PHENIX Flow Measurements at RHIC: Overview

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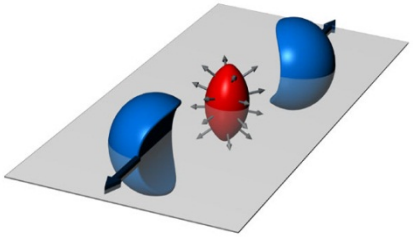
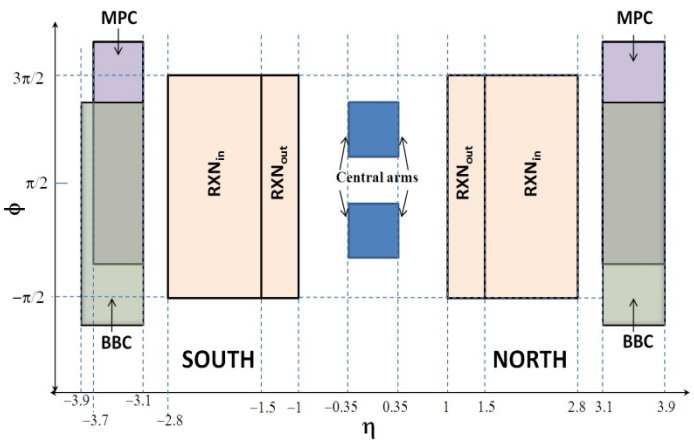
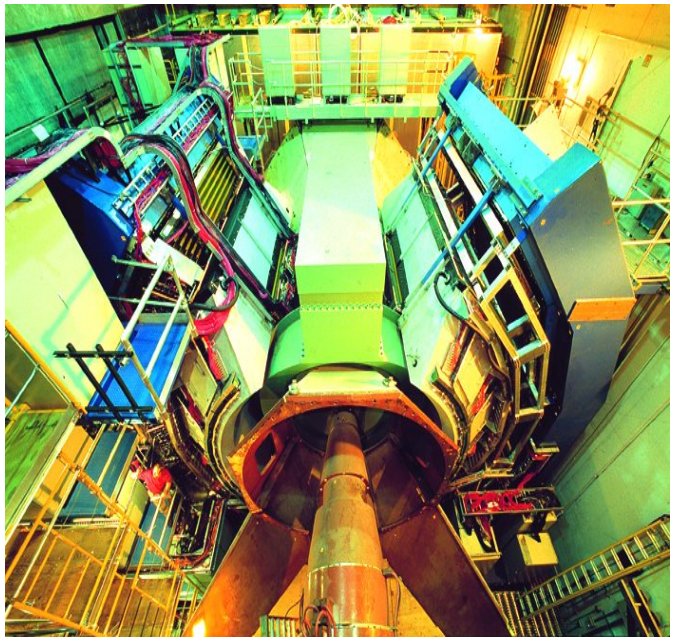


RHIC/AGS User Meeting , BNL , June 20-24, 2011
HI Workshop: Hydro/Soft Physics Session

PHENIX Flow Measurements : Outline





1) Methods / flow and non-flow

2) Are flow measurements at RHIC reliable?

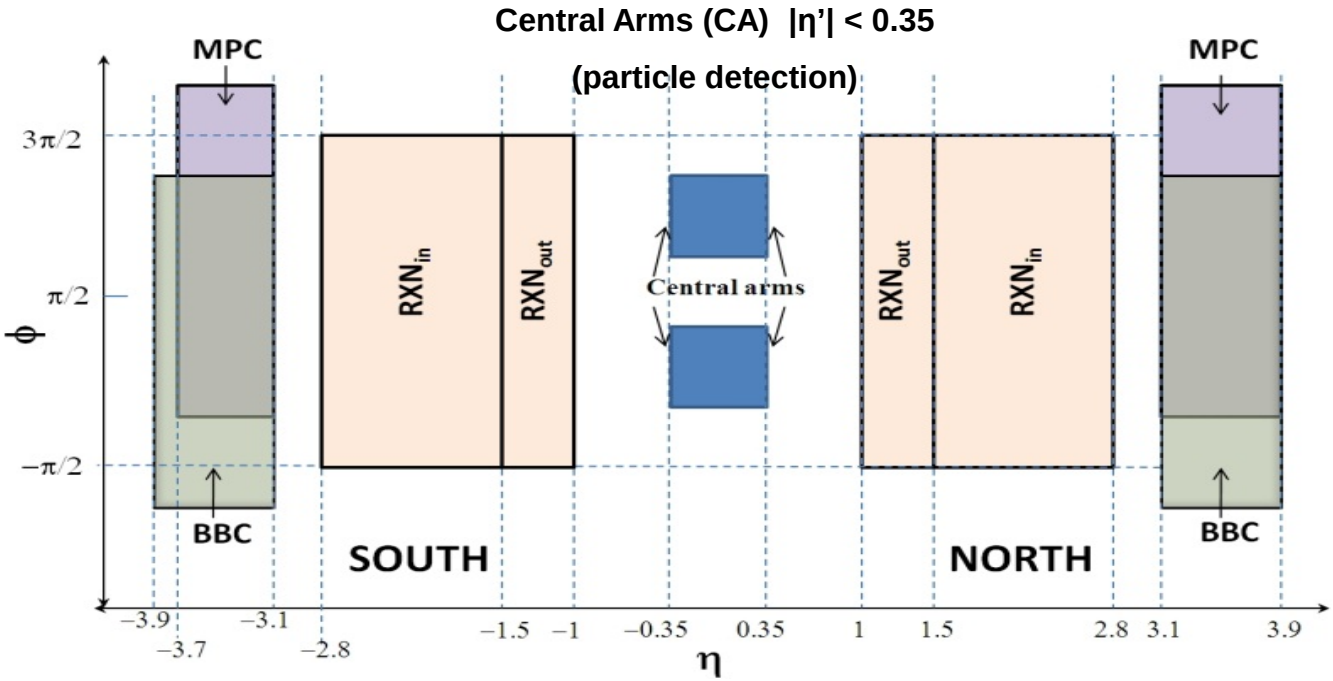
3) New constrains for models of initial conditions and η/s

4) PID V_n results and hadronization at RHIC

5) Beam energy dependence of V_n

6) Conclusions and Outlook

PHENIX Flow Measurements : Methods



ψ_n RXN (|η|=1.0~2.8)

MPC (|η|=3.1~3.7)

BBC (|η|=3.1~3.9)

Correlate hadrons in central Arms with event plane (RXN, etc)

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right) \quad \textit{(I)}$$

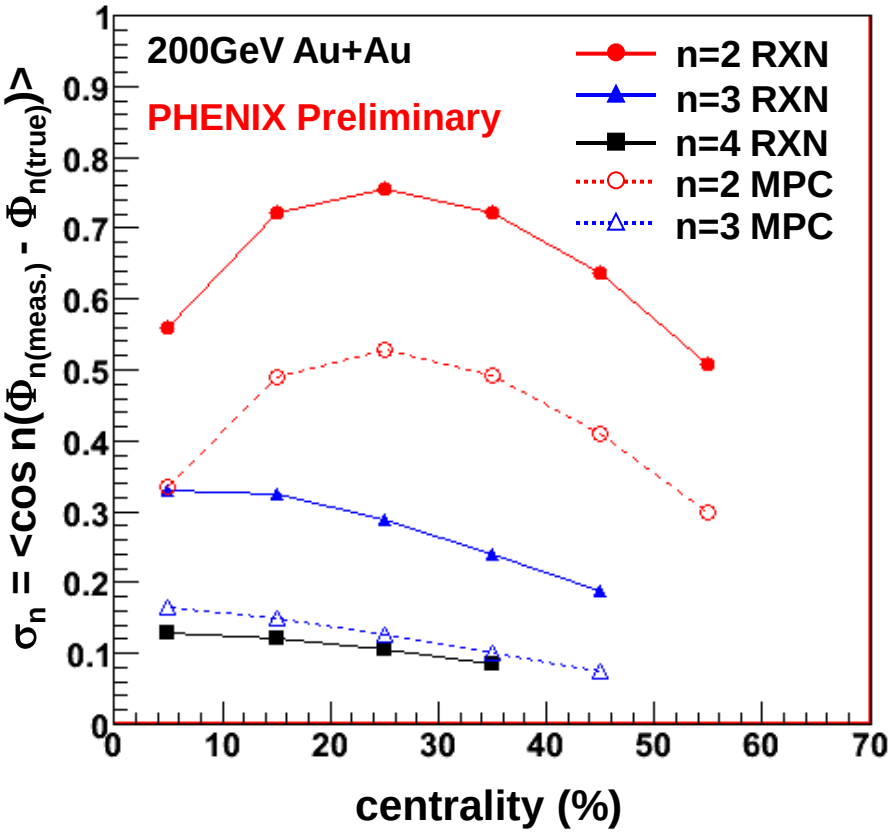
$$v_n\{\psi_n\} = \left\langle \cos\left[n\left(\varphi - \psi_n\right)\right]\right\rangle, \quad n = 1, 2, 3..,$$

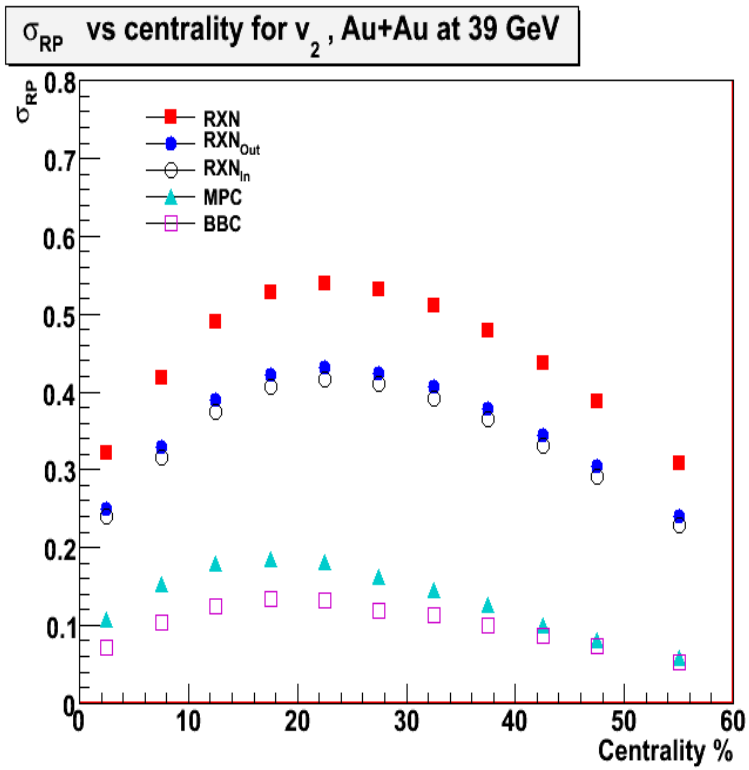
- ***Δφ correlation function for EP_N - EP_S***

$$\frac{dN^{\text{pairs}}}{d\left(\Delta\varphi\right)} \propto \left(1 + \sum_{n=1} 2 v_n^a v_n^b \cos(n\Delta\varphi)\right) \quad \textit{(II)}$$

- ***Δφ correlation function for EP - CA***

PHENIX Flow Measurements : Event Plane Resolution





ψ_n RXN ($|\eta|$=1.0~2.8)

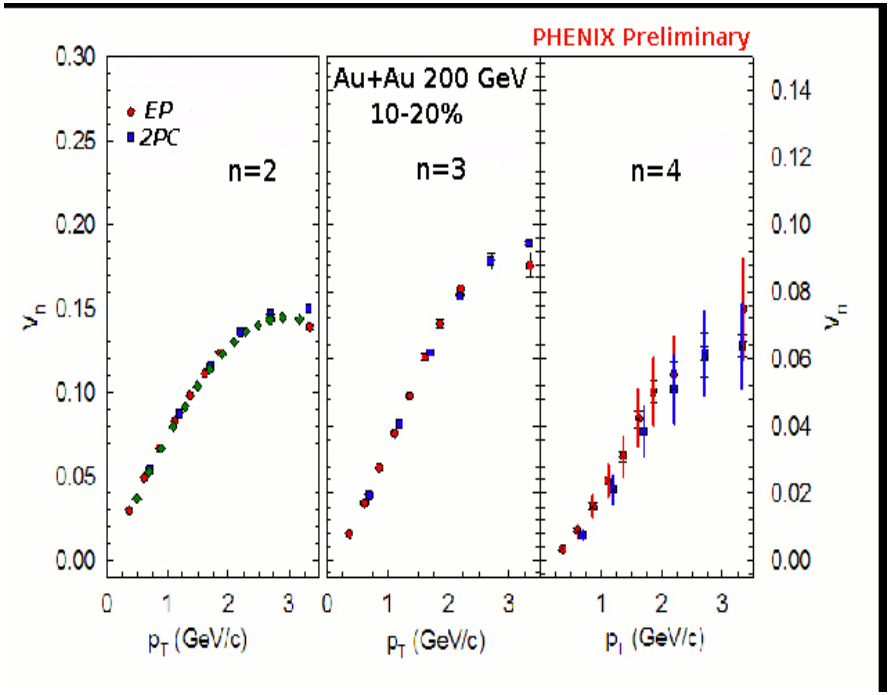
MPC ($|\eta|$=3.1~3.7)

BBC ($|\eta|$=3.1~3.9)

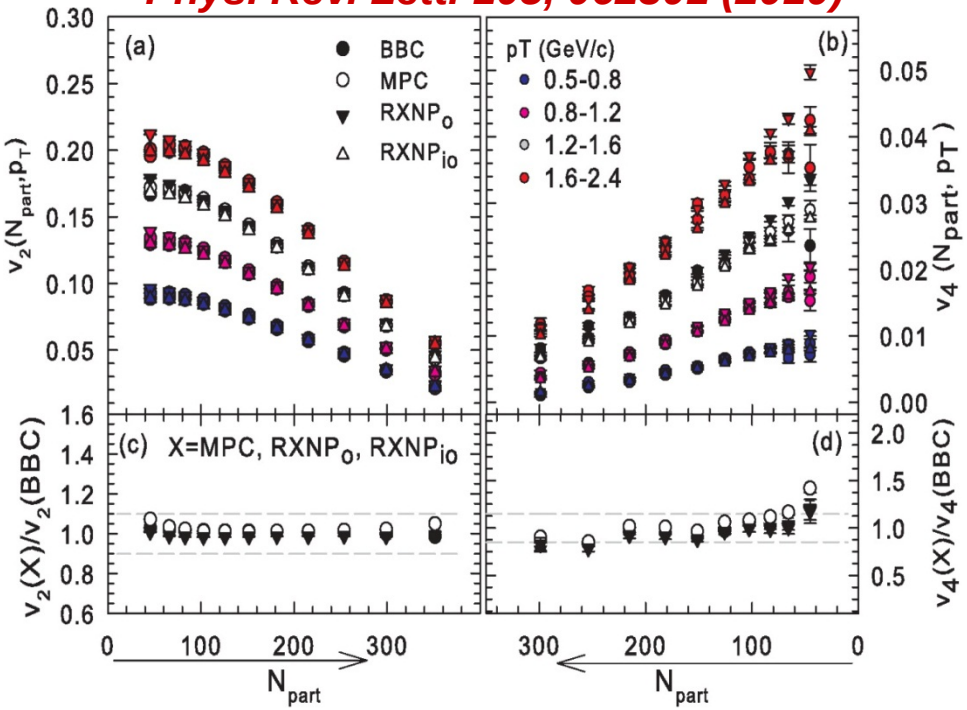
Overall good event plane resolution for V_n measurements and study beam energy dependence of the flow.

PHENIX Flow Measurements : Methods

V_n (EP): arXiv:1105.3928



Phys. Rev. Lett. 105, 062301 (2010)



- ***Good agreement between V_n results obtained by event plane (EP) and two-particle correlation method (2PC)***
- ***No evidence for significant η-dependent non-flow contributions from di-jets.***

ψ_n RXN (|η|=1.0~2.8)

MPC (|η|=3.1~3.7)

BBC (|η|=3.1~3.9)

Effect of rapidity gap on V_n measurements at LHC

J. Jia [ATLAS Collaboration]

QM 2011

- Significant bias from near-side jet for $|\Delta\eta|<0.5$
- Consistent for larger $\Delta\eta$ at $p_T<4$ GeV
- Deviation again for $p_T>4$ GeV due to swing of recoil jet
- EP method ($|\Delta\eta|< 2.5$ with EP from full FCAL: $3.3<|\eta|<4.8$)

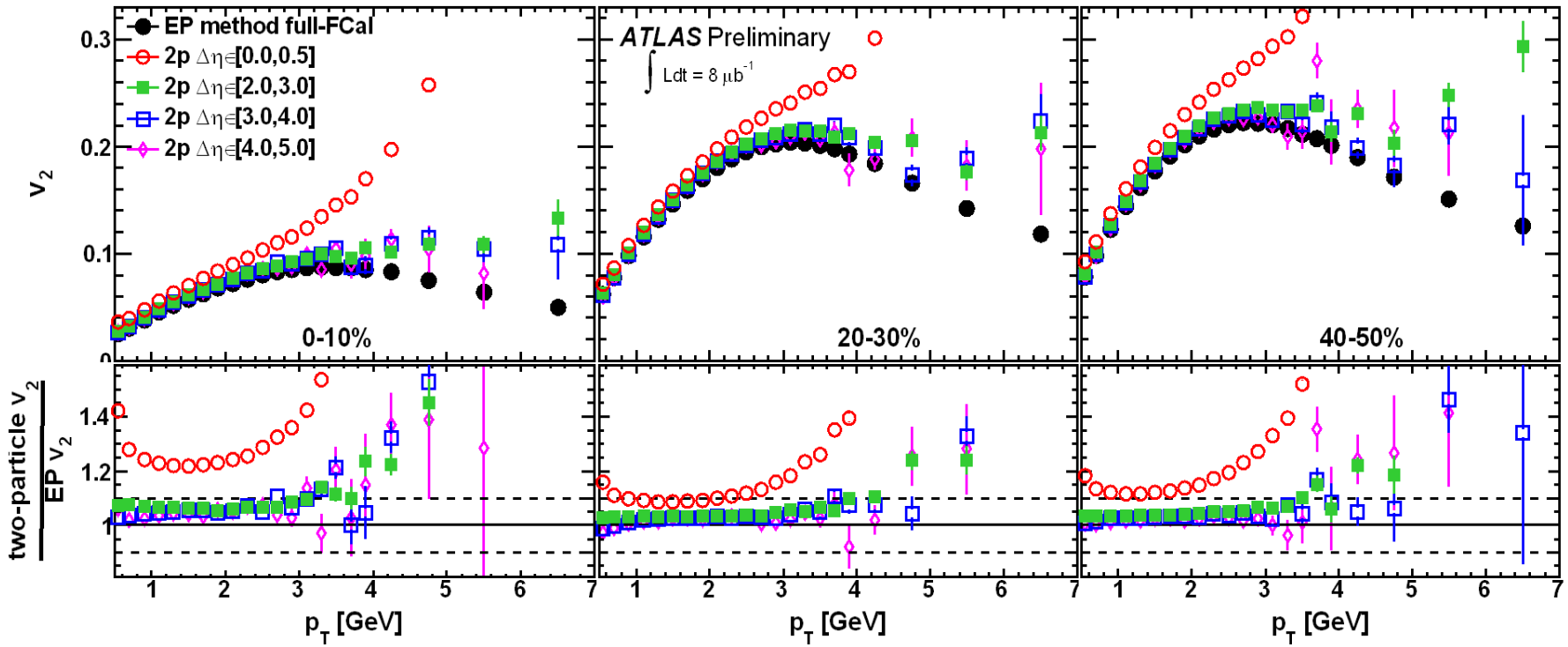


Figure 14: Top row: Comparison for four centrality selections of the v_2 between the EP method and two-particle fixed-p_T correlation method in several $\Delta\eta$ slices. Bottom row: Ratios of v_2 between two-particle and EP results.

ATLAS AN: http://cdsweb.cern.ch/record/1352458

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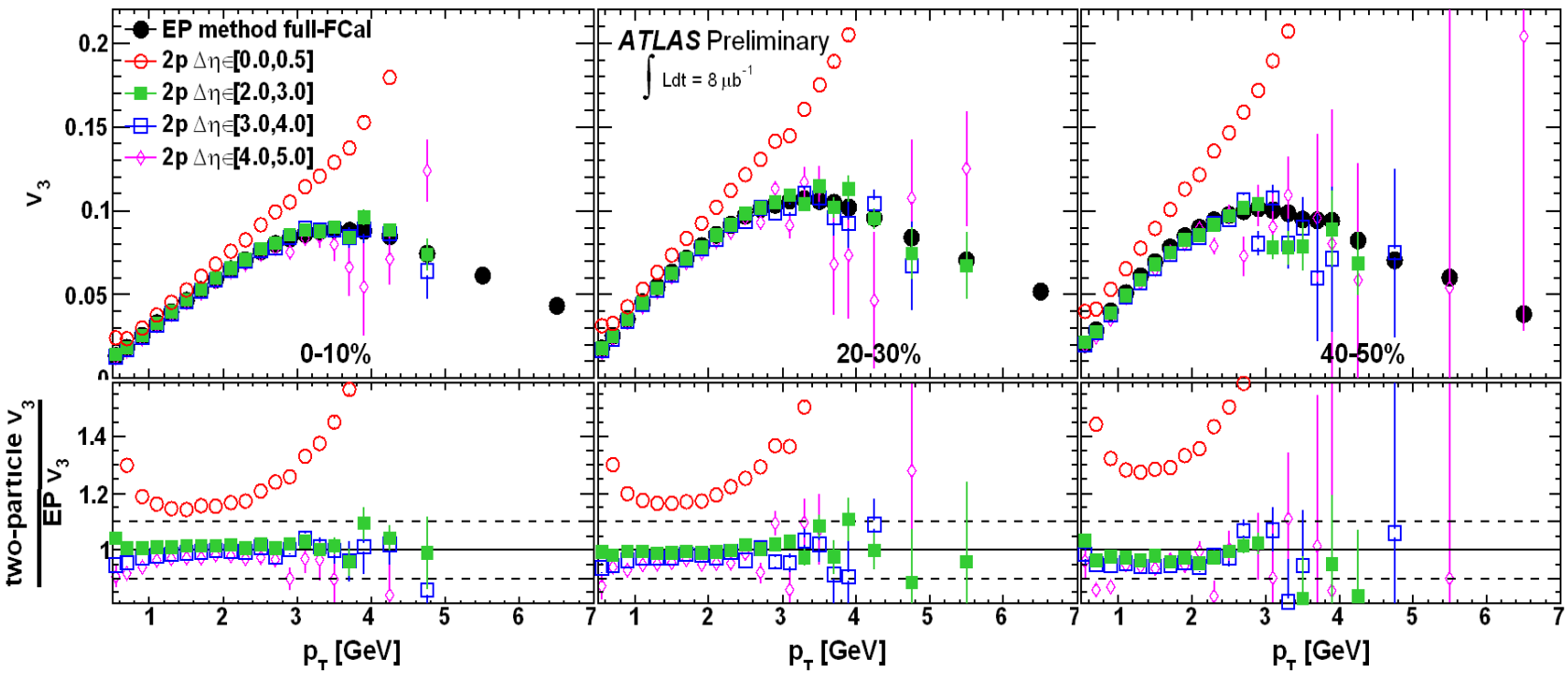
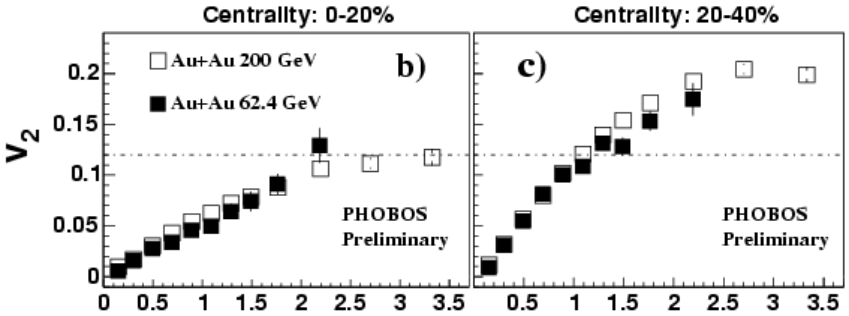
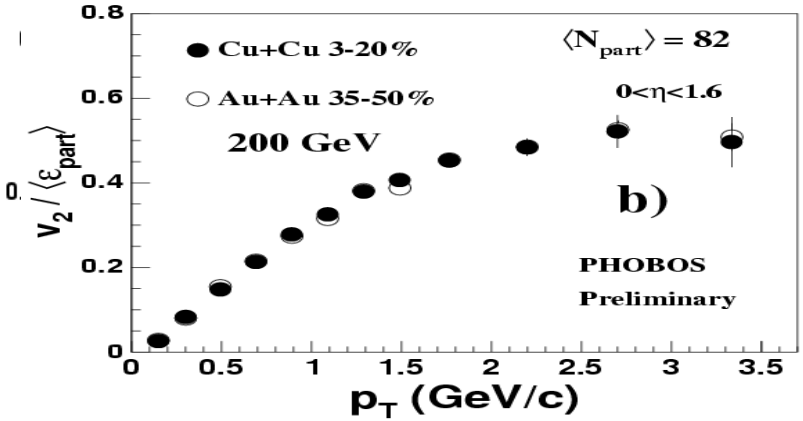


Figure 25: Top row: Comparison for four centrality selections of the v_3 between the EP method and two-particle fixed-p_T correlation method in several $\Delta\eta$ slices. Bottom row: Ratios of v_3 between two-particle and EP results.

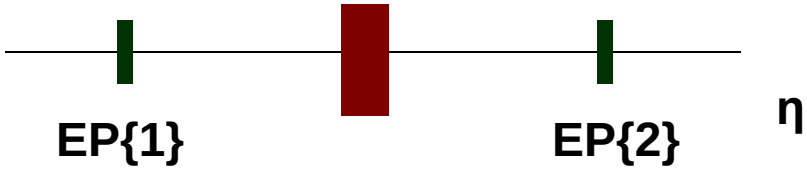
ATLAS AN: http://cdsweb.cern.ch/record/1352458

Are Flow Measurements at RHIC Reliable?: PHENIX / PHOBOS

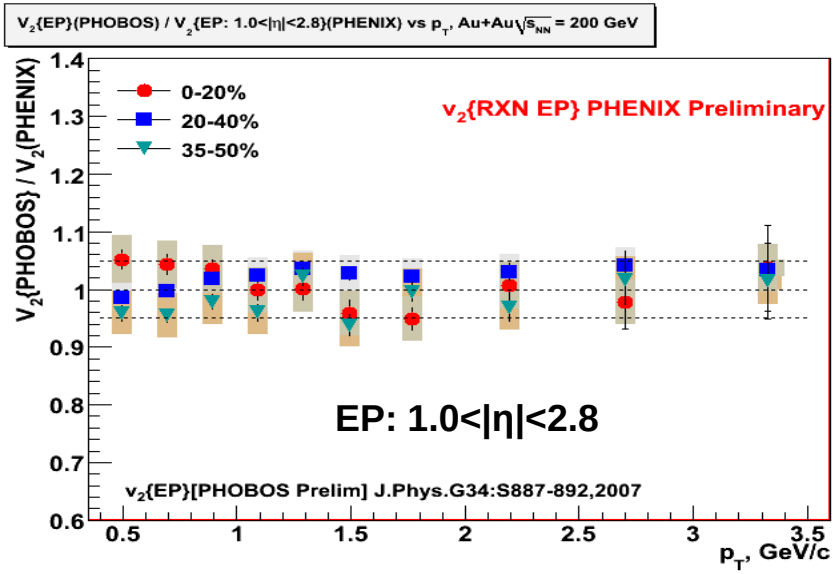


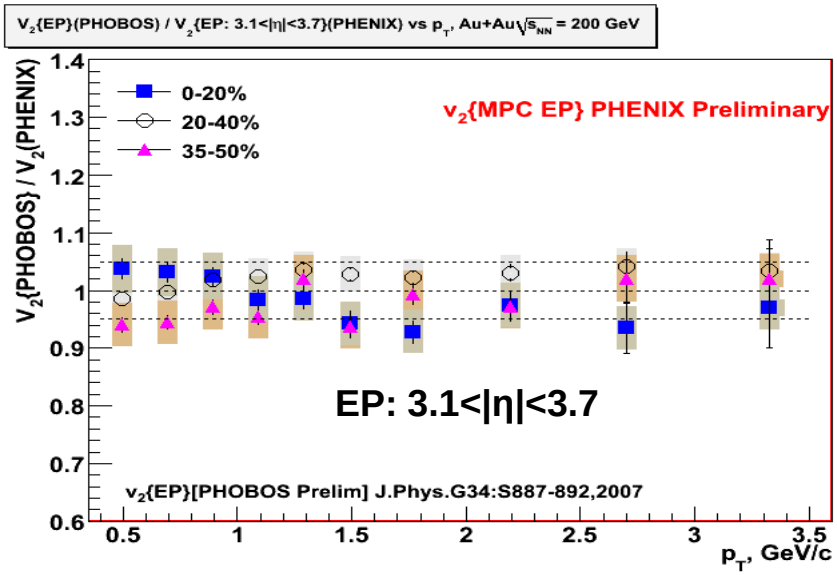


from PHOBOS QM06 proc. J. Phys. G34 S887 (2007)



PHOBOS EP: 2.05<|η|<3.2

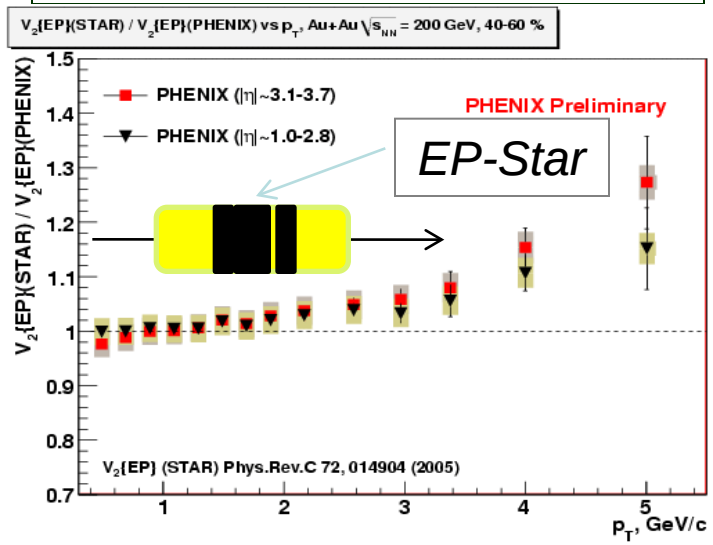


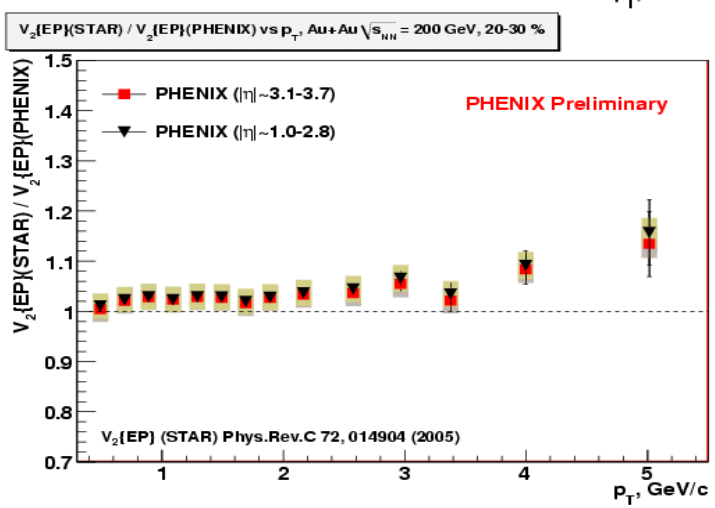


Overall good agreement between differential flow measurements

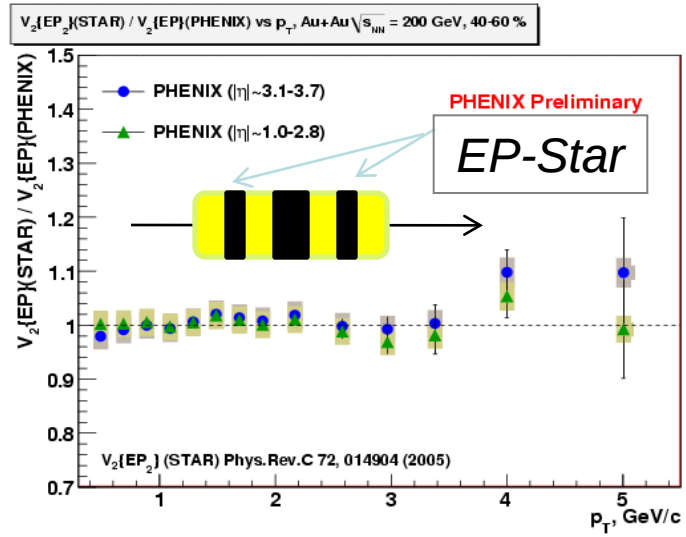
Are Flow Measurements at RHIC Reliable?: PHENIX / STAR (1)

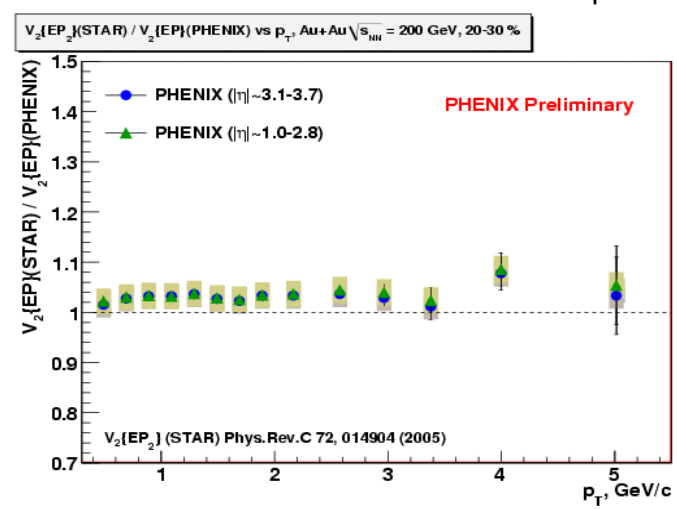
$V_2\{EP\}$ – standard EP method





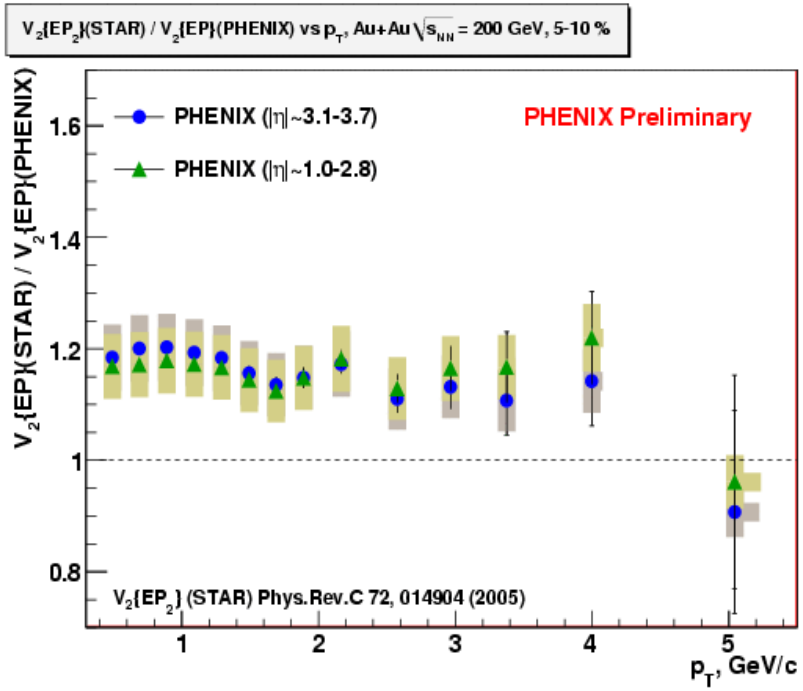
$V_2\{EP_2\}$ – modified EP method

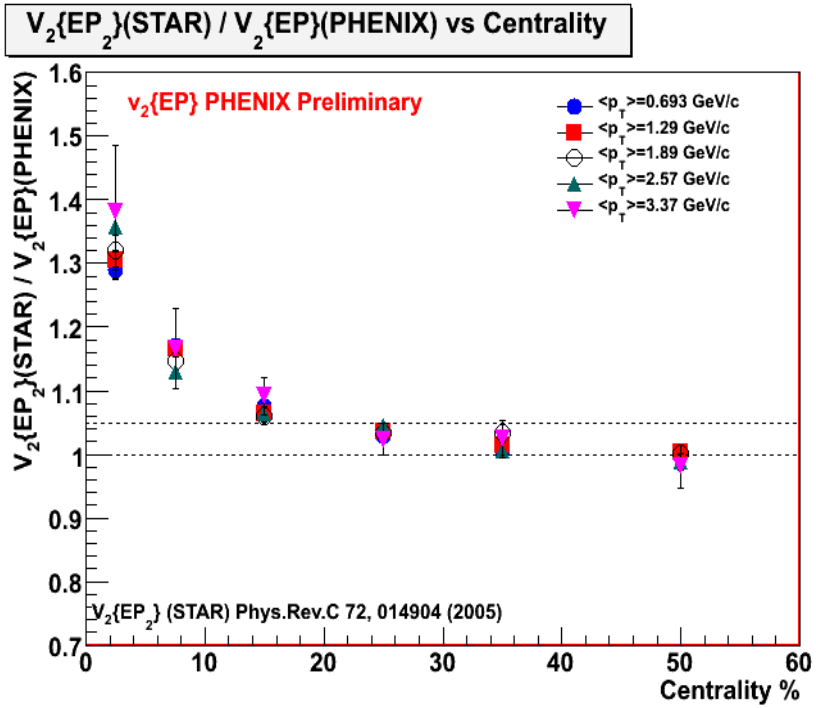




Overall good agreement for mid-central collisions with STAR results obtained using modified EP method (exclude $|\Delta\eta|<0.5$)

Are Flow Measurements at RHIC Reliable?: PHENIX / STAR (2)



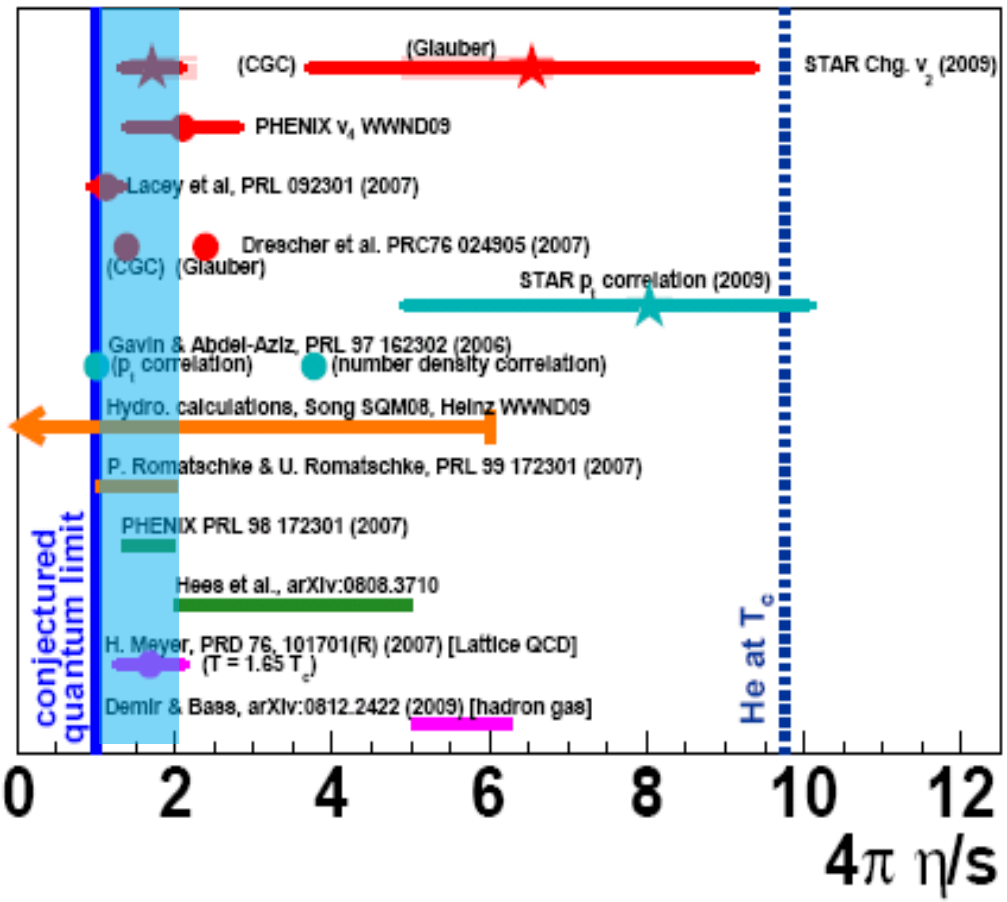


For 0-20% central collisions STAR V_2 > PHENIX V_2 :

Is rapidity gap in STAR TPC too small ? Need detailed comparison with STAR FTPC results (2.5 <|η|< 4.0)

Do we have the same centrality definition between experiments?

η/s estimates – QM2009



Remarkable Convergence

Conjectured Lower bound

$4\pi\eta/s \sim 1 - 2$

(still 100% uncertainty)

Major remaining uncertainty stems from Incomplete knowledge of the Initial eccentricity

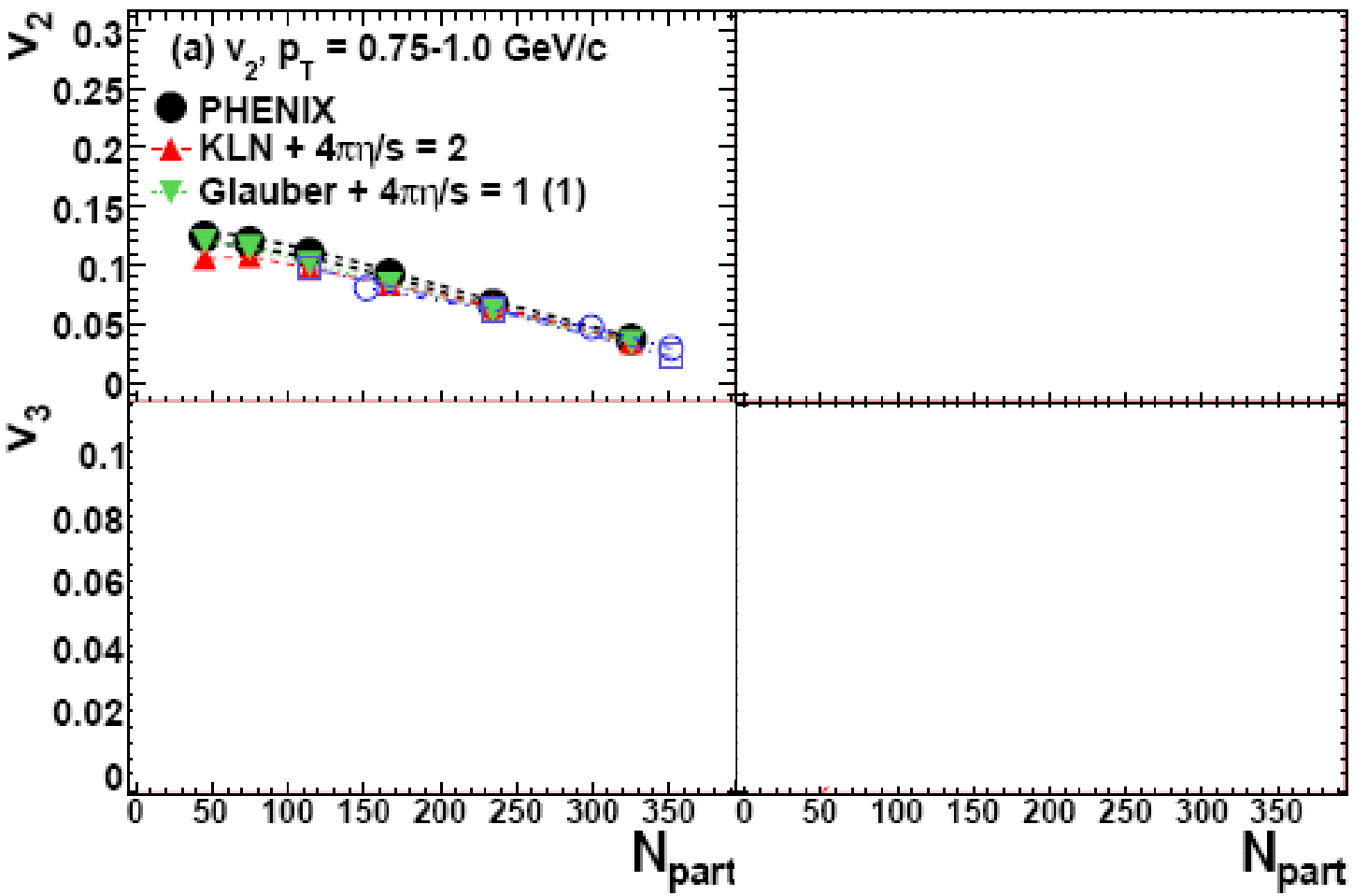
ε_n – η/s interplay

New constraints required for the initial eccentricity model and η/s

→Do higher-order flow harmonics provide such constraints?

New constraints for ε_n and η/s

http://arxiv.org/abs/1105.3928



v_3 breaks the ambiguity between CGC vs. Glauber initial conditions and η/s

Pls. see P. Stankus talk on PHENIX V_3 results

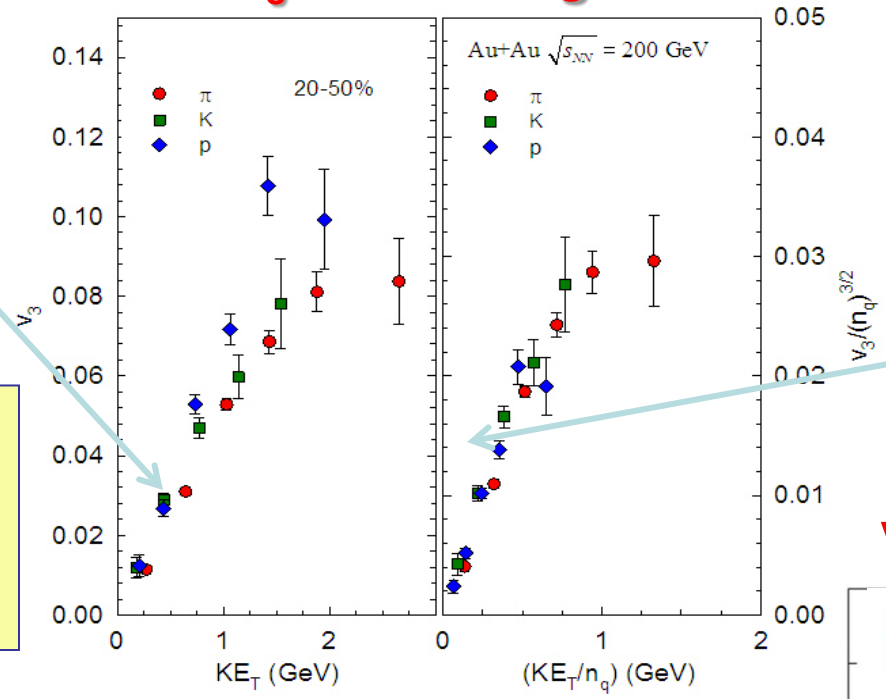
Flow is partonic

Flow is pressure driven

KE_T & $(n_q)^{n/2}$ scaling validated for v_3

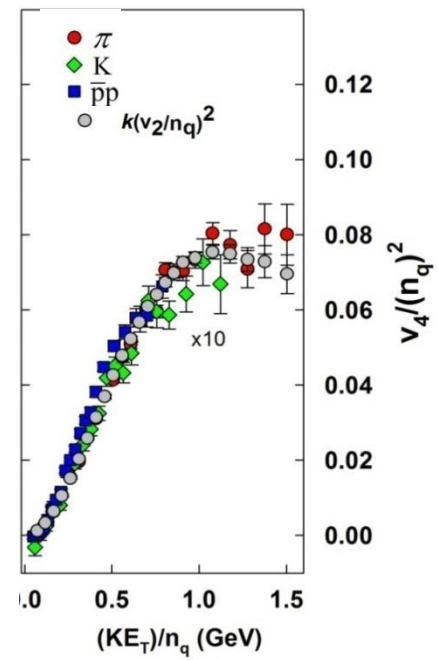
→ Partonic flow

v_3 PID scaling

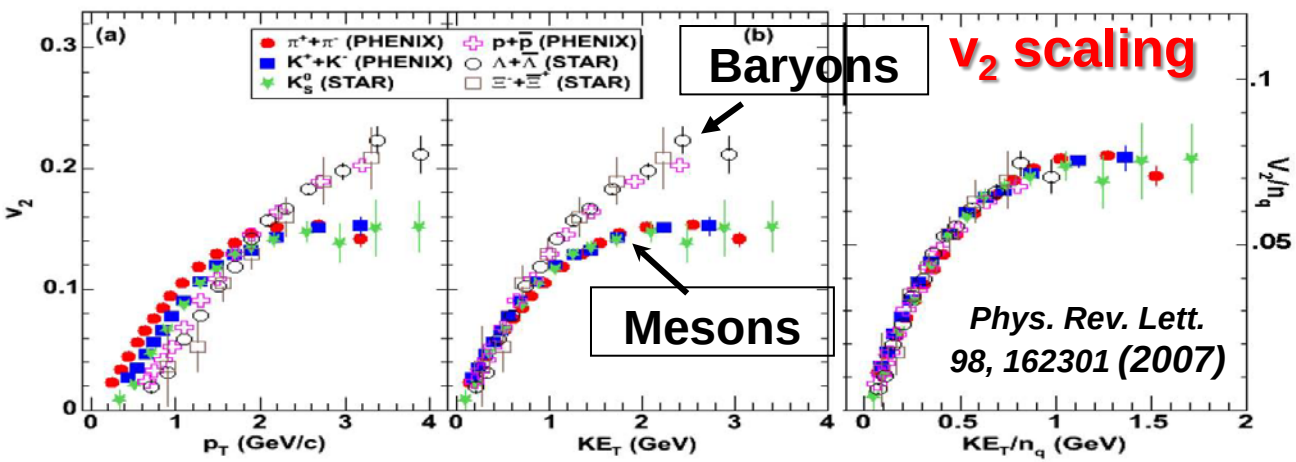


Flow is partonic

v_4 scaling



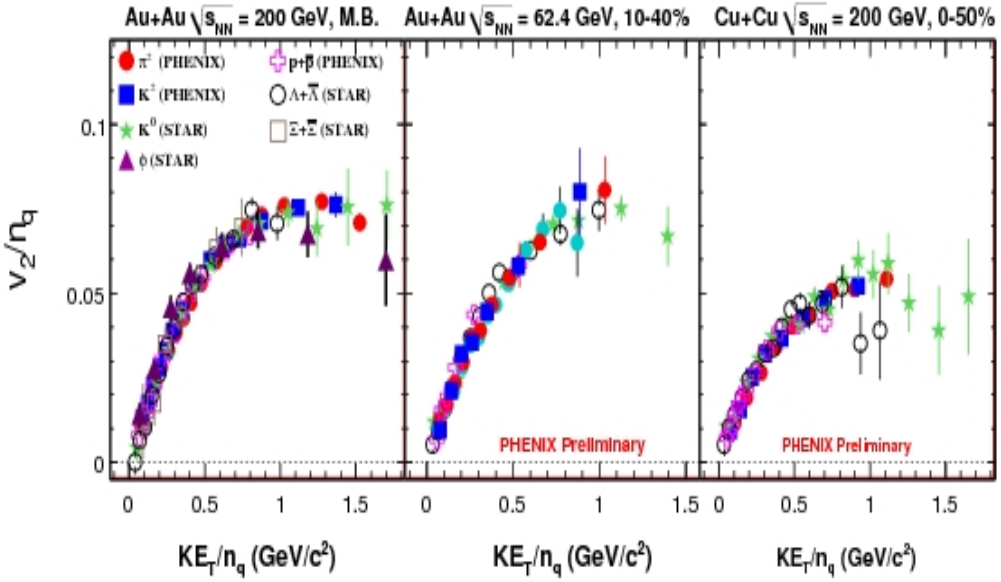
v_2 scaling

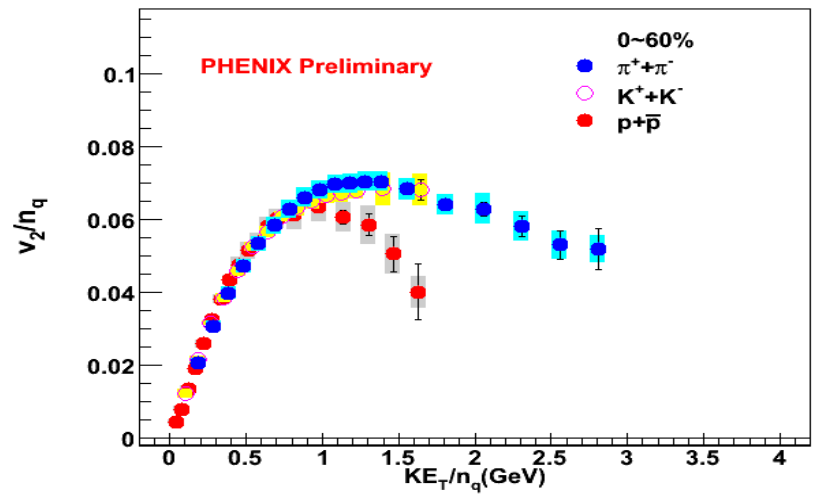


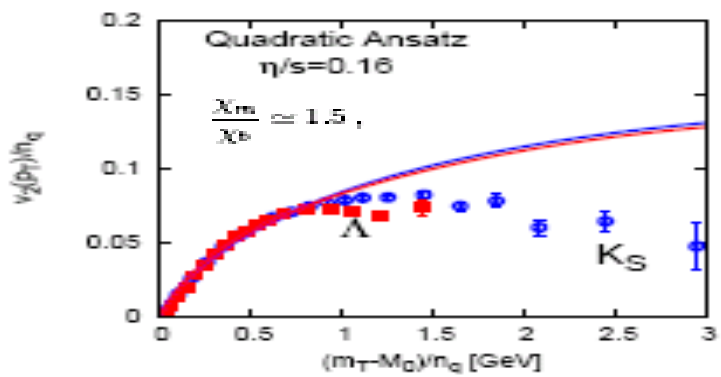
Phys. Rev. Lett. 98, 162301 (2007)

Consistent partonic flow picture for v_n

KE_T / n_q scaling for V_2 and hadronization at RHIC







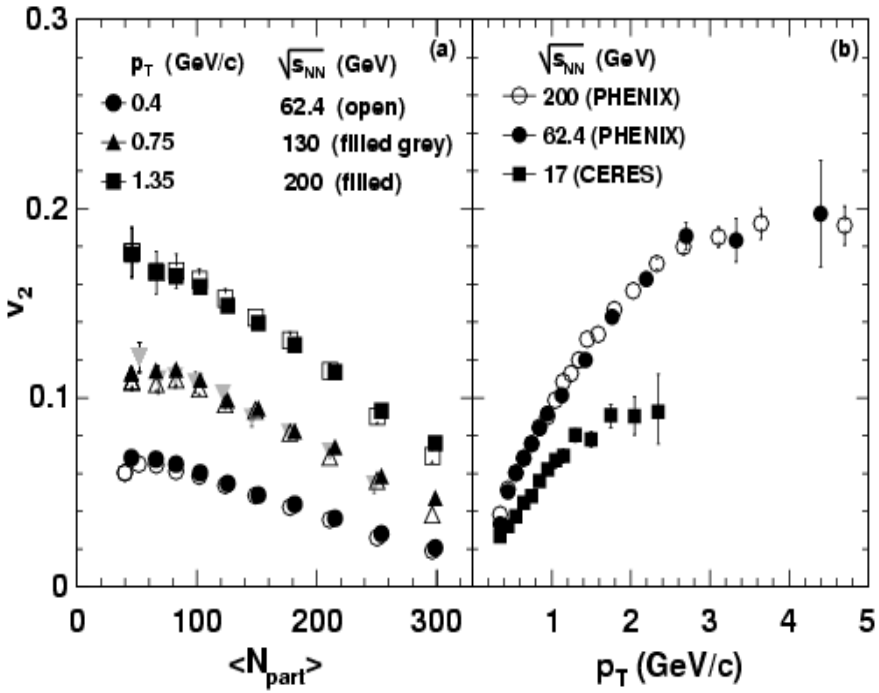
$$\chi_m(\tilde{p}) = C_m(\alpha)\tilde{p}^{2-\alpha},$$
$$\chi_b(\tilde{p}) = C_b(\alpha)\tilde{p}^{2-\alpha},$$

What is the mechanism of hadronization at RHIC? Can we describe PID scaling using hydro or we need coalescence?

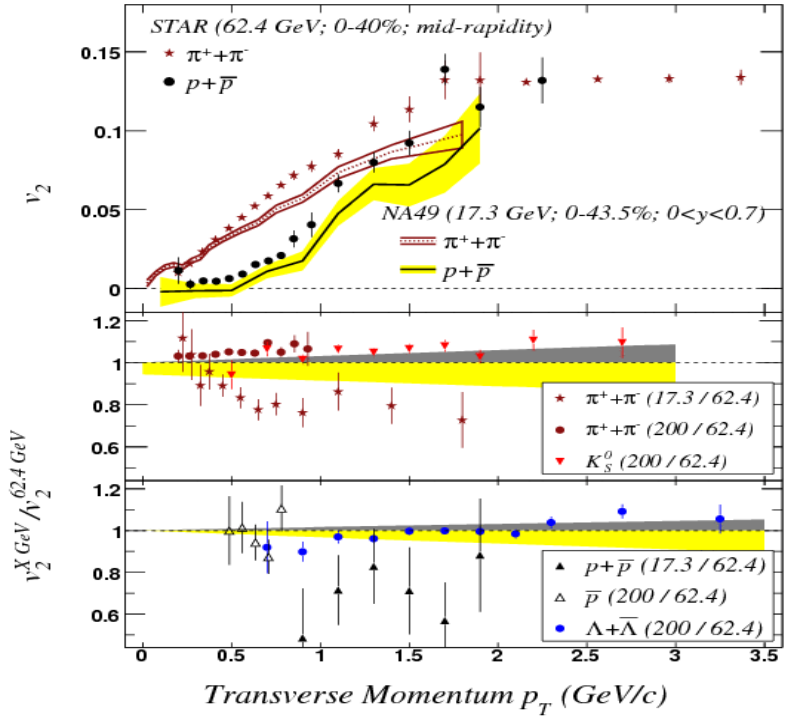
K.Dusling, G.Moore, D. Teaney : Phys. Rev. C 81,2010

Beam Energy dependence of V_2 : before 2010

Phenix: Phys. Rev. Lett. 94, 232302 (2005)

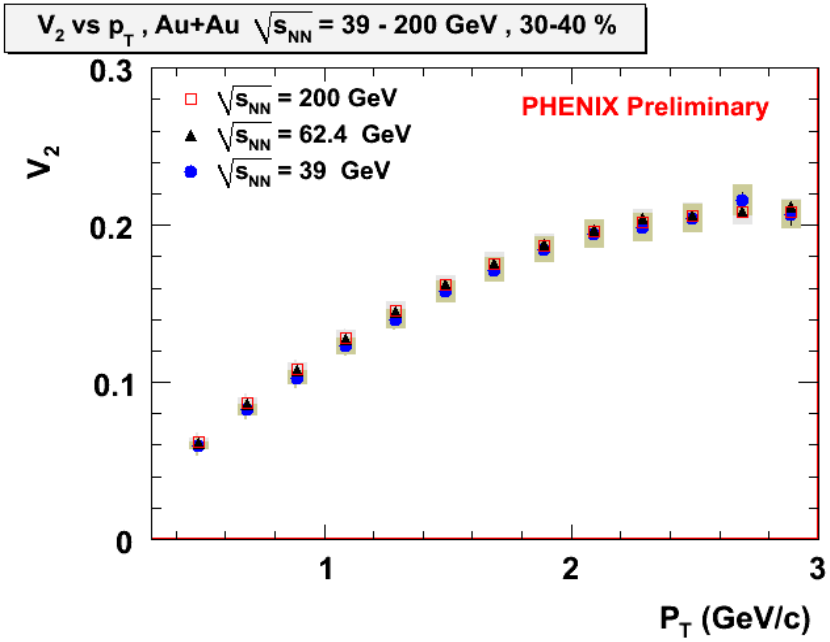


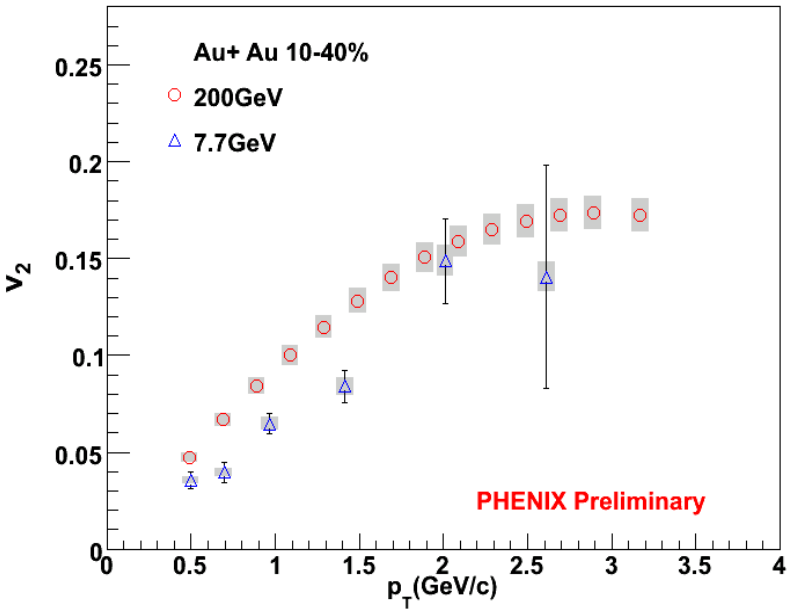
STAR: Phys.Rev.C75:054906,2007



- ***Saturation of differential elliptic flow at 62.4–200 GeV (STAR/PHENIX)***
- ***PHENIX: RHIC/SPS: ~ 50% difference . STAR: RHIC/SPS ~ 10-15% difference in the differential flow results !***
- ***2011: New measurements at RHIC (BES program) and LHC !***

Beam Energy dependence of V_2

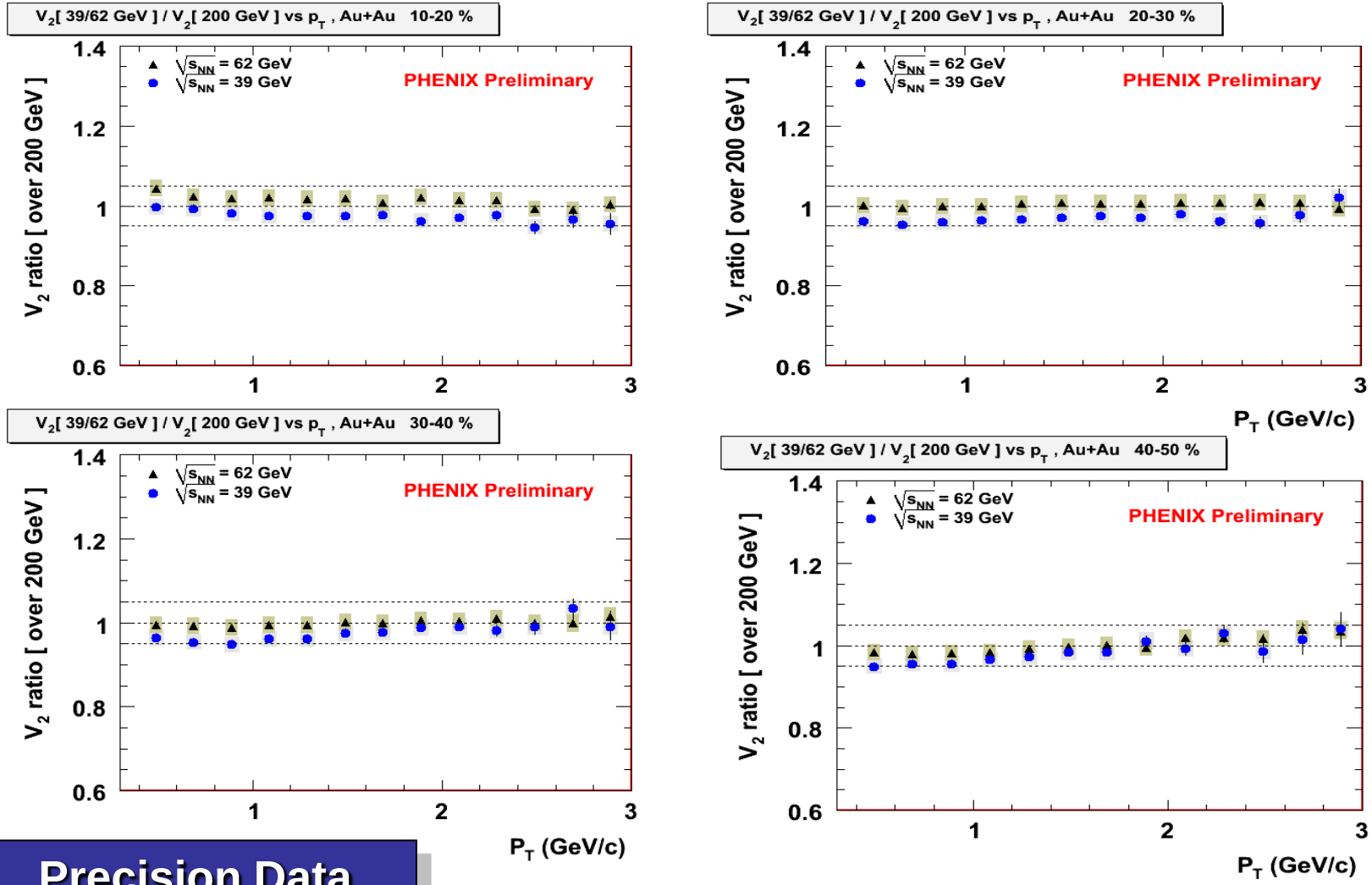




- ***Saturation of differential elliptic flow at 39–200 GeV***
- ***V_2 at 7.7 GeV is significantly lower than at 39-200 GeV***

Pls. see D. Reynolds and J. Mitchell talks for details

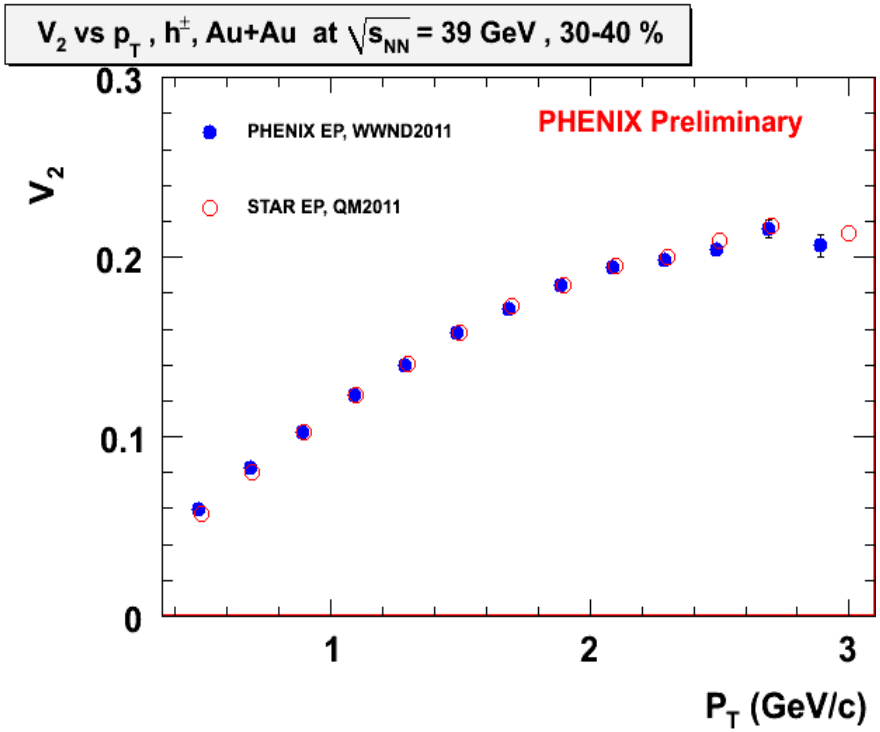
Elliptic Flow of Charged Hadrons: Au+Au at 39-200 GeV

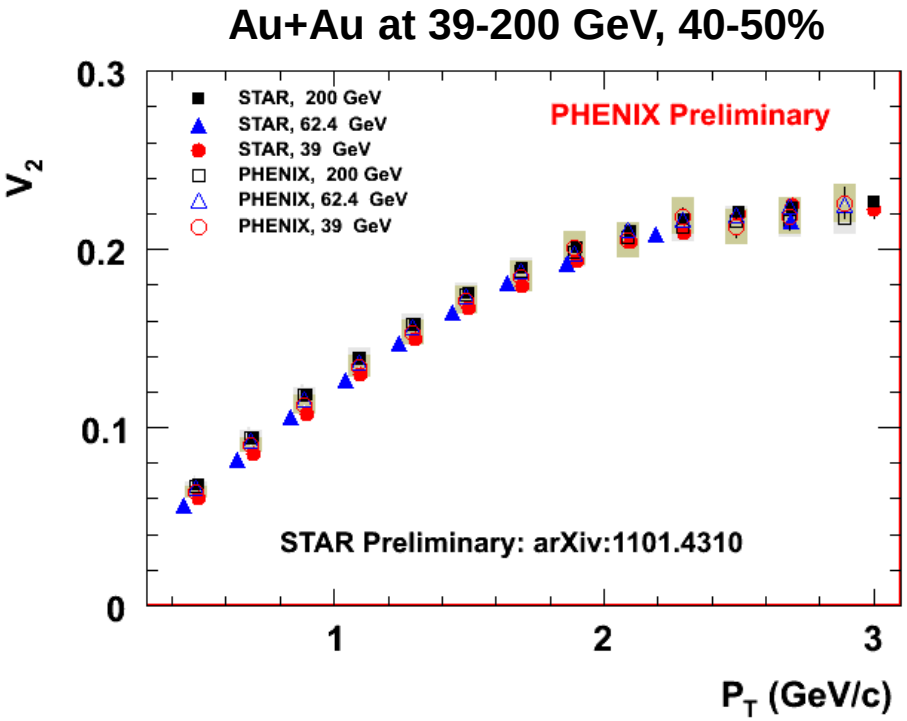


Precision Data

No significant change in $v_2(p_T)$ for $\sqrt{s}$ = 39 -200 GeV !

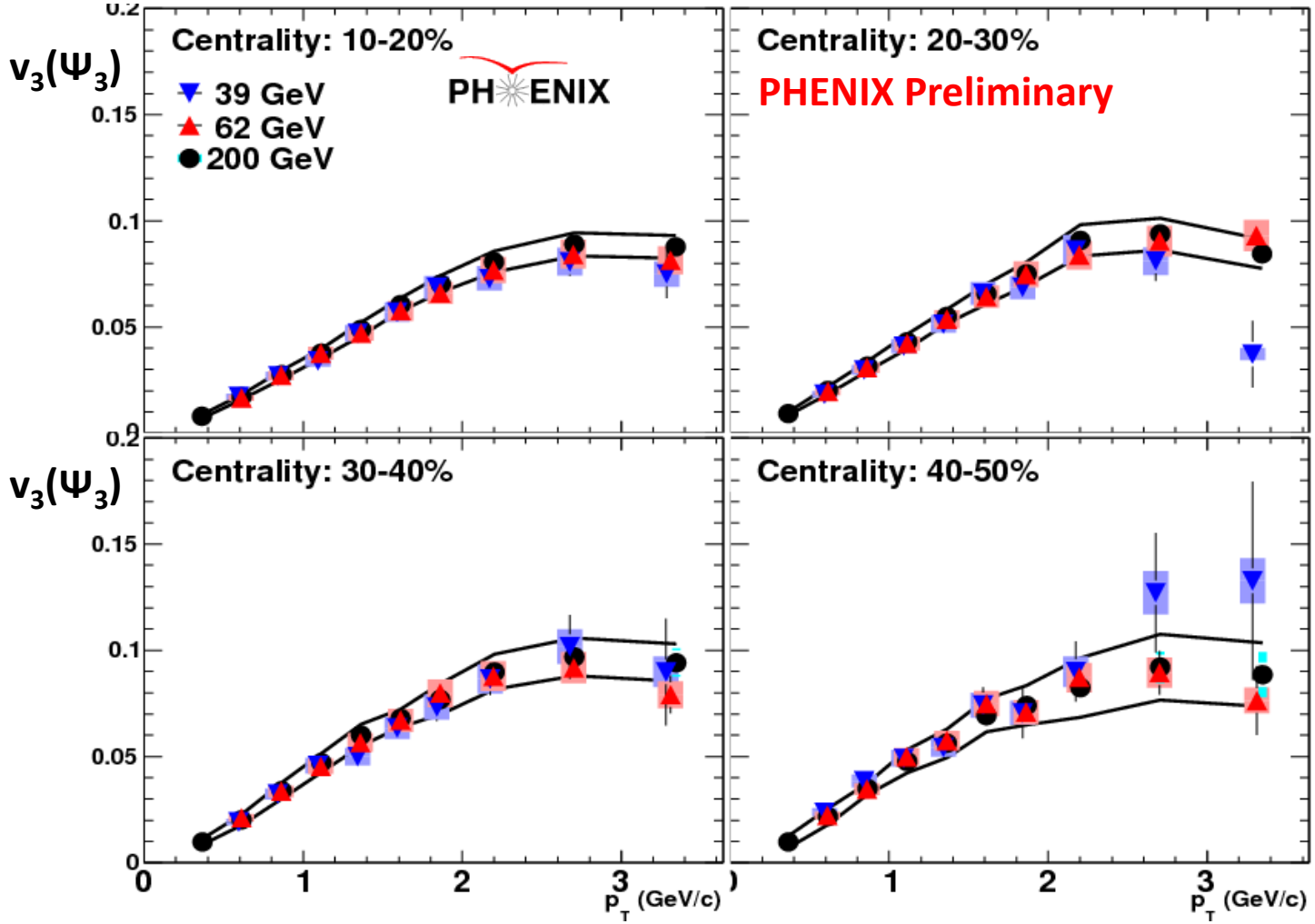
Elliptic Flow of Charged Hadrons: Au+Au at 39-200 GeV





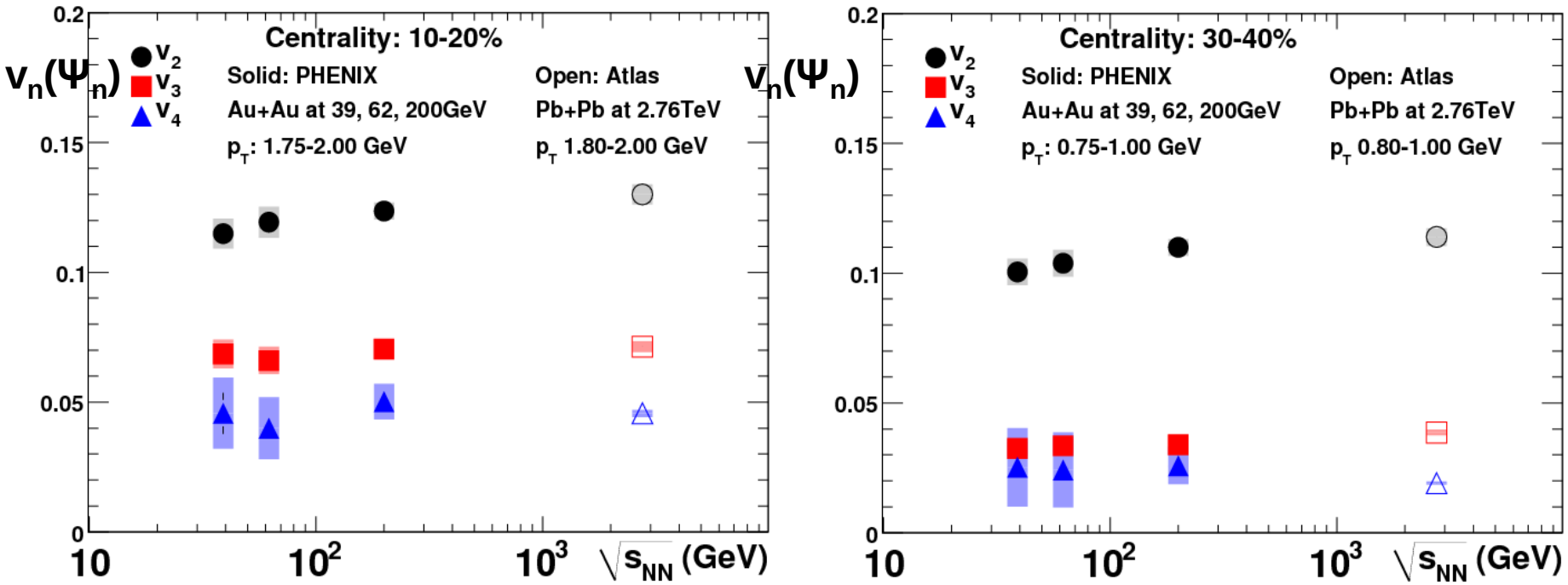
Overall good agreement between PHENIX/STAR preliminary results for V_2 of charged hadrons from mid-central Au+Au collisions at 39-200 GeV

$V_3(p_T)$ of Charged Hadrons: Au+Au at 39-200 GeV



No significant change in $v_3(p_T)$ for $\sqrt{s}$ = 39 -200 GeV !

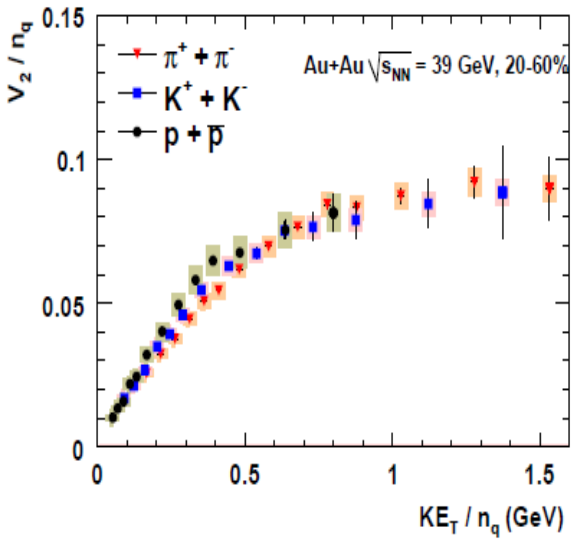
V_n of Charged Hadrons: from RHIC to LHC



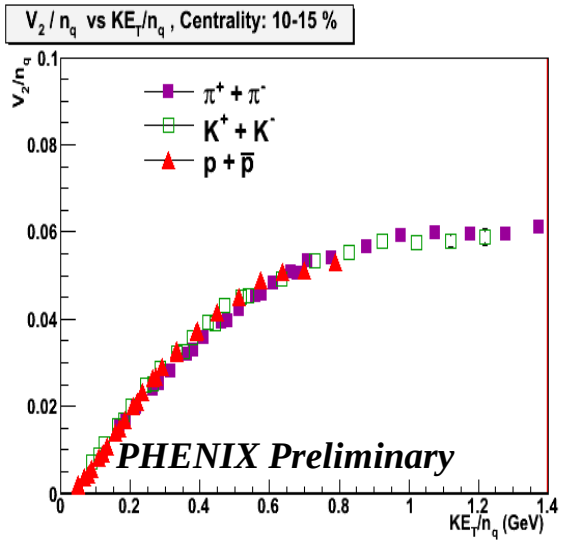
V_2, V_3 and V_4 of charged hadrons saturate above 39GeV, up to LHC energy (?!)

V_2 of Identified Hadrons: from RHIC to LHC

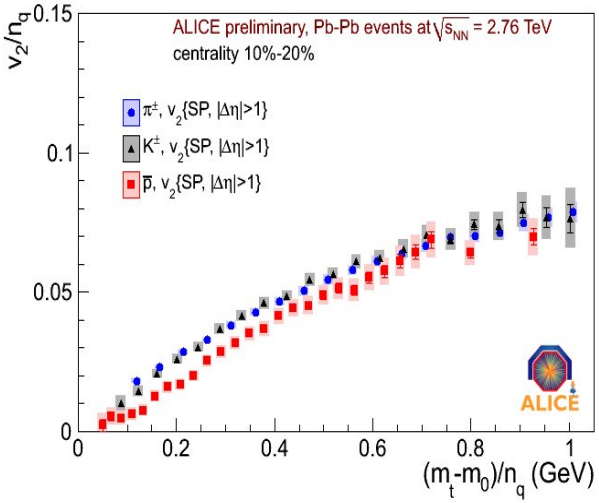
$\sqrt{s}$ = 39 GeV



$\sqrt{s}$ = 200 GeV



$\sqrt{s}$ = 2.76 Tev



More detailed systematic studies are needed to undertand the beam energy dependence of V_n for identified hadrons

Summary

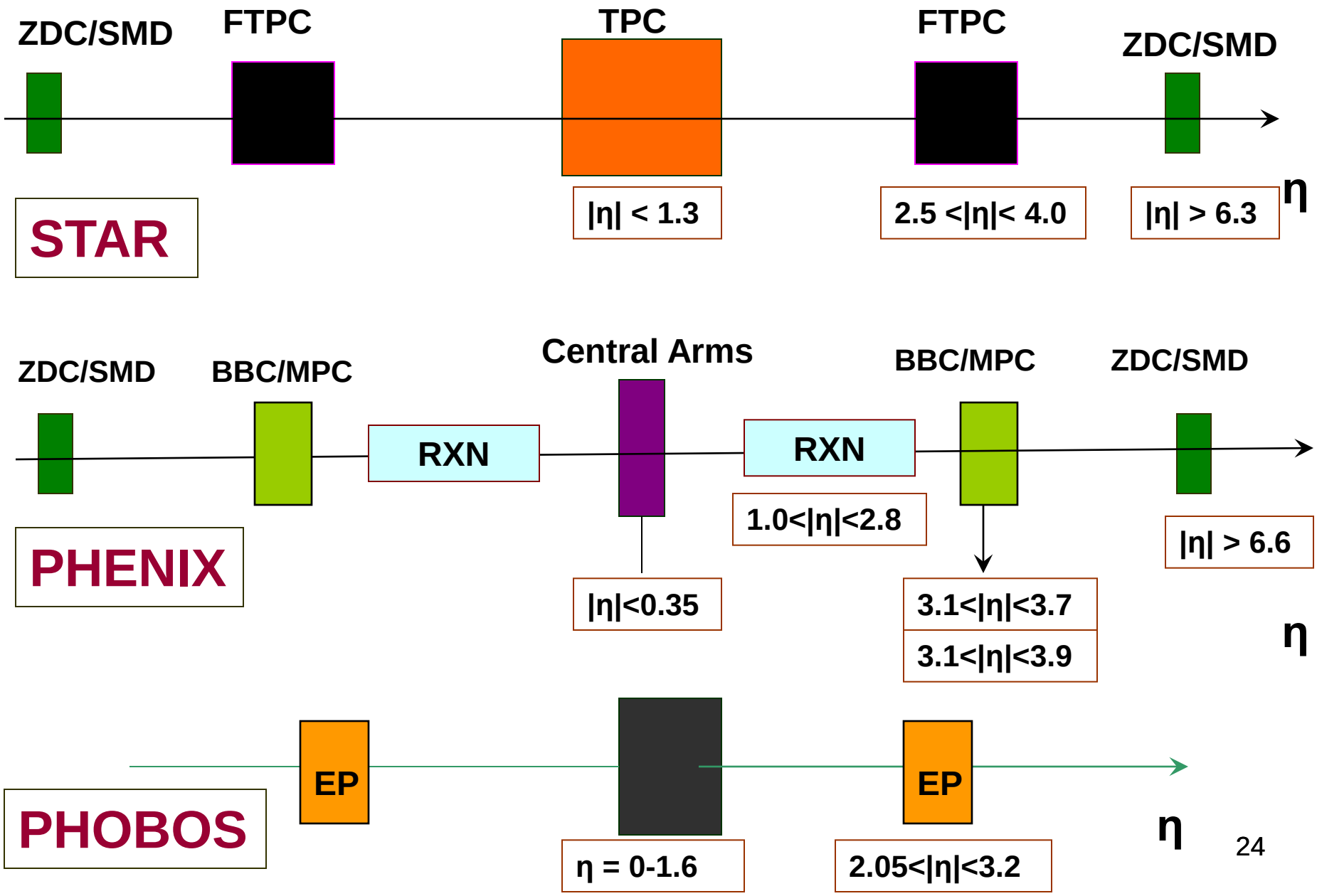
- **High order flow harmonics results extracted by PHENIX**
  - **Provide new constraints for ε_n and η/s**
  - **Further confirm that flow at RHIC is partonic**
  - **$v_{2,3,4}$ for charged hadrons saturates for $\sqrt{s_{NN}}$ 39 - 200 GeV way to LHC (?!)**

    These observations may suggest similar initial geometry fluctuations and dynamic evolution of matter above 39GeV.
- **PHENIX: There is good quantitative agreement between different methods of study V_n**
- **RHIC: Reasonable quantitative agreement found for event plane results for V_2 (p_T , centrality) for charged hadrons from Au+Au collisions at 200 GeV:**
  - ✓ **PHENIX/PHOBOS and PHENIX/STAR [for mid-central collisions].**
  - ✓ **Futher comparisons with results from STAR FTPC are needed to undertand the source of the difference in central collisions?**
  - ✓ **Comparison for PID results in under way.**

The transition to the detailed measurements of V_n of identified hadrons started and it is very important.

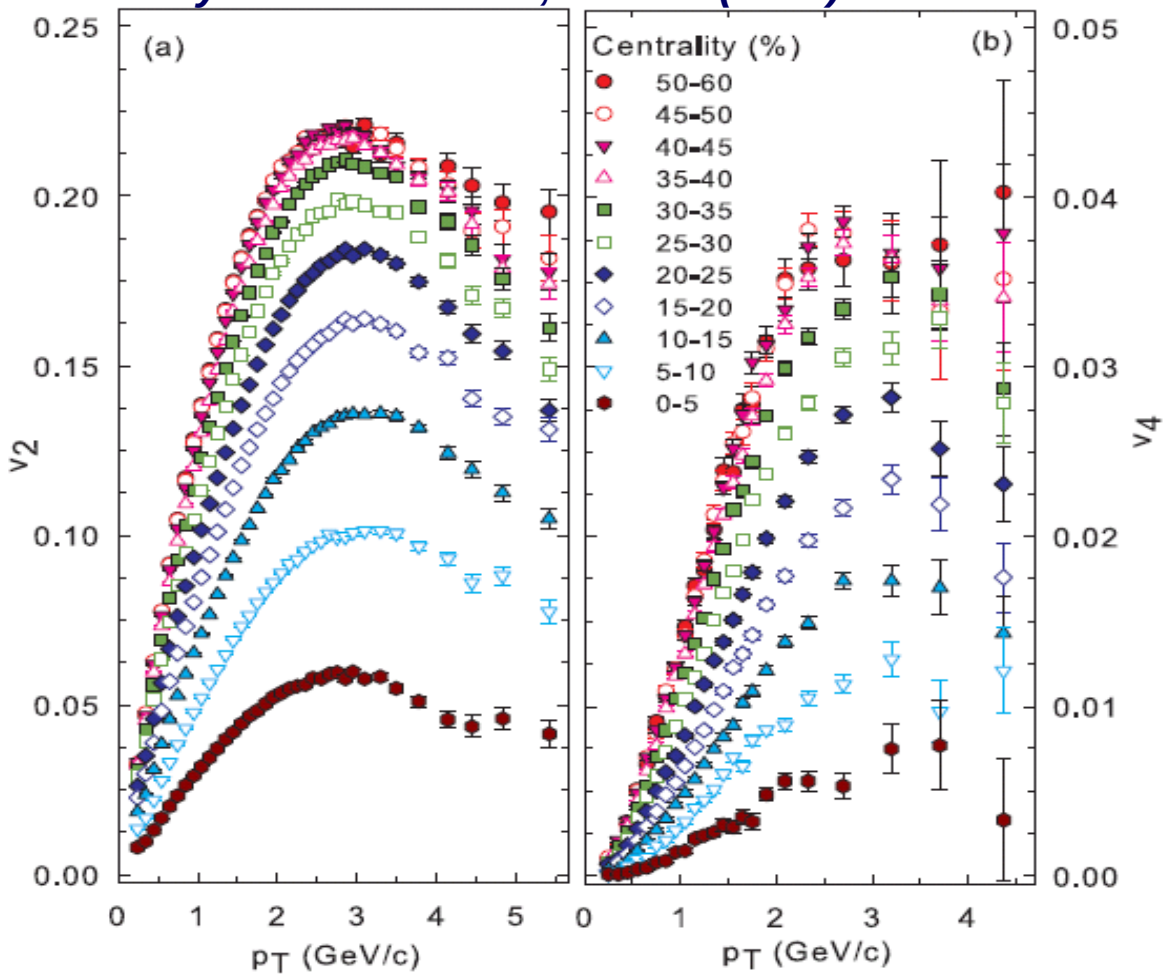
Backup Slides

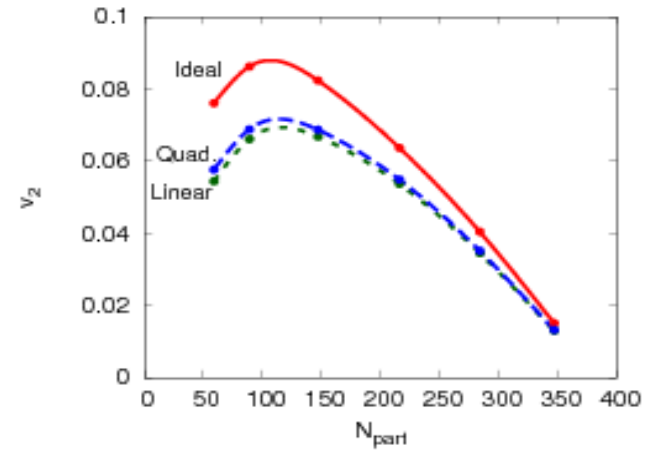
Elliptic Flow Measurements V_2 (p_T , centrality) in PHOBOS/STAR/PHENIX



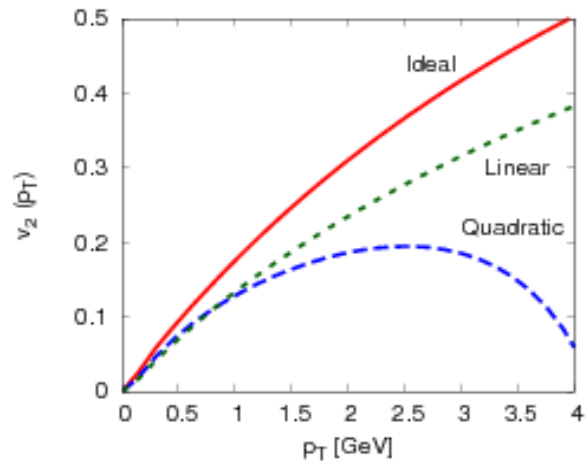
PHENIX: Extensive anisotropy Data

Phys. Rev. Lett. 105, 062301 (2010)

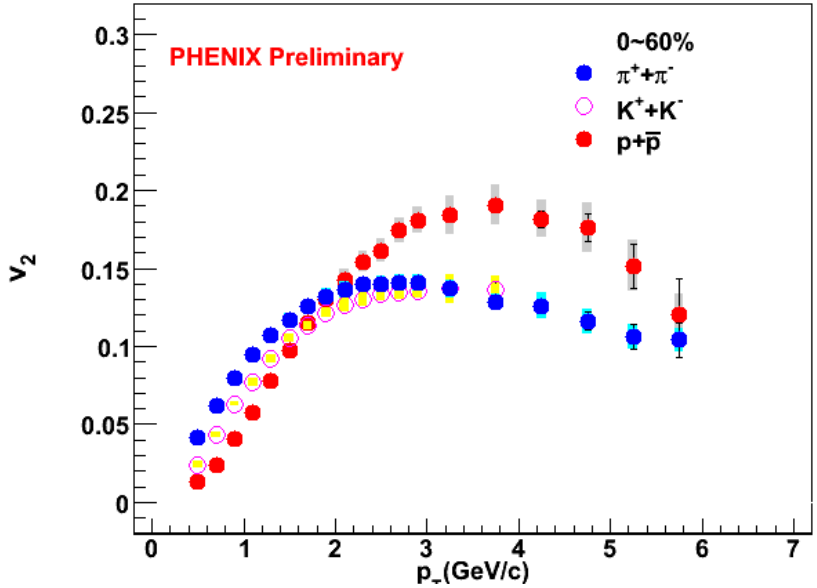


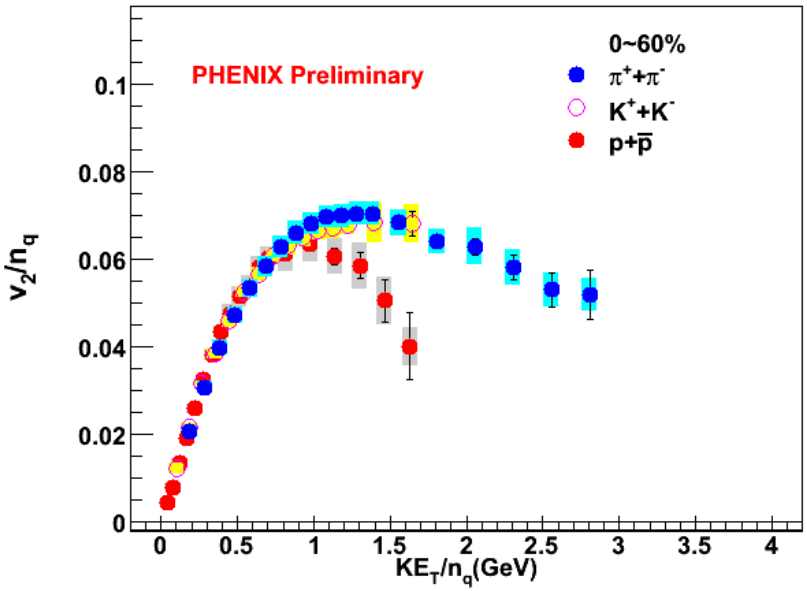


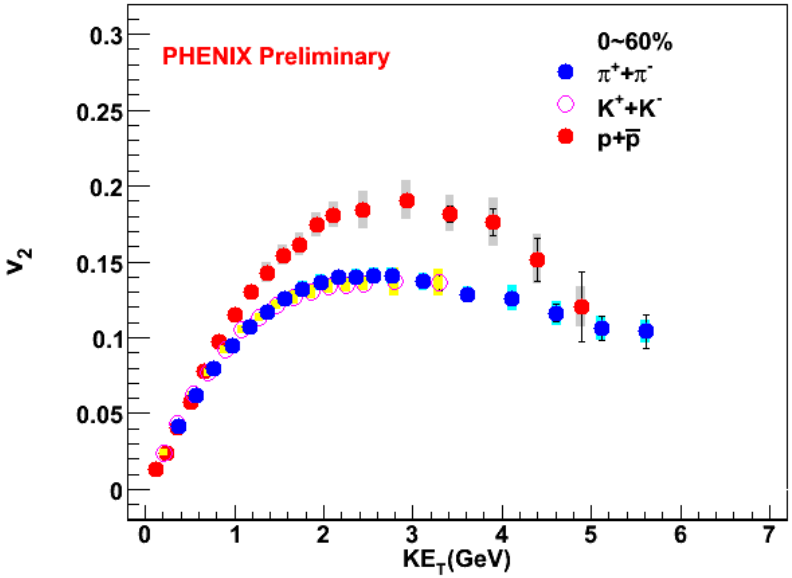
Phys.Rev.C81:034907,2010



High precision double differential measurements







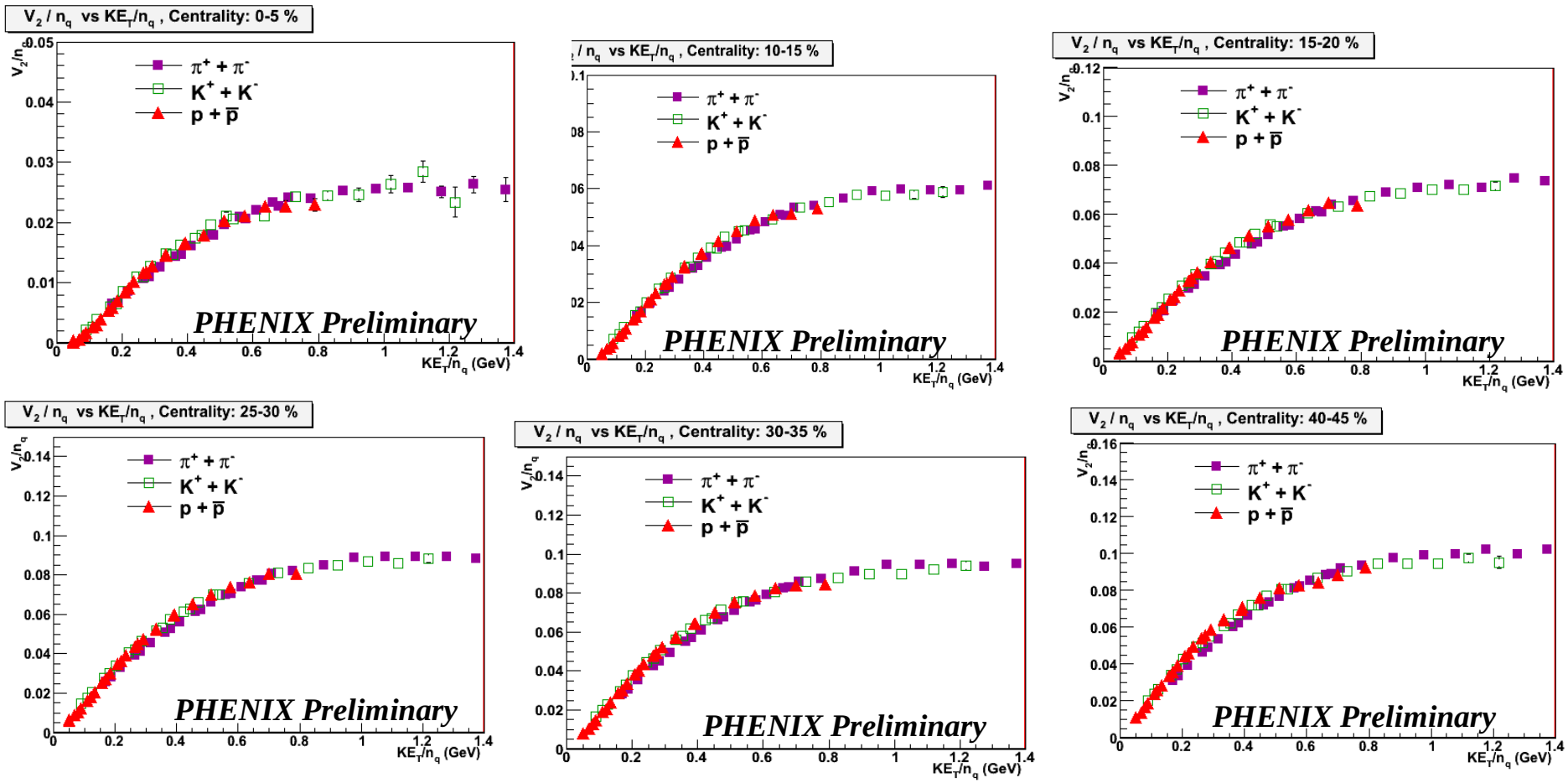
- *KE_T/n_q< 1GeV – soft physics*

  Hydrodynamic flow

- *Interplay soft-hard 3.0 < p_T< 5 GeV/c ?*

- *Hard dominates: p_T> 5 GeV/c*

Flow scales across centrality

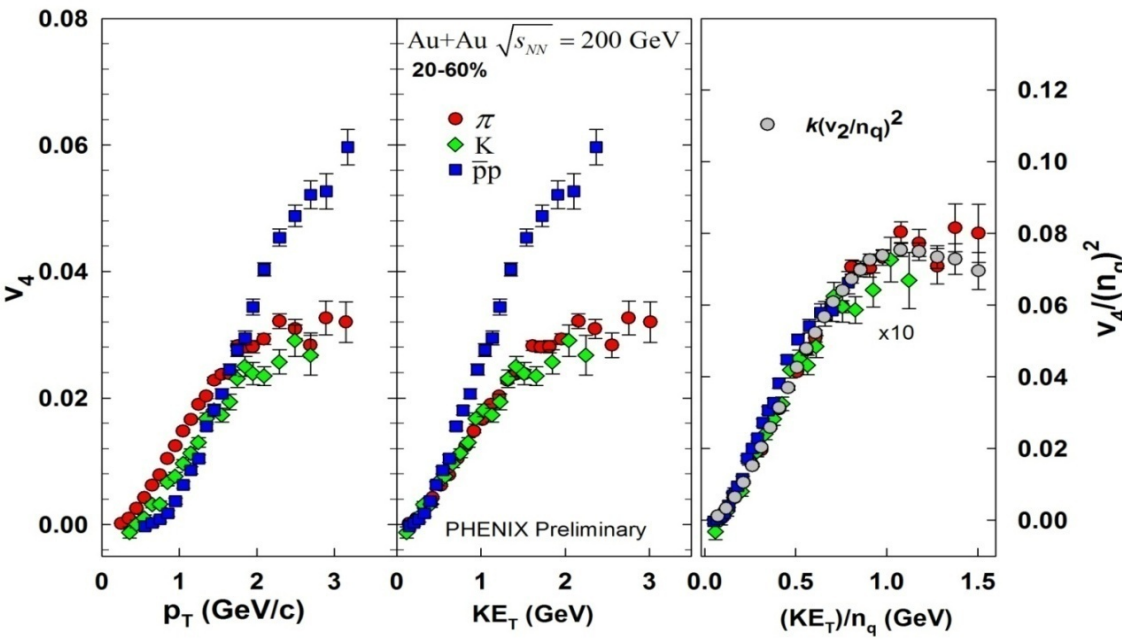


KE_T & n_q scaling validated for v_2 as a function of centrality

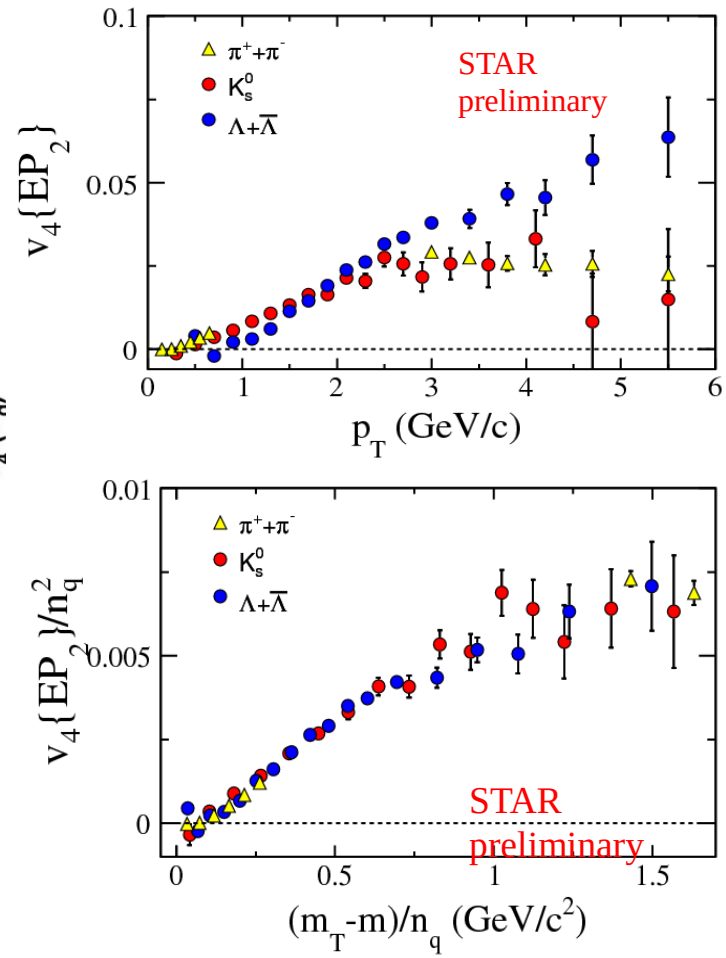
V_4 : A Small, But Sensitive Observable For Heavy Ion Collisions

PHENIX: QM 08, WWND 08, DNP 08, QM 09

J.Phys.G35:104105,2008,J.Phys.G36:064061,2009



STAR: WWND 09, QM 2009



$V_4 \sim k * (V_2^2)$ – very small signal

Do we have qualitative agreement ? Answer is : YES!!!