GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Recent results from hydrodynamics

Pasi Huovinen
J. W. Goethe Universität

RNM workshop

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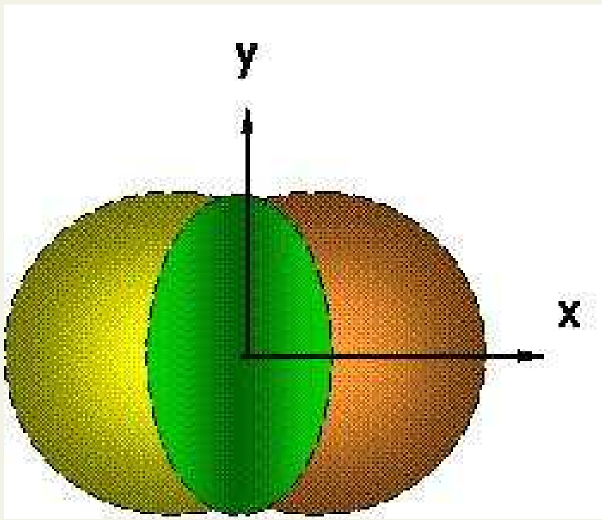
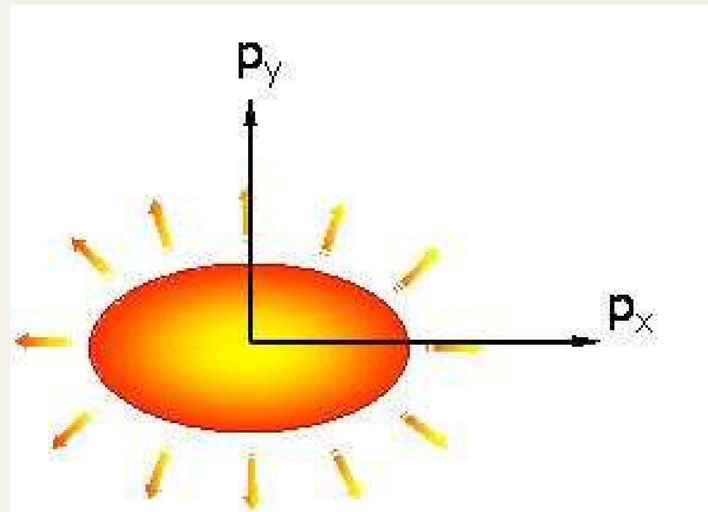
in collaboration with Harri Niemi and Gabriel Denicol

Elliptic flow

spatial anisotropy $\rightarrow$ final azimuthal momentum anisotropy



$\longrightarrow$



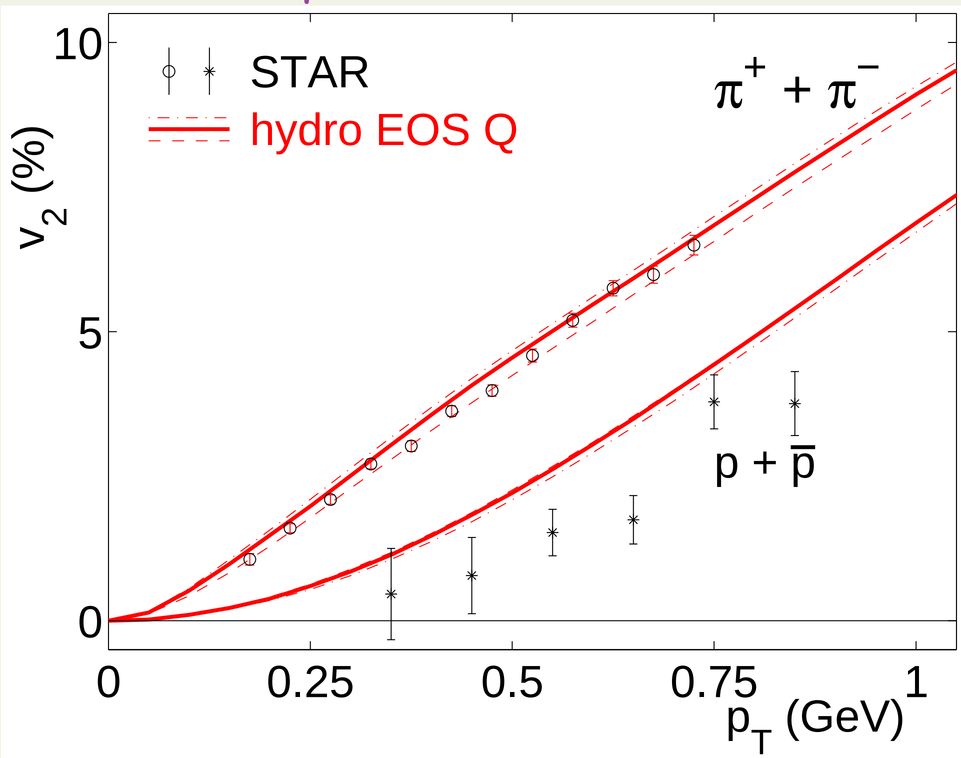
$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle} \qquad\qquad v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

sensitive to speed of sound $c_s^2 = \partial p / \partial e$ **and shear viscosity** η

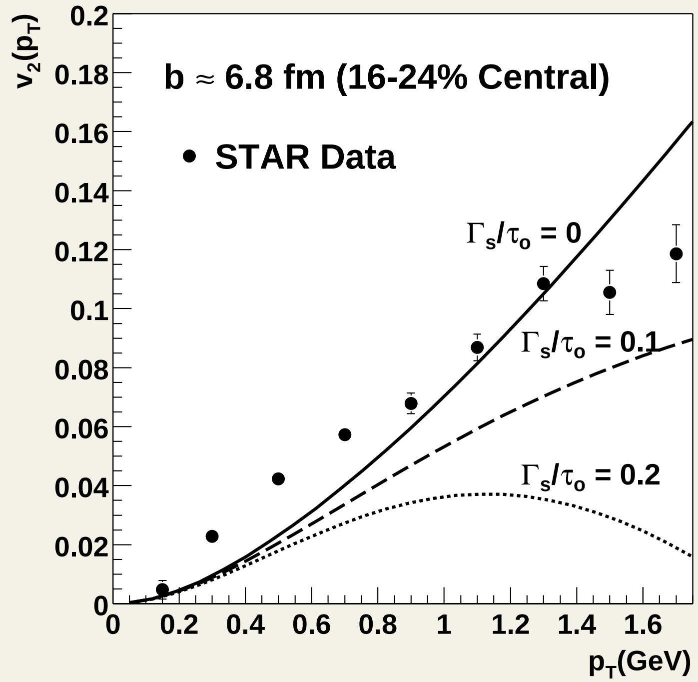
Success of ideal hydrodynamics

Kolb, Heinz, Huovinen et al ('01)

minbias Au+Au at RHIC



Teaney ('04): $\eta/s \propto \Gamma_s/\tau_0$



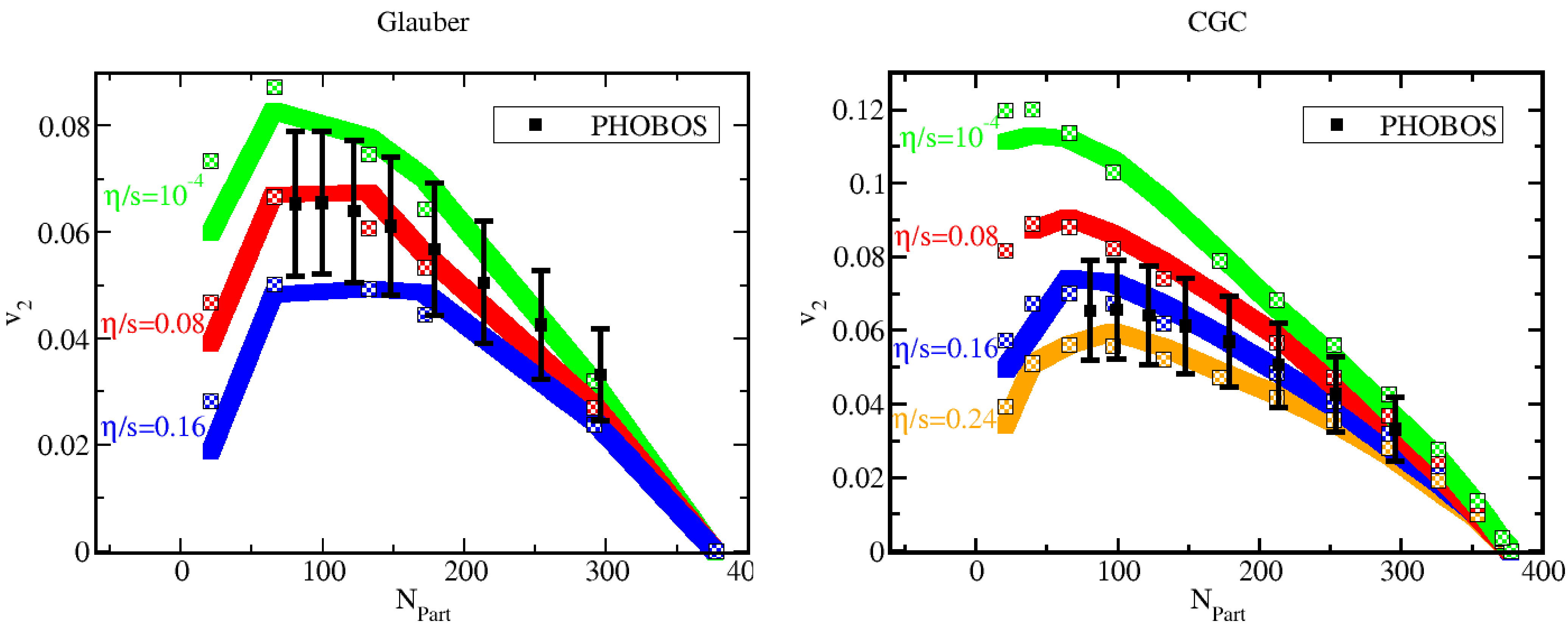
dissipation $\rightarrow$ reduction of v_2

$\Rightarrow$ the idea of plasma as "perfect fluid"

- but how perfect?
- $\eta/s \sim$?

estimate for η/s

Luzum & Romatschke, PRC78, 034915 (2008)

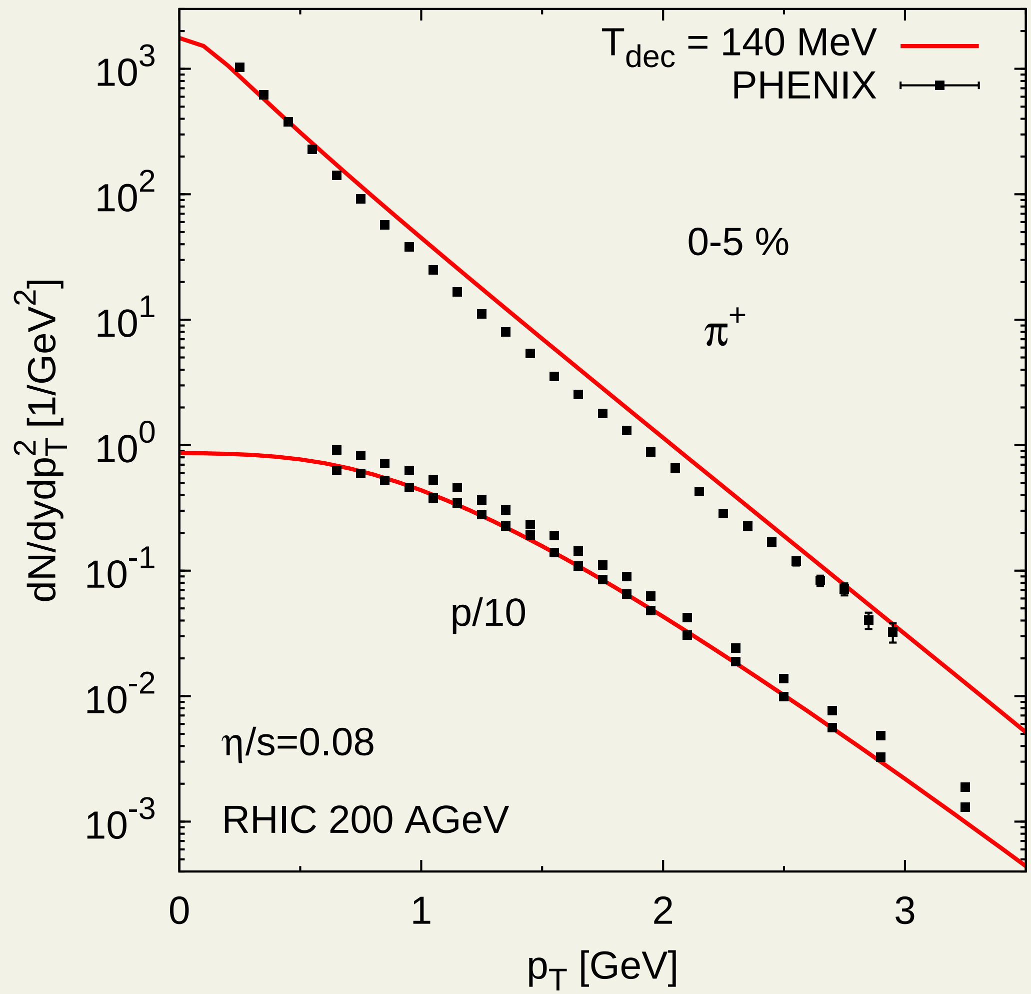


- $\eta/s = 0.08$ **or** $\eta/s = 0.16$ **depending on initialization**

p_T spectra from viscous hydro

Reproduction of Luzum & Romatschke:

- **eBC Glauber**
- **lattice EoS**
- $\eta/s = 0.08$
- **chemical equilibrium**
- $T_{\mathrm{dec}} = 140$ **MeV**



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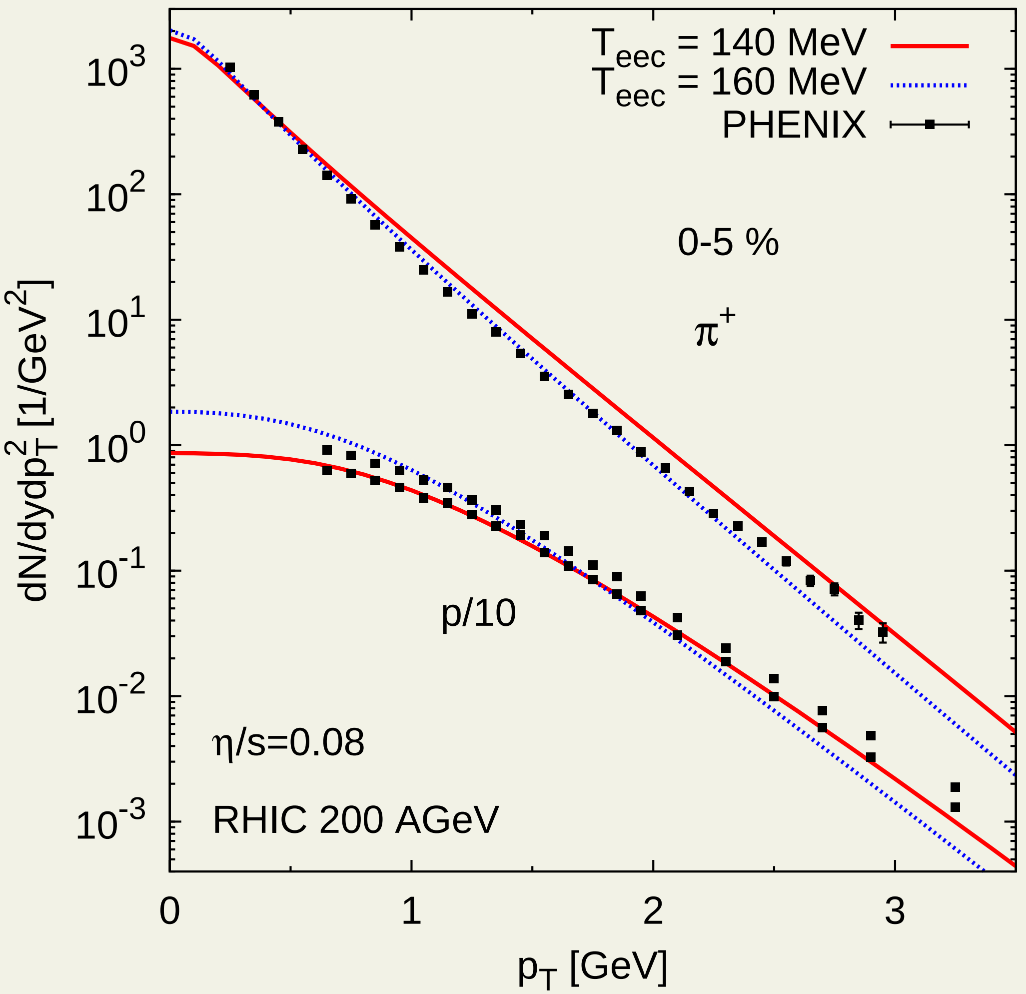

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$v_2(p_T)$ from viscous hydro

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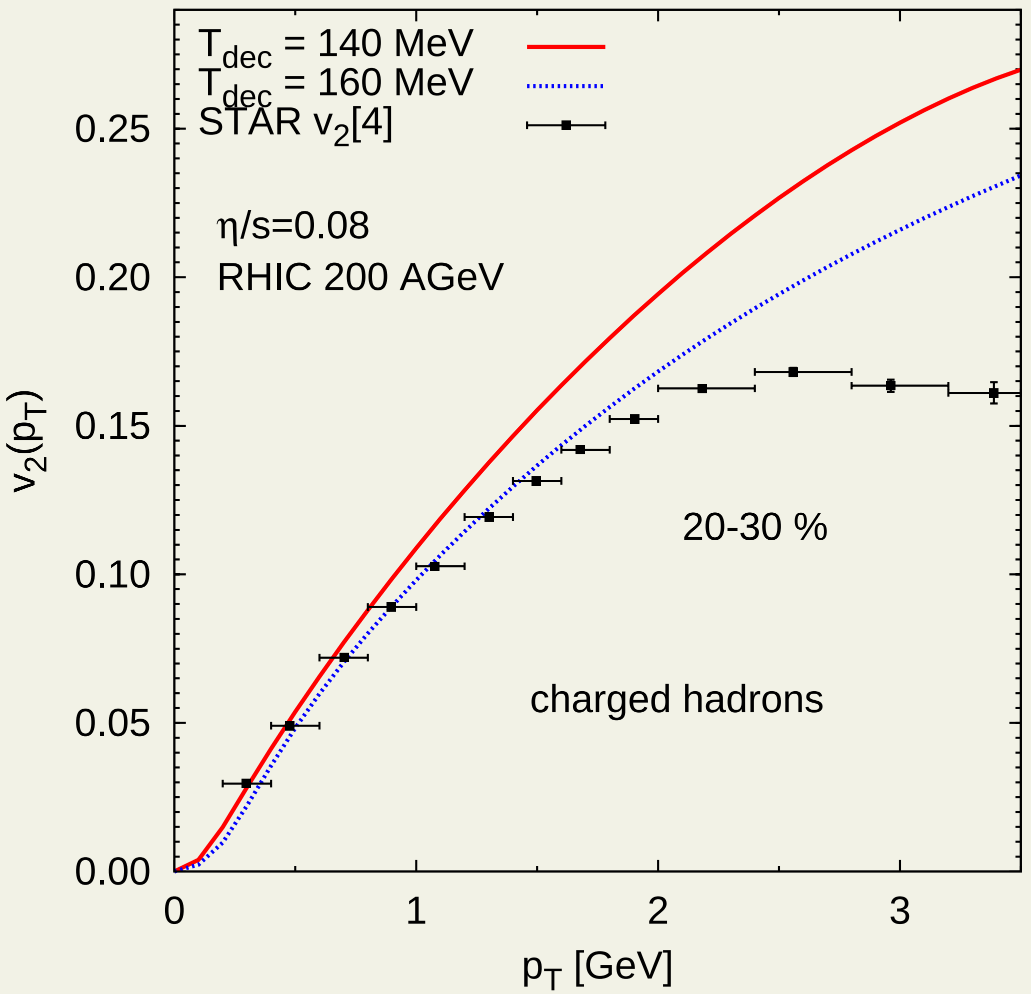

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$v_2(p_T)$ of protons

Reproduction of Luzum & Romatschke:

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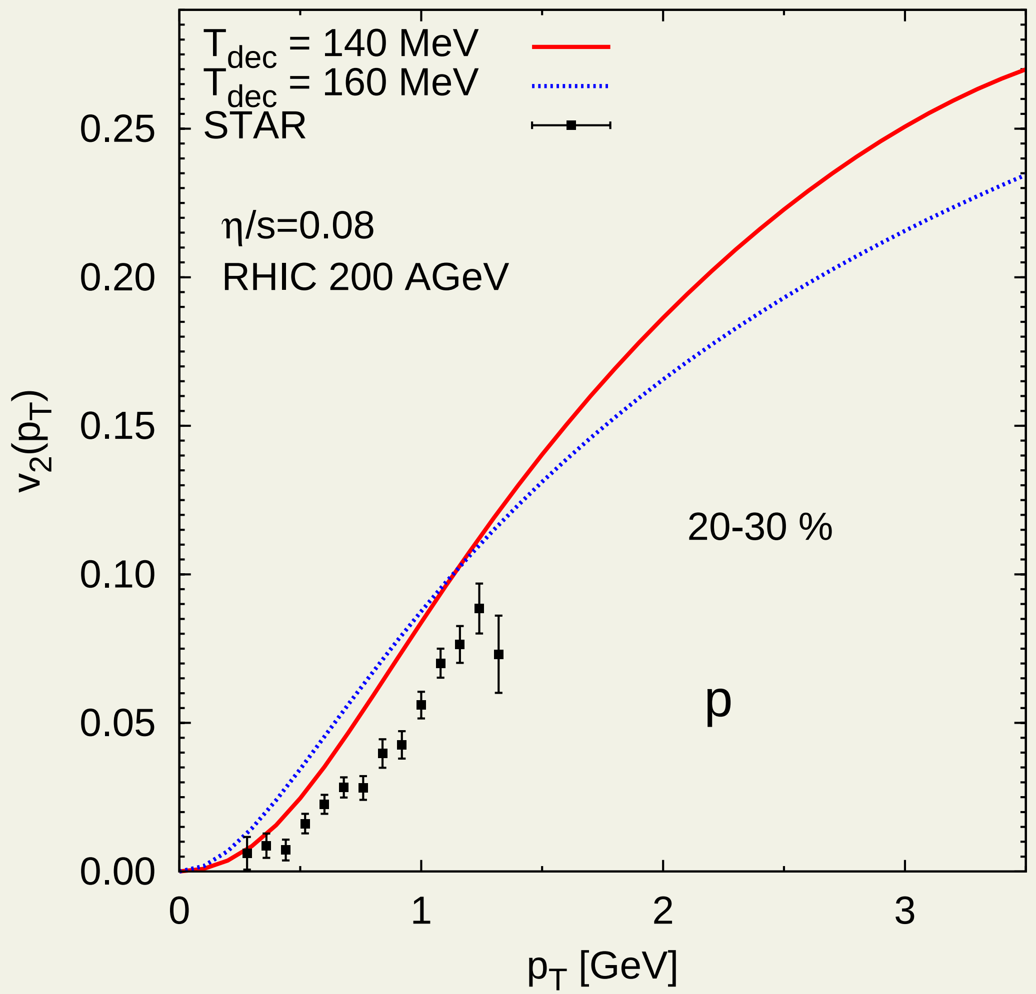

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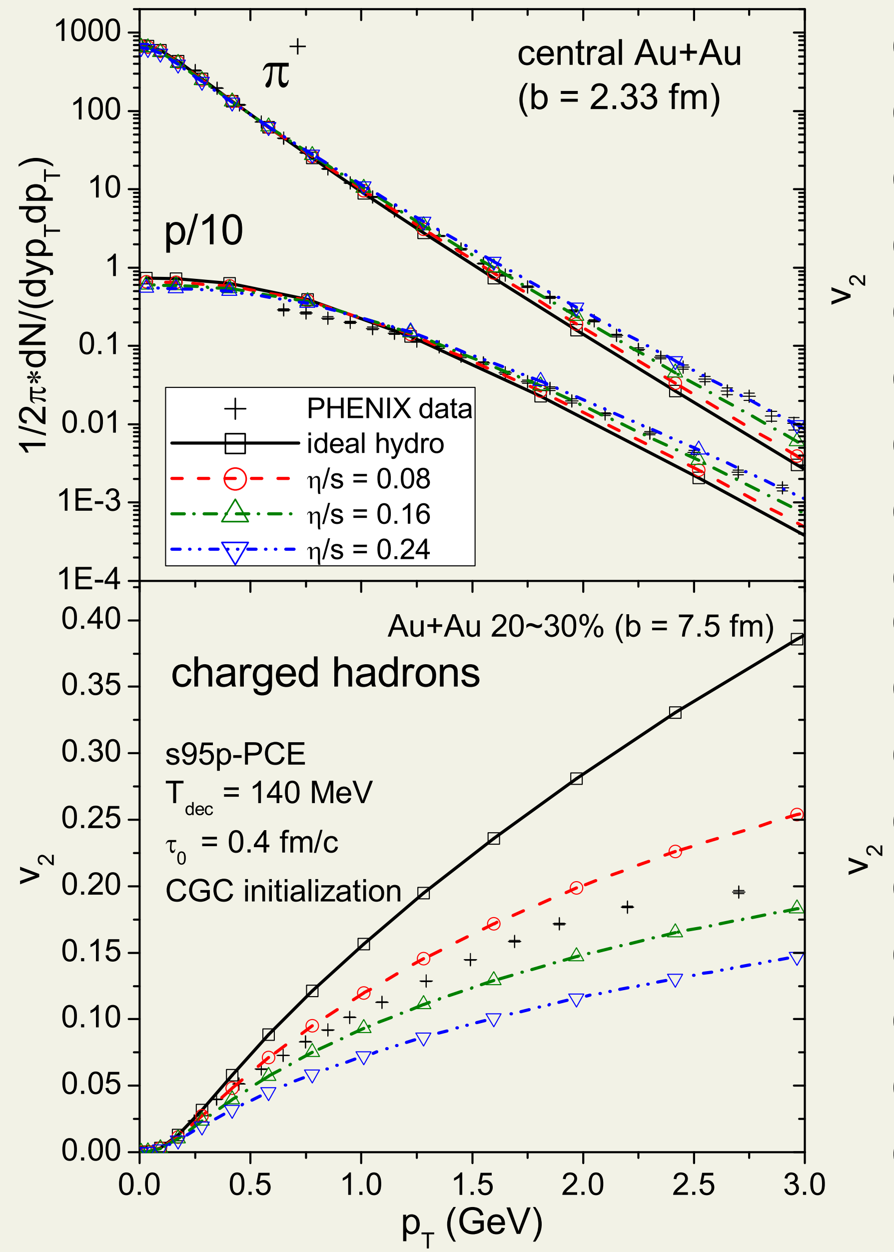
no sweet spot!

Shen *et al.*, PRC82, 054904 (2010)

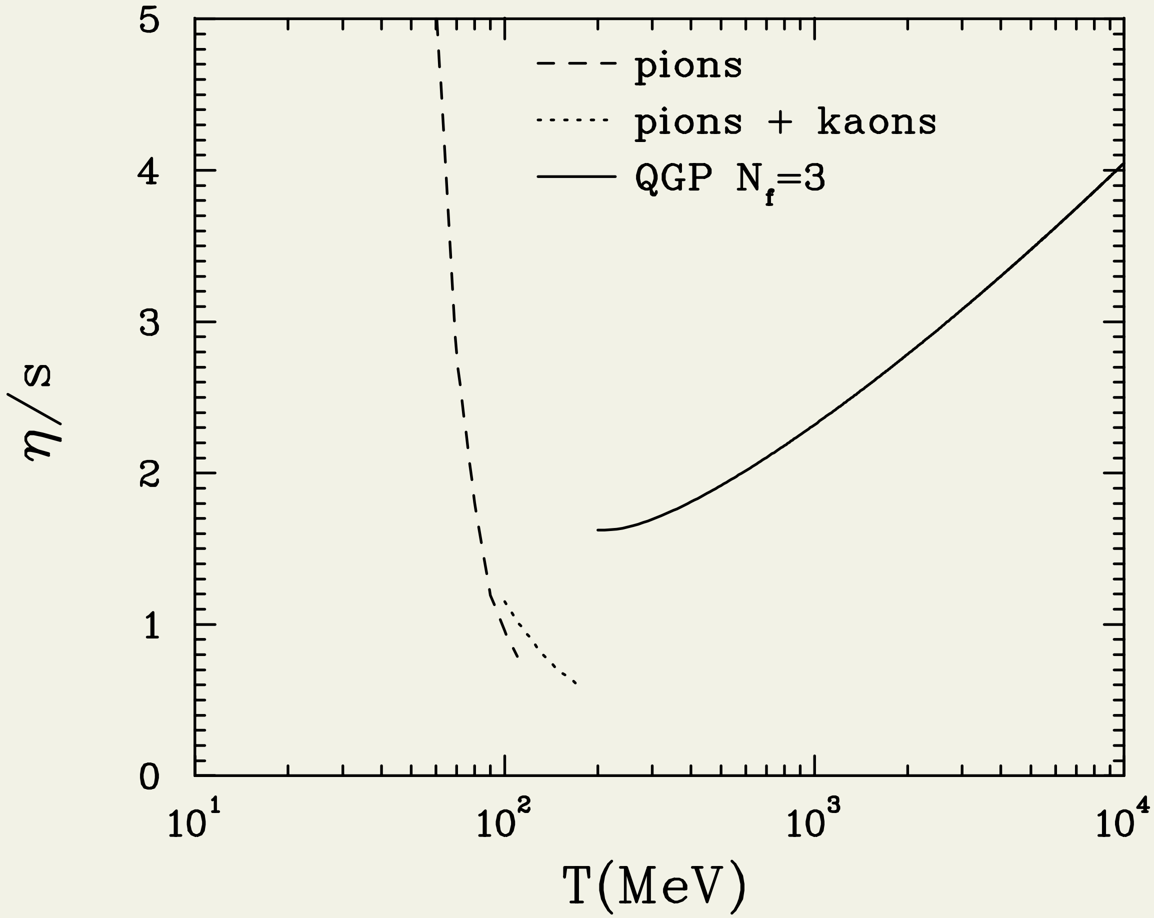
Systematic study:
(chemically frozen EoS)

- **protons:** $\eta/s \sim 2\text{-}3 \times \frac{1}{4\pi}$
- **charged hadrons:** $\eta/s \sim 1\text{-}2 \times \frac{1}{4\pi}$
- **cannot be resolved by adjusting other parameters**



$\eta/s(T)$

Kapusta, McLerran and Csernai, nucl-th/0604032:

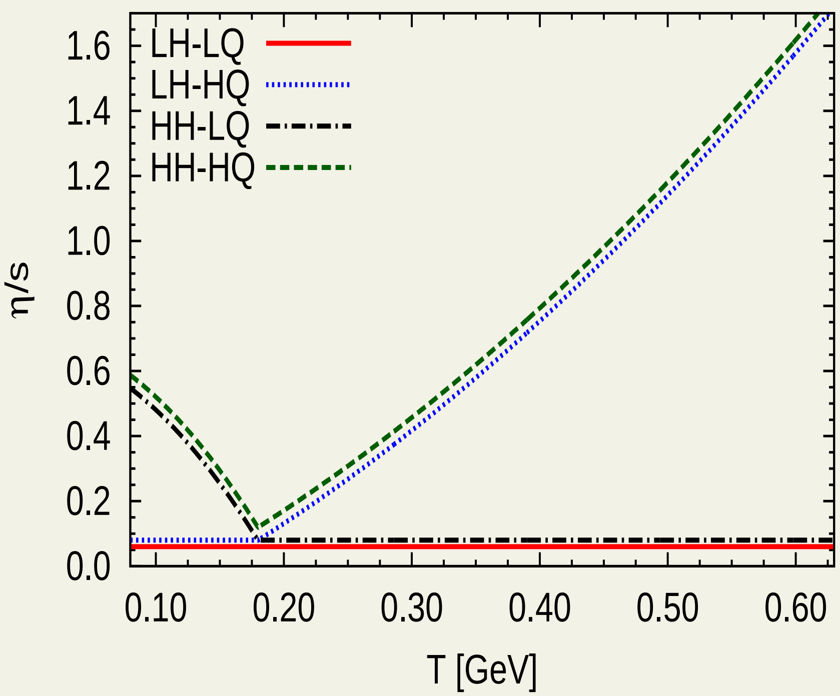


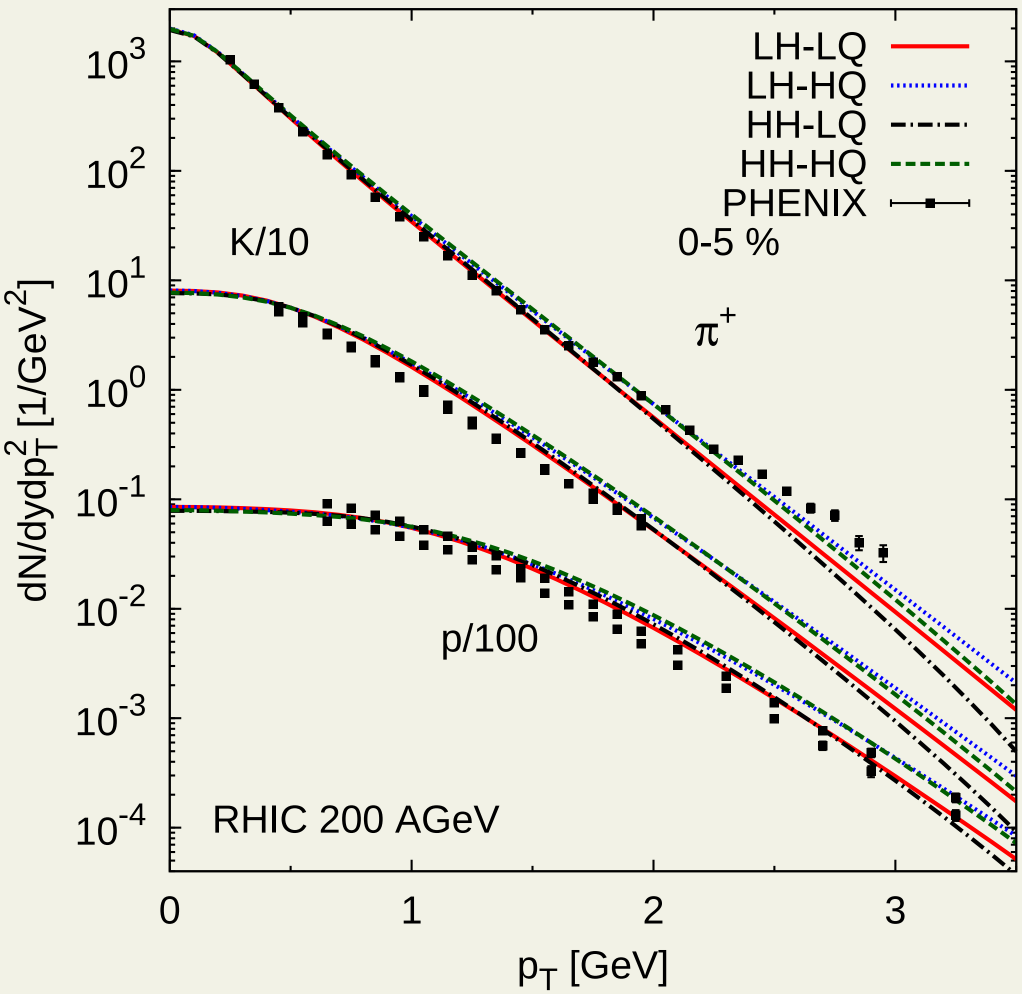
Low T (*Prakash et al.*) **using experimental data for 2-body interactions**

High T (*Yaffe et al.*) **using perturbative QCD**

$\eta/s(T)$

Niemi *et al.*, arXiv:1101.2442

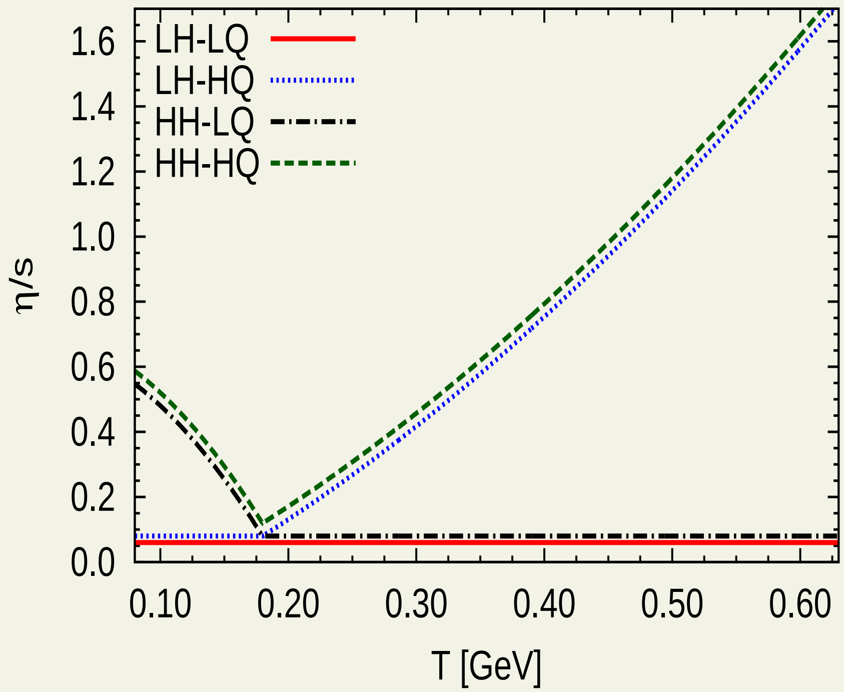


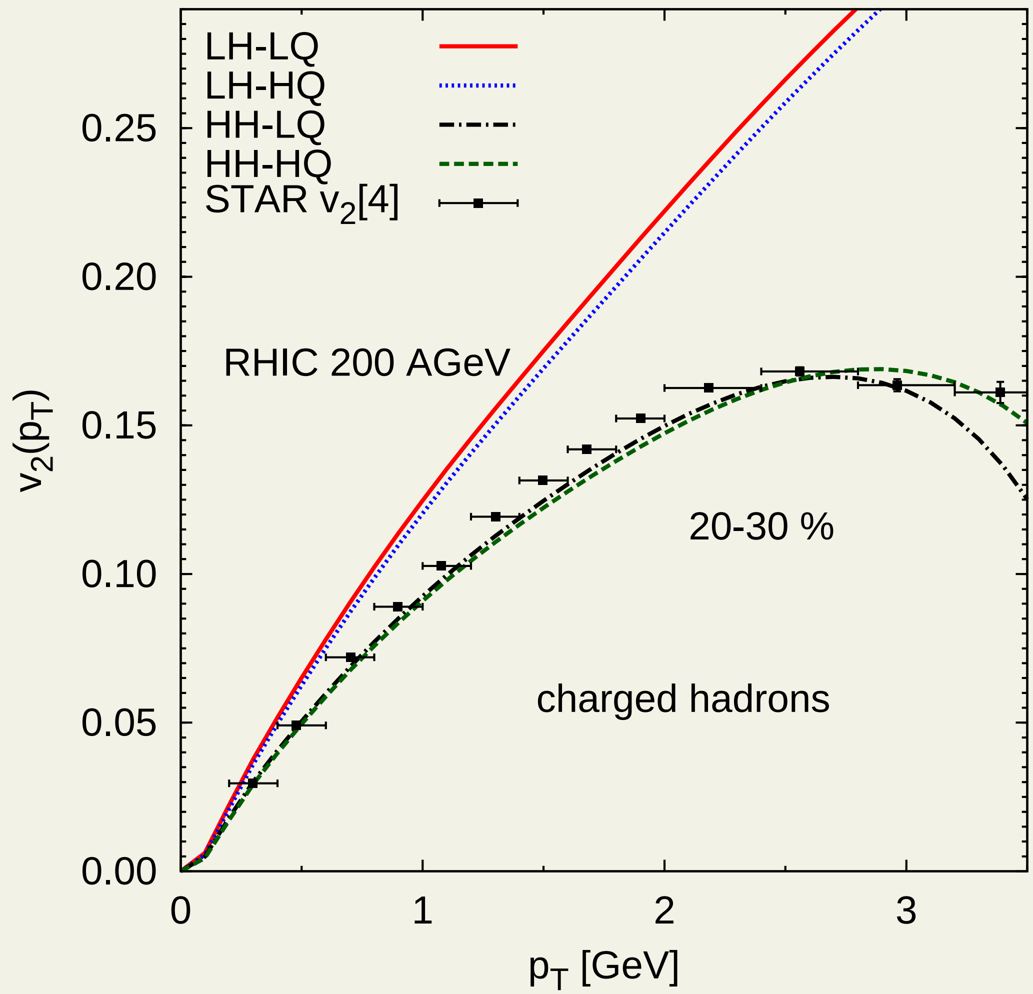


- p_T **spectra mostly sensitive to** $\eta/s(T)$ **in QGP**

$\eta/s(T)$

Niemi *et al.*, arXiv:1101.2442

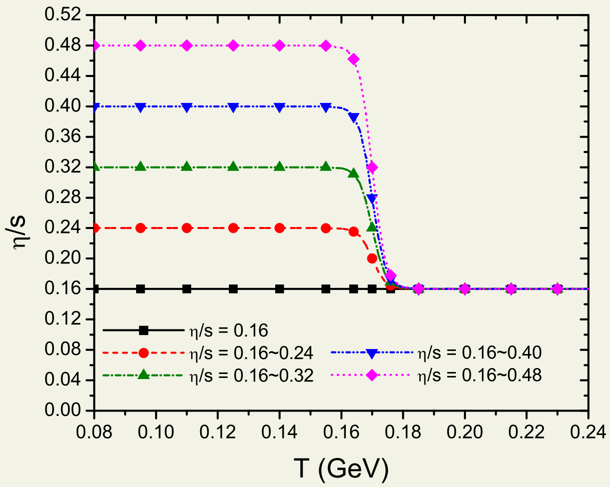


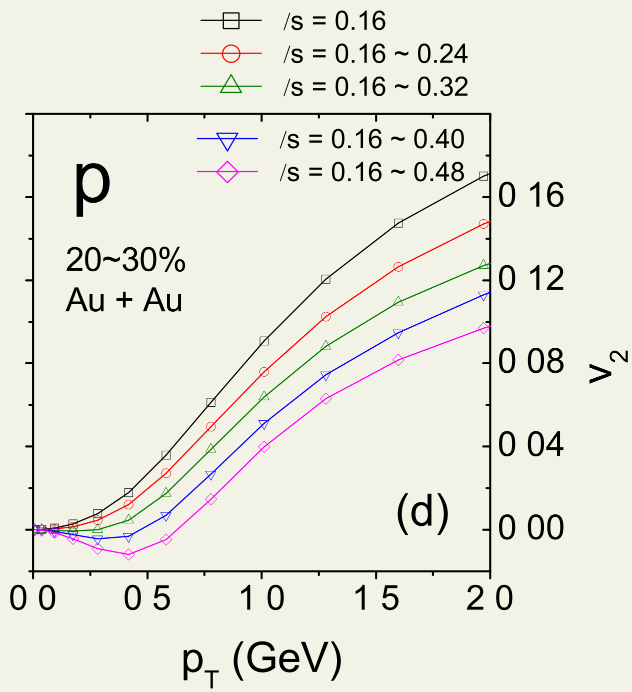


- $v_2(p_T)$ **mostly sensitive to hadronic** $\eta/s(T)$**!**

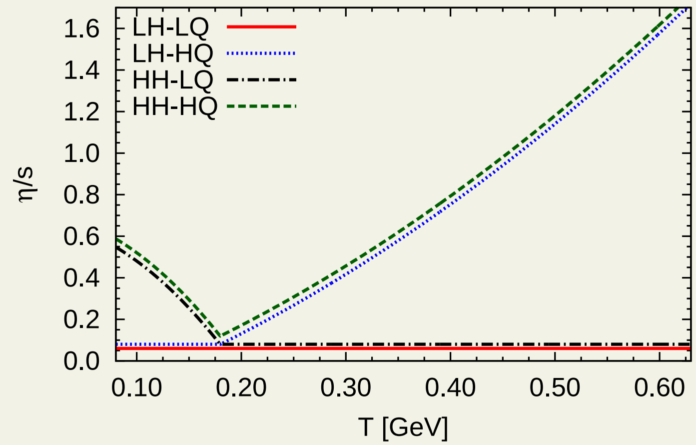
$\eta/s(T)$ and protons

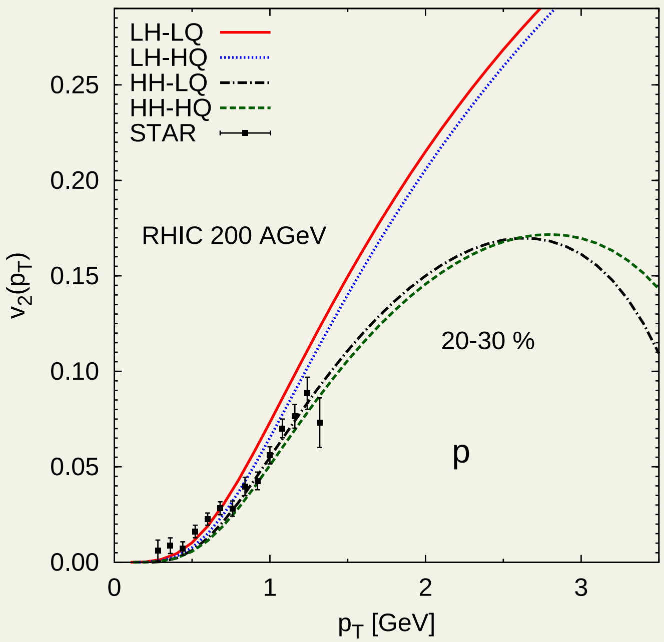
Shen & Heinz, arXiv:1101.3703





Niemi *et al.*, arXiv:1101.2442



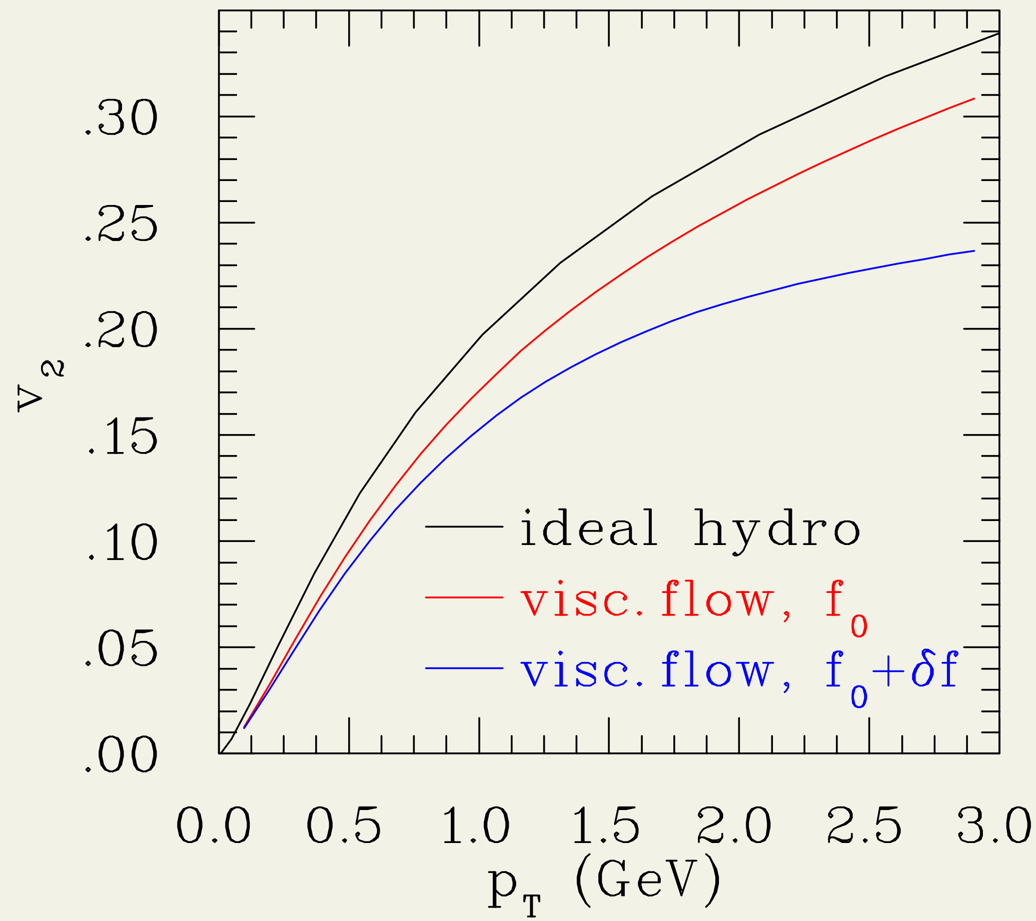


δf

TWO effects: - **dissipative corrections to hydro fields** u^μ, T, n
- **dissipative corrections to thermal distributions** $f \to f_0 + \delta f$

$\eta/s \approx 1/(4\pi)$ $(\sigma_{\rm tr} \propto \tau^{2/3})$

$$\delta f = f_0 \frac{p^\mu p^\nu \pi_{\mu\nu}}{8nT^3}$$



Grad 14-moment ansatz

Single particle distribution function

$$f = f_0(1 + \epsilon + \epsilon_\mu p^\mu + \epsilon_{\mu\nu} p^\mu p^\nu) = f_0(1 + \delta f)$$

Landau matching conditions $\Longrightarrow$ single component system, shear only:

$$\delta f = \frac{p_\mu p_\nu \pi^{\mu\nu}}{2(\varepsilon + P)T^2}$$

- **No reason why this would hold in multicomponent system**

δf for mixtures

Denicol *et al.*, work in progress:

Analogous to single component system:

$$\delta f_i = \frac{p_\mu p_\nu \, \pi_i^{\mu\nu}}{2(\varepsilon_i + P_i)T^2}$$

Using kinetic theory:

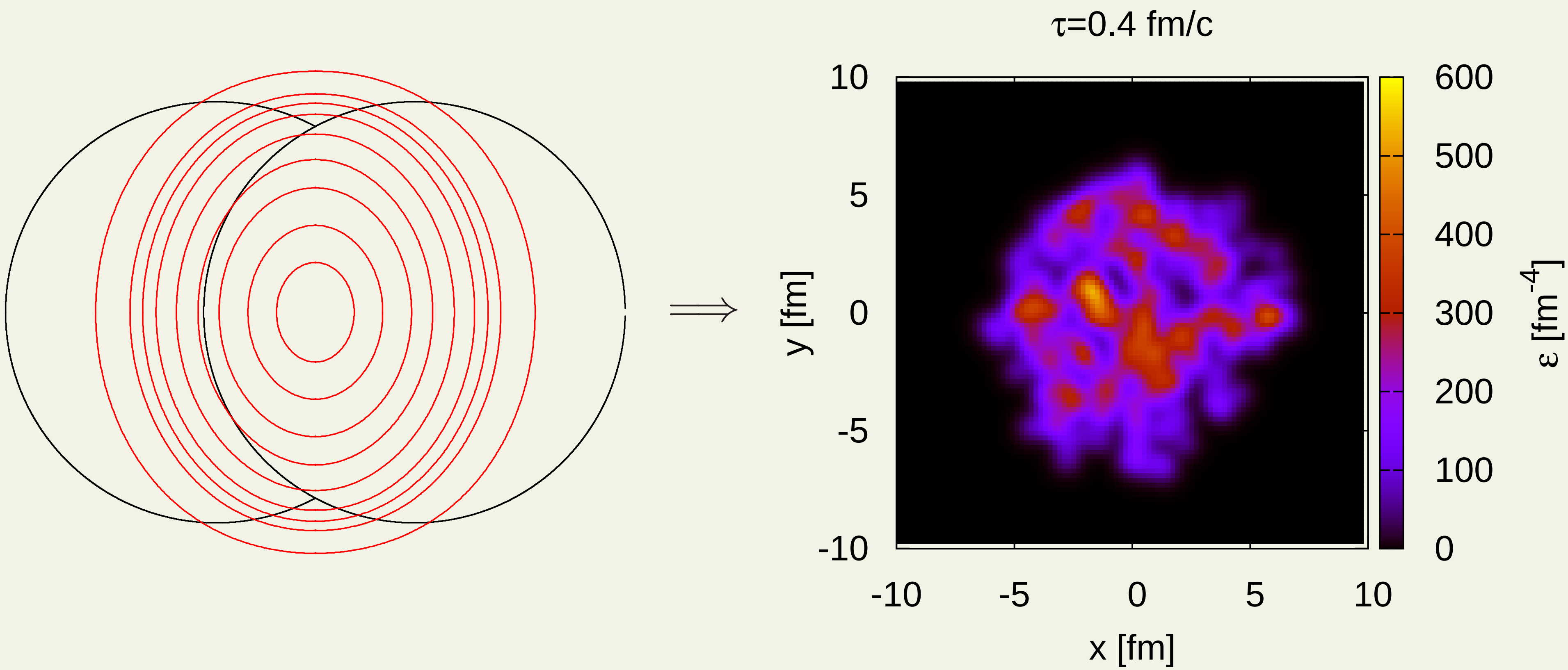
$$\delta f_i \approx \frac{p_\mu p_\nu}{2(\varepsilon_i + P_i)T^2} \frac{\eta_i}{\eta} \pi^{\mu\nu},$$

where

$$\eta_i = \mathcal{F}(\sigma_{ij}, \{m_i\}, T, \{\mu_i\})$$

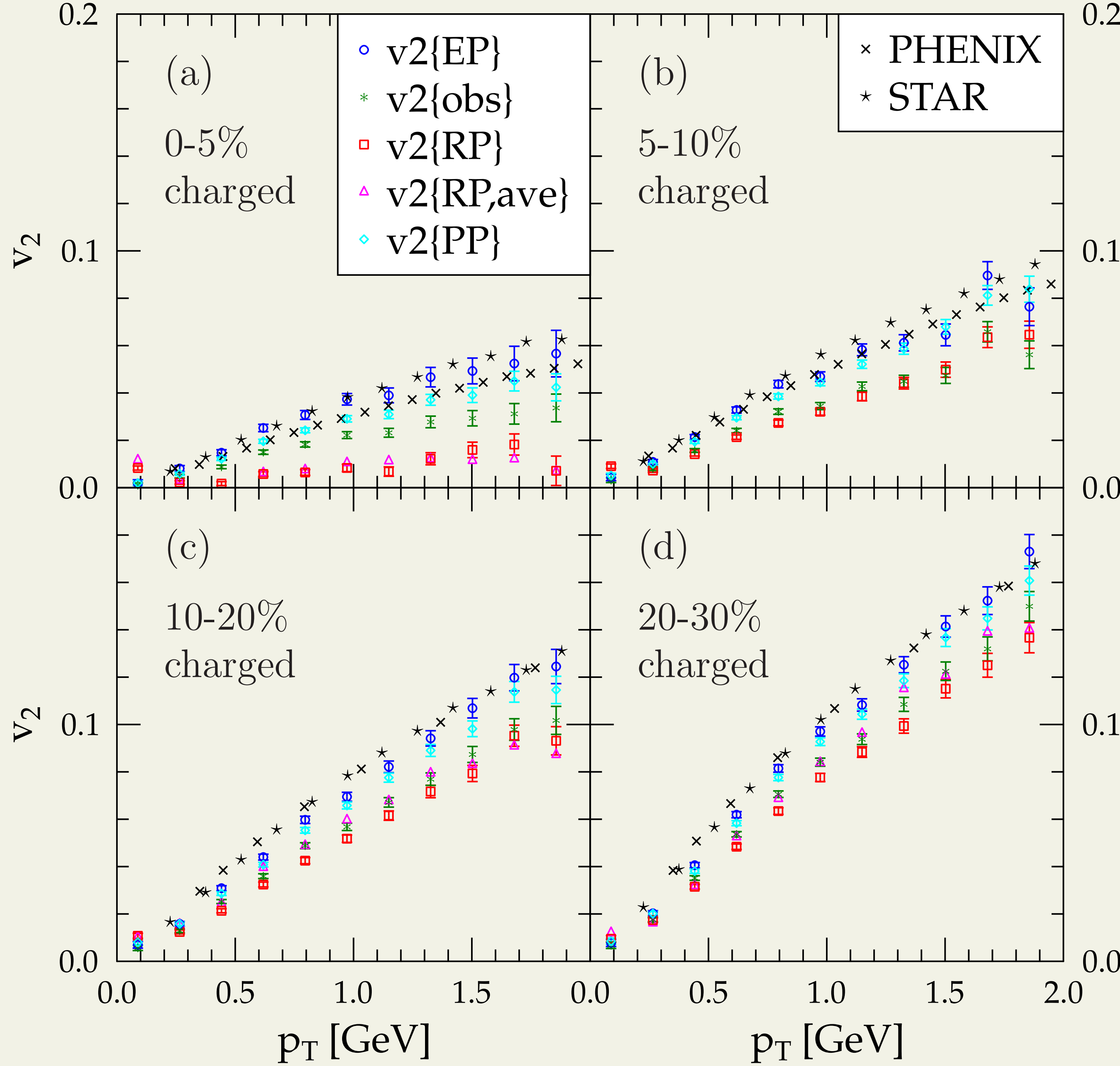
is a complicated integral over thermal distributions

Initial shape



- **shape fluctuates event to event**

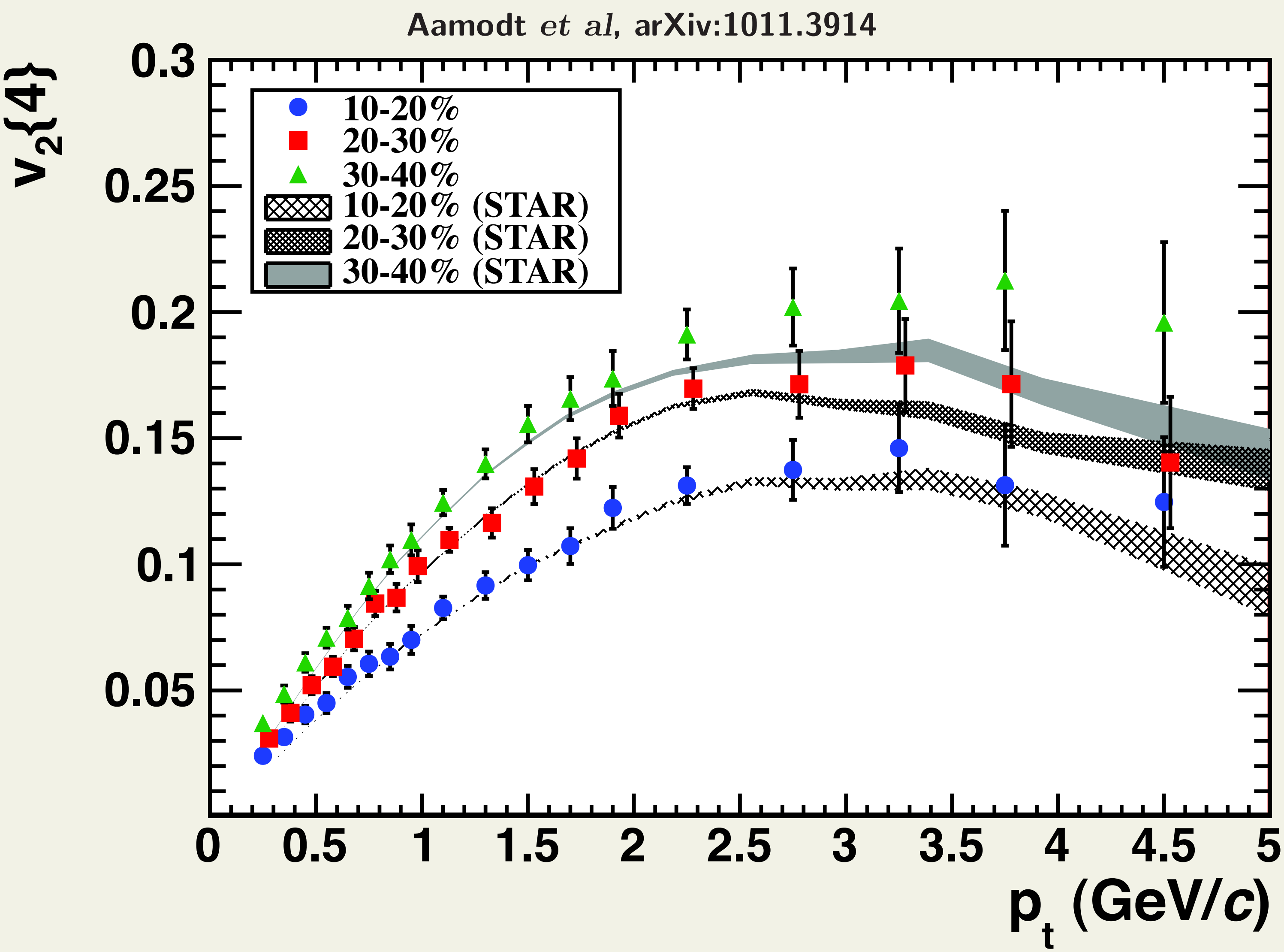
Holopainen *et al.*,
arXiv:1007.0368



- finite # of ples in final state
- WN initialization

$\Rightarrow$ room for $\eta > 0$

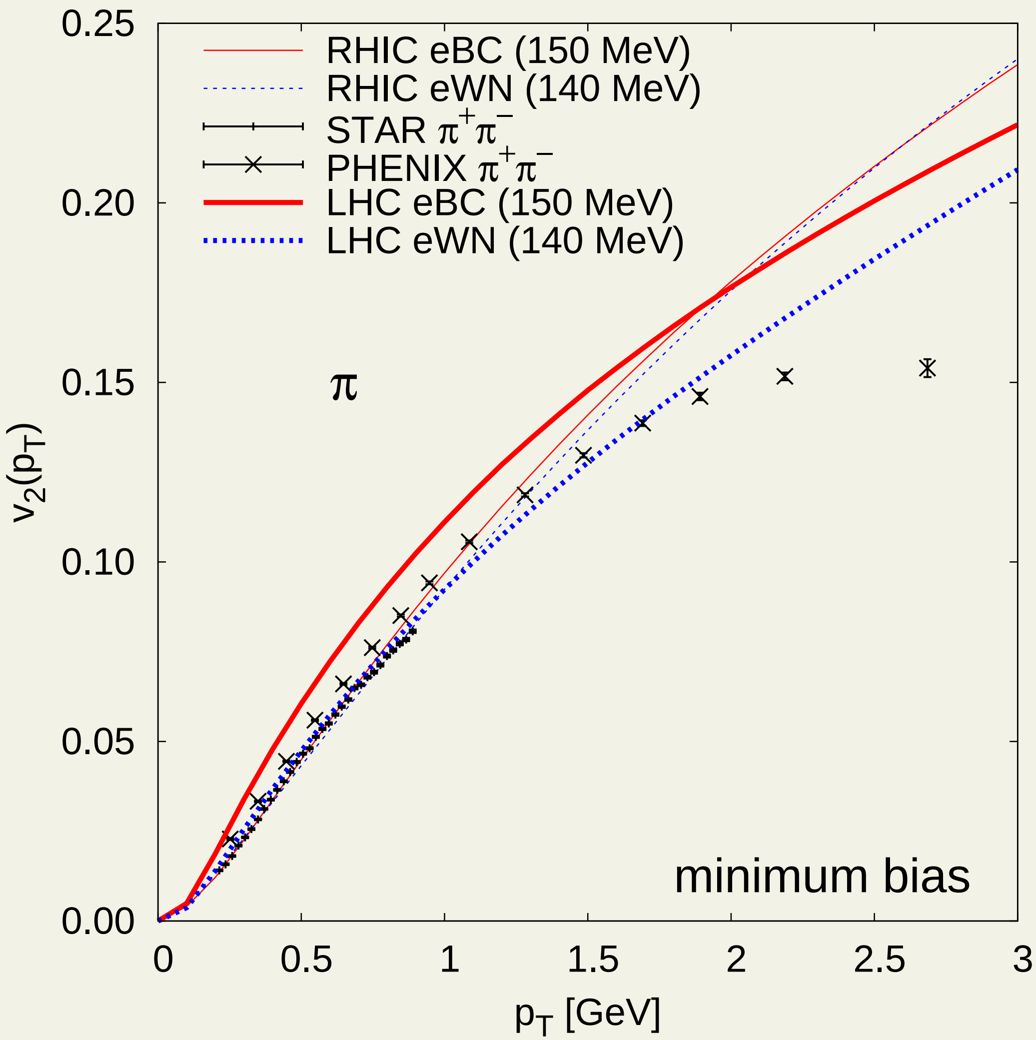
v_2 at LHC



- surprisingly **similar** $v_2(p_T)$ than at RHIC

ideal fluid prediction

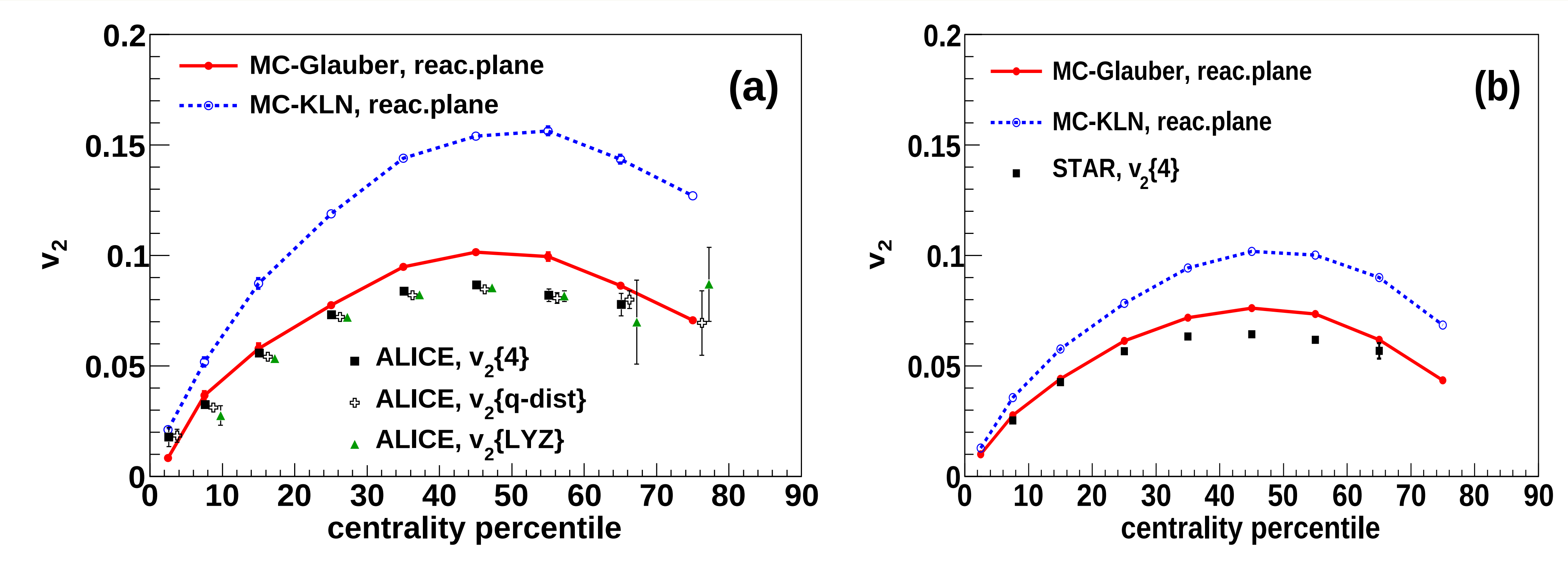
Niemi *et al*, PRC79, 024903 (2009)



- $v_2(p_T)$ **may or may not change**

hybrid model postdiction

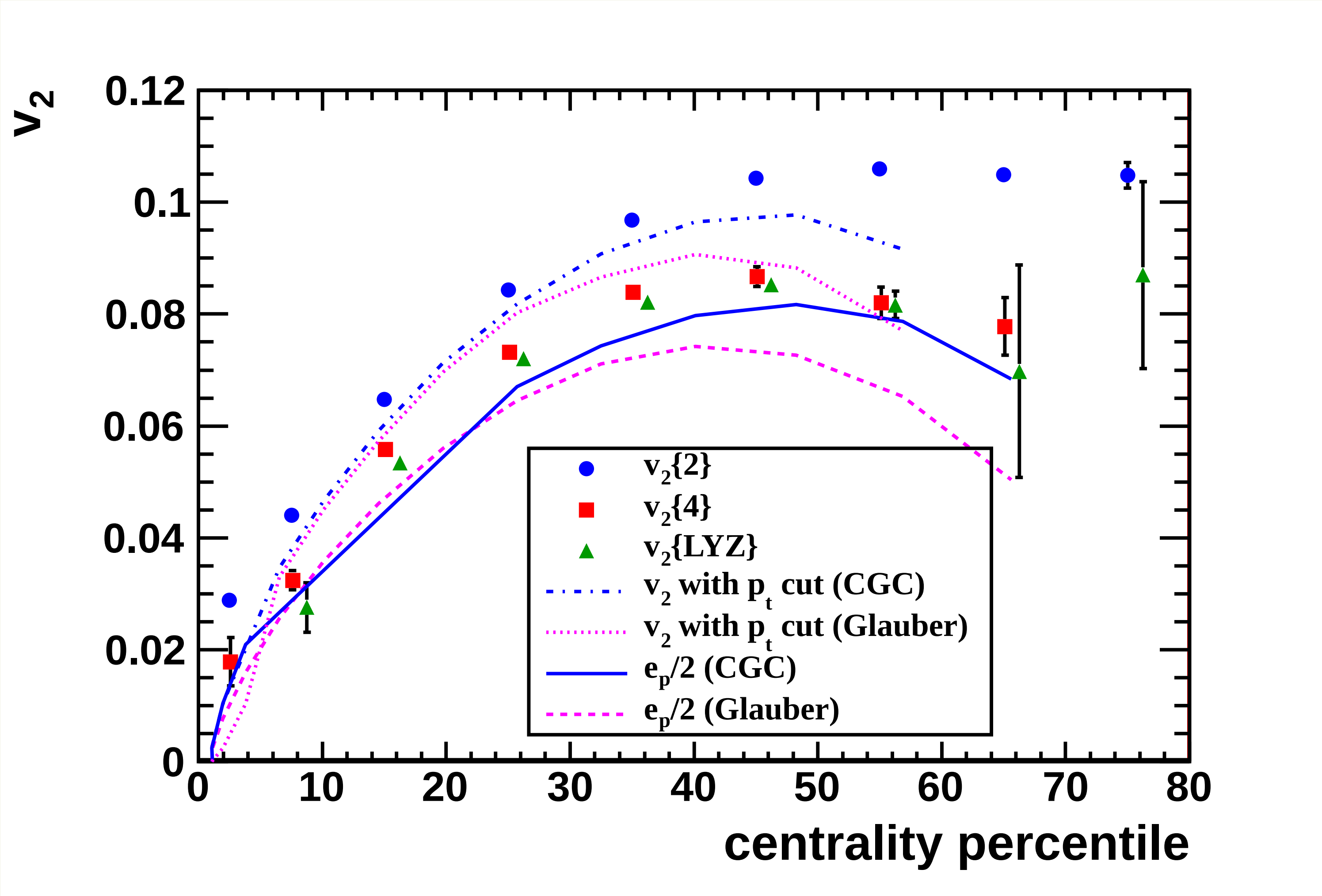
Hirano *et al.*, arXiv:1012.3955



- QGP viscosity required for CGC
- only tiny viscosity allowed for Glauber

viscous hydro prediction

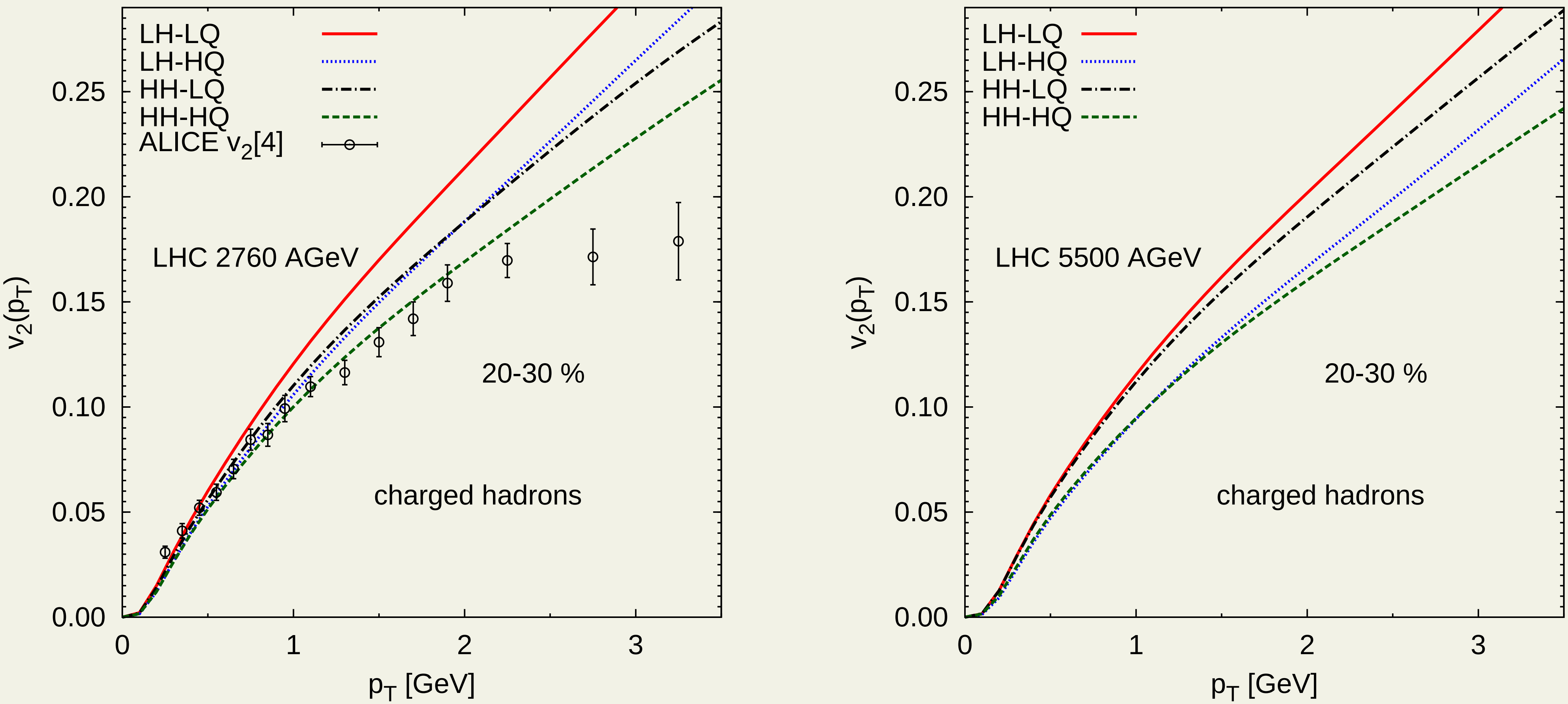
Luzum, arXiv:1011.5173; Luzum & Romatschke, PRL103, 262302 (2009)



- $\eta/s = 0.08$ **or** $\eta/s = 0.16$ **depending on initialization**

$\eta/s(T)$ at LHC

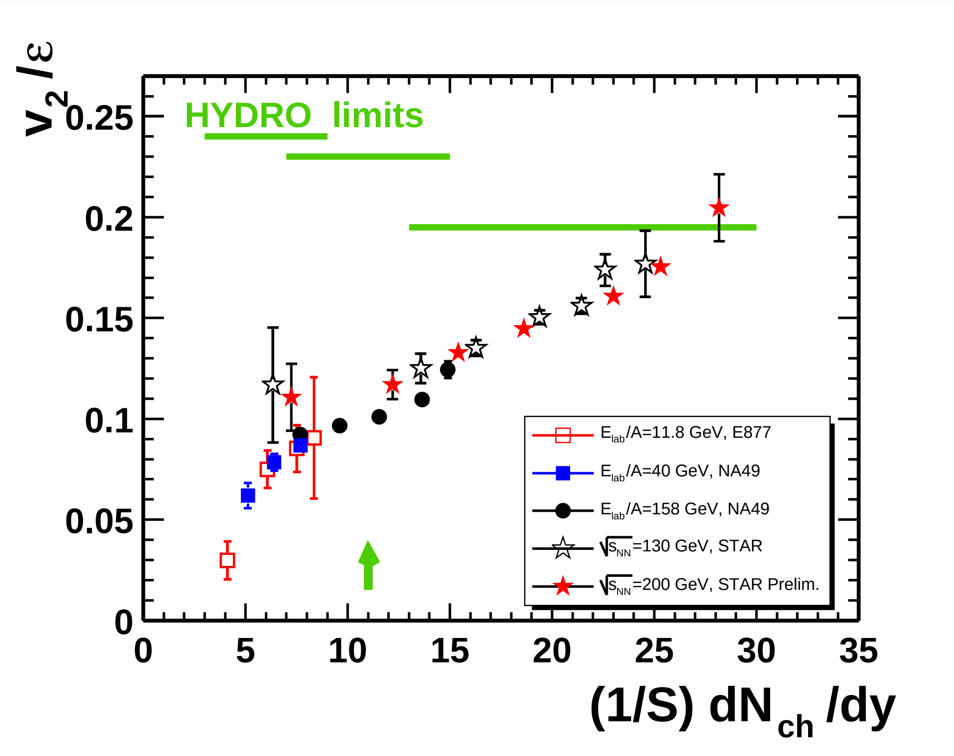
Niemi *et al.*, arXiv:1101.2442



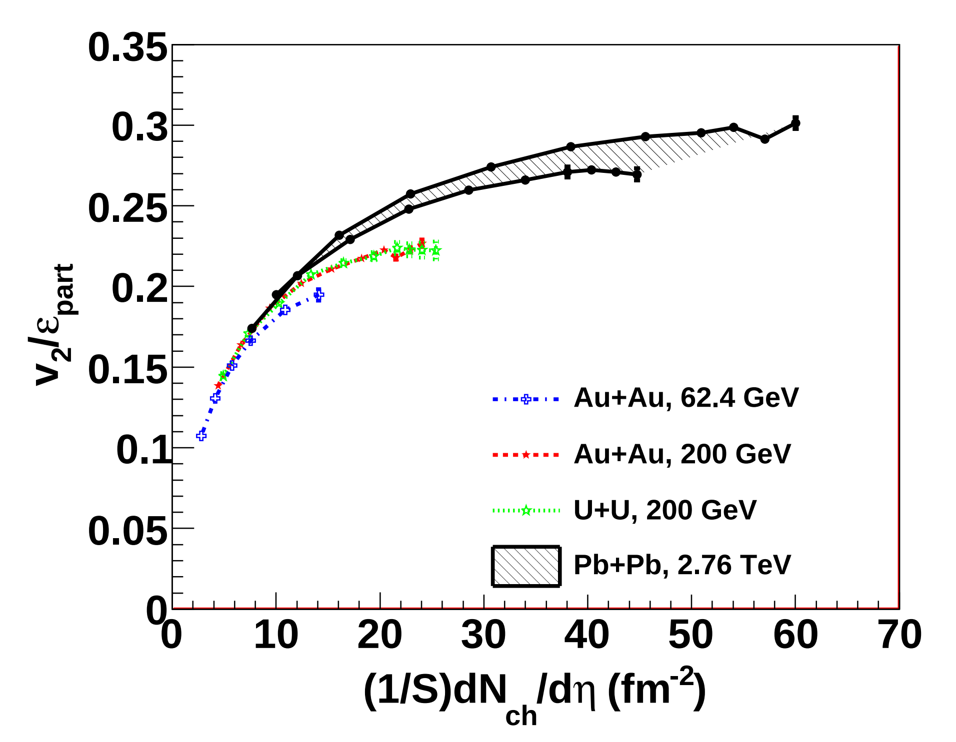
- **at the top LHC energy η/s of plasma dominates**

v_2/ϵ vs. $(1/S)\,dN/dy$

Alt *et al.*, PRC68, 034903 (2003)



Hirano *et al.*, arXiv:1010.6222



- scaling may be broken at LHC!

Conclusions

- fitting data using viscous hydro is difficult
- $\eta/s(T)$ of QGP cannot be constrained using RHIC v_2 data only
  - LHC helps
- δf a big uncertainty
- initial state fluctuations important
- @ LHC v_2 depicts hydrodynamical behaviour