Collective flow - status and open questions

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Theory meets Experiment:
Theory-Experiment Collaboration for Hot QCD Matter
(TECHQM)

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What is flow?

- Correlations of position and momentum

- Is there longitudinal flow at RHIC?
  - yes
  - no, those correlations originate in primary collisions

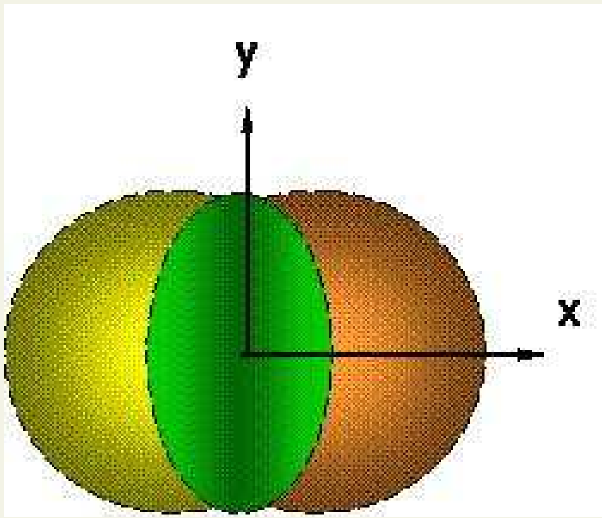
$\rightarrow$ Collective motion arising from rescatterings is difficult to define. . .

- Transverse flow: flow velocity

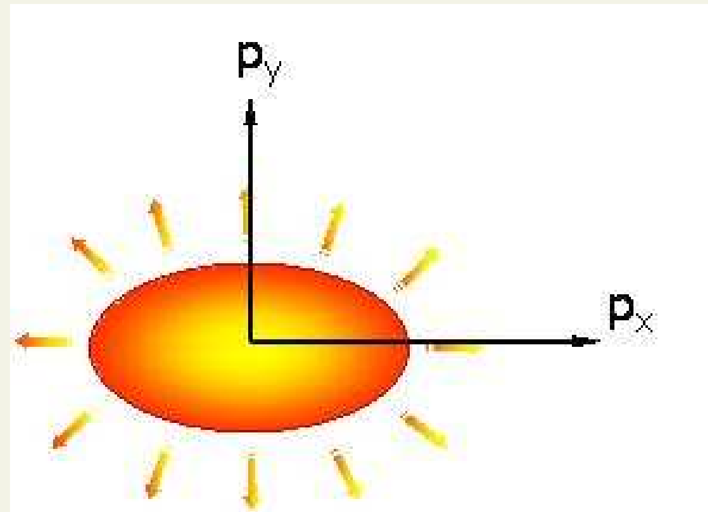
- Anisotropic flow: elliptic flow, v_2, and hexadecupole flow, v_4

Flow as anisotropy

spatial anisotropy $\longrightarrow$ final azimuthal momentum anisotropy



$\longrightarrow$



$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

$$v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

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

Two extremes

- **Ideal fluid hydrodynamics works fine!**
  - **Broniowski** $et\ al$**, arXiv:0801.4361**
  - **reproduces spectra, yields,** v_2 **and HBT in Au+Au collisions at RHIC.**
  - **steep initial profile, hard EoS, resonance decays in HBT calculation**

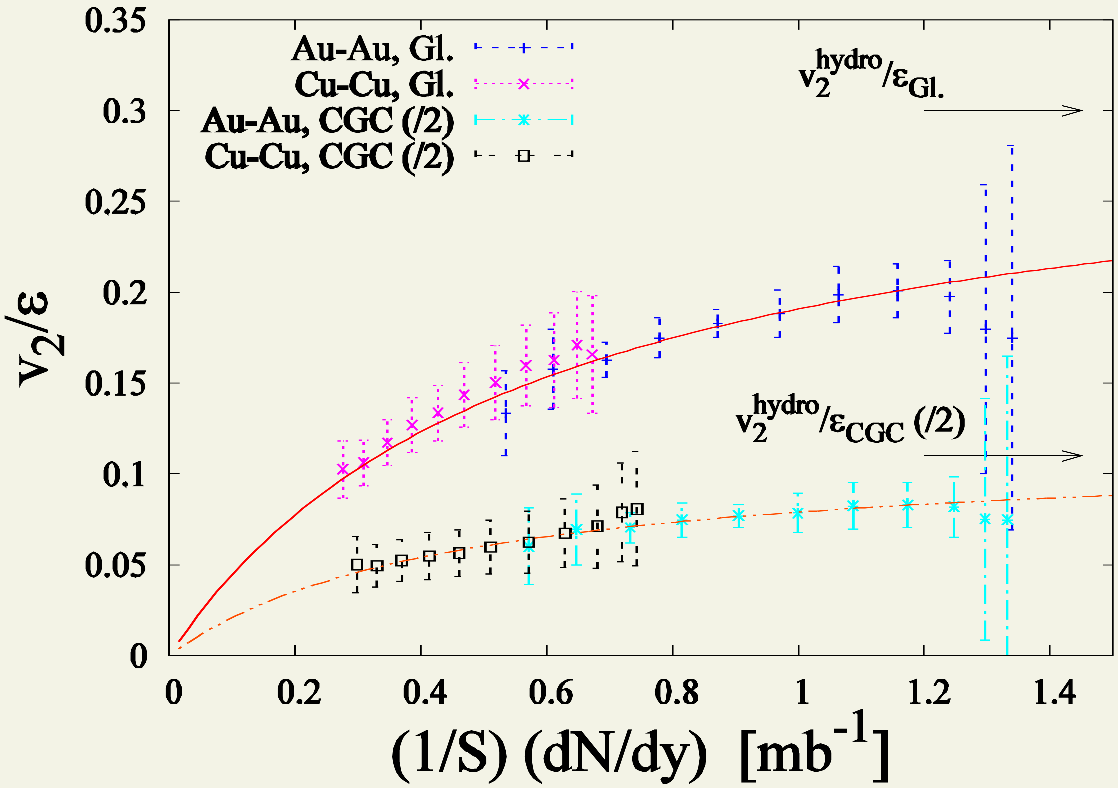
- **Collision system is not thermal**
  - **Ollitrault** $et\ al$**, Phys. Rev. C 76, 024905 (2007)**
  - **incomplete thermalization based on** v_2/ϵ vs. $1/S\,dN/dy$

Incomplete thermalization

- In (2D) Boltzmann hydro v_2 depends on Knudsen number:

$$K = \frac{\lambda}{R}, \qquad \frac{v_2}{\epsilon} = \frac{v_2^{\mathrm{hydro}}}{\epsilon} \frac{1}{1+1.4K}$$

- Assuming $1/K = (\sigma/S)(dN/dy)$
- Fit the data using σ and v_2^{hydro} as fit parameters
- v_2 30% below ideal hydro!



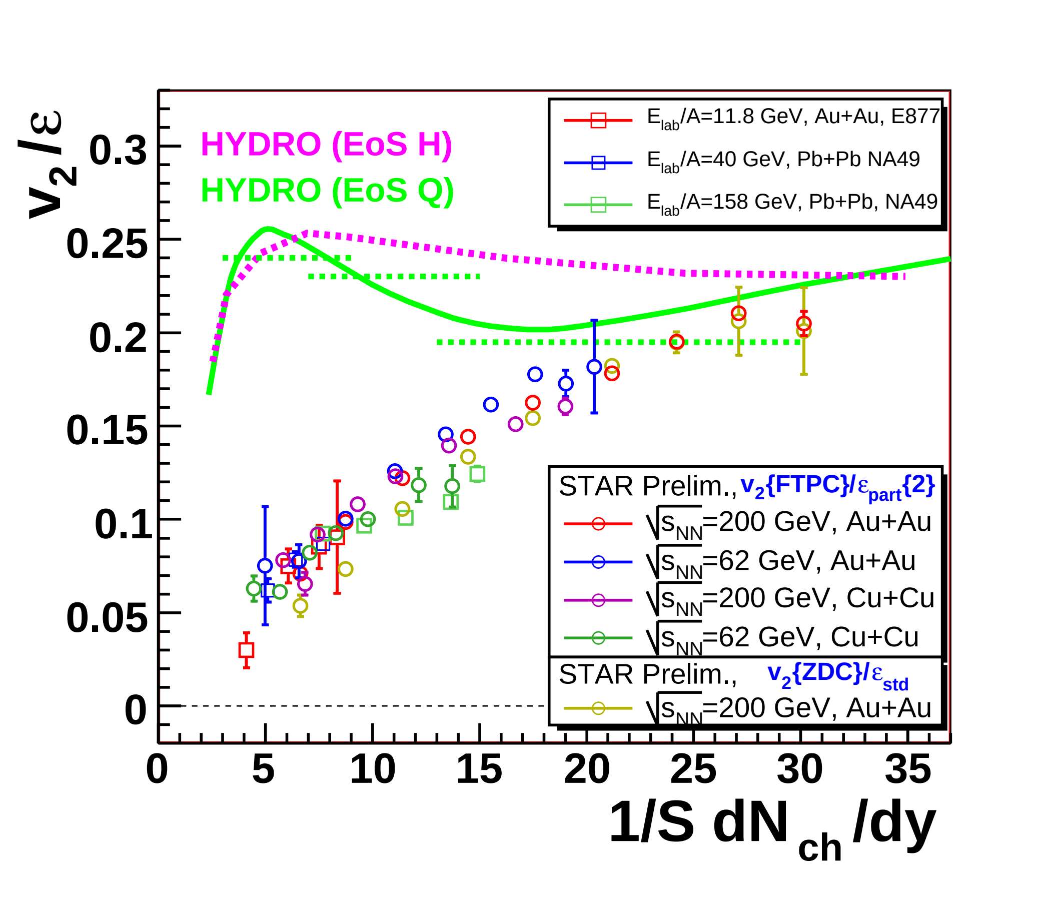
J.-Y. Ollitrault, talk at hydro workshop at BNL

But

- **Based on 2 dimensional Boltzmann transport. . .**
- **Does this work for any EoS?**
- **Even freeze-out spoils perfect v_2/ϵ scaling**
- **In this argument even freeze-out means non-zero mean free path and thus incomplete thermalization**

First task:

- Multiplicity/centrality behavior of v_2/ϵ?

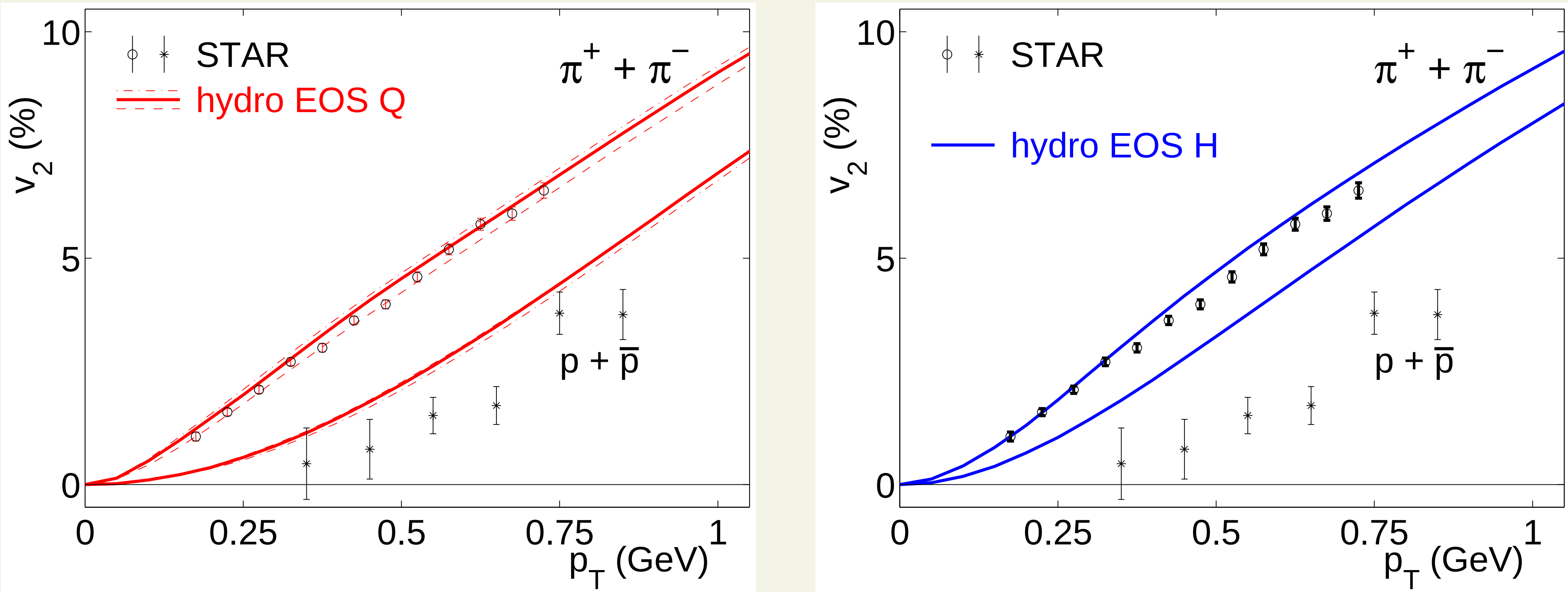


S. Voloshin and STAR collaboration, J. Phys. G. 34, S883 (2007)

- is ideal hydro+cascade able to explain it?
- is viscous hydrodynamics able to explain it?

Success of ideal hydrodynamics

Kolb, Heinz, Huovinen et al ('01) **minbias Au+Au at RHIC**

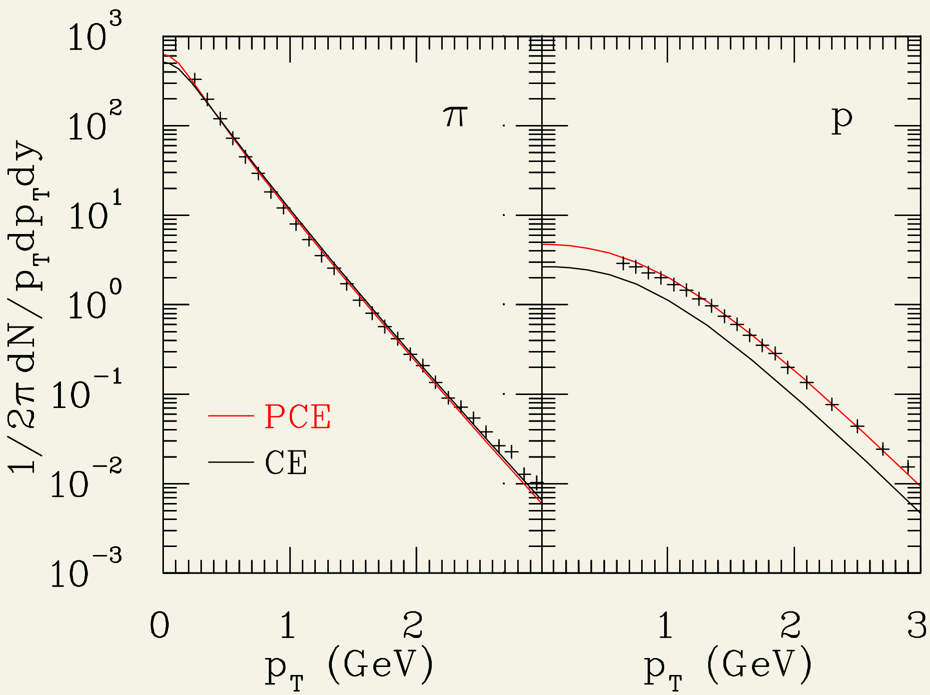


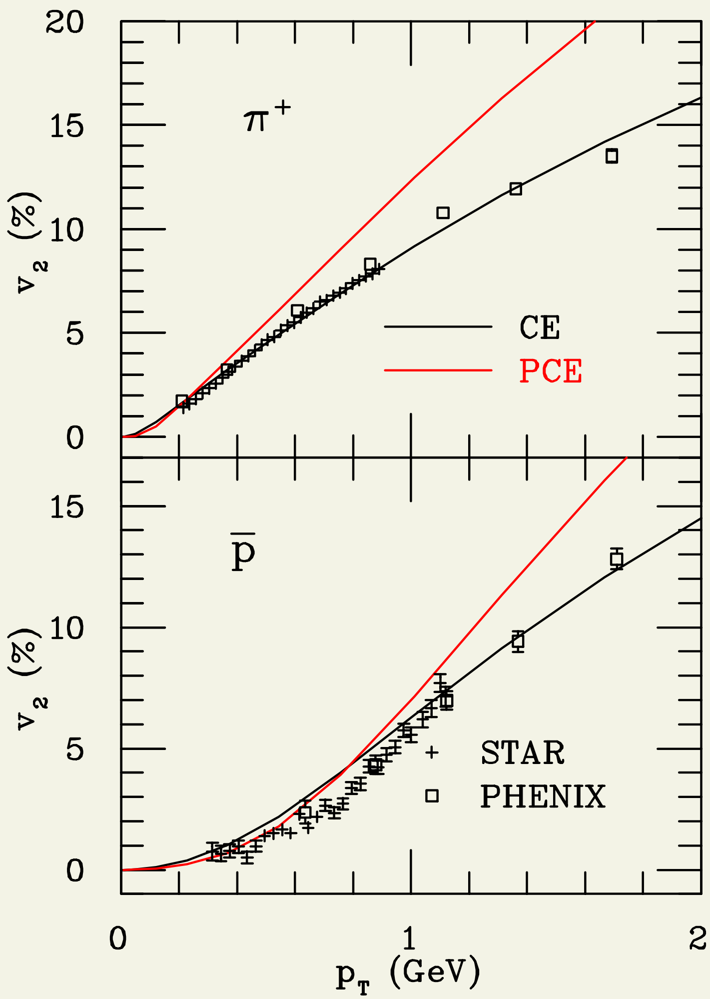
not perfect agreement but plasma EoS favored

- **crucial assumption: chemical equilibrium in hadron gas**

Chemical non-equilibrium

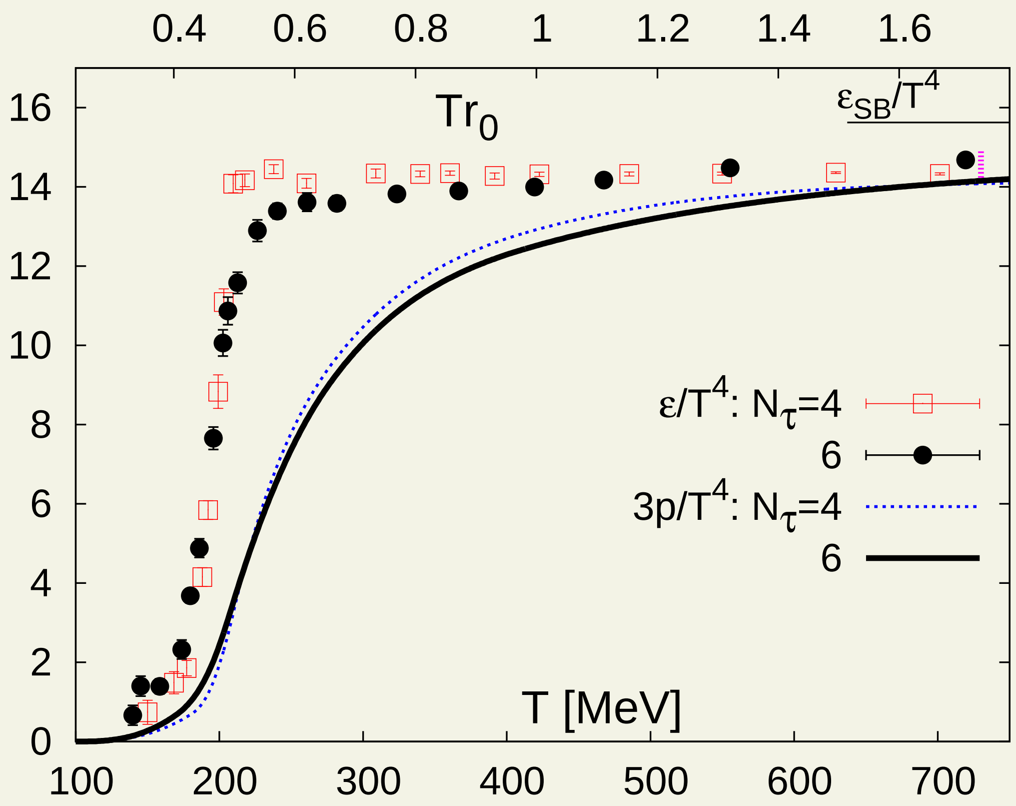
- required to fit observed particle yields
- Hirano & Tsuda and Kolb & Rapp ('02), PH ('07):
  one can fit two of the following: slopes, yields, $v_2(p_T)$, not all of them





- dissipation in hadron gas required
  - hadron cascade
  - viscous hydro

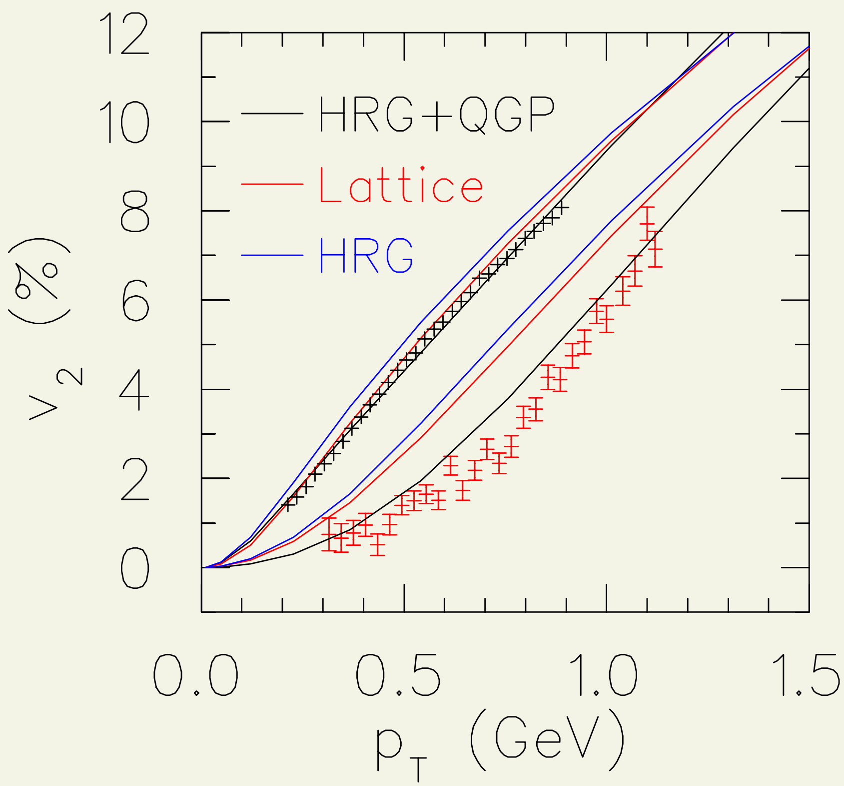
Equation of State



Cheng *et al*, Phys. Rev. D 77, 014511 (2008)

- **Lattice QCD: crossover**
- **First order phase transition in many calculations**
- **Any effect?**

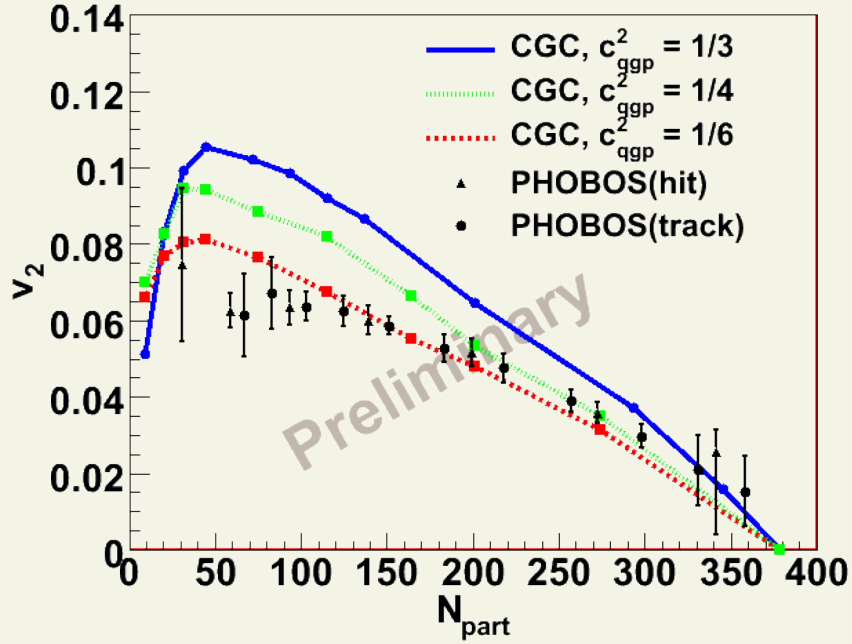
Equation of State



proton v_2 sensitive to EoS

- first order phase transition better than lattice?
- true for hydro + cascade?

T. Hirano, BNL workshop



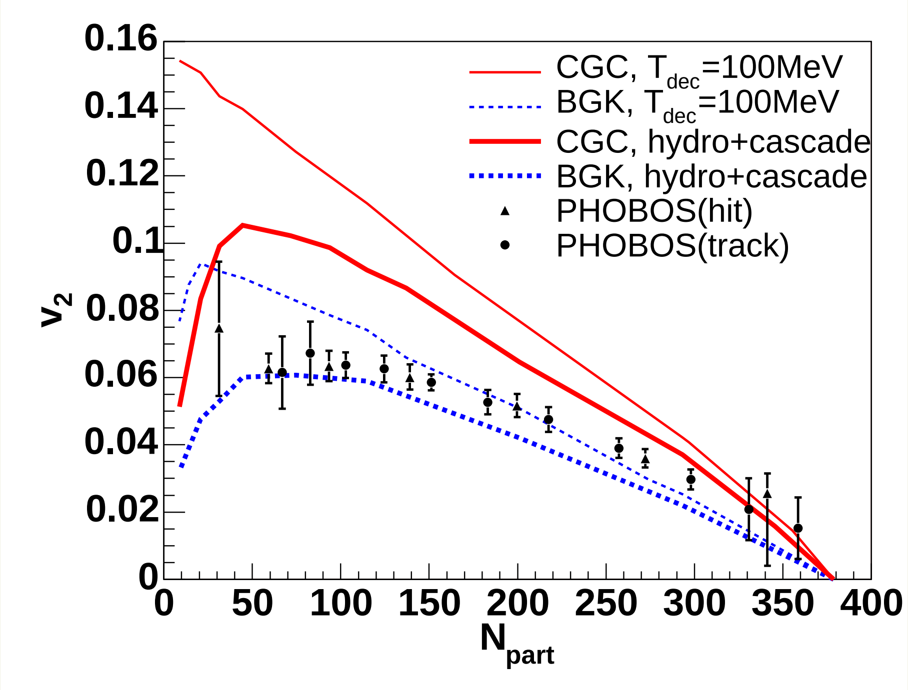
softer EoS $\rightarrow$ smaller v_2

Initial State

Glauber model or Color Glass Condensate? — or something else?

- **the steeper the initial profile, the larger the transverse flow**
- **the larger the spatial anisotropy, the larger the v_2**

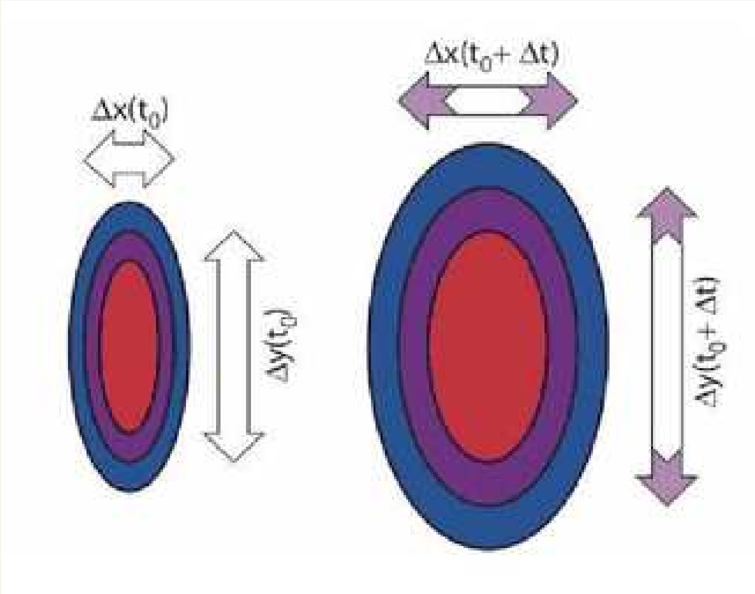
Hirano *et al.*, PLB 636, 299 (2006)



Second TASK: Better constraints to the initial state essential

Initial time?

– particles/matter won't stand still waiting for thermalization



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– what happens before of hydrodynamical evolution?
– or instead?

Viscous hydrodynamics

relativistic Navier-Stokes hydro: small corrections linear in gradients

$$T^{\mu\nu}_{NS} = T^{\mu\nu}_{ideal} + \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha) + \zeta\Delta^{\mu\nu}\partial^\alpha u_\alpha$$

$$N^\mu_{NS} = N^\mu_{ideal} - \frac{n}{e+p}\kappa\nabla^\mu T$$

where $\Delta^{\mu\nu} \equiv u^\mu u^\nu - g^{\mu\nu}$, $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$

η, ζ shear and bulk viscosities, κ heat conductivity

two problems:

parabolic equations $\rightarrow$ acausal Müller ('76), Israel & Stewart ('79) ...

instabilities Hiscock & Lindblom, PRD31, 725 (1985) ...

Causal viscous hydro

Müller, Israel & Stewart...

$$\Delta T^{\mu\nu} \equiv \pi^{\mu\nu} + \Pi\Delta^{\mu\nu} \quad , \qquad \Delta N^{\mu} = -\tfrac{n}{e+p} q^{\mu}$$

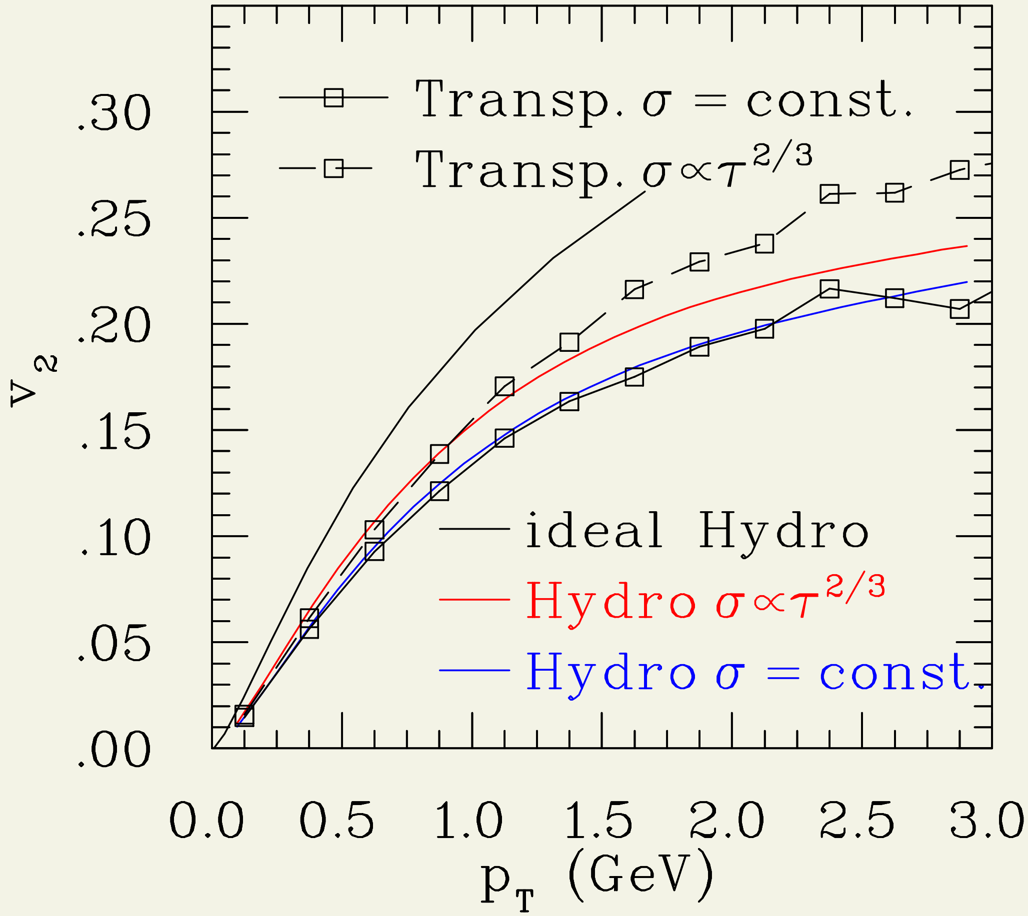
bulk pressure Π, shear stress $\pi^{\mu\nu}$ heat flow q^{μ} treated as independent dynamical quantities that relax to their Navier-Stokes value on time scales $\tau_{\Pi}(e,n)$, $\tau_{\pi}(e,n)$, $\tau_{q}(e,n)$ - corresponds to keeping not only first but (certain) second derivatives.

schematically

$$\dot{X} = -\frac{X - X_{NS}}{\tau_X} + \frac{Y}{\tau_X}$$

Caveat: Israel-Stewart hydro is NOT a controlled approximation
$\rightarrow$ test against transport
$\rightarrow$ require conformal invariance

Viscous hydro vs transport v_2

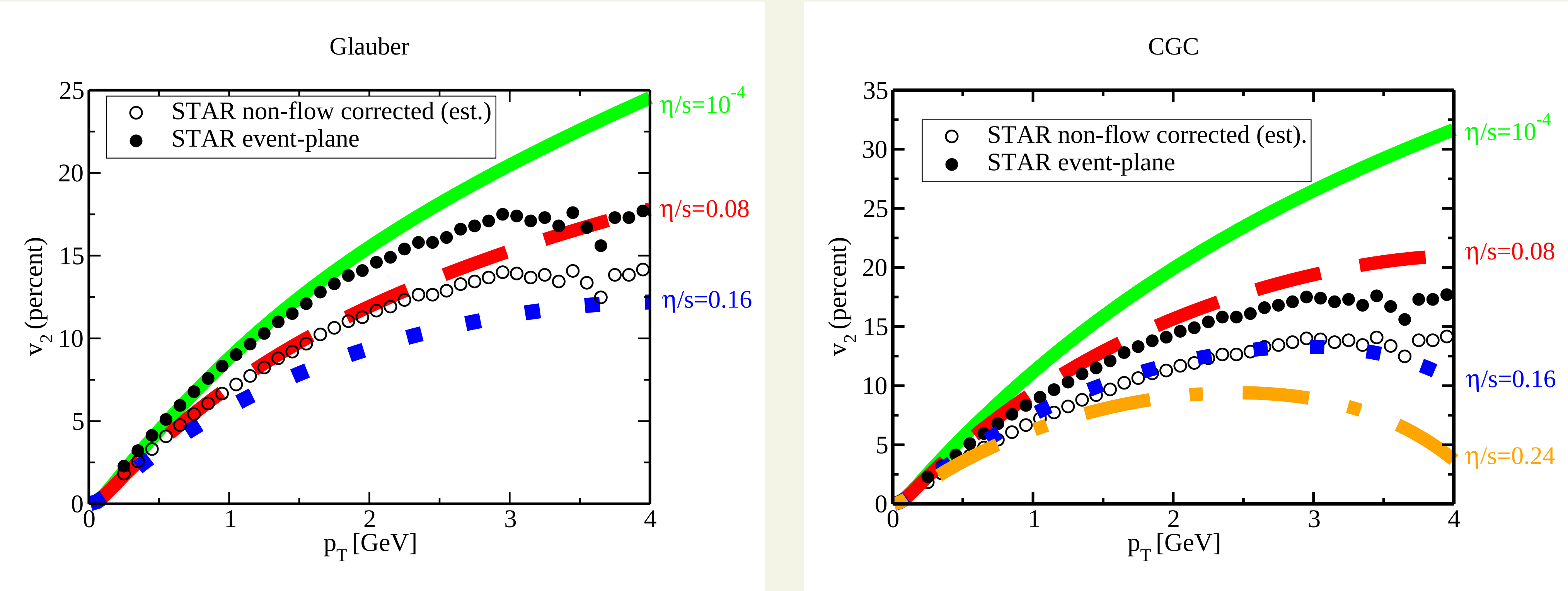


- **excellent agreement when $\sigma =$ const ~ 47 mb**
- **good agreement fo $\eta/s \approx 1/(4\pi)$, i.e. $\sigma \propto \tau^{2/3}$**

- **BUT results sensitive to freeze-out criterion, especially at high p_T**

Shear

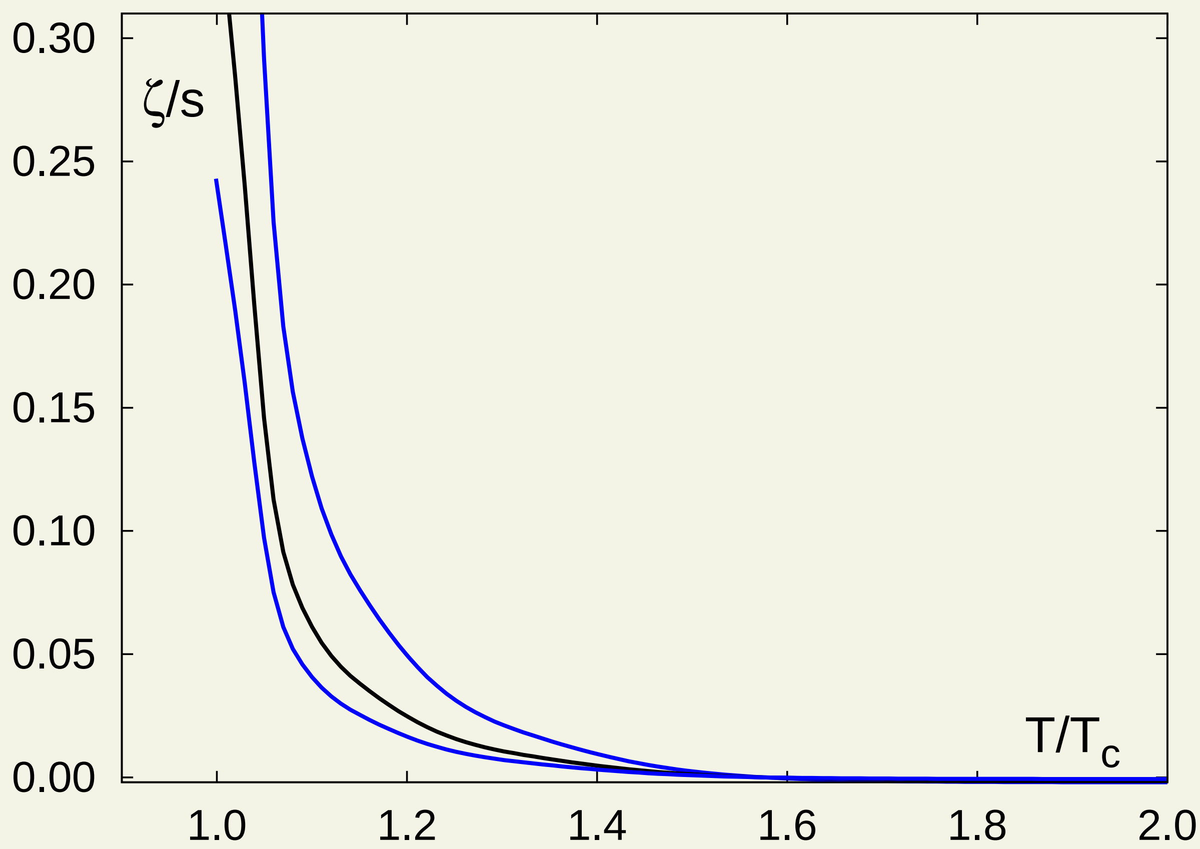
- Only $\eta/s = \text{const.}$ so far
- Luzum & Romatschke, arXiv:0804.4015



- $\eta/s = 0.08$ **to 0.16** depending on the initial state
- non-constant η/s?
- large shear in hadron gas?
- viscous hydro + hadron cascade?

Bulk viscosity

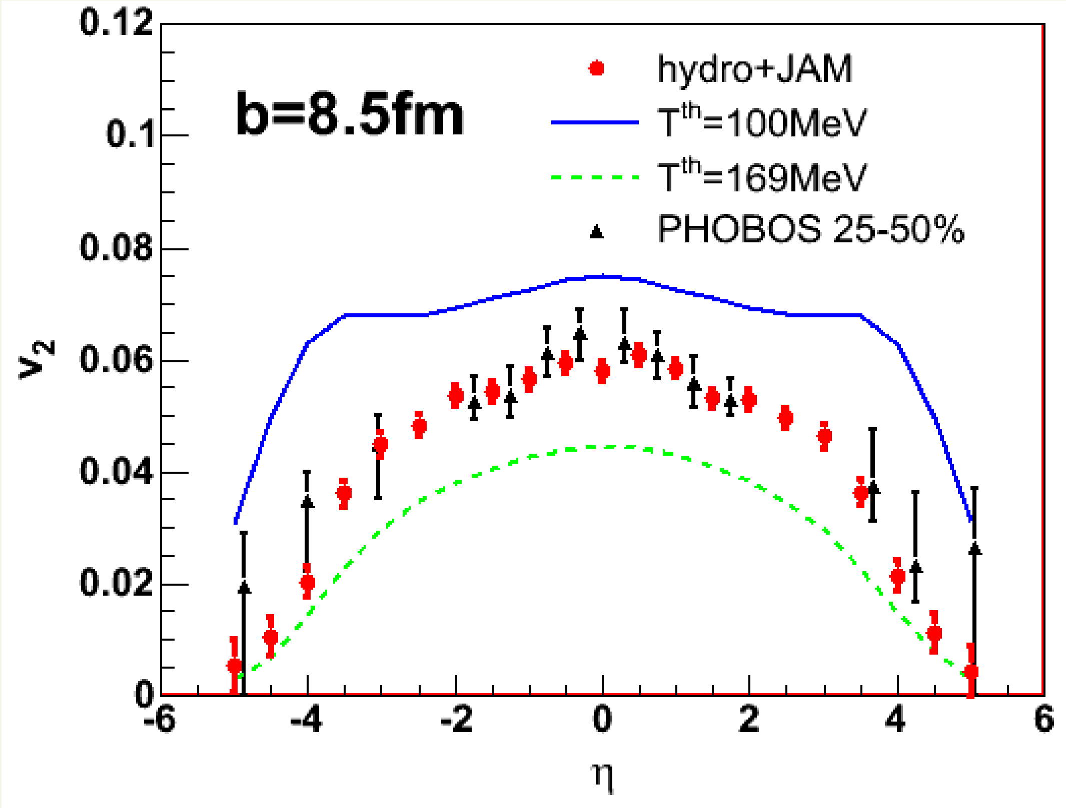
- **Bulk viscosity is LARGE at T_c: (Karsch, Kharzeev & Tuchin, arXiv:0711.0914)**



- **G. Torrieri *et al*: fragmentation at T_c**
- **R. Fries: 50% of the produced entropy due to bulk viscosity**
  (no transverse expansion)

Dimensions

- most models assume boost-invariance: 2+1D
- 3D ideal hydro and hydro+cascade models are in use (Hirano and Nonaka)
- $v_2(\eta)$ reproduced – remember uncertainties in initial state:



Hirano *et al.*,Phys.Lett.B636, 299 (2006)

- tiny effect at midrapidity – but essential for jet-quenching studies
- no viscous 3D code planned – tedious but not impossible

Conclusions

Relativistic viscous hydrodynamics is coming of age

– **expect more results and more confident results soon**

– **uncertainty in initial state makes extracting the EoS or transport coefficients a mess**