Summary of STAR Flow Results

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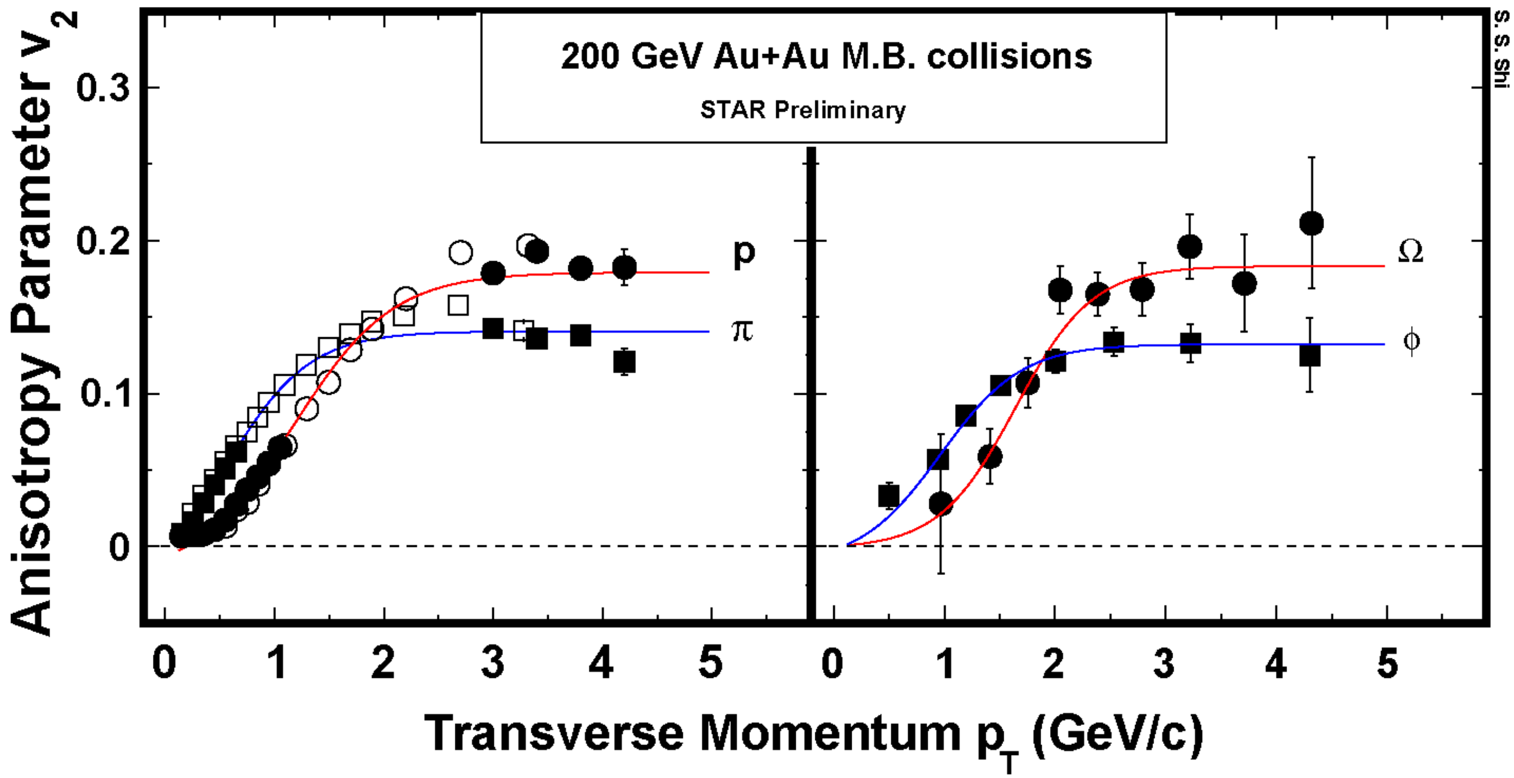
Topics Covered :

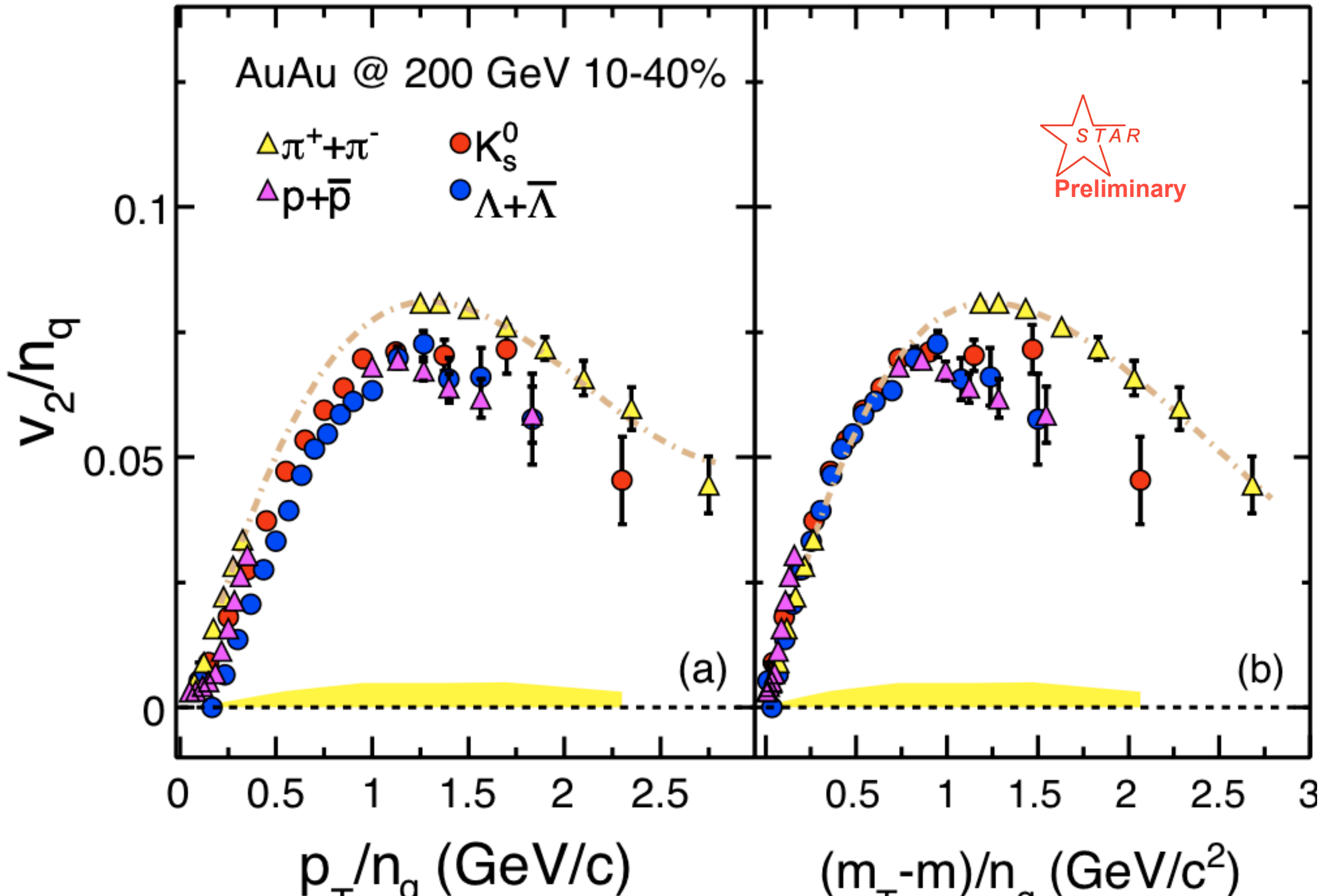
- NCQ scaling – A Close Look.
- Knudsen Fit of Identified Particle v_2.
- Directed Flow of Identified Particles.

The Success of NCQ scaling



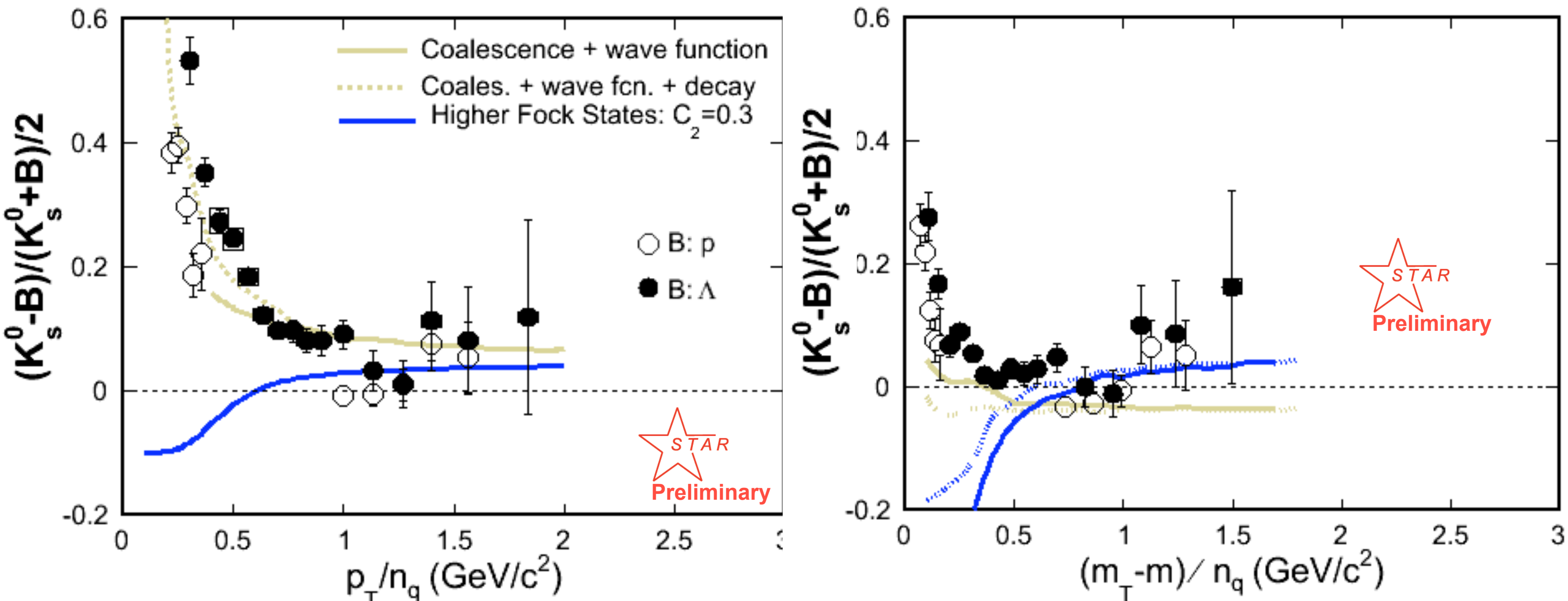
PHENIX π and p: nucl-ex/0604011v1
NQ inspired fit: X. Dong et al. Phy. Let. B 597 (2004) 328-332

Time to Take a Close Look



New results with a forward reaction plane detector (FTPC) which reduces systematic uncertainties. Best available data-set for studying NCQ scaling.

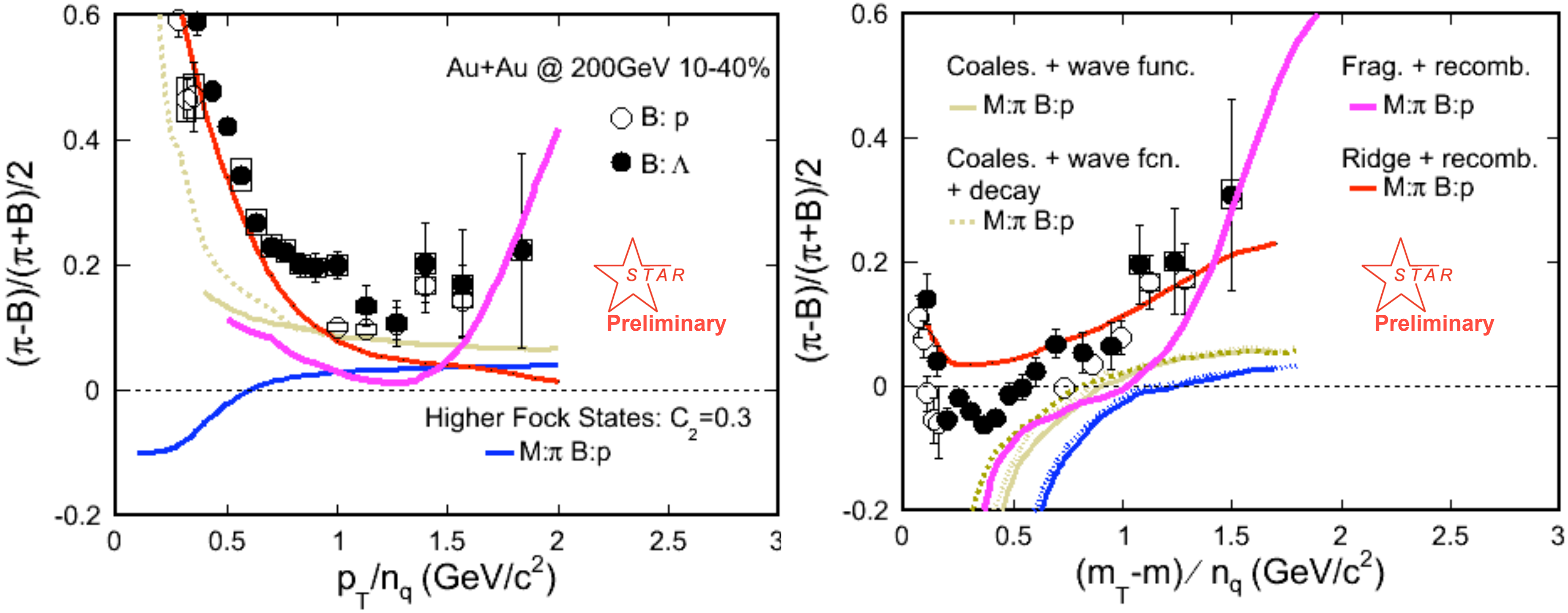
A Close Look at the NCQ Scaling



Curves : V.Greco and C.M.Ko, PRL 70 024901 (2004); B. Muller, R.J.Fries and S.A.Bass, PLB 618 77 (2005)

Models with realistic effects describe the difference between kaons and baryons well.

A Close Look at the NCQ Scaling



Curves : V.Greco and C.M.Ko, PRL 70 024901 (2004); B. Muller, R.J.Fries and S.A.Bass, PLB 618 77 (2005)
C.B.Chiu, R.C. Hwa and C..B. Yang, PRC 78 044903 (2008), R.J. Fries, B.Muller, C. Nonaka and S.A. Bass, PRC 68 044902 (2003)

In the range of $0.5<p_T/n_q<1.5$ (GeV/c), the deviation between pions and baryons is ~20%, while models with realistic effects can tolerate up to only 5-10%.

Summary so far :

• **NCQ scaling is more complicated than it appears to be. Models with realistic effects cannot explain the deviation between pions and baryons.**

Thermalization and Flow

What is thermalization ?

Equal partition of energy.

How is the thermalization achieved ?

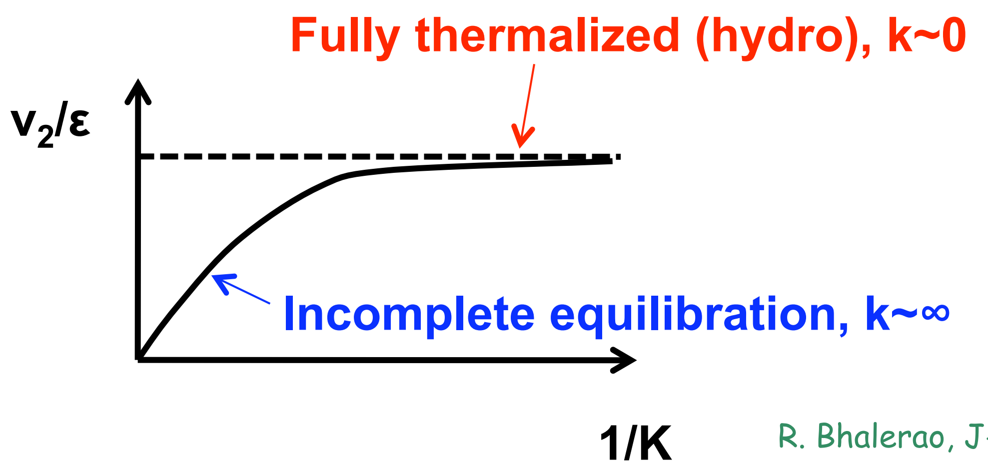
Interactions !

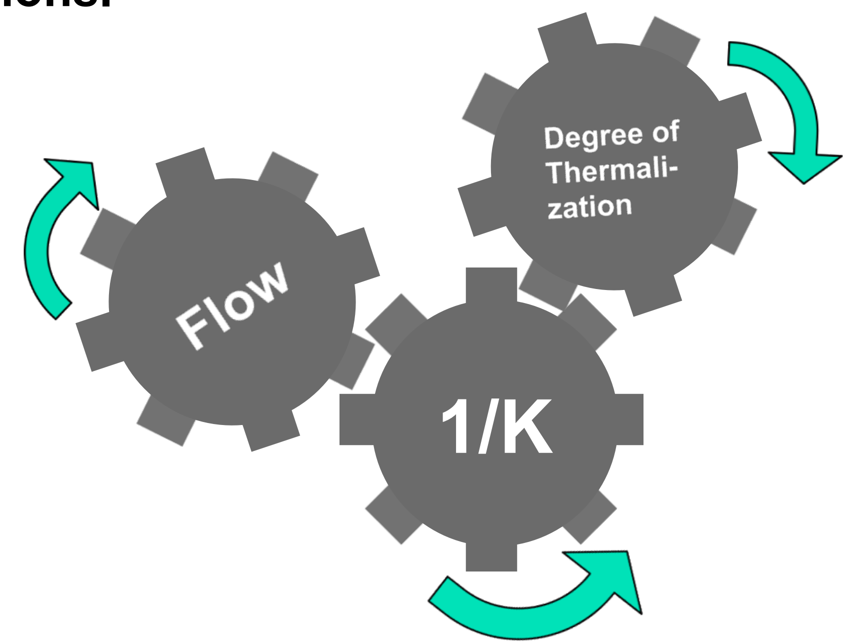
How do we address the degree of thermalization ?

Knudsen number ($K=\lambda/R$), $1/K$ ~ # of collisions.

What observable is sensitive to 1/K ?

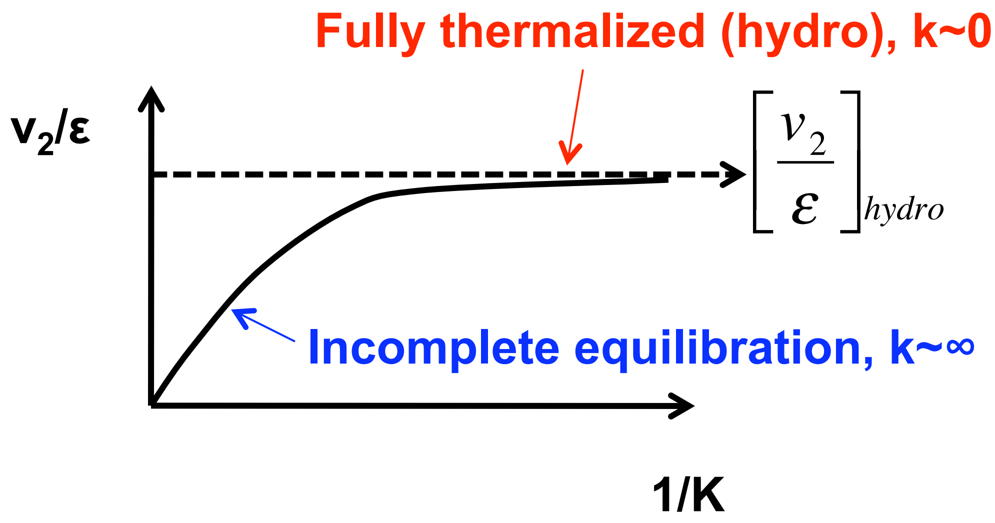
Flow !





R. Bhalerao, J-P Blaizot, N.Borghini and J-Y Ollitrault, PLB 627 49 (2005)

How do we measure 1/K ?



$$1-\left[\frac{v_2}{\varepsilon}\right]\Big/\left[\frac{v_2}{\varepsilon}\right]_{hydro} \propto K$$

When K is small (Hydro Limit)

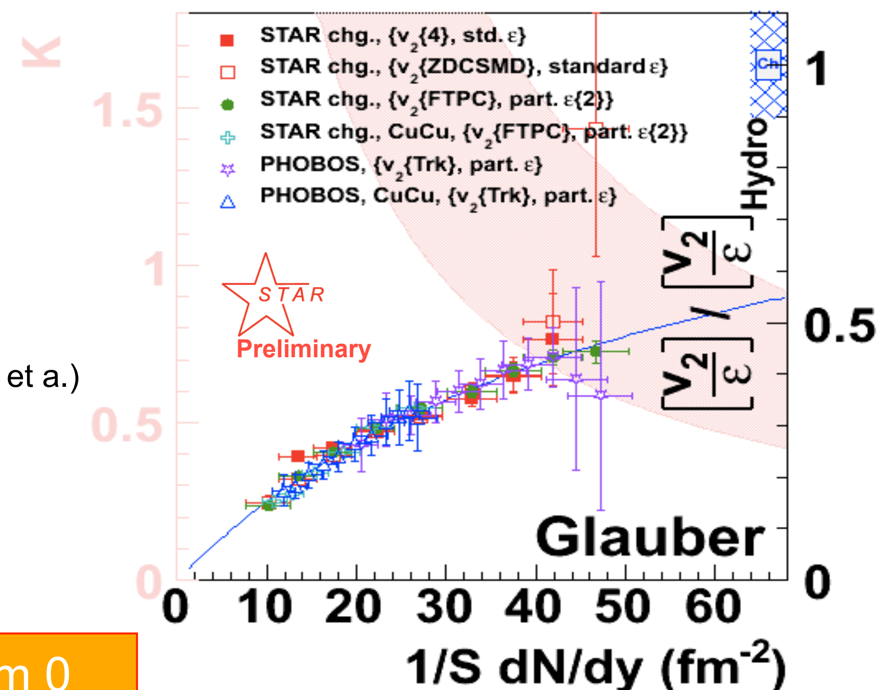
$$\left[\frac{v_2}{\varepsilon}\right]\Big/\left[\frac{v_2}{\varepsilon}\right]_{hydro} \propto 1/K$$

When K is large (Low Density Limit)

$$\left[\frac{v_2}{\varepsilon}\right]\Big/\left[\frac{v_2}{\varepsilon}\right]_{hydro} = \frac{1}{1+K/K_0}$$

$K_0 = 0.7$ from both AMPT and 2-D transport model (Ollitrault et a.)

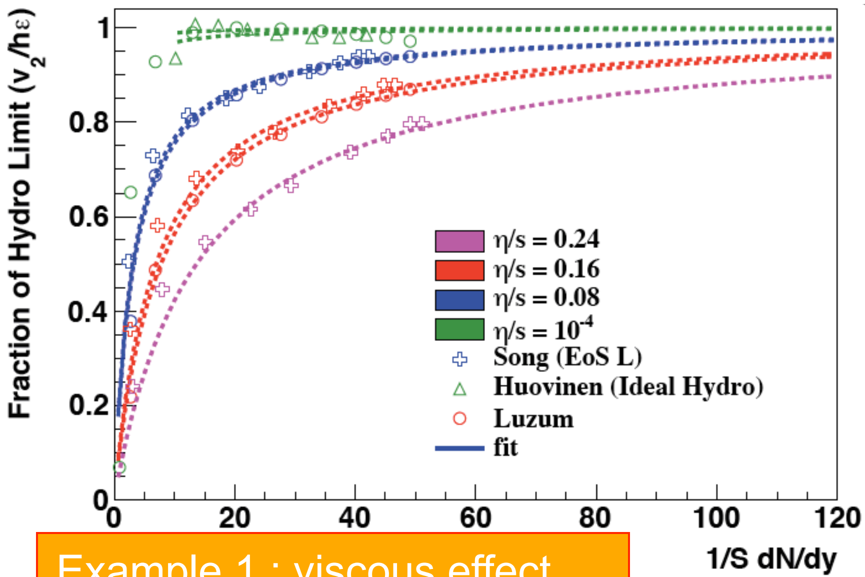
$$\frac{1}{K} = \frac{R}{\lambda} = \sigma c_s \frac{1}{S}\frac{dN}{dy}$$



Knudsen number is considerably away from 0 (K=0 is required by ideal Hydro.)

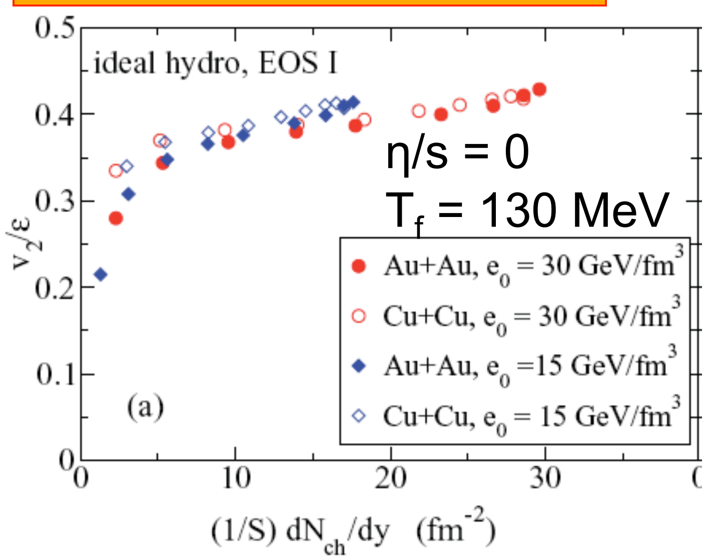
Through this talk, $[v_2/\varepsilon]_{hydro}$ denotes the saturated value extracted from Knudsen fitting.

Side Remarks with Knudsen Fit

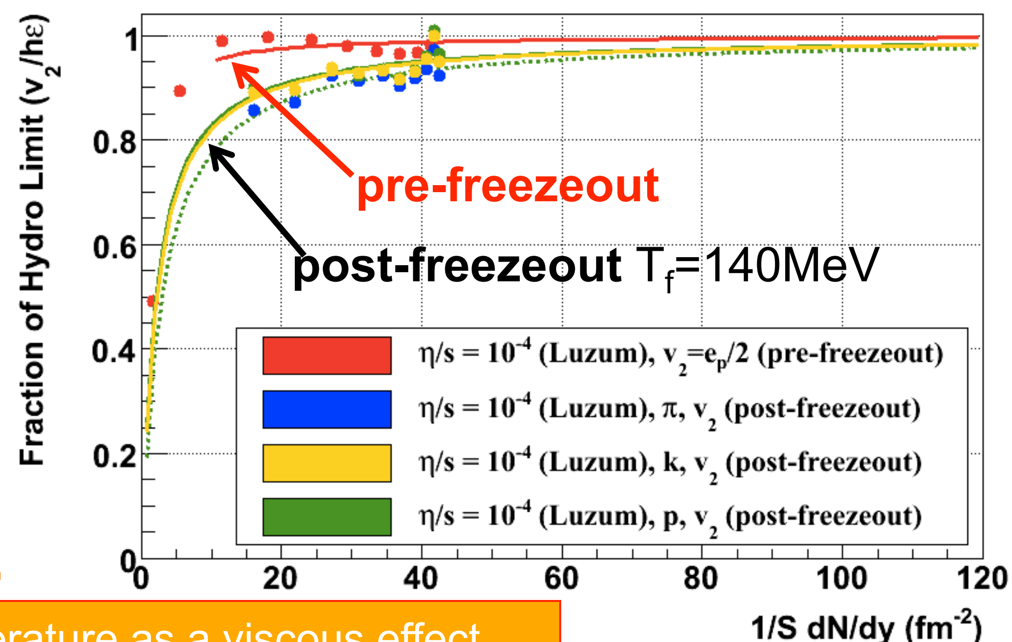


- The Knudsen Fit gives us the **effective** η/s. Any effect that contributes to the curvature of v_2/ε vs. 1/S dN/dy will be captured as viscosity – **an upper limit on η/s.**

Example 1 : viscous effect.



H. Song and U. Heinz, PRC 78 024902 (2008)



Example 2 : Freeze-out at finite temperature as a viscous effect.

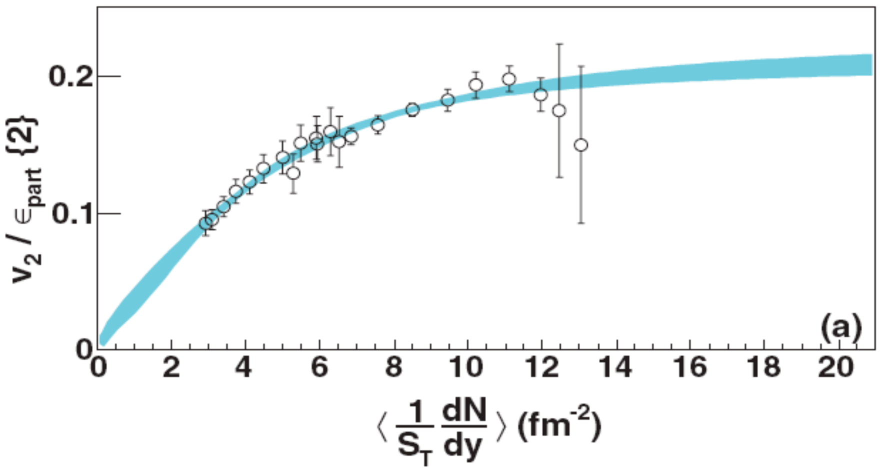
Side Remarks with Knudsen Fit

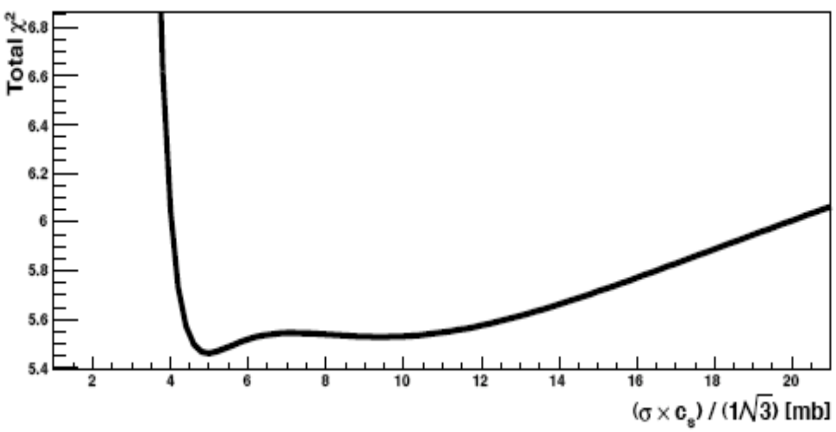
- We all agree that we have to be very careful with Knudsen Fit (Nagle, Steinberg and Zajc, PRC 81, 024901):
  - The mixture ratio (x) between N_bin and N_part we used is 0.14 (PHOBOS used 0.13)
  - We use fMCKLN, which has the fluctuation folded in and can produce dN/dy well.
  - The correlated error are propagated according to the standard procedure in pdg book.
  - We have tried different formula (but not the Pade formula for a reason – see next slides) to fit our data and examined χ^2 distributions.

  … …

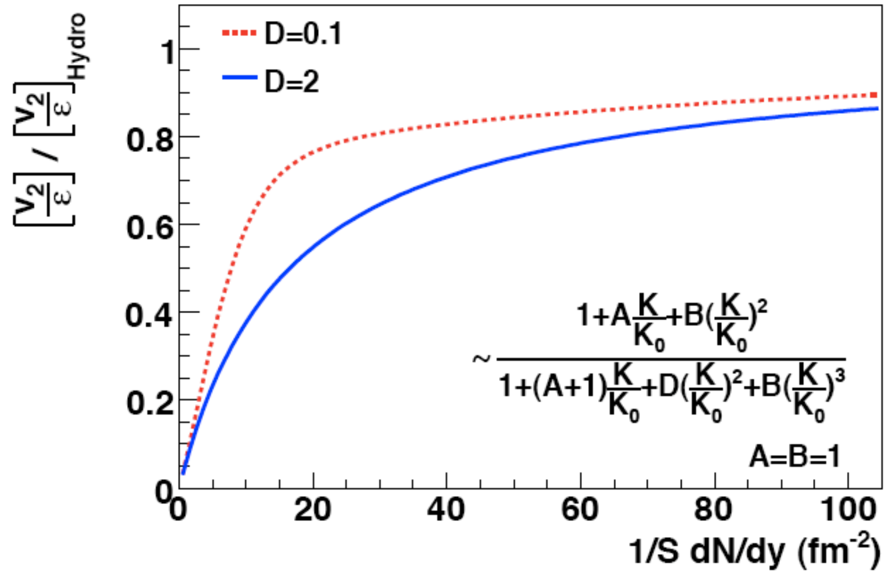
  – All of the above have been included in the systematics of results shown at QM09.

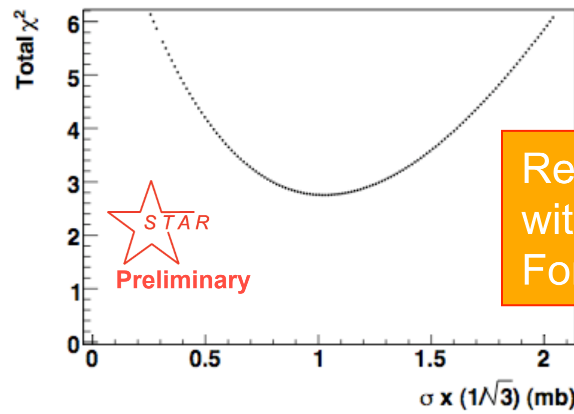
Side Remarks on Pade Formula





J. Nagle, P. Steinberg and W. Zajc, PRC 81 024901 (2010)



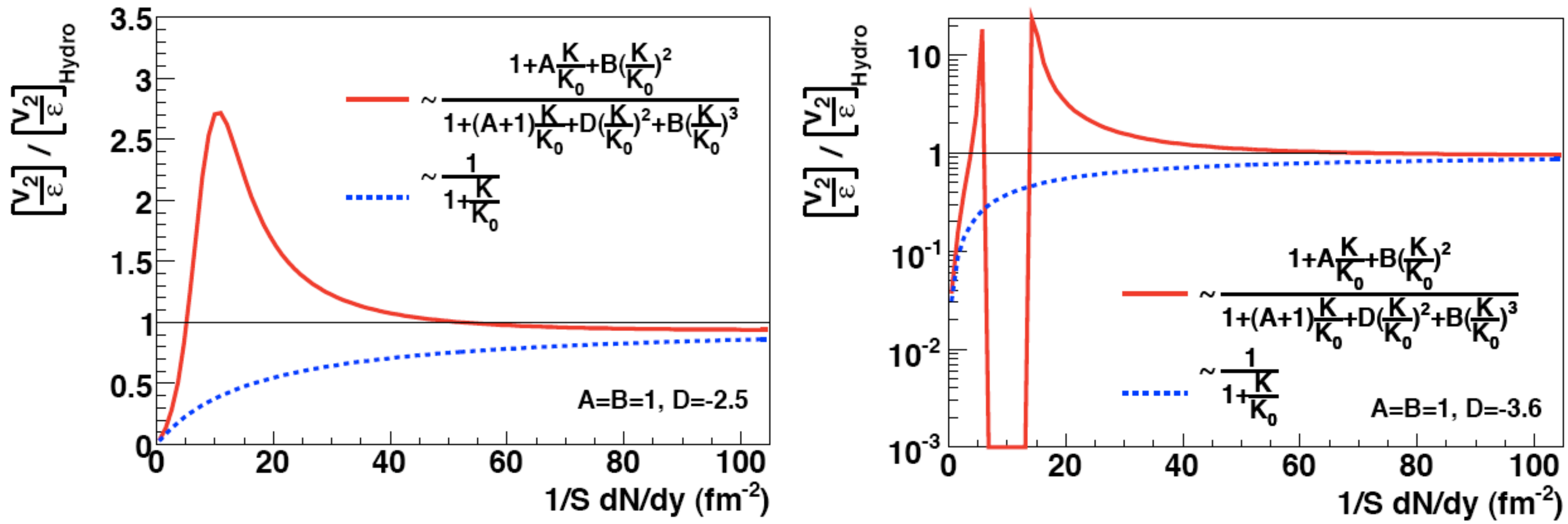


Reasonable χ^2 with J.-Y. Formula.

Pade formula has been used to demonstrate the "Fragility" of Knudsen fit.

Technically, this can be understood as, similar to the $\sigma * c_s$, the coefficient of the higher order terms can also change the curvature ➔ No reliable, simultaneous constraint on D and $\sigma * c_s$.

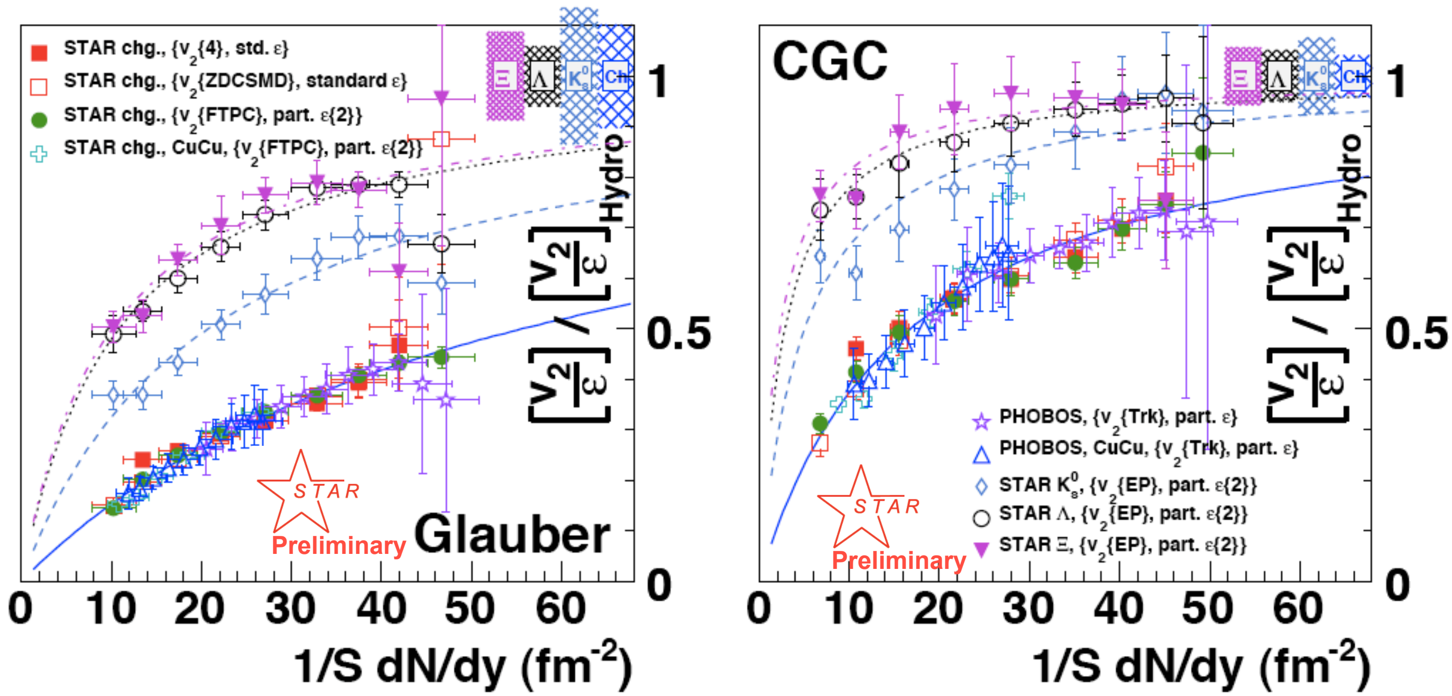
Side Remarks on Pade Formula



The Pade formula violates the boundary condition.

The Pade formula exhibits wiggling structures at the region where a smooth curvature should be expected.

What causes the mass hierarchy of curvature ?



The heavier the mass, the larger the curvature.

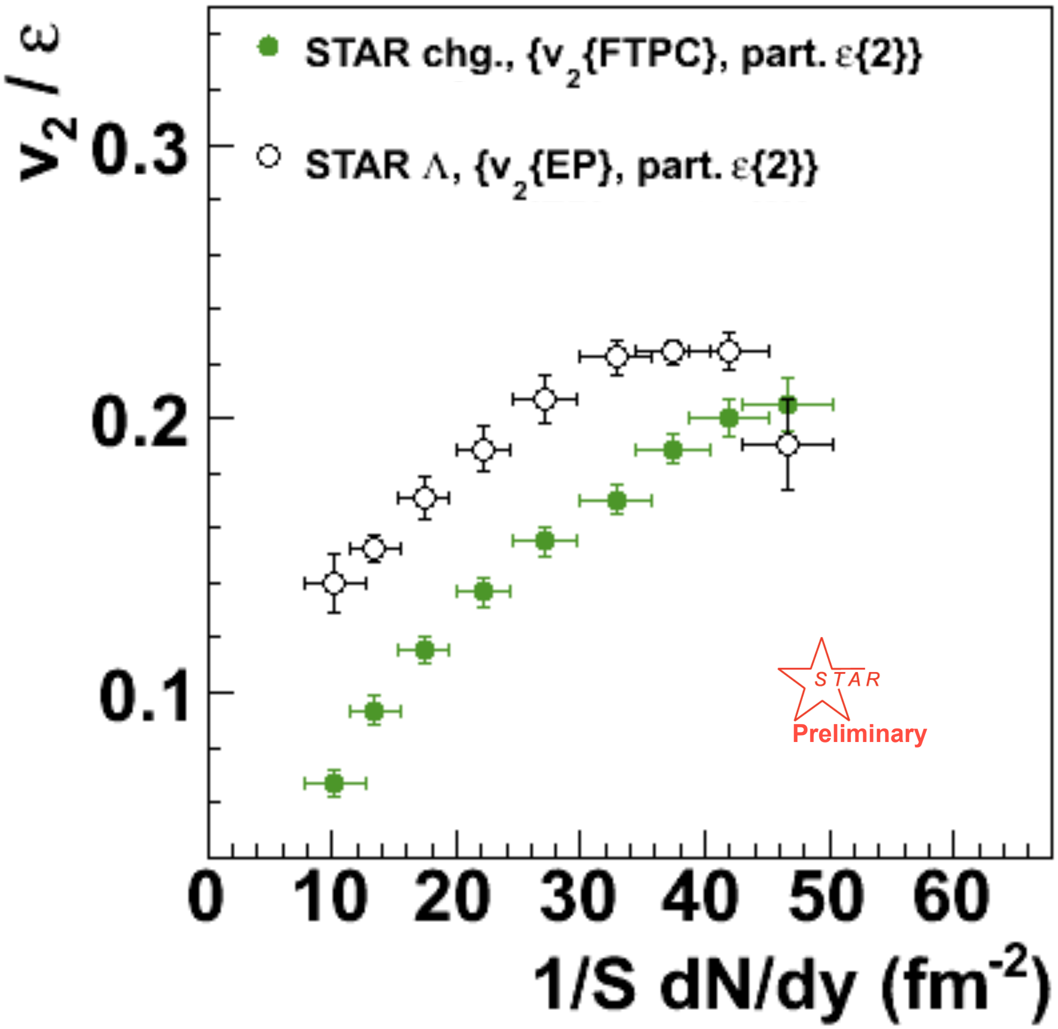
Ideal hydro[1] does not have the mass hierarchy of the curvature, adding the viscous effect[1] and hadronic rescattering[2] gives the opposite order of the mass hierarchy (see later slides).

So far only AMPT gives the right order of mass hierarchy of curvature.

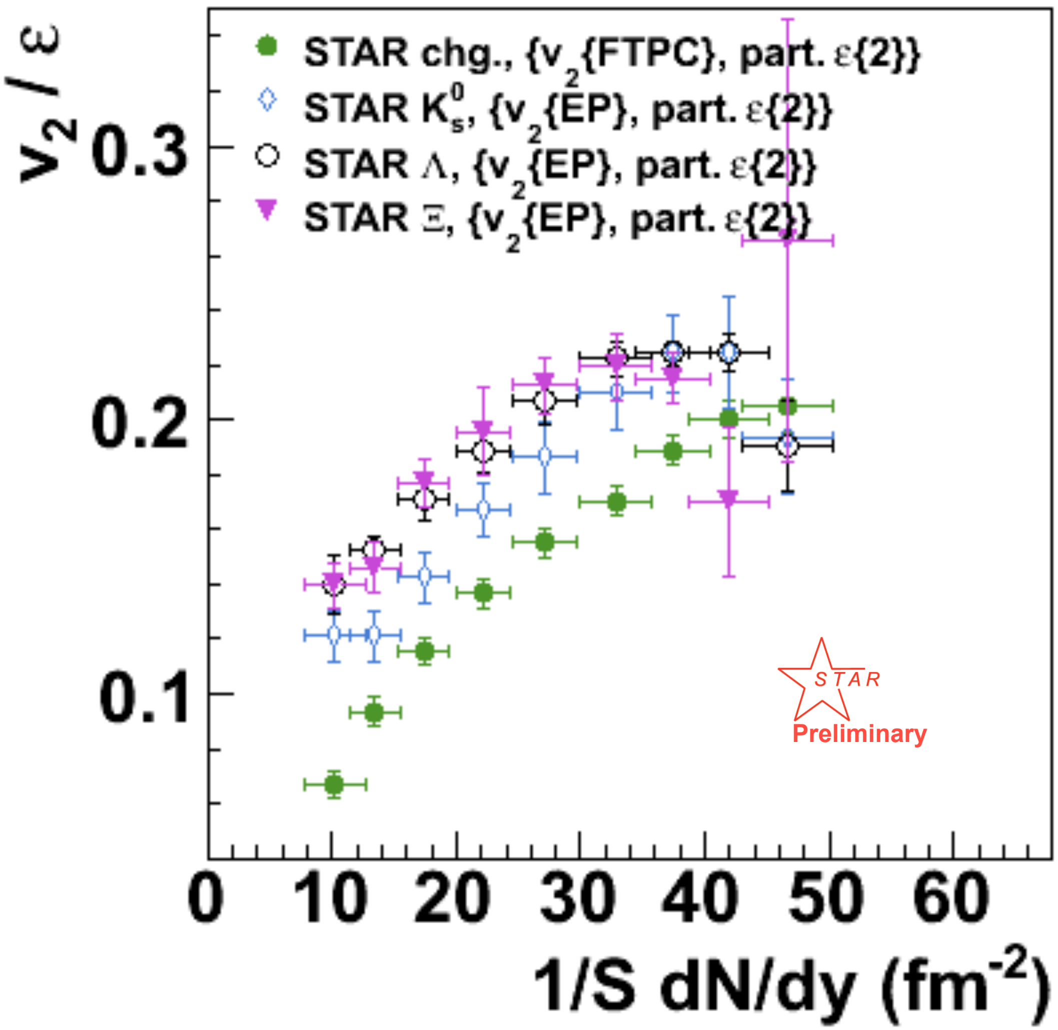
Note : Through this talk, $[v_2/\varepsilon]_{hydro}$ denotes the saturated value extracted from Knudsen fitting, it is not necessarily the same as limits from various hydro models.

1. Luzum & Romatschke, private communication
2. Hirano, private communication

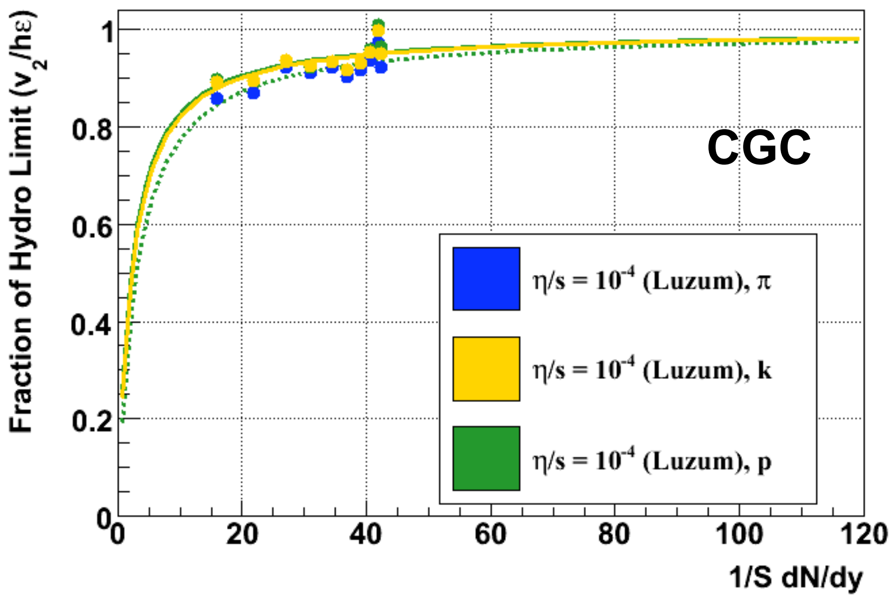
The mass hierarchy can be seen w/o K fitting

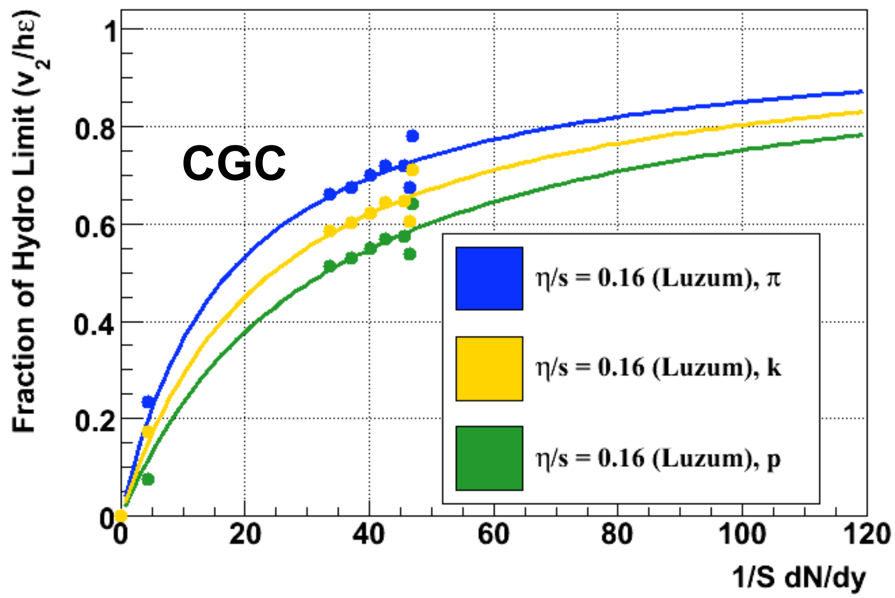


The mass hierarchy can be seen w/o K fitting



Can hydro explain the mass hierarchy of curvature ?

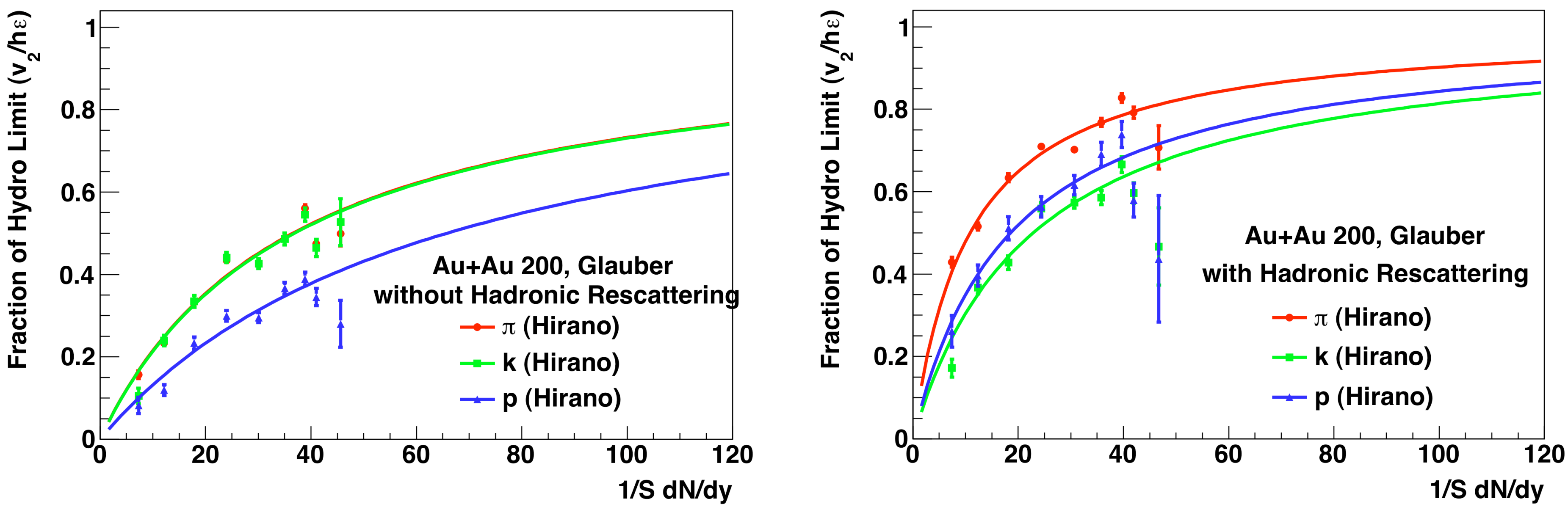




Ideal Hydro does not have the mass hierarchy of curvature.

Viscous Hydro gives the opposite order of mass hierarchy of curvature.

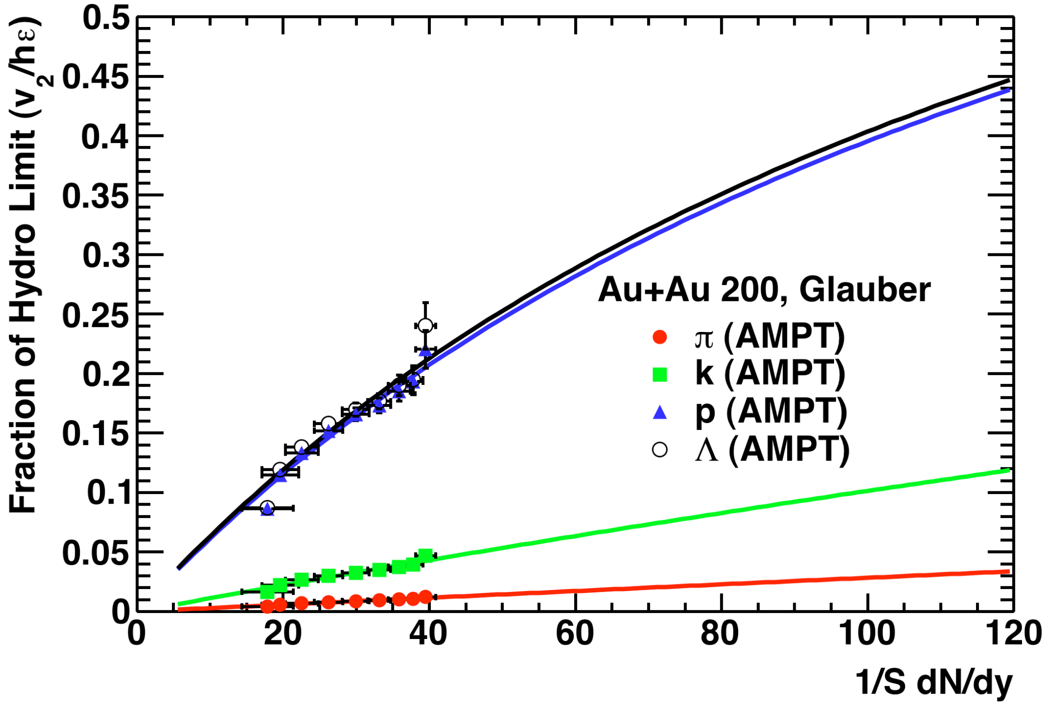
Can the hadronic rescattering explain the mass hierarchy of curvature ?



Plot courtesy : N. Li

Hadronic rescattering gives the opposite order of mass hierarchy of curvature.

What does AMPT say ?



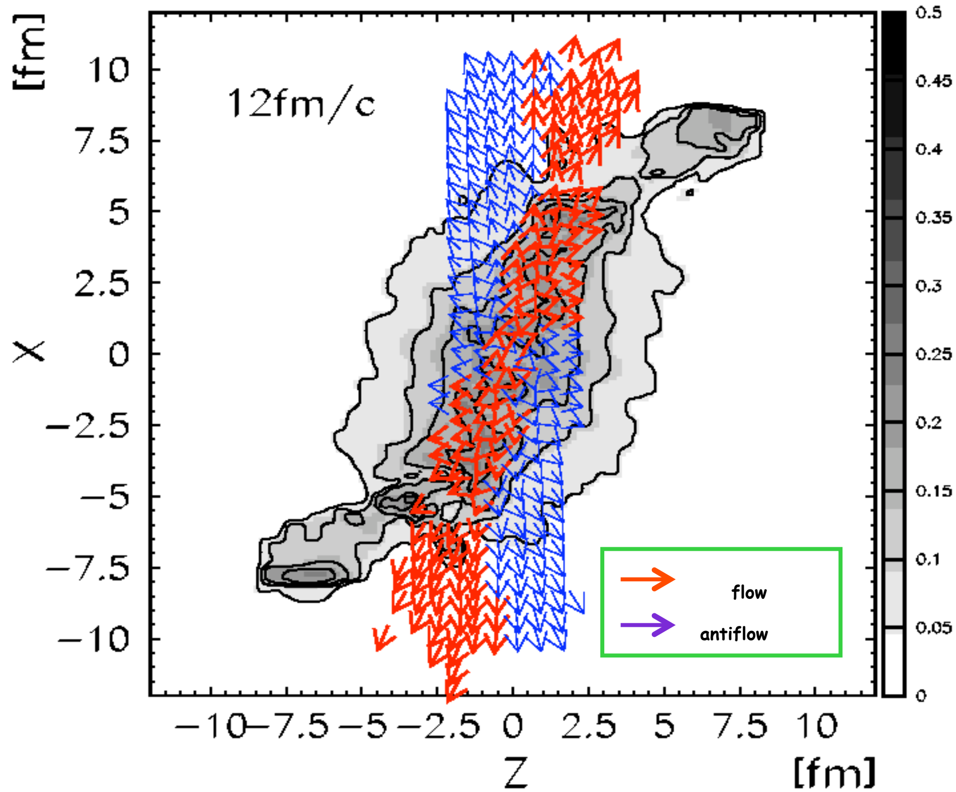
Plot courtesy : N. Li

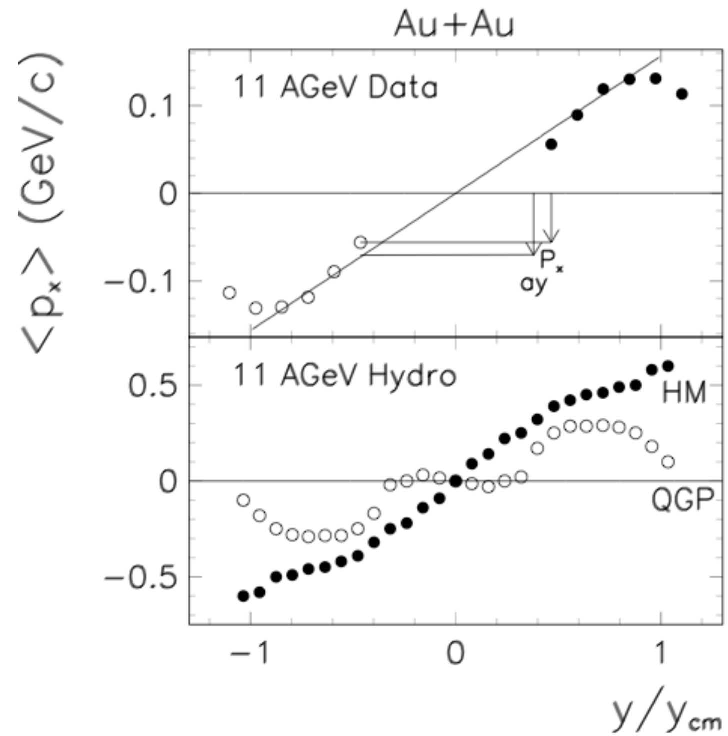
So far for models checked, only AMPT has the right order of mass hierarchy of curvature.

Summary so far :

- Knudsen Fit gives the upper limit of η/s
- The heavier the particle, the more curvature is seen in the plot of v_2/ε scaled by its saturation value, as a function of 1/S dN/dy. Such feature is not seen in Hydro models (ideal or viscous/hybrid), but is seen in AMPT.

Anti-flow / 3rd flow component

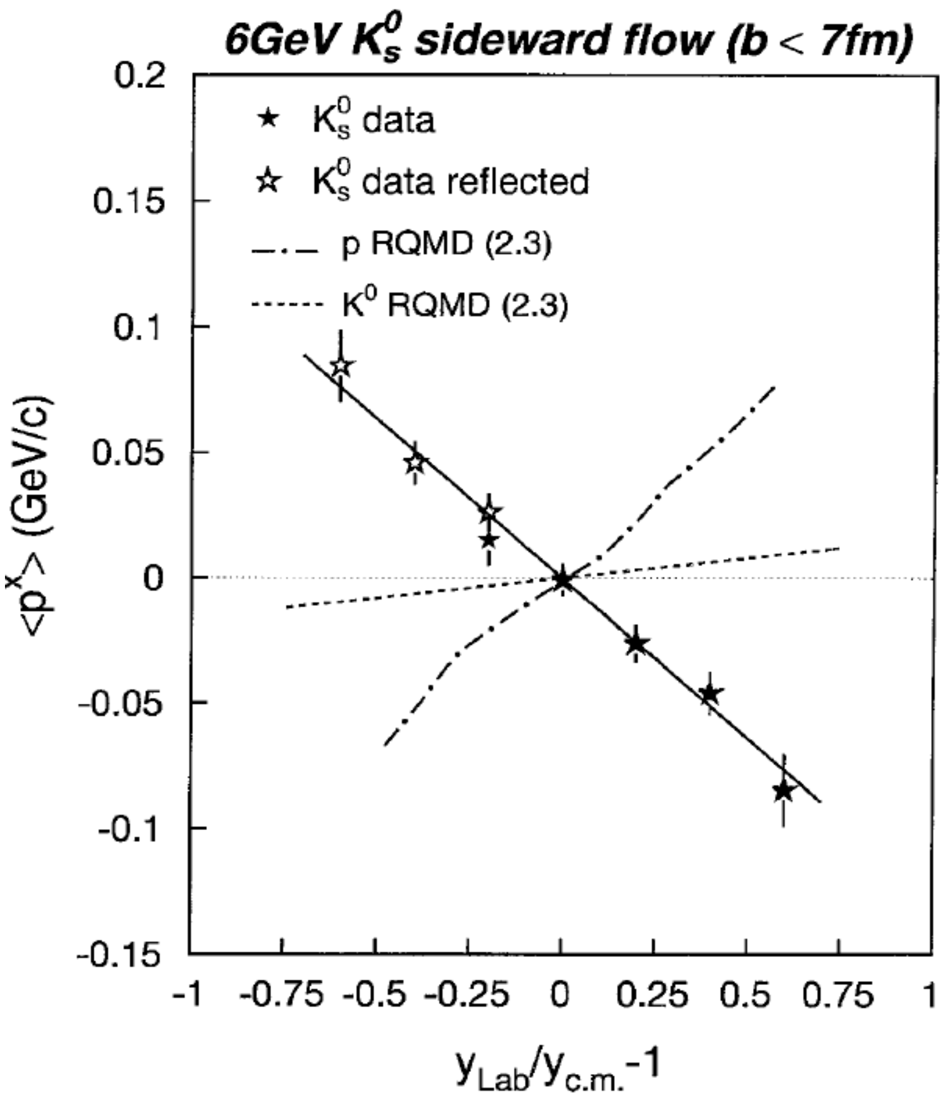




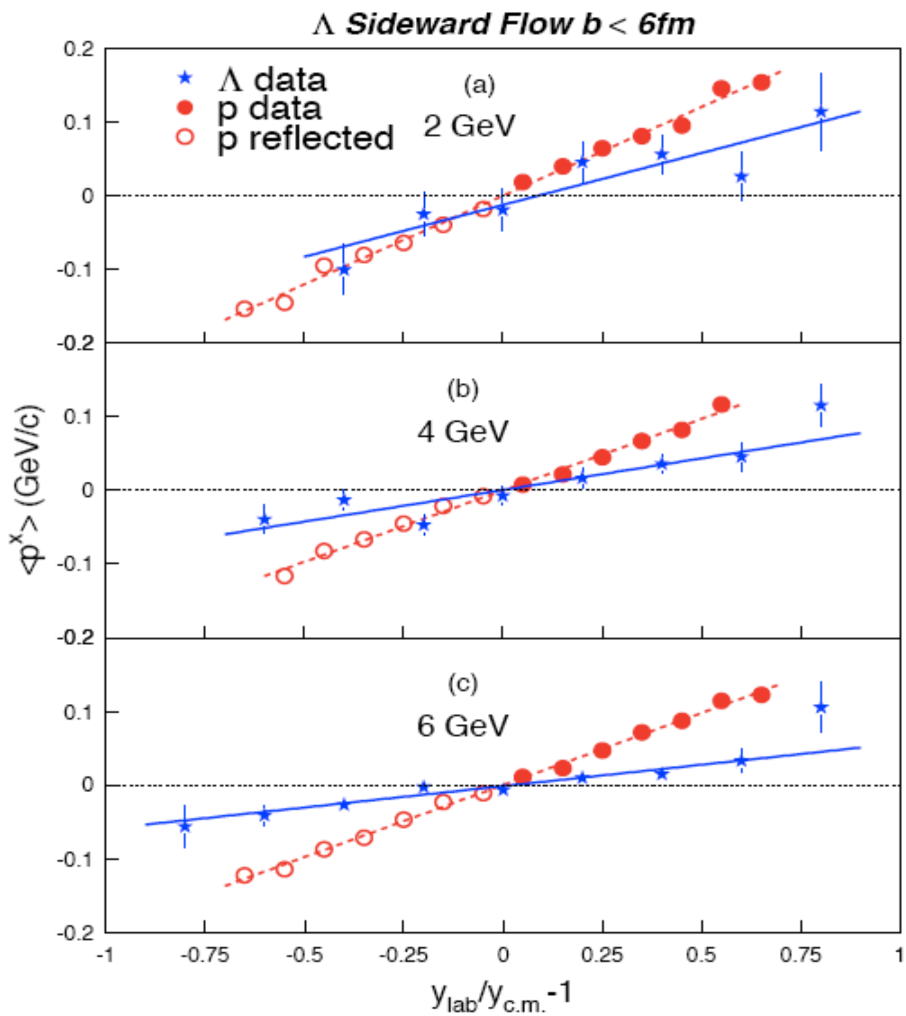
Brachmann, Soff, Dumitru, Stocker, Maruhn, Greiner Bravina, Rischke , PRC 61 (2000) 024909.
L.P. Csernai, D. Roehrich PLB 458, 454 (1999) M.Bleicher and H.Stocker, PLB 526,309(2002)

Anti-flow/3rd flow component : Flat v_1 at midrapidity due to 1st order phase transition
Caution : Seeing anti-flow does not necessarily mean that there is a QGP EoS. (refer to UrQMD). In following slides, anti-flow only means zero or negative slope at midrapidity, due to the fast expansion of a tilted source.

v_1 at low energies

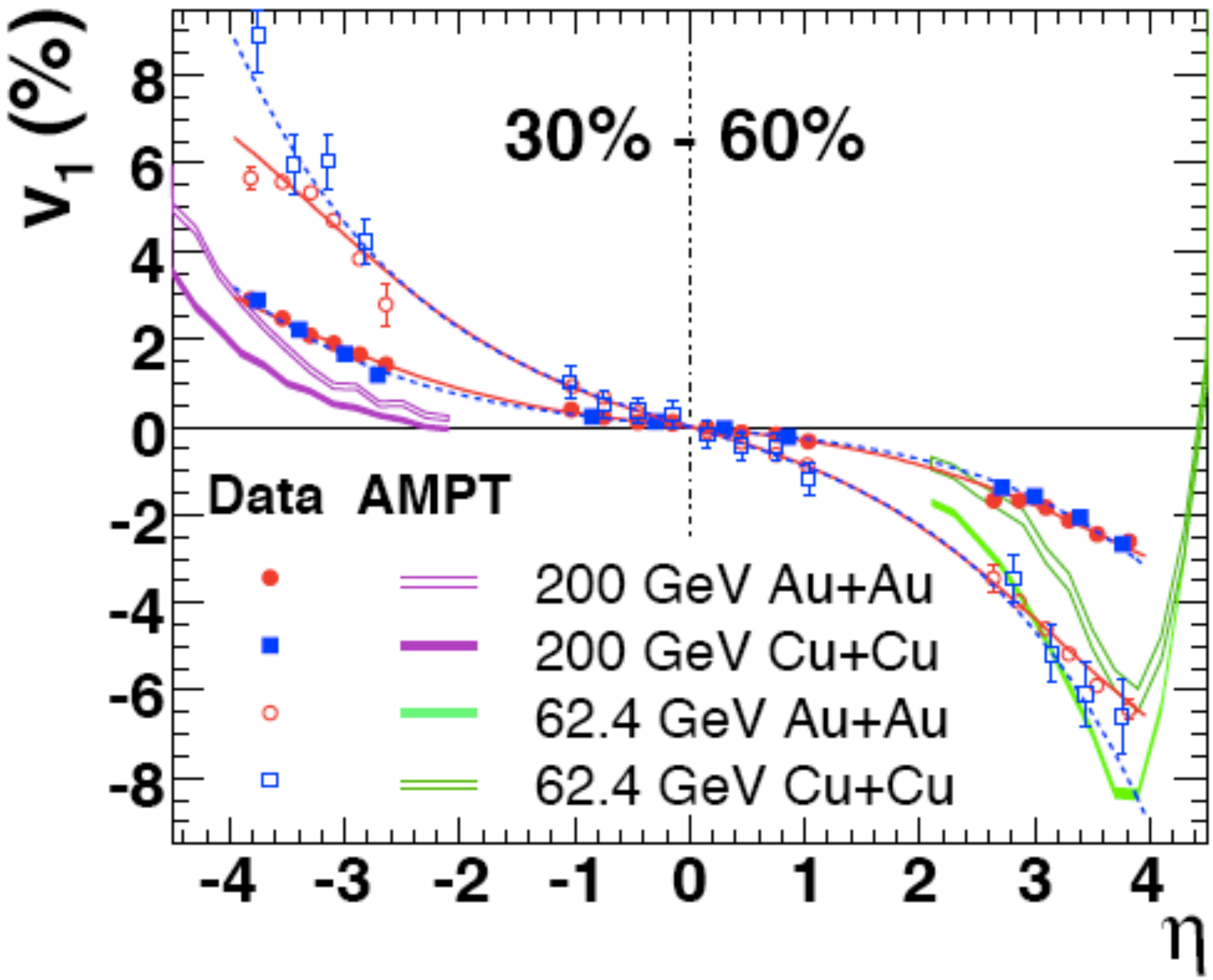


e895, PRL 85 940 (2000)



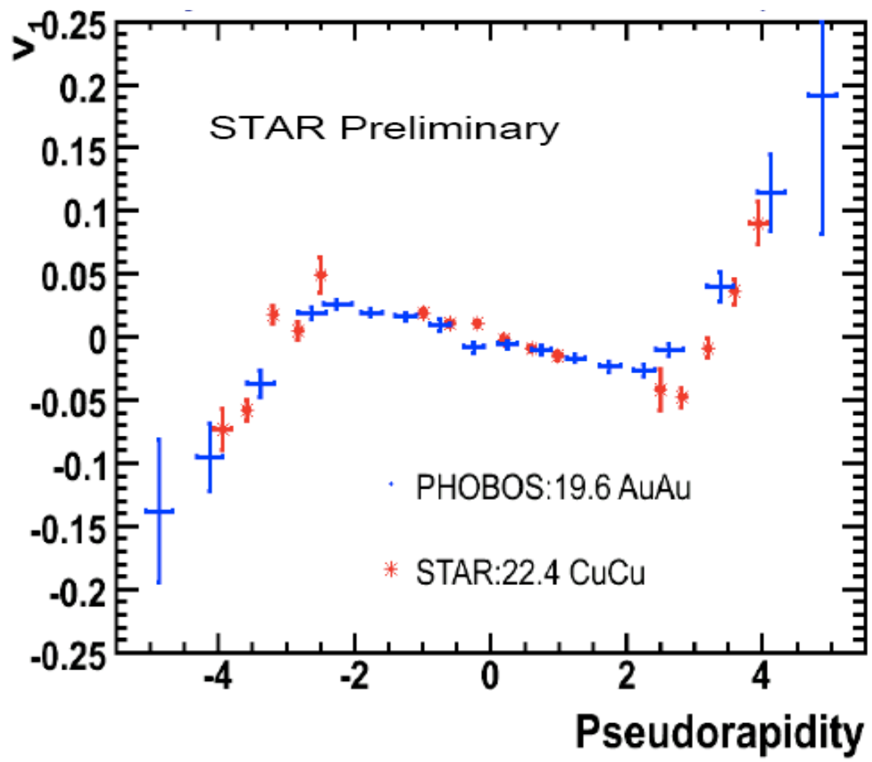
E895, PRL 86 2533 (2001)

v_1 at RHIC, measured by STAR



STAR, PRL 101 252301 (2008)

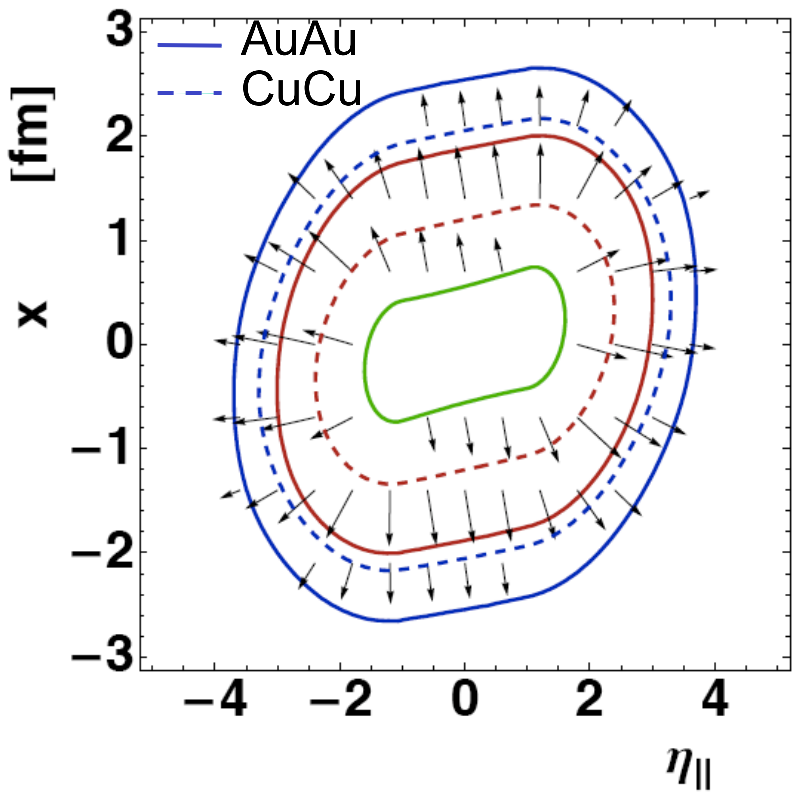
v_1 at RHIC, measured by STAR



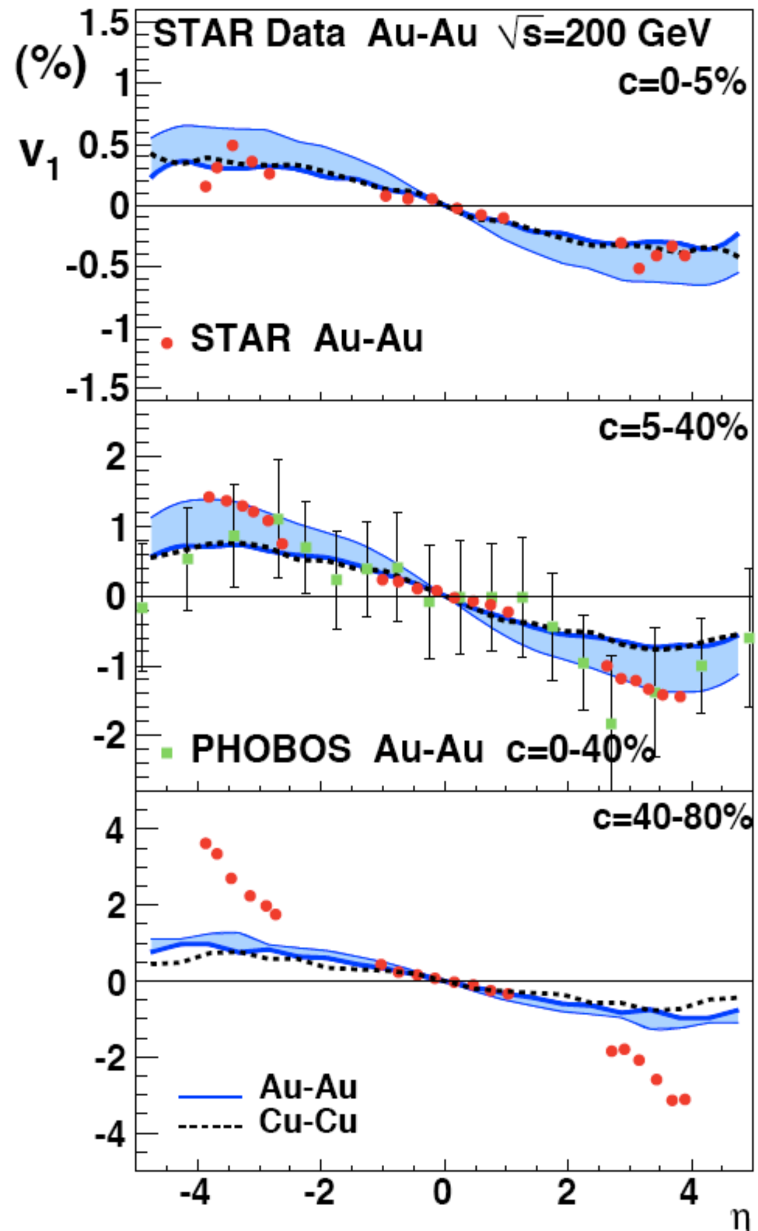
PHOBOS data points : PRL 97, 012301 (2006)

New result for CuCu at 22 GeV strengthen the published conclusion.

v_1, System size independence explained by Hydro+tilted source

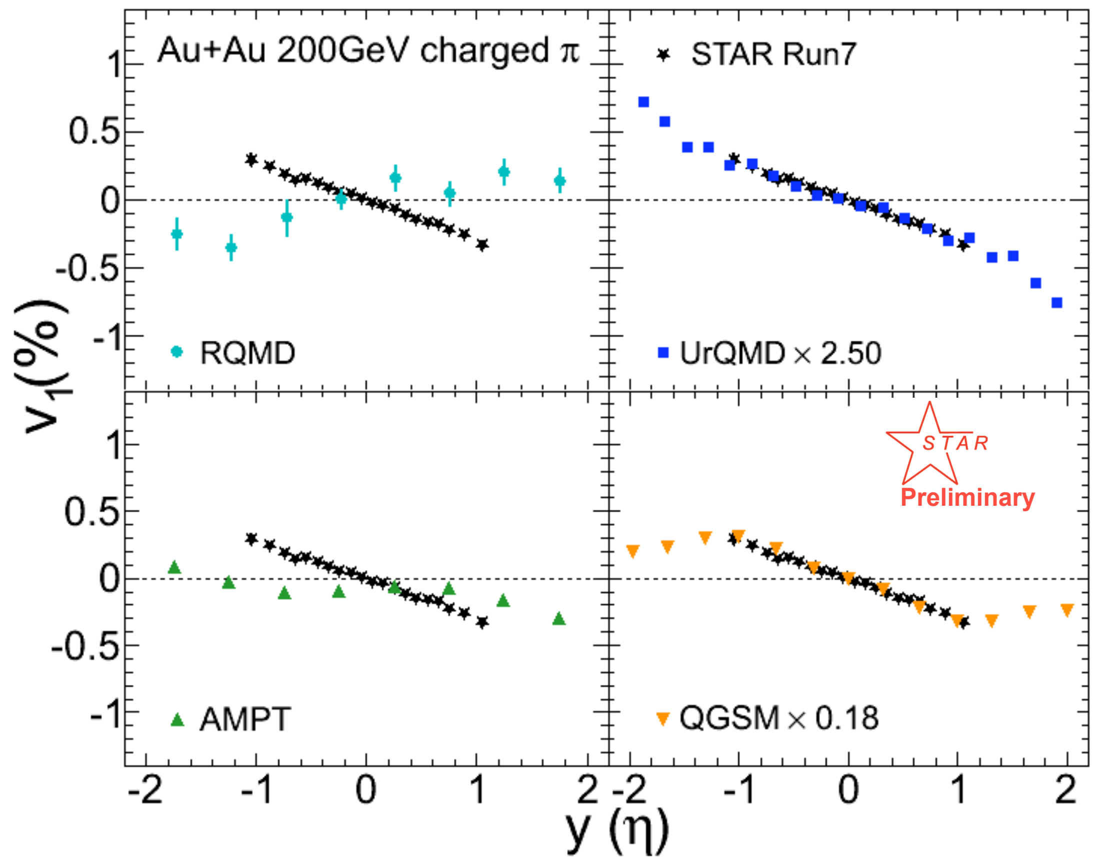


P. Bozek and I. Wyskiel nucl-th/1002.4999,



Similarity of flow between AuAu and CuCu at the same centrality reflects the similarity in the initial density profiles.

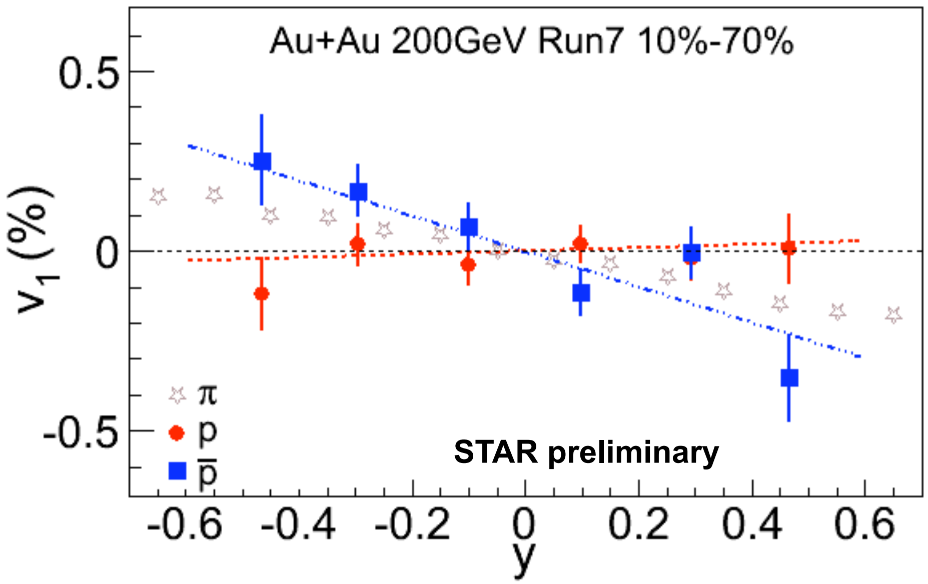
PID v_1



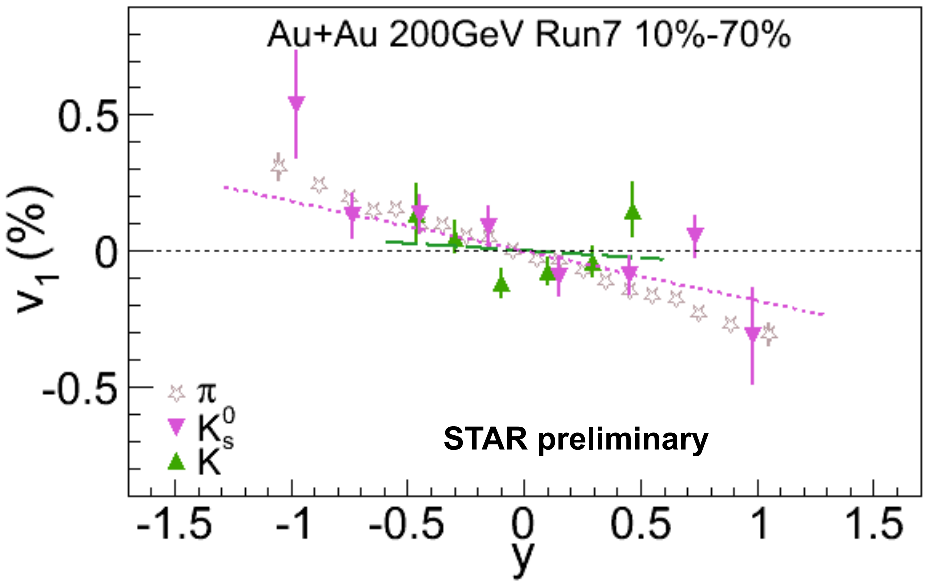
Phys. Rev. Lett. 84 (2000) 2803;
Phys. Lett. B 526 (2002) 309–314;
Phys. Rev. C 71, 054905 (2005).

Other models fail in describing the data

PID v_1



Proton ***0.4<pT<1.0 (GeV/c)***
Antiproton ***0.4<pT<1.0 (GeV/c)***

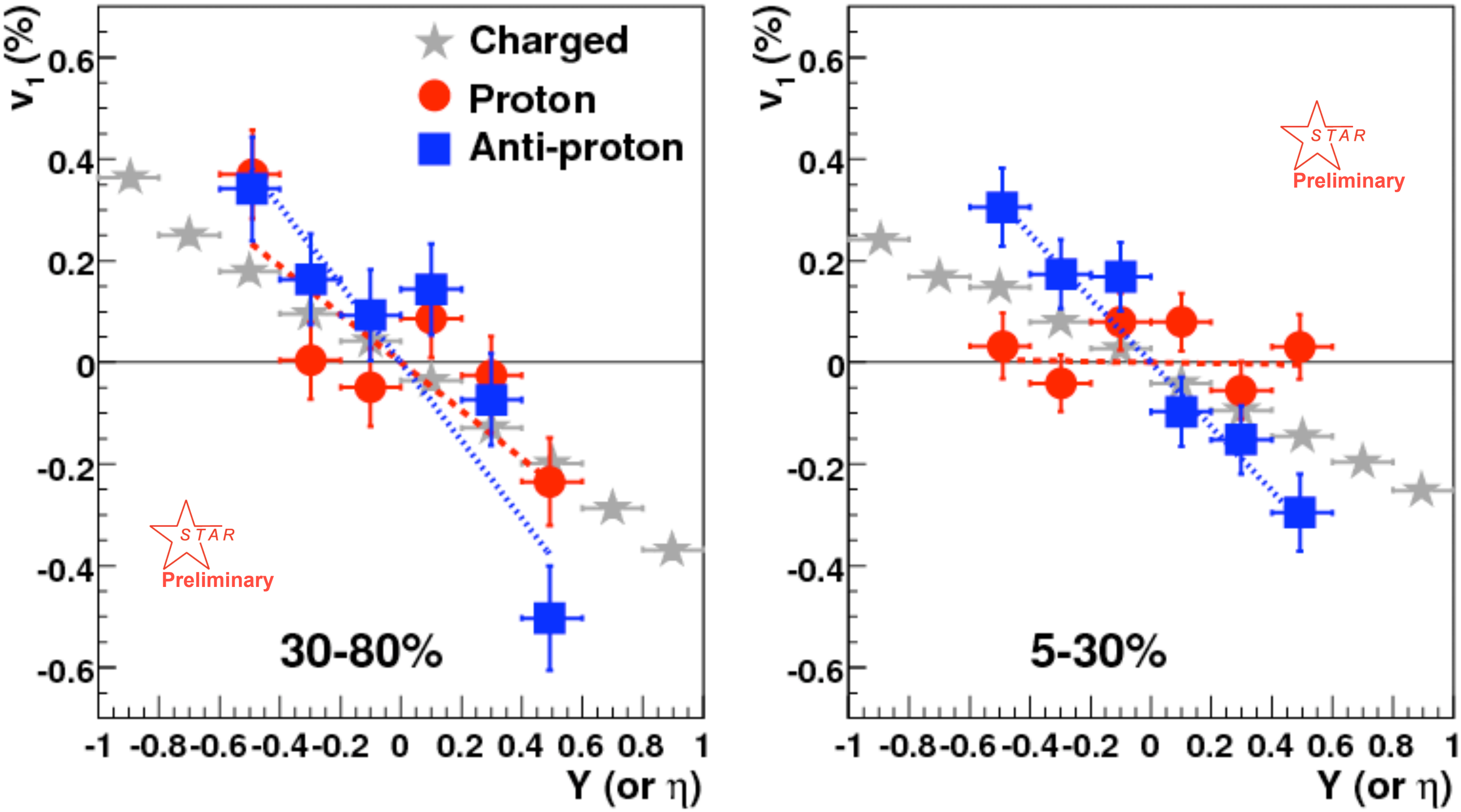


Pion ***0.15<pT<0.75 (GeV/c)***
Kaon ***0.2<pT<0.6 (GeV/c)***

Anti-proton slope has the same sign of pions – consistent with anti-flow

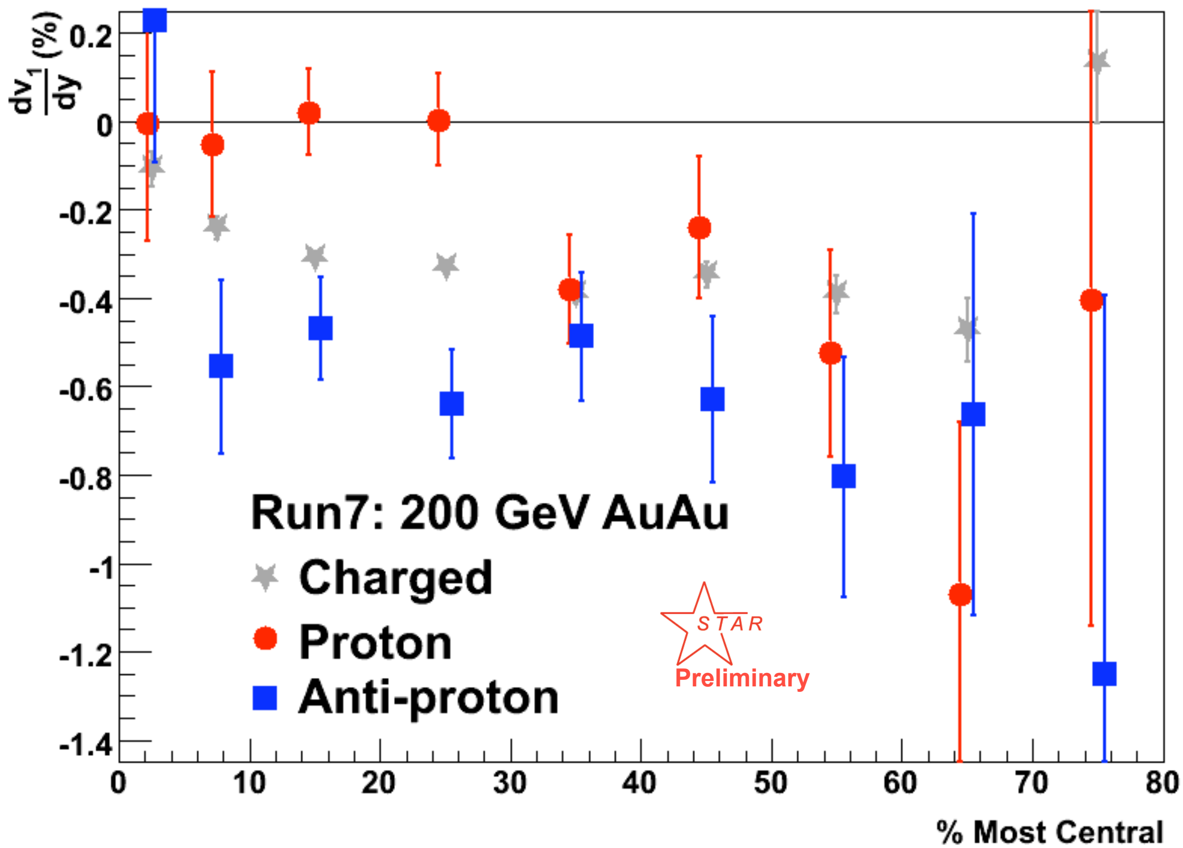
Kaon suffers less shadowing effect due to smaller k/p cross section, yet we found negative v_1 slope for both charged kaon and Kshort – consistent with anti-flow

PID v_1



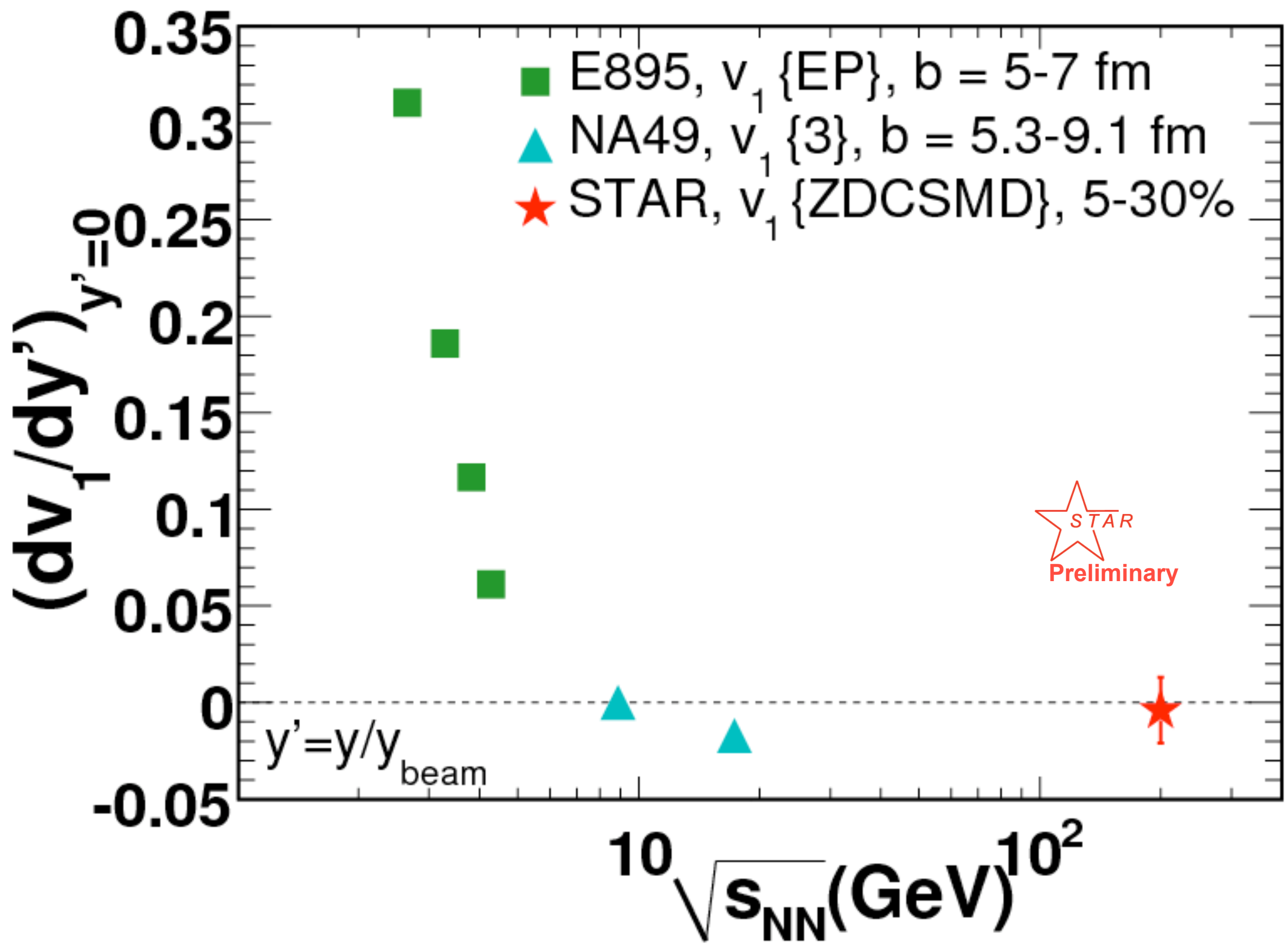
Difference seen between v_1 of protons and anti-protons in mid-central collisions.

Centrality dependence of proton v_1 slope



Negative v_1 slope for protons is observed in 30-80% centralities.
Large difference seen between v_1 of protons and anti-protons in 5-30% centralities.
Difficult for anti-flow to explain both simultaneously.

Centrality dependence of v_1 slope



Rapidity window used in STAR : [-0.6,0.6]

Proton v_1 in mid-central collisions at RHIC stays small

Summary

- NCQ scaling is more complicated than it appears to be.
  - Pions deviate from NCQ scaling by 20% (while models can tolerate only 5-10%), kaons by 10%.

- Knudsen Fit gives the upper limit of η/s

- The heavier the particle, the more curvature is seen in the plot of v_2/ε scaled by its saturation value, as a function of 1/S dN/dy. Such feature is not seen in Hydro models (ideal or viscous/hybrid), but is seen in AMPT.

- PID v_1 is presented. Negative $v_1(y)$ slopes are found at midrapidity. Sizable difference is seen between $v_1(y)$ slope of protons and anti-protons in 5-30% central collisions. Anti-flow can explain the negative $v_1(y)$ slopes but it has difficulties in explaining the centrality dependence of the difference between the $v_1(y)$ slope of protons and anti-protons.