Viscous hydrodynamics – Overview of current issues*

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Activities since TECHQM I Workshop (BNL, May 2008)

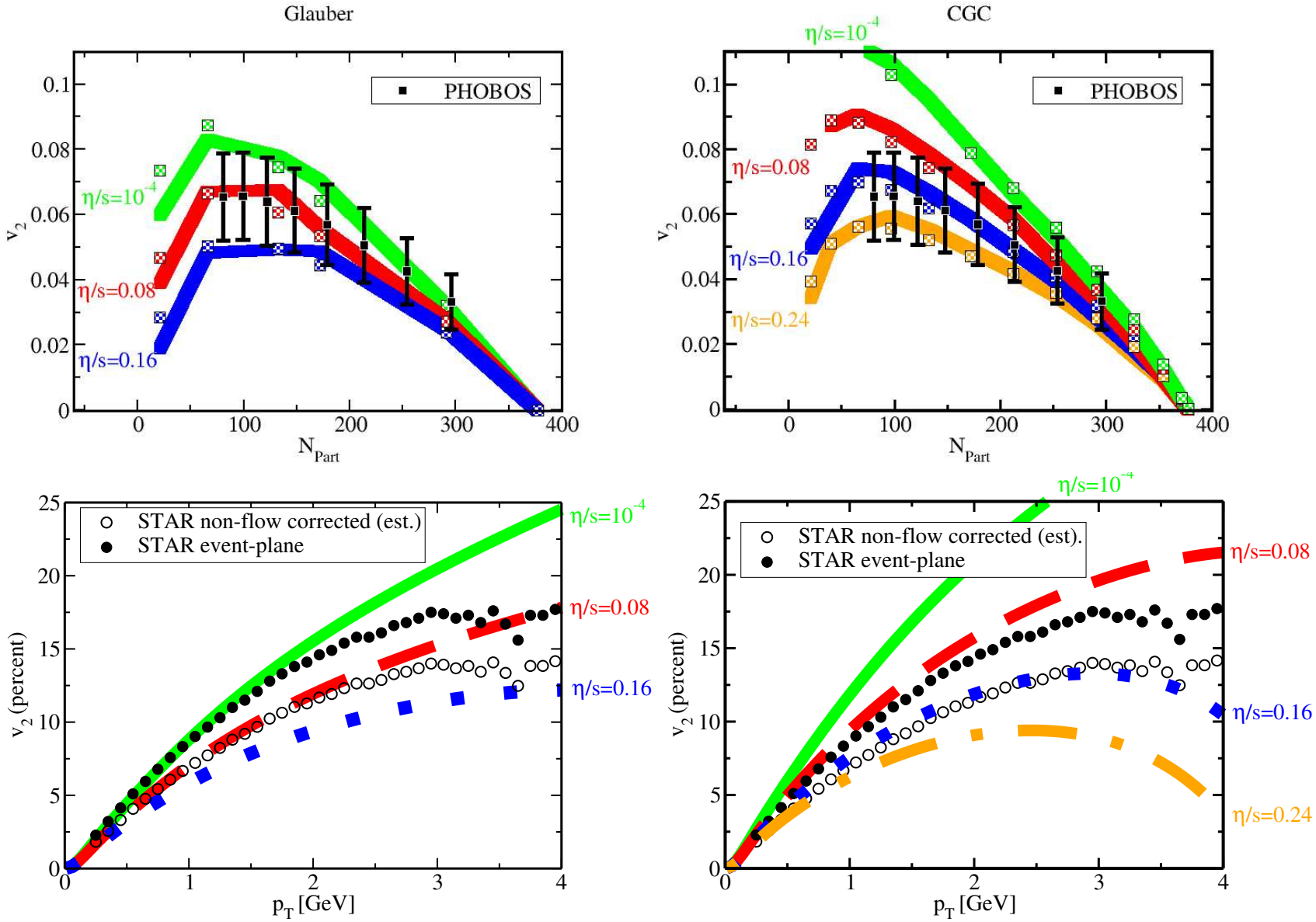
Or: What we'll hear about this morning . . .

- First attempt to extract η/s from v_2 data using viscous hydro $\Longrightarrow$ $\boldsymbol{\frac{\eta}{s} < 0.5}$

  Luzum & Romatschke PRC 78 (2008)

Constraining η/s from charged hadron elliptic flow data

Luzum & Romatschke, PRC 78 (2008) 034915



- **Largest uncertainty ($\sim 100\%$): initial source eccentricity!**
- Others: EOS near T_c ($\sim 25-30\%$); chemical comp. below T_c (??); late hadronic viscous effects not subtracted
- "Conservative" upper limit: $\frac{\eta}{s} < \frac{6}{4\pi}$ (Luzum & Romatschke '08)

Activities since TECHQM I Workshop (BNL, May 2008)

- First attempt to extract η/s from v_2 data using viscous hydro $\Longrightarrow$ $\frac{\eta}{s} < 0.5$

  Luzum & Romatschke, PRC 78 (2008)

- General structure of Israel-Stewart equations clarified

  Baier, Romatschke, Son, Starinets, Stephanov, JHEP 0804 (2008) 100 (shear viscosity only)

  Betz, Henkel, Rischke, arXiv:0812.1440 (shear + bulk viscosity, heat conductivity)

- Definitive weak-coupling computation of $2^{\rm nd}$-order IS coefficients for the shear pressure tensor $\pi^{\mu\nu}$ from Boltzmann transport theory

  York & Moore, arXiv:0811.0729

- Comparison of different variants of Israel-Stewart and Öttinger-Grmela equations in (2+1)-d viscous hydro evolution

  Song & Heinz, PRC 78 (2008)

  Luzum & Romatschke, PRC 78 (2008)

  Dusling & Song, TECHQM wiki

  - all approach same Navier-Stokes limit as $\tau_\pi \longrightarrow 0$
  - sensitivity to τ_π depends on specific choice of coefficients for $2^{\rm nd}$-order terms in IS-equations
  - existing numerical studies suggest that, except for the so-called "conformal term" $-\frac{1}{3}\pi^{\mu\nu}\theta$, most $2^{\rm nd}$-order terms are unimportant, but systematic quantitative investigation still to be done

- Successful code verification for 3 viscous hydro codes (VISH2+1, Romatschke^2, Dusling&Teaney)

  Dusling & Song, TECHQM wiki

Activities since TECHQM I Workshop (contd.)

- Extensive discussion of QGP bulk viscosity
  Most likely small in both QGP and HG phases, with a peak near T_c

  Paech & Pratt, PRC 74 (2006) 014901

  Meyer, PRL 100 (2008) 122001

  Kharzeev et al., JHEP 0809 (2009) 093; PLB 663 (2008) 217

  Moore & Saremi, JHEP 0809 (2008) 015

- First numerical studies of bulk viscous effects on hydro evolution and v_2

  Torrieri & Mishustin, PRC 78 (2008) 021901

  Fries, Müller, Schäfer, PRC 78 (2008) 034913

  Song & Heinz, SQM2008

  Dusling, TECHQM II

- Extraction of η/s, ζ/s from partonic and hadronic cascades

  Molnar, arXiv:0806.0026 (η/s from MPC with binary colls.)

  Xu, Greiner, Stöcker, PRL 101 (2008) 082302 (η/s from BAMPS)

  Bass & Demir, in progress (η/s, ζ/s from UrQMD)

- Dilepton emission from viscous hydro

  Dusling & Lin, NPA 809 (2008) 246

- Matching pre-equilibrium early-time evolution to (ideal) hydro

  Pratt & Vredevoogt, arXiv:0810.4325

Open issues & remaining roadblocks to extracting η/s, ζ/s from data (my personal list. . .)

Or: What we should discuss this afternoon and on Wednesday . . .

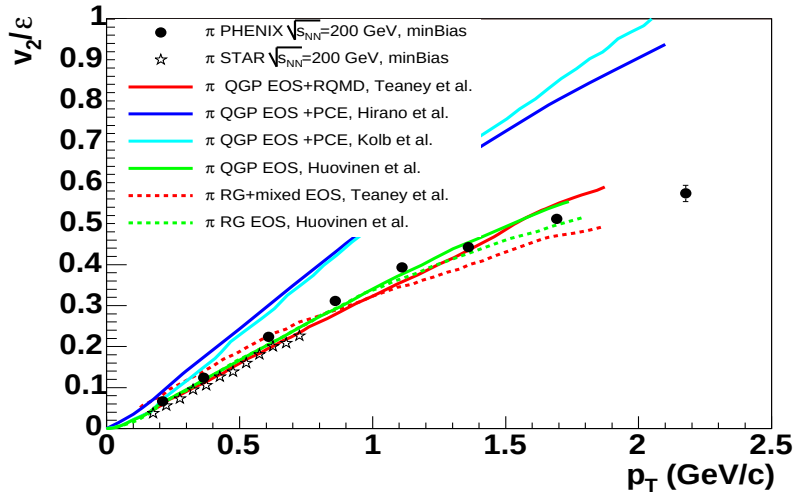
How to improve over the Luzum & Romatschke plot:

- Systematic and quantitative analysis of sensitivity of v_2 and other observables to τ_π (including full reasonable ranges for all 2nd-order IS coefficients)
- Can we find independent constraints on the initial source eccentricity ε_x !?
  Can we exploit v_2/ε_x scaling and its violation through viscous effects?
- Chemical non-equilibrium effects in HG phase on v_2 can be huge!
  Must study $v_2(p_T)$ of identified hadrons

Hadronic viscosity and chemical non-equilibrium effects:

compilation from PHENIX White Paper, NPA 757 (2005) 184

pions



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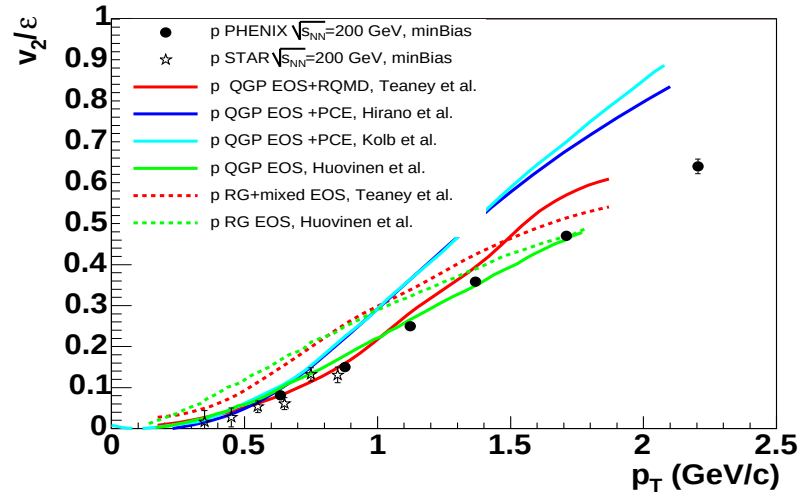

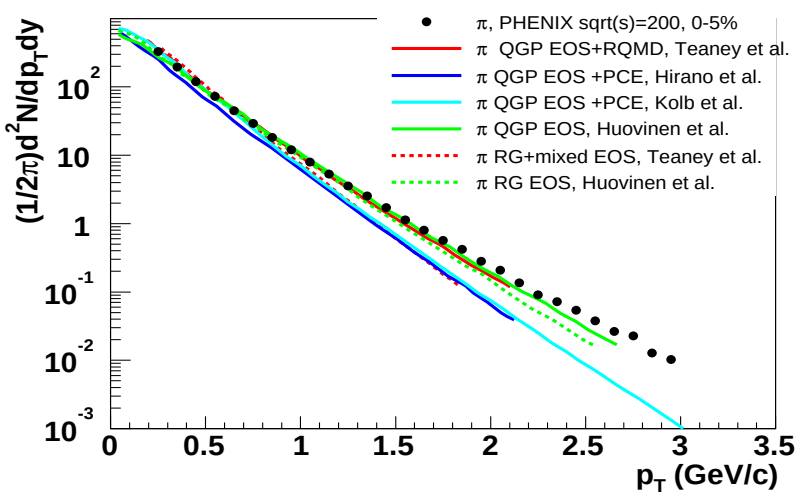

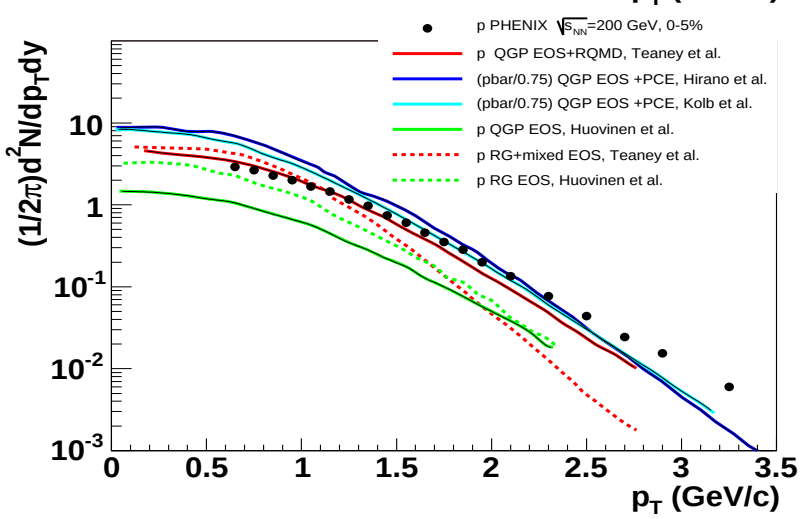

All theory curves use the same (ideal) hydrodynamics and EOS in QGP phase!

How we deal with the hadron phase makes all the difference . . .

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- Interfacing *viscous* hydro with pre-equilibrium early-time dynamics and late-time hadron cascade (early-time "transverse push" and late-time viscosity)
- Event-by-event eccentricity fluctuations: simulate numerically with fluctuating initial conditions or correct experimentally? ($\Longrightarrow$ PHOBOS, Poskanzer's talk)
- How to systematically separate shear and bulk viscous effects and extract η/s(QGP) and $\zeta/s(T_c)$?

Let's get to work!