The quark-gluon plasma shear viscosity from RHIC to LHC*

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Work done in collaboration with

S.A. Bass, T. Hirano, P. Huovinen, Zhi Qiu, Chun Shen, and H. Song

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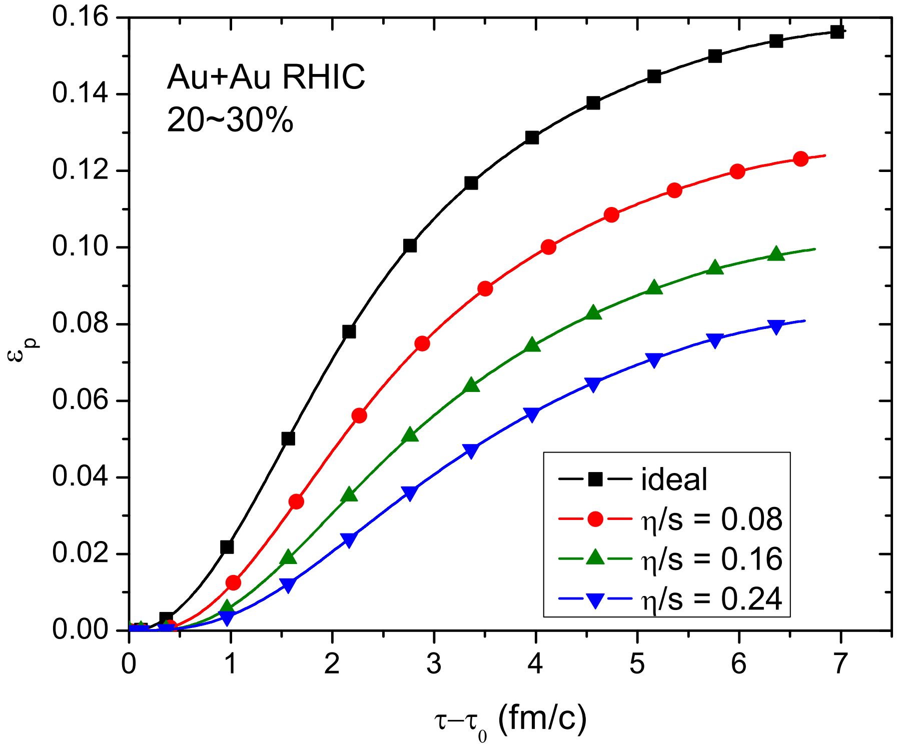
Prologue: How to measure $(\eta/s)_{\mathrm{QGP}}$

Hydrodynamics converts
spatial deformation of initial state $\Longrightarrow$
momentum anisotropy of final state,
through anisotropic pressure gradients



Shear viscosity degrades conversion efficiency

$$\varepsilon_x = \frac{\langle\langle y^2-x^2\rangle\rangle}{\langle\langle y^2+x^2\rangle\rangle} \Longrightarrow \varepsilon_p = \frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle}$$

of the fluid; the suppression of ε_p is monotonically related to η/s.

The observable that is most directly related to the total hydrodynamic momentum anisotropy ε_p is the **total (p_T-integrated) charged hadron elliptic flow v_2^{ch}**:

$$\varepsilon_p = \frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle} \Longleftrightarrow \frac{\sum_i \int p_T dp_T \int d\phi_p \, p_T^2 \, \cos(2\phi_p) \, \frac{dN_i}{dy p_T dp_T d\phi_p}}{\sum_i \int p_T dp_T \int d\phi_p \, p_T^2 \, \frac{dN_i}{dy p_T dp_T d\phi_p}} \Longleftrightarrow v_2^{\mathrm{ch}}$$

Prologue: How to measure $(\eta/s)_{\mathrm{QGP}}$ (ctd.)

- **If** ε_p **saturates** before hadronization (e.g. in PbPb@LHC (?))

$\Rightarrow$ $v_2^{\mathrm{ch}} \approx$ not affected by details of hadronic rescattering below T_{c}

but: $v_2^{(i)}(p_T)$, $\frac{dN_i}{dyd^2p_T}$ change during hadronic phase (addl. radial flow!), and these changes depend on details of the hadronic dynamics (chemical composition etc.)

$\Rightarrow$ $v_2(p_T)$ of a single particle species **not** a good starting point for extracting η/s

- **If** ε_p **does not saturate** before hadronization (e.g. AuAu@RHIC), dissipative hadronic dynamics affects not only the distribution of ε_p over hadronic species and in p_T, but even the final value of ε_p itself (from which we want to get η/s)

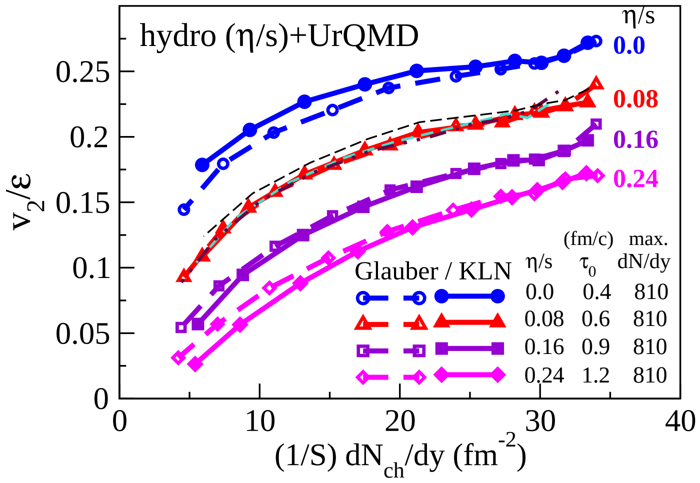
$\Rightarrow$ need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase

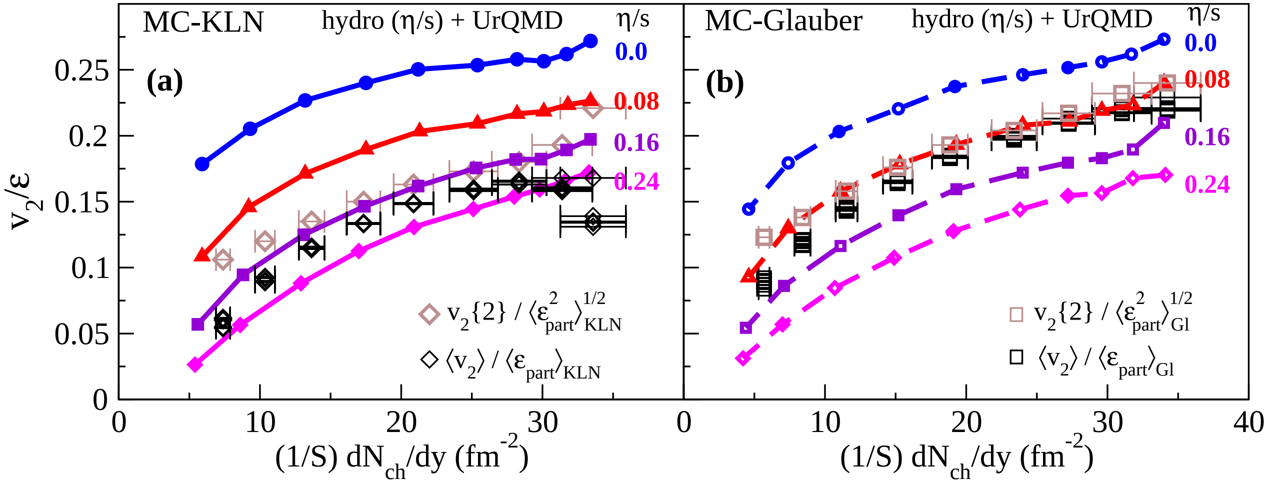
$\Rightarrow$ **VISHNU** ("Viscous Israel-Steward Hydrodynamics 'n' UrQMD")

(Song, Bass, Heinz, PRC83 (2011) 024912) Note: this paper shows that UrQMD $\neq$ viscous hydro!

Extraction of $(\eta/s)_{\mathrm{QGP}}$ from AuAu@RHIC

H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRL106 (2011) 192301



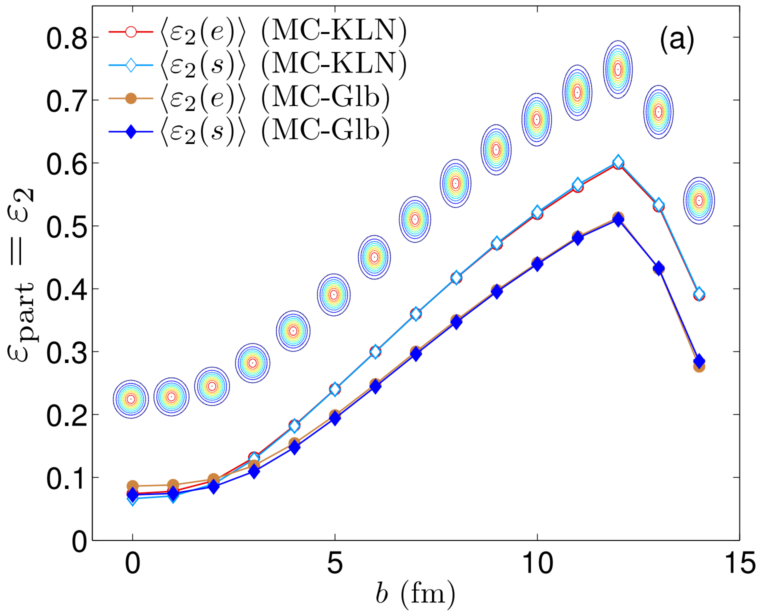


$$\boxed{1 < 4\pi(\eta/s)_{\mathrm{QGP}} < 2.5}$$

- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as p_T-spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\mathrm{ch}}/\varepsilon_x$ vs. $(1/S)(dN_{\mathrm{ch}}/dy)$ is "universal", i.e. depends **only on** $\boldsymbol{\eta/s}$ but (in good approximation) not on initial-state model (Glauber vs. KLN, optical vs. MC, RP vs. PP average, etc.)
- dominant source of uncertainty: $\varepsilon_x^{\mathrm{Gl}}$ vs. $\varepsilon_x^{\mathrm{KLN}}$ $\longrightarrow$
- smaller effects: *early flow* → increases $\frac{v_2}{\varepsilon}$ by $\sim$few % → larger η/s

  bulk viscosity → affects $v_2^{\mathrm{ch}}(p_T)$, but $\approx$ not v_2^{ch}

Zhi Qiu & UH, PRC84 (2011) 024911



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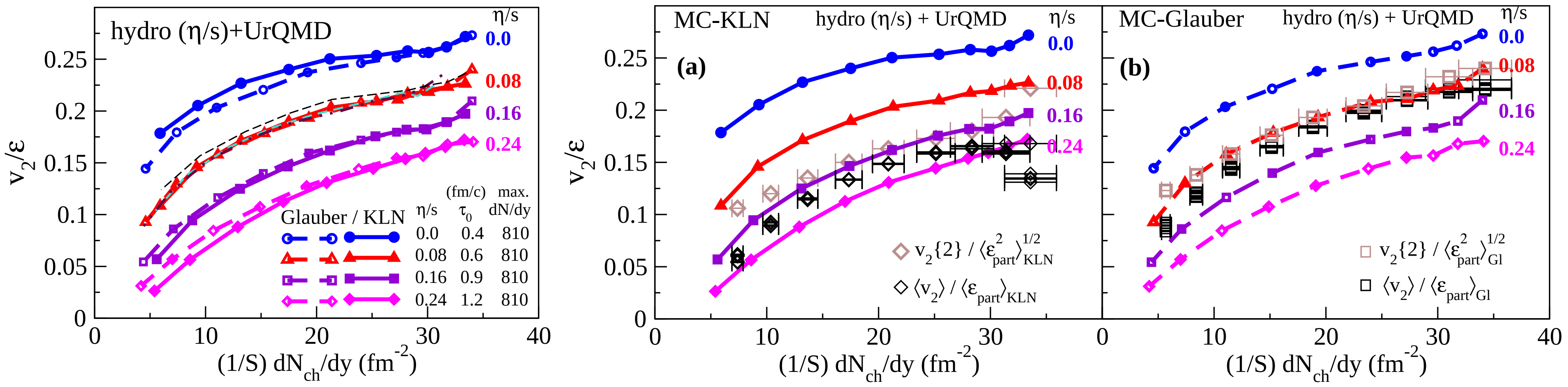

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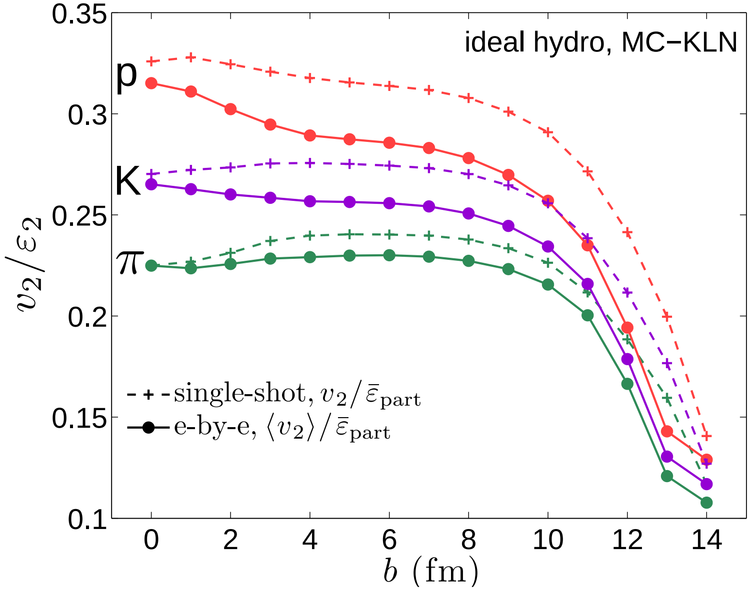
  bulk viscosity → affects $v_2^{\mathrm{ch}}(p_T)$, but $\approx$ not v_2^{ch}

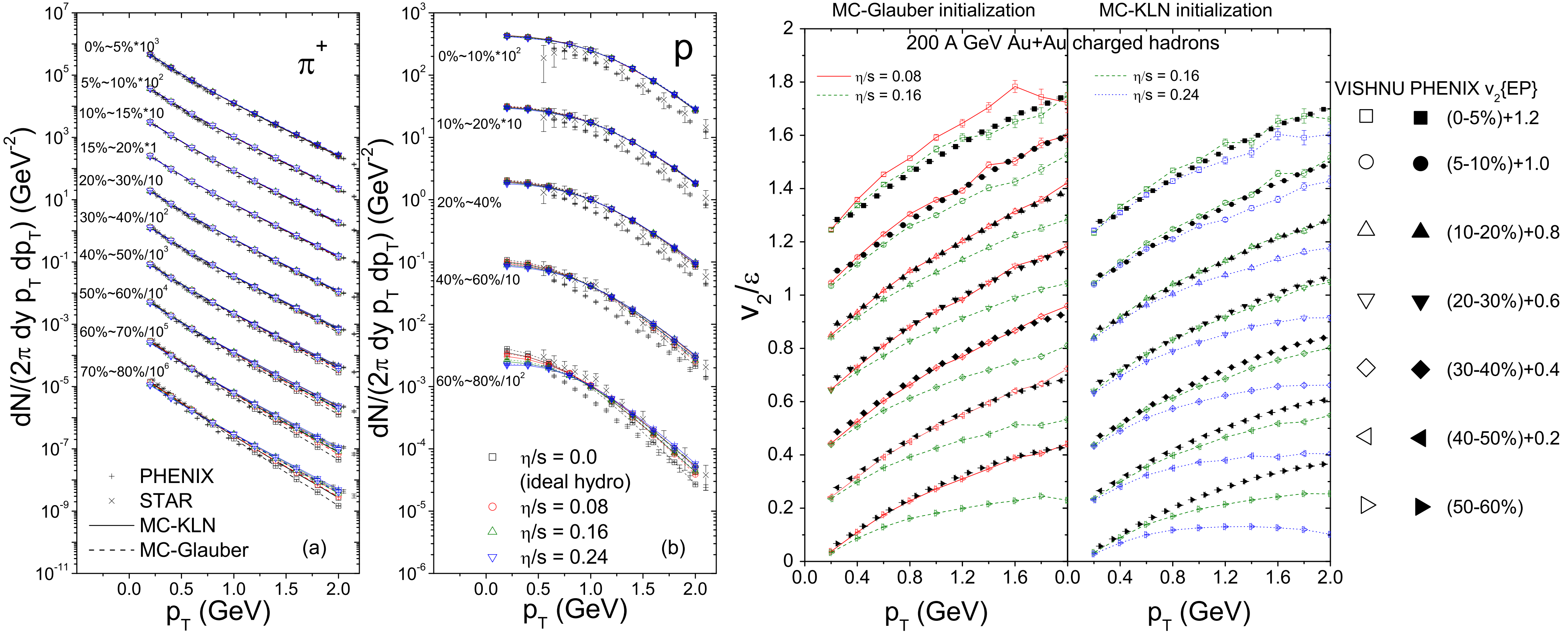
  e-by-e hydro → decreases $\frac{v_2^{\mathrm{ch}}}{\varepsilon}$ by $\lesssim 5\%$ → smaller η/s

Zhi Qiu & UH, PRC84 (2011) 024911



Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC 83 (2011) 054910)



- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities

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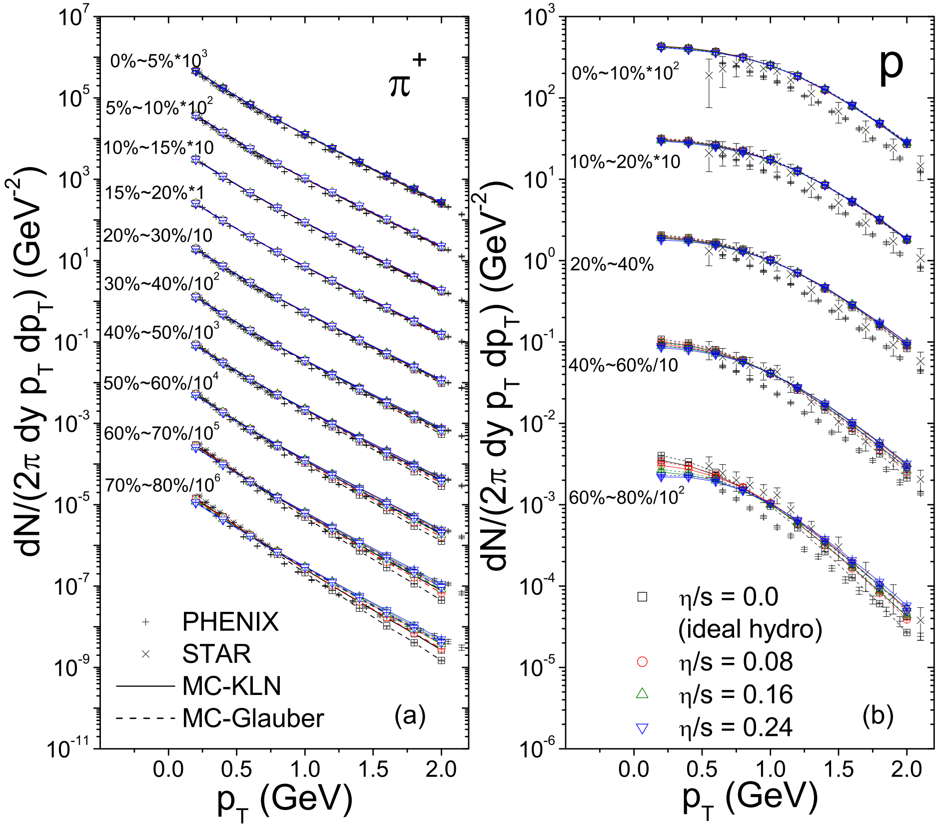
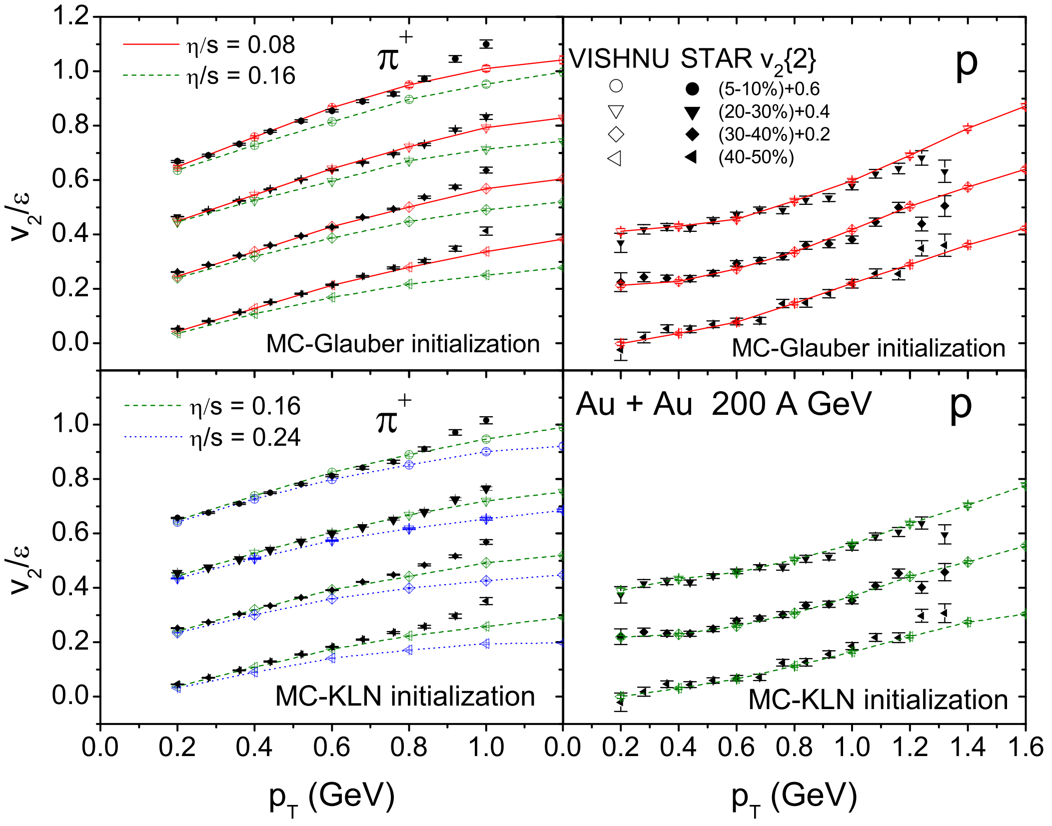
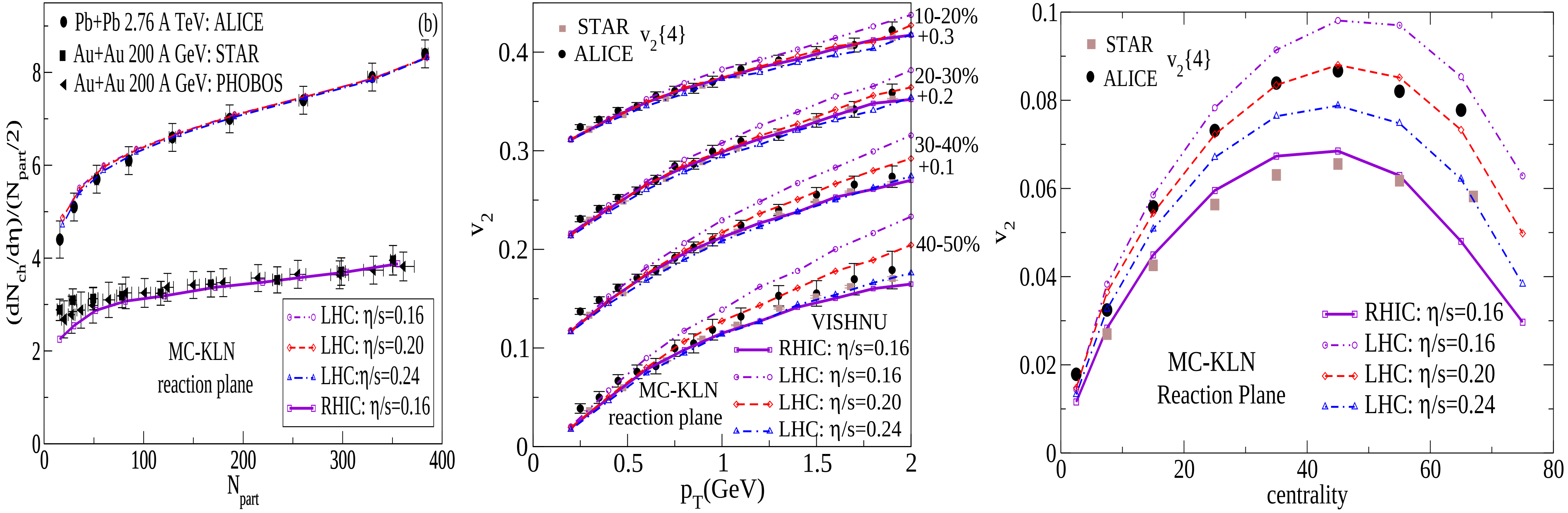




- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities
- A purely hydrodynamic model (without UrQMD afterburner) with the same values of η/s does almost as well (except for centrality dependence of proton $v_2(p_T)$) $\Longrightarrow$ Shen et al., arXiv:1105.3226
- Main difference: VISHNU develops more radial flow in the hadronic phase (larger shear viscosity), pure viscous hydro must start earlier than VISHNU ($\tau_0 = 0.6$ instead of $0.9\,$fm/c), otherwise proton spectra are too steep
- These η/s values agree with Luzum & Romatschke, PRC78 (2008), even though they used EOS with incorrect hadronic chemical composition $\Longrightarrow$ shows robustness of extracting η/s from total charged hadron v_2

Pre- and postdictions for PbPb@LHC

VISHNU with MC-KLN (Song, Bass, Heinz, PRC 83 (2011) 054912)



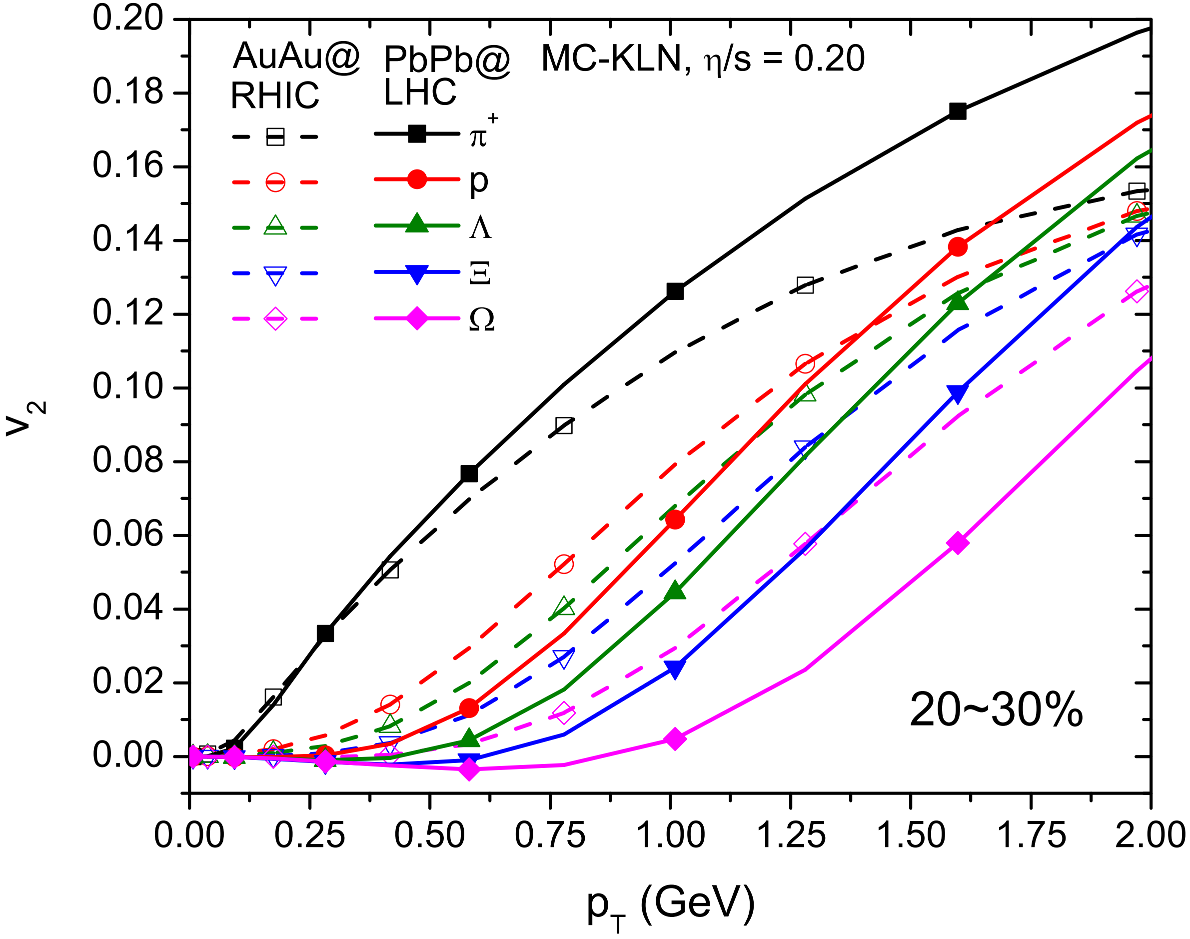
- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{\rm ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ and integrated v_2 in AuAu@RHIC, but overpredicts both by about 10-15% in PbPb@LHC
- Similar results from predictions based on pure viscous hydro $\Longrightarrow$ Shen et al., arXiv:1105.3226
- **but:** At LHC, we see significant sensitivity of v_2 to initialization of viscous pressure tensor $\pi^{\mu\nu}$ (Navier-Stokes or zero), and it is not excluded that it may be possible to bring down v_2 at LHC to the ALICE data without increasing η/s at higher T (requires more study)

  $\Longrightarrow$ **QGP at LHC perhaps a bit, but not dramatically more viscous than at RHIC!**

Why is $v_2^{\rm ch}(p_T)$ the same at RHIC and LHC?

Answer: Pure accident! (Kestin & Heinz EPJC61 (2009) 545)

C. Shen, U. Heinz, P. Huovinen, H. Song, arXiv:1105.3226



$v_2^\pi(p_T)$ increases a bit from RHIC to LHC, for heavier hadrons $v_2(p_T)$ at fixed p_T decreases

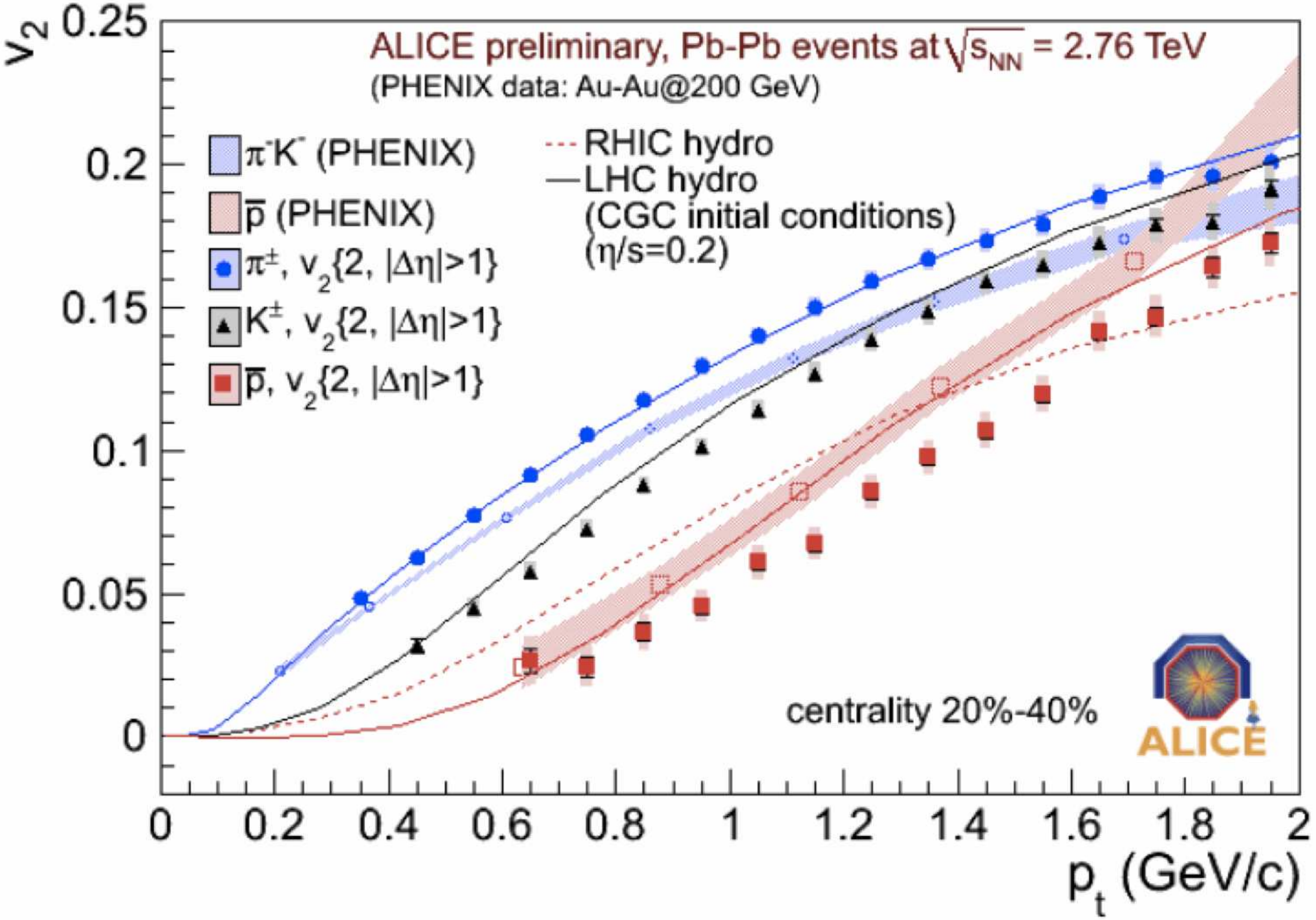
(radial flow pushes momentum anisotropy of heavy hadrons to larger p_T)

This is a hard (and successful!) prediction of hydrodynamics! (See also Nagle et al., arXiv:1102.0680)

Confirmation of increased mass splitting at LHC

Data: ALICE @ LHC, Quark Matter 2011 (symbols), PHENIX @ RHIC (shaded)

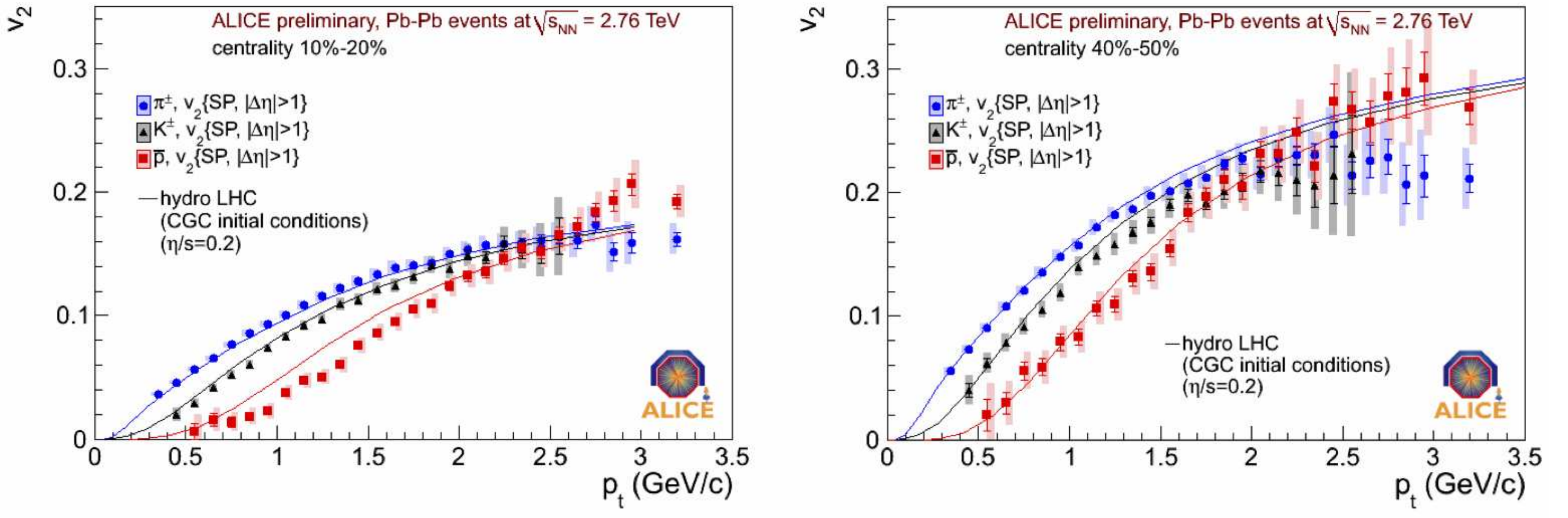
Lines: Shen et al.,arXiv:1105.3226 (VISH2+1)



- Qualitative features of data agree with VISH2+1 predictions
- VISH2+1 does not push proton v_2 strongly enough to higher p_T, both at RHIC and LHC
- At RHIC we know that this is fixed when using VISHNU – is the same true at LHC?

Successful prediction of $v_2(p_T)$ for identified hadrons in PbPb@LHC

Data: ALICE, Quark Matter 2011 Lines: Shen et al., arXiv:1105.3226 (VISH2+1)



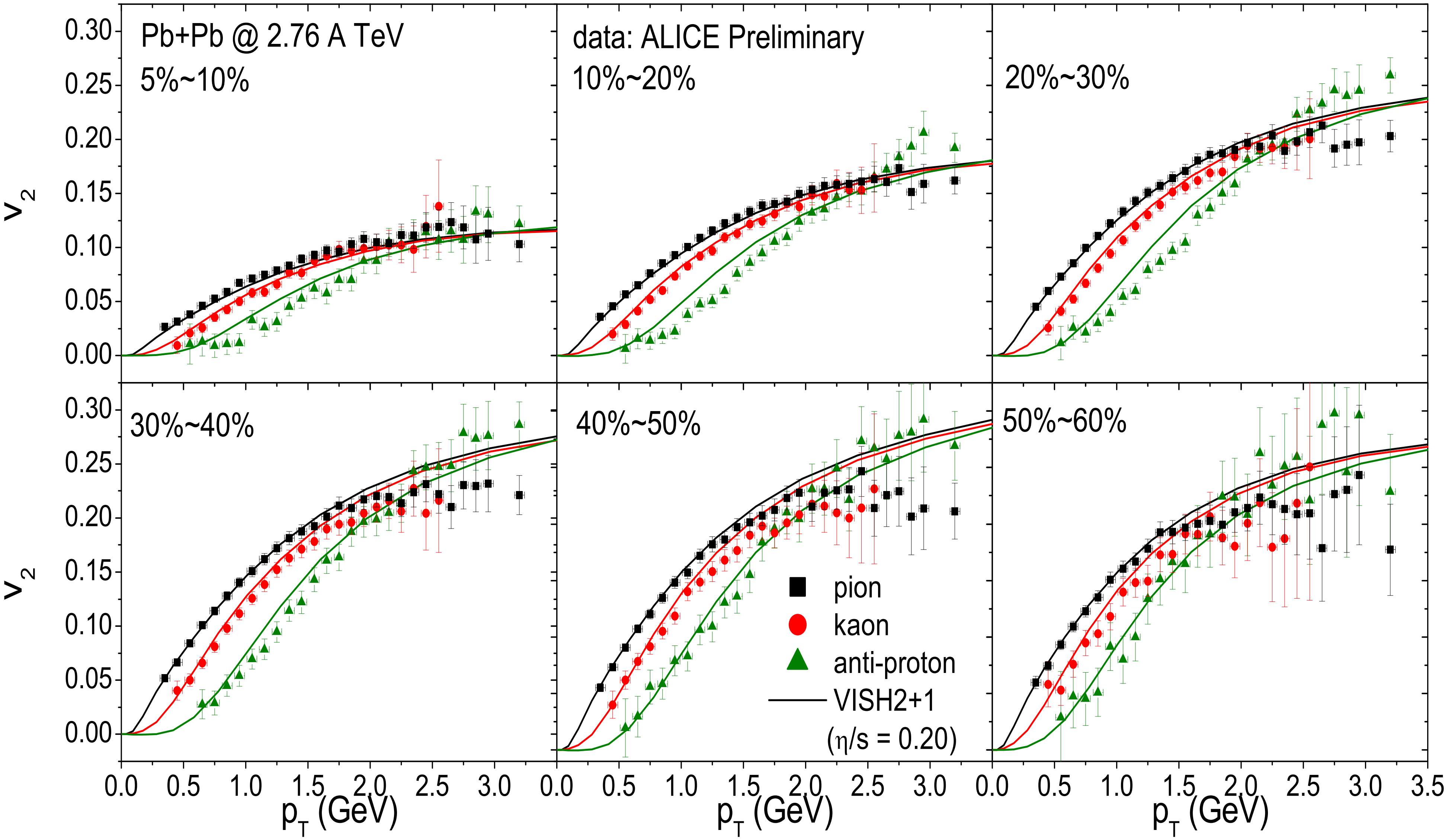
Perfect fit in semi-peripheral collisions!

The problem with insufficient proton radial flow exists only in more central collisions
$\Longrightarrow$ hadronic cascade (VISHNU) may help!

Comparison VISH2+1 . . .

Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)

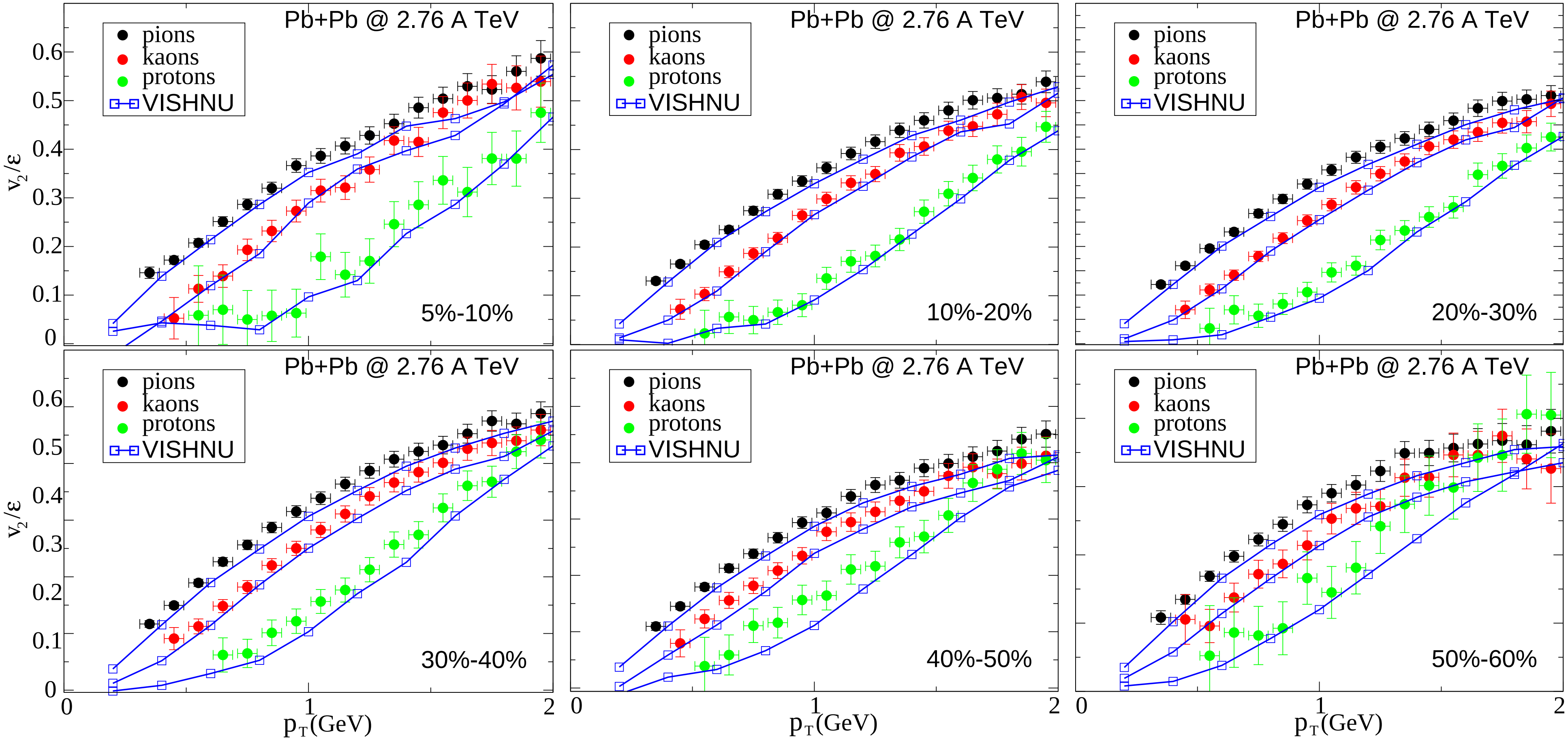
Lines: C. Shen et al., arXiv:1105.3226 (VISH2+1, MC-KLN, $\eta/s=0.2$)



. . . vs. VISHNU

Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)

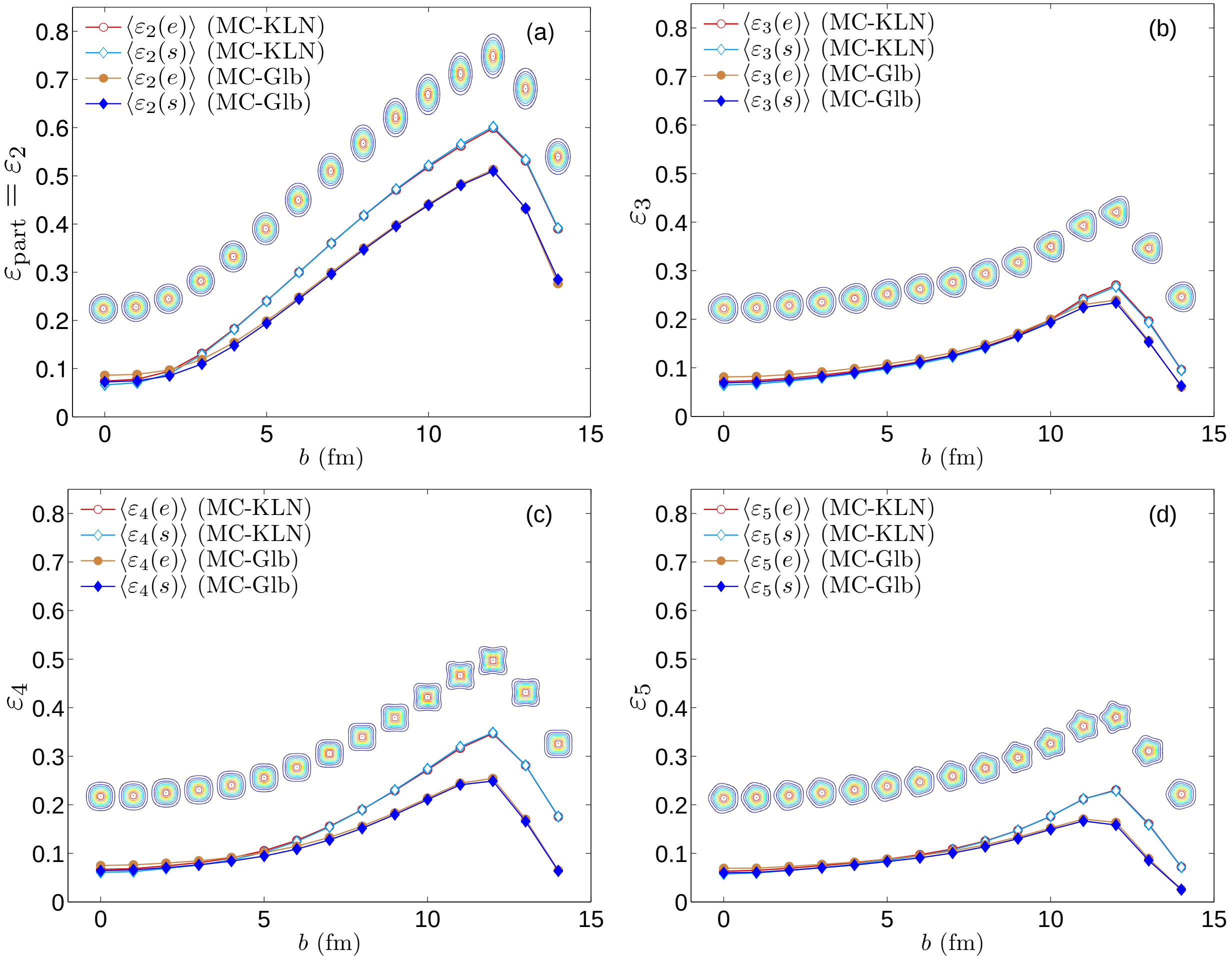
Lines: UH, Shen, Song, arXiv:1108.5323 (VISHNU, MC-KLN, $(\eta/s)_{\rm QGP}$=0.2)



- VISHNU yields correct centrality dependence of $v_2(p_T)$ for pions, kaons **and protons!**
- $v_2(p_T)$ slightly too low (by $\sim 5{-}10\%$, increasing with peripherality) for all particle species $\Longrightarrow$ $(\eta/s)_{\rm QGP}$=0.16 will probably work better

Back to the elephant in the room: How to eliminate the large model uncertainty in the initial eccentricity?

Zhi Qiu and U. Heinz, PRC84 (2011) 024911



Initial eccentricities ε_n and angles ψ_n:

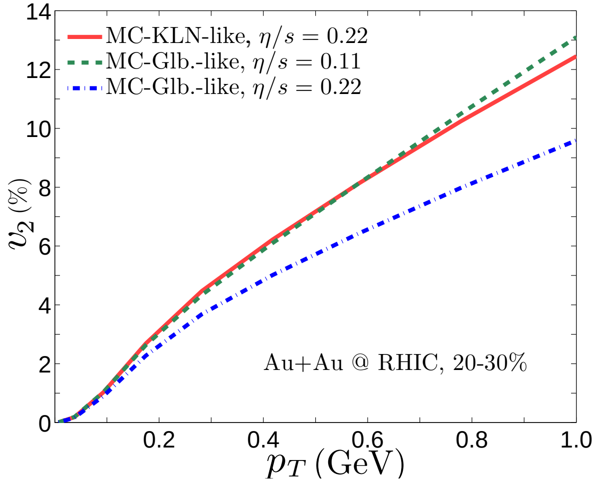
$$\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$$

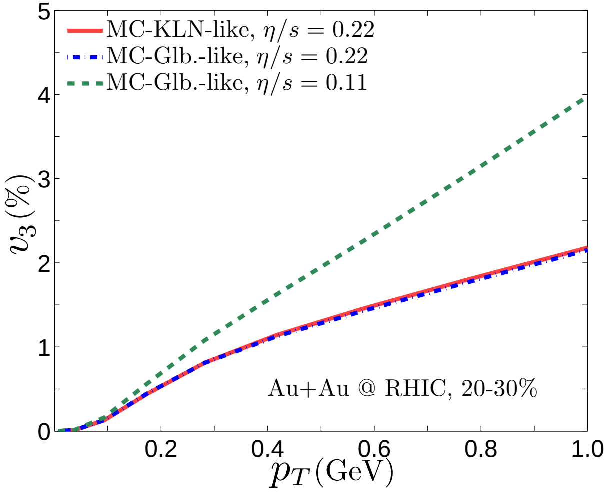
- MC-KLN has larger ε_2 and ε_4, but similar ε_5 and almost identical ε_3 as MC-Glauber
- Angles of ε_2 and ε_4 are correlated with reaction plane by geometry, whereas those of ε_3 and ε_5 are random (purely fluctuation-driven)
- While v_4 and v_5 have mode-coupling contributions from ε_2, v_3 is almost pure response to ε_3 and $v_3/\varepsilon_3 \approx$ const. over a wide range of centralities (for details see PRC84 (2011) 024911)

$\Longrightarrow$ **Idea:** Use total charged hadron $v_3^{\rm ch}$ to determine $(\eta/s)_{\rm QGP}$,
then check $v_2^{\rm ch}$ to distinguish between MC-KLN and MC-Glauber!

Shooting the elephant

Zhi Qiu & U. Heinz, arXiv:1108.1714





Proof of principle calculation:

- Take ensemble of sum of deformed Gaussian profiles, $s(\boldsymbol{r}_\perp) = s_2(\boldsymbol{r}_\perp; \tilde{\varepsilon}_2, \psi_2) + s_3(\boldsymbol{r}_\perp; \tilde{\varepsilon}_3, \psi_3)$, with
  1. equal Gaussian radii $R_2^2 = R_3^2 = 8\,\mathrm{fm}^2$ to reproduce $\langle r_\perp^2 \rangle$ of MC-KLN source for 20-30% AuAu
  2. $\tilde{\varepsilon}_2$ and $\tilde{\varepsilon}_3$ adjusted such that
     - $\bar{\varepsilon}_{2,3} = \langle \varepsilon_{2,3} \rangle_{\mathrm{KLN}}^{20-30\%}$ ("MC-KLN-like")
     - $\bar{\varepsilon}_{2,3} = \langle \varepsilon_{2,3} \rangle_{\mathrm{Gl}}^{20-30\%}$ ("MC-Glauber-like")
  3. $\psi_2 = 0$, ψ_3 (direction of triangularity) distributed randomly
- Use $v_2^\pi(p_T)$ from VISH2+1 for $\eta/s = 0.20$ with MC-KLN initial conditions for 20-30% AuAu as "mock data"
- Fit mock $v_2^\pi(p_T)$ data with VISH2+1 for "MC-Glauber-like" or "MC-KLN-like" Gaussian initial conditions with both elliptic and triangular deformations by adjusting η/s
  $\Longrightarrow$ $(\eta/s)_{\mathrm{KLN}} = 0.22$ for "MC-KLN-like",
  $(\eta/s)_{\mathrm{Gl}} = 0.11$ for "MC-Glauber-like"
- Compute $v_3^\pi(p_T)$ for "MC-KLN-like" fit with $(\eta/s)_{\mathrm{Gl}}{=}0.22$ and reproduce it with "MC-Glauber-like" initial condition by readjusting η/s
  $\Longrightarrow$ $(\eta/s)_{\mathrm{Gl}}^{v3} = 0.22$ for "MC-Glauber-like"
- Compute $v_2^\pi(p_T)$ for "MC-Glauber-like" initial profiles with readjusted $(\eta/s)_{\mathrm{Gl}}^{v3} = 0.224$ and compare with "MC-Glauber-like" fit to original mock data $\Longrightarrow$ clearly visible (and measurable) difference!

This exercise proves: (i) Fitting v_3 data with MC-Glauber and MC-KLN initial conditions yields the same η/s (within narrow error band); (ii) The corresponding v_2 fits are quite different, and only one (more precisely: at most one!) of the models will fit the corresponding $v_2(p_T)$ data.

Conclusions

- Hybrid codes (e.g. VISHNU) that couple viscous hydro evolution of QGP to microscopic hadron cascade now allow a determination of $(\eta/s)_{\rm QGP}$ with $\mathcal{O}(25\%)$ precision **if the initial fireball eccentricity is known to better than 5% relative accuracy**

- With VISHNU good global fits that describe all single-particle observables for soft hadron production (spectra, elliptic flow) at all but the most peripheral AuAu collision centralities are obtained, for both MC-Glauber and MC-KLN initial conditions, by using $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16{-}0.20$ for MC-KLN. This appears to carry over to PbPb@LHC.

- Event-by-event ideal hydrodynamics with fluctuating initial conditions yields somewhat less v_2/ε_2 than single-shot hydro with smooth average initial profiles $\Longrightarrow$ Event-by-event hydro may be necessary for a precise extraction of $(\eta/s)_{\rm QGP}$ from charged hadron v_2. Depending on $(\eta/s)_{\rm QGP}$, event-by-event hydro can matter a lot for proton v_2.

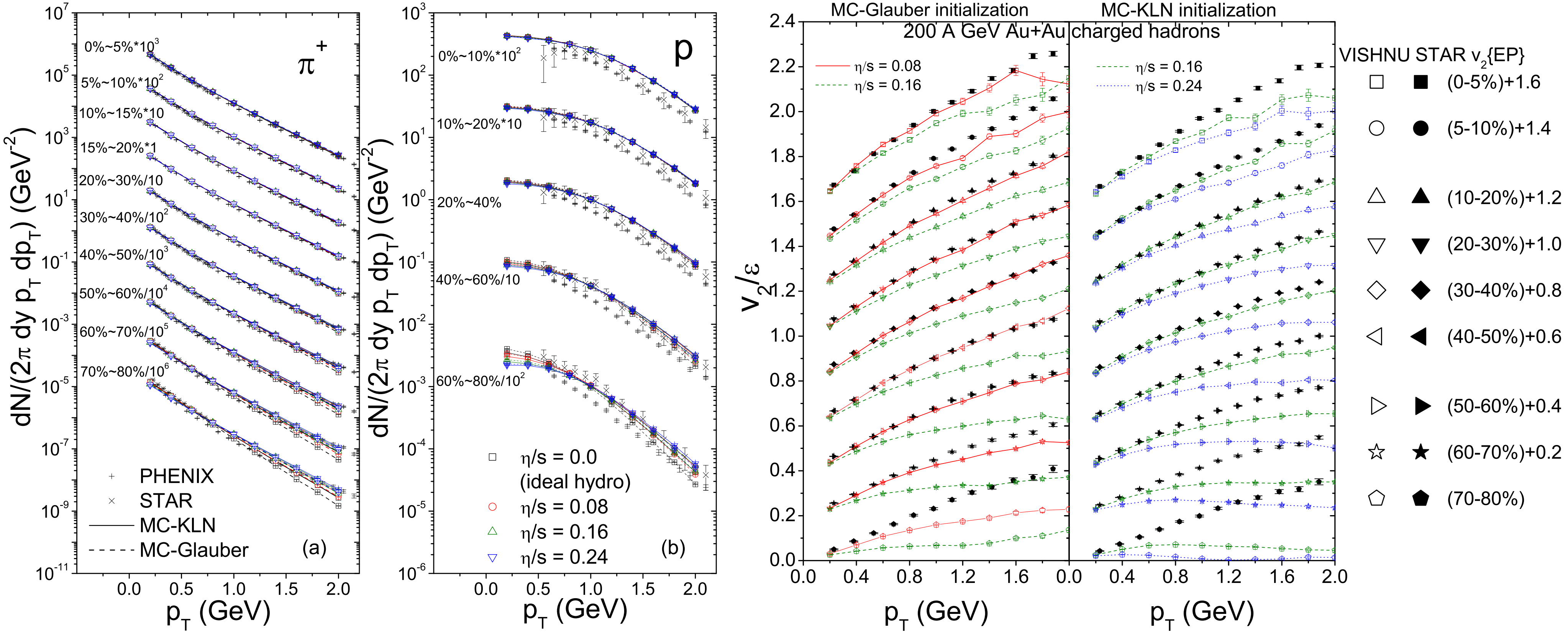
- While MC-Glauber and MC-KLN give ε_2 that differ by 20-25%, they give almost identical ε_3 (which is not geometric but fluctuation-driven). Only one of them will be able to fit simultaneously both v_2 and v_3 (analysis in progress).

- This should enable us to gain the necessary control over initial conditions to make a precise (i.e. much better than factor 2) measurement of $(\eta/s)_{\rm QGP}$.

Supplements

Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC 83 (2011) 054910)



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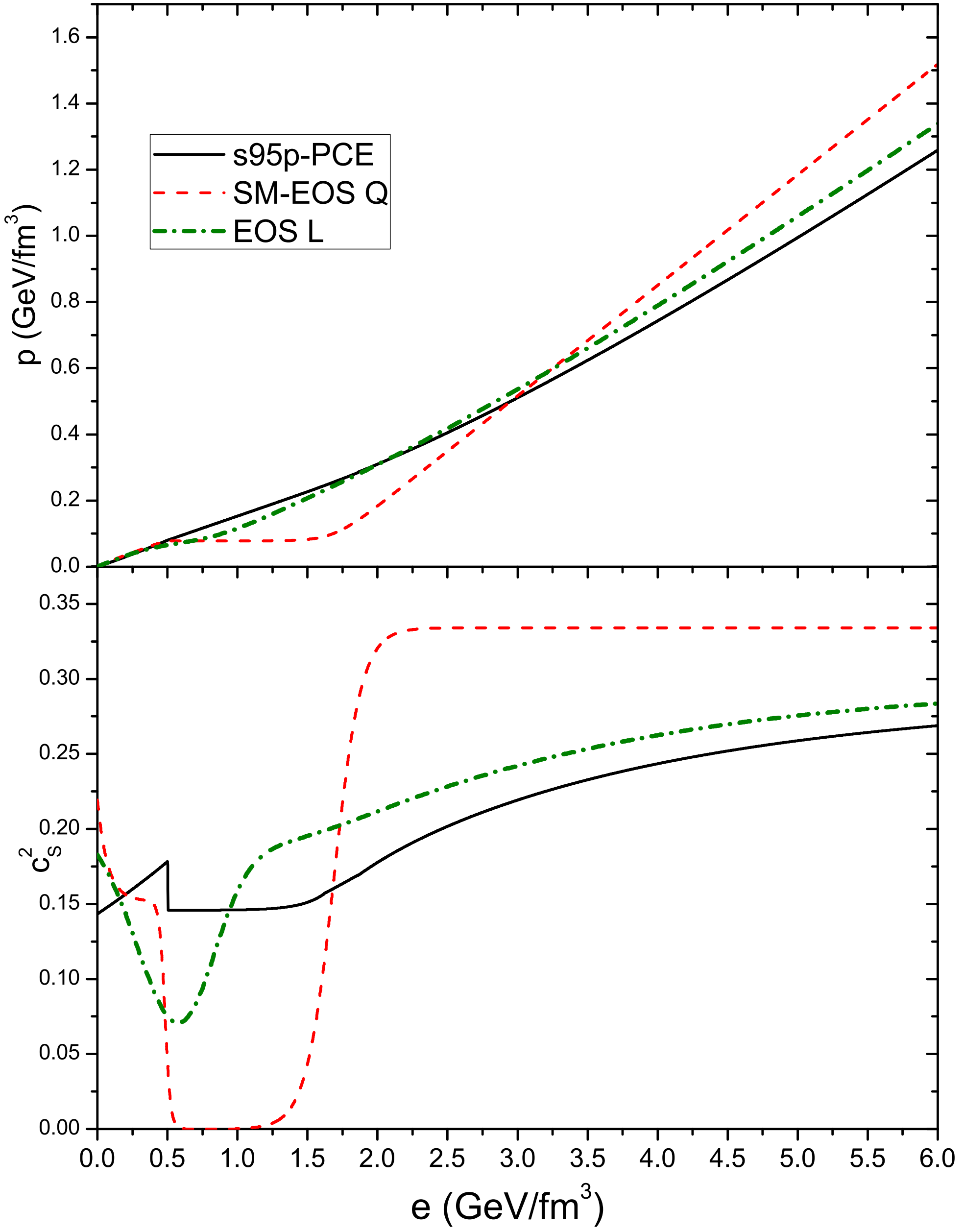
s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904



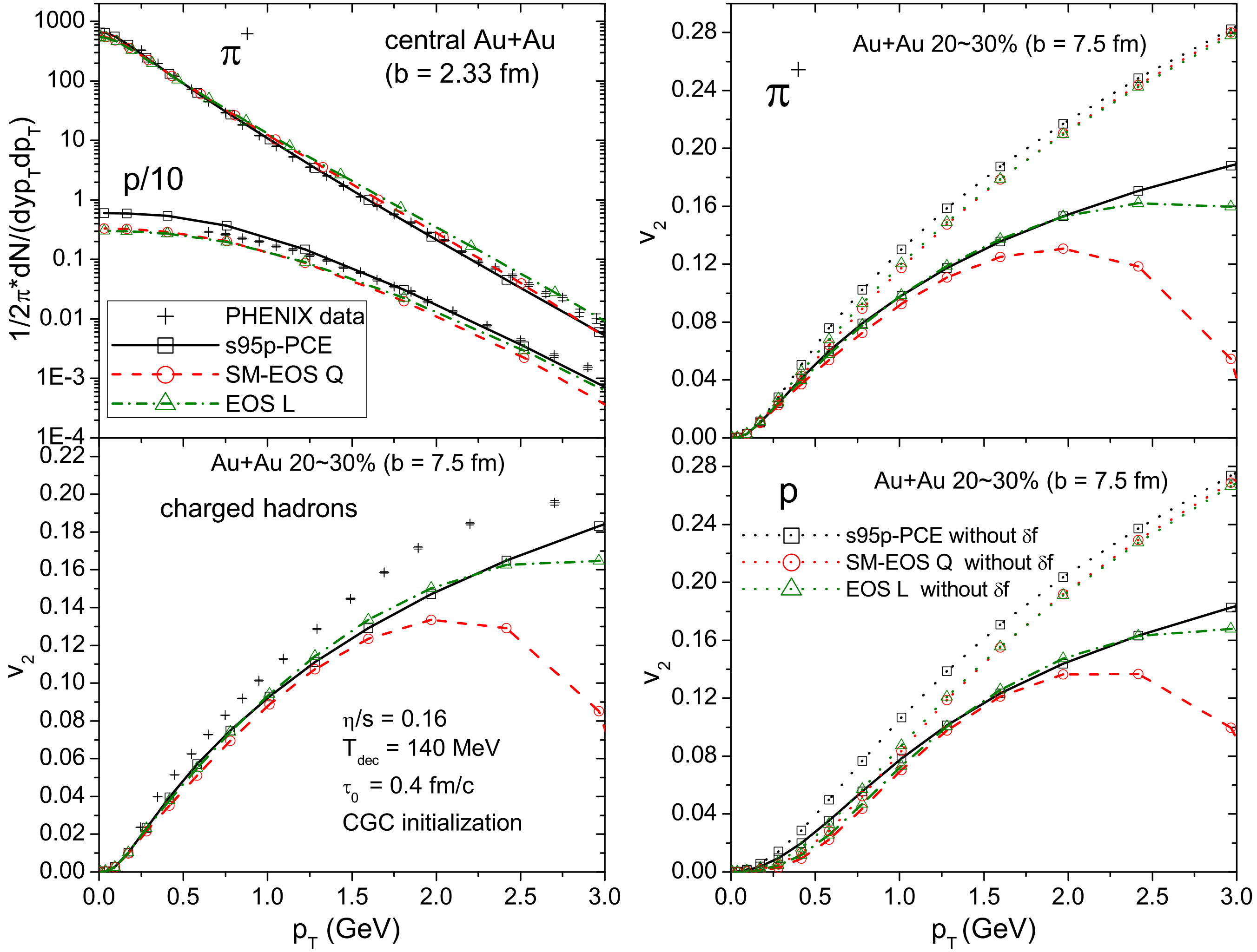
High T: Lattice QCD (latest hotQCD results)

Low T: Chemically frozen HRG ($T_{\text{chem}} = 165\,\text{MeV}$)

No softest point!

s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904



Generates less radial flow than SM-EOS Q and EOS L but larger momentum anisotropy

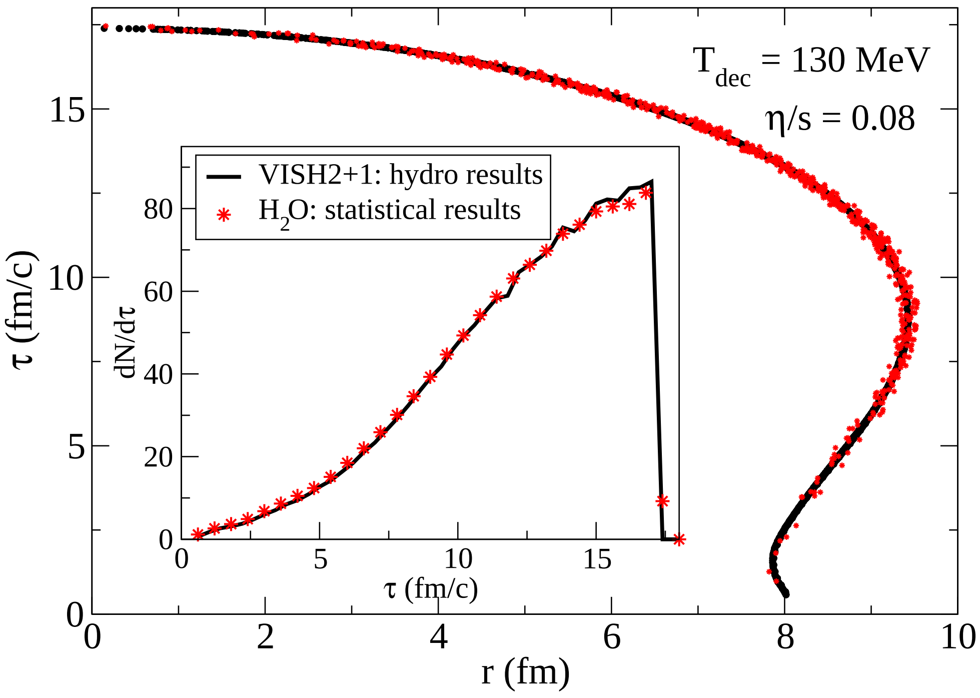
Smooth transition leads to smaller δf at freeze-out

$\Longrightarrow$ larger v_2

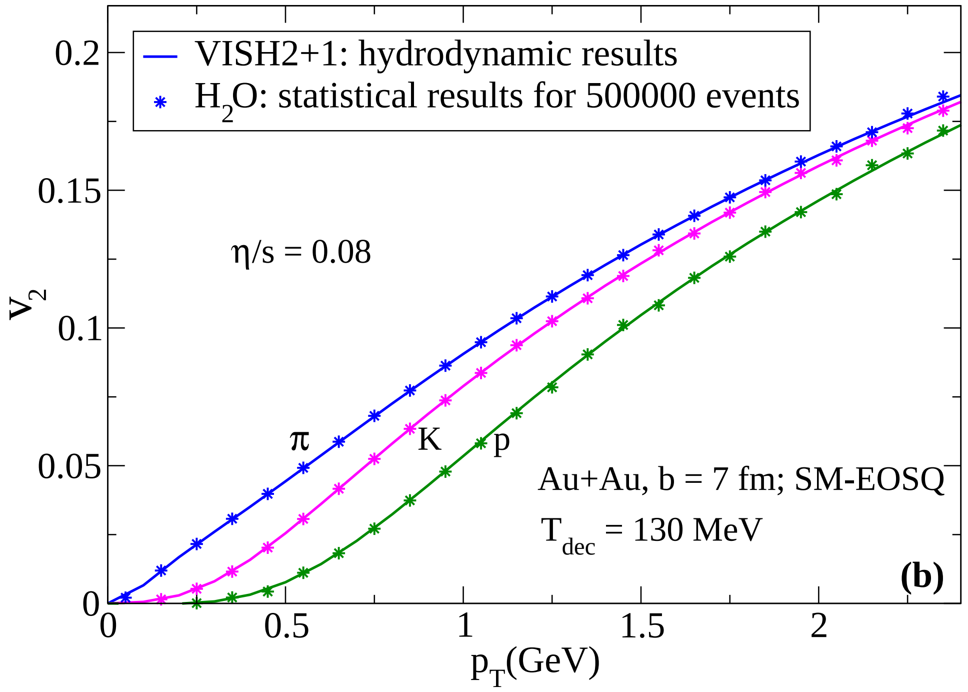
H_2O: Hydro-to-OSCAR converter

Monte-Carlo interface that samples hydrodynamic Cooper-Frye spectra (including viscous correction δf) on conversion surface to generate particles at positions x_i^μ with momenta p_i^μ for subsequent propagation in `UrQMD` (or any other OSCAR-compatible hadron cascade afterburner)

Song, Bass, Heinz, PRC 83 (2011) 024912



200 A GeV Au+Au, $b = 0$



200 A GeV Au+Au, $b = 7$ fm

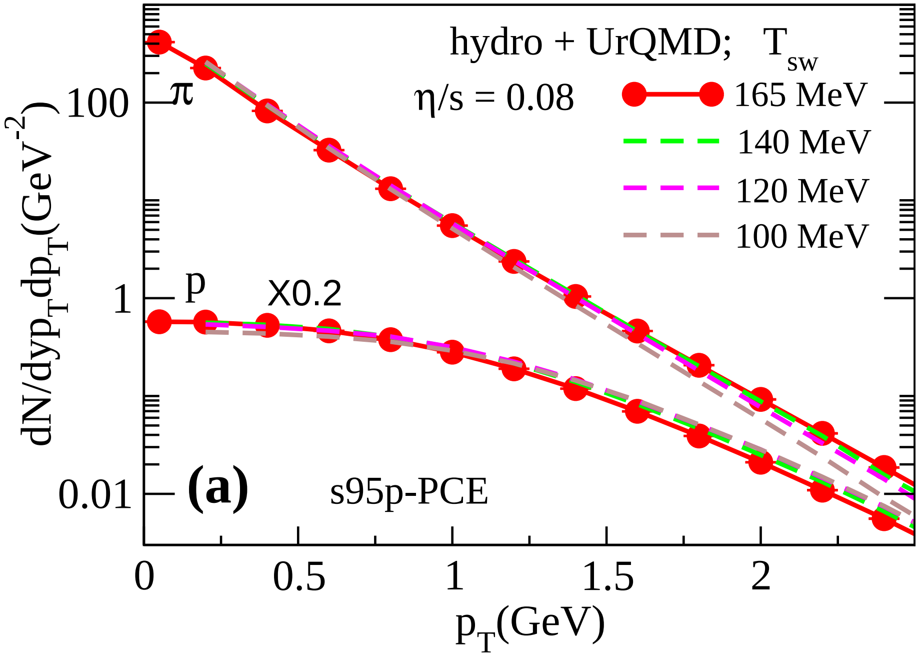
VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid

Sensitivity to H_2O switching temperature:

With chemically frozen EOS (s95p-PCE),
p_T-spectra show very little sensitivity to $T_{\rm sw}$ (Teaney, 2000):

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 7$ fm



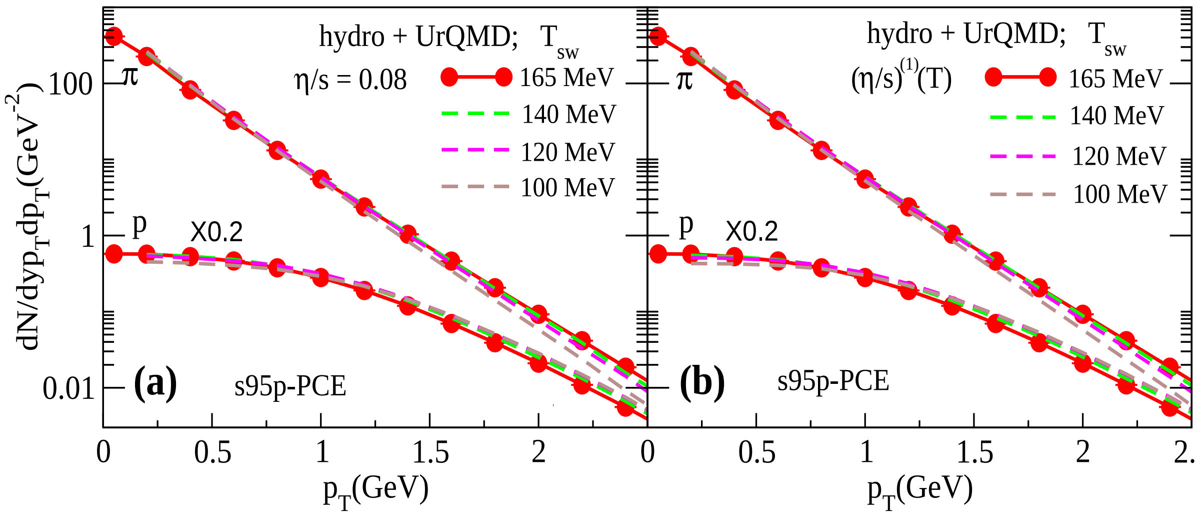
VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid

Sensitivity to H_2O switching temperature:

With chemically frozen EOS (s95p-PCE),
p_T-spectra show very little sensitivity to $T_{\rm sw}$ **but v_2 does:**

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 7$ fm



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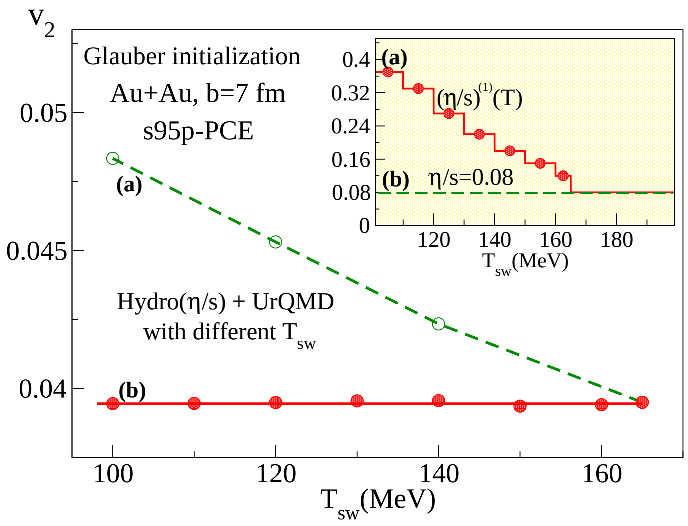


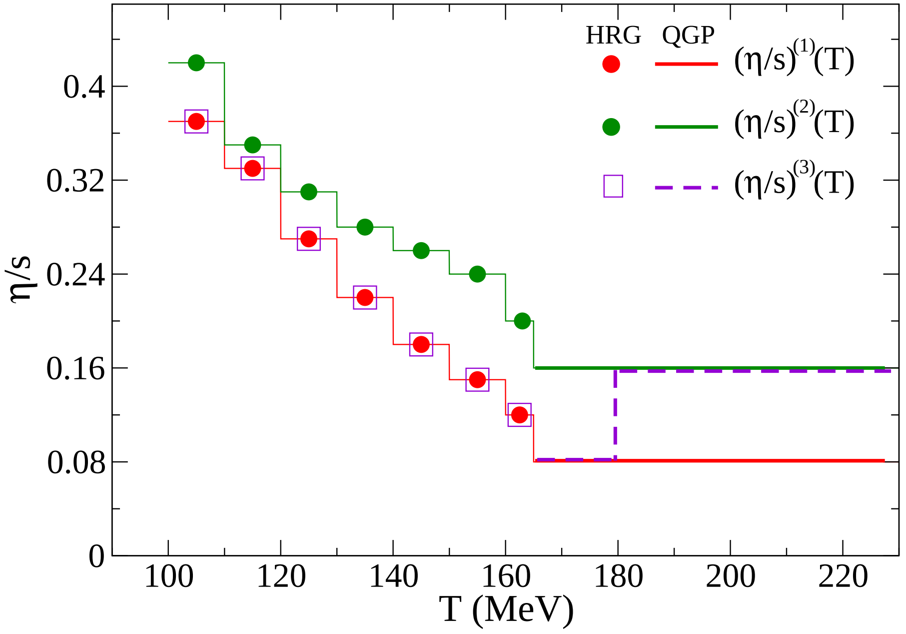
Viscous hydro with fixed $\eta/s = 0.08$ generates more v_2 below T_c than does UrQMD
$\Longrightarrow$ UrQMD is more dissipative

VISH2+1 simulation of UrQMD dynamics requires T-dependent $(\eta/s)(T)$ that increases towards lower temperature

Is there a switching window in which UrQMD can be simulated by viscous hydro?

Unfortunately NO!

Song, Bass, Heinz, PRC 83 (2011) 2011



$(\eta/s)(T)$ extracted by trying to reproduce v_2 independent of switching temperature depends on δ_f input into UrQMD from hadronizing QGP

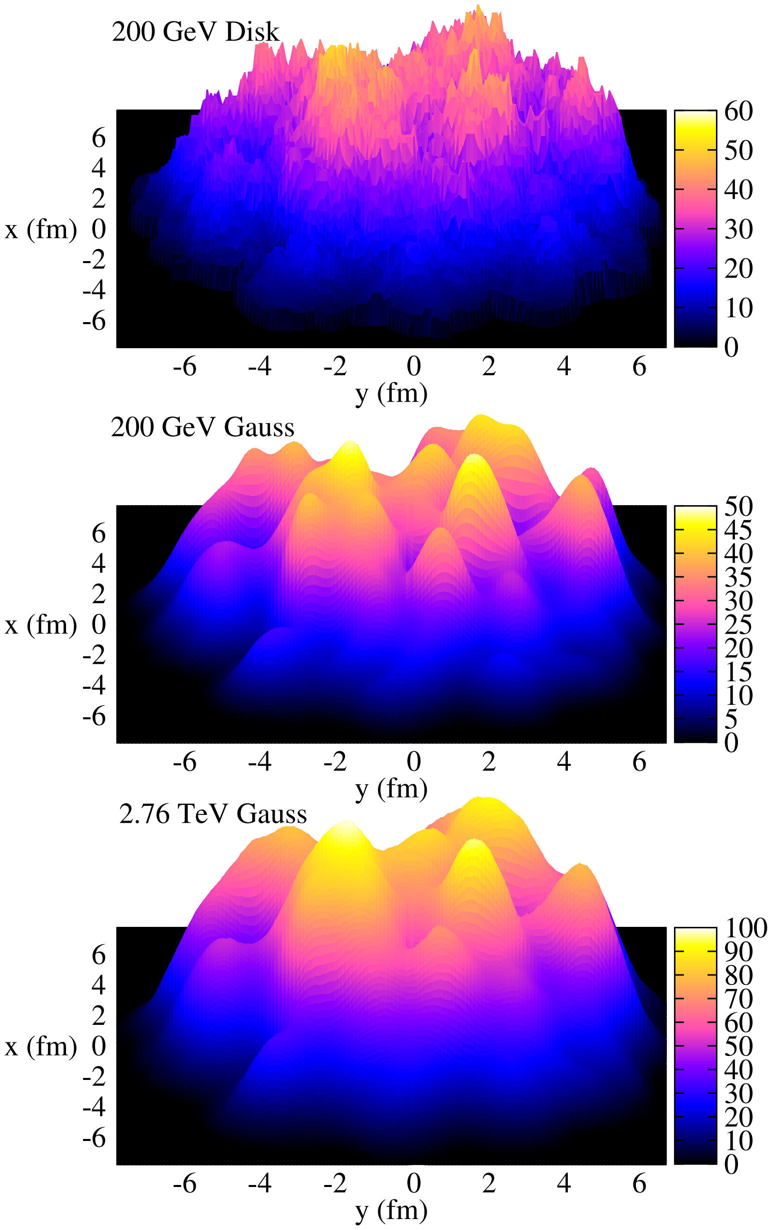
$\Longrightarrow$ δf relaxes too slowly in UrQMD to be describable by viscous Israel-Stewart hydro

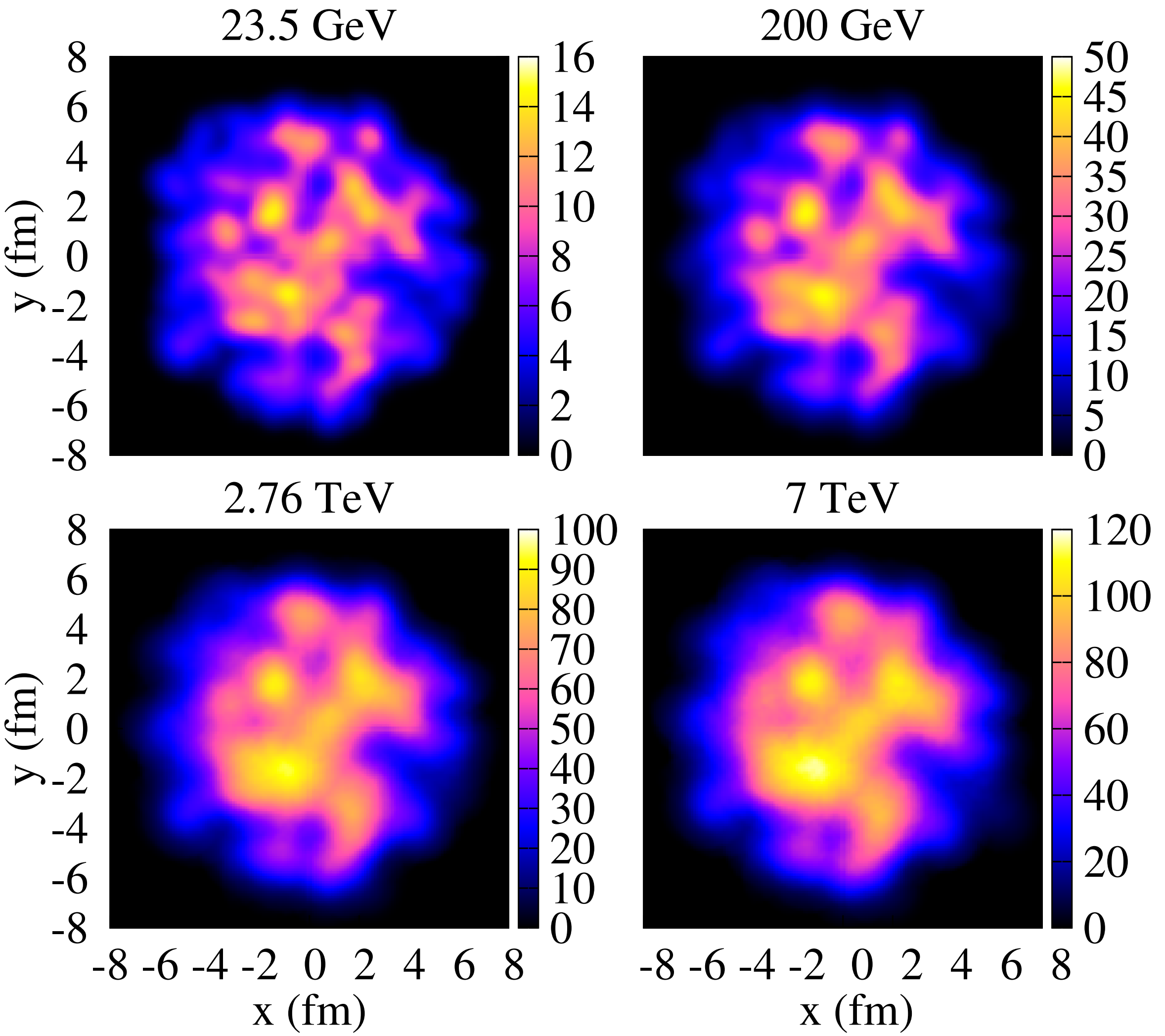
$\Longrightarrow$ extracted $(\eta/s)(T)$ not a proper UrQMD transport coefficient

$\Longrightarrow$ UrQMD dynamics can't be described by viscous Israel-Stewart hydrodynamics

Smearing effects from nucleon growth at high energies

U. Heinz & Scott Moreland, arXiv:1108.5379





Between $\sqrt{s} = 23.5$ and 7,000 GeV, nucleon area grows by factor $\mathcal{O}(2) \Longrightarrow$ significant smoothing of event-by-event density fluctuations from RHIC to LHC