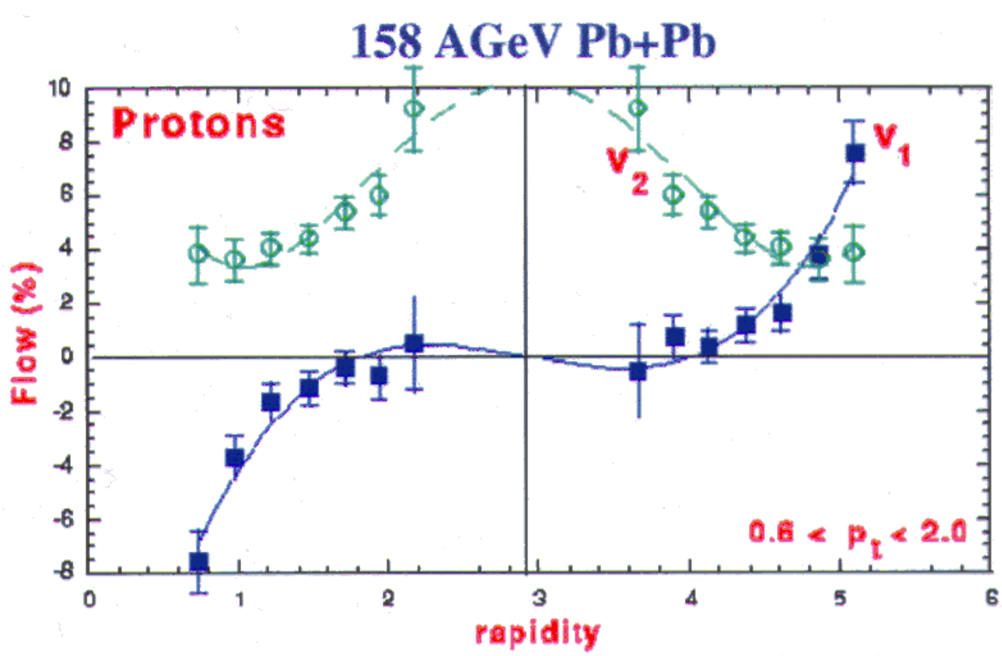
$$\langle p_x\rangle = \frac{1}{N}\int v_1(p_T)p_T\frac{dN}{dp_T}dp_T$$

$$\frac{d^3N}{p_T dy dp_T d\phi} = \frac{1}{2\pi}\frac{d^2N}{p_T dy dp_T}\cdot(1+2v_1\cos(\phi)+2v_2\cos(2\phi)+\ldots)$$

$$v_1 = \langle\cos(\phi)\rangle$$

$$v_2 = \langle\cos(2\phi)\rangle$$

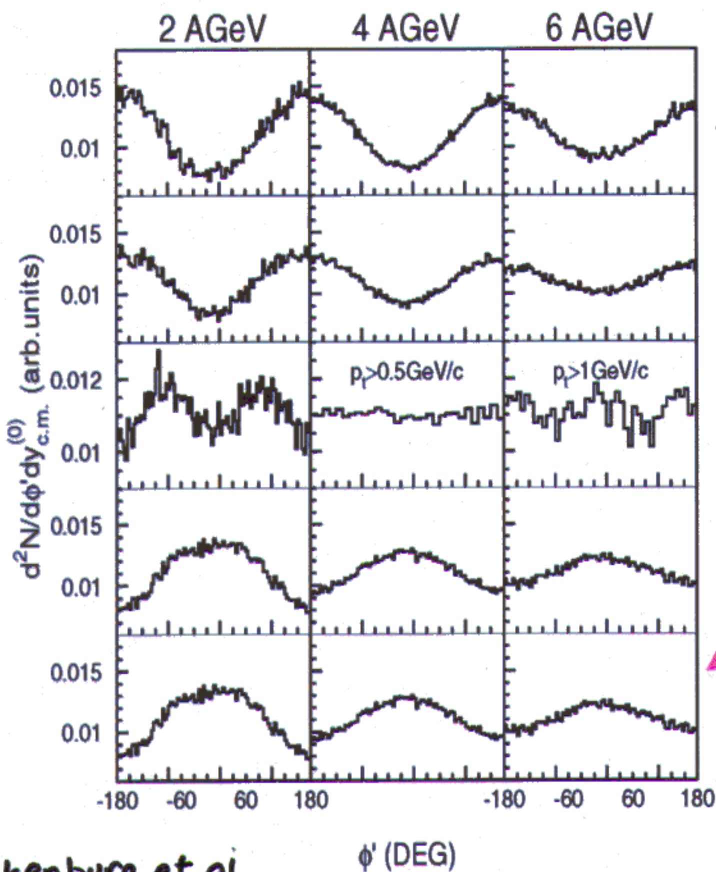
Higher moments not yet observed



Appelshauser *et al* (NA49) PRL **80**, 4136 (1998)

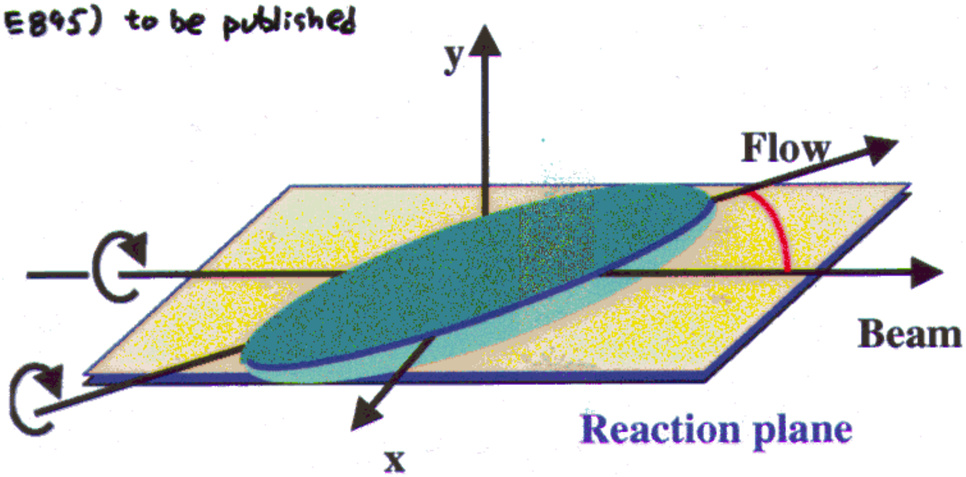
Elliptic Flow

$$1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots$$

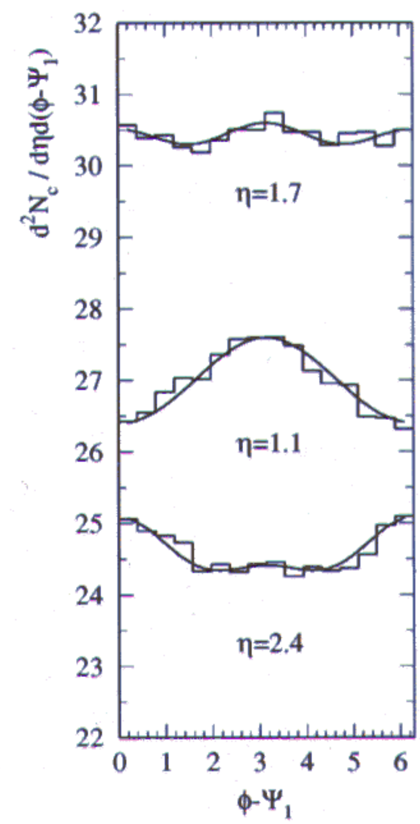


Pinkenburg et al (E895) to be published

Sideward flow in unrotated frame



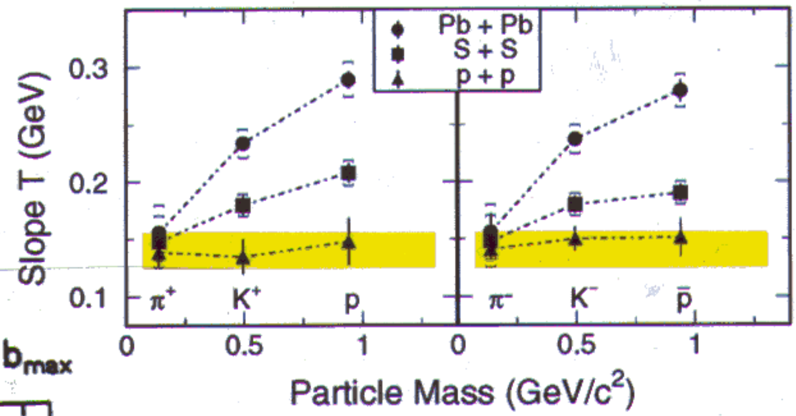
Barrette *et al* (E877), PRC **55**,1420 (1997)



First observed at AGS & SPS as correlated anisotropies in energy

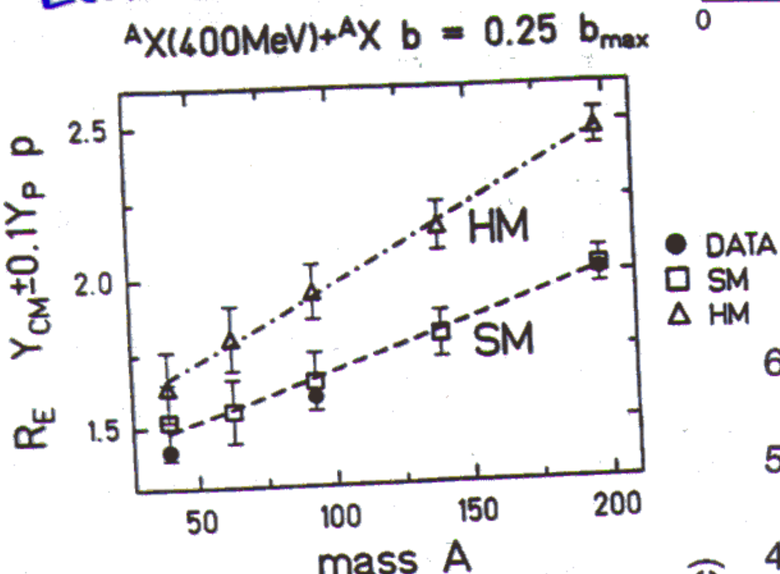
Flow - bulk property- depends on system mass

RADIAL FLOW (160 A GeV)



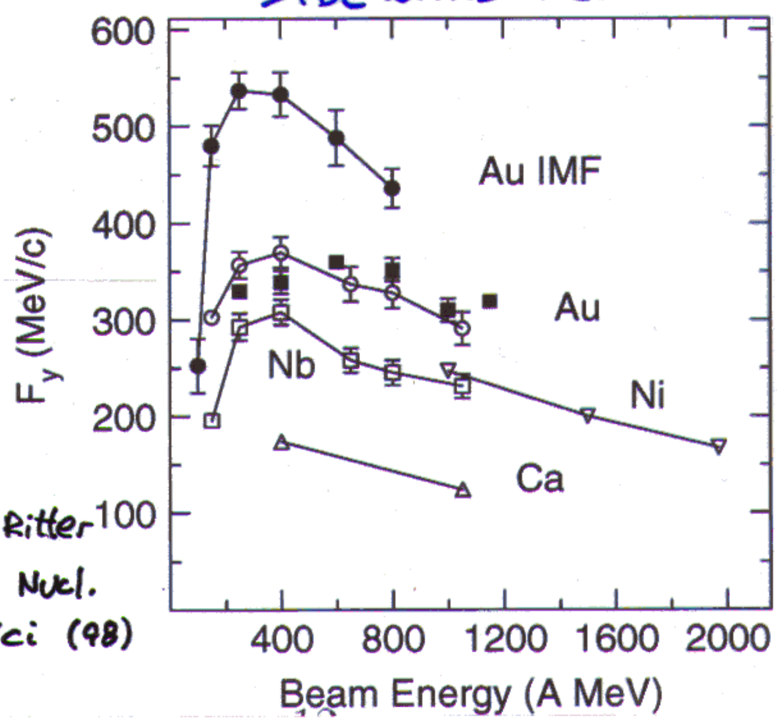
NA44 PRL (97)

ELLIPTIC FLOW



HARTNACK et al
Mod Phys Lett A9 (94)

SIDEWARD FLOW



Reisdorf + Ritter
Rep. Prog. Nucl.
Part. Sci (98)

p

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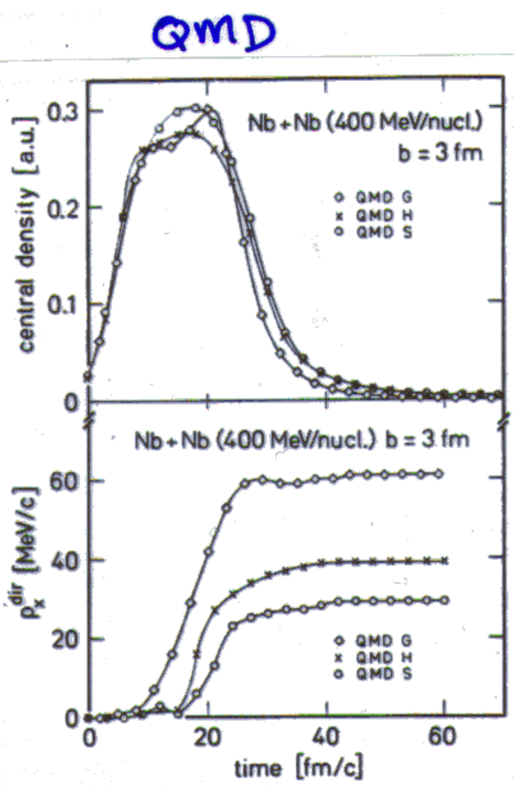
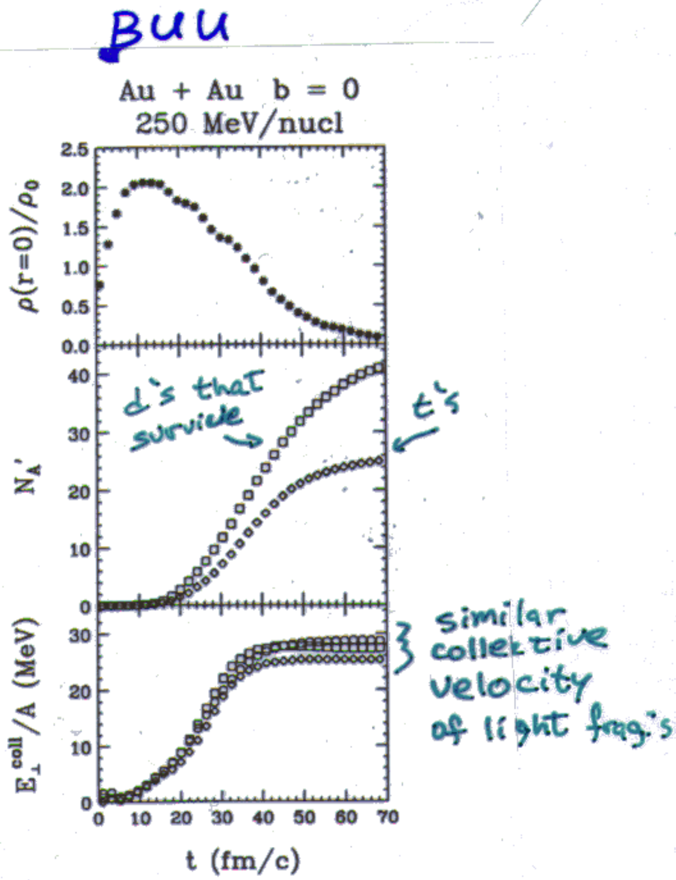
Probing the dynamics at different timescales



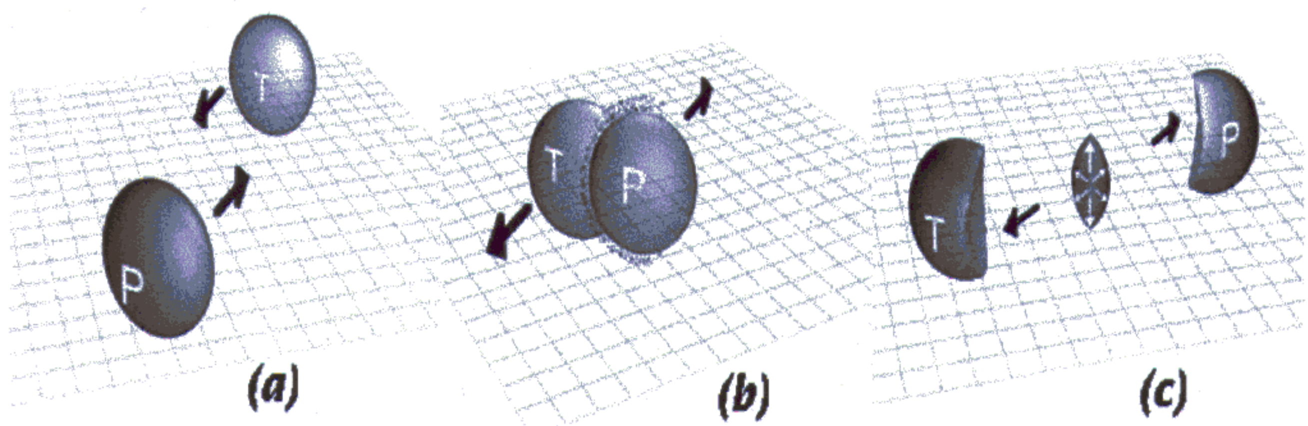
Jaenicke *et al*, NPA **536**, 201 (1992)



Danielewicz and Pan, PRC **46** 2002 (1992)

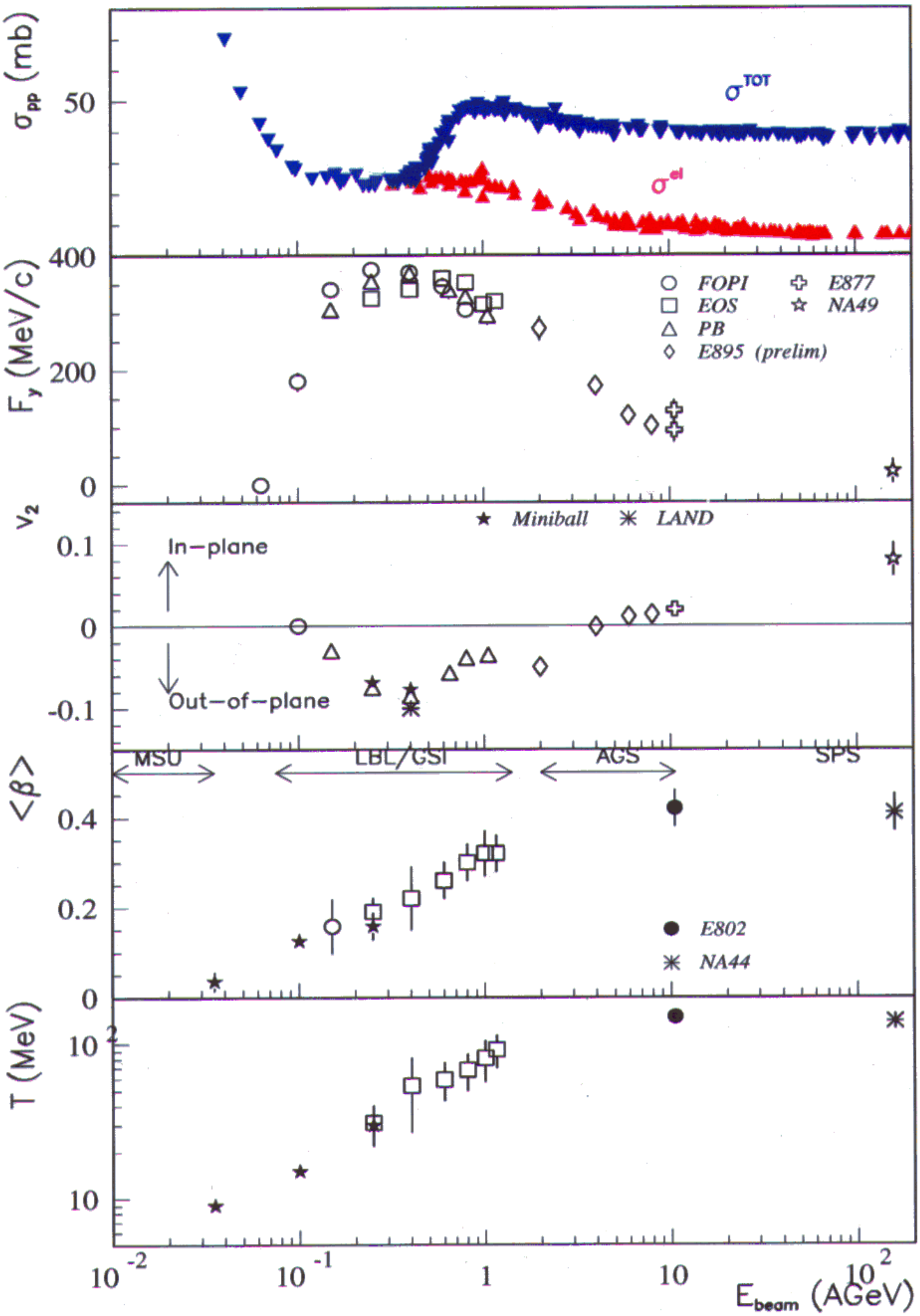
- Directed flow built up early in compressed phase
- Radial flow develops late, via rescattering, stopped by freeze-out
- Elliptic flow results from competition between early pressure/shadowing and later radial-type flow

MEASURE THEM SEPARATELY

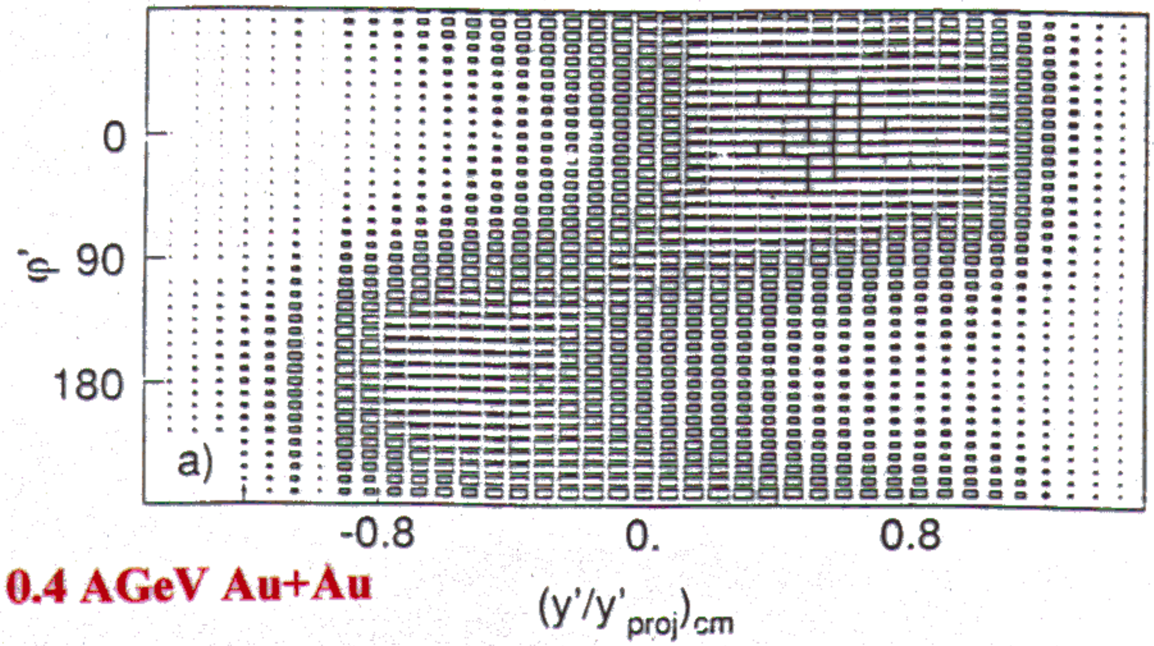


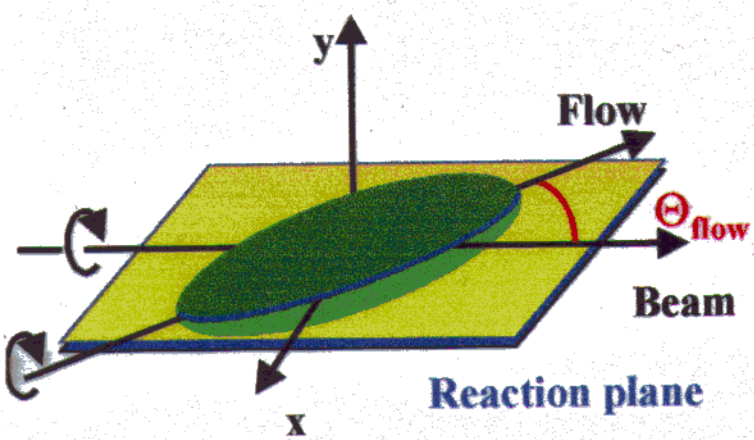
P. Danielewicz *et al*,PRL **81**, 2438 (1998)

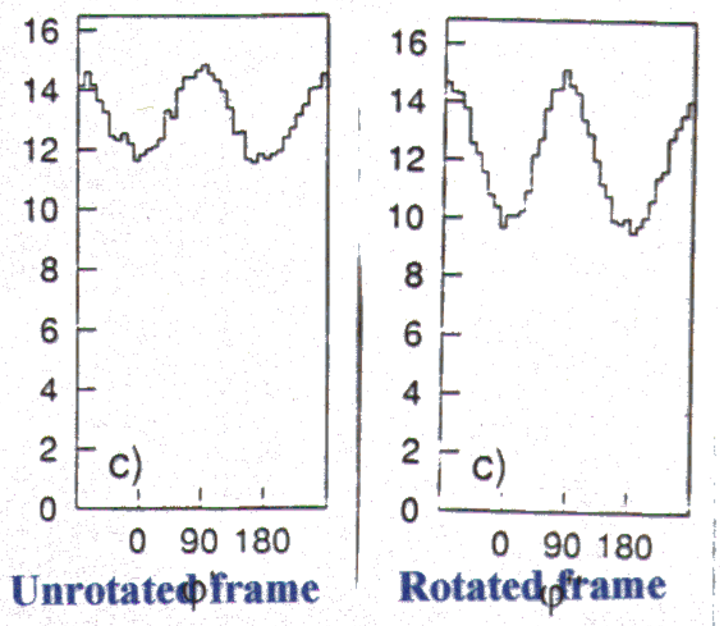
Much of available data on heaviest systems



Entanglement of Sidewards and elliptic flow

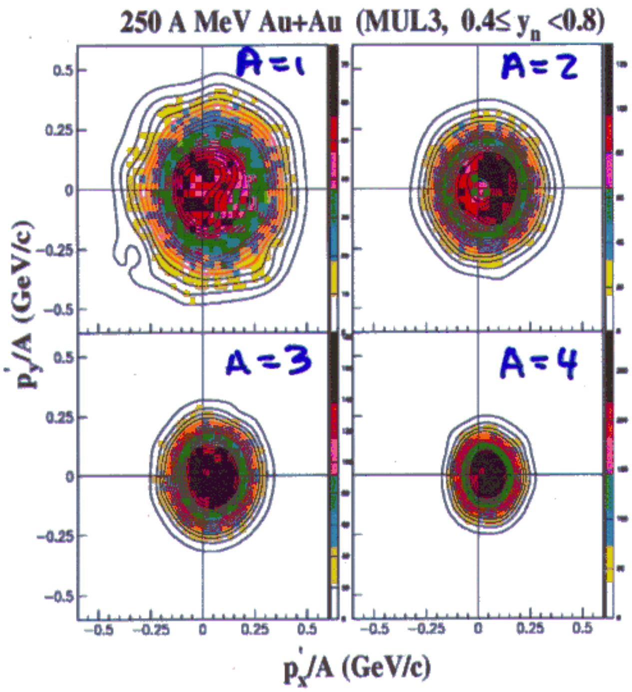






Gutbrod *et al* (Plastic Ball), PLB **216**, 267 (1989)

Entanglement of sidewards and radial flow



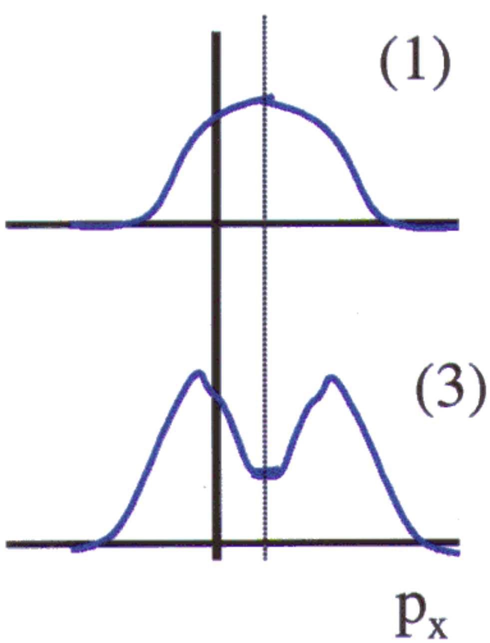
D. Keane & Shan Wang

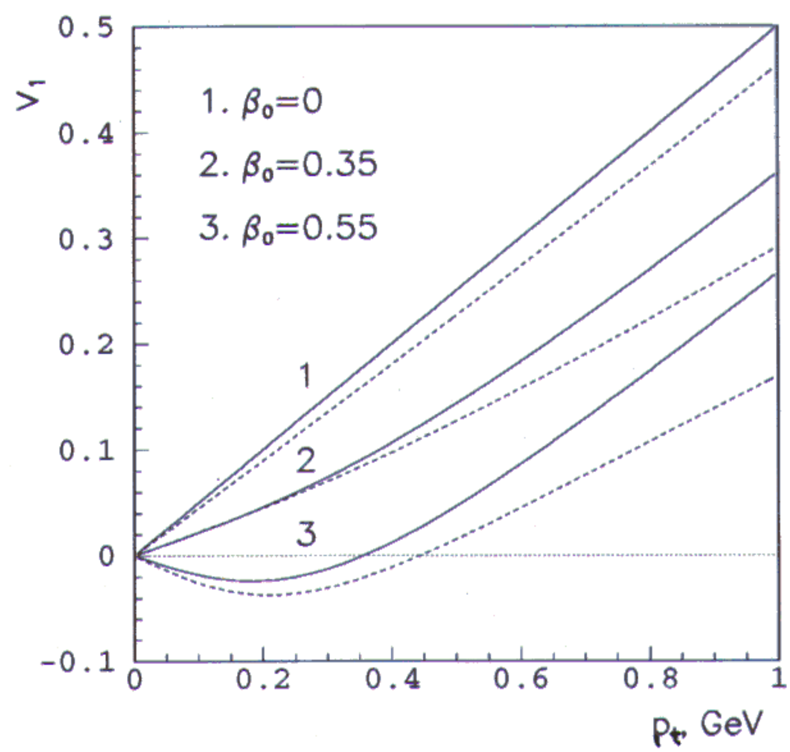
Sidewards flow
≅ "shift" of symmetry axis in velocity space

explosive (radial) flow relative to this axis

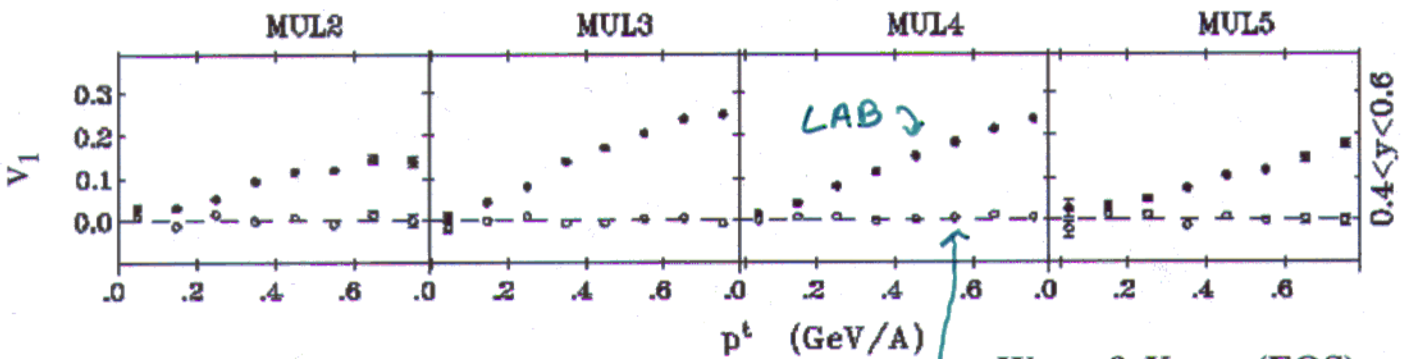
measurement in unnatural frame → entanglement

S. Voloshin PRC55 R1630 (1997)





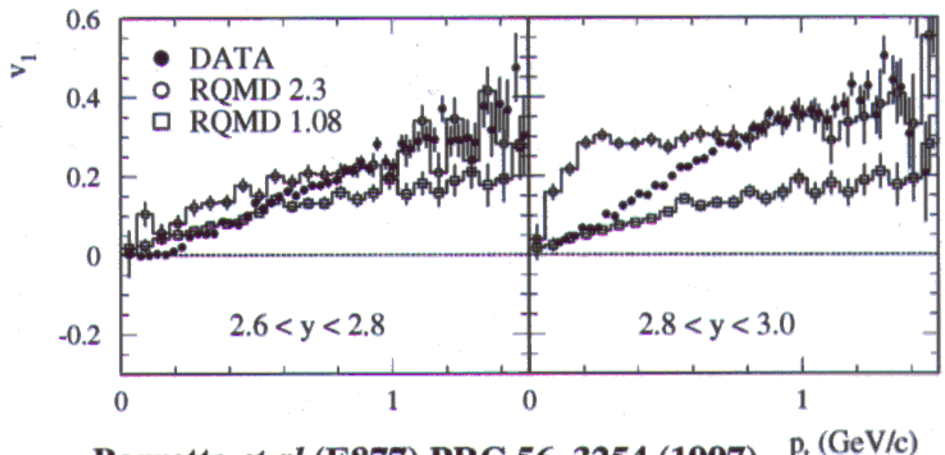
Au+Au E = 1.15 AGeV



Wang & Keane (EOS)

1 GeV - single rotation flattens v_1

Au+Au E = 10.6 AGeV

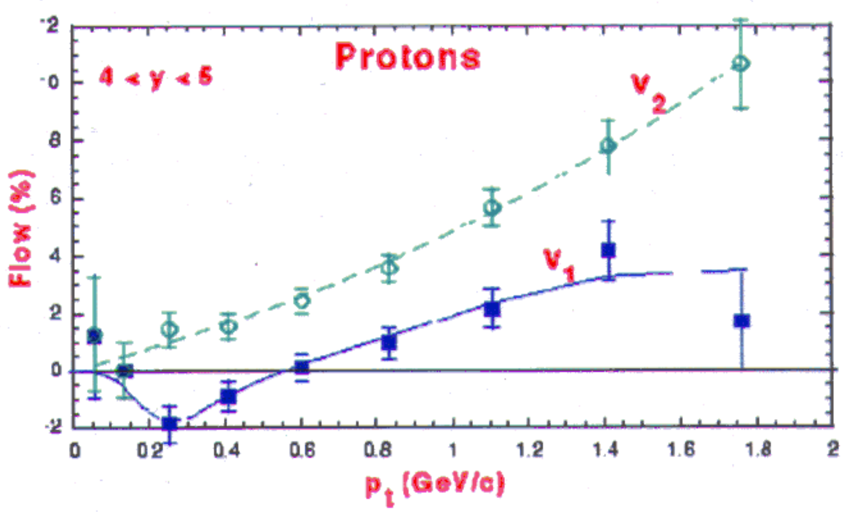


Barrette *et al* (E877) PRC 56, 3254 (1997)

Radial flow . . . . . ↑
Sideward flow . . . ↓
→ more interference

Most (all?) of p_T dependence likely an artifact of viewing in skewed frame

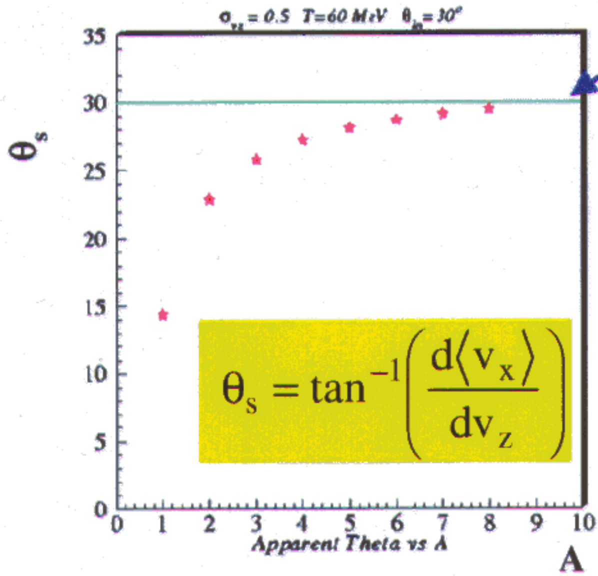
Pb+Pb E = 158 AGeV



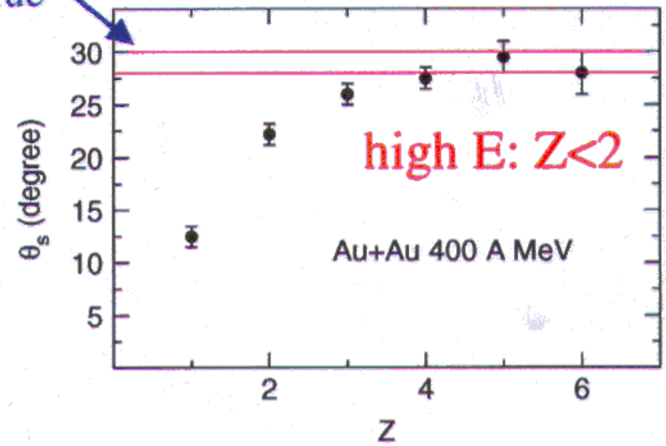
Appelshauser *et al* (NA49) PRL 80, 4136 (1998)

Decoupling effects may allow clearer investigation of model discrepancies

(much of) **A-dependence of sidewards flow:** interplay between <u>constant</u> velocity field + T



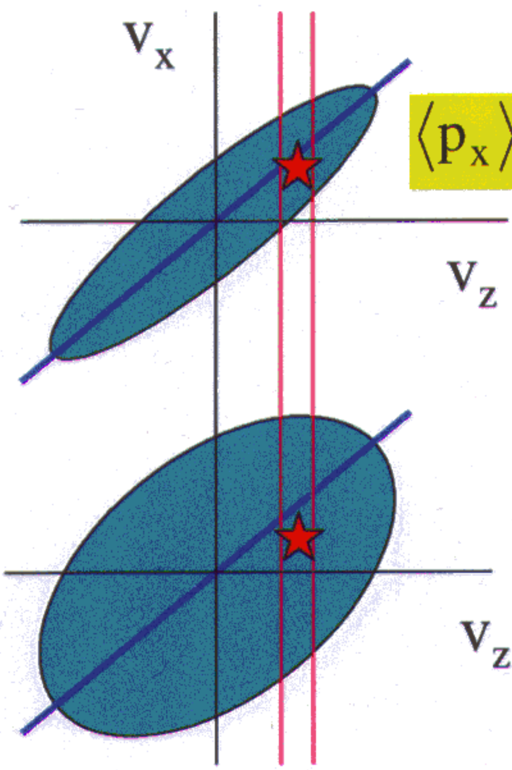
θ_{true}



Tilted velocity source with thermal smearing

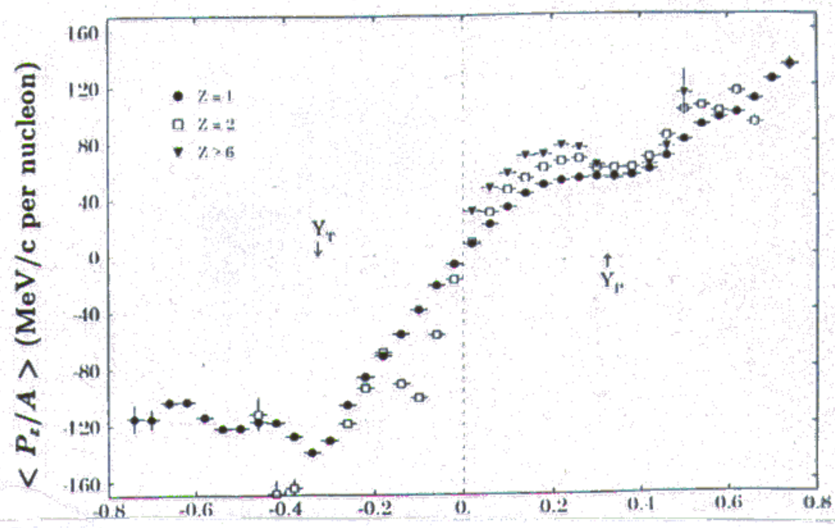
Reisdorf & Ritter Ann. Rev. Nucl. Part. Sci. 47 663 (1997); Crochet (FOPI)

DIFF. BETWEEN VARIOUS SCENARIOS SUBTLE
⇒ REMOVE "BASELINE" SYSTEMATICS



$$\langle p_x\rangle_A \neq A\langle p_x\rangle_p$$

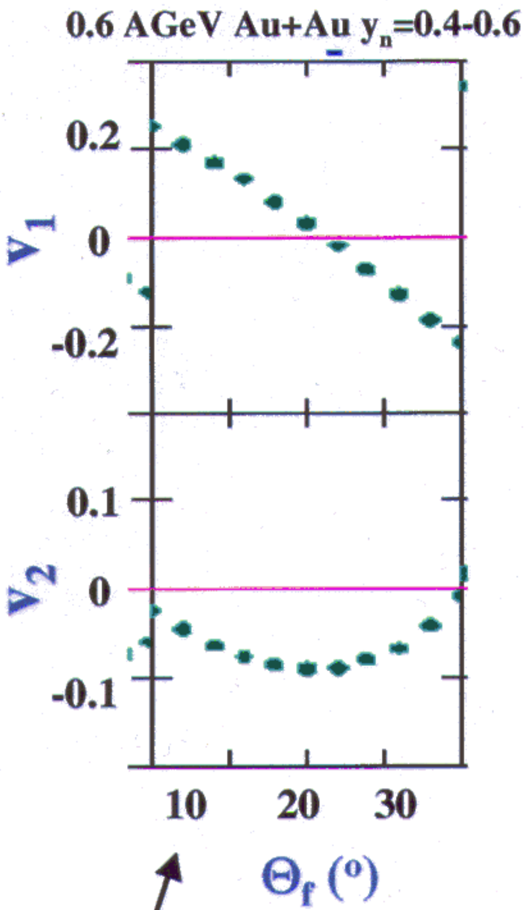
54

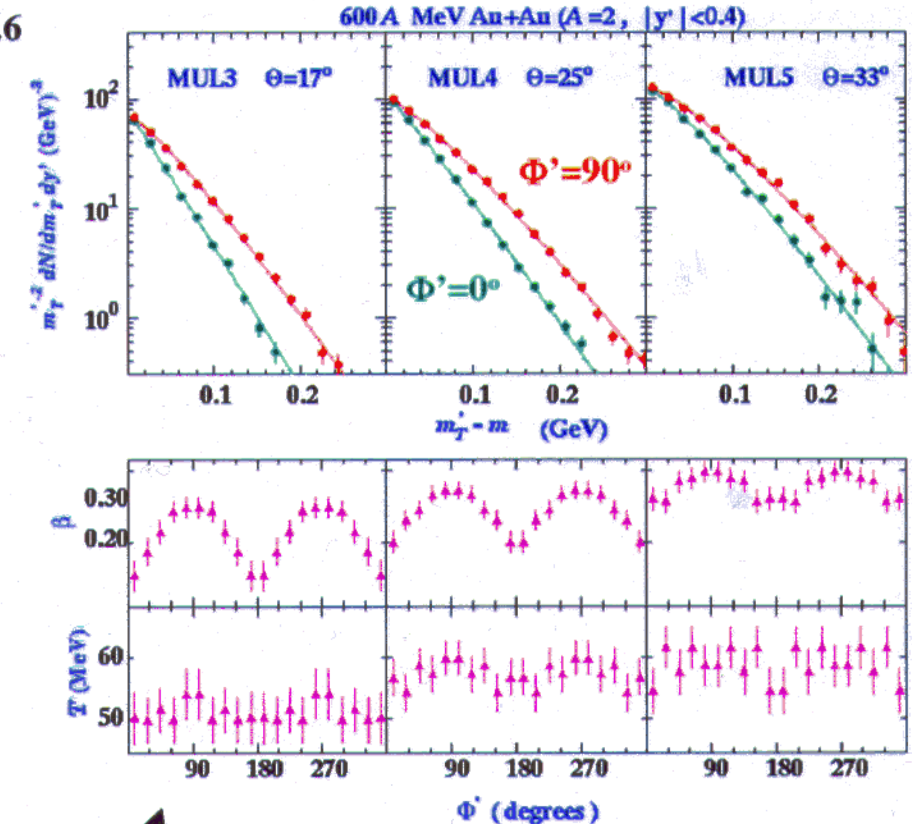


$Y_{c.m.}$

GUTBROD, POSKANZER, + RITTER (PB) (1989)

Flow and "thermal" motion in the natural frame





"True" flow angle
→ minimize v_1
maximize v_2

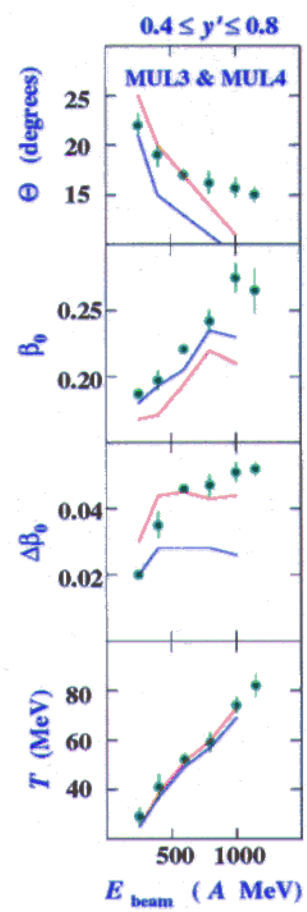
★ Consistent θ_f for all fragments (A=1-4)

★ Natural consequence: rise of v_2 with p_T

NO NEED FOR $v_2(p_T)$

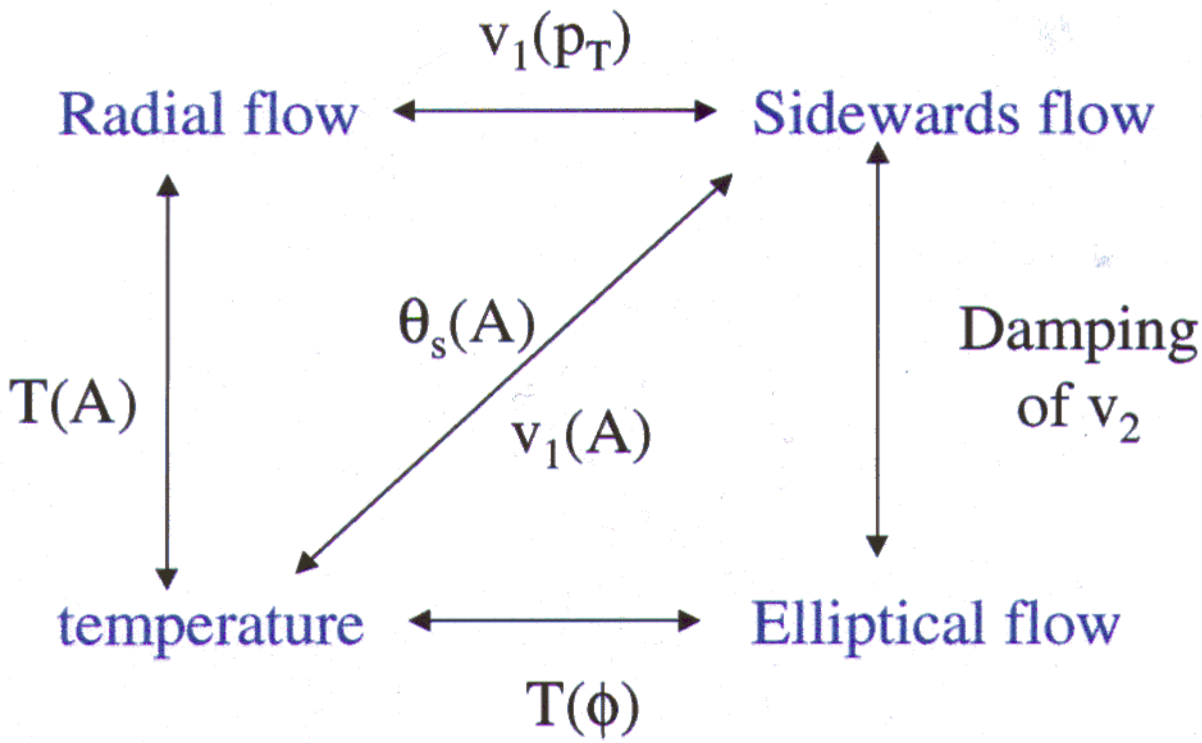
★ Typical level of model agreement

QMD
hard EOS
soft EOS



S. Wang *et al* (EOS) PRL **76**, 3911 (1996)

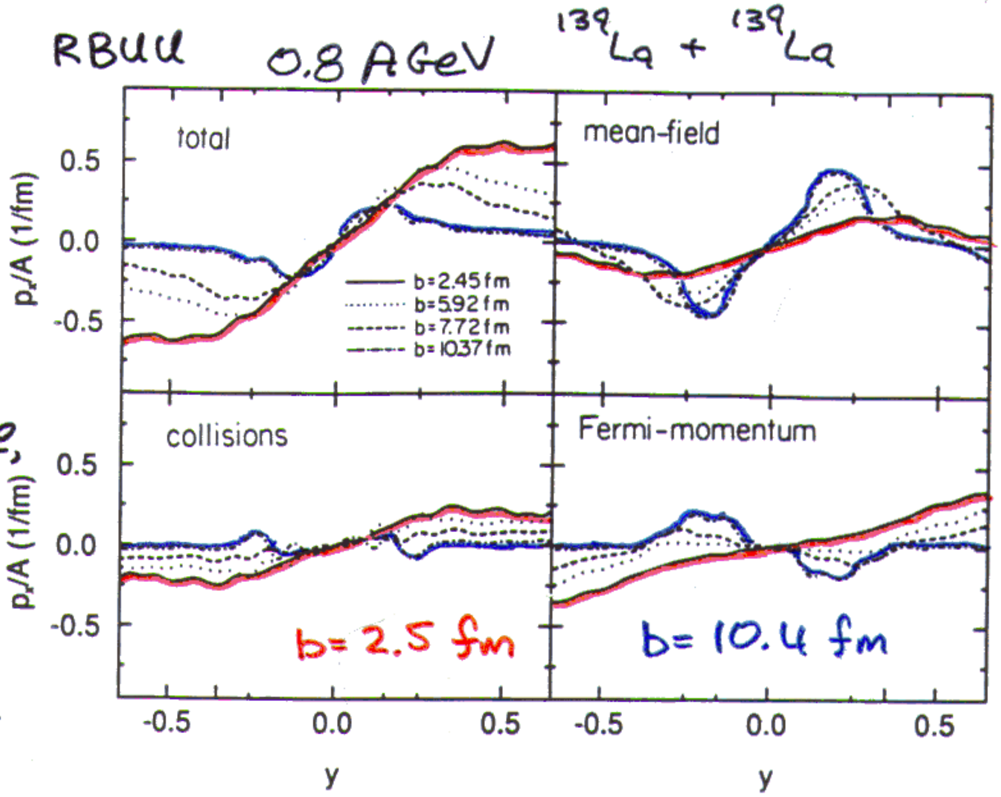
Artifacts of entanglement complicate interpretation/comparison



To understand discrepancies with models (which may concentrate on a particular aspect), desirable to disentangle these dominant effects of d^3N/dp^3

Concentrate on flow systematics with high information content

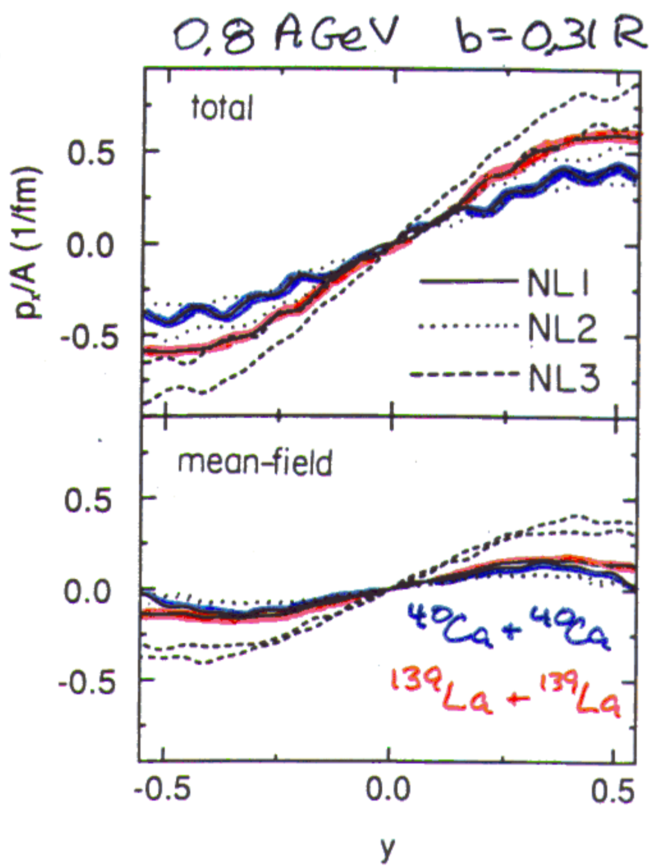
LOW ENERGY MODEL STUDIES



ORIGINS OF FLOW VARIED + CONVOLUTED

$U(\rho, p)$, σ_{NN}^*, μscopic reaction plane, non-hard-sphere finite nucleon size, initial conditions ...

Increasing contribution of collisions for small b → increased stopping → decreased contribution of $U(p)$

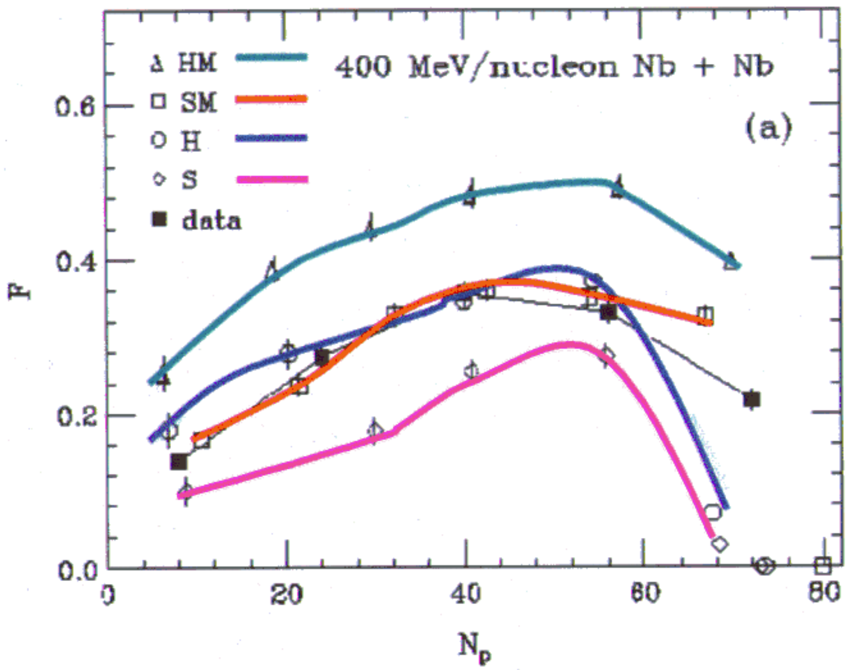


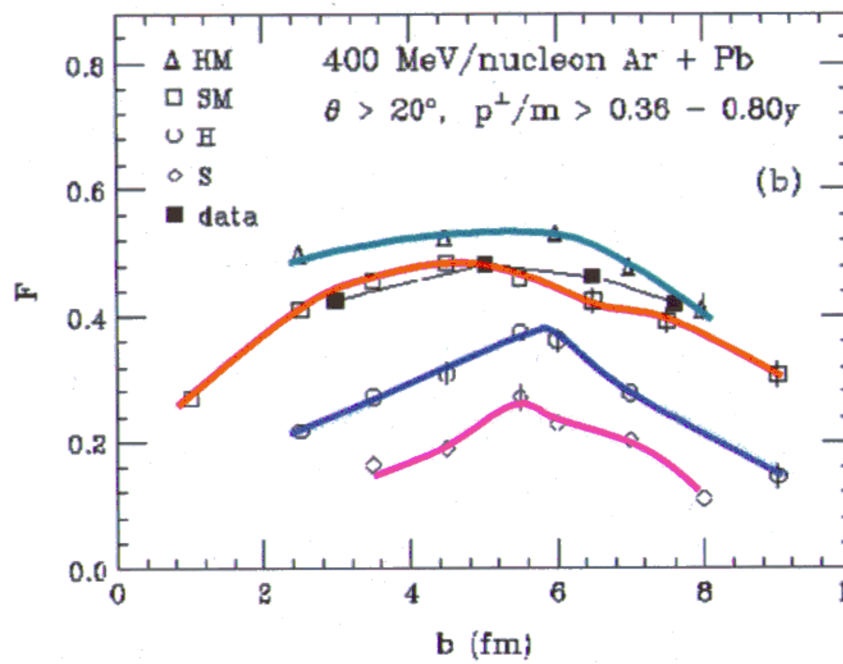
VARY CONTROL PARAMETERS TO DECONVOLUTE

e.g. A_{sys} scaling originates in collisional term

BLÄTTEL et al, PRC 43 2728 (91)

Disentangling contributions of the mean field - how much does momentum dependence matter?



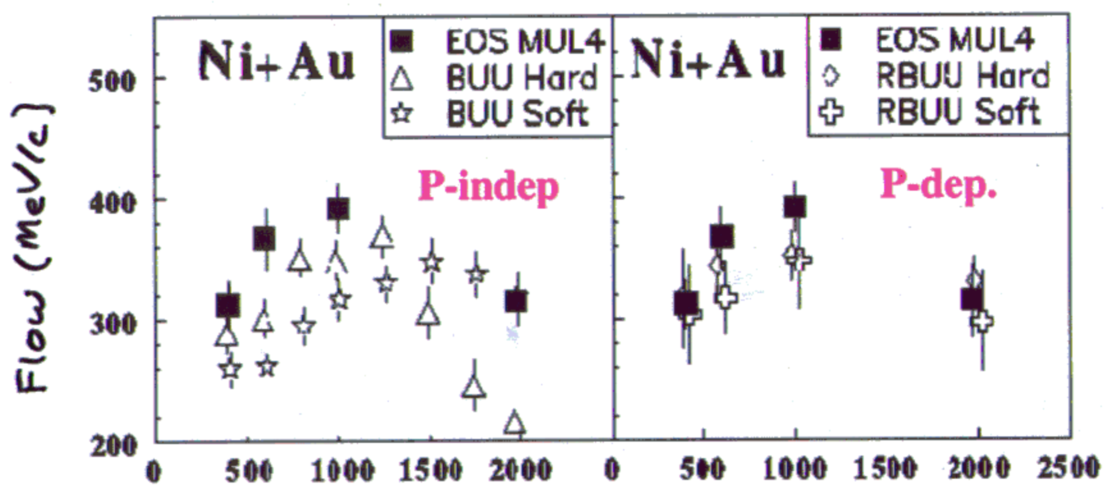


Pan & Danielewicz, PRL **70**, 2062 (93)
data: Gustafsson *et al* (1988)
Demoulins *et al* (1990)

Varying system symmetry allows tuning of aspects of the mean field

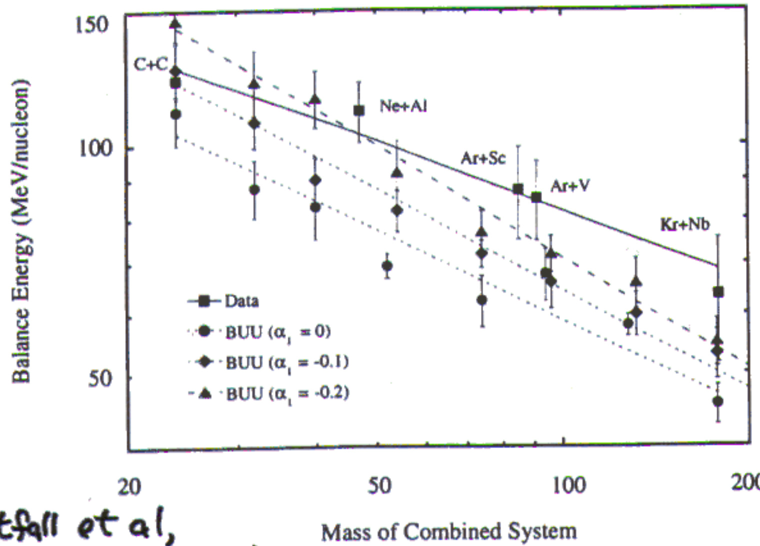
Description of symmetric and asymmetric systems → Soft EoS with explicit momentum dependence

? Ambiguities with σ_{nn}
? Sensitivity to form of EoS



Chance *et al*, PRL **78** 2535 (1997)

Systematics of balance energy challenge models

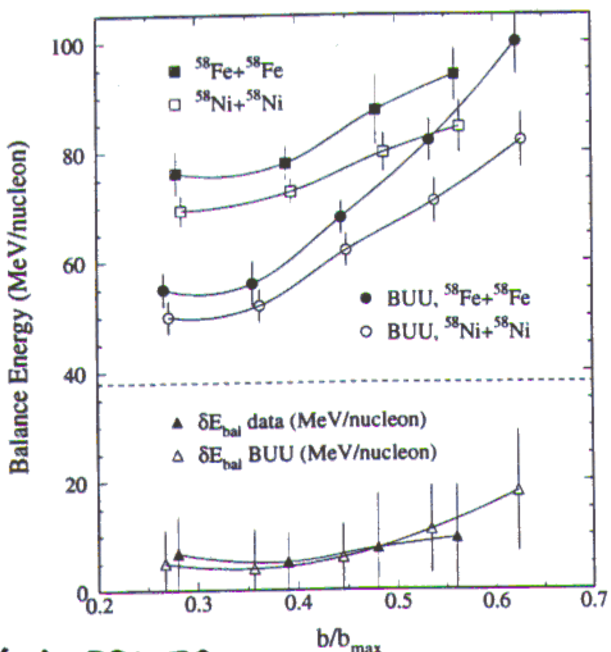


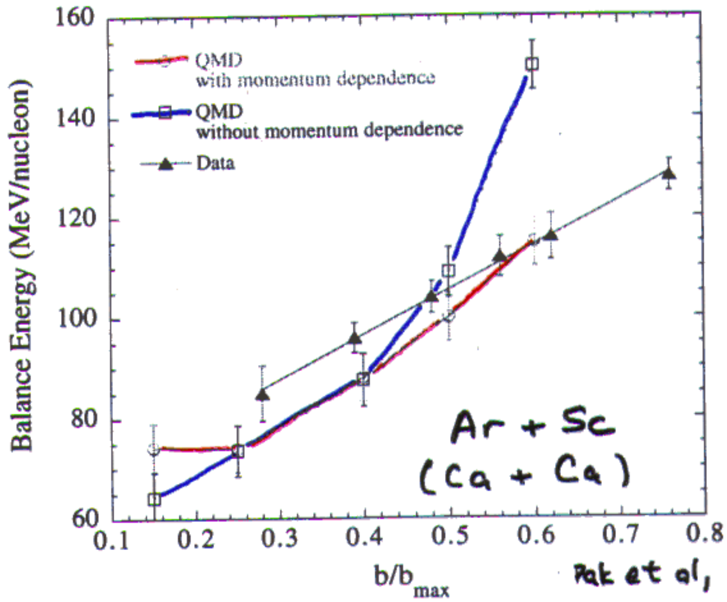
REPULSIVE COLLISIONS ($\sim A$) VS. MEANFIELD SURFACE ($\sim A^{2/3}$) ATTRACTION : $E_{bal} \sim A_{sys}^{-1/3}$

← BUU (w/o $U(p)$) ⇒ E_{bal} too low unless $\sigma_{NN}(\rho_0) = 0.8\,\sigma_{NN}^{FREE}$ ←

Westfall et al, PRL 71 1986 (1993)

$E_{bal}(b) \Rightarrow U(p)$ manifest for peripheral collisions ↓

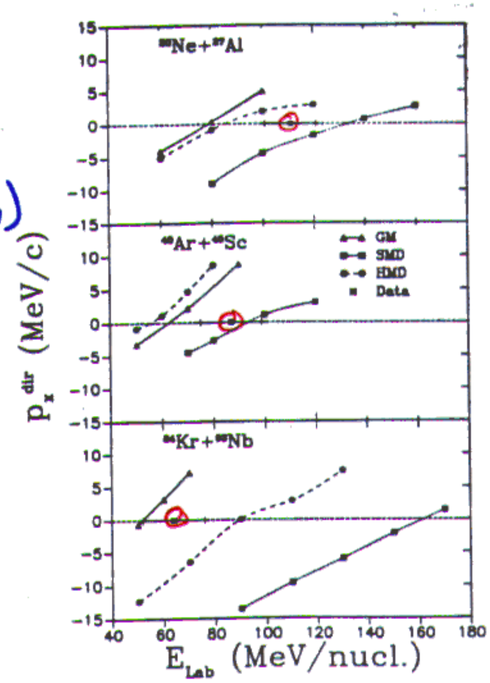




Pak et al, PRC 54 2457 (1996)

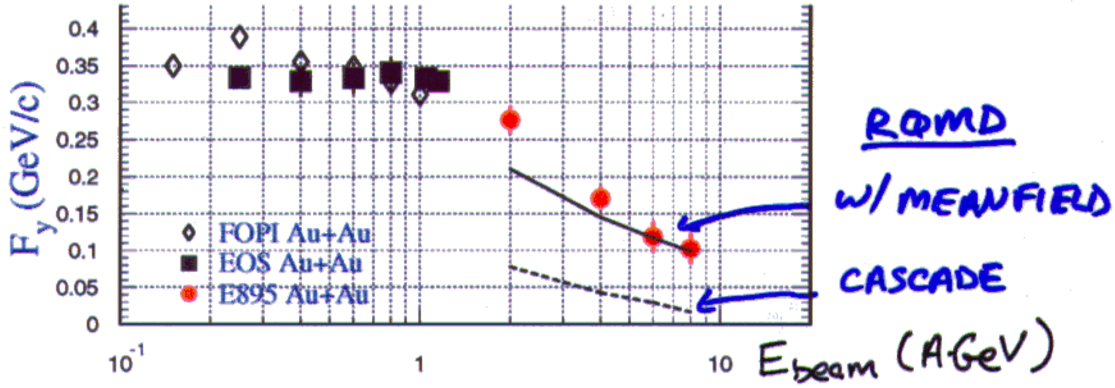
Pak et al PRL 78 1026 (1997)

↑ VARYING ISOSPIN GIVES CHECK ON COLLISIONAL CONTRIBUTION ($\sigma_{PN} \sim 3\sigma_{NN}$)



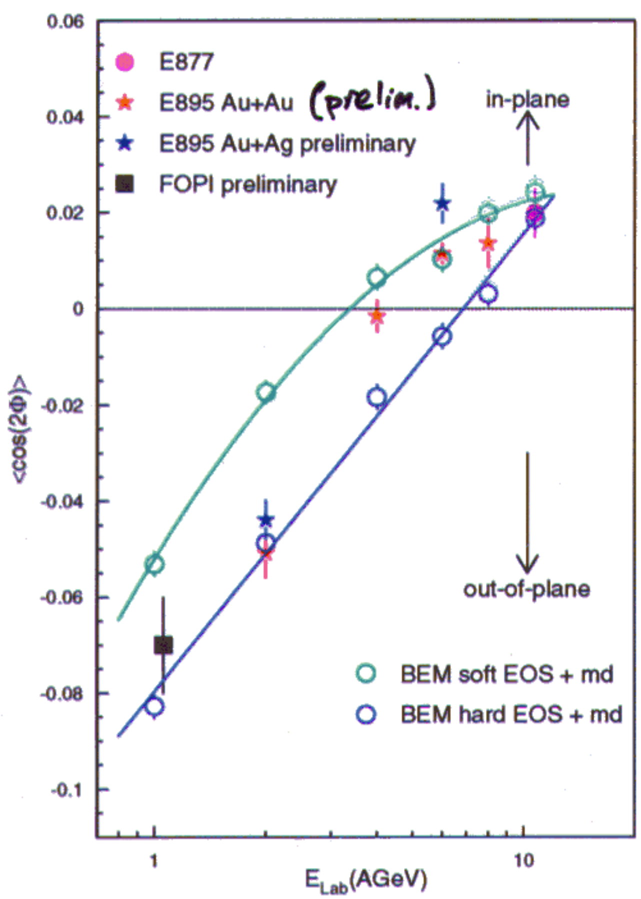
Lehmann et al Z. Phys A355, 55 (1996)

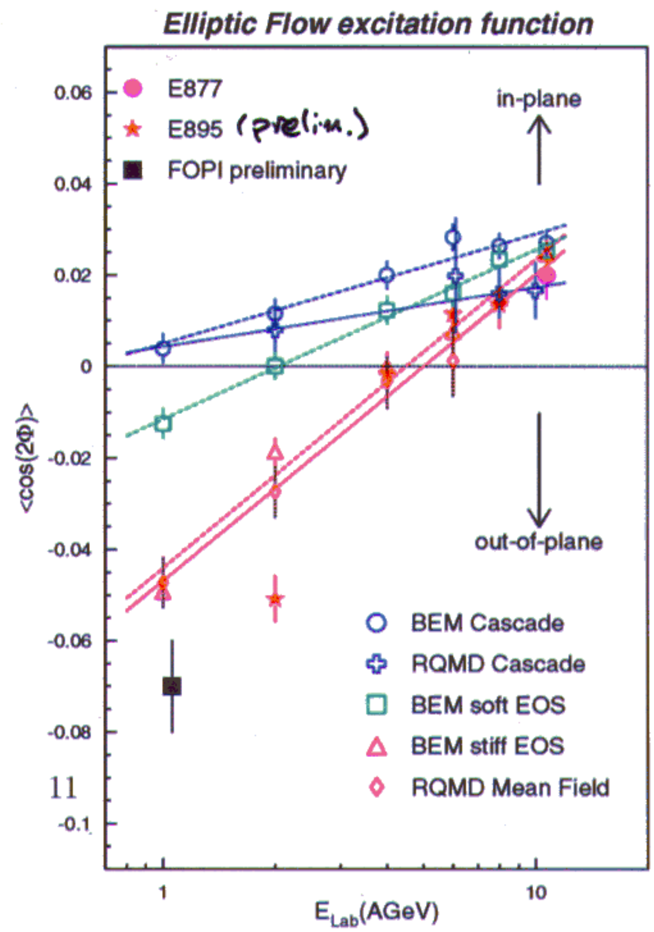
TRANSPORT MODELS CANNOT REPRODUCE SYSTEMATICS WITH SINGLE σ_{nn}, $U(\rho, p)$ →



Liu *et al* (E895), to be published

Elliptic flow: **mass dependence important**
sensitive to EoS/meanfield
softening of EoS???



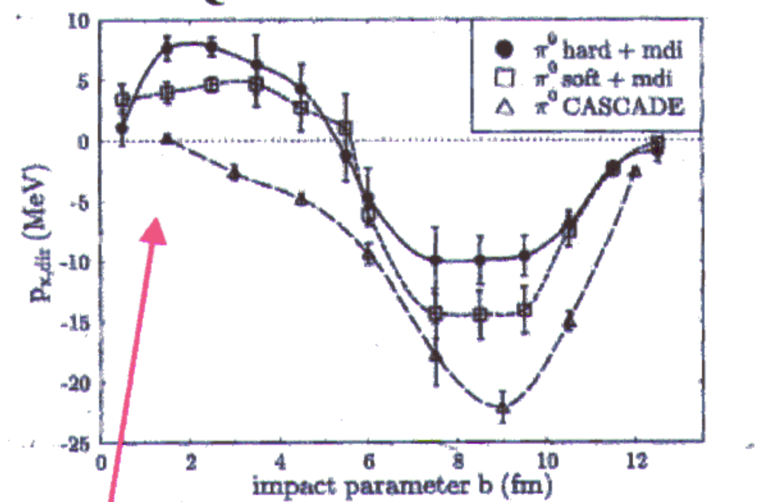


Pinkenburg *et al* (E895), to be published

π flow/antiflow

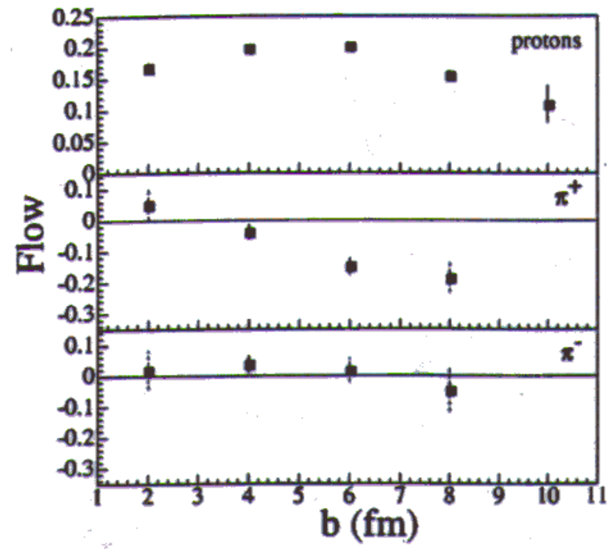
Gross features understood/predicted in transport framework

IQMD - 1 AGeV Au+Au



S. Bass *et al*, PRC **51** 3343 (1995)

1.15 AGeV Au+Au

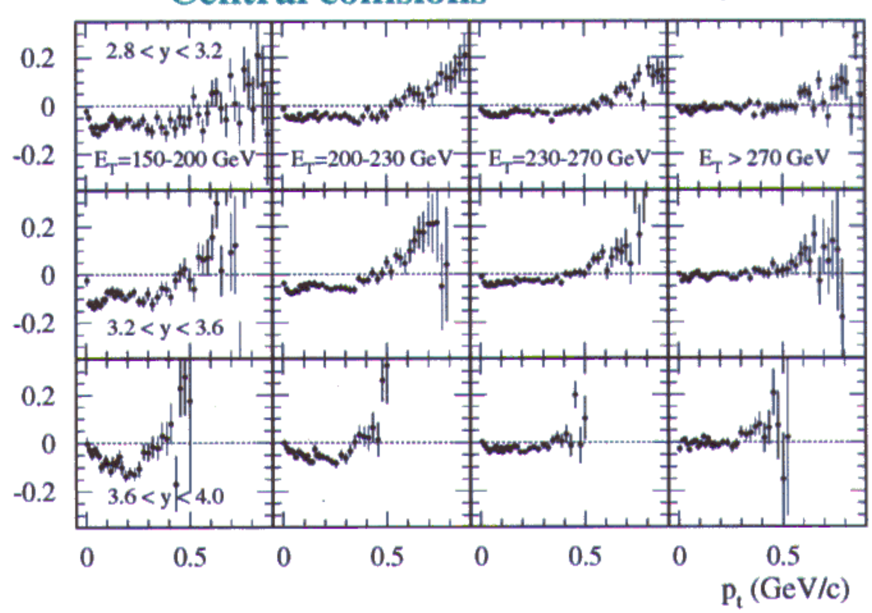


Kintner *et al* (EOS), PRL **78** 4165 (1997)

Residual Δ flow (+)
with meanfield effects

π^+ from 10.6 AGeV Au+Au

Central collisions →

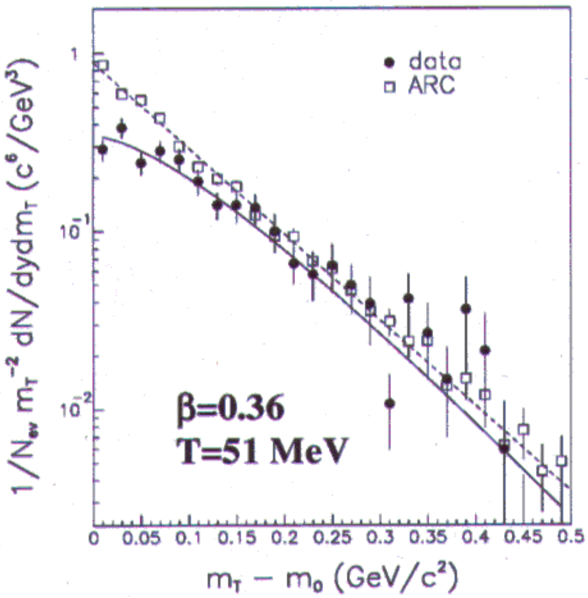


Rich structure of pion flow at AGS may probe details of Coulomb, absorption, resonance production in models

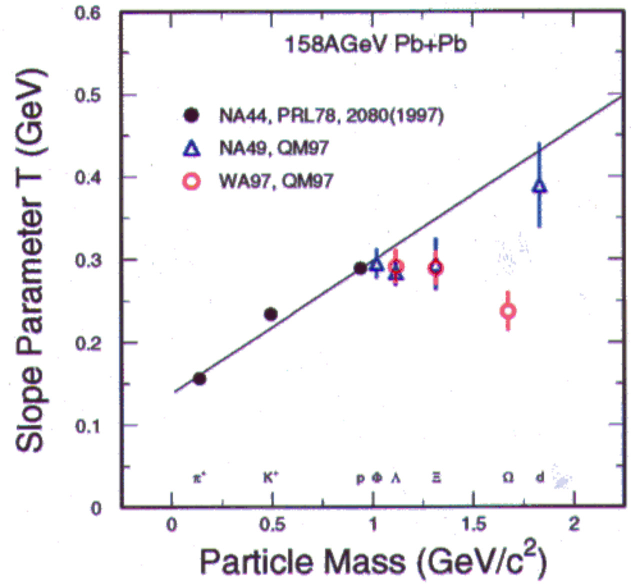
Barrette *et al* (E877), PRC **56** 3254 (1997)

A and (multi) strangeness dependence of radial flow

1.9 AGeV Ni+Cu (threshold)



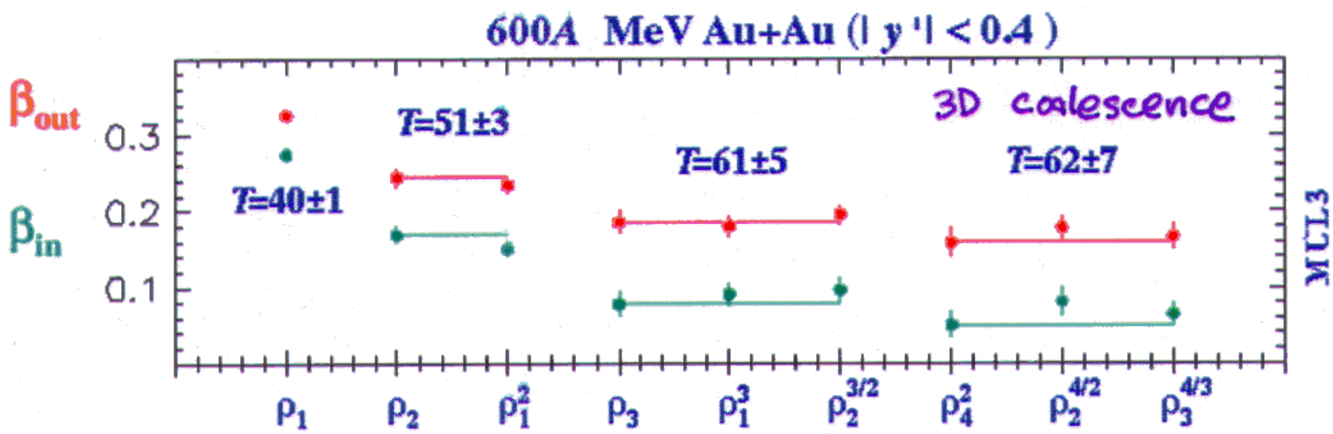
Justice *et al* (EOS), PLB **440**, 12 (1998)



Van Hecke *et al*, nucl-th/9804035
PRL ('98)

Reduced β for mulistrange baryons → early freeze-out?

Reduced β for A=2 (?) → coalescence mechanism?



Wang et al (EOS), PRL **76** 3911 (1996)

c.f. MATTIELLO et al.,
PRC 55 1443 (1997)
6D coalescence

Summary

Sideward, elliptical, & radial flow

- major components of d^3N/dp^3 at all energies
- collective feature of bulk systems
- major impact on other physics studies

Different flows sensitive to different dynamics within collision → want measures of each

Origins of flow in realistic models are convoluted, & effects on flow from different dynamical scenarios may be subtle
→ concentrate on information-rich systematics

- is there a "natural frame" for flow?
  - Eliminate interference between v_1, v_2, β, T
  - Eliminate systematics generated solely by skewed frame.
  - Can compare to (perhaps limited) models (alternative: model should get it all correct so that frame does not matter)

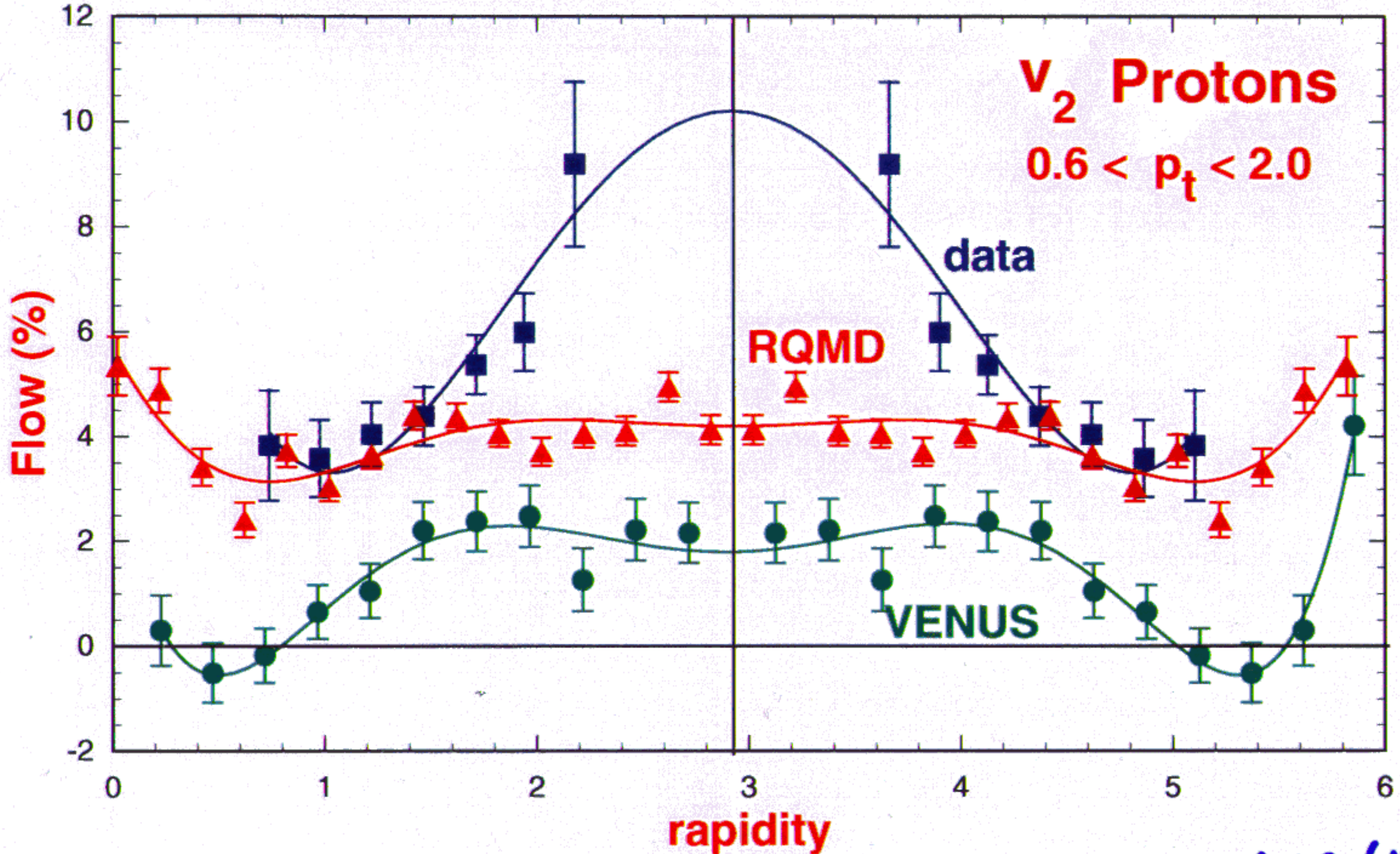
Low energy (15 year-old game)

- tinkering with aspects of models, a given model works well over limited range of conditions
- no model/parameter set stands up to all systematics
  - bad news for seekers of softening of EoS
- clearly, meanfield impt at least through top AGS
- momentum-dependence must be included
- collision term (responsible for A-dependence)
  - varying σ_{NN} (thru N/Z) appears in data
  - maybe $\sigma_{NN}^* < \sigma_{NN}^{FREE}$ (distinguishable from U(p))?
- Gross features of π flow/antiflow correctly predicted
- Useful probes of model-dependent physics:
  - A_{sys}, A_t/A_p, N/Z, b, E_{beam}

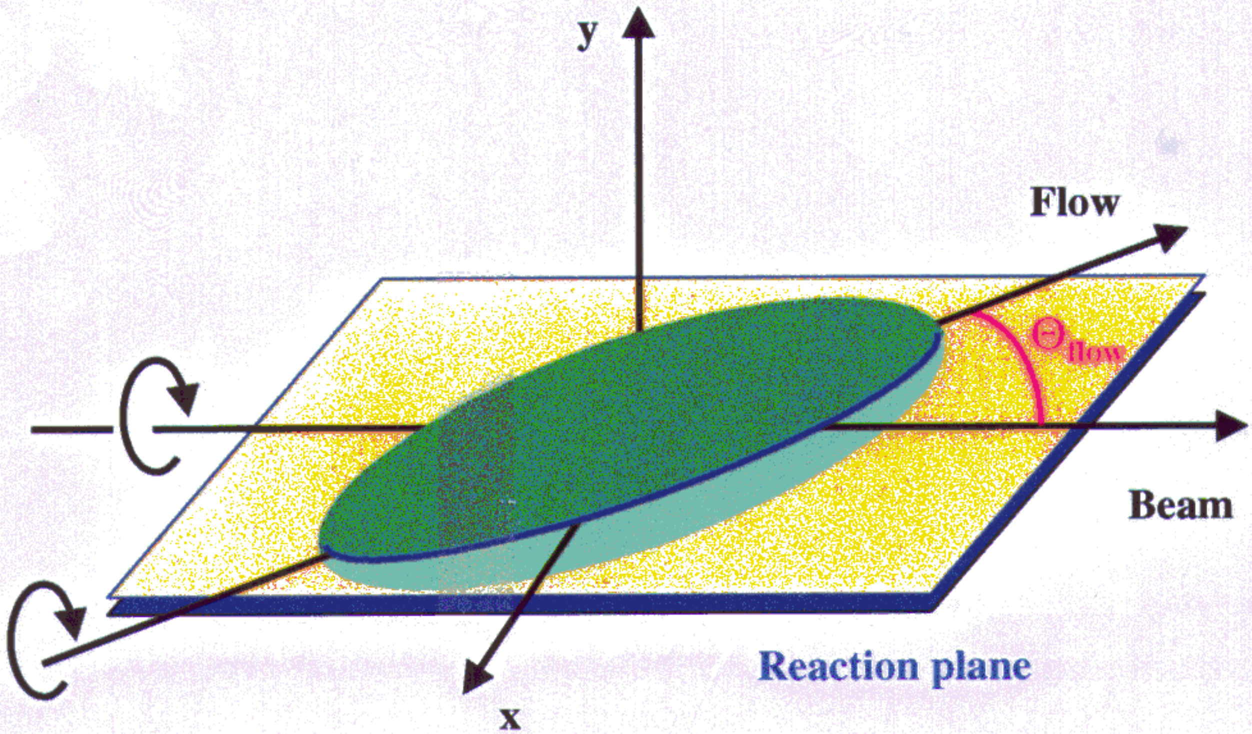
High energy

- just starting, after impressive establishment of effect
- clearest parameterization/extraction of effect - work in progress
- cascade-type models show some flow
  - but not much physics tinkering yet…

DETAILED MEASUREMENTS AT SPS NEED TO BE FOLLOWED BY MODEL MODIFICATIONS



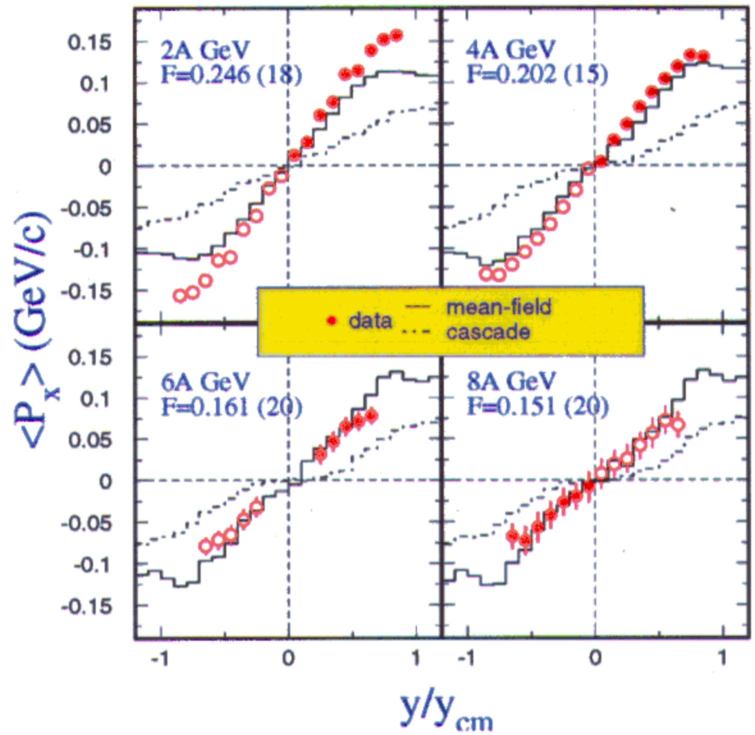
NA 49 (1998)


y
Flow
Θ_{flow}
Beam
Reaction plane
x

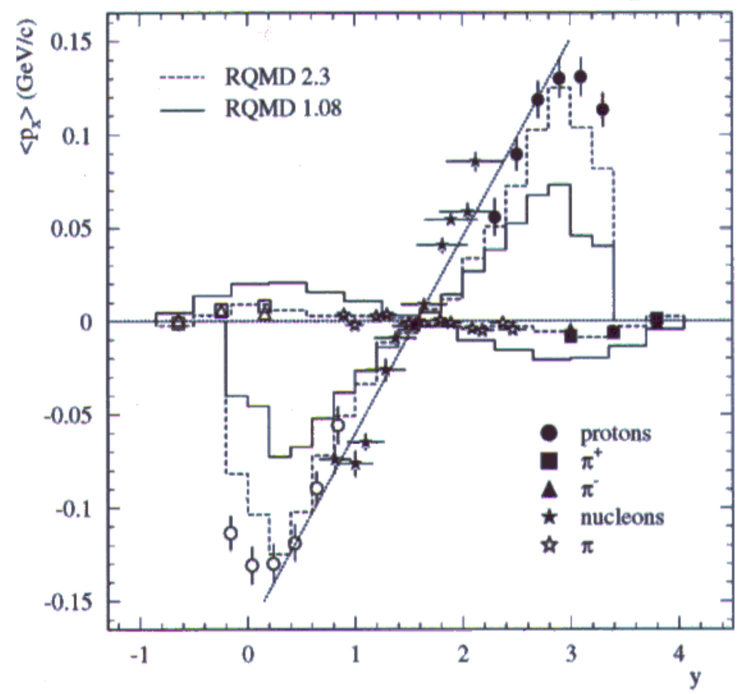
F_y near top AGS energy

Near top AGS energy, "S-curve" takes on multi-slope feature → F_y excitation function more difficult

FIGURES



H. Liu (E895) to be published



Barrette *et al* (E877) PRC 1997