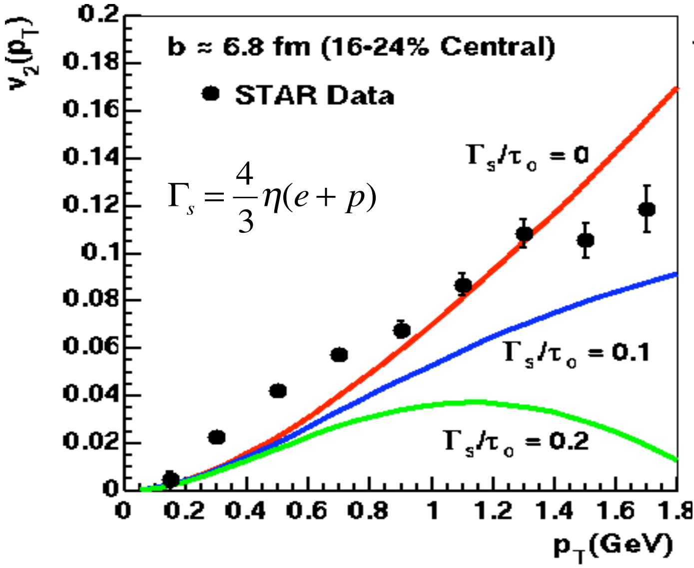
Flow Results and Hydrodynamic Limit

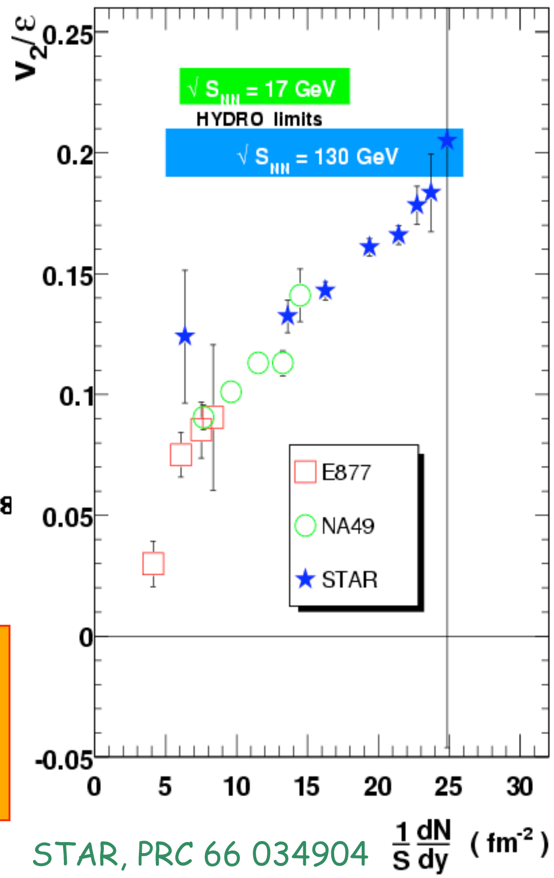
Aihong Tang for the STAR Collaboration

The story rewinded

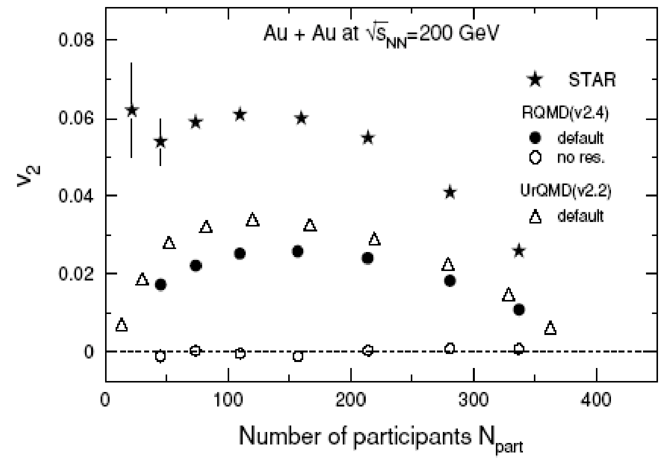


D. Teaney, PRC 68 034913 (2003)

Viscosity reduces v_2
Viscosity needs to be small in order to explain data



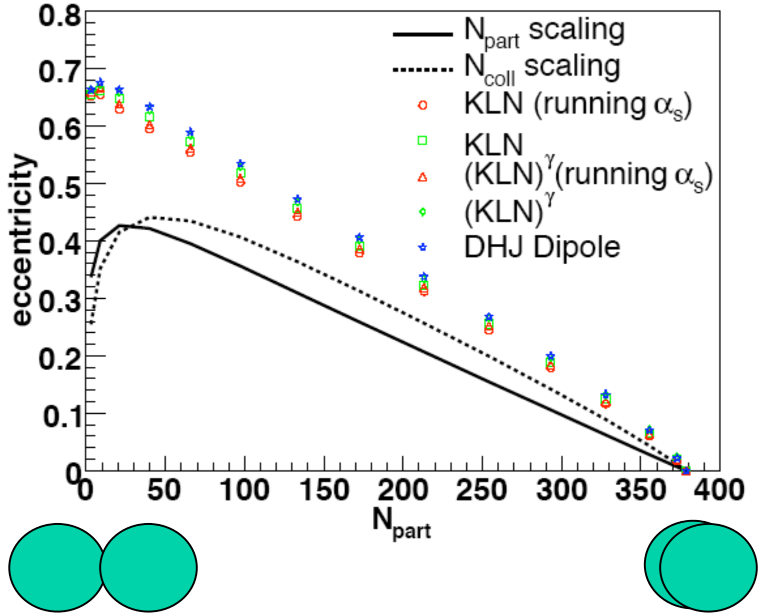
STAR, PRC 66 034904 (2002)

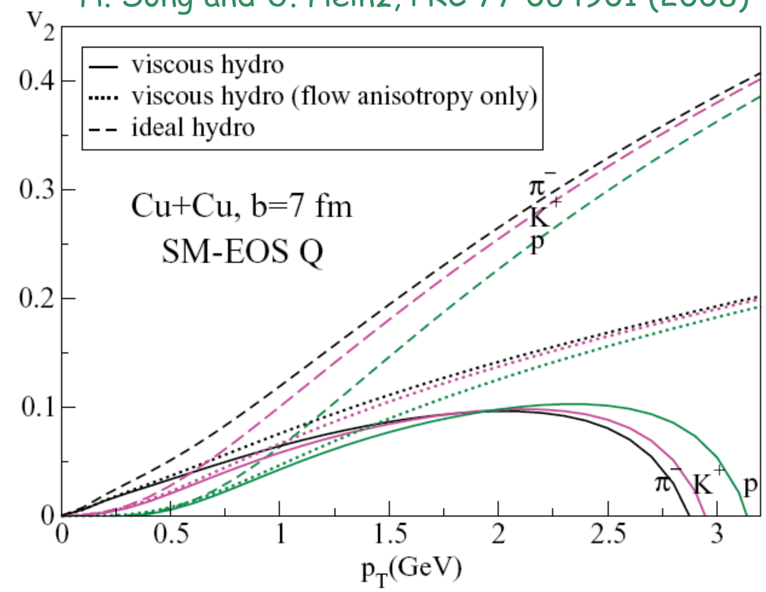


Y. Lu et al. Journal of Phys. G 32 1121 (2006)

v_2/ε approaches the limit of ideal hydrodynamics
Hadronic interaction alone does not produce enough v_2

The story continues

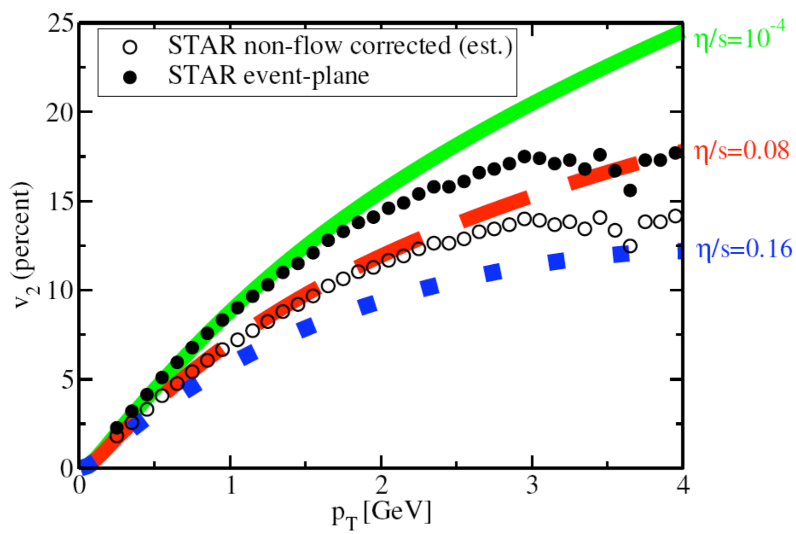


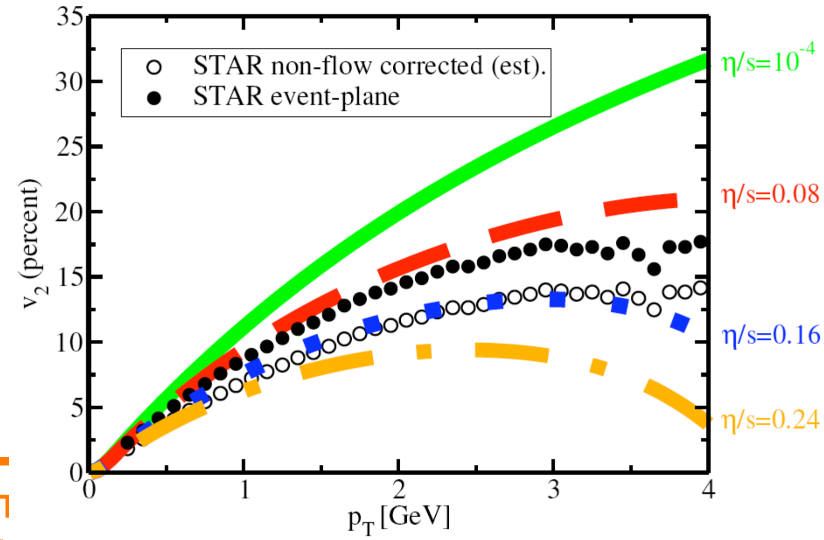


H. Song and U. Heinz, PRC 77 064901 (2008)

T. Hirano, RHIC & AGS Users Mtg 06

Glauber M. Luzum and P. Romatschke arXiv0804.4015 CGC






Are we saturated already ?
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Are we still far away from there ?
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How to view the hydro behavior better ? - Move away from it

- Ideal fluid and low viscosity ⇔ local equilibrium (small λ or large σ)

- **To study the local equilibrium, we have to move away from it**, say, check what if we relax the constraint of local equilibrium

- How to get a complete view? Study Boltzman equation for diluted system. It recovers Hydro when λ becomes small.

"To have a complete view of Lu Mountain, one has to move away from it."
- Shi Su (1037~1101)

Transport Theory and Hydrodynamics

Transport Theory	Hydrodynamics
Microscopic	Macroscopic
Applicable out of equilibrium	Local equilibrium
Cannot describe phase transition	Can treat phase transition
D<<1	K<<1

D (Dilution parameter) = $\frac{\text{Typical distance between two particles}}{\text{Mean free path}}$

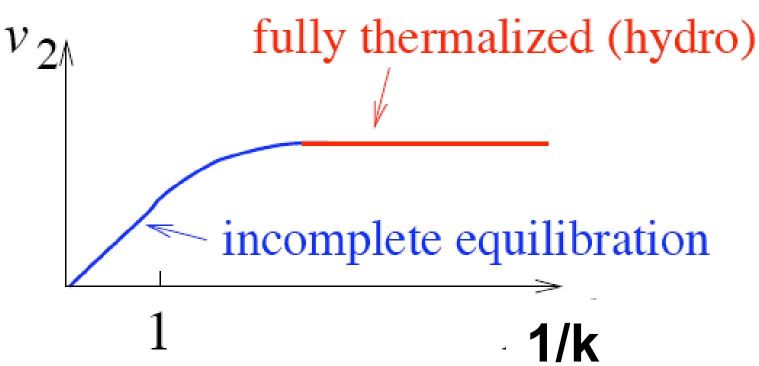
K (Knudsen number) = $\frac{\text{Mean free path}}{\text{System size}}$

Boltzmann Equation will be reduced to Hydrodynamics when both D<<1 and K<<1

Connecting Pieces

$$D \equiv \frac{n^{-1/3}}{\lambda} = \sigma n^{2/3}$$

n: particle density
σ: parton cross section
R: system size
λ: mean free path



$$\frac{1}{K} \equiv \frac{R}{\lambda}$$ ← Number of collisions.

$$\lambda = \frac{1}{\sigma n}$$

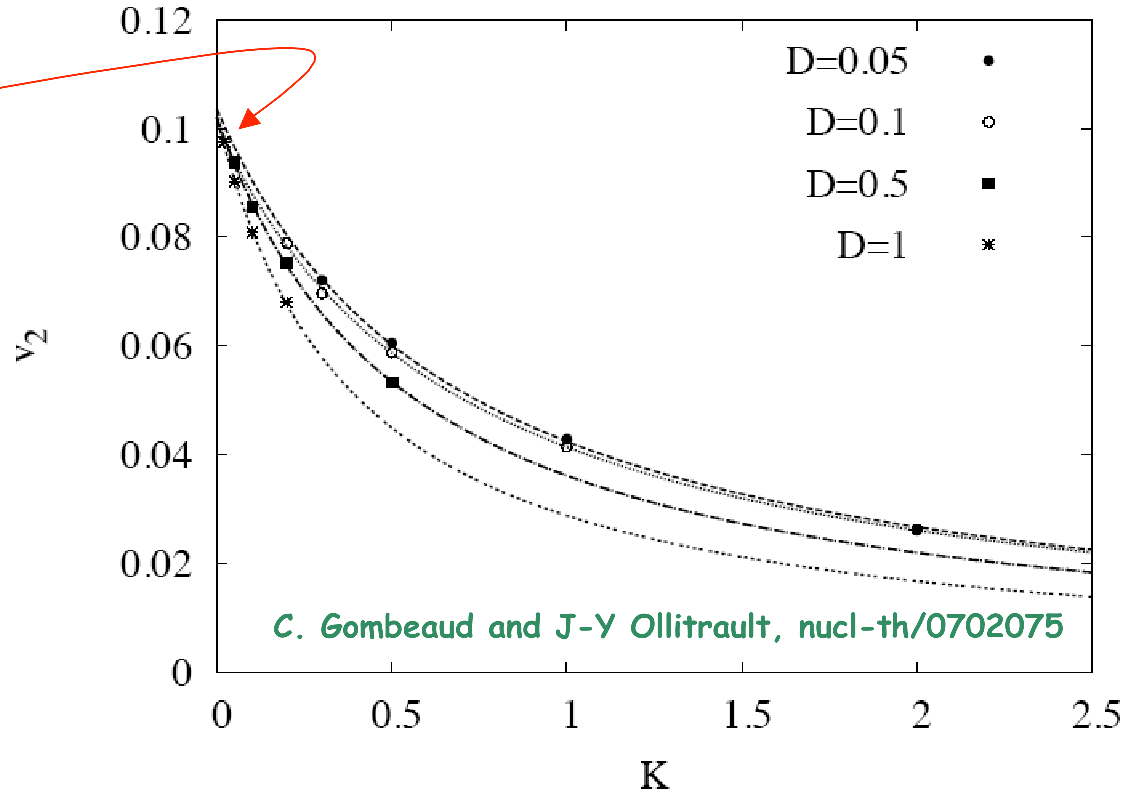
$$n = \frac{1}{ct}\frac{1}{S}\frac{dN}{dy}$$

$$t \sim R / c_s$$

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

v_2 from Solving the Boltzmann Equation

Hydro limit is recovered when D<<1 and K <<1



$v_2 \propto 1/K$, and v_2 saturates eventually when the system reaches local equilibrium

$$\Rightarrow \quad \frac{v_2}{\varepsilon} = \frac{v_2^{hydro}}{\varepsilon} \frac{1}{1 + K / K_0}$$

$K \to 0$ Hydro limit

$K >> 1$ Low density limit,

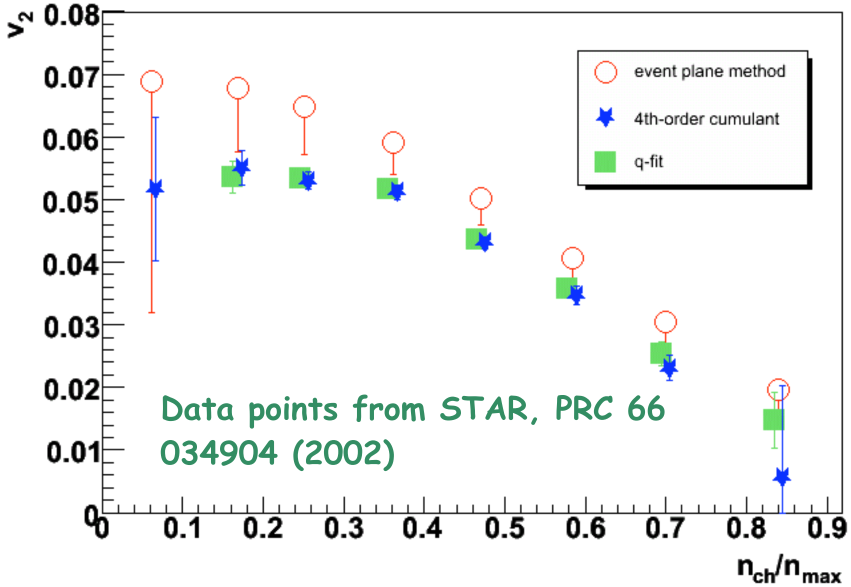
$v_2/\varepsilon \propto 1/S\ dN/dy$

Choose the right $\{v_2, \varepsilon\}$ pairs

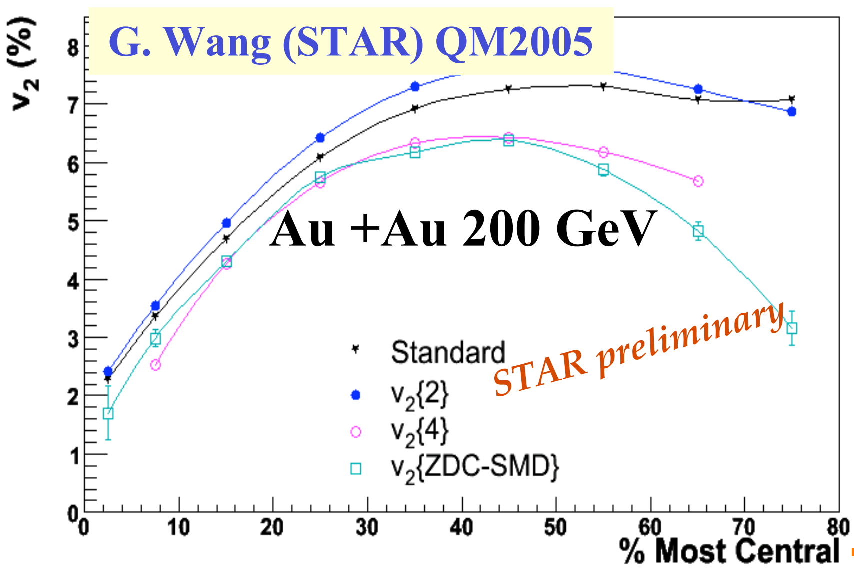
v_2 that are sensitive to anisotropy w.r.t. the **Reaction Plane v_2:** $v_2\{4\}$, $v_2\{qDist\}$, $v_2\{qCumulant4\}$, $v_2\{ZDCSMD\}$	v_2 that are sensitive to anisotropy w.r.t. the **Participant Plane :** $v_2\{2\}$,$v_2\{EP\}$,$v_2\{uQ\}$ etc.
ε that are sensitive to anisotropy w.r.t. the **Reaction Plane**: $\varepsilon\{std\}$, $\varepsilon\{4\}$	ε That are sensitive to anisotropy w.r.t. the **Participant Plane:** $\varepsilon\{part\}$ $\varepsilon\{2\}$

R.Bhalerao and J-Y. Ollitrault, Phys. Lett. B 614 (2006) 260
S.Voloshin, A.Poskanzer,A.Tang and G.Wang, Phys. Lett. B 659 (2008) 537

v_2 methods

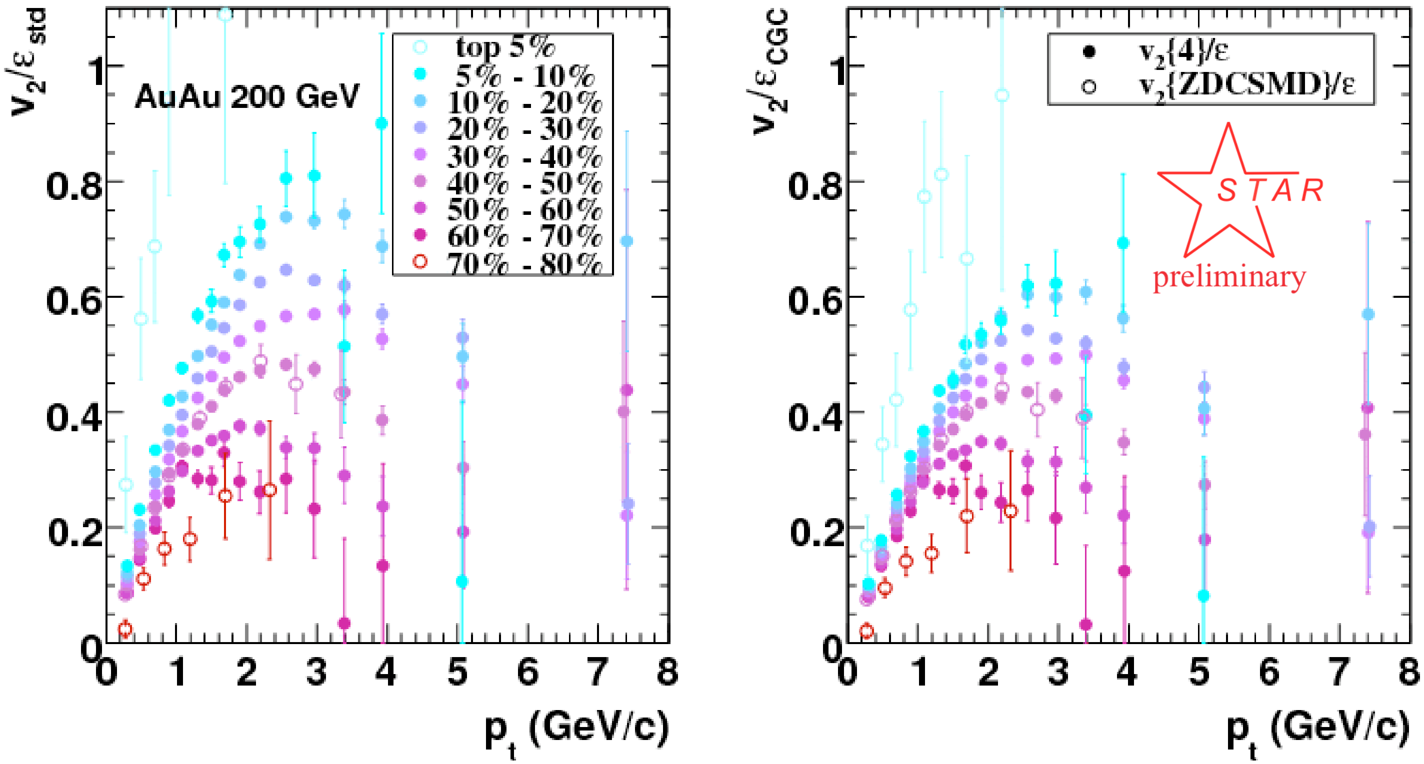


$v_2\{4\}=v_2\{qDist\}$



$v_2\{4\}=v_2\{ZDC\text{-}SMD\}$

Flow increases



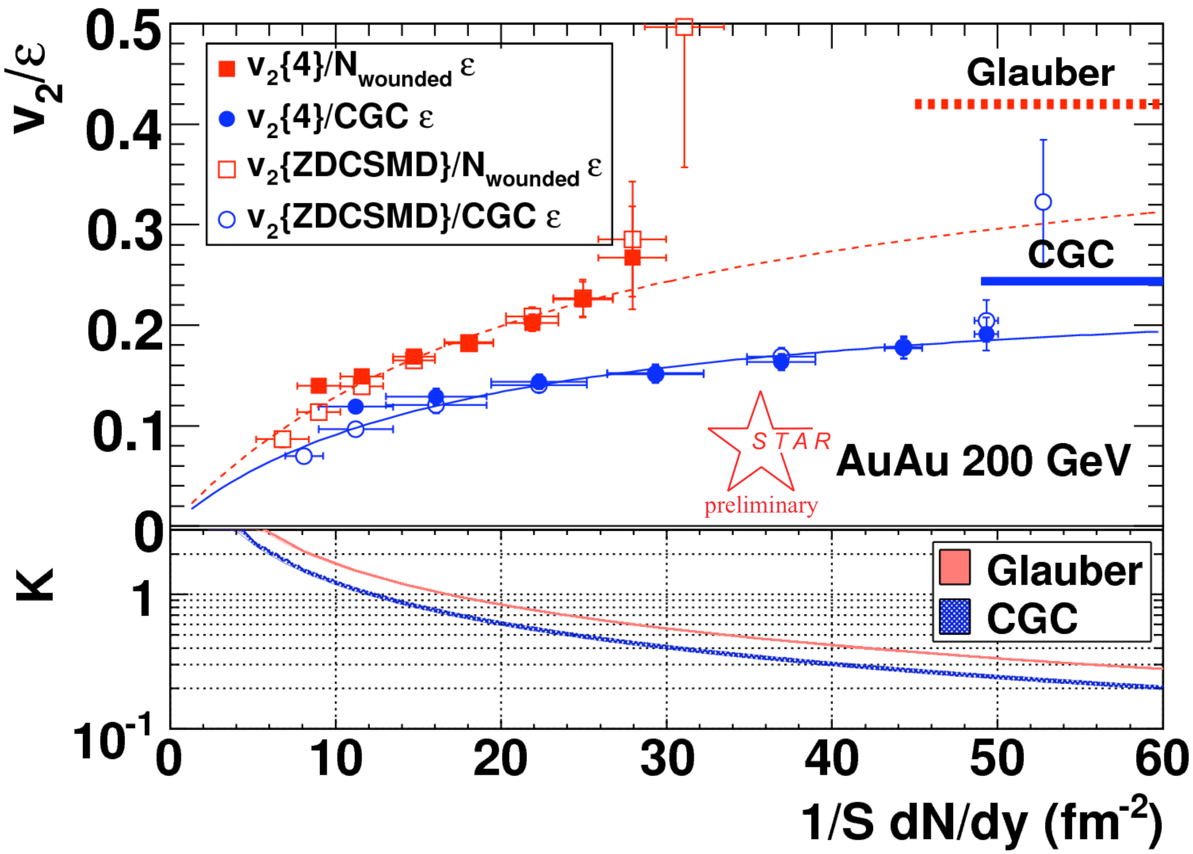
The p_t where v_2/ε peaks increases with p_t - the applicable range
For hydrodynamics extends to large p_t in central collisions.
v_2/ε for the CGC case sees hints of saturation.

How much deviation from ideal hydro ?

$$\frac{v_2}{\varepsilon} = \frac{v_2^{hydro}}{\varepsilon} \frac{1}{1 + K / K_0}$$

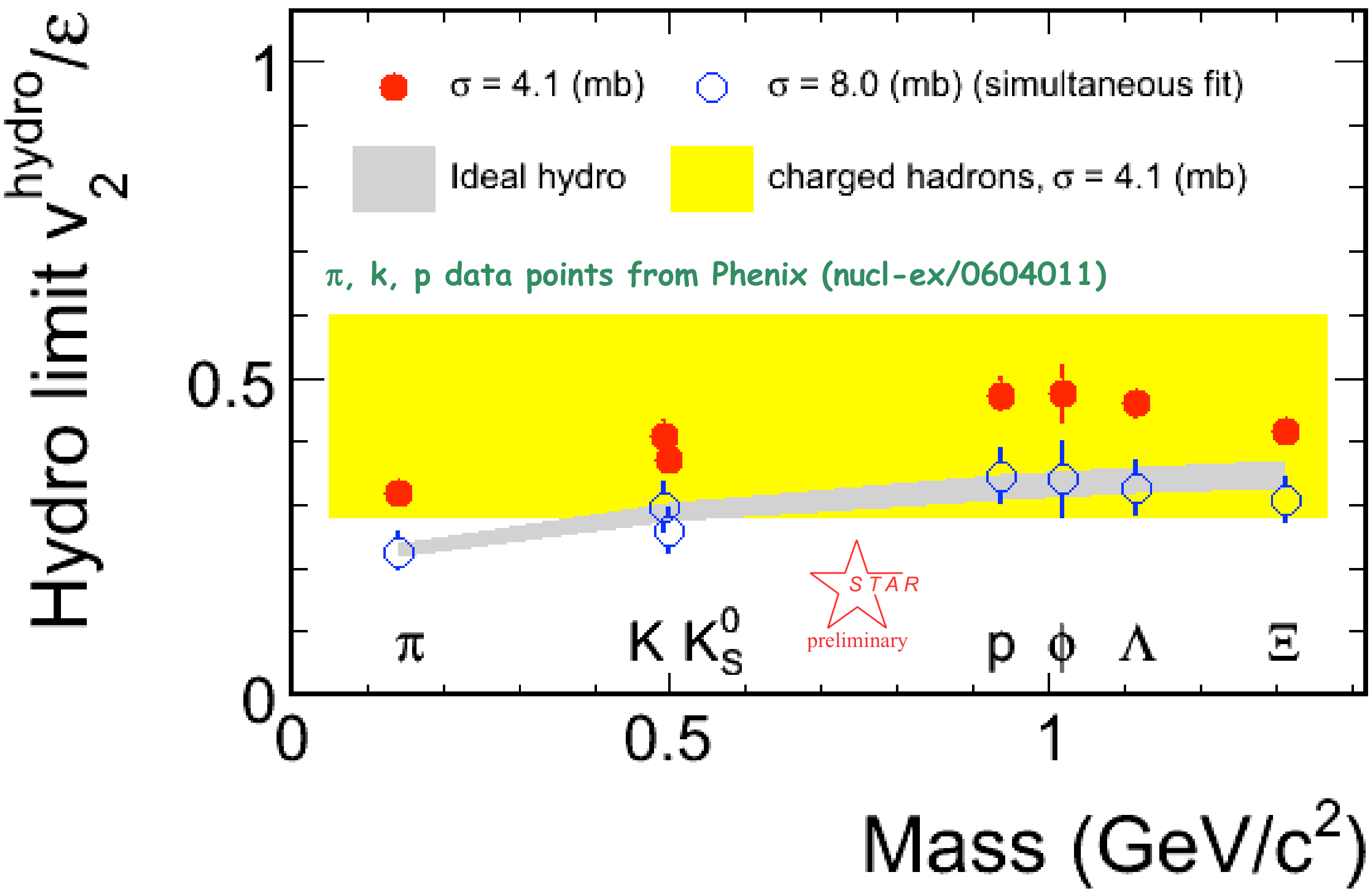
$$K = \lambda / R$$

$$\frac{1}{K} = \frac{\sigma}{S} \frac{dN}{dy} C_s$$



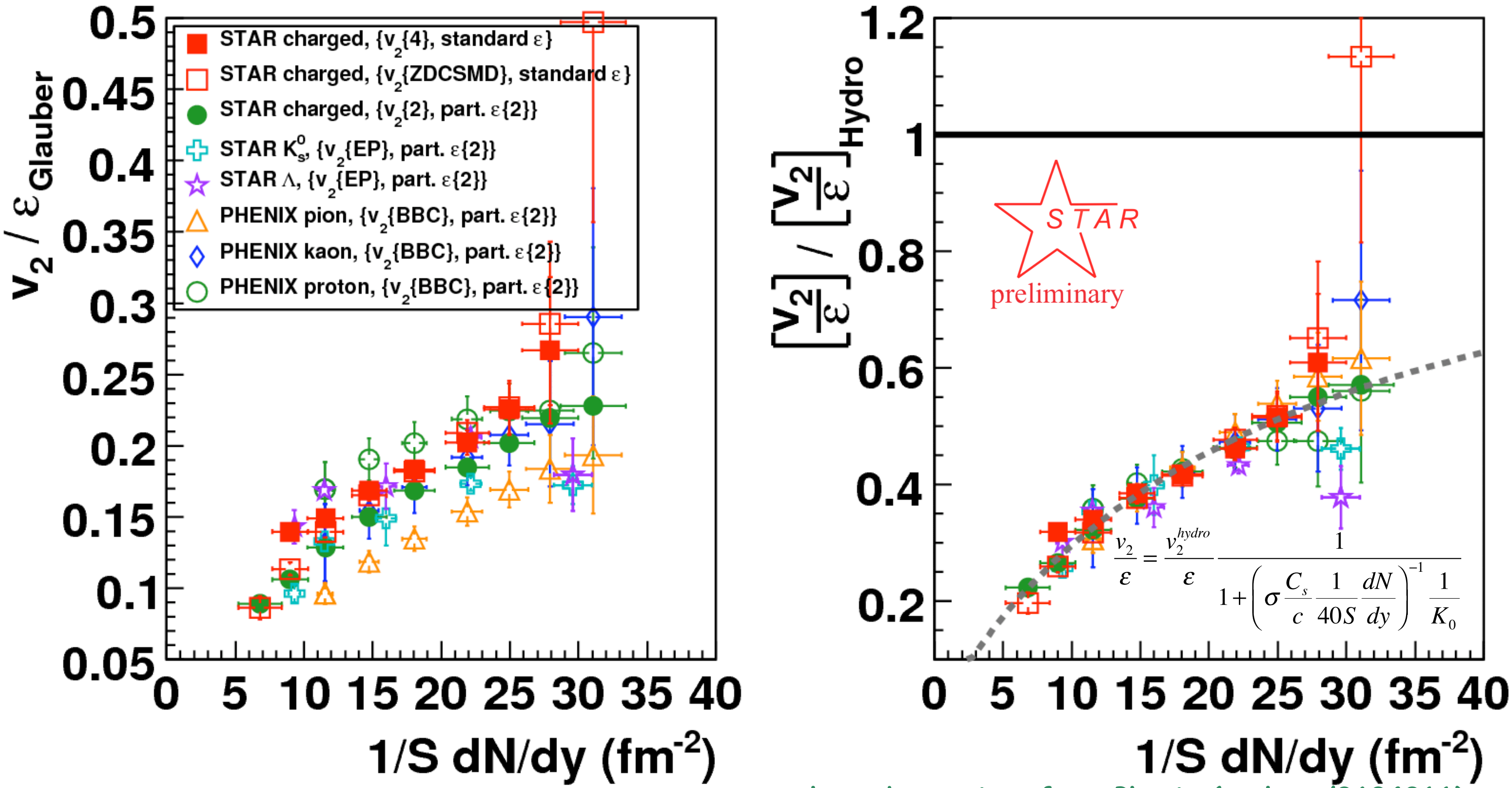
Fitting function from Drescher, Dumitru, Gombeaud, J.Ollitrault, Phys. Rev. C76, 024905(2007)
CGC ε obtained from A.Adil, H-J Drescher,A.Dumitru, A.Hayashigaki and Y.Nara, Phys. Rev. C 74 044905 (2006)

Hydro limit for ID'd particles



Fitted limit increases with mass

How much deviation from ideal hydro ?



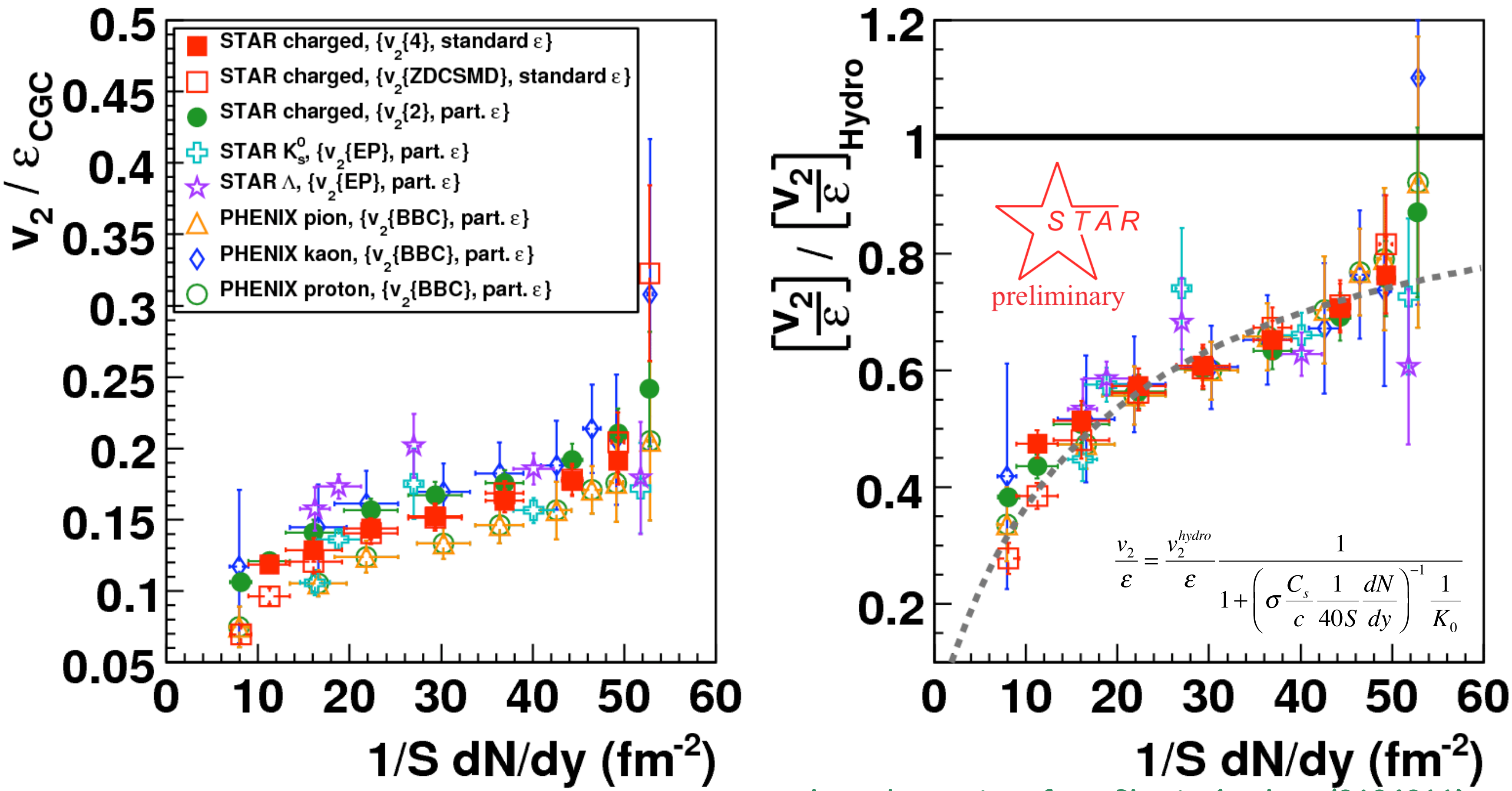
π, k, p data points from Phenix (nucl-ex/0604011)

With the assumption that parton cross section (σ) is same for all ID'd particles, a universal trend of approaching hydro limit is established.

Anti-correlation found between σ and C_s.

Good constraint on EoS

How much deviation from ideal hydro ?



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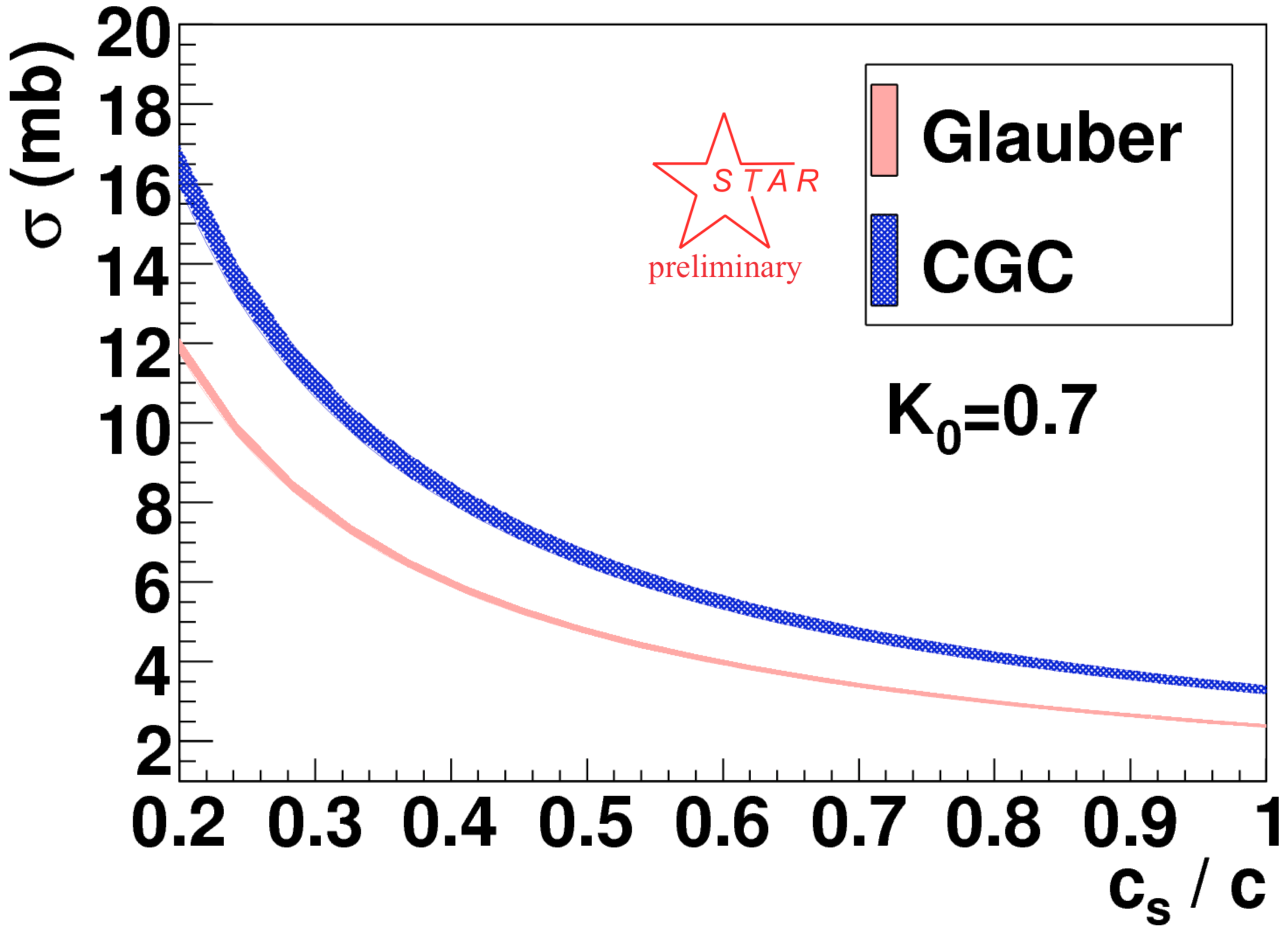
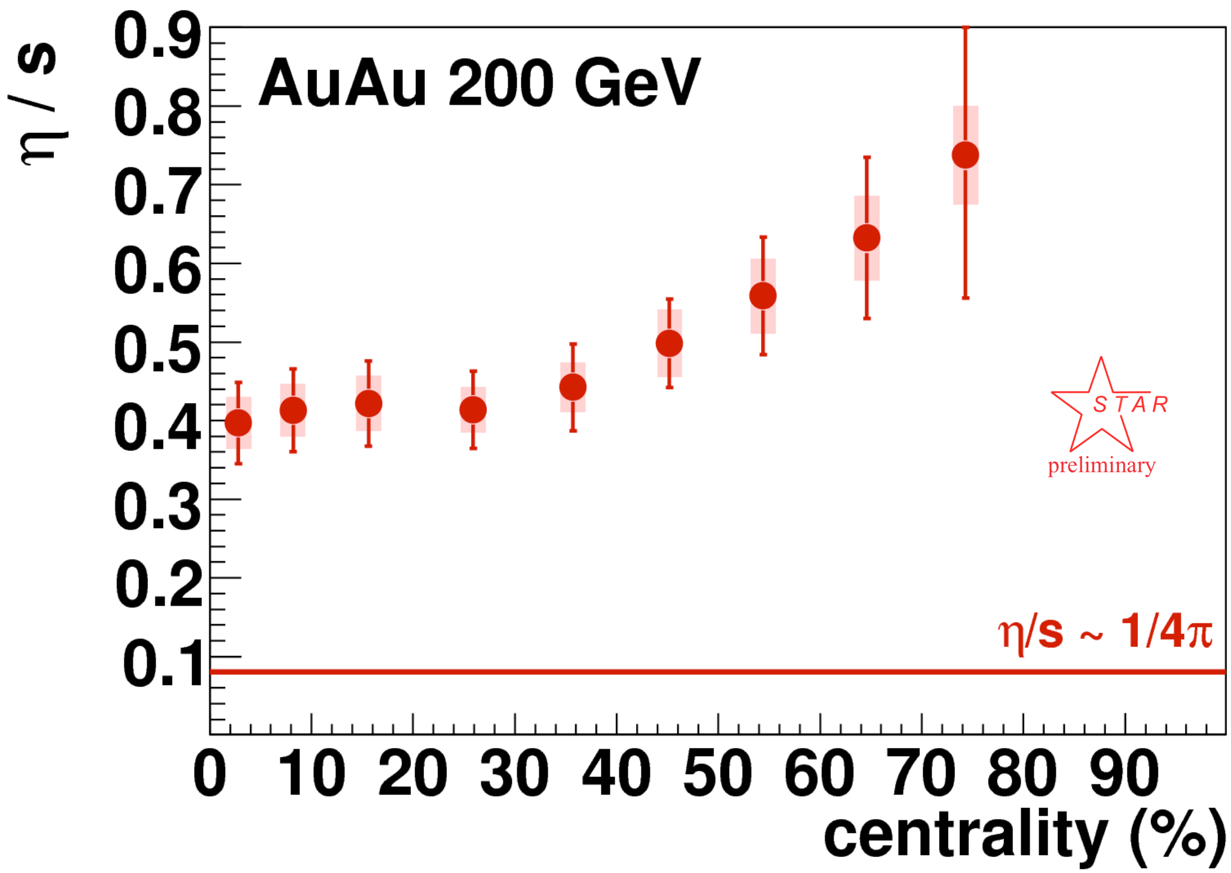
Constraint on EoS



$$\sigma\left(\frac{c_s}{c}\right)k_0 = const.$$

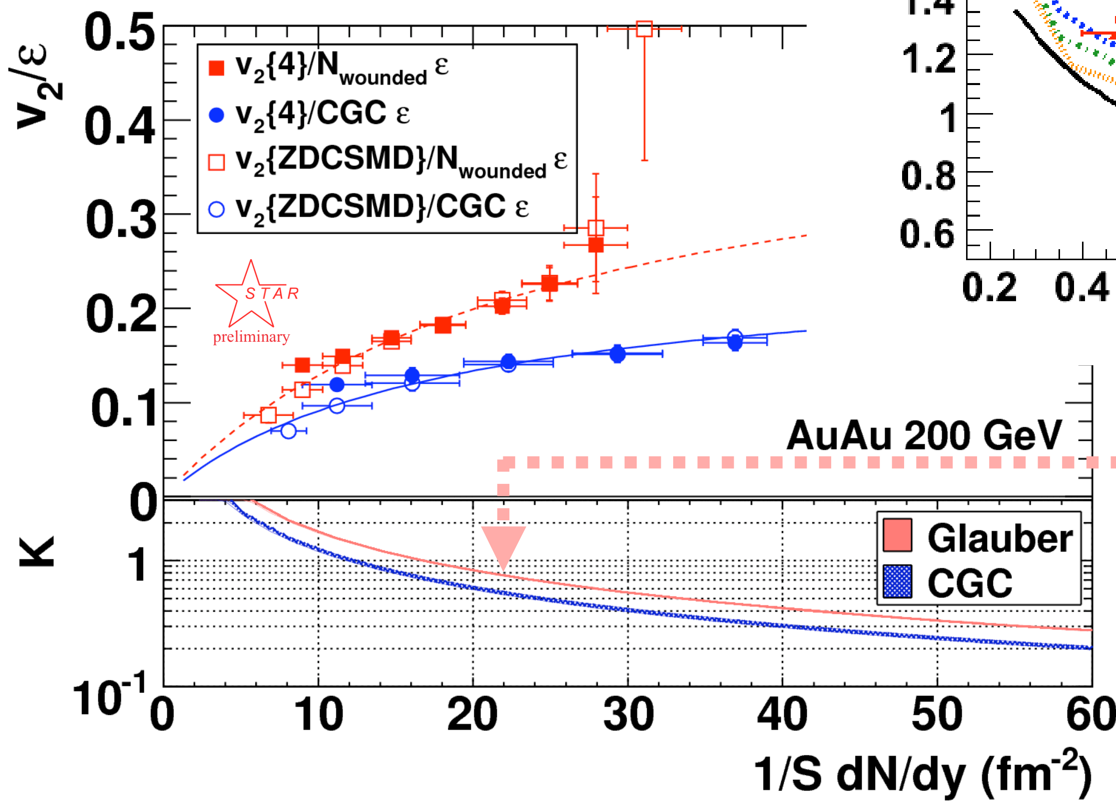
Constraint on η/s

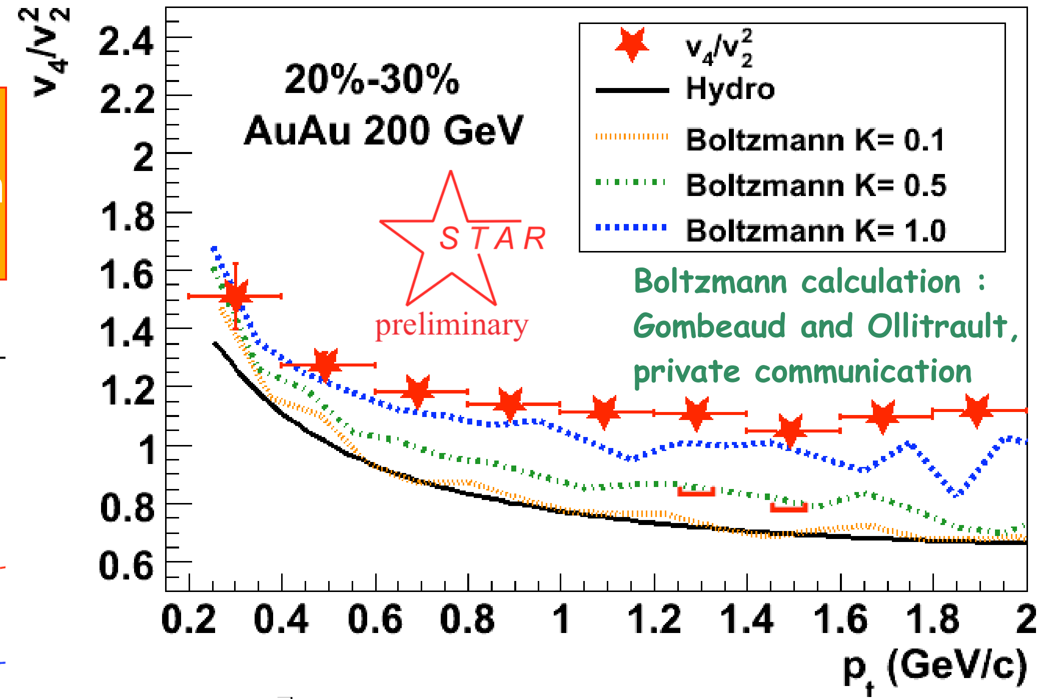


η/s ~4xquantum limit.
Discrepancies between different approaches need to be understood.

A slightly different approach on Knudsen number

For centrality 20-30%, Knudsen number needs to be greater than 0.5 in order to explain data





$$K = \frac{\lambda}{R}$$

K=0 : Ideal Hydro
K>>1 : Free Streaming

Summary

- v_2/ε, if examined with transport motivated formula with certain assumptions, approaches Hydro limit in a similar way for different particle species.
- In central AuAu collisions, v_2/ε is considerably away from Hydro limit. This conclusion is independent of PID, initial conditions, and choice of $\{v_2, \varepsilon\}$ pairs.
- Knudsen number extracted from fitting v_2/ε vs. 1/S dN/dy, as well as that extracted from v_4/v_2^2, stays finite for central collisions - not as zero as required by ideal hydrodynamics.
- Good constraint on EoS obtained.
- For the first time the centrality dependence of η/s is presented.