Latest Flow Results From PHENIX at RHIC

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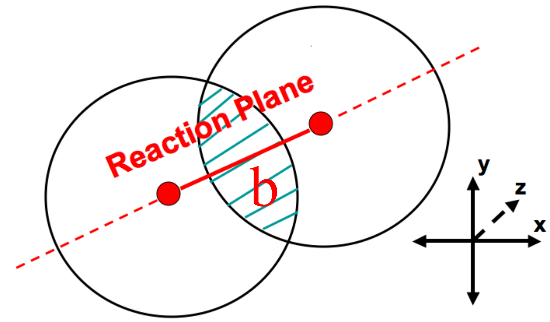
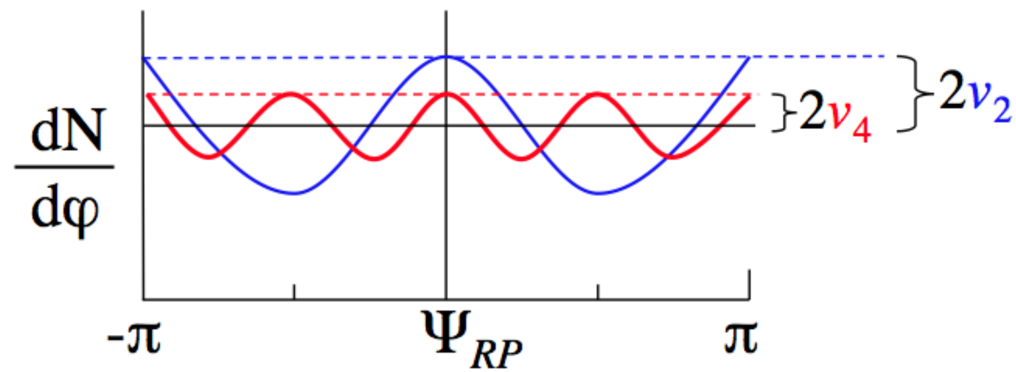
Outline

- Particle Identified (PID) v_2
- Beam Energy Scan
- Higher Order Flow (v_3,v_4)

Flow



- Flow is measured as the asymmetry of the emitted particle's ϕ distribution w.r.t. the Reaction Plane angle (Ψ_{RP})
- Quantized as v_n, where n is the harmonic of the distribution



$$\frac{dN}{d\phi} \alpha 1 + \sum_{n=1} 2v_n \cos\left[2\left(\phi - \Psi_{RP}\right)\right]$$

$$v_n = \left\langle \cos\left[n\left(\phi - \Psi_{RP}\right)\right]\right\rangle,\ n = 1,2,3...$$

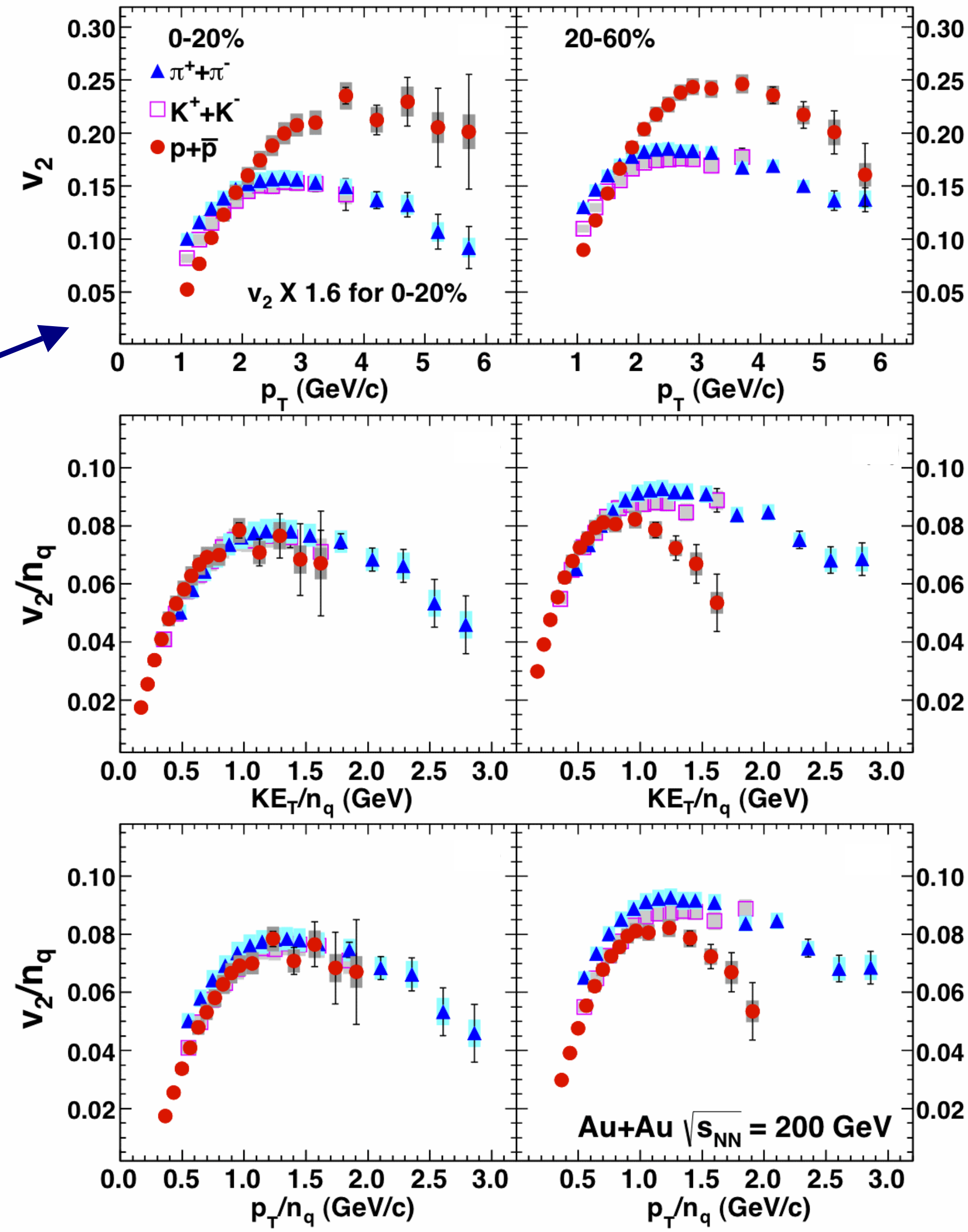
PID v_2

Measured to higher p_T than previous PHENIX measurements

- Possible plateau for higher p_T protons in central collisions, not so for more peripheral

- Quark number (n_q) scaling better for KE_T/n_q than p_T/n_q
- For KE_T/n_q scaling holds for central events, but breaks at ~0.8 GeV for more peripheral

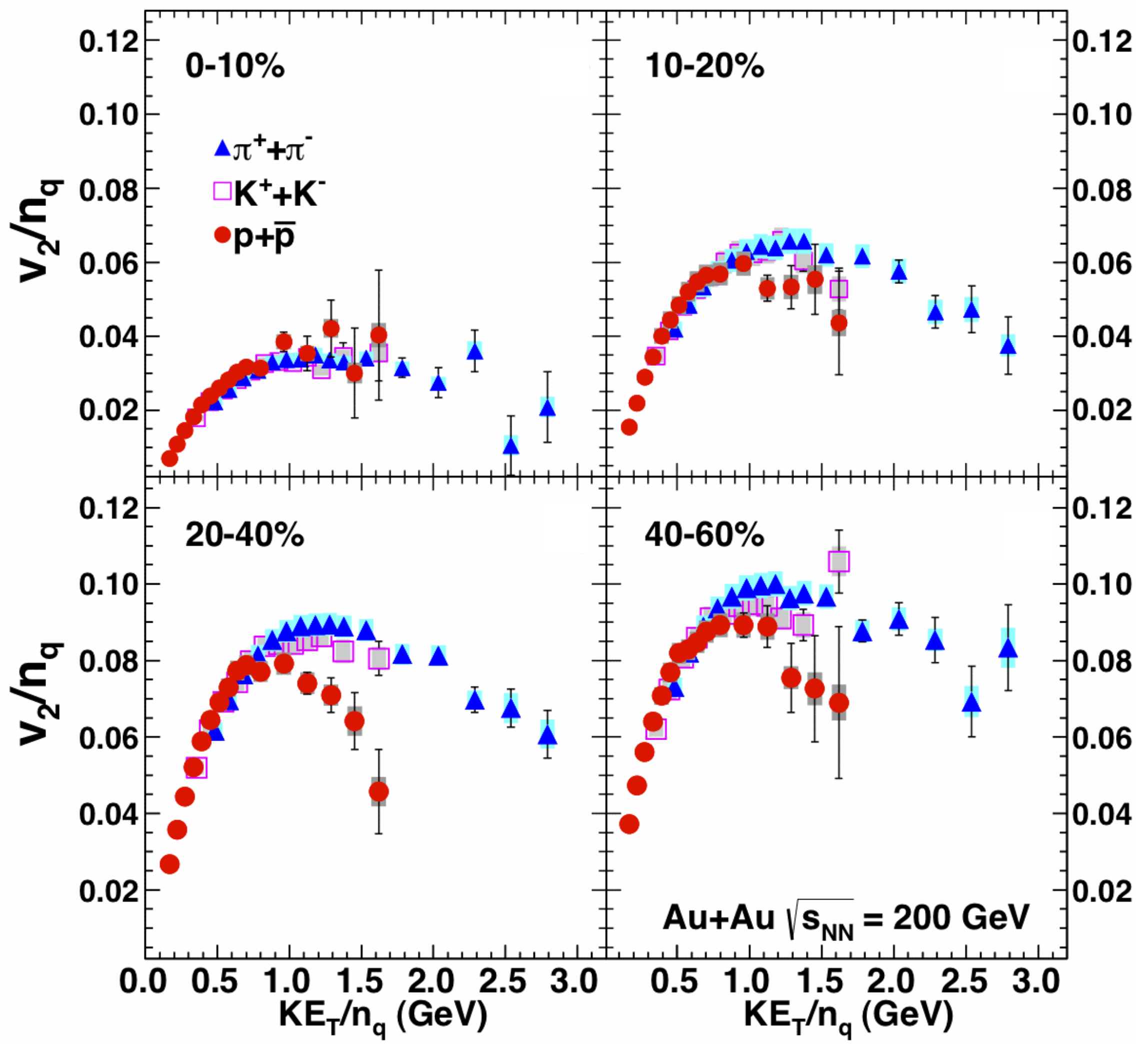
Newly submitted to PRC, arXiv:1203.2644



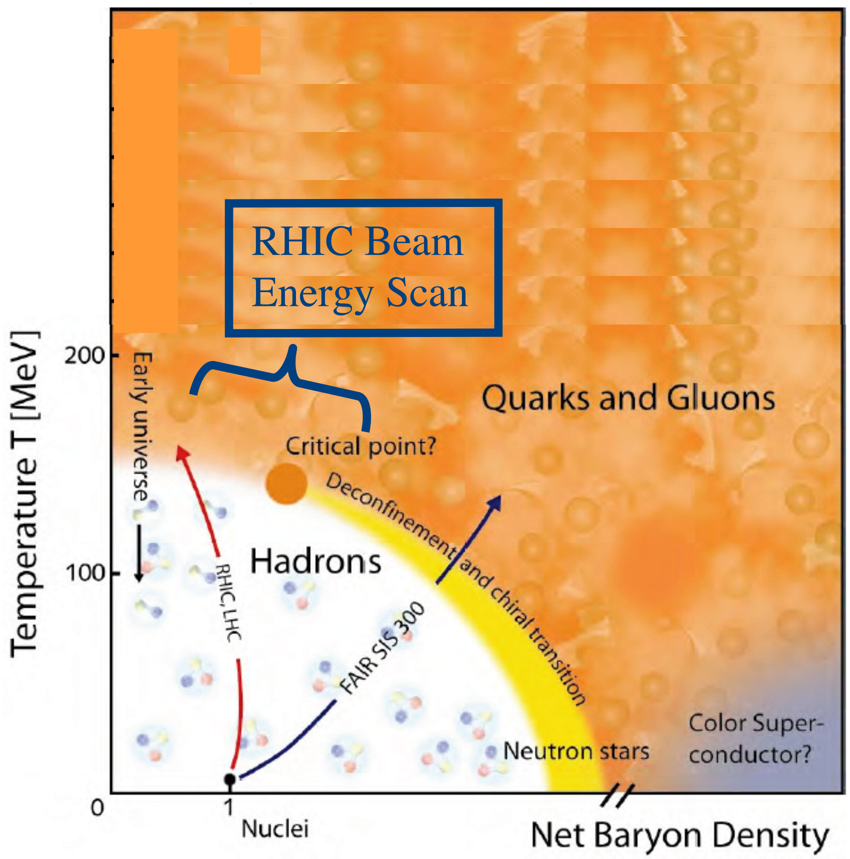
$v_2/n_q(KE_T/n_q)$ Centrality Dependence

- In measured range quark number scaling holds for 0-10%, but breakdown is observable starting at ~1.1 GeV for 10-20%
- Breaking of n_q scaling has clear centrality dependence

arXiv:1203.2644

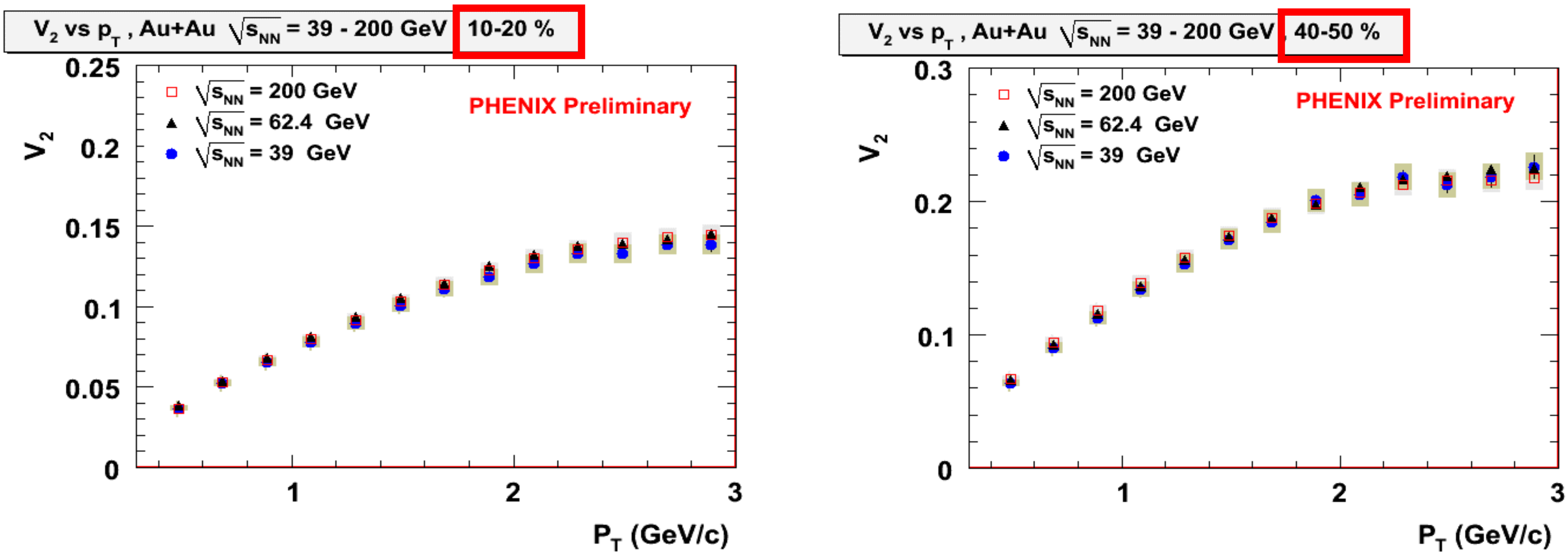


Beam Energy Scan



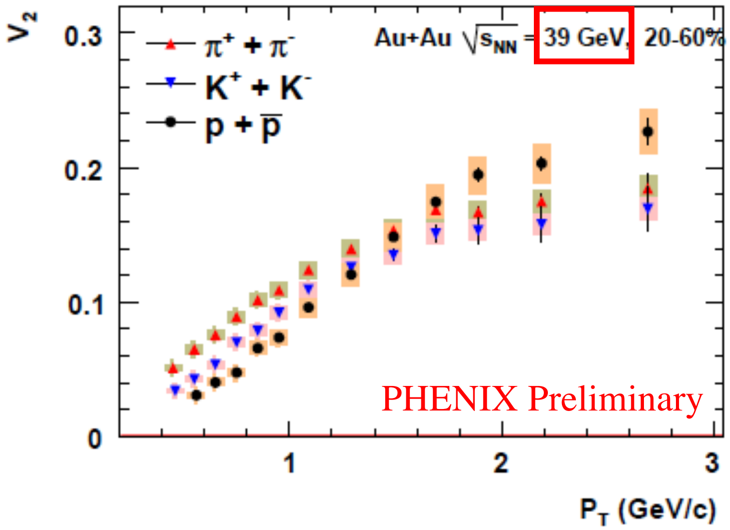
- Expanding upon the knowledge gained from RHIC's 200 GeV Au+Au collisions a beam energy scan is being undertaken to:
  - probe the nuclear phase diagram
  - further study the fundamental properties of the QGP (T, η, etc…)
  - determine at what collision energy partonic level behavior stops
  - study how initial geometry effects change with beam energy
  - find the critical point
- Measuring flow can help us investigate these issues

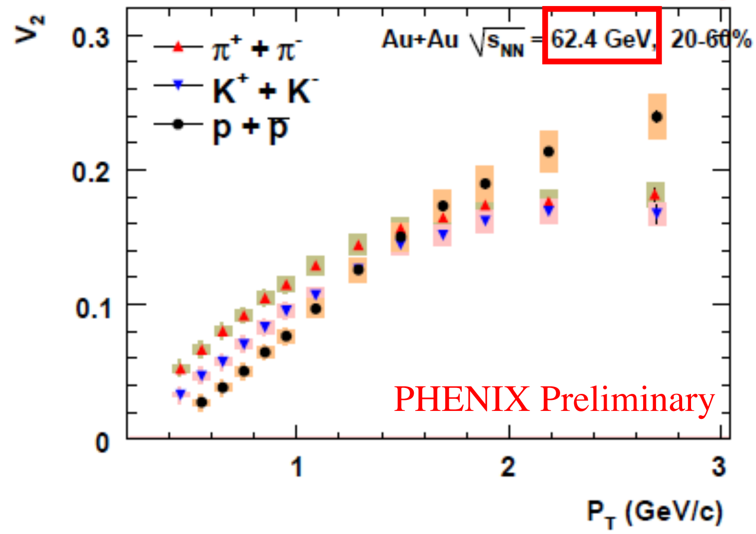
v_2 for $\sqrt{s_{NN}}$ = 39, 62.4 and 200 GeV



- v_2 signal is consistent between 39→200 GeV
- v_2 shows saturation down to at least 39 GeV collisions

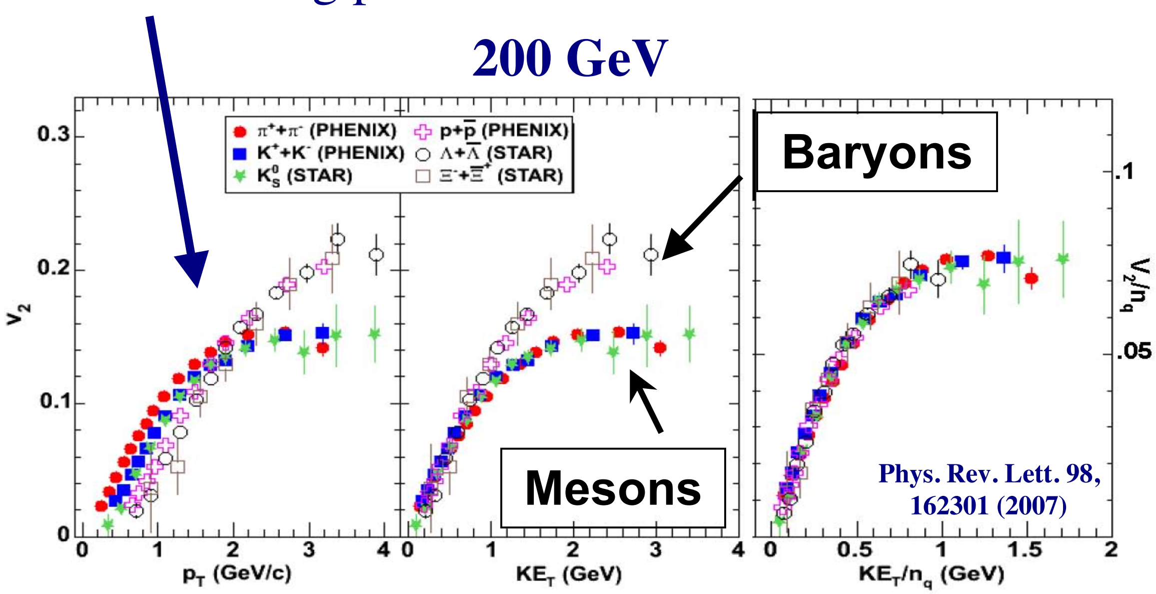
PID v_2



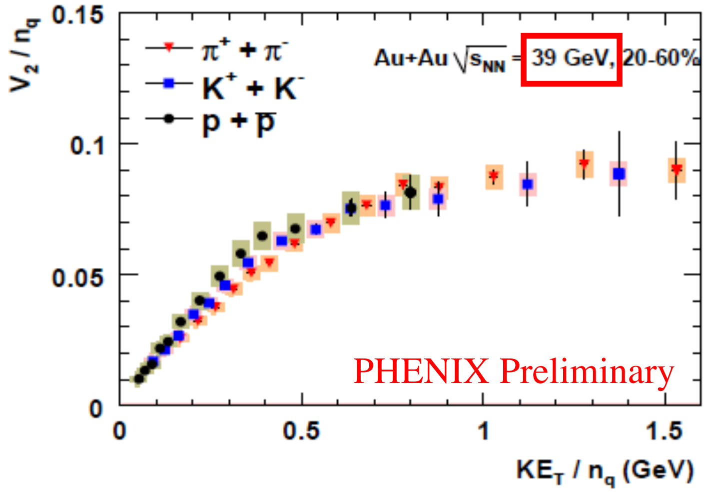


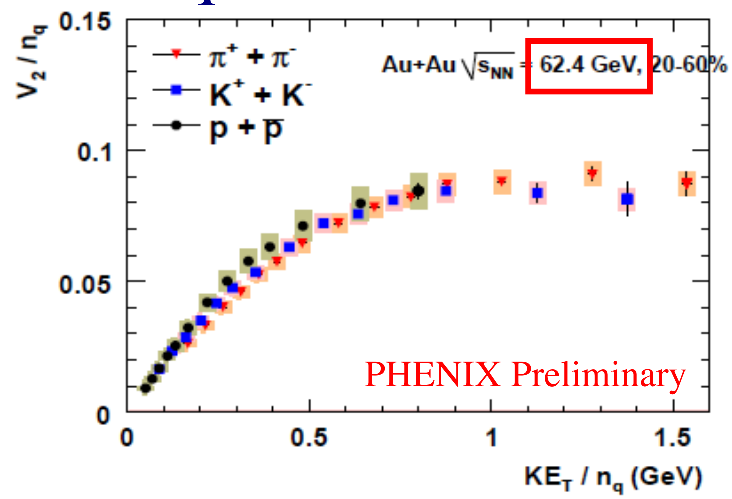
- Same mass scaling pattern as seen in 200 GeV collisions

200 GeV



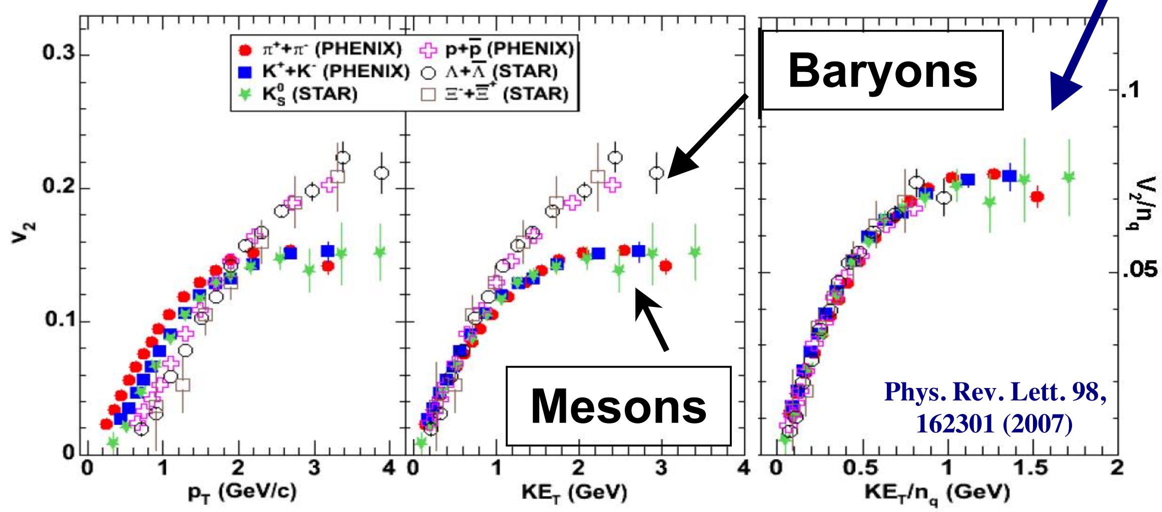
PID v_2/n_q



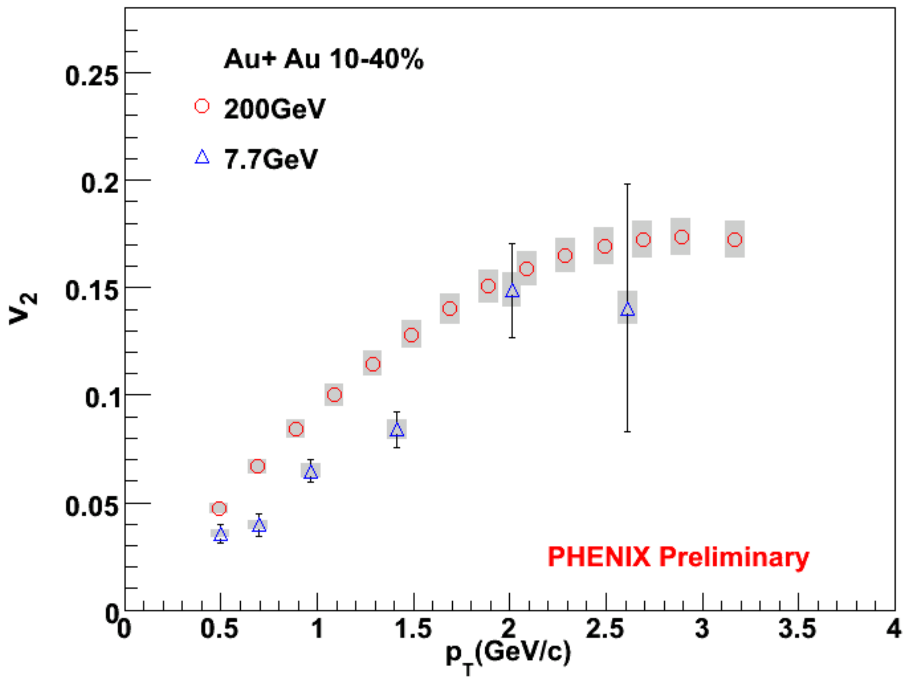


- Despite small discrepancy at $KE_T/n_q \sim 0.4$ GeV, quark number (n_q) scaling indicates partonic collective flow down to 39 GeV
- Likely due to increase prominence of (anti)protons

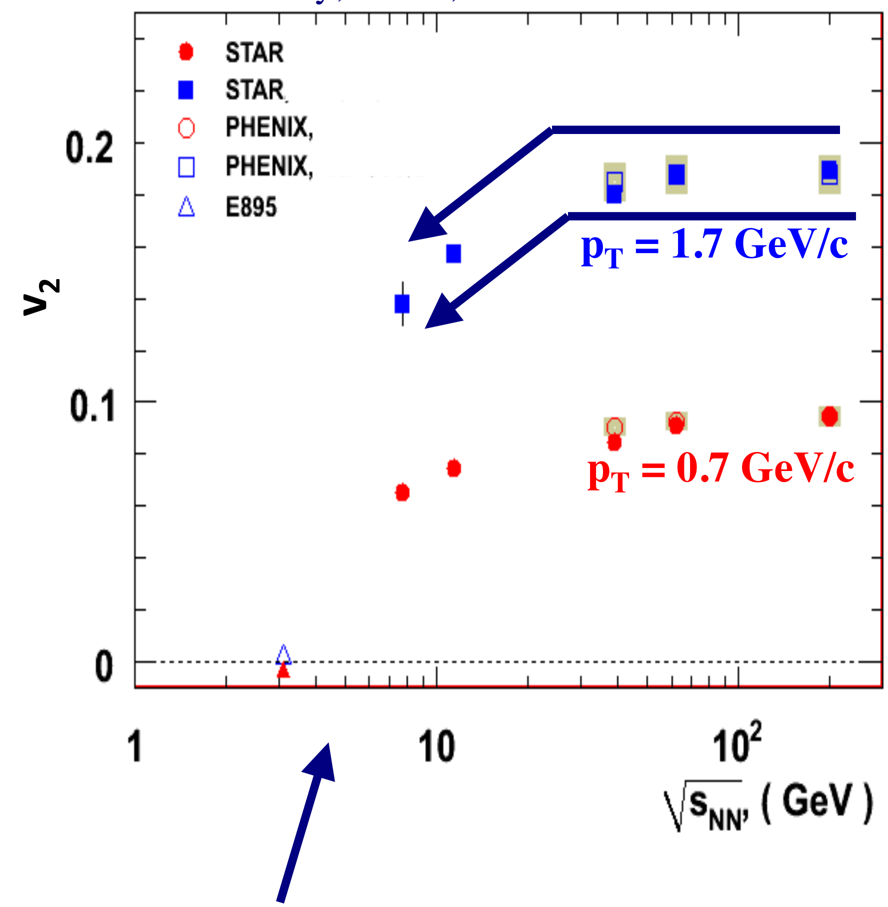
200 GeV



Beam Energies < 39 GeV



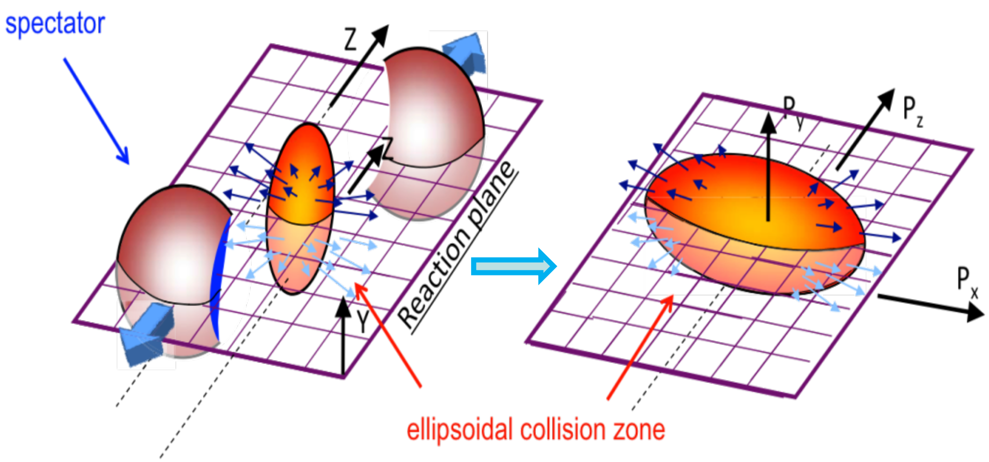
Preliminary, STAR, PHENIX and E895 data



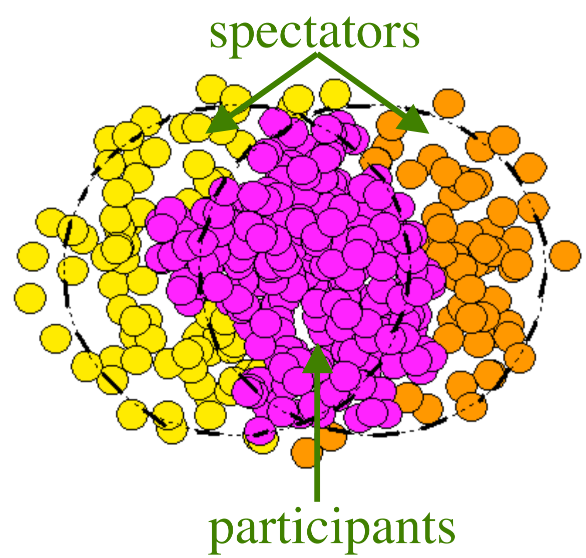
- v_2 at 7.7 GeV is lower than 39, 62 and 200 GeV collisions
- v_2 flattens at 39 GeV and above, but starts decreasing somewhere below 39 GeV
- Change from partonic to hadronic flow between 39 GeV → 7.7 GeV?

Higher Order Harmonics: v_3 & v_4

<u>Smooth</u>



<u>Chunky</u>



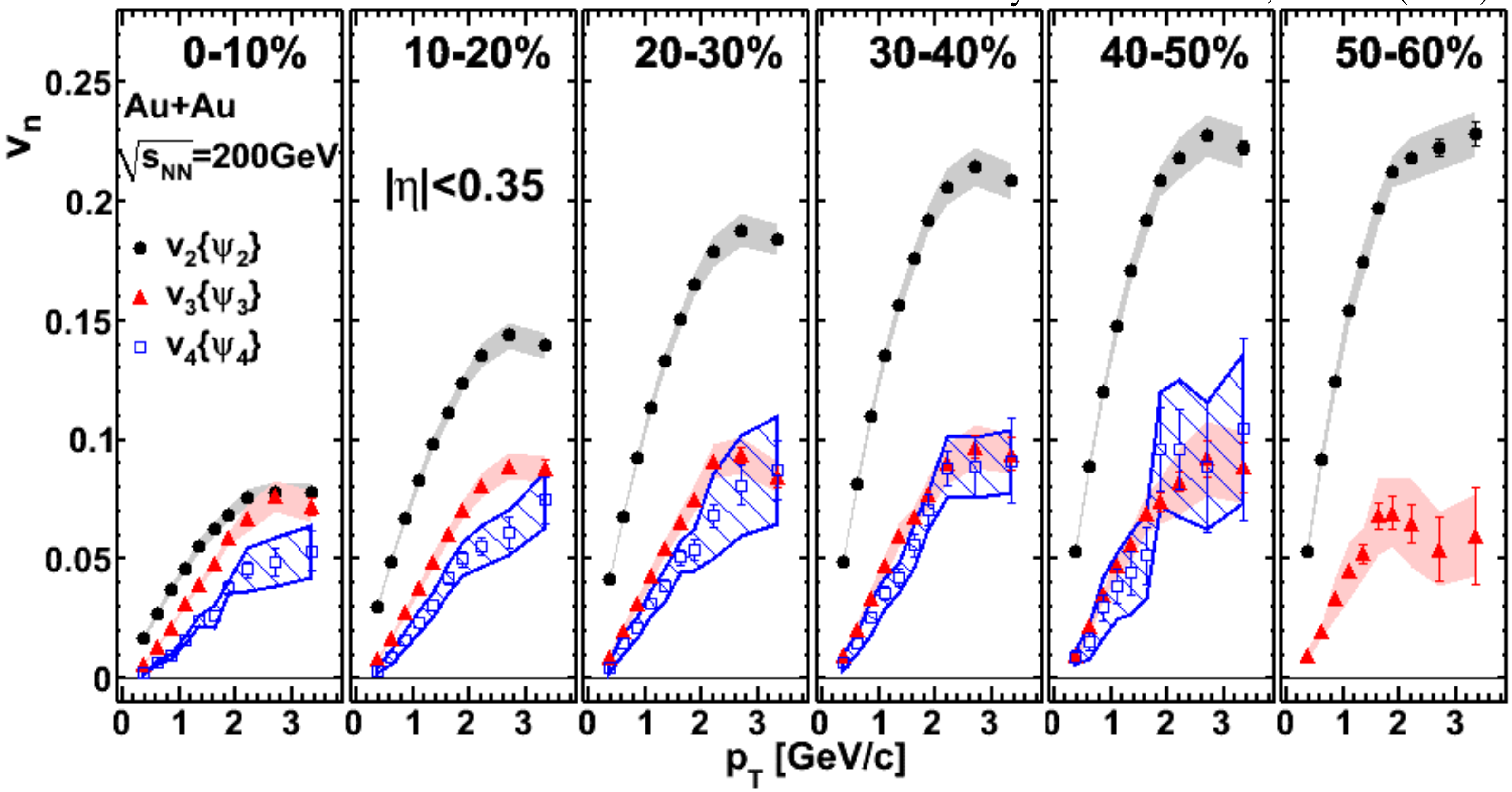
Odd harmonics **cancel**

Odd harmonics **persist**

- Higher order harmonics could provide additional constraints on initial geometry models (smooth or chunky?)
- Do v_3 and v_4 saturate at 62 and 39 GeV as v_2 did?

$v_n\{\Psi_n\}$ at 200 GeV Au+Au

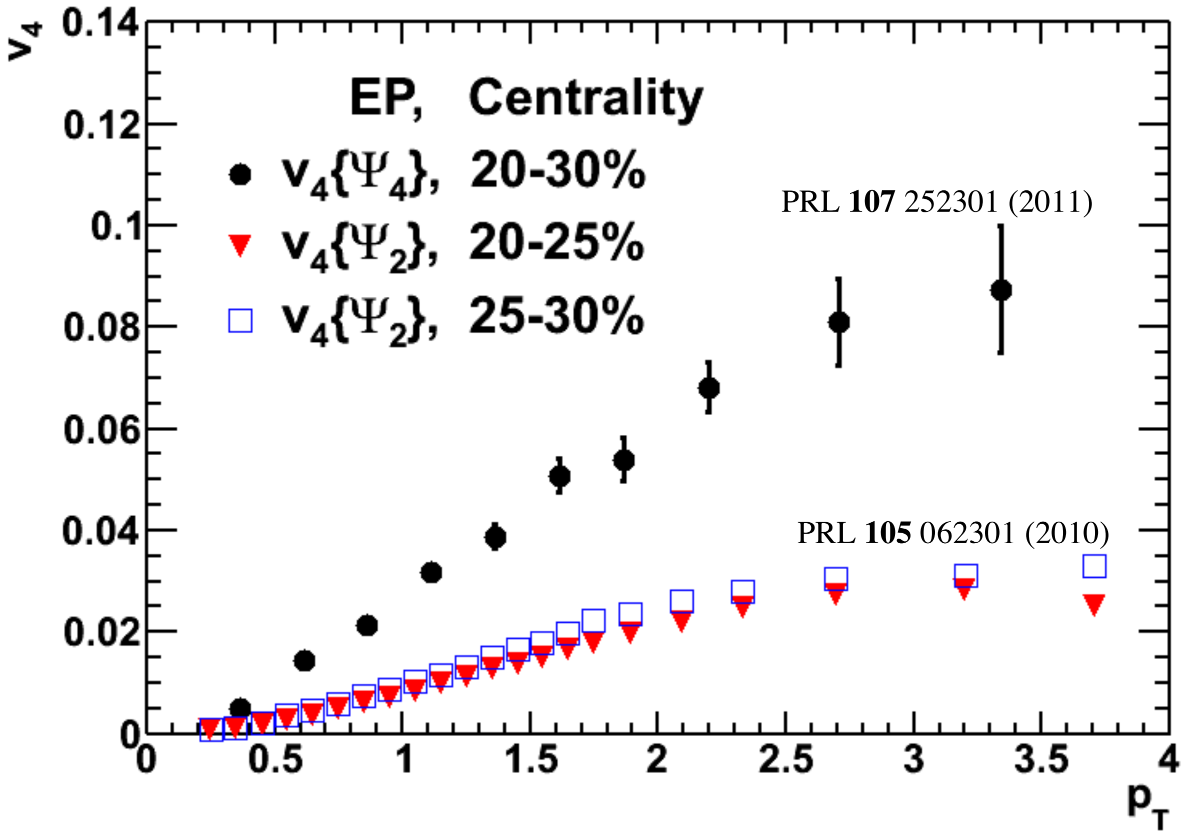
Phys. Rev. Lett. 107, 252301 (2011)



(1) Significant v_3 signal - indicates "chunky" origins
(2) v_3 comparable to v_2 at 0~10%, but increasingly deviates with decreasing centrality
(3) Weak centrality dependence on v_3

Consistent with:
- v_3 originating from initial fluctuation

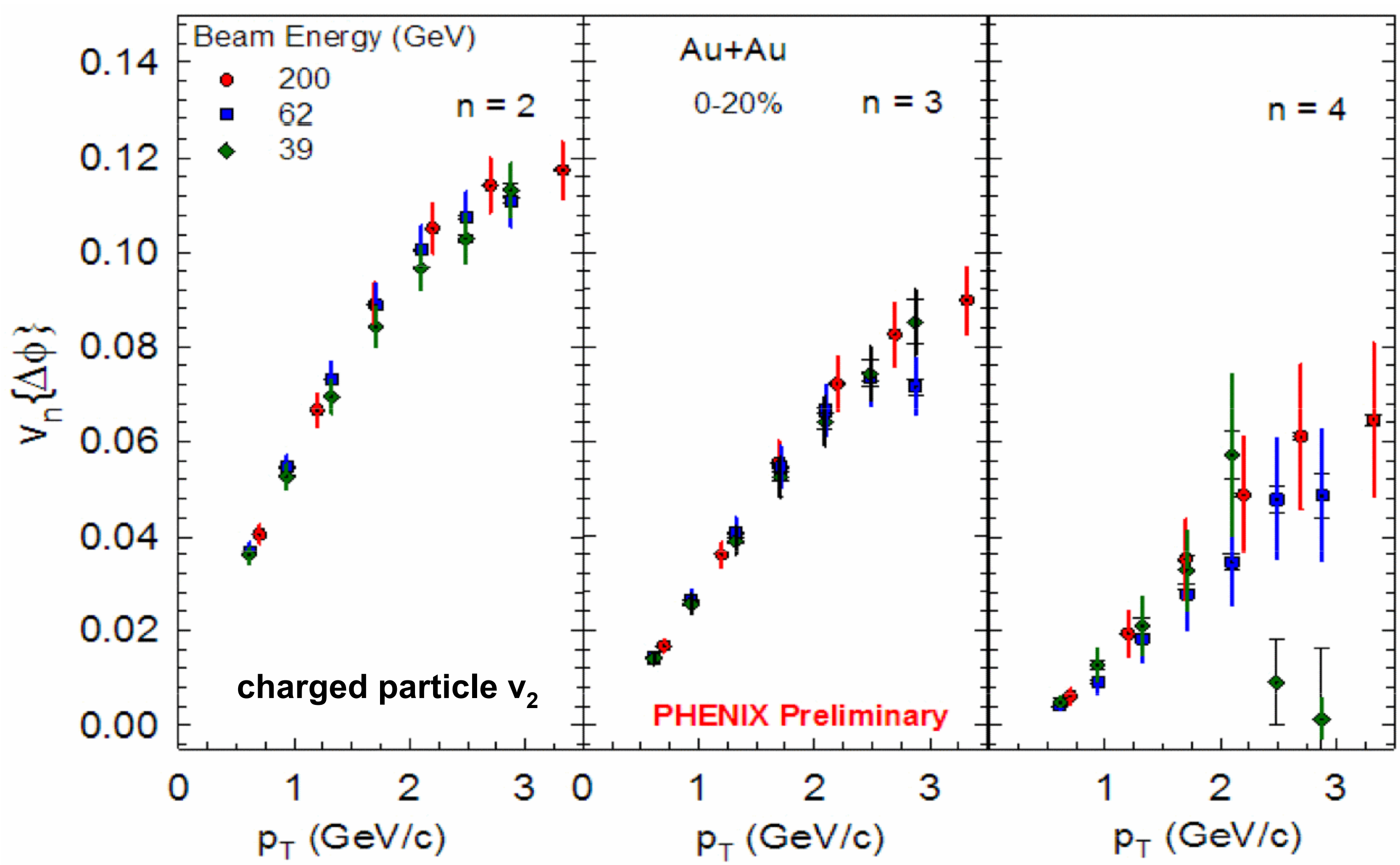
$v_n\{\Psi_n\}$ at 200 GeV Au+Au



(1) Significant v_3 signal - indicates “chunky” origins
(2) v_3 comparable to v_2 at 0~10%, but increasingly deviates with decreasing centrality
(3) Weak centrality dependence on v_3
(4) $v_4\{\Psi_4\} \sim 2 \times v_4\{\Psi_2\}$

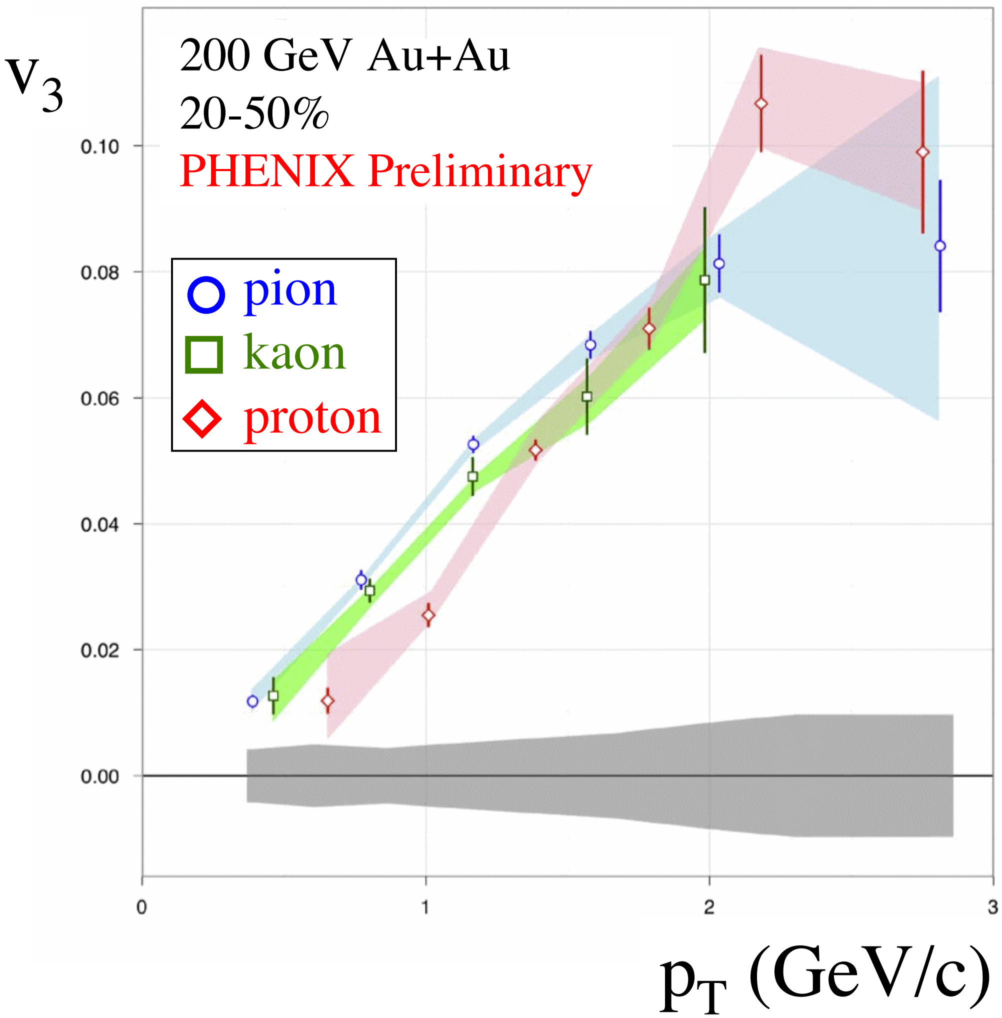
Consistent with:
- v_3 originating from initial fluctuation
- initial fluctuations contributing to v_4 signal

Beam Energy Dependence for Different Harmonics



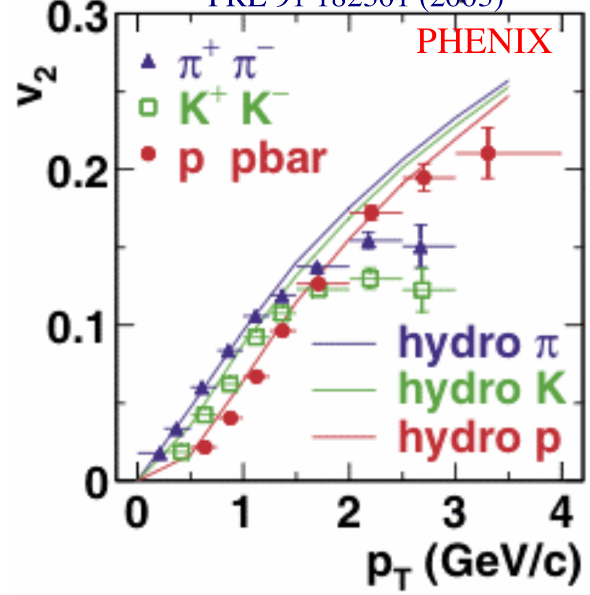
Similar hydro properties down to 39 GeV

PID v_3 @ $\sqrt{s_{NN}}$ = 200 GeV



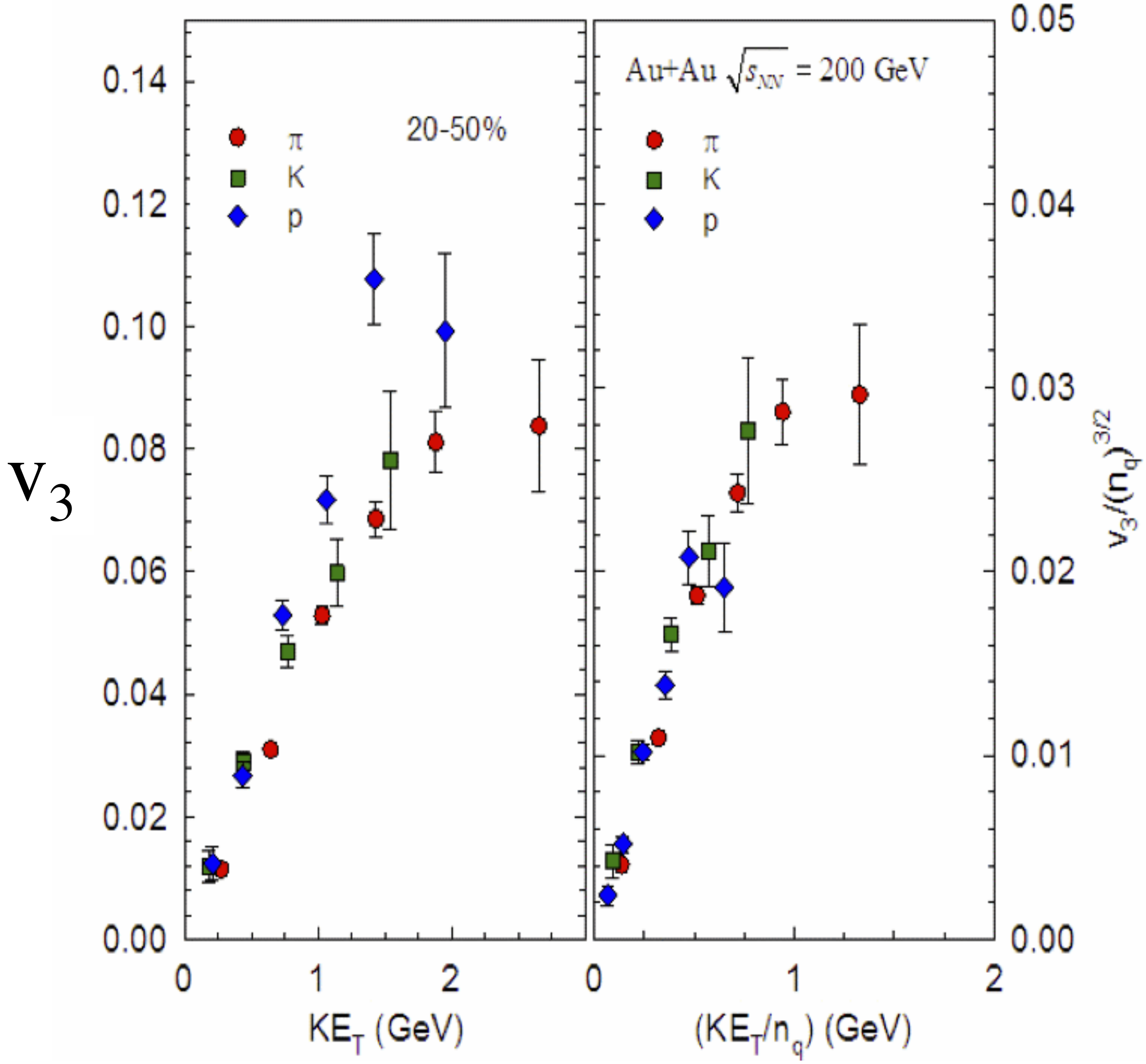
As with v_2, mass ordering is observed with v_3, confirming hydrodynamic behavior, *i.e*. low viscosity.

PRL 91 182301 (2003)



v_3 PID Scaling

- Like v_2, constituent quark scaling is seen with v_3
- Evidence of partonic flow



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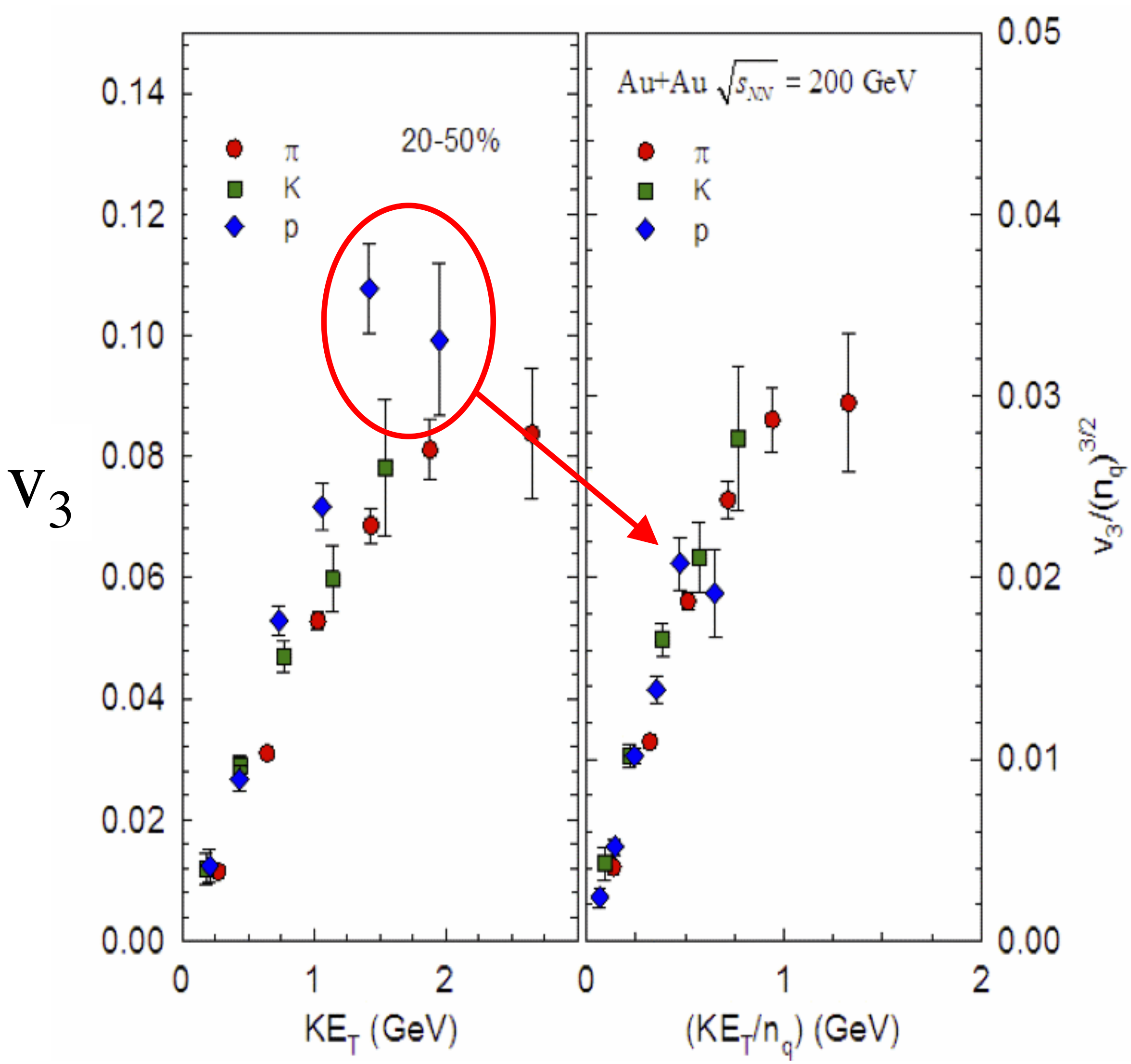
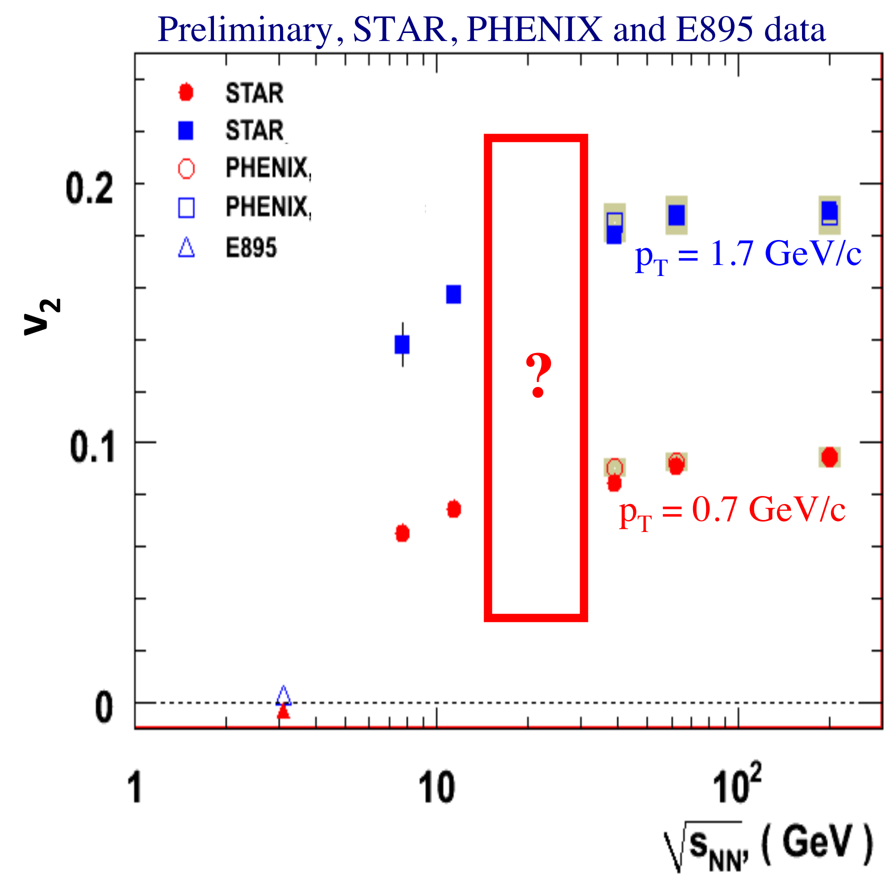


Summary

- When p_T < 6 GeV/c, $v_2/n_q(KE_T/n_q)$ scaling holds for 0-10%, but begins to break at ~0.8-1.0 GeV for more peripheral centralities
- PHENIX has measured v_2, v_3, v_4 from 39→200 GeV where measurements appear independent of beam energy within this range
- However, at 7.7 GeV v_2 is noticeably lower than at 39 GeV. No longer a QGP?

Summary

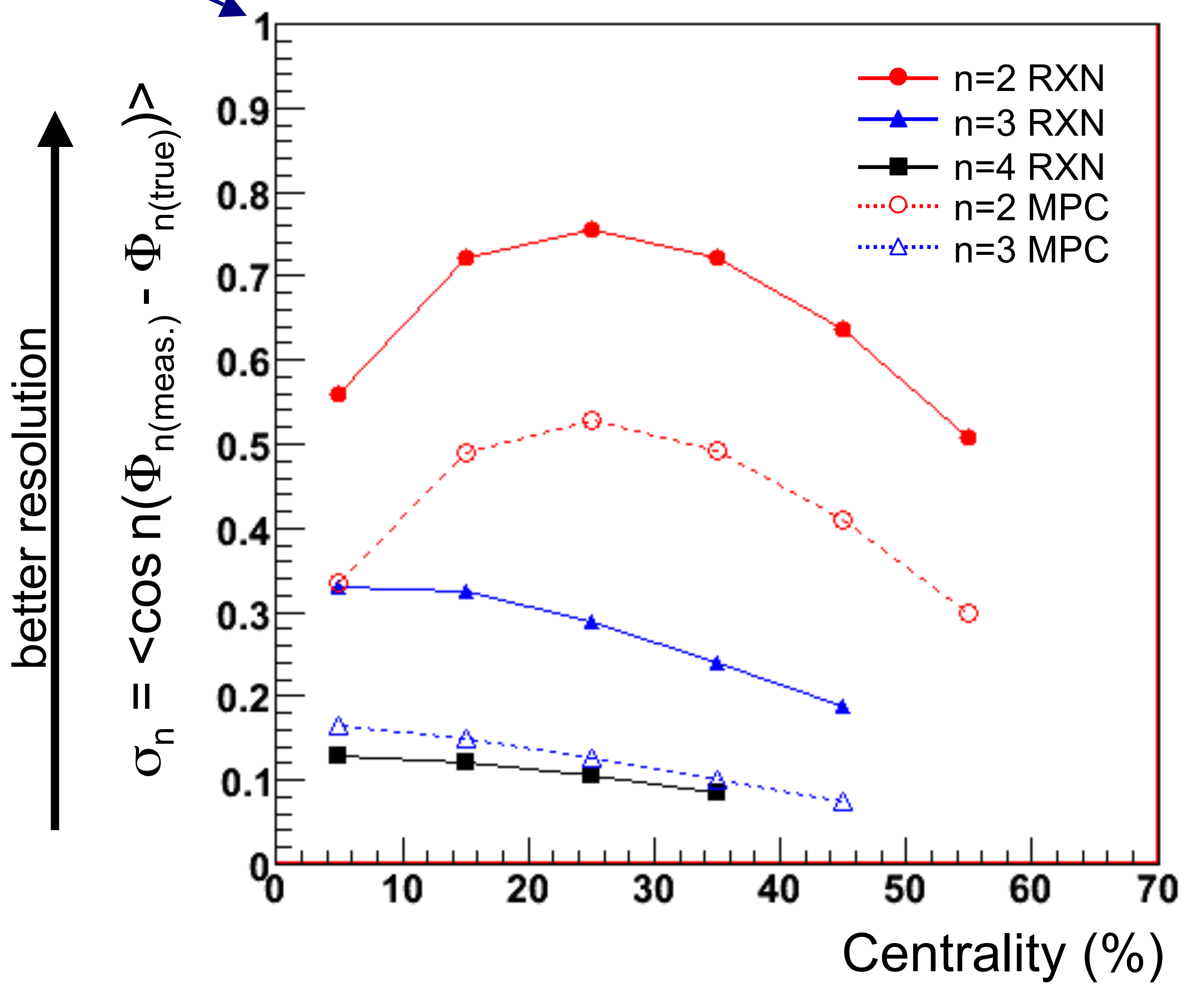
- v_3 appears to originate from fluctuations & v_4 partially so, which should aid in better understanding initial geometry and medium conditions
- 2011 RHIC run collected data at 19.6 and 27 GeV to help fill gap in transition region



Backup

Reaction Plane Resolution

Perfect Resolution



RXN |η| = 1.0 ~ 2.8

MPC |η| = 3.1~ 3.7

$$v_n = \frac{v_n^{meas}}{\sigma_n}$$

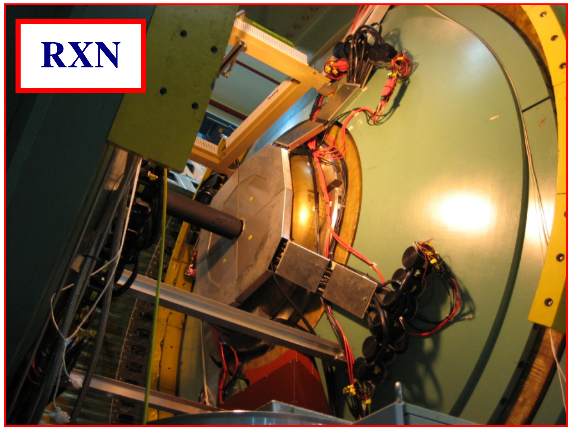
Detectors

Reaction Plane Detector

Scintillator Paddles

Inner Ring: $1.5 < |\eta| < 2.8$

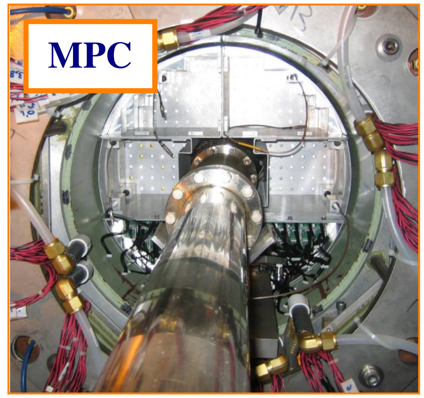
Outer Ring: $1.0 < |\eta| < 1.5$



Muon Piston Calorimeter

$PbWO_4$ Calorimeter

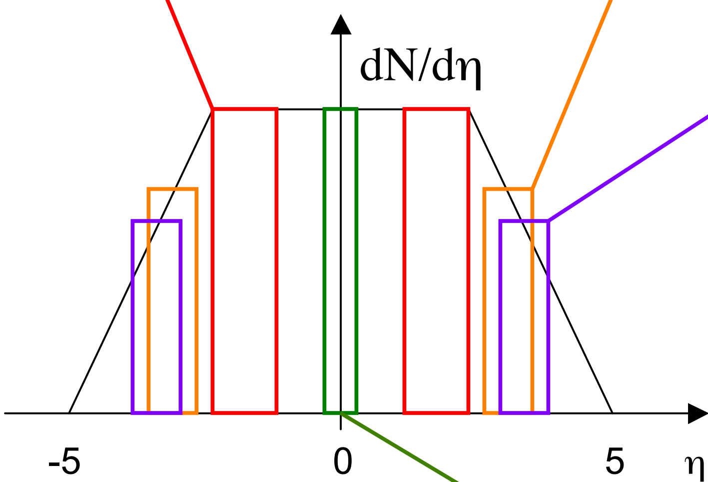
$3.1 < |\eta| < 3.9$



Beam Beam Counter

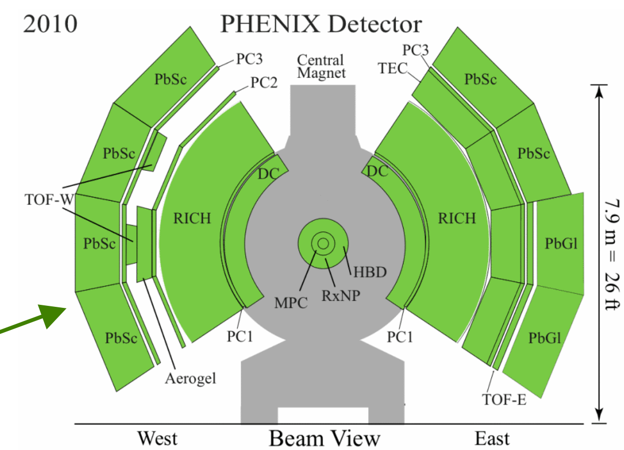
Quartz Cherenkov

$3.1 < |\eta| < 3.9$

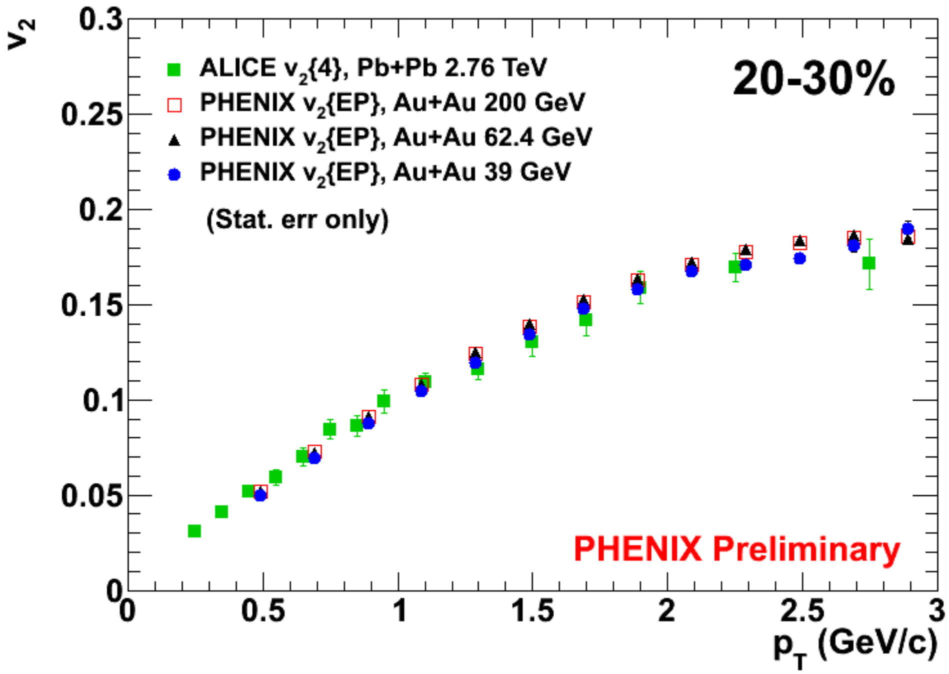


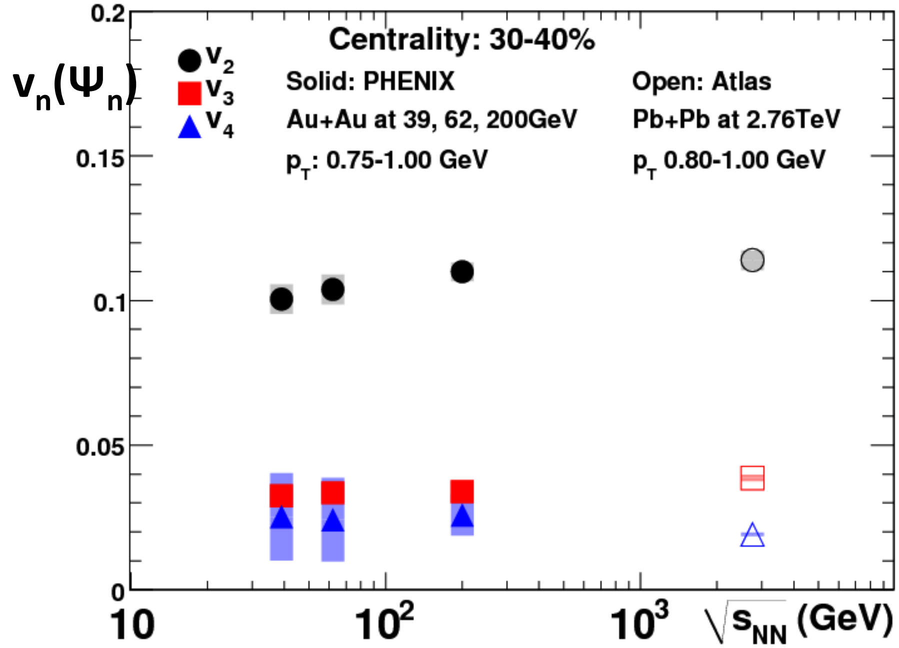
Central Arm Tracking

$|\eta| < 0.35$



Comparison with LHC

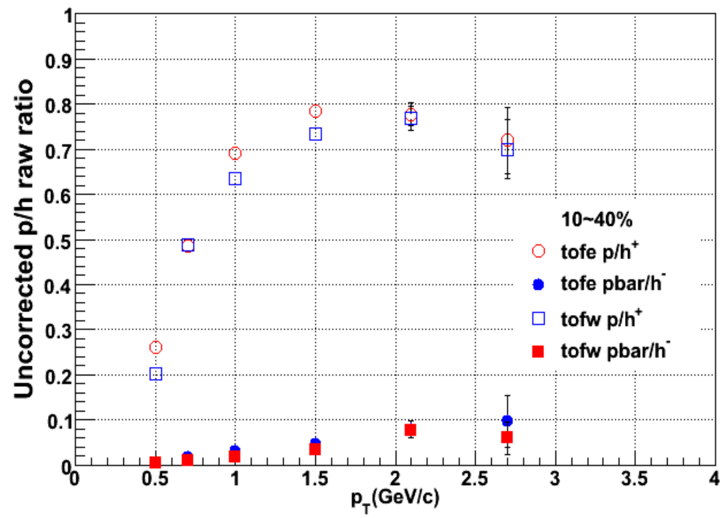


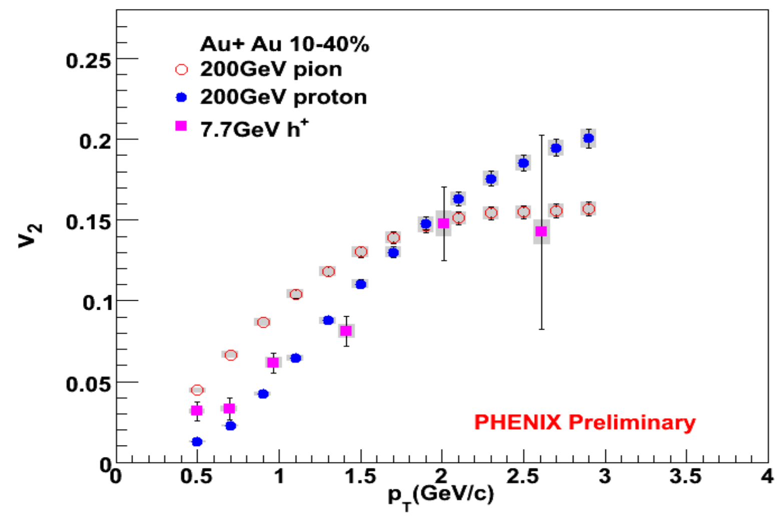


Caution: PHENIX & ALICE use different flow methods.

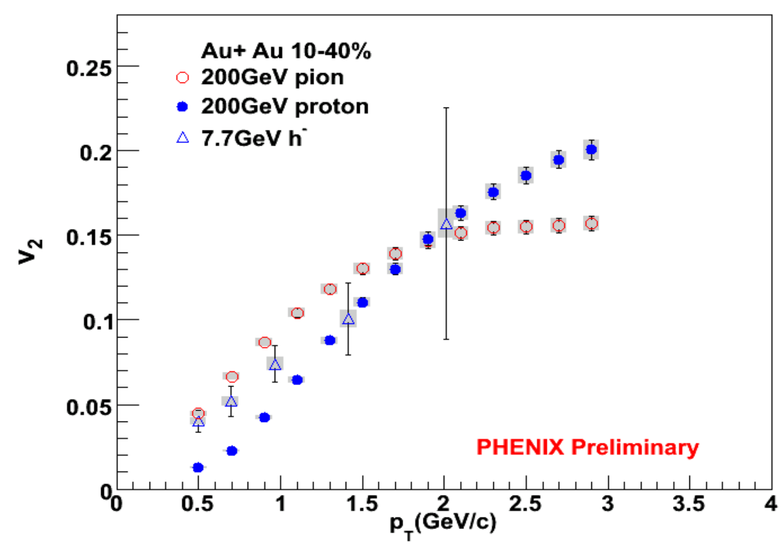
- Similar v_n signal at LHC energy, $\sqrt{s_{NN}}$ = 2.76 TeV
- Similar hydrodynamic behavior seen from 0.039 → 2.76 TeV

The Baryon Contribution



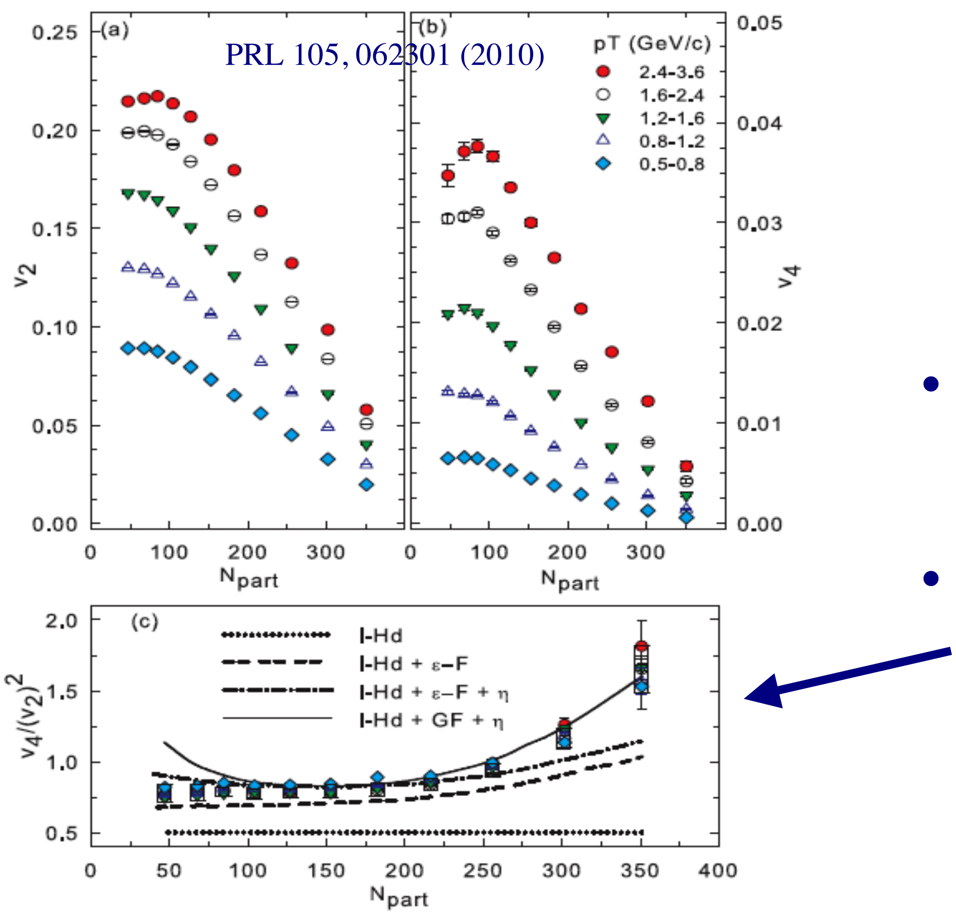


Proton yield dominates in the positive hadrons, while pion yield dominates in the negative hadrons



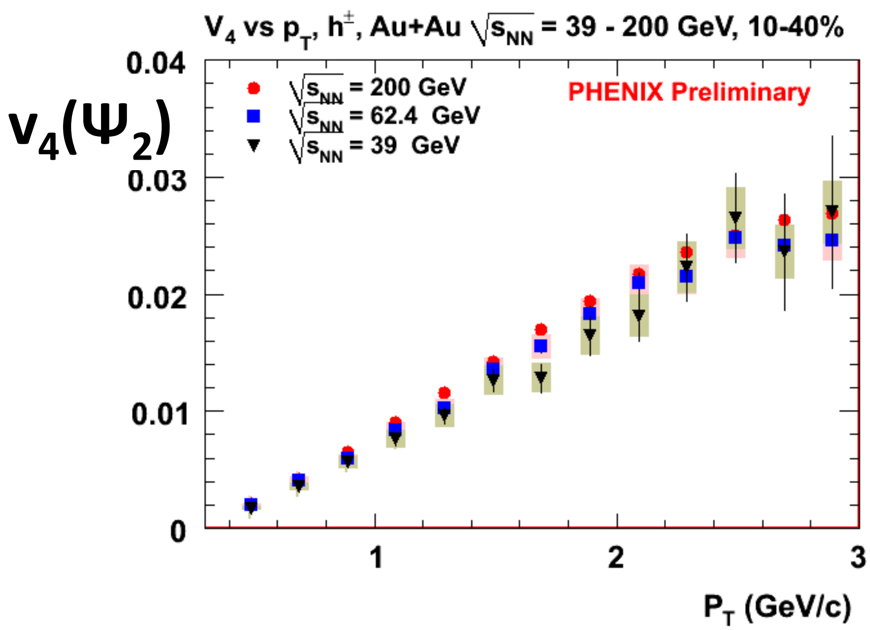
The v_2 of negative hadrons at 7.7 GeV Au+Au is lower than v_2 of pions at 200 GeV AuAu

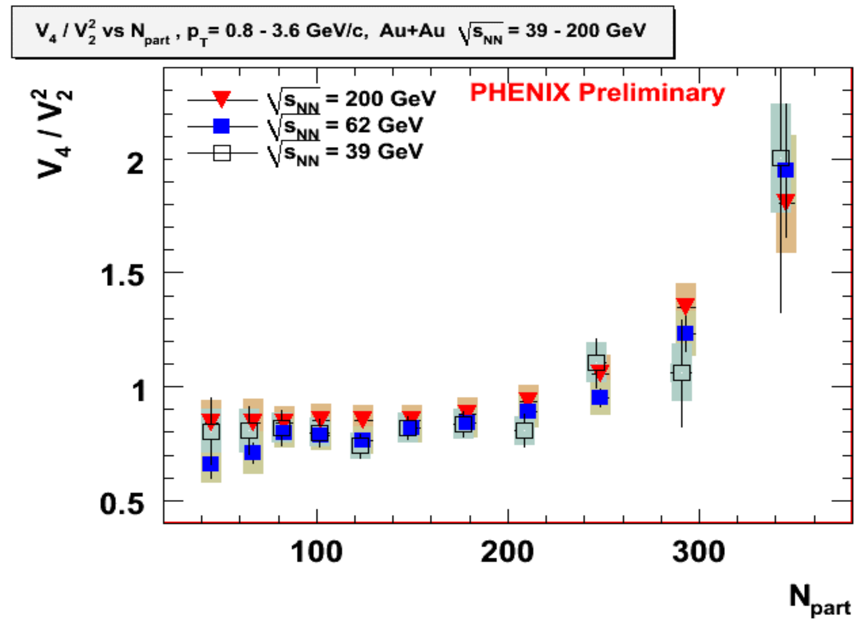
$v_4(\Psi_2)/v_2^2$ @ $\sqrt{s_{NN}}$ = 200 GeV



- v_4/v_2^2 (both w.r.t. Ψ_2) could be used to constrain initial geometric fluctuations and specific viscosity.
- Adding fluctuations and viscosity to hydrodynamic model improves agreement with data.

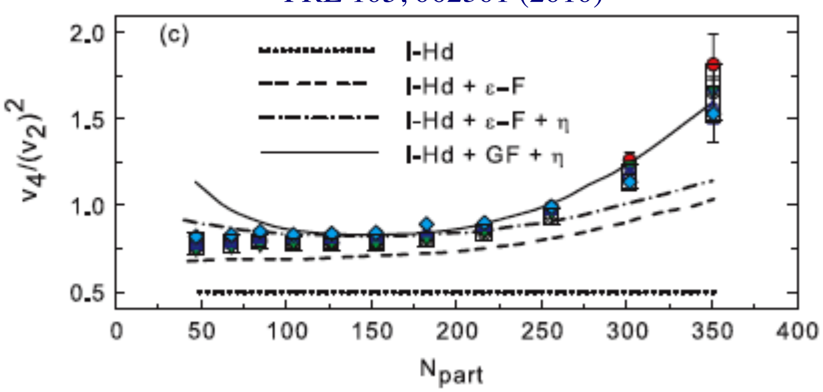
Beam Energy Dependence of $v_4(\Psi_2)$



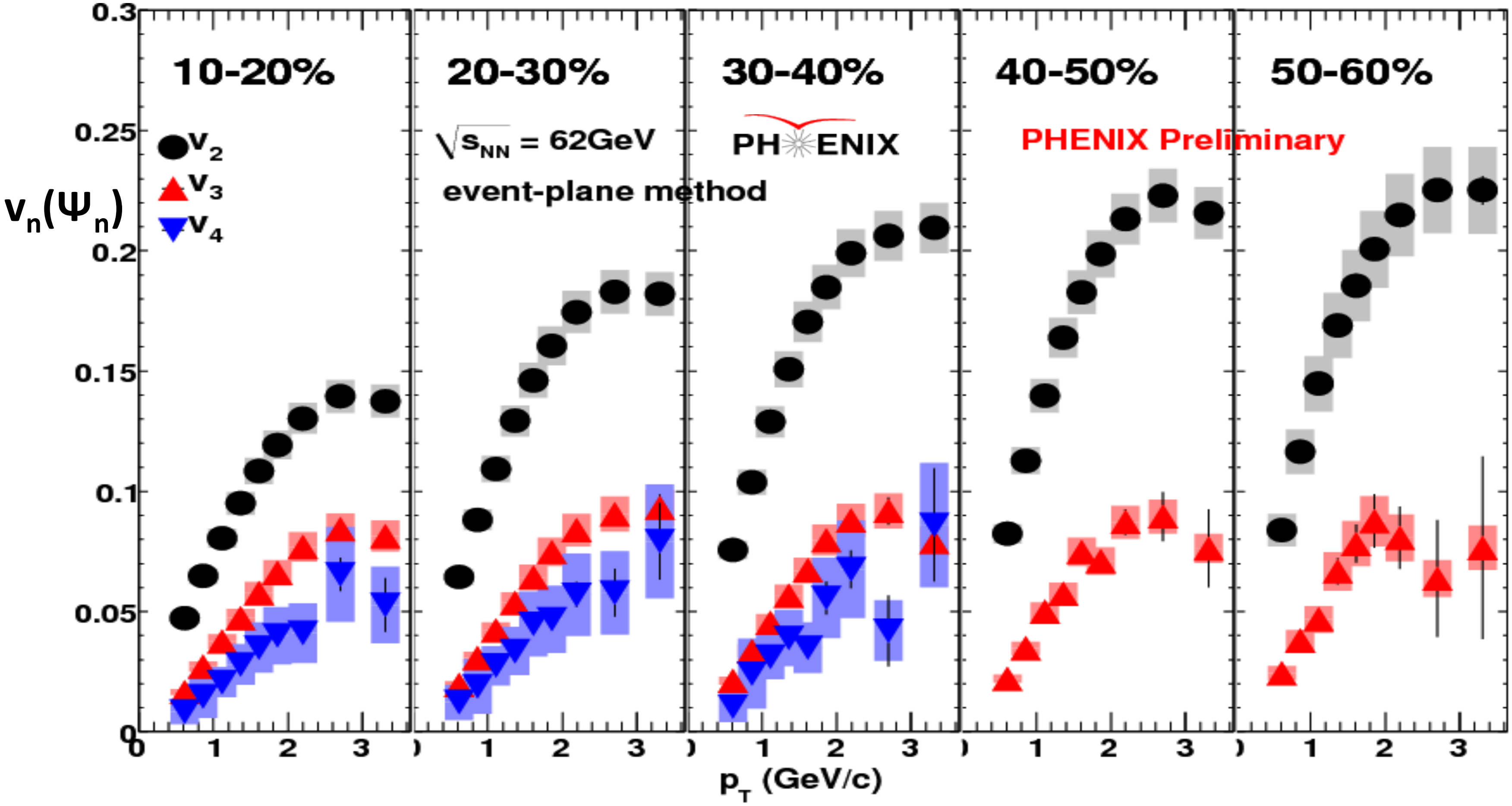


See similar behavior with 62 and 39 GeV collisions

PRL 105, 062301 (2010)

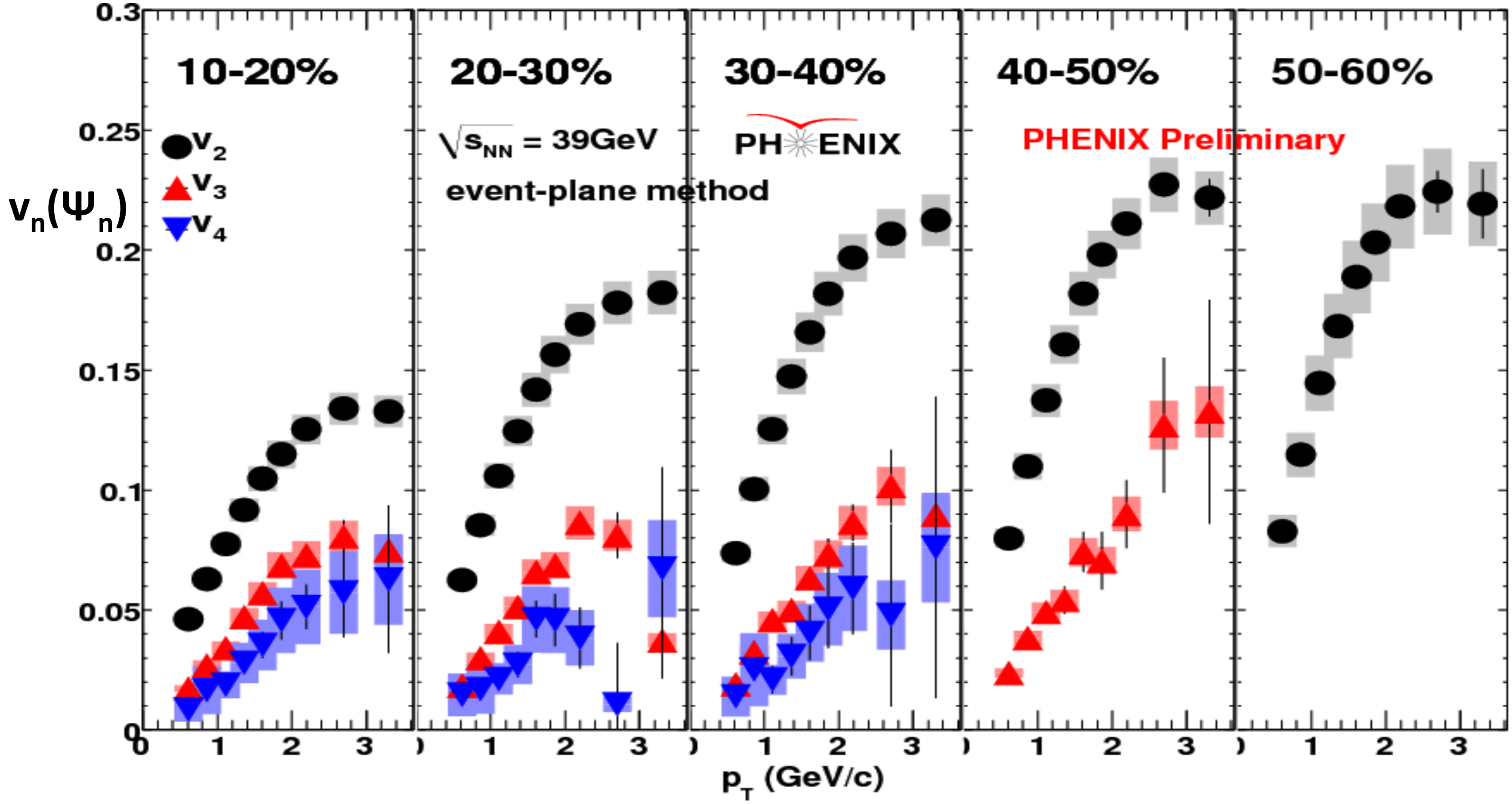


Charged Hadron $v_n(\Psi_n)$ @ 62.4 GeV



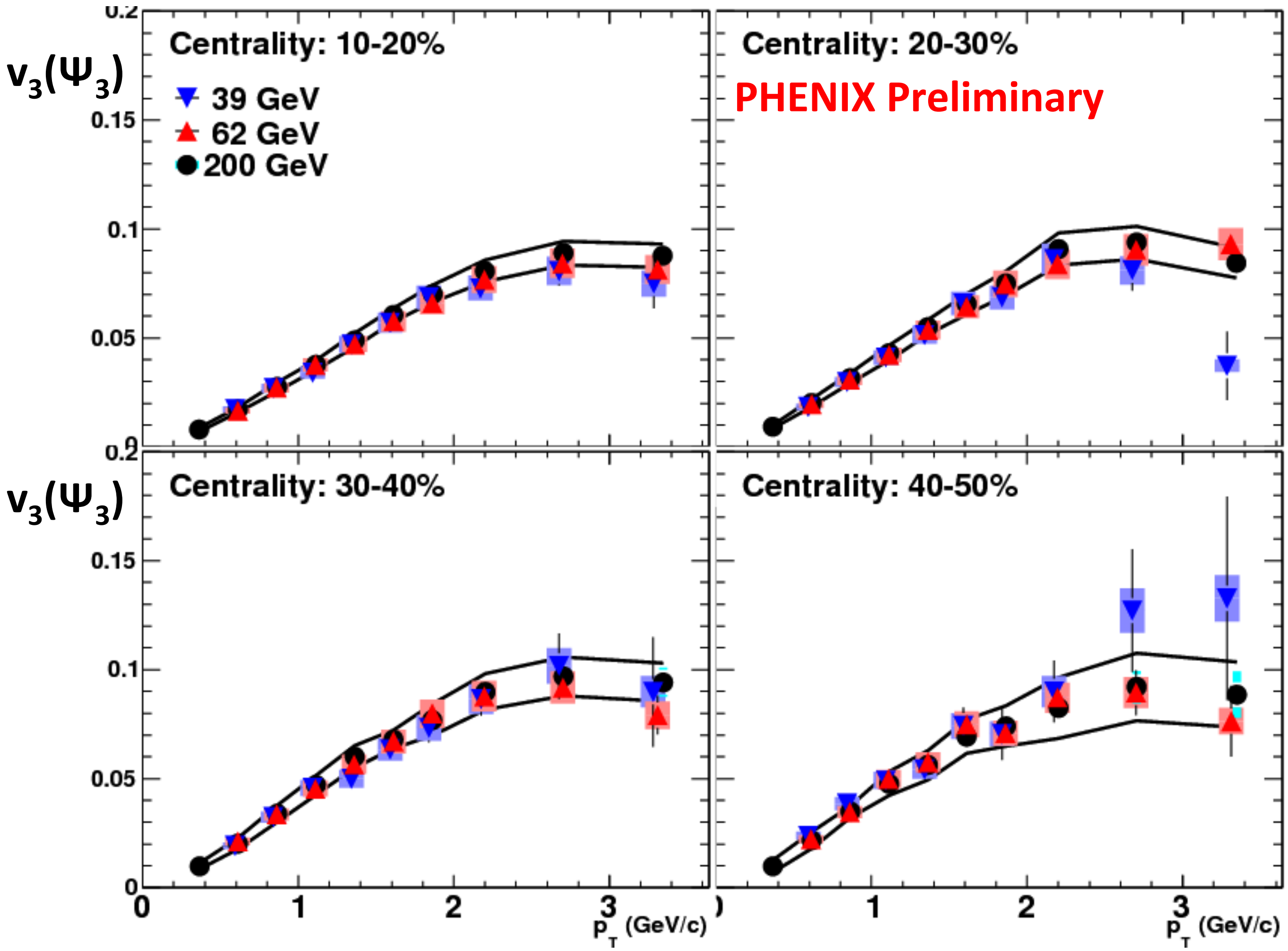
- v_3 has very little centrality dependence. This is consistent with "chunky" origin in fluctuations.
- v_4 slightly increases with centrality.

Charged Hadron $v_n(\Psi_n)$ @ 39 GeV



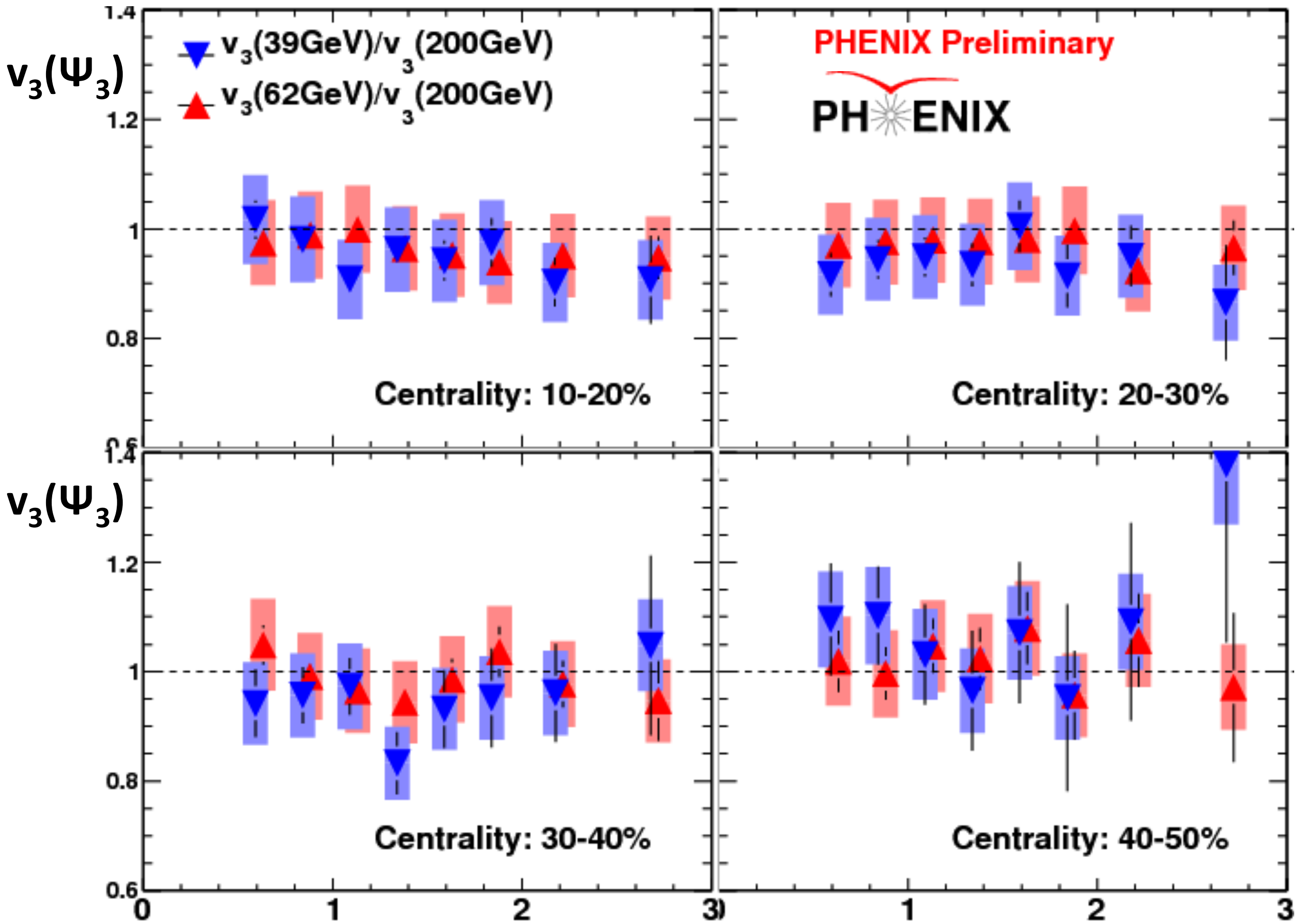
- Similar behavior at 39 GeV.

Beam Energy Dependence on v_3 (Ψ_3)



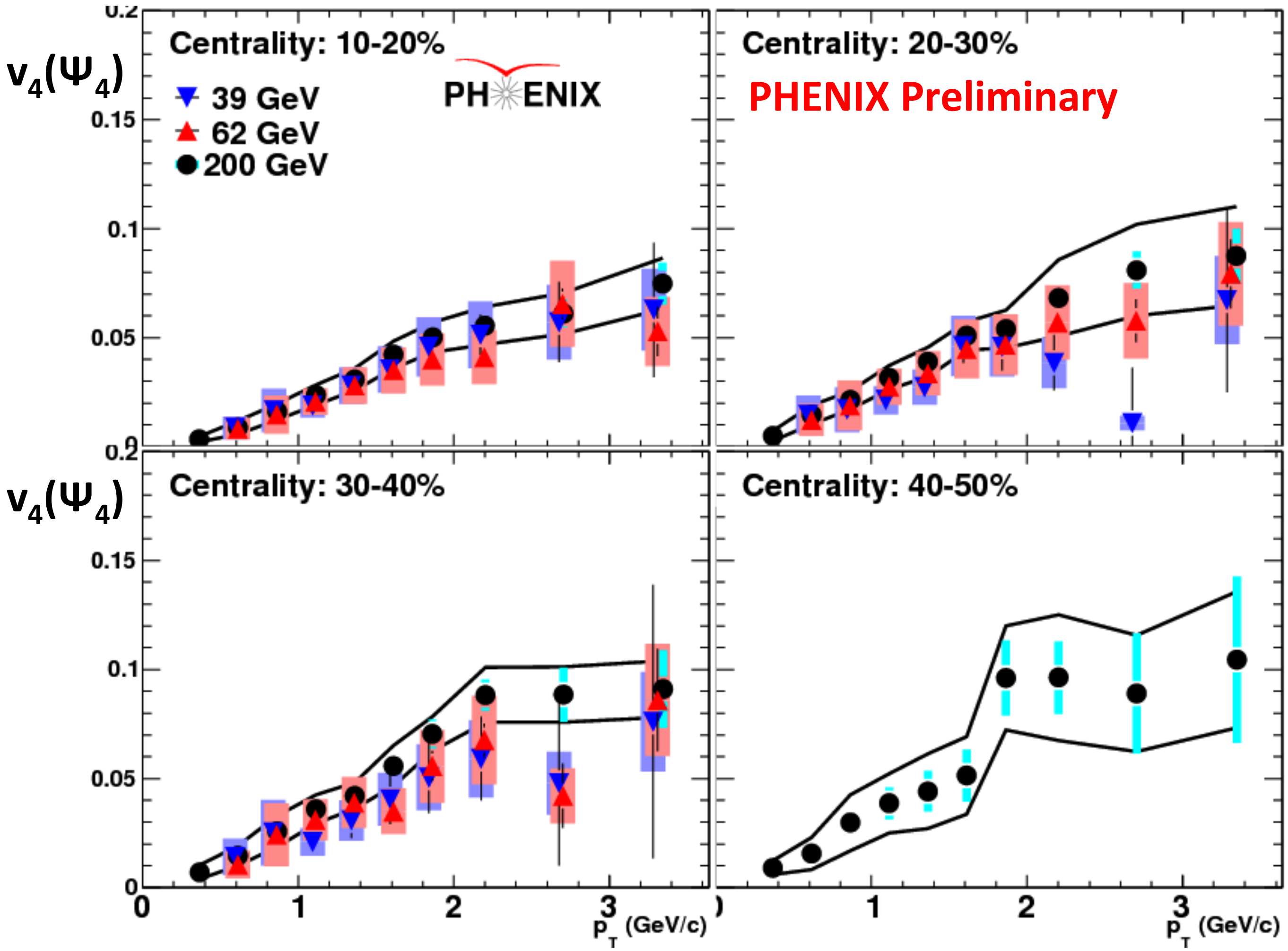
- Like v_2, v_3 also shows saturation from 39→200 GeV.

Beam Energy Dependence on v_3 (Ψ_3)



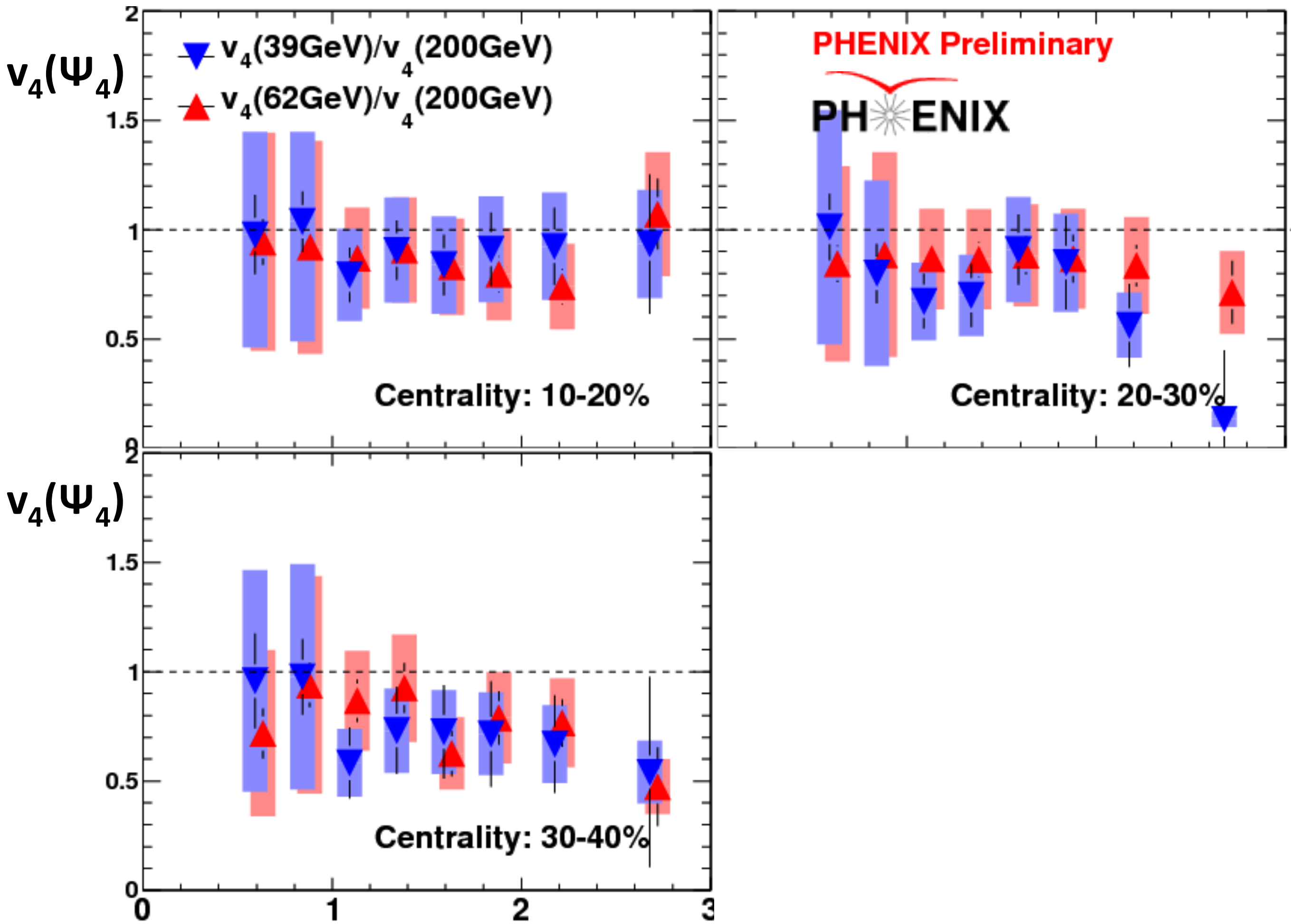
- Ratio of 39 & 64 GeV with 200 GeV is consistent with unity within errors.

Beam Energy Dependence on v_4 (Ψ_4)



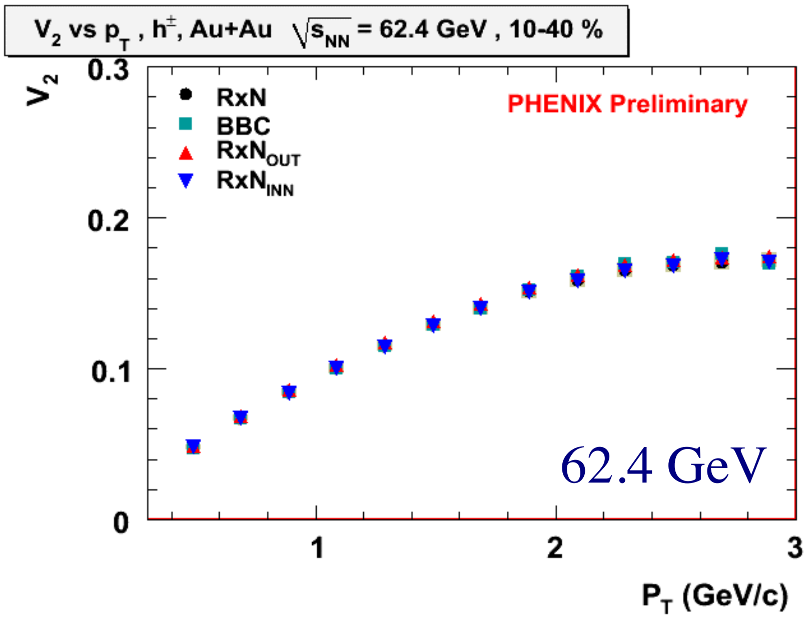
- Similar to v_2 & v_3, v_4 also saturates within errors from 39→200 GeV.

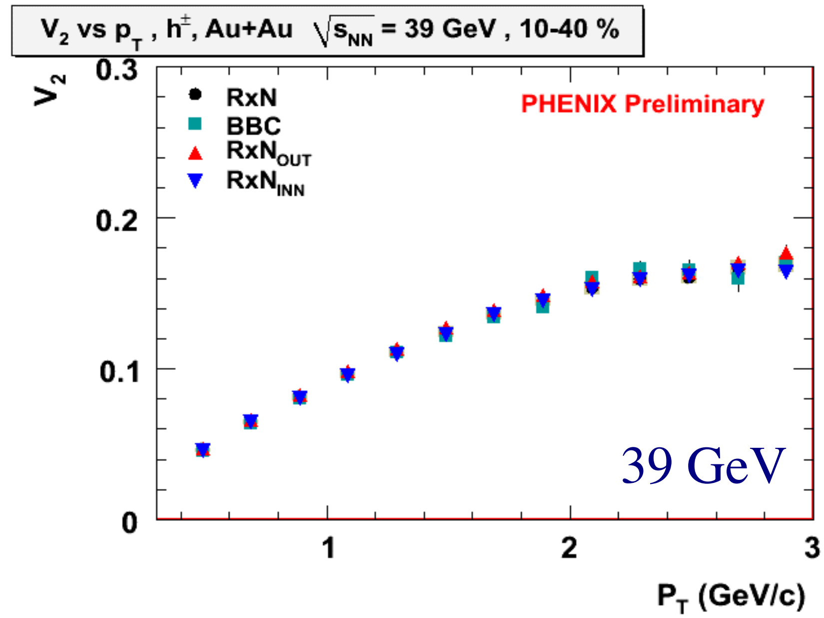
Beam Energy Dependence on $v_4\,(\Psi_4)$



- Again, ratio of 39 & 64 GeV with 200 GeV is consistent with unity within errors.

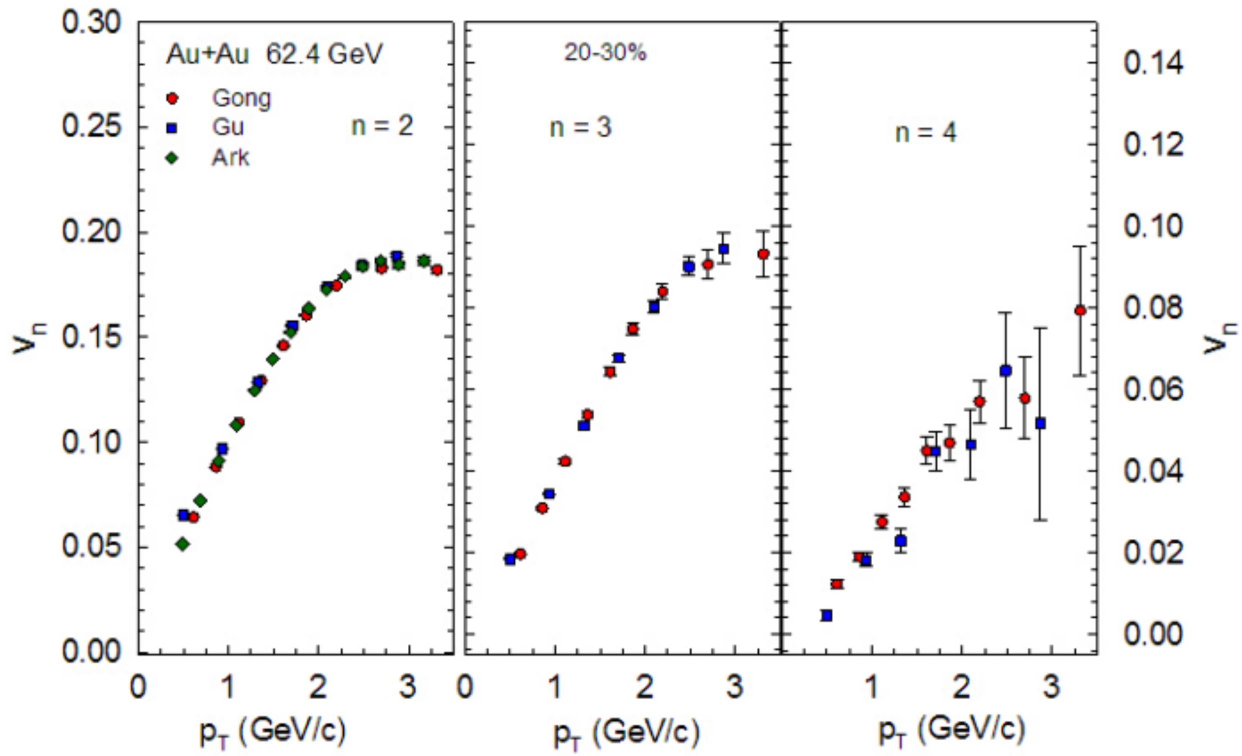
Measurement Consistency





- Similar v_2 signal using detectors with different size η gaps with central arms.
- v_2 not dependent on detector.

Measurement Consistency



- **Gong** and **Ark** use *event-plane method*: reconstruct event planes in the **forward detectors**; measure **central arm** particle azimuthal distributions relative to event plane.
- **Gu** uses *long-range correlation method*: Fourier decomposition of correlation functions built with one particle from **central arm** and the other from **forward detectors**.

Different methods agree very well!

Beam Energy Scan PID v_2