Beam Energy Dependence of Azimuthal Anisotropy at RHIC-PHENIX

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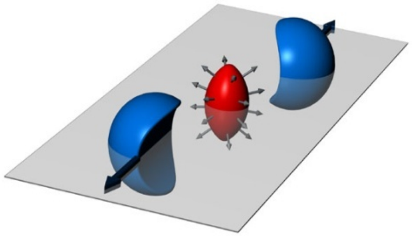
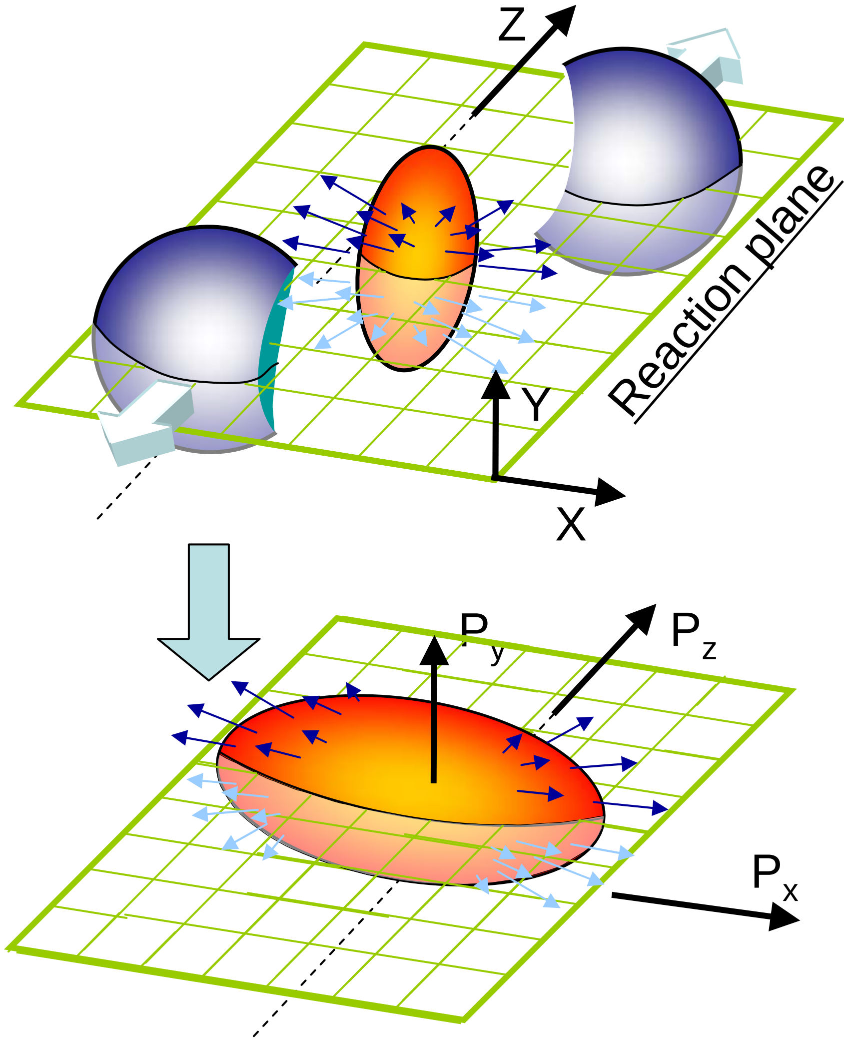


Critical Point and Onset of Deconfinement (CPOD 2010), Dubna , 23-29.08.2010

Elliptic Flow at RHIC



Two nuclei pass each other in a time of $t_{pass} \sim 0.15$ fm/c

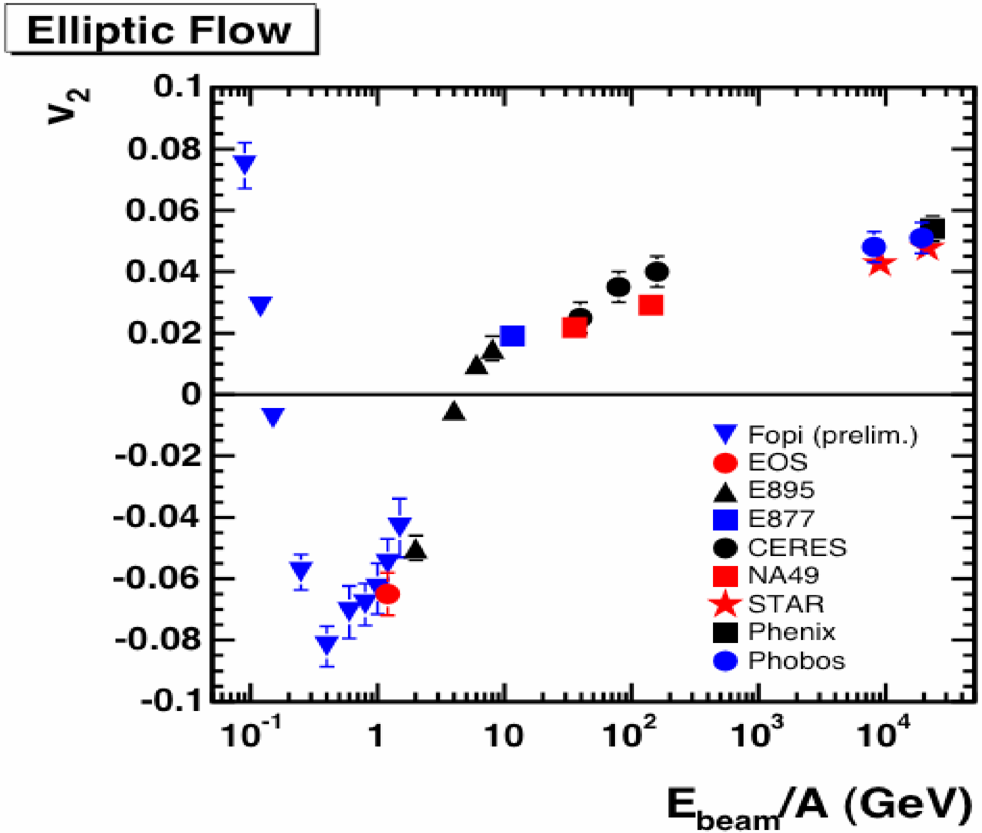
- The probe for early time
  - The dense nuclear overlap is ellipsoid at the beginning of heavy ion collisions
  - Pressure gradient is largest in the shortest direction of the ellipsoid
  - The initial spatial anisotropy evolves (via interactions and density gradients) → Momentum-space anisotropy
  - Signal is self-quenching with time

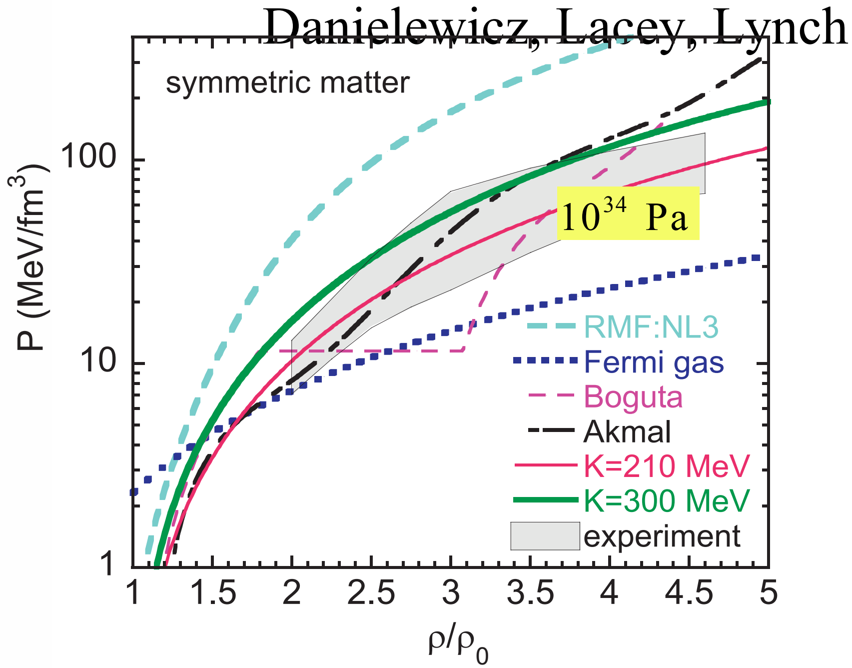
$$E\frac{d^3N}{d^3p} = \frac{1}{\pi}d^2\frac{N}{dp_T^2 dy}\left[1 + 2v_1\cos(\varphi - \Psi_R) + 2v_2(2[\varphi - \Psi_R]) + \ldots\right]$$

→

$$v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle$$

Beam Energy dependence of Elliptic Flow: Constraints for the Hadronic EOS

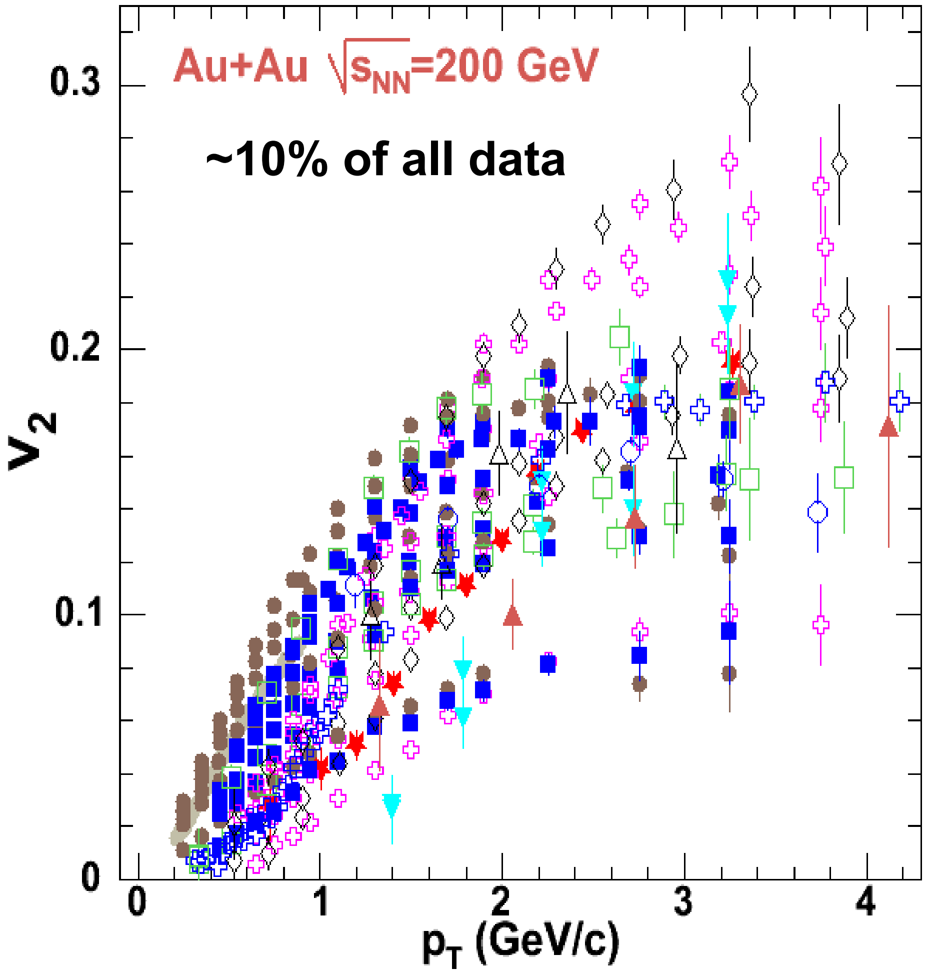


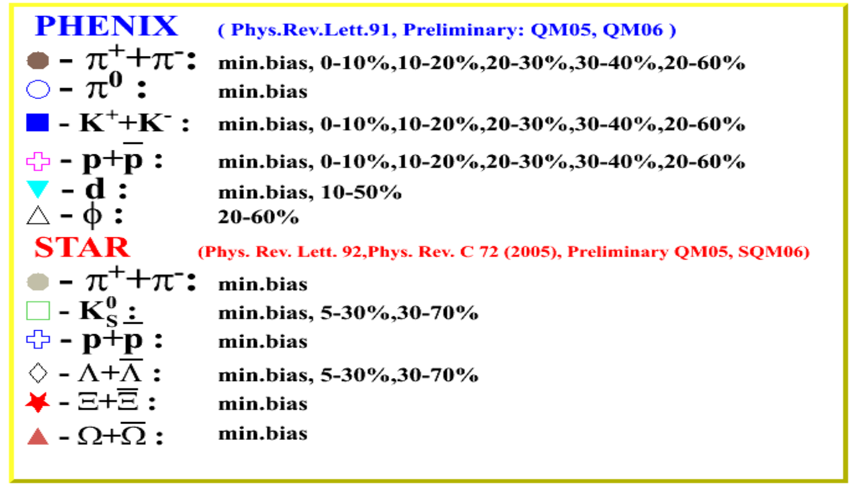


The extraction of transport properties is an iterative process.

What kind of flow measurements do we need for it?

Ten Years of Elliptic Flow Measurements at RHIC

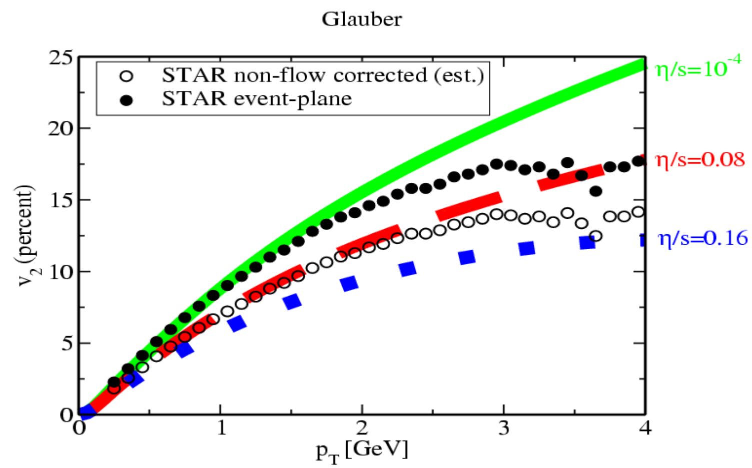




Substantial elliptic flow signals are observed for a variety of particle species at RHIC

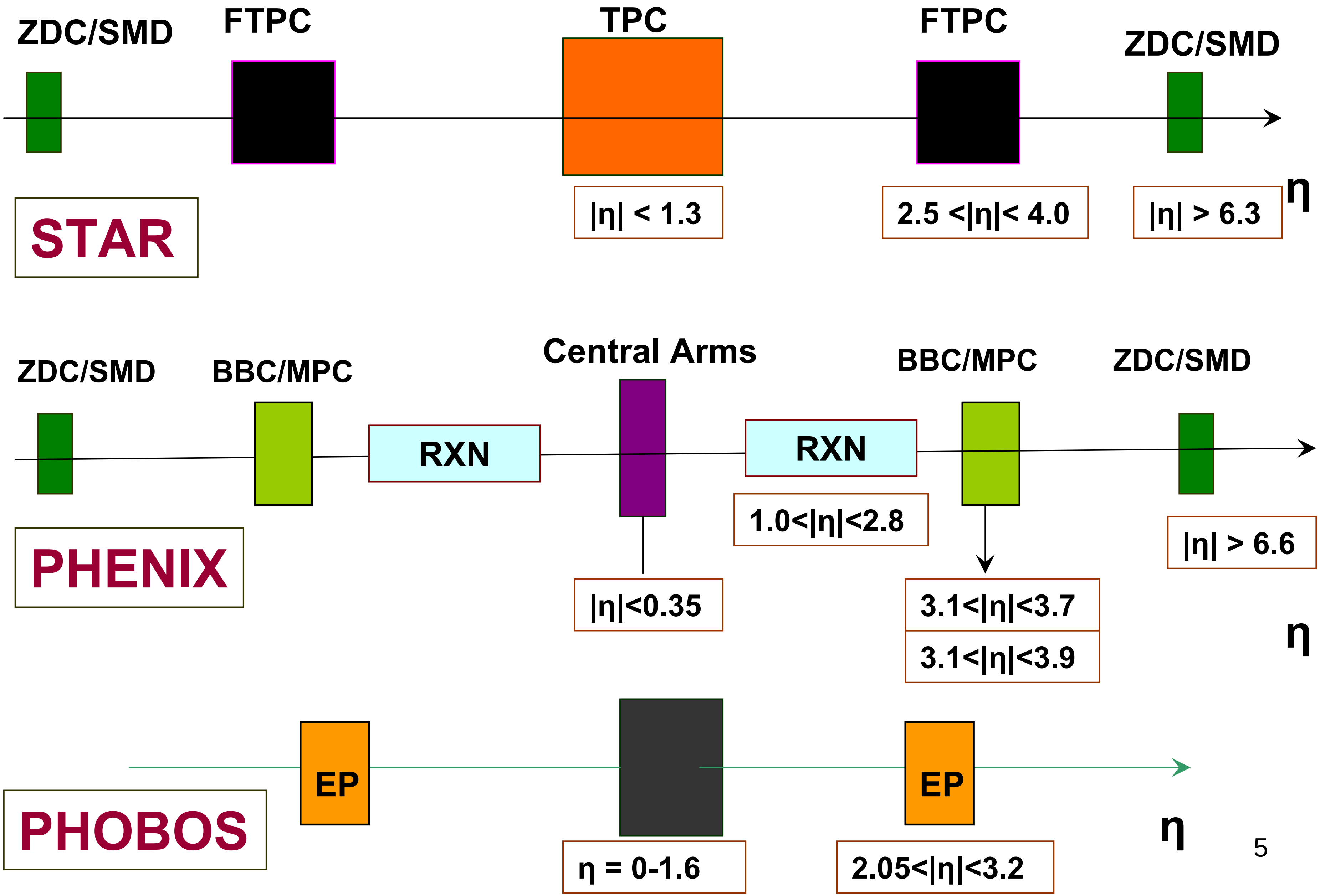
P. Romatschke and U. Romatschke,

Phys. Rev. Lett. 99:172301, 2007

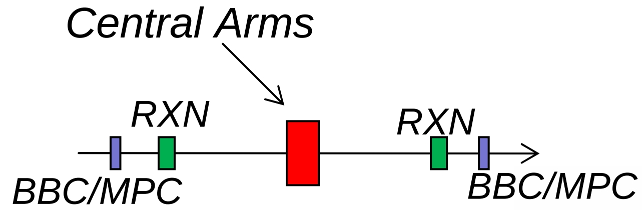


Are flow measurements at RHIC reliable?

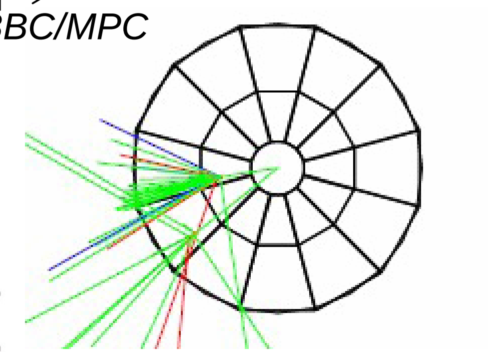
Elliptic Flow Measurements V_2 (p_T , centrality) in PHOBOS/STAR/PHENIX



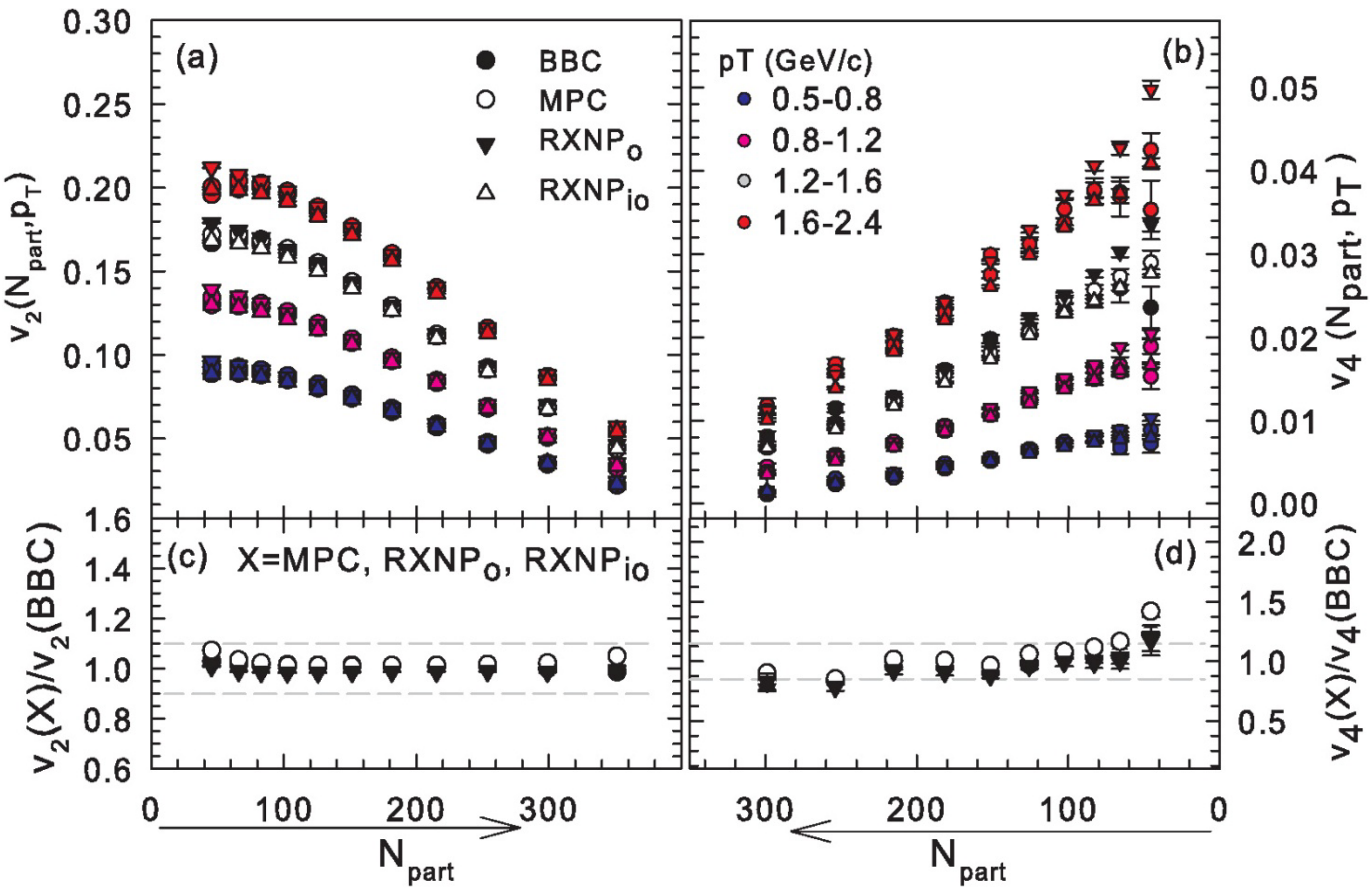
Data Precision



New RXN detector



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



$3.1 < |\eta_{BBC}| < 3.9$

$3.1 < |\eta_{MPC}| \lesssim 3.9$

$1.5 < |\eta_{RXN_i}| < 2.8$

$1.0 < |\eta_{RXNo}| < 1.5$

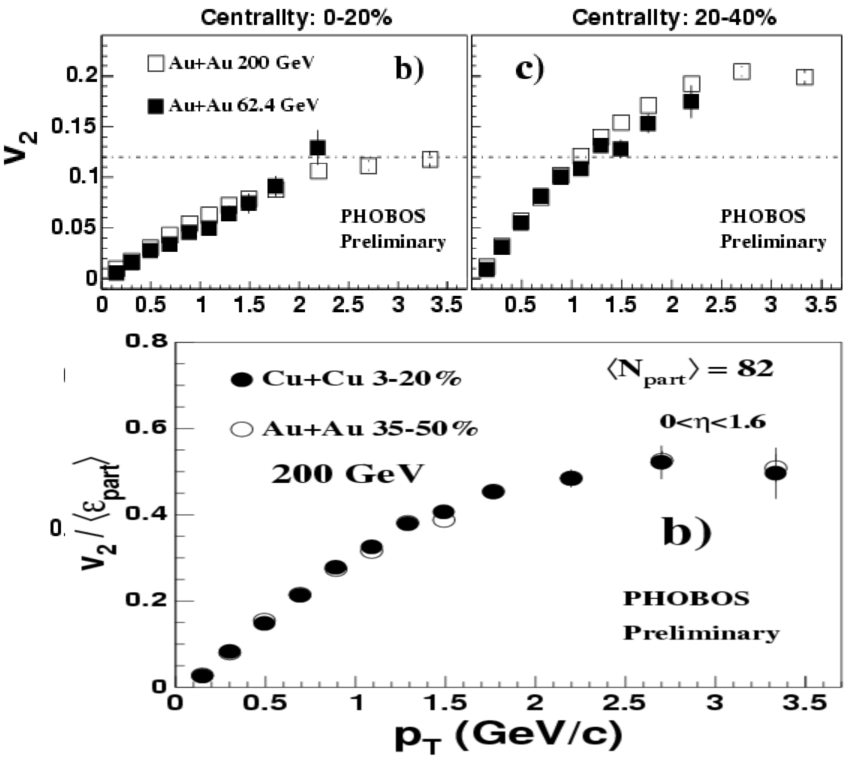
$1.0 < |\eta_{RXN_{io}}| < 2.8$

Event planes

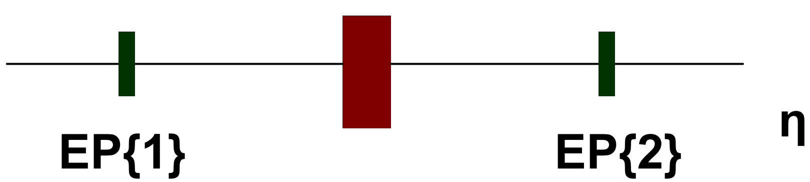
➢ ***No evidence for significant η-dependent non-flow contributions***

Results from different methods should Not be used as a measure of systematic error!

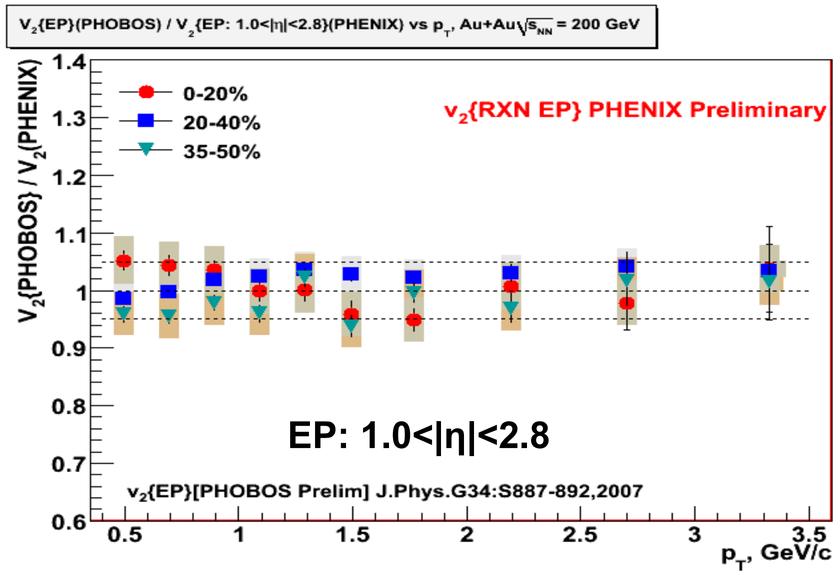
Comparison of differential $v_2(p_T$, centrality): PHOBOS/PHENIX

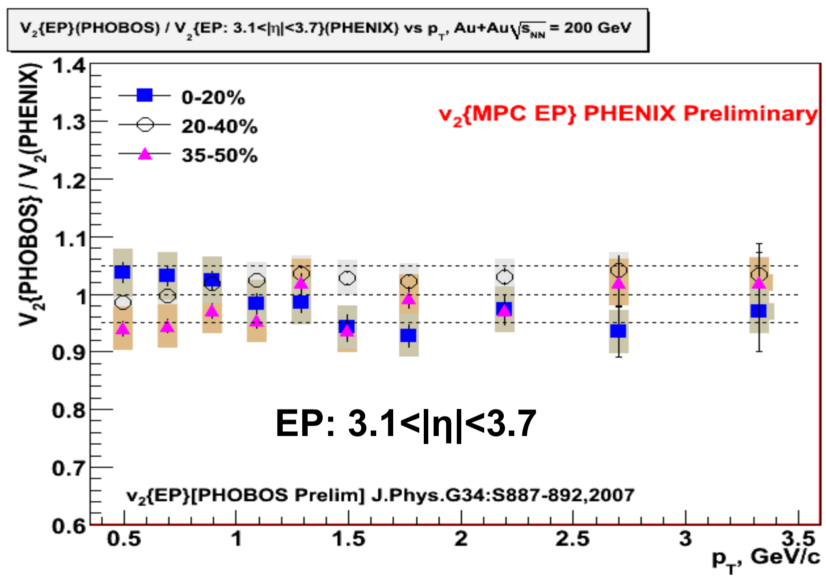


from PHOBOS QM06 proc. J. Phys. G34 S887 (2007)



PHOBOS EP: $2.05<|\eta|<3.2$



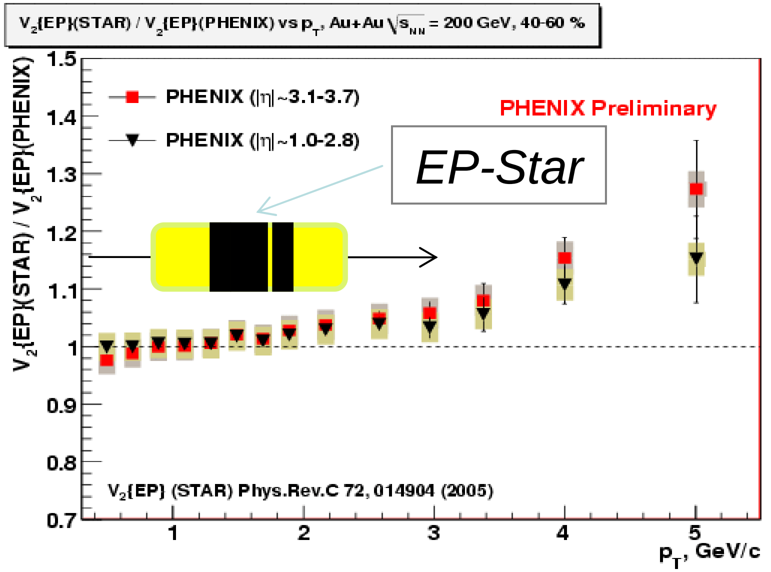


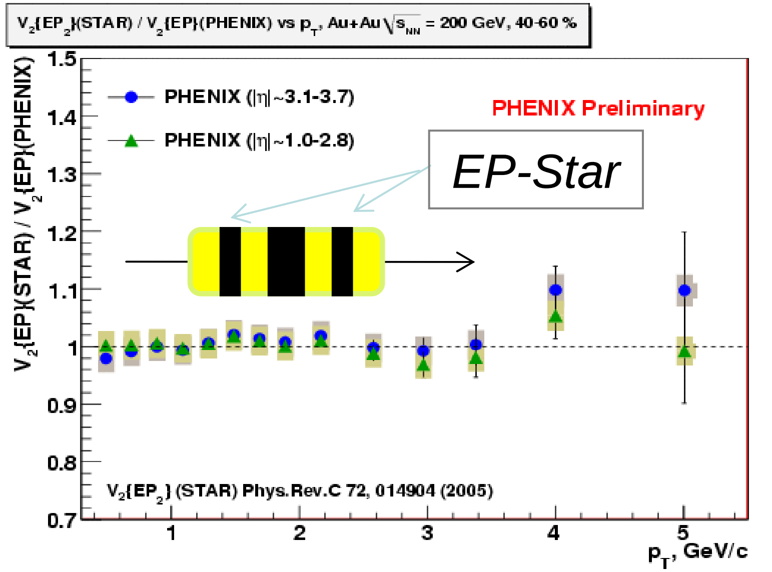
Overall good agreement between differential flow measurements

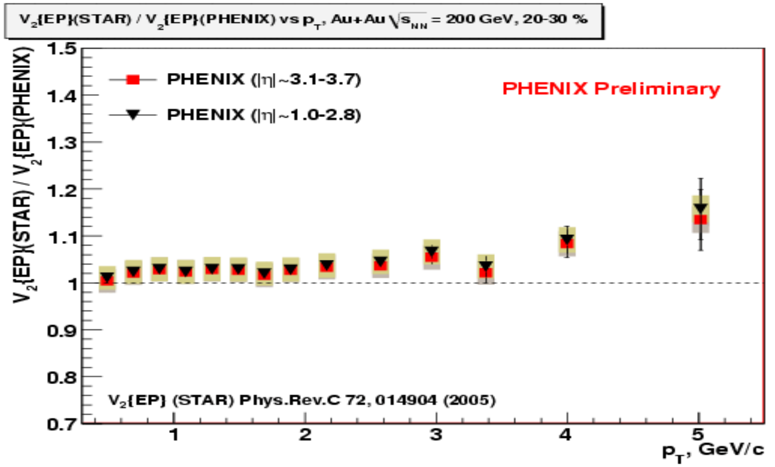
Comparison $v_2(p_T, \text{centrality})$: STAR [Central TPC $|\eta|<1.0$] / PHENIX

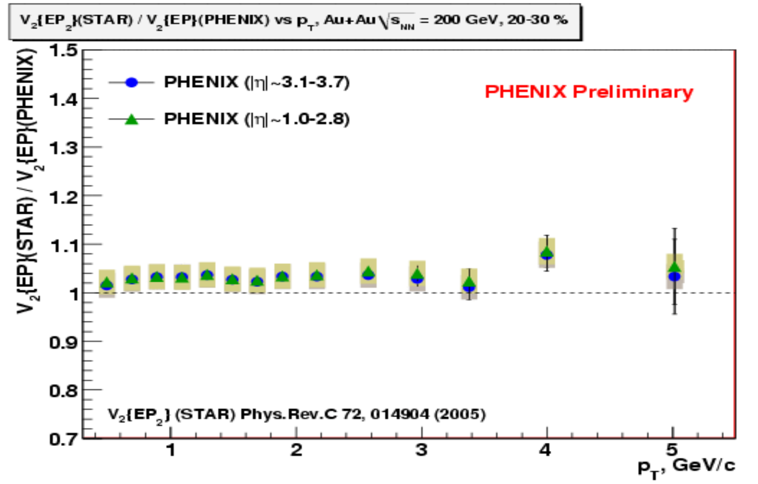
$V_2\{EP\}$ – standard EP method

$V_2\{EP_2\}$ – modified EP method





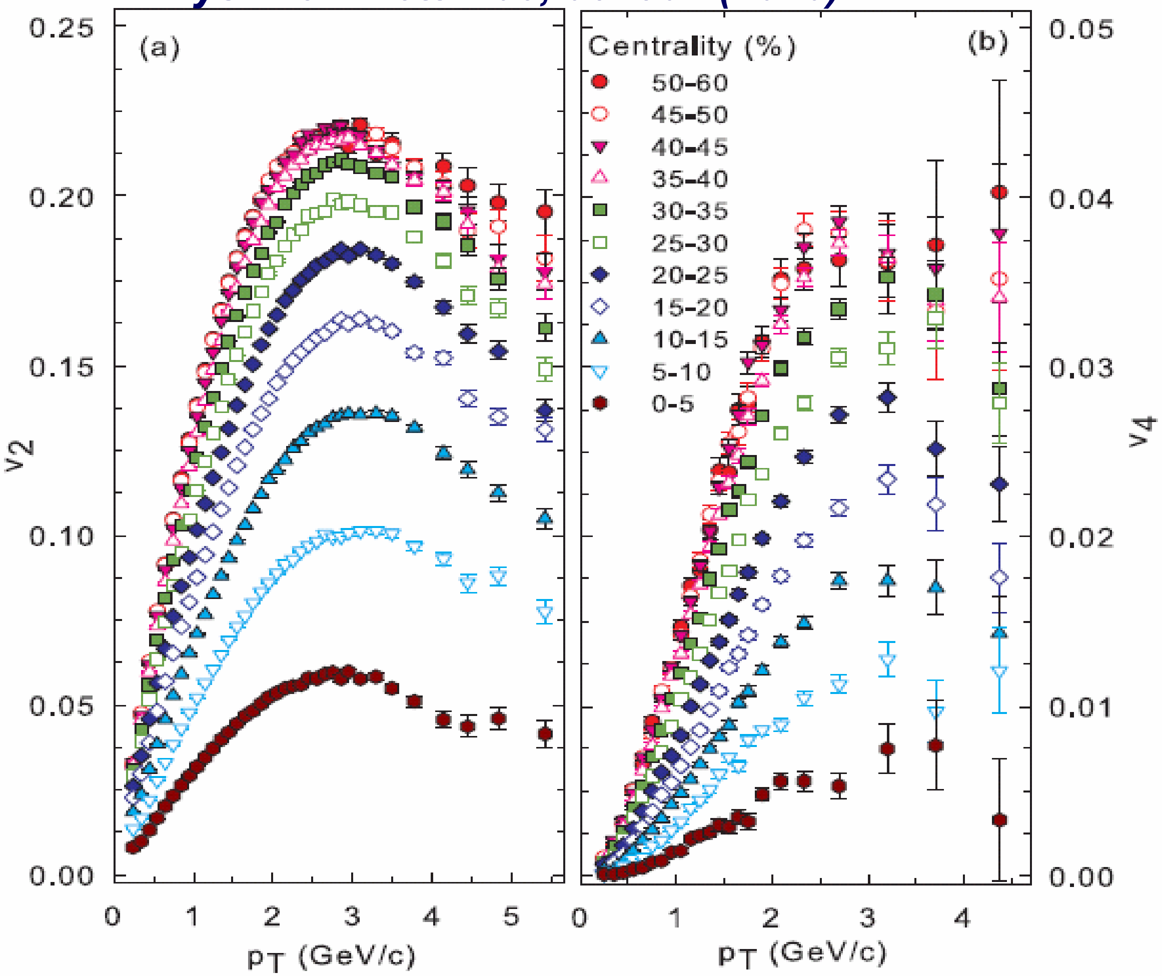




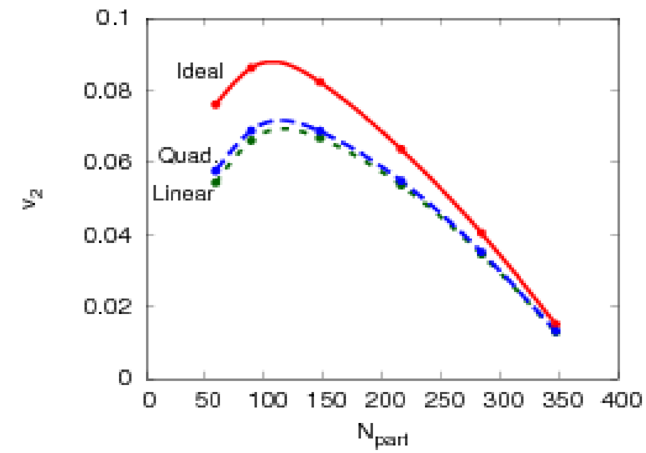
http://quark.phy.bnl.gov/www/cathie_files/ca-te/

PHENIX: Extensive anisotropy Data

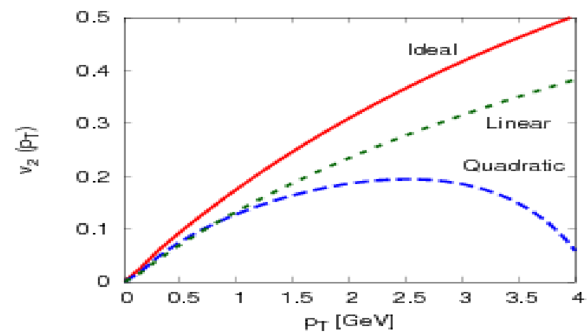
Phys. Rev. Lett. 105, 062301 (2010)



K. Dusling, D. Teaney, ..



Phys.Rev.C81:034907,2010



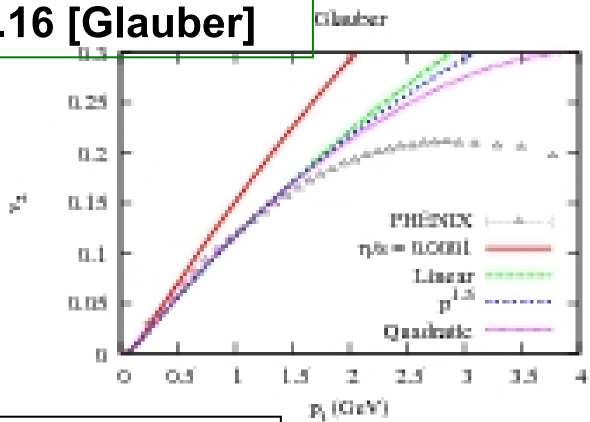
Departure from equilibrium on the freeze out surface – largest part of viscous correction to v2=f[pt)

Lesson 1: ***One need high precision double differential flow measurements***

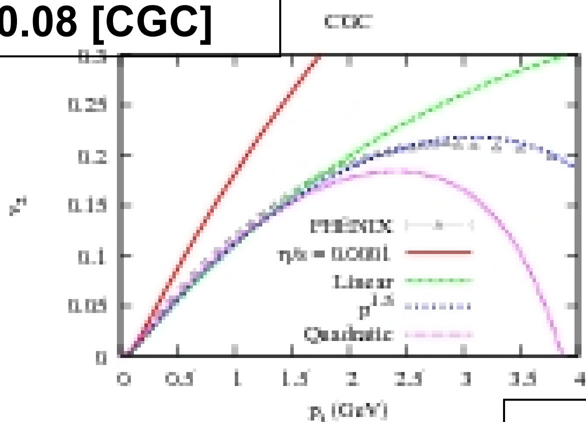
Estimates for η/s

Comparison with viscous hydrodynamics calculations

η/s=0.16 [Glauber]



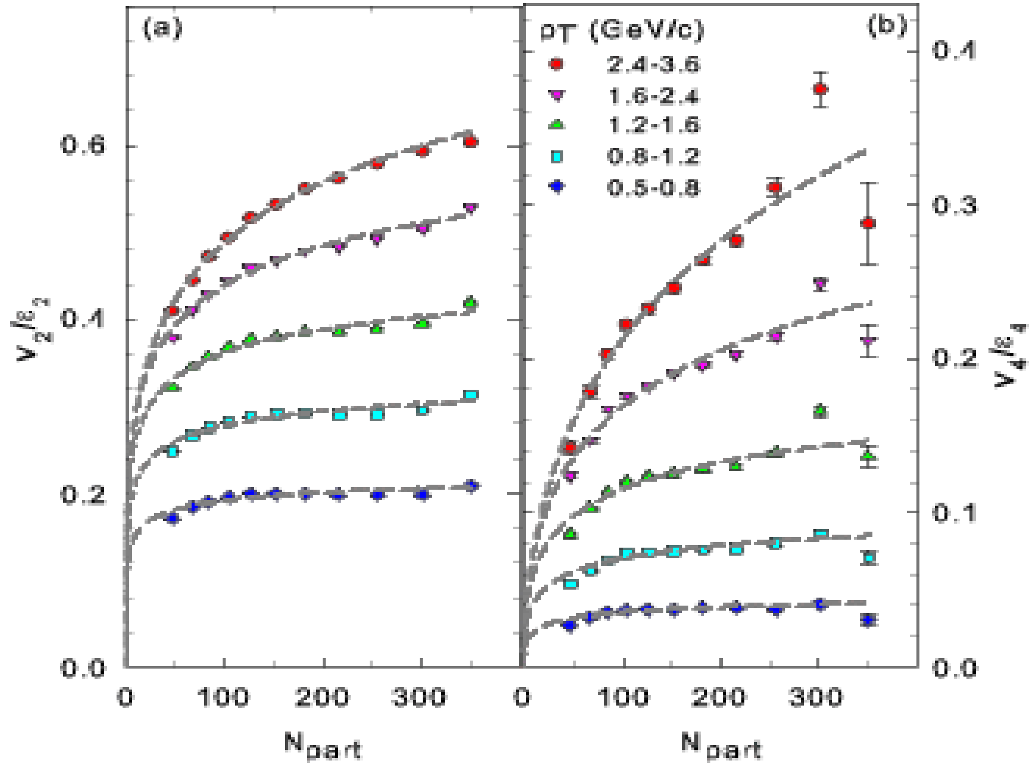
η/s = 0.08 [CGC]



M. Luzum, J-Y Ollitrault

Phys.Rev.C82:014906,2010

quantify viscous corrections via a fitting procedure, to obtain Knudsen number as a function of N_{PART}



R. Lacey et al (arXiv:1005.4979)

Similar values extracted for η/s

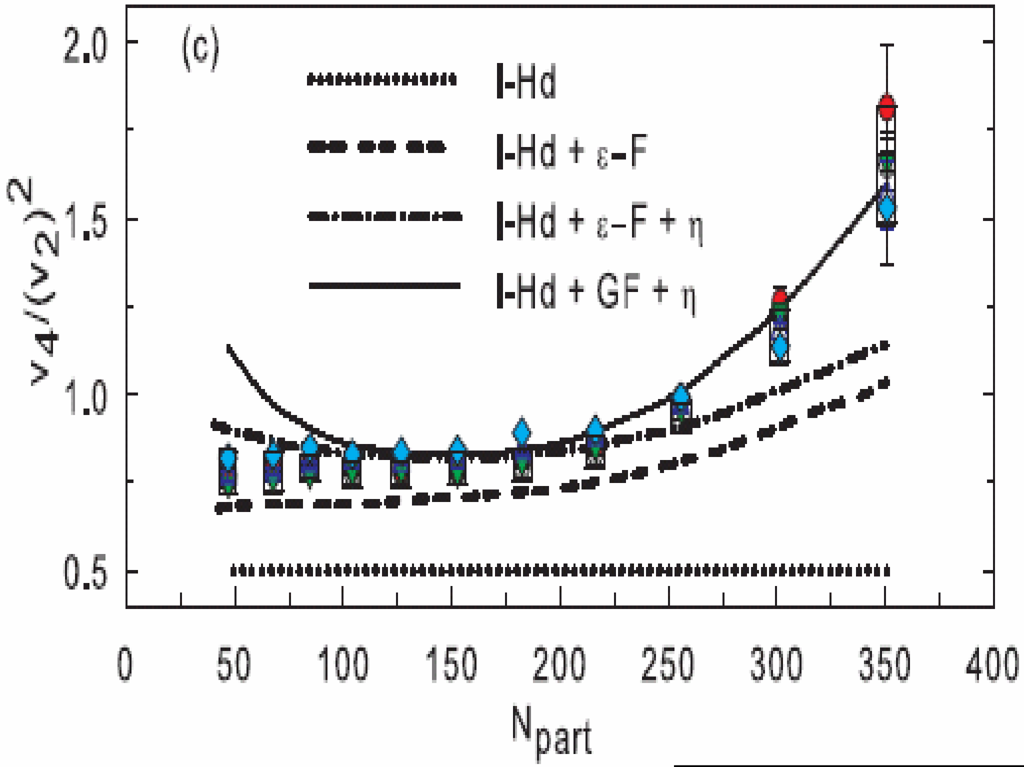
•Measurements compatible with a small value of η/s

One need a new experimental constraint for distinguishing Glauber and CGC Initial geometry:

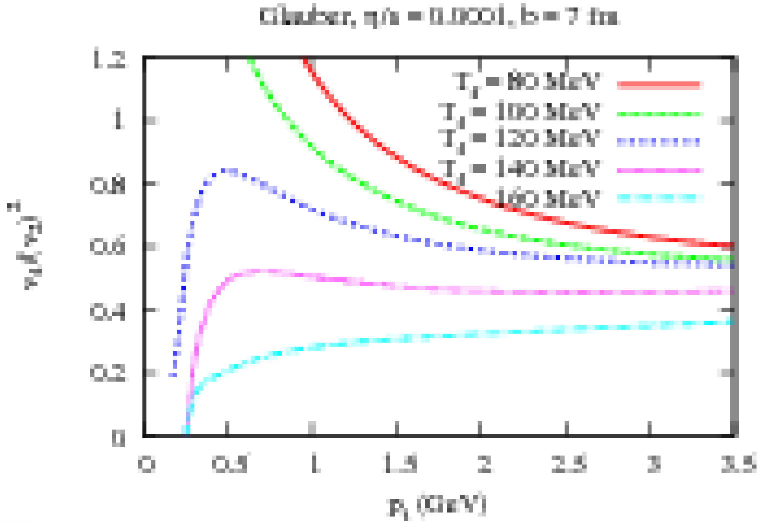
Phys. Rev. C 81, 061901(R) (2010)

importance of higher harmonics of anisotropy

Data PHENIX: Phys. Rev. Lett. 105, 062301 (2010)
Calculations: C. Gombeaud, J-Y Ollitrault
Phys.Rev.C81:014901,2010



Luzum, Gombeaud, J-Y Ollitrault
Phys.Rev.C81:054910,2010



$V_4/(V_2^2)$ - is sensitive to *(η/s)* and the freeze-out temperature

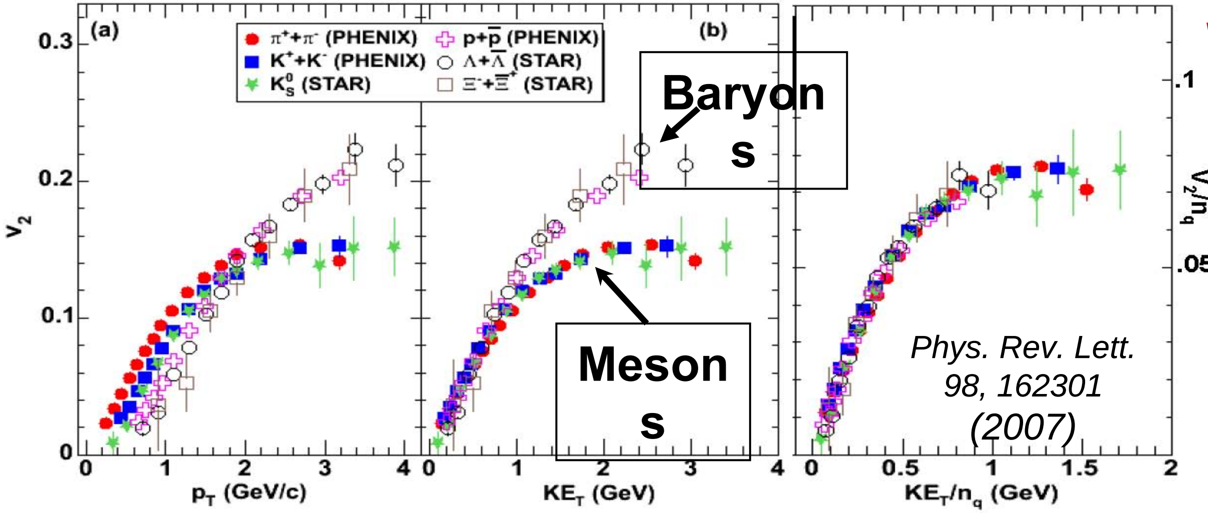
Estimate → 4π(η/s) ~ 1- 2

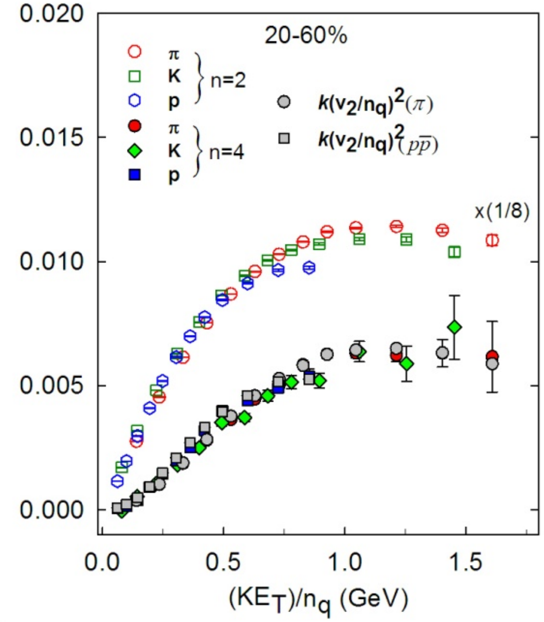
Stay tuned for new V_3 and V_4(EP V_4) results!!

Lesson2: Simultaneous measurements of all available harmonics of azimuthal anisotropy are important for extraction of transport properties

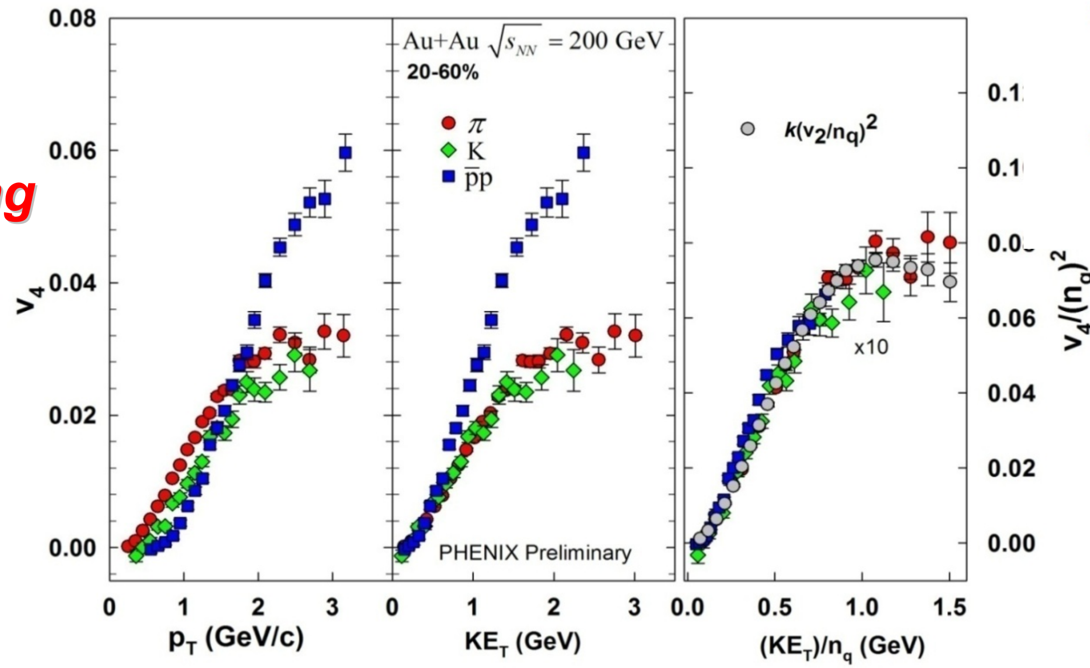
Universal scaling of harmonic flow at RHIC

v_2 scaling





v_4 scaling



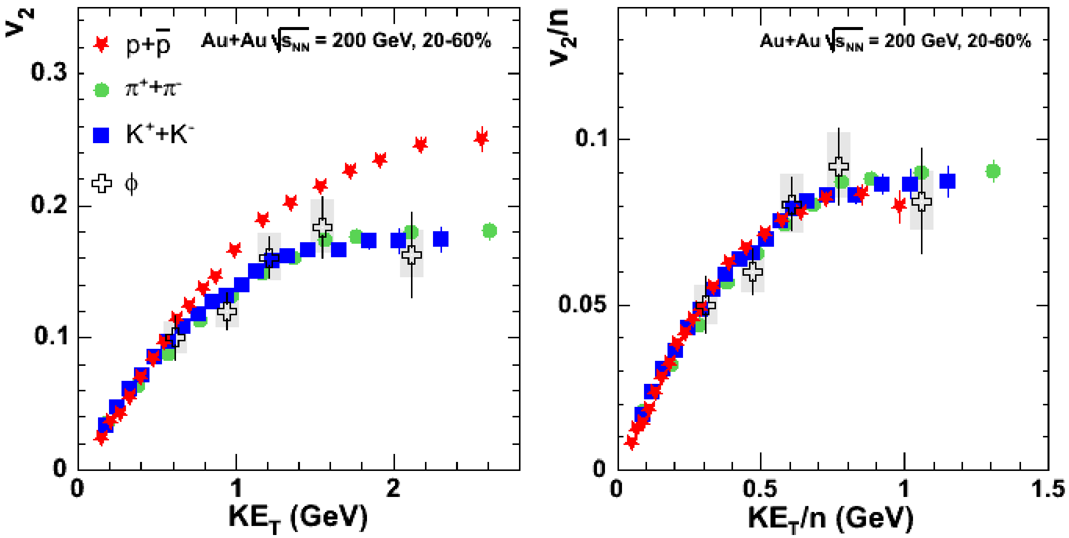
Universal scaling

KE_T & n_q (n_q^2) scaling validated for v_2 (v_4)
→ Partonic flow

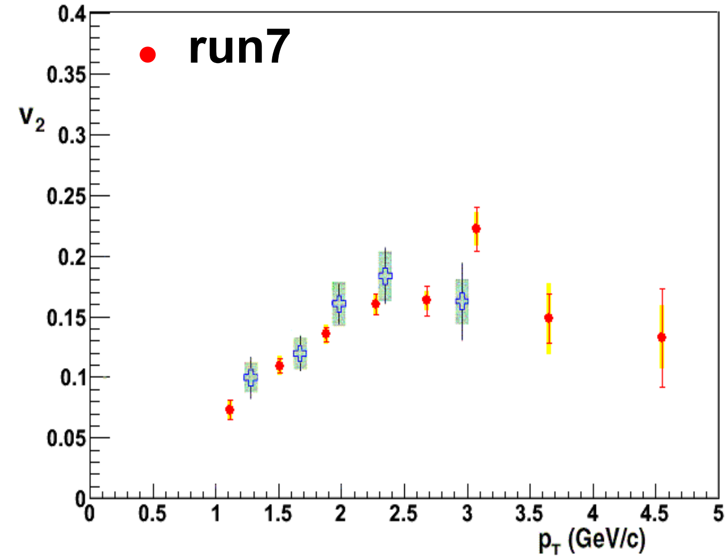
Lesson3: Flow measurements for different particle species are very important

Scaling constrains η/s

PHENIX: Phys. Rev. Lett. 99, 052301 (2007)



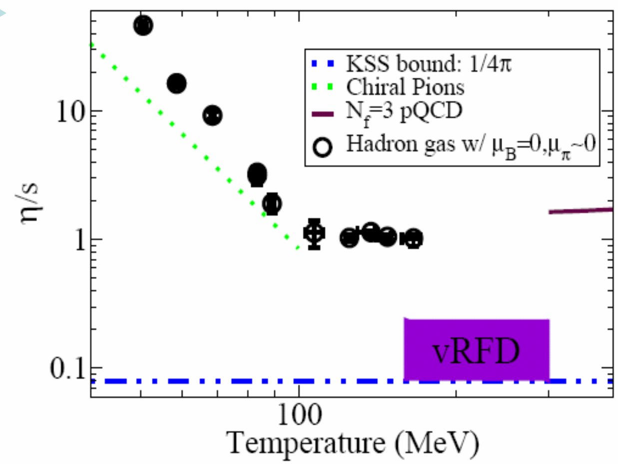
PHENIX phi meson V_2 results: [run7/run4]



η/s from hadronic phase is very large 10-12x(1/4π) No room for such values!

N. Demir, S. A. Bass

Phys.Rev.Lett.102:172302,2009

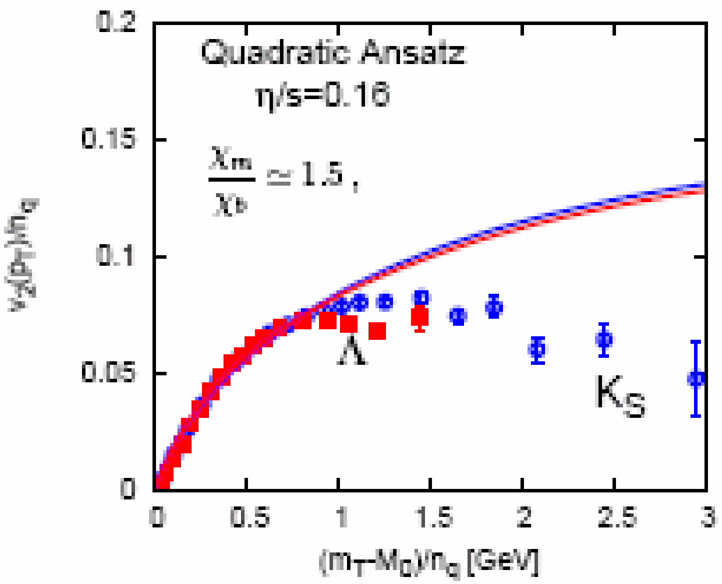


Partonic flow dominates at RHIC! Hadronic contribution cannot be large

Scaling constrains η/s

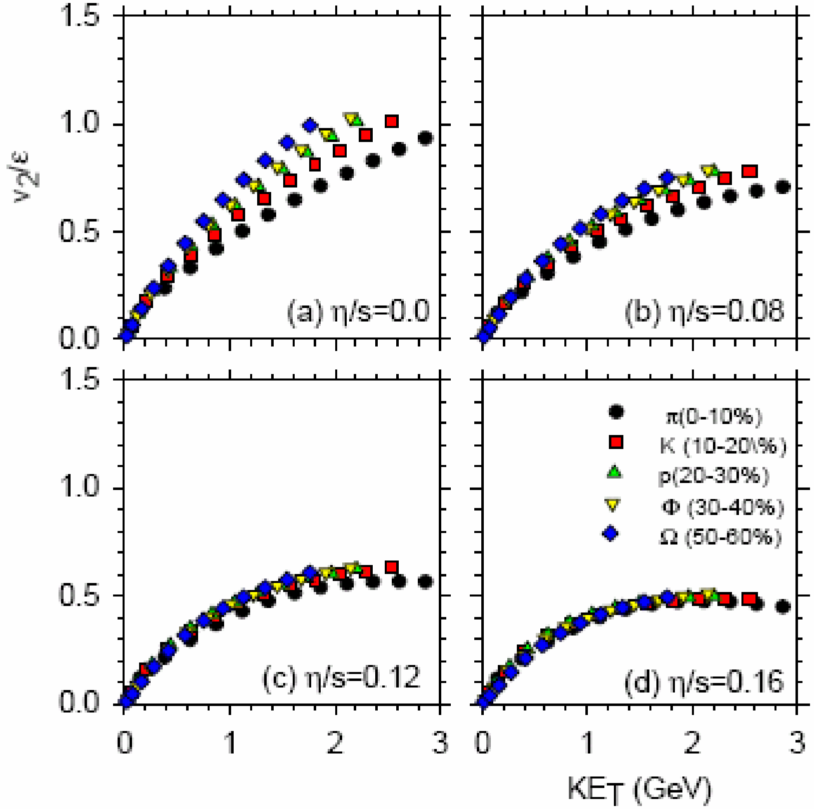
D. Teaney, K. Dusling,

Phys.Rev.C81:034907,2010



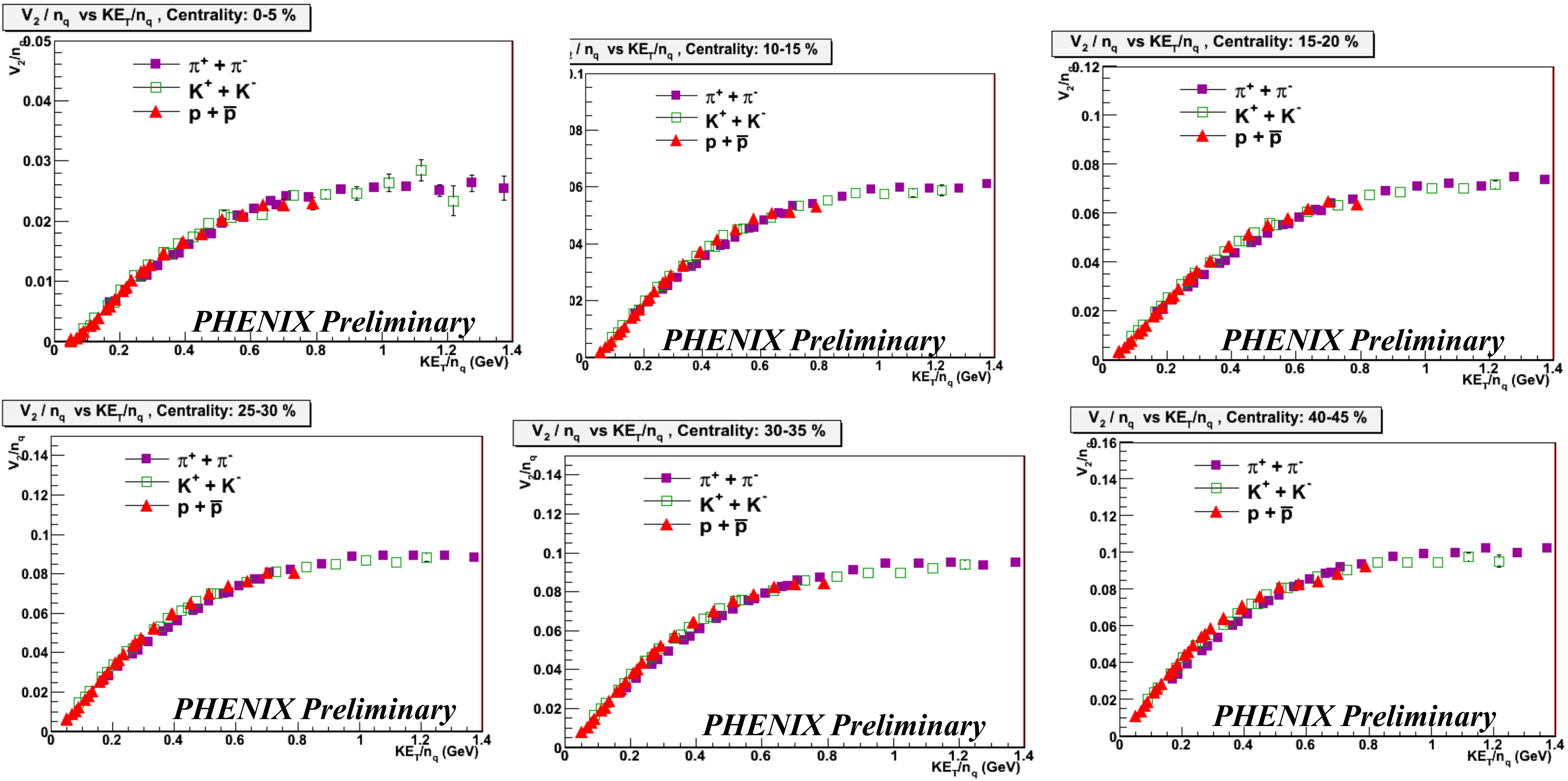
$$\chi_m(\tilde{p}) = C_m(\alpha)\tilde{p}^{2-\alpha},$$
$$\chi_b(\tilde{p}) = C_b(\alpha)\tilde{p}^{2-\alpha},$$

A. K. Chaudhuri, Phys. Rev. C81, 2010



Viscosity required
for KE_T scaling → Lower Limit ?

Flow scales across centrality

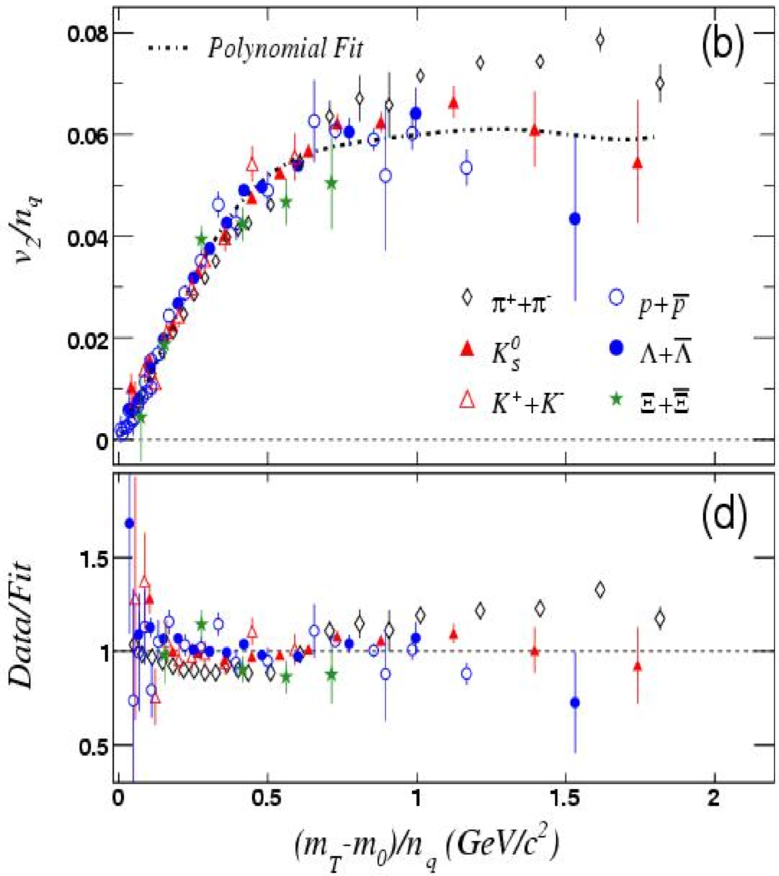


KE$_T$ & n_q (n_q^2) scaling validated for v_2 as a function of centrality

KE_T + NCQ scaling at RHIC: beam energy/system size

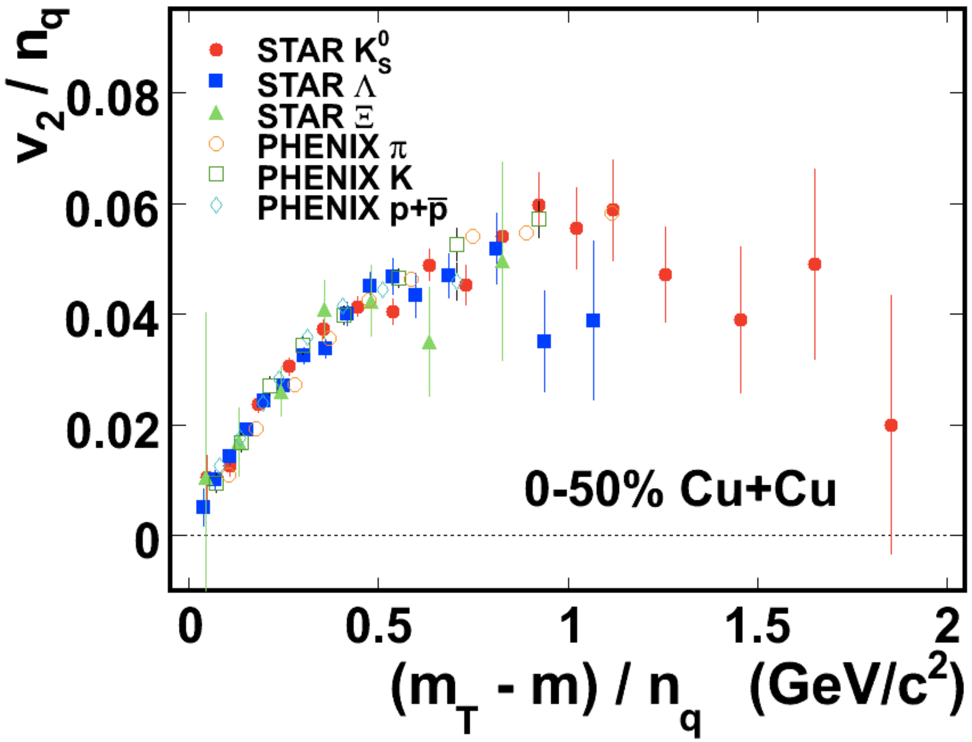
Au+Au at 62.4 GeV

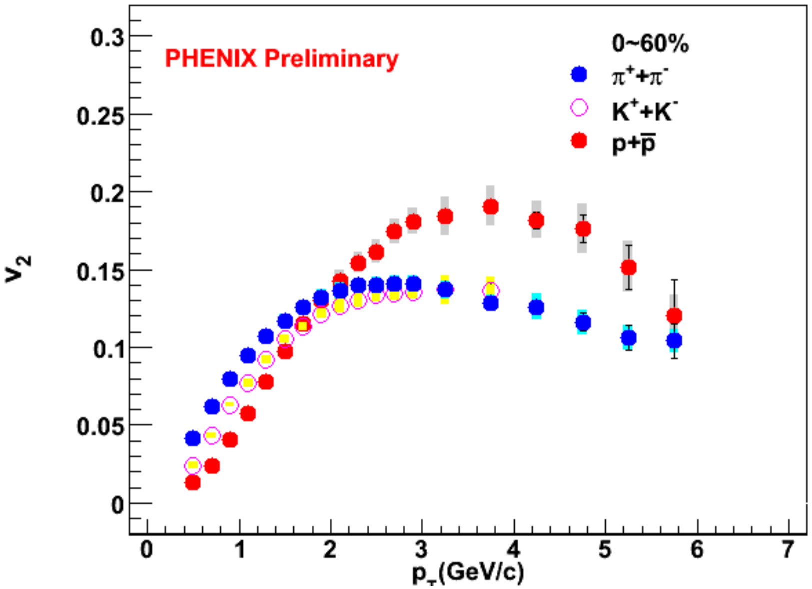
STAR: Phys.Rev.C75:054906,2007

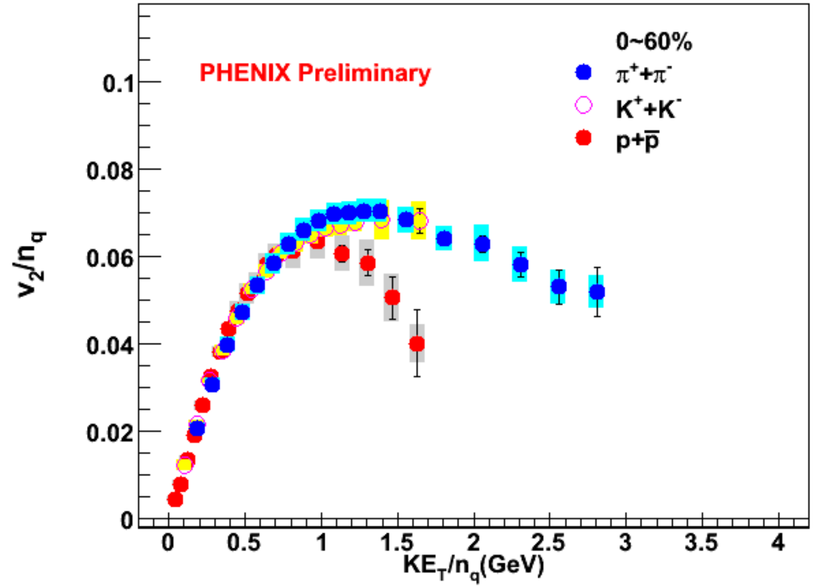


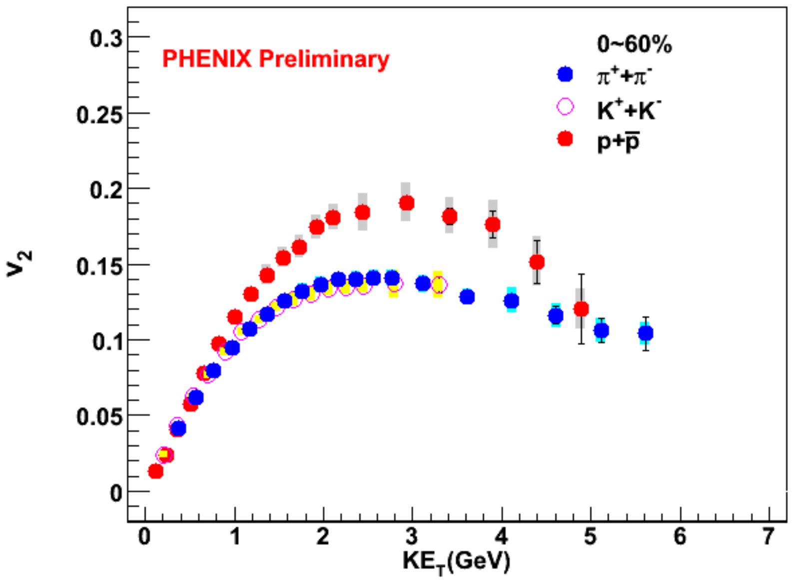
Cu+Cu at 200 GeV

Nucl.Phys.A830:187C-190C,2009









- ***KE_T/n_q< 1GeV – soft physics***

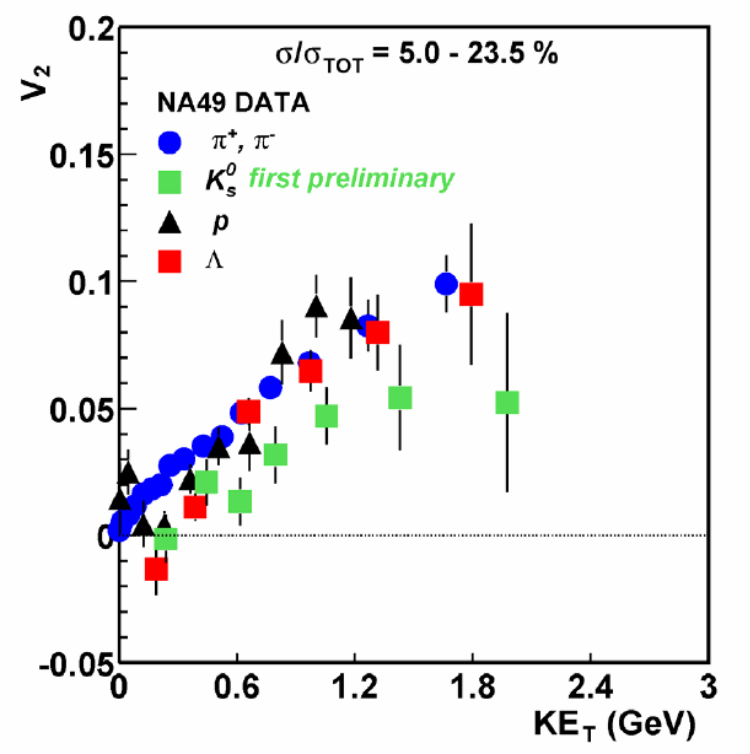
  Hydrodynamic flow

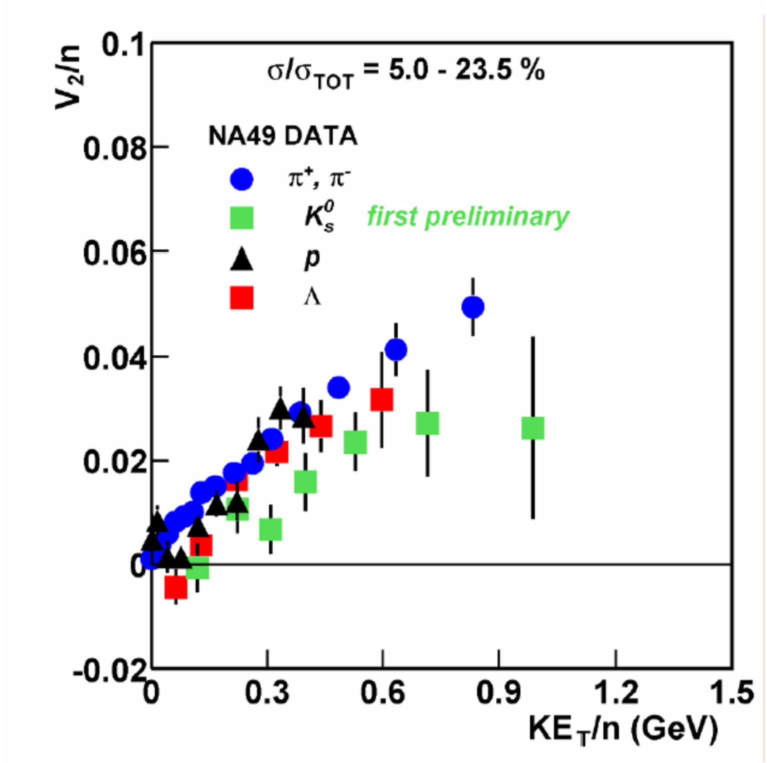
- ***Interplay soft-hard 3.0 < p_T< 5 GeV/c ?***

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

Transverse Kinetic Energy + NCQ scaling at SPS

Pb+Pb at 158 GeV [sqrt(Snn) ~ 17.3 GeV]



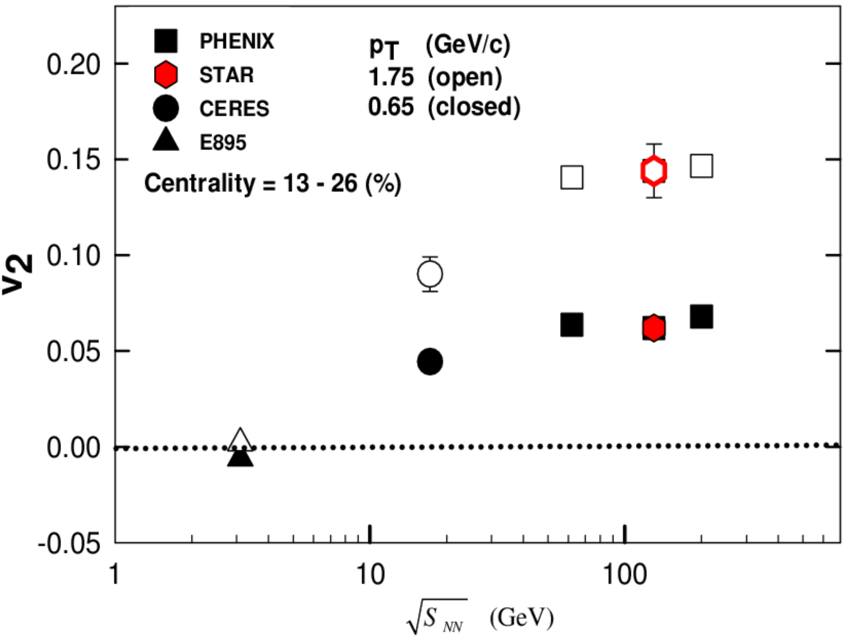


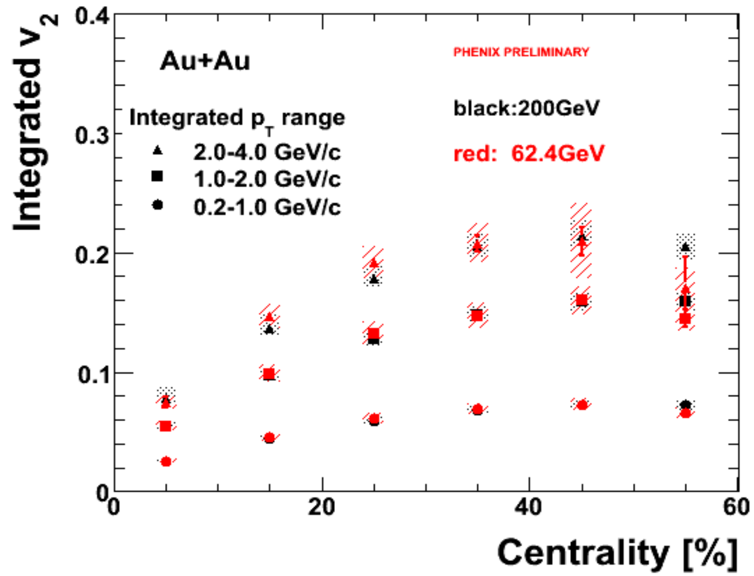
M. Mitrovski for NA49 Collaboration , SQM 2009

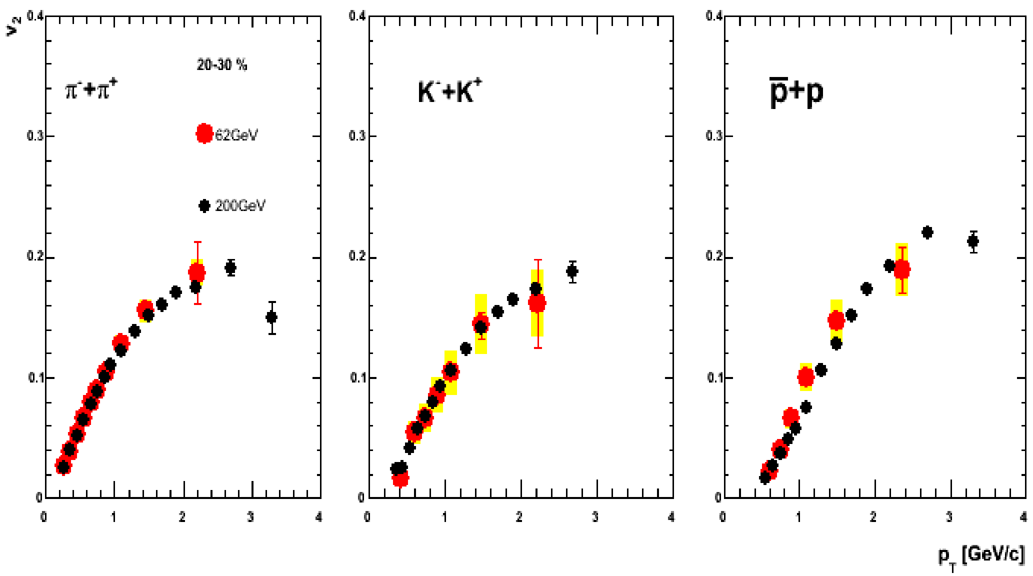
Do we have scaling at SPS?? Hard to tell…..

Beam Energy dependence of v_2

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







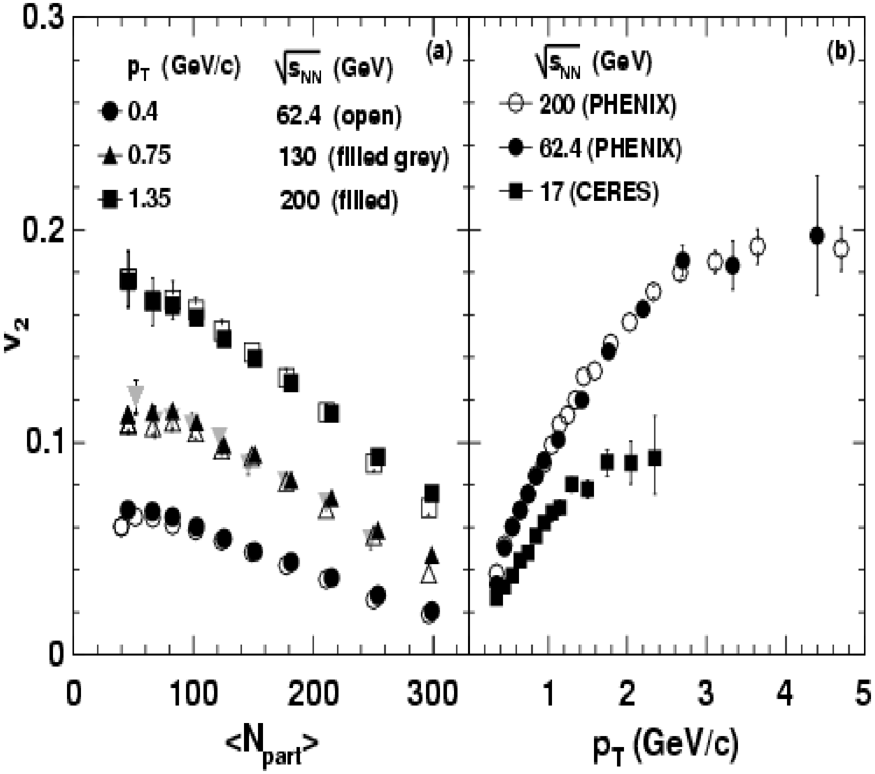
Apparent saturation above 62.4 GeV for differential elliptic flow

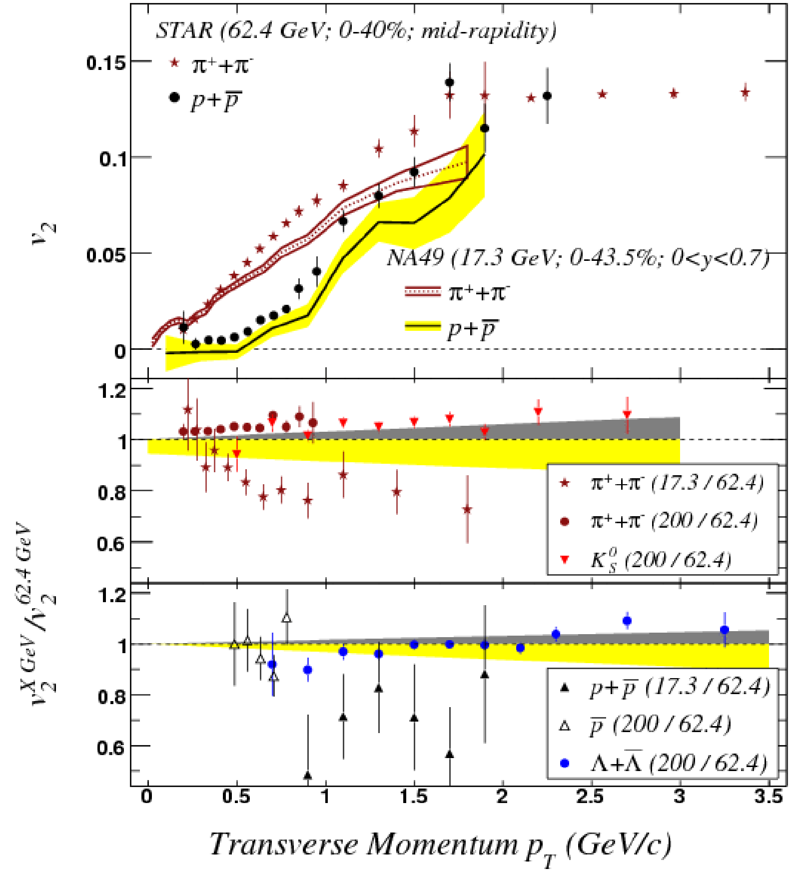
Evidence of a softening of the EOS due to a phase transition ????

Elliptic Flow at RHIC/SPS

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

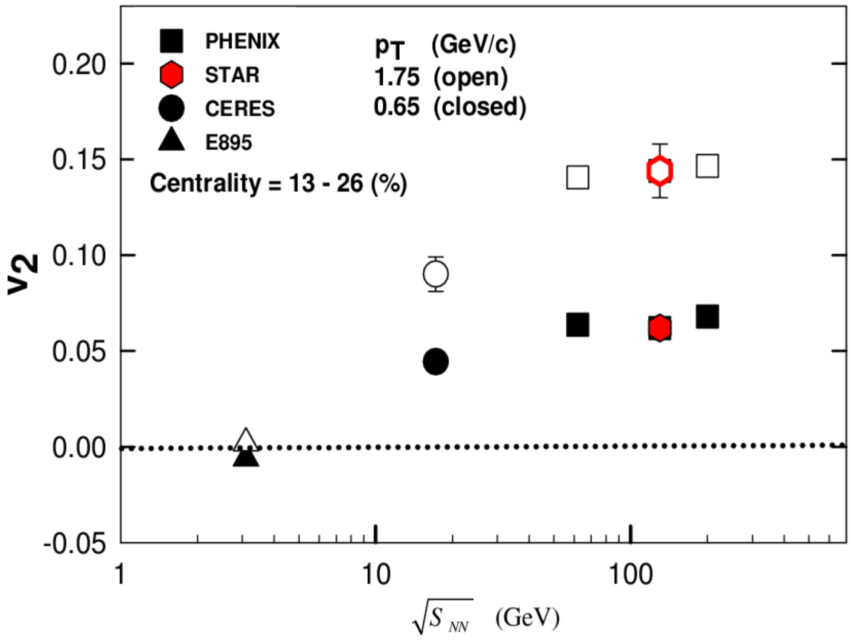
STAR: Phys.Rev.C75:054906,2007

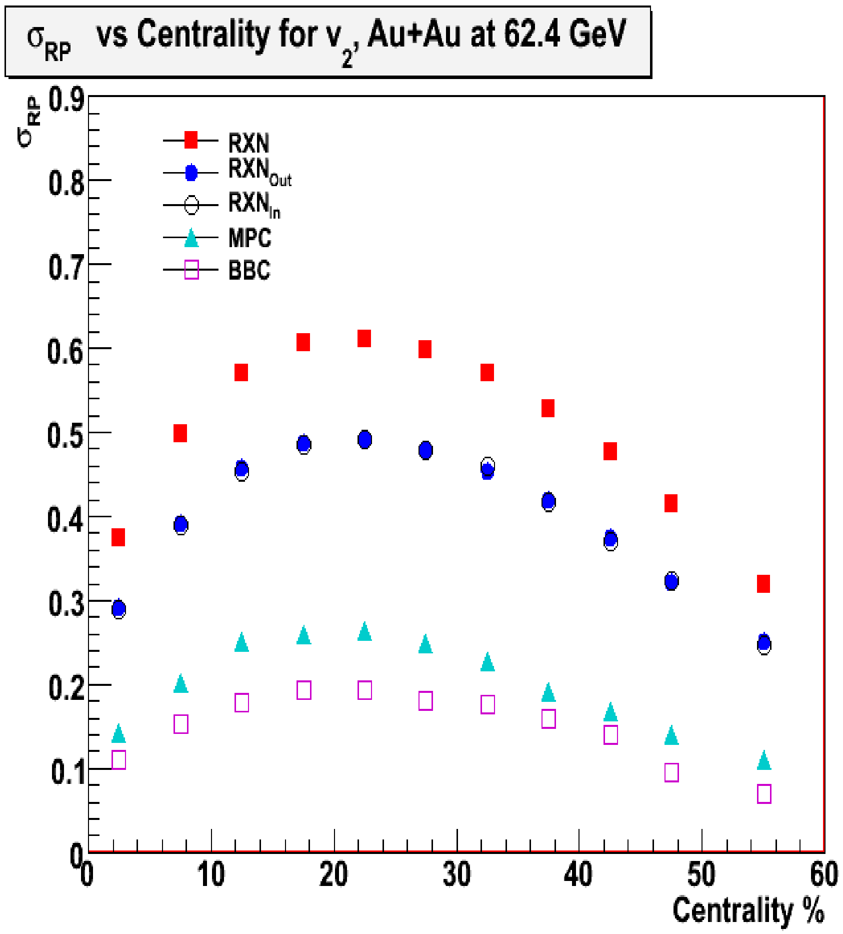




PHENIX: RHIC/SPS **~50% difference.** **STAR:** RHIC/SPS ~ **10-15% difference** in the differential V_2 results.

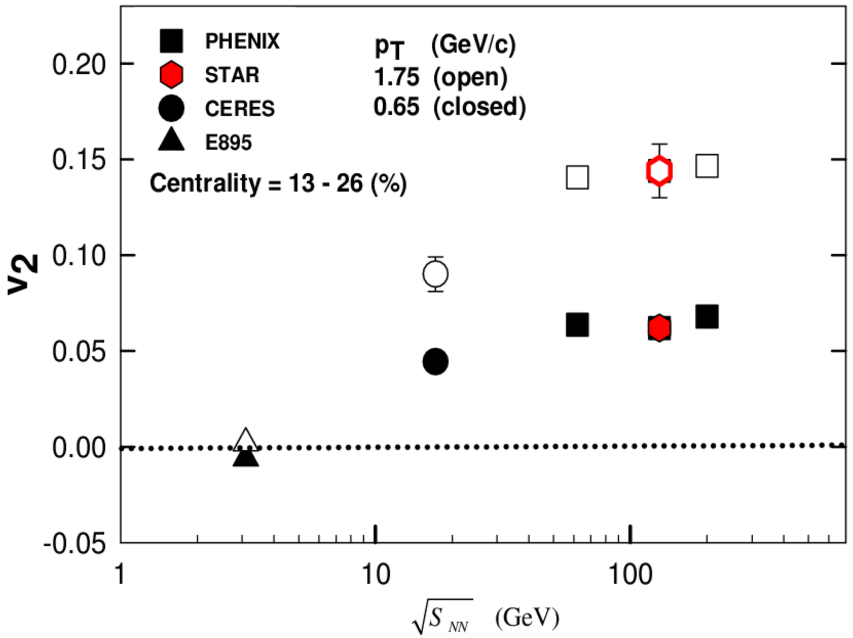
Beam Energy dependence of v_2 : Au+Au at 62.4 GeV Run10/Run4

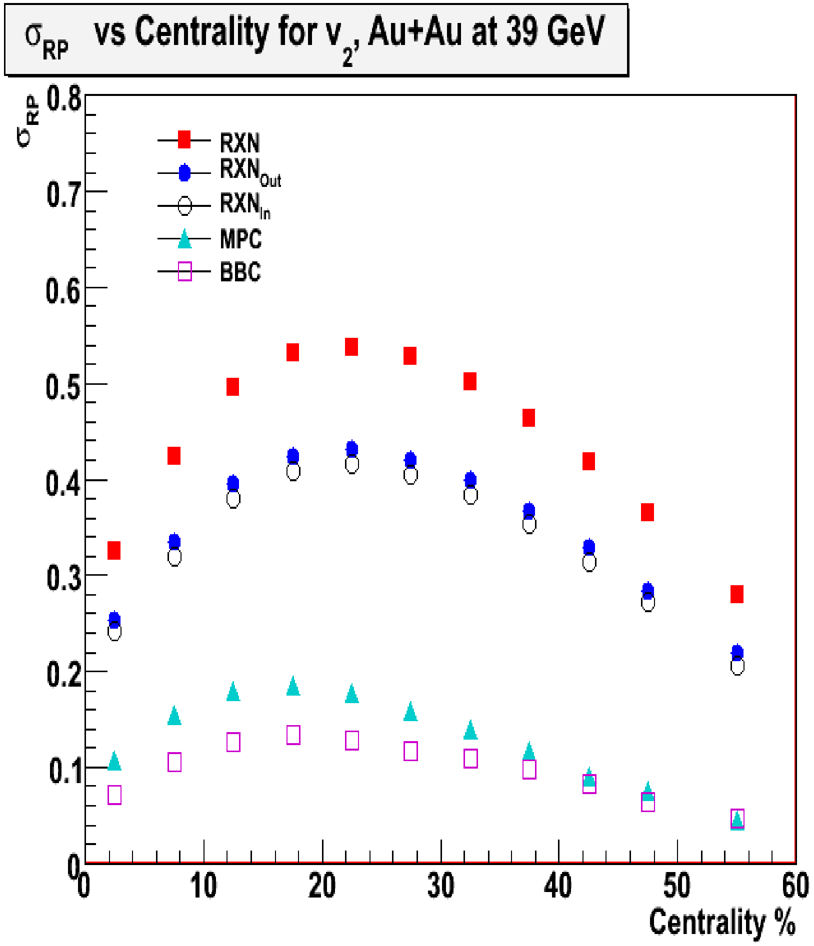




Significant improve in statistics:
Run10 [~500 M] / Run4 [~40 M]
and event plane resolution

Beam Energy dependence of v_2 : Au+Au at 39 GeV Run10





~200 M events: centrality/pT dependence of v2 for identified charged hadrons + scaling and comparison with 62.4-200 GeV data

Summary

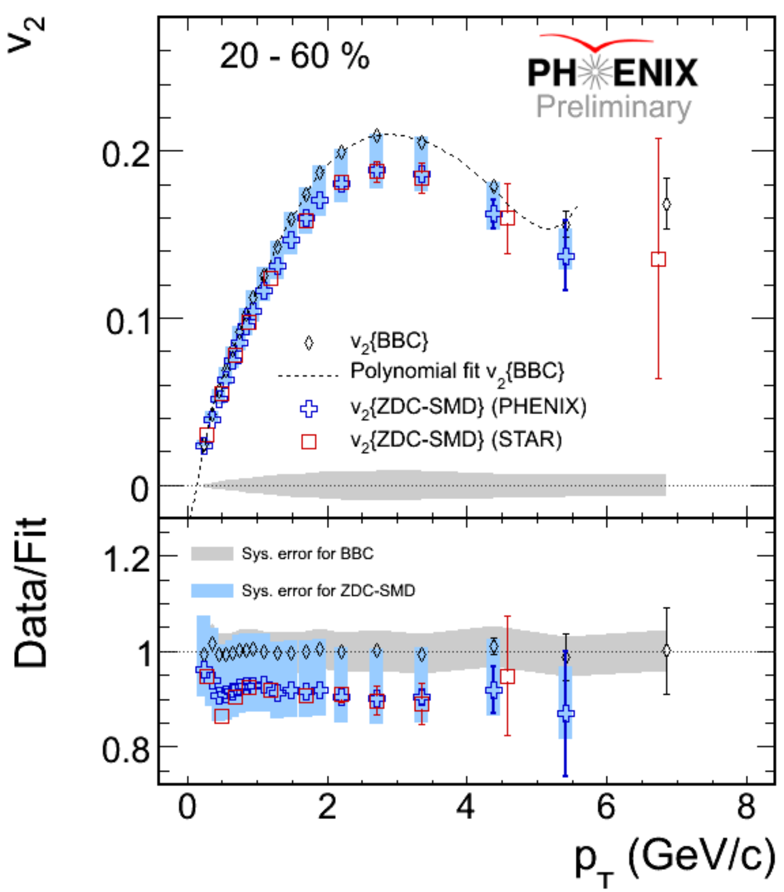
- There is good qualitative agreement between STAR/PHENIX for v_2 v_4 and scaling results.
- Reasonable quantitative agreement found for event plane results for V_2 (p_T , centrality) for charged hadrons from Au+Au collisions at 200 GeV:
  - ✓ PHENIX/PHOBOS and PHENIX/STAR [for mid-central collisions].
  - ✓ The difference in central collisions can be explained by a small difference in centrality definition
  - ✓ No evidence for a strong $\Delta\eta$ dependent non-flow contribution.
- Measurements compatible with a small value of η/s
- Universal scaling (KET + NCQ) of v_2 and higher harmonics below pT ~ 3 GeV/c implying partonic flow.
- Analysis of data from the initial RHIC low energy scan is well launched
-

!! Stay tuned for new results and implications for critical point !!

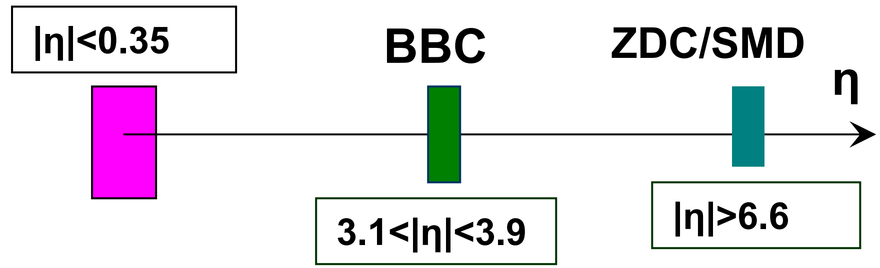
Backup Slides

Comparison $v_2(p_T$, centrality) PHENIX: BBC vs ZDC/SMD event plane

Phys. Rev. C 80, 024909 (2009)



H. Masui, Eur.Phys.J.C62:169-173,2009



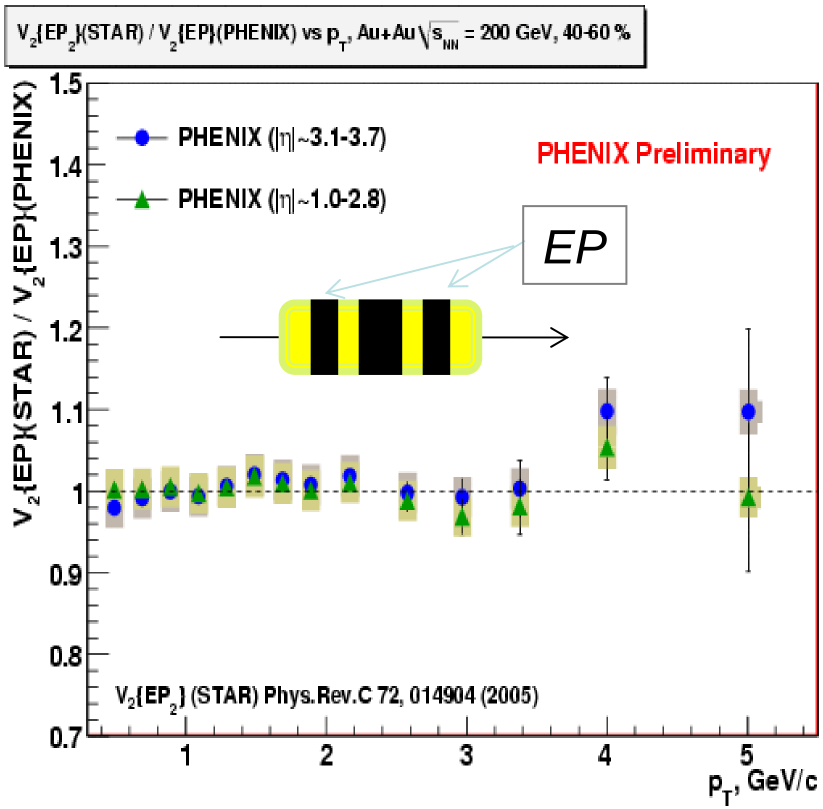
Ratio $R=V_2\{ZDC/SMD\}/V_2\{BBC\}$ does not depends on p_T [checked for 0-10,10-20,20-30,30-40,40-50,20-60%]

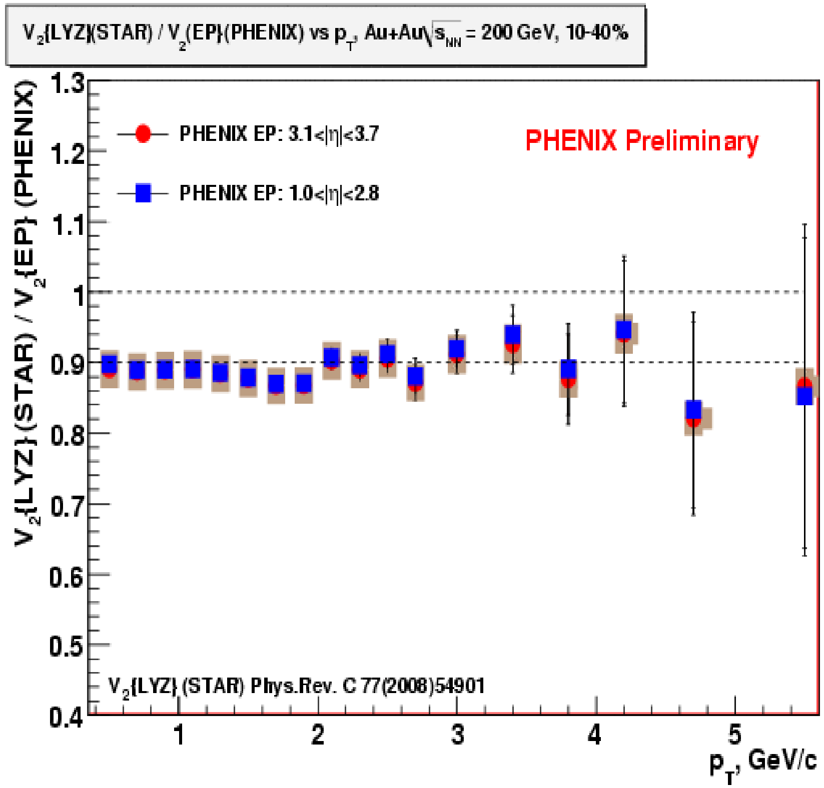
$V_2\{ZDC/SMD\} < V_2\{BBC\}$ – different fluctuations ?

Very large systematic errors for $V_2\{ZDC/SMD\}$ measurements – can we reduce them ?

Good agreement with prelim. STAR V_2 results from ZDC/SMD analysis

Agreement between RHIC measurements!





✓ *There is good agreement between experiments*

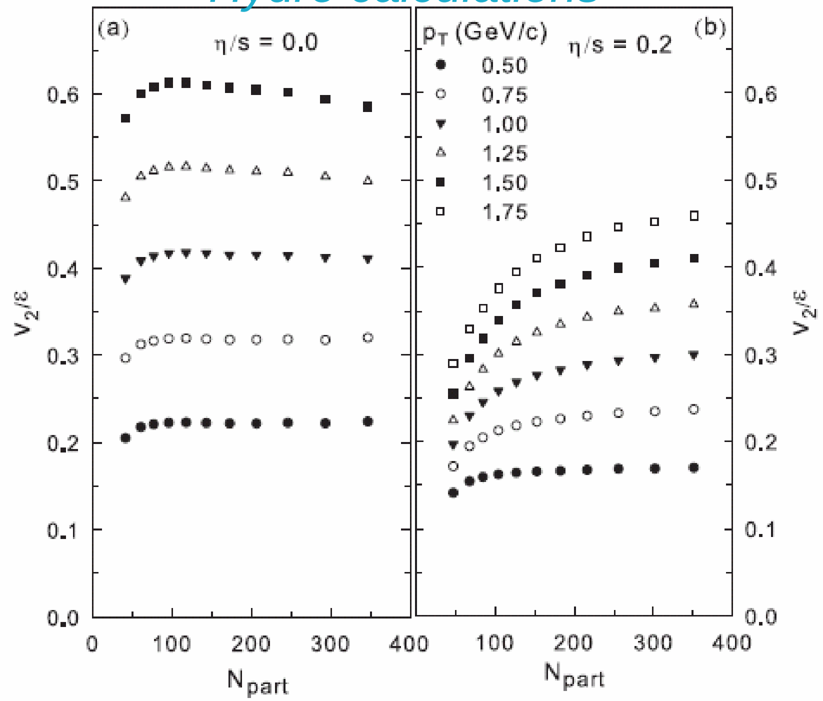
✓ *Consideration of fluctuations important when comparing different methods*

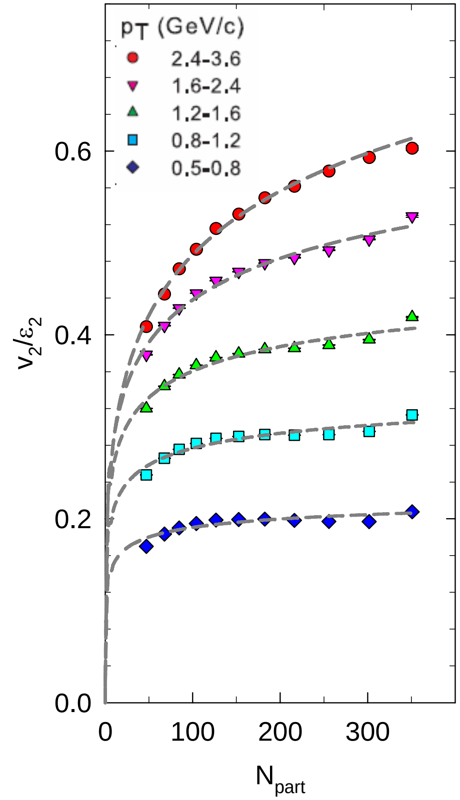
The results from different methods should Not be used as a measure of systematic error!

Further constraints for η/s

Data

Hydro calculations





l)

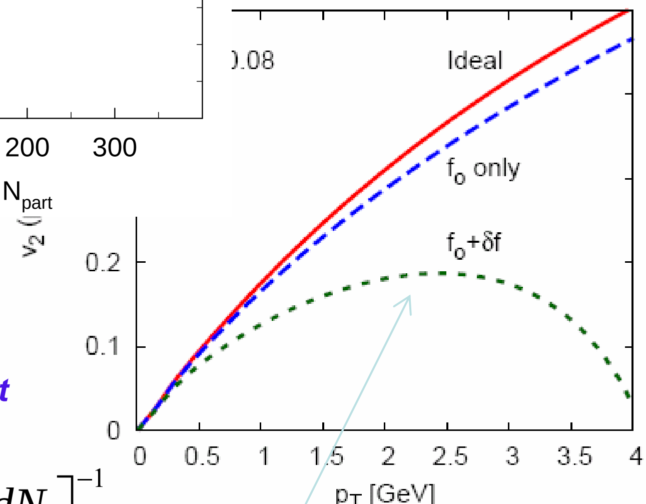
Constrained by data

$$(K\bar{R})\langle T\rangle c_s$$

data

on)

Lattice EOS



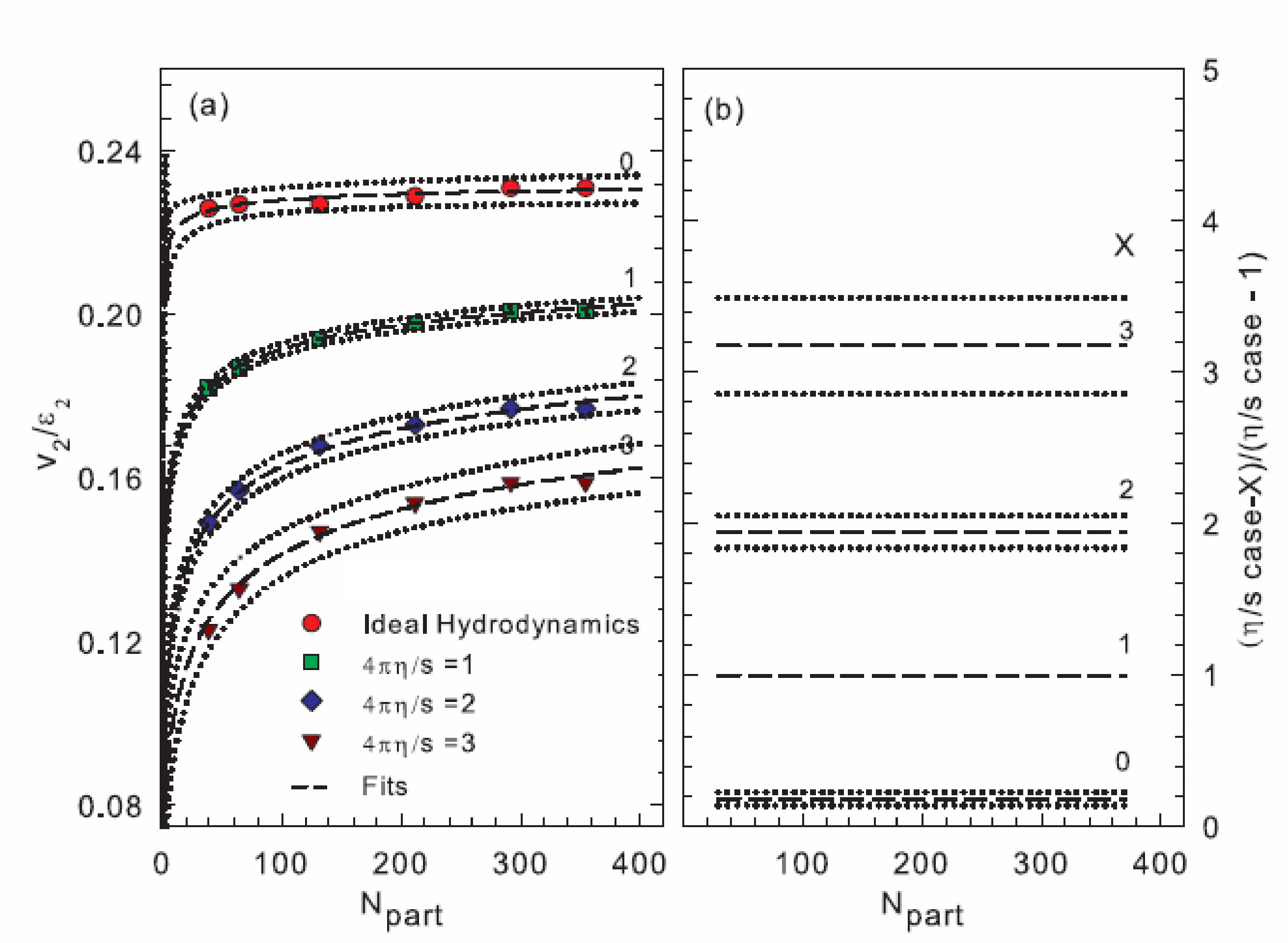
Viscous correction influence v_2/ε

Strategy → ***quantify viscous Corrections via a fitting procedure, to obtain K as a function of N_{part}***

$$\frac{v_{2k}(p_T)}{\varepsilon_{2k}} = \frac{v_{2k}(p_T)}{\varepsilon_{2k}}\left[\frac{1}{1+\frac{K^*(p_T)}{K_0}}\right]^k , \quad \left[K^*(p_T)\right] = \left[\beta(p_T)\frac{1}{S}\frac{dN}{dy}\right]^{-1}$$

$$K^*(p_T) = K + \frac{B}{T_f}\left(\frac{p_T}{T_f}\right)^{2-\alpha}$$

Proofing of the methodology

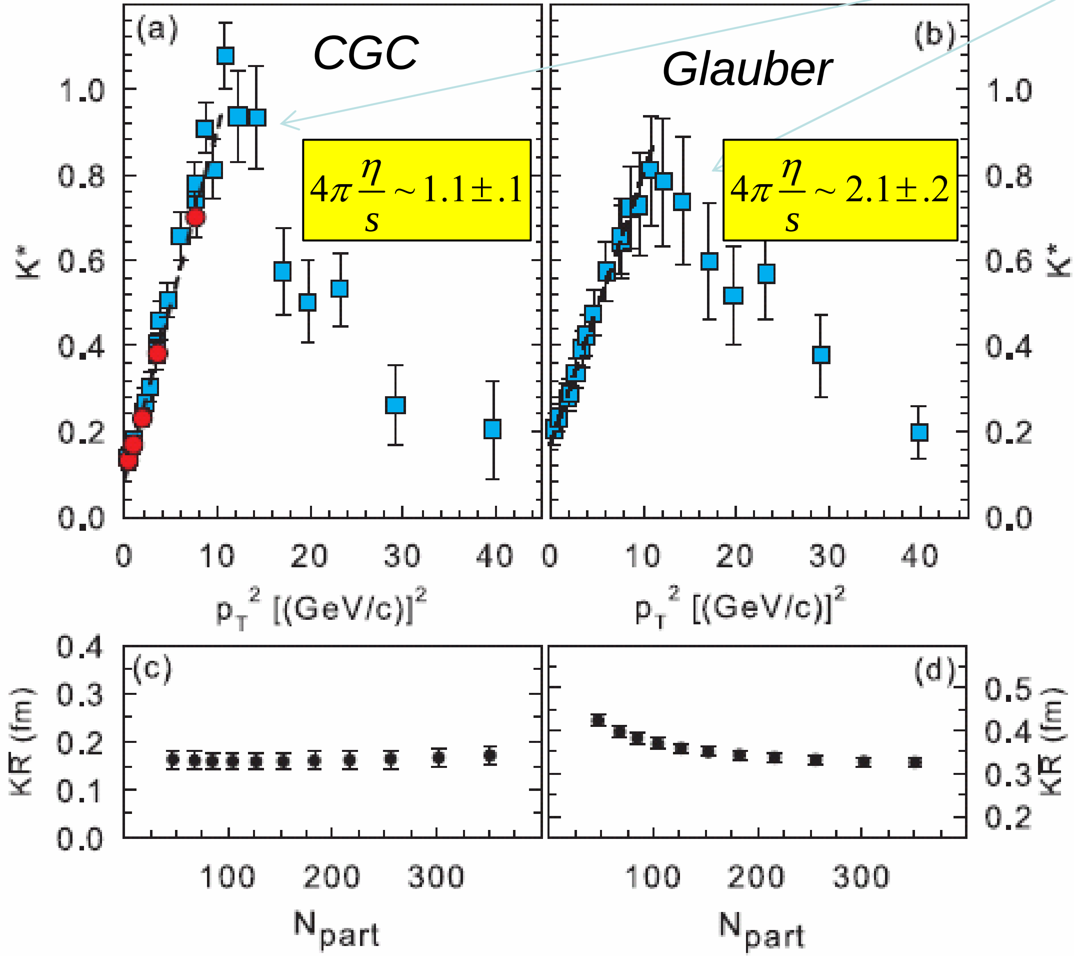


Methodology successfully proofed – very important

Viscous Corrections

Onset of suppression!

arXiv:1005.4979



Plasma viscosity is > 0

$$K^* = K + \frac{B}{T_f}\left(\frac{p_T}{T_f}\right)^{2-\alpha}$$

$\alpha = 2$

$T_f \sim 165 \pm 11$ MeV

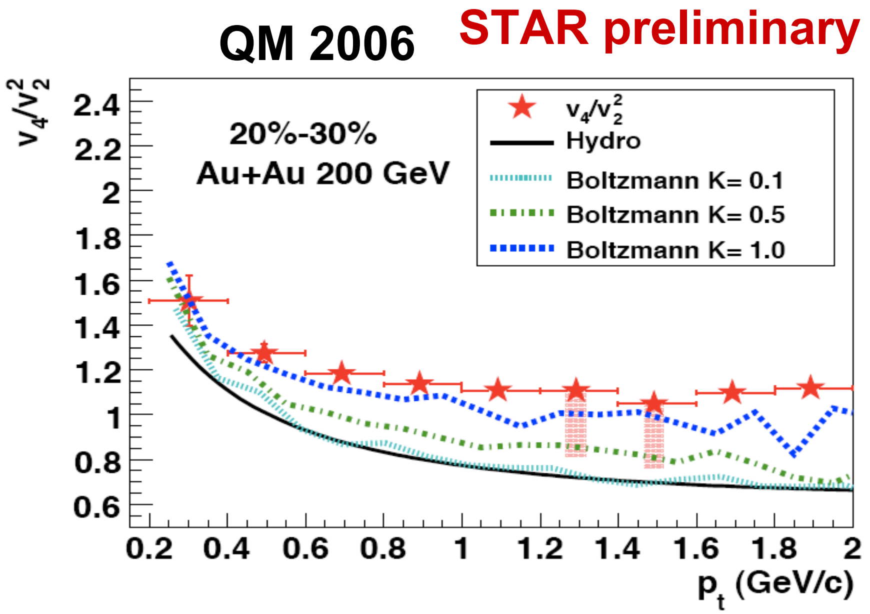
$\langle c_s \rangle \sim 0.47 \pm .03$ c (lattice)

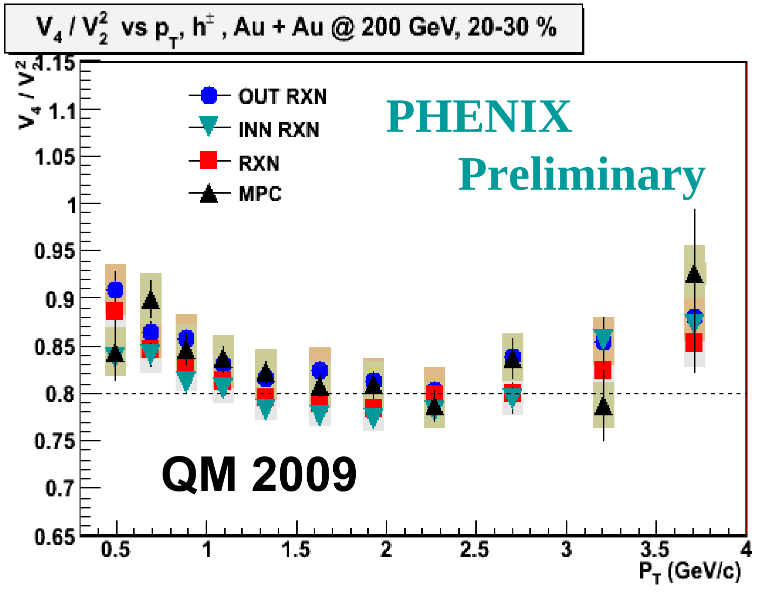
$\frac{\zeta}{s}$ is small

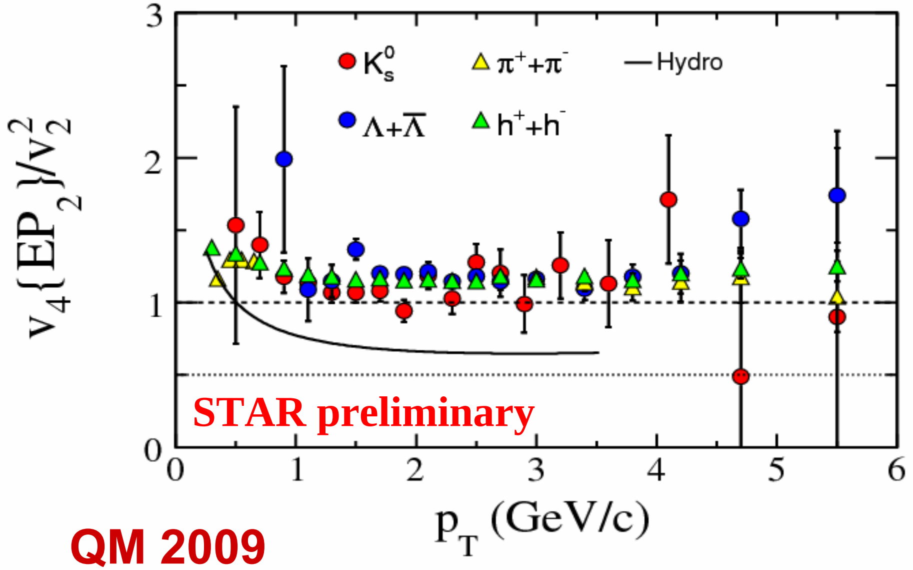
$\lambda \sim 0.2$-0.3 fm

- ***Quadratic dependence of δf***
- ***Breakdown of hydrodynamic ansatz for K* ~ 1***
- ***Onset of jet suppression***

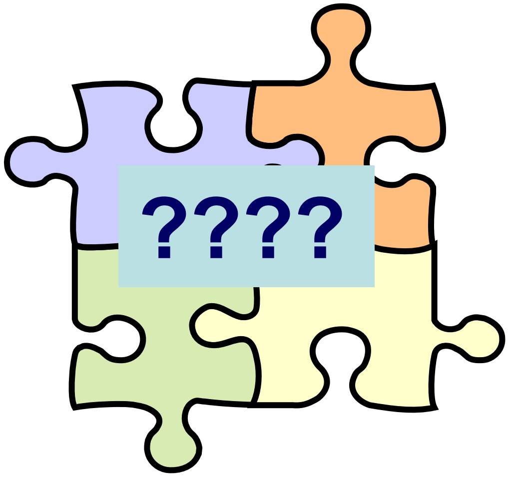
Comparison of integral flow results from different methods …





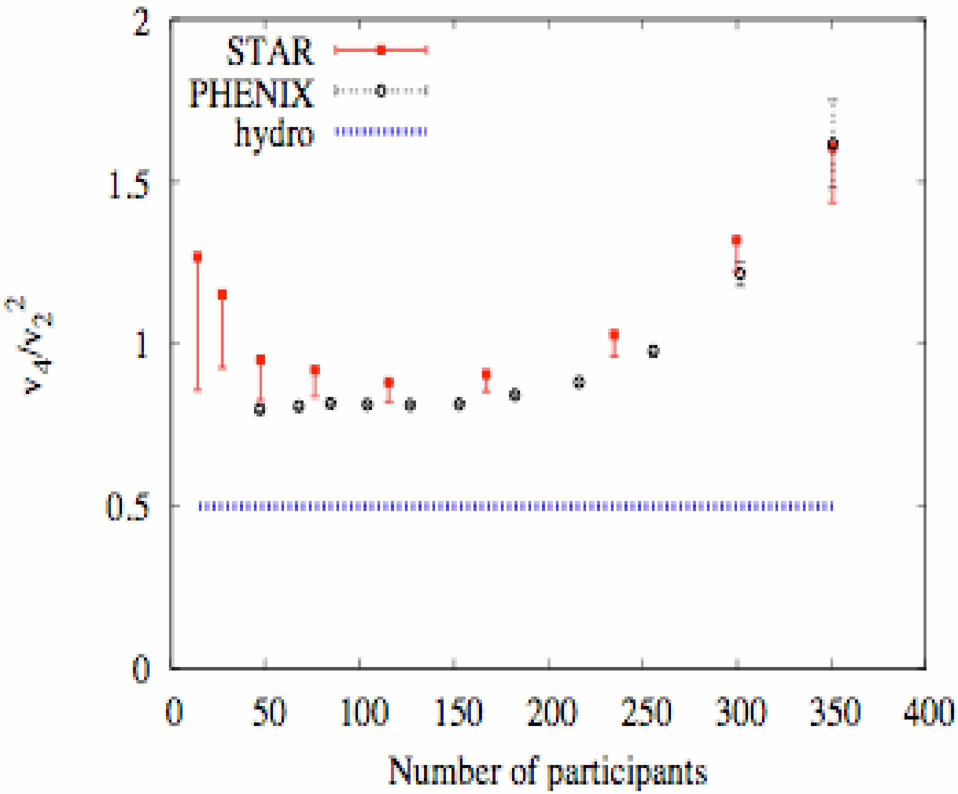


QM 2009

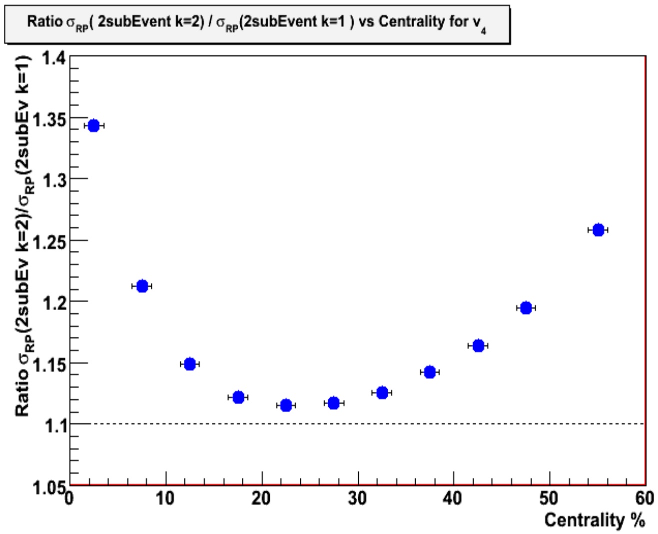


Centrality dependence of $V_4 / (V_2^2)$ ratio STAR/PHENIX

C. Gombeaud, J-Y Ollitrault [arXiv:0907.4664]



STAR/PHENIX Preliminary data for charged hadrons: p_T = 1.0-2.7 GeV/c for STAR p_T=1.0-2.4 GeV/c for PHENIX – looks very close



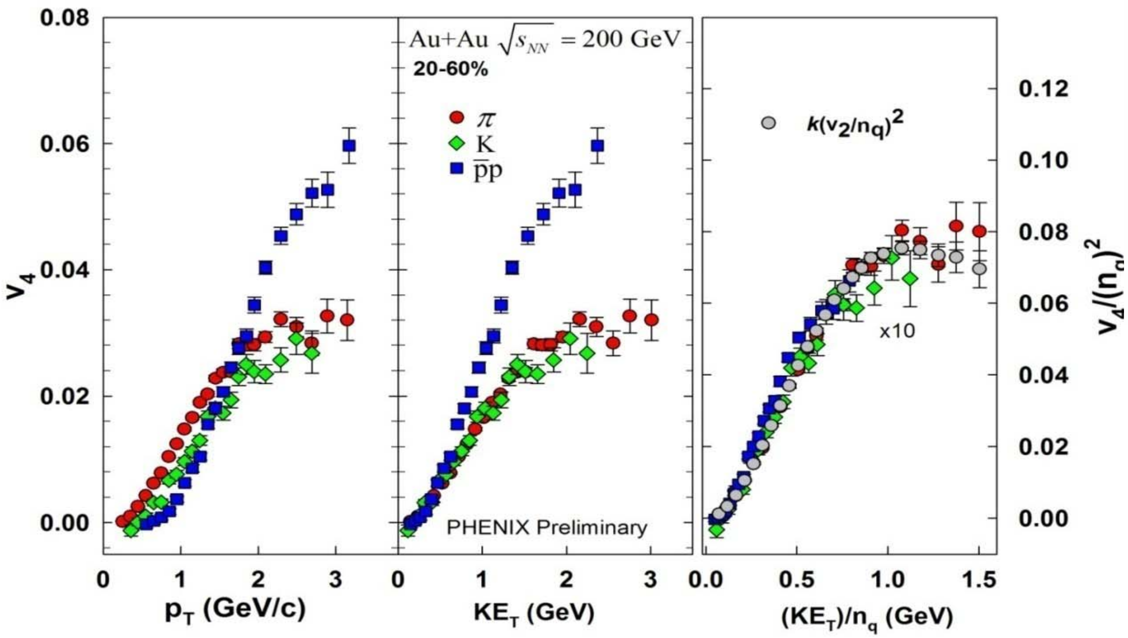
What about $V_6 \sim k * (V_2^3)$ – very-very small signal …..???

The potential difference in methods for event plane resolution [for v_4 measurements] may explain the residual difference in $v_4/(v_2^2)$ ratios

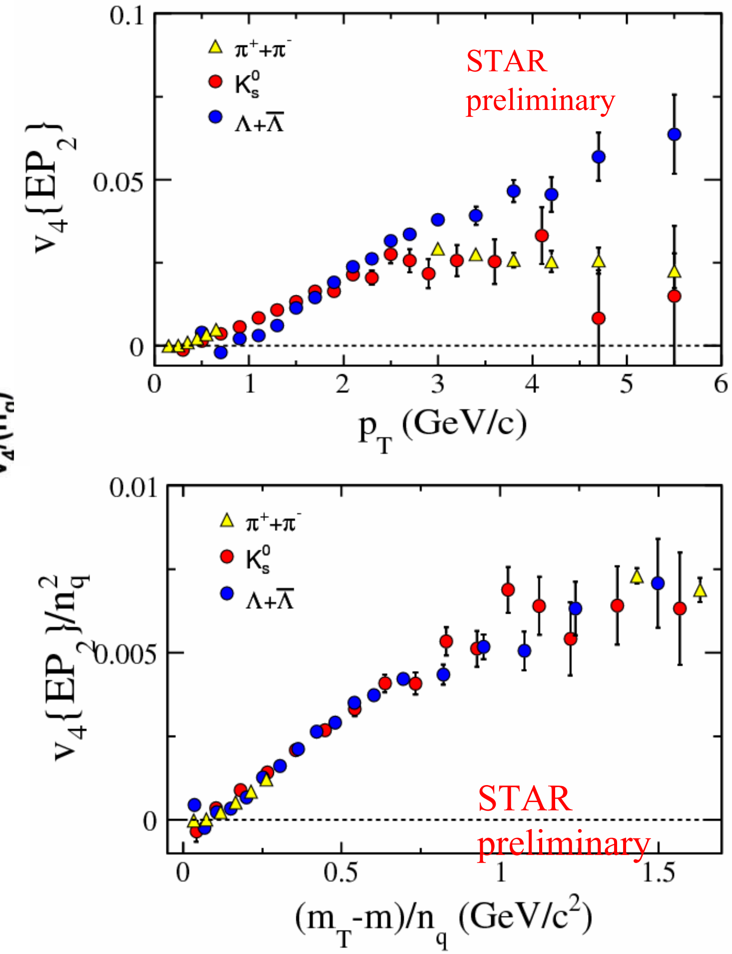
V_4 : A Small, But Sensitive Observable For Heavy Ion Collisions

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!!!