# Measuring Collective Behaviour at RHIC

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- Motivation and Introduction
- Directed and Elliptic Flow
  - RQMD, HIJING
  - Asymmetries in coordinate space
- Event-by-Event Measures of Flow
- Transverse Radial Flow
  - Rescattering
  - Space-Momentum Correlations
  - Deuteron production
- Experimental Capabilities at RHIC
- Summary and Outlook

# Measuring Collective Behaviour at RHIC

## Contributors to this talk

- Heng Liu
- Peter Jacobs
- Art Poskanzer
- Iwona Sakrejda
- Raimond Snellings
- Sergei Voloshin
- Nu Xu

- Heinz Sorge
- Xin-Nian Wang

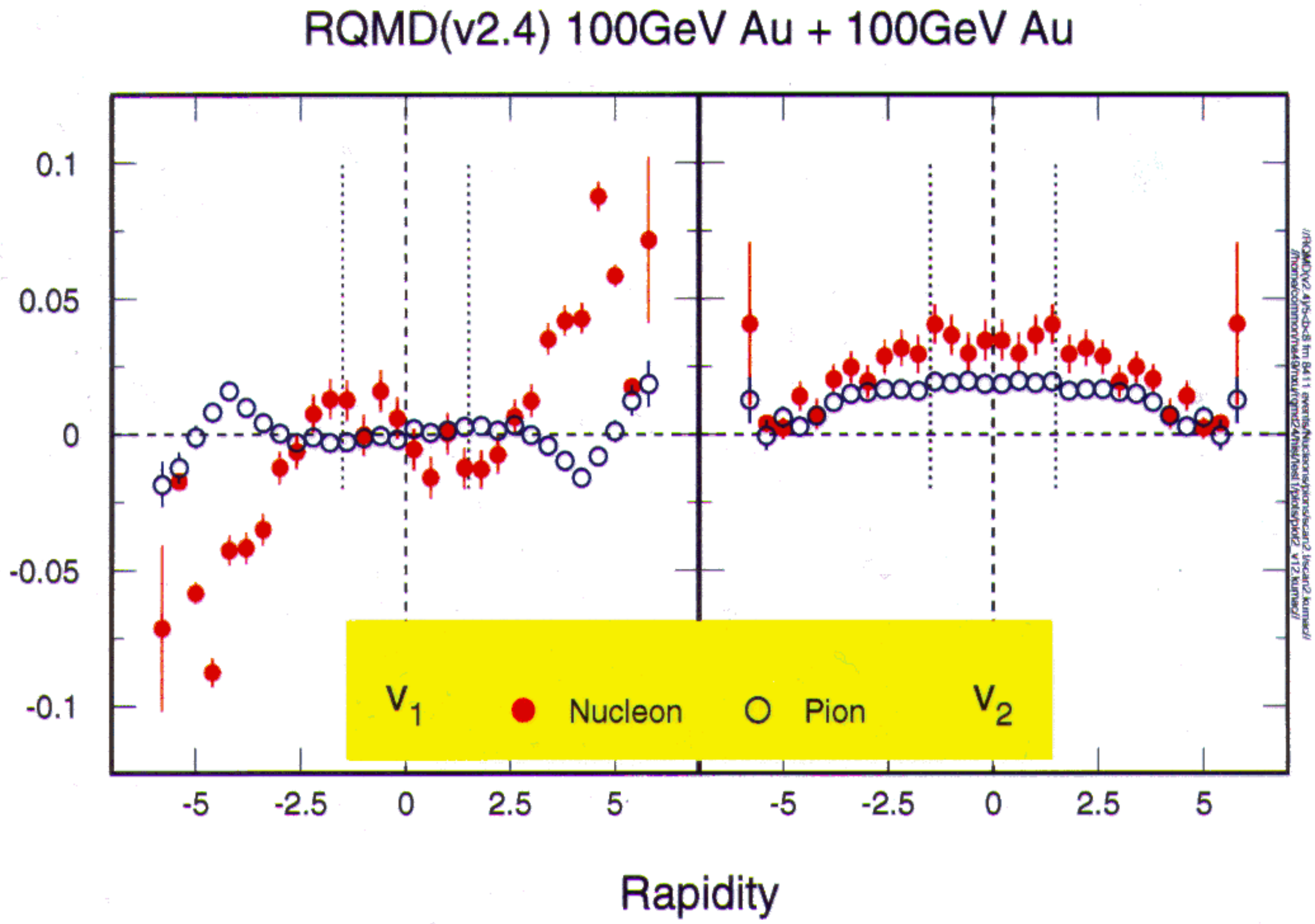
- Ben Monreal

## Motivation for Anisotropic Flow Studies at RHIC

Why bother? What new can we learn? How helpful can it be in understanding dynamics of the collision?

- Sensitivity, Sensitivity, Sensitivity...
  - Collision geometry
  - Early pressure
  - Equation of state
  - QGP
  - Etc, etc, etc
- Beneficial for other types of analyses
  - Sometimes it's good to know reaction plane orientation
- Capable detectors at RHIC
- Historical and Sociological
  - Well established subfield
  - Impressive recent theoretical progress
  - Lots of recent experimental results at SPS and AGS
  - Many research groups already involved

# Flow at RHIC

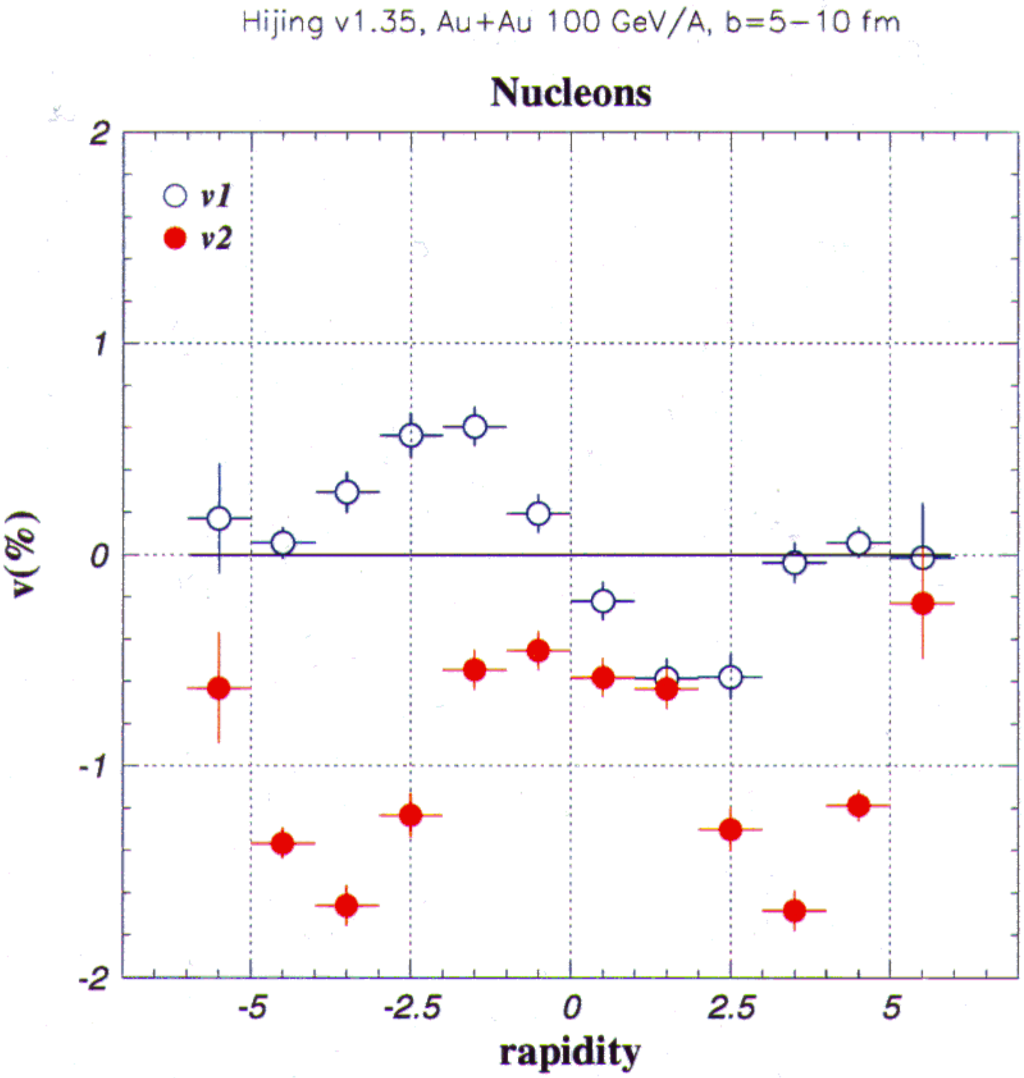



Dashed lines: STAR TPC acceptance

- Directed Flow - $V_1$
  - Nucleon "Antiflow" around mid-rapidity
  - Very small values for pions at mid-rapidity
  - Opposite flow of pions and nucleons at beam rapidities
- Elliptic Flow - $V_2$
  - In-plane emission of both nucleons and pions
  - Larger signal for nucleons

*RQMD (v2.4) predicts signal similar to observed at SPS*

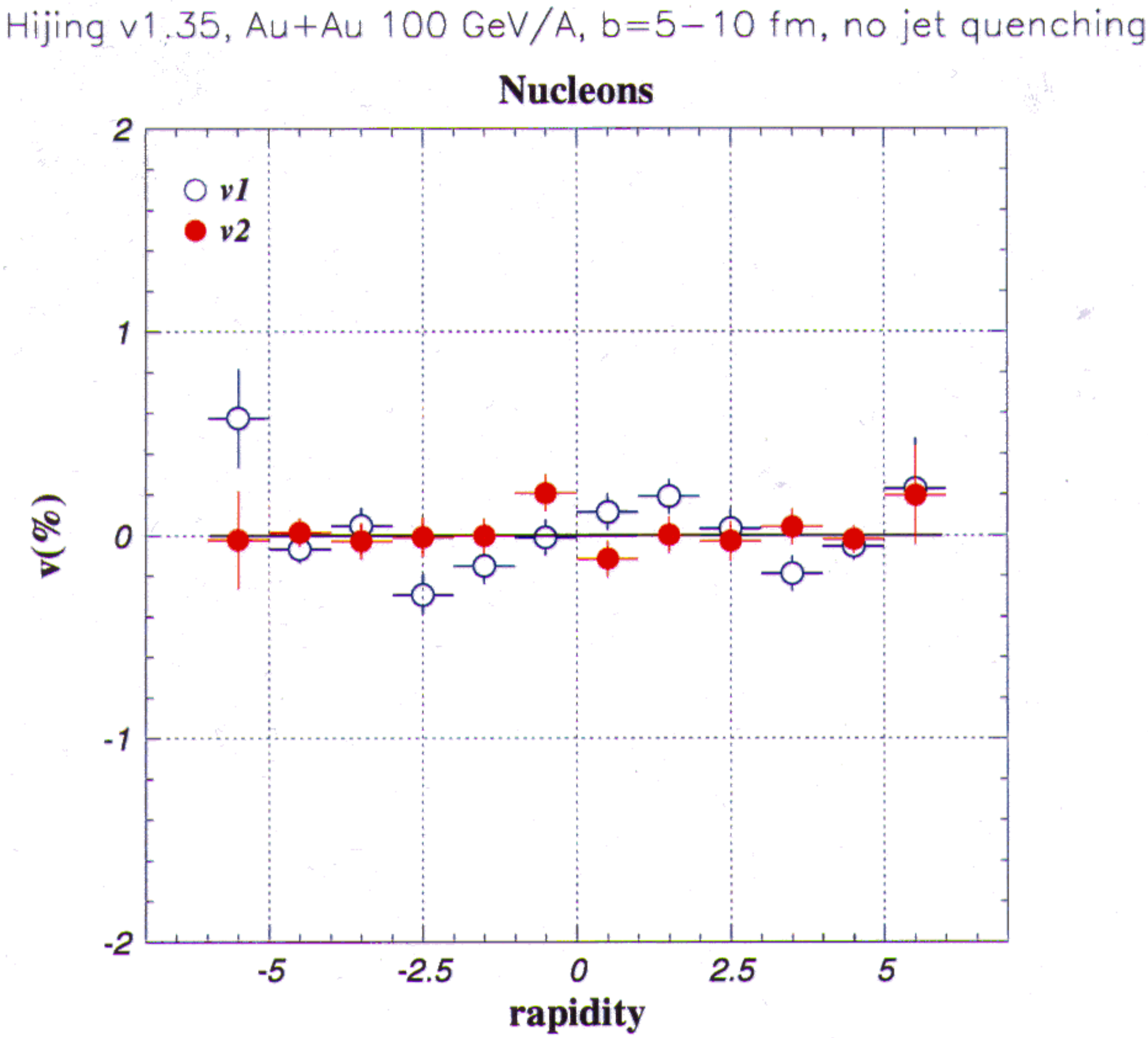
## HIJING with Jet Quenching (R. Snellings)




- $V_1$ behaviour at mid-rapidity similar to RQMD - "antiflow"
- Negative $V_2$ (out of plane) in HIJING, unlike in RQMD
- Remember that HIJING has no rescattering of secondaries!
- *Reinteractions as a source of azimuthal asymmetries?*

# Flow at RHIC

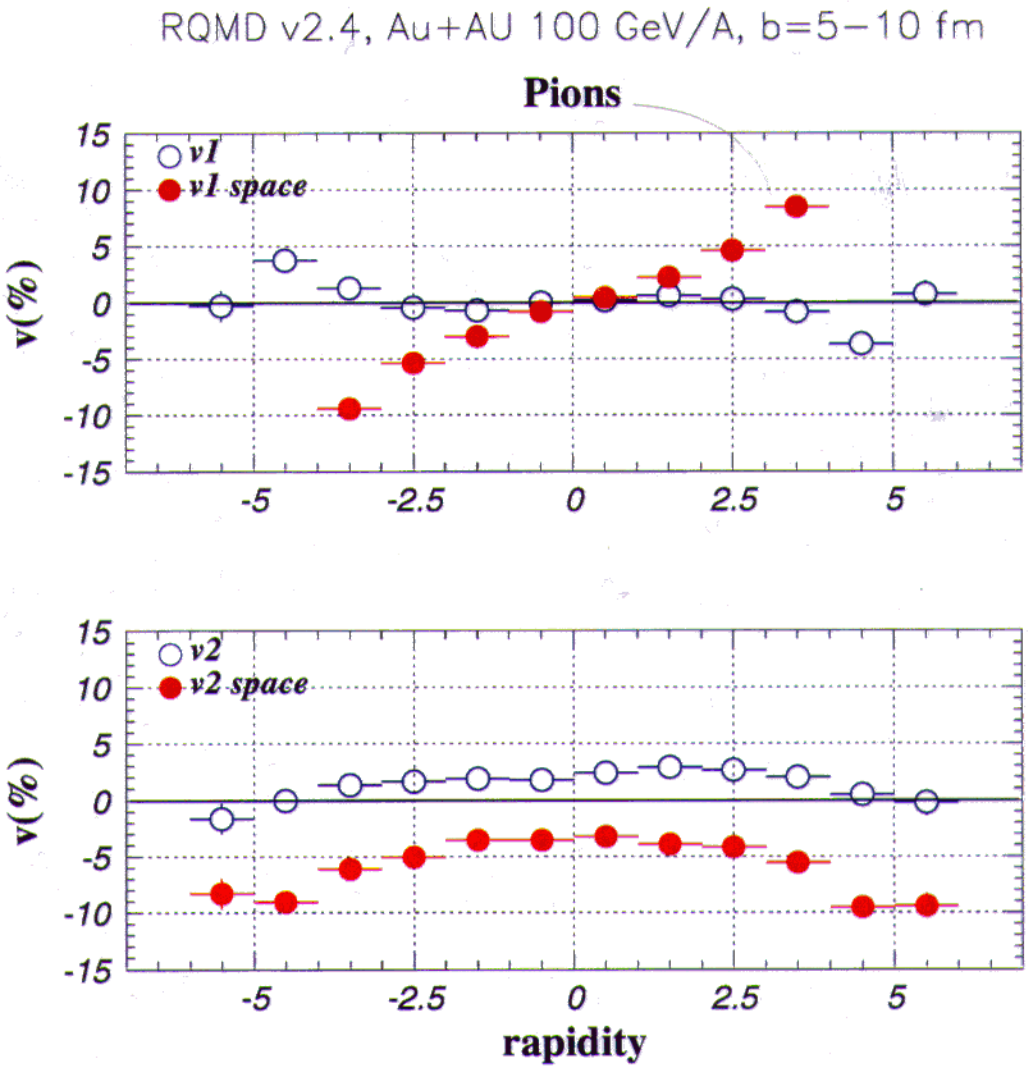
## HIJING, NO Jet Quenching (R. Snellings)




- Flat distributions both for $V_1$ and $V_2$

# Flow at RHIC

## Asymmetries in Coordinate Space (R. Snellings)




- Asymmetries in coordinate and momentum spaces are different

H. Liu, SP, N. Xu, LANL nucl-th/9807021, PRC 1999, in print

- HBT relative to the reaction plane. Plausible to measure?

S. Voloshin and W. Cleland, PRC 54 (1996)

S. Voloshin, R. Lednicky, SP, N. Xu, PRL 79 (1997)

U. Wiedemann, PRC 57 (1998)

H. Heiselberg, LANL nucl-th/981234

# Event-by-Event Measure of Flow

A. Poskanzer, S. Voloshin

## Flow Strength

$$Q_n = \sqrt{(\Sigma w sin(n\phi))^2 + (\Sigma w cos(n\phi))^2}$$

$w$ - some weighting factor, for example:

$w = P_T$, *a la* P. Danielewicz and G. Odyniec, PLB 157 (1985)

$w = 1$ Number flow

## Normalized Flow Strength

$$q_n = \frac{Q_n}{\sqrt{\Sigma w^2}}$$

$$\frac{dP}{dq_n} = \frac{q_n}{\sigma_q^2} exp\left(-\frac{q_n^2 + \frac{v_n^2 <N-1><w>^2}{<w^2>}}{2{\sigma_q}^2}\right) I_o\left(\frac{\frac{q_n v_n \sqrt{N-1}<w>}{\sqrt{<w^2>}}}{\sigma_q^2}\right)$$

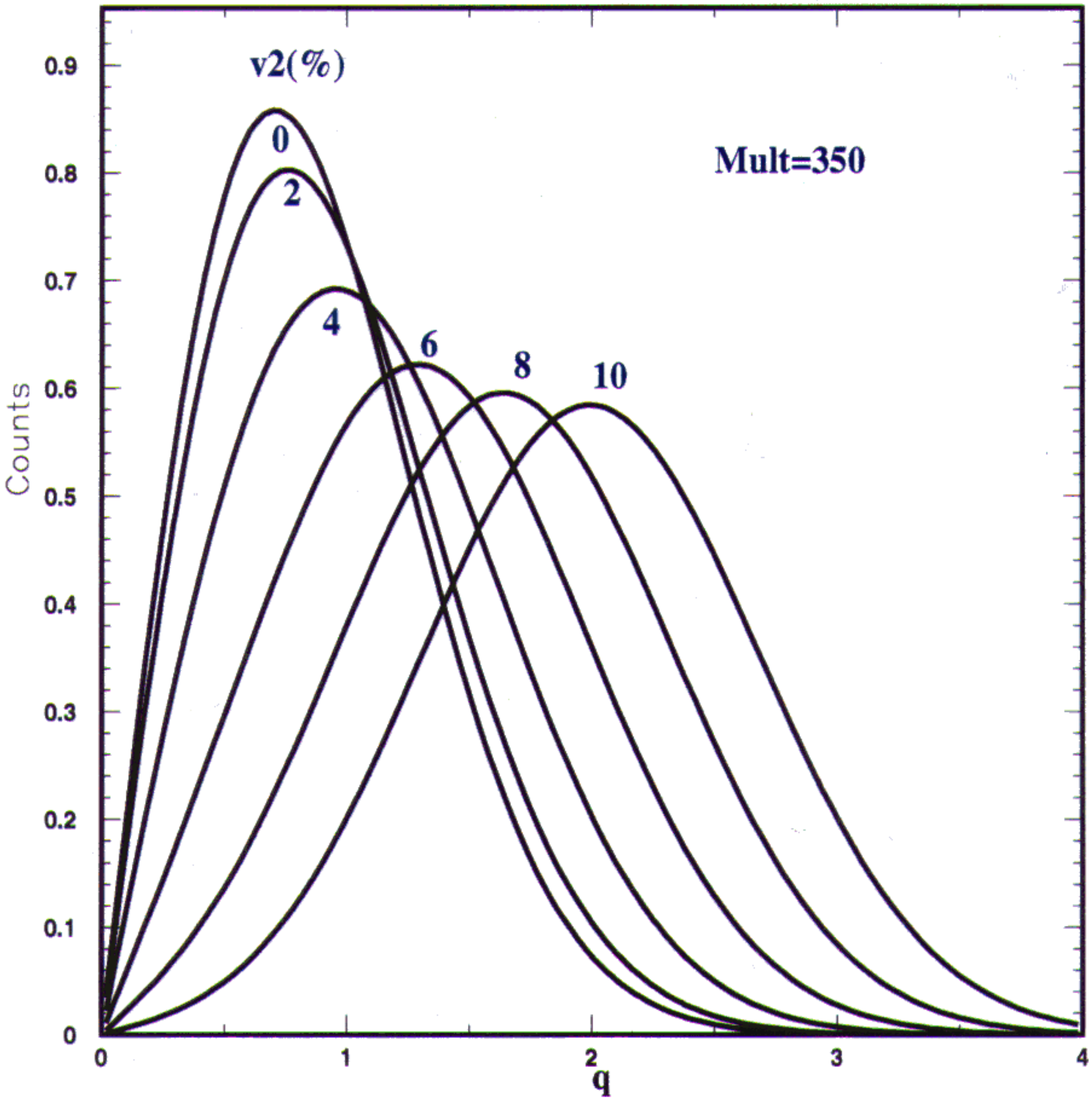
$$< q_n^2 >= 1 + \frac{v_n^2 < N-1 >< w >^2}{< w^2 >}$$

$$\sigma_q = \frac{1}{2}\sqrt{2}$$

*Conveniently dispersion of $q_n$ is constant for all $n$*

# Event-by-Event Measure of Flow

## Event Classes Selection (A. Poskanzer, S. Voloshin)

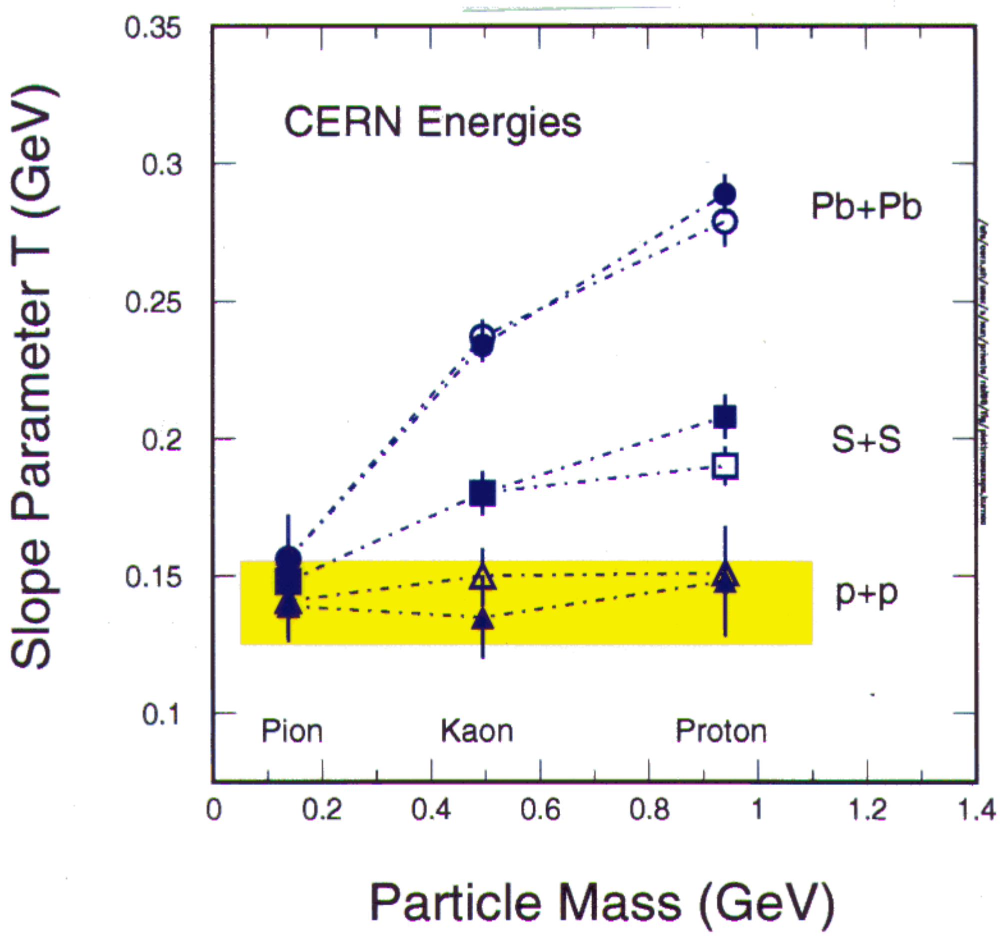



- Separation of possible event classes with different flow

# Flow at RHIC

## Summary #1

- Azimuthal Event Anisotropies ($v_1$, $v_2$)
  - are robust and generic features of the collision
  - are sensitive observables
  - can be useful for other types of analyses




NA44, Phys. Rev. Lett. 78, 2080 ('97)

A. Dumitru, D.H. Rischke nucl-th/9806003

nance decays. For all other (heavier) hadrons these effects on $\langle p_T \rangle$ are less significant.

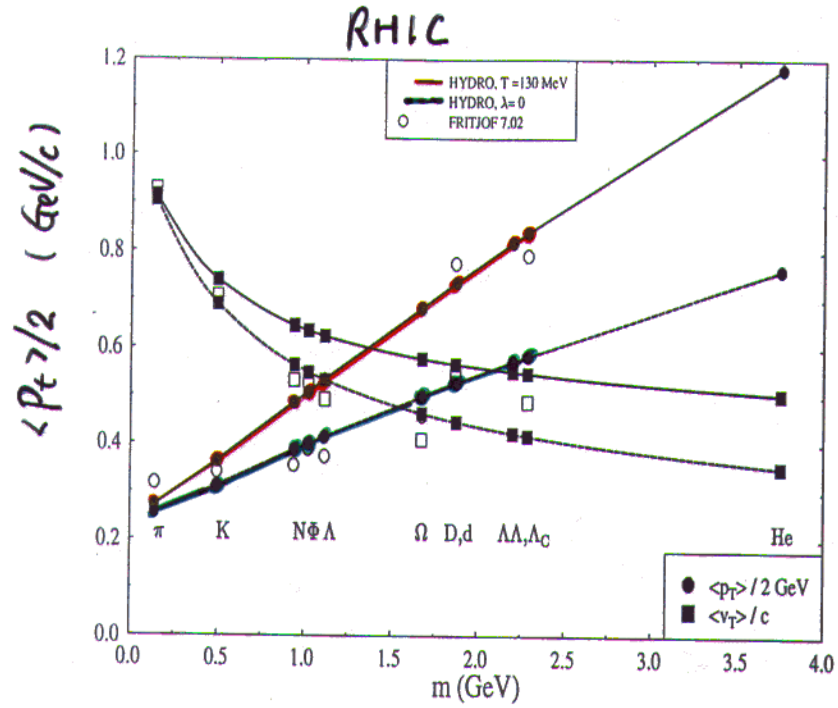
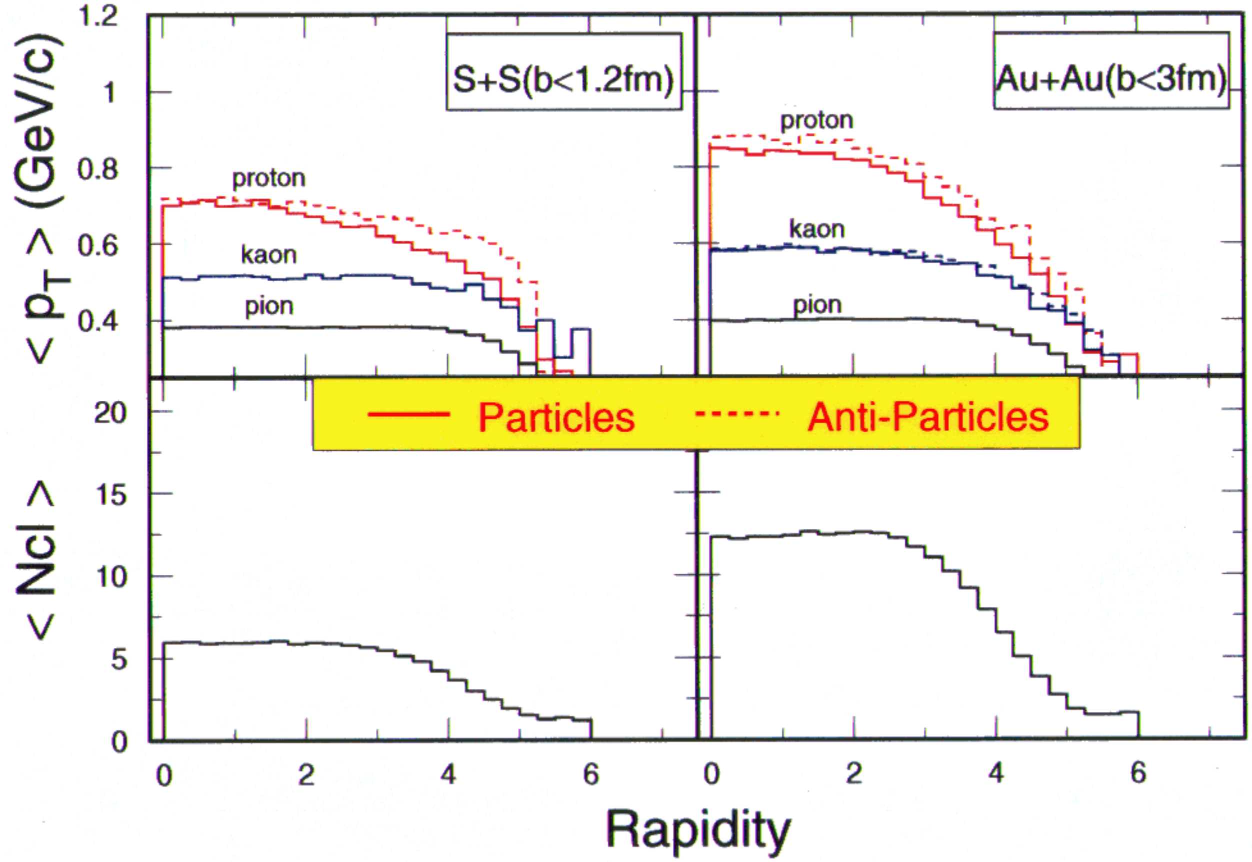



FIG. 7. Same as fig. 6 but for central Au+Au collisions at RHIC. Open symbols depict the predictions of FRITJOF 7.02.

Also, $\langle v_T \rangle$ saturates with increasing $m$, since the thermal velocities $\sim \sqrt{T_{fo}/m}$ become negligible and $\langle v \rangle \approx v_{flow}$. Thus, clusters ($d$, $He$, ...) provide the opportunity to determine the transverse flow velocity *directly* [5,34], while the thermal averaging can not be neglected for nucleons and especially for pions and kaons. To extract the collective flow from their $\langle p_T \rangle$ or $\langle v_T \rangle$ requires the knowledge of the freeze-out temperature, and moreover might be distorted by decays of resonances [4,35]. The average transverse flow velocity in Pb+Pb at SPS is $\approx 0.3$ on the boundary between mixed and hadronic phase (i.e. $\lambda = 0$), and increases to $\approx 0.4$ on the $T = 130$ MeV isotherm. This is consistent with other fluid dynamical

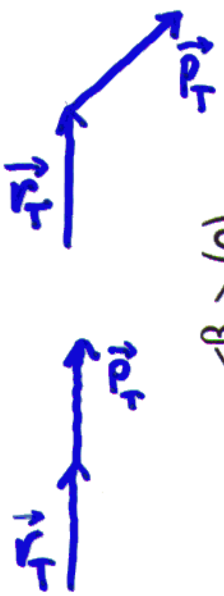
# RQMD(v2.4) 100AGeV Au(S) + 100AGeV Au(S)

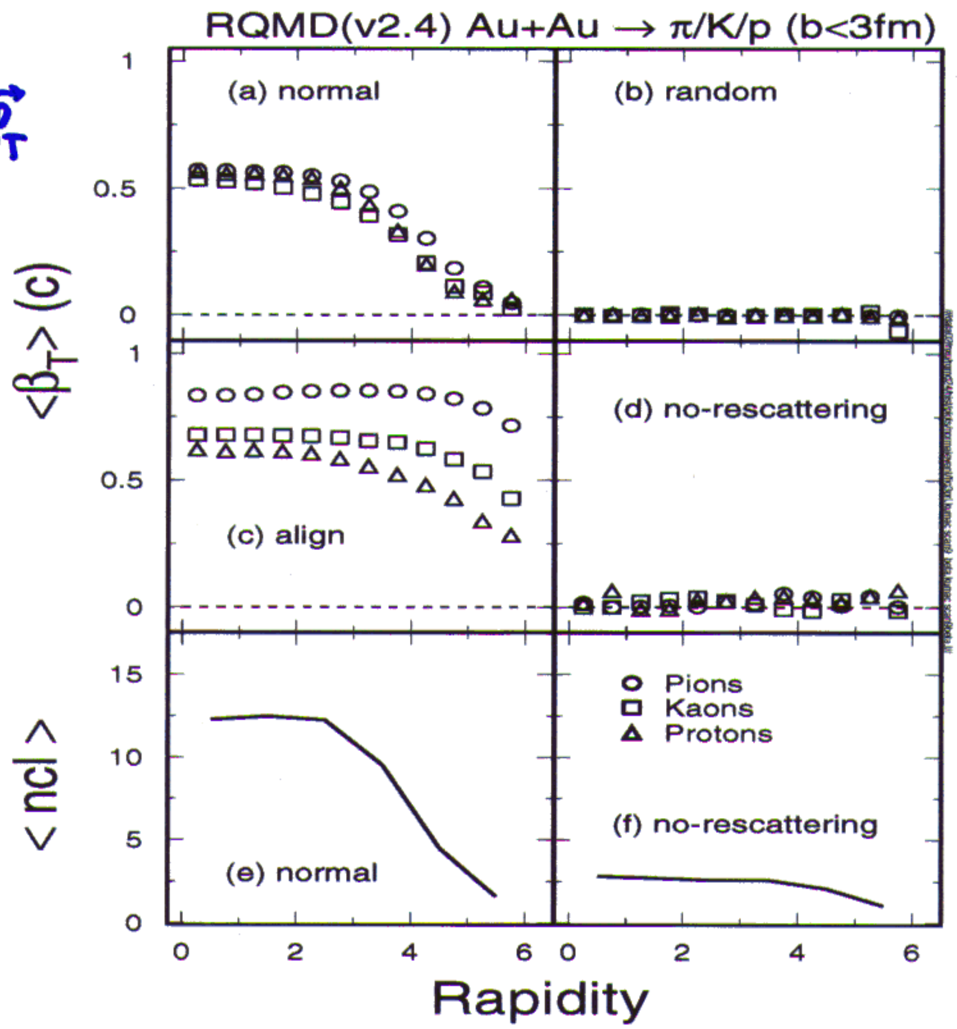


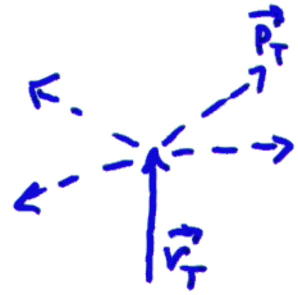

#qqbar2/rxu/home/rxu/models/rhic/rqmd/ssdata/hist/slopeh.kumac#
#pdslhp/comm/rqmd24/hist/test/hist/scan3.kumac/6441events/

# Collective Behaviour at RHIC

## Transverse Radial Flow



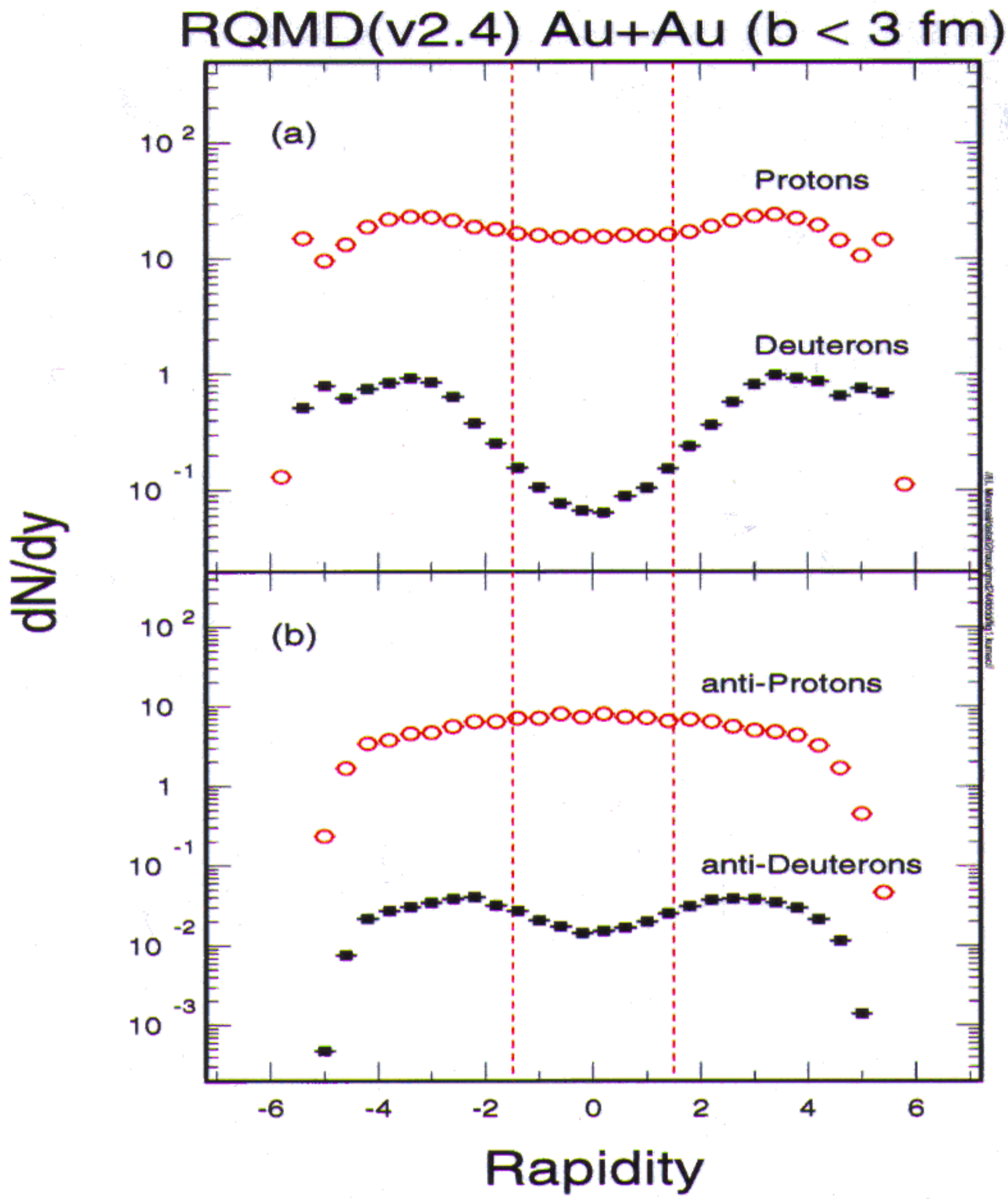

$$\beta_t = \frac{\vec{P}_t \cdot \vec{r}_t}{r_t m_t}$$

- Common velocities → Particles flowing together → Collectivity!
- Rescattering is the source of collective flow
- Radial Flow → Momentum-Position Correlation
- Different Expansion Scenario → Different M.-P. Correlation?

# Motivation for Deuteron Measurements

- Yield and Spectra depend on:
  - Baryon distributions
  - Collective flow
  - Size of the system
  - Etc, etc, etc
- Complimentary to HBT and proton-proton correlations
  - Proton correlations may be at the limit of sensitivity
  - Use d/p ratios and dp correlations
  - Freeze-out sequence

## Probing Baryon Freeze-out with Deuterons

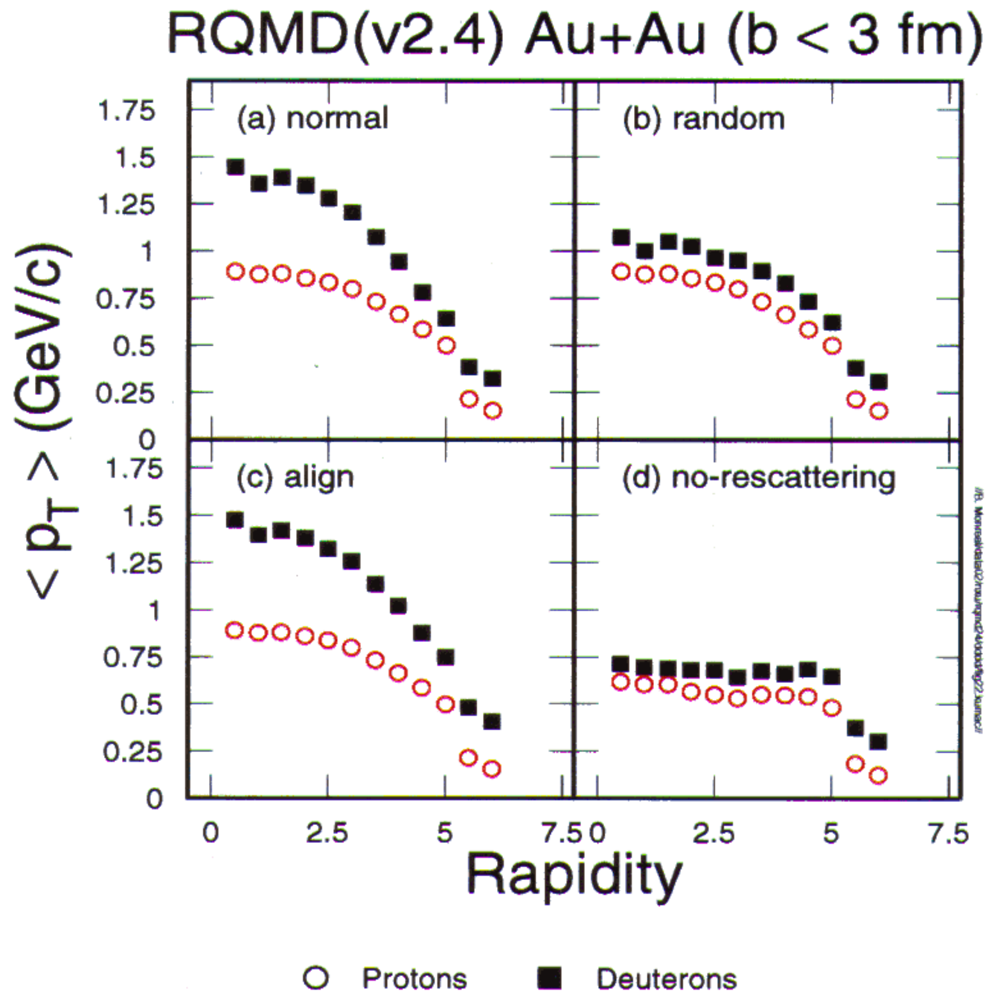



Dashed lines: STAR TPC acceptance

- 1 Deutron per 10 central event
- 1 Anti-Deuteron per 50 central events

# Collective Behaviour at RHIC

## Probing Baryon Freeze-out with Deuterons




- Deuterons are sensitive to transverse radial flow
- Different M.-P. correlation → Different deuteron $< P_T >$

  → Different deuteron yield

# Flow at RHIC

## Summary #2

- Azimuthal Event Anisotropies ($v_1$, $v_2$)
  - are robust and generic features of the collision
  - are sensitive observables
  - can be useful for other types of analyses
- **Transverse Radial Flow**
  - Large number of rescatterings leads to space-momentum correlations and collective velocity
    *Does it look like hydro behaviour?*
  - Nuclear clusters are an interesting probe

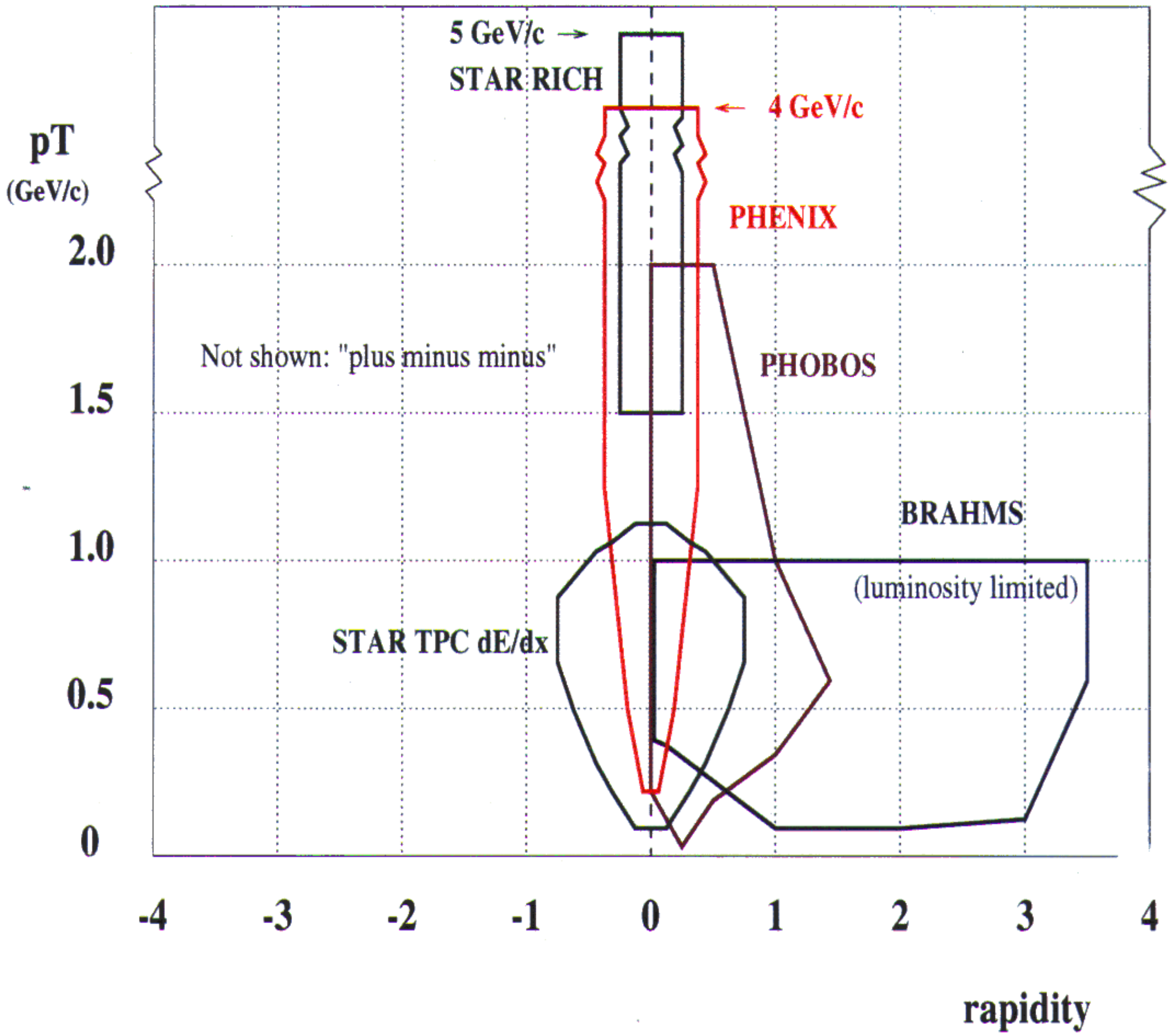
## Experimental Capabilities at RHIC

- RHIC
  - Different energies
  - Different beams
  - Long runs

- STAR
  - Large Azimuthally Symmetric Acceptance (TPC, FTPC)
    - Reaction plane determination
    - Measurements with respect to the reaction plane
- BRAHMS, PHENIX, PHOBOS
  - Multiplicity arrays
    - Event plane determination
  - Spectrometers
    - Measurements with respect to the reaction plane

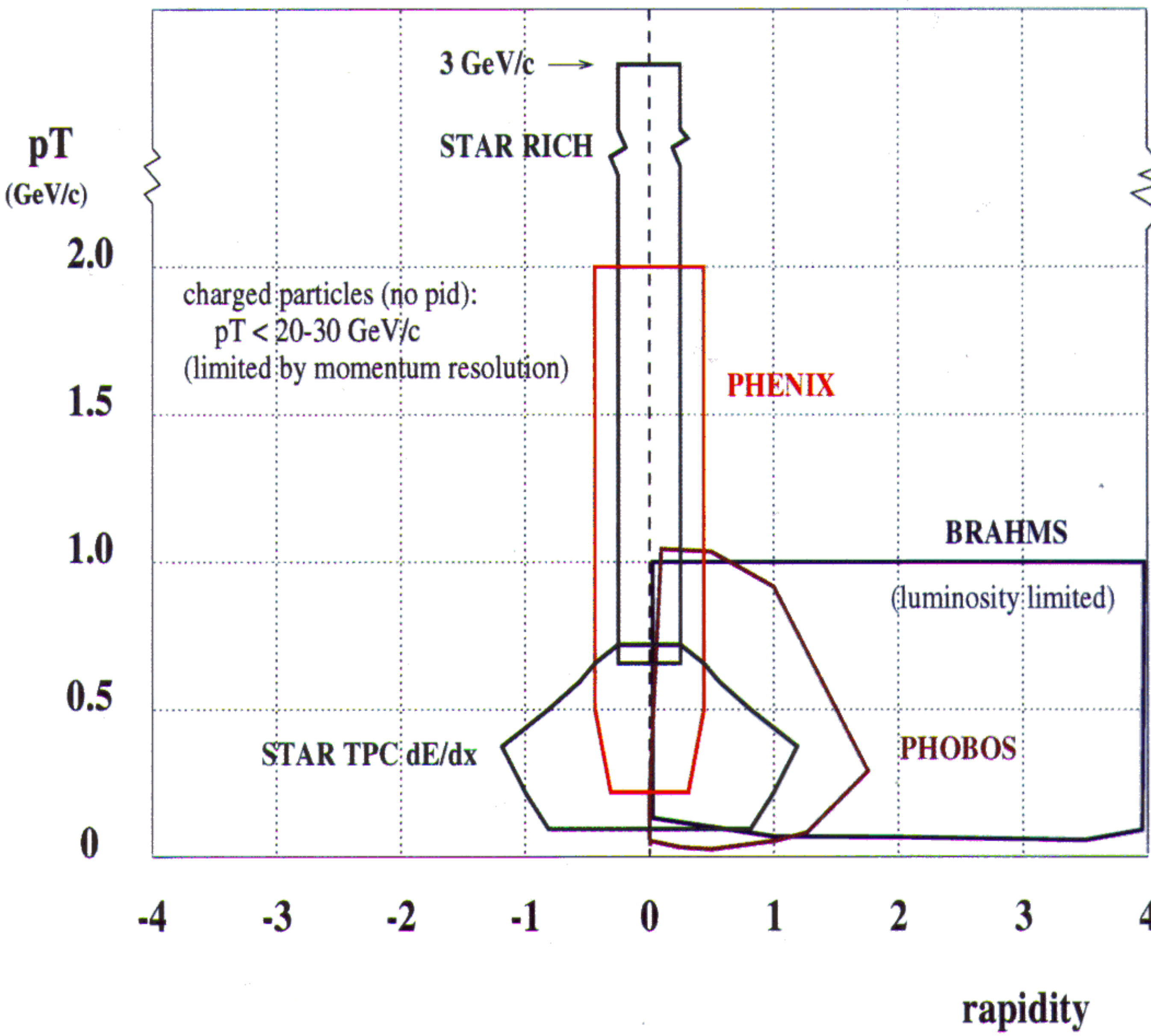
# Experiments at RHIC

## Identified Proton Acceptance. Year 1. (P.M. Jacobs)



# Experiments at RHIC

## Identified Pion Acceptance. Year 1. (P.M. Jacobs)



# Flow at RHIC

## Summary

- Azimuthal Event Anisotropies ($v_1$, $v_2$)
  - are robust and generic features of the collision
  - are sensitive observables
  - can be useful for other types of analyses
- Transverse Radial Flow
  - Large number of rescatterings leads to space-momentum correlations and collective velocity
    *Does it look like hydro behaviour?*
  - Nuclear clusters are an interesting probe
- **We will learn a lot in the next 12 month.**