Theory of collective dynamics: flow, fluctuations and correlations

Gabriel S. Denicol (BNL)

Current Theoretical Description
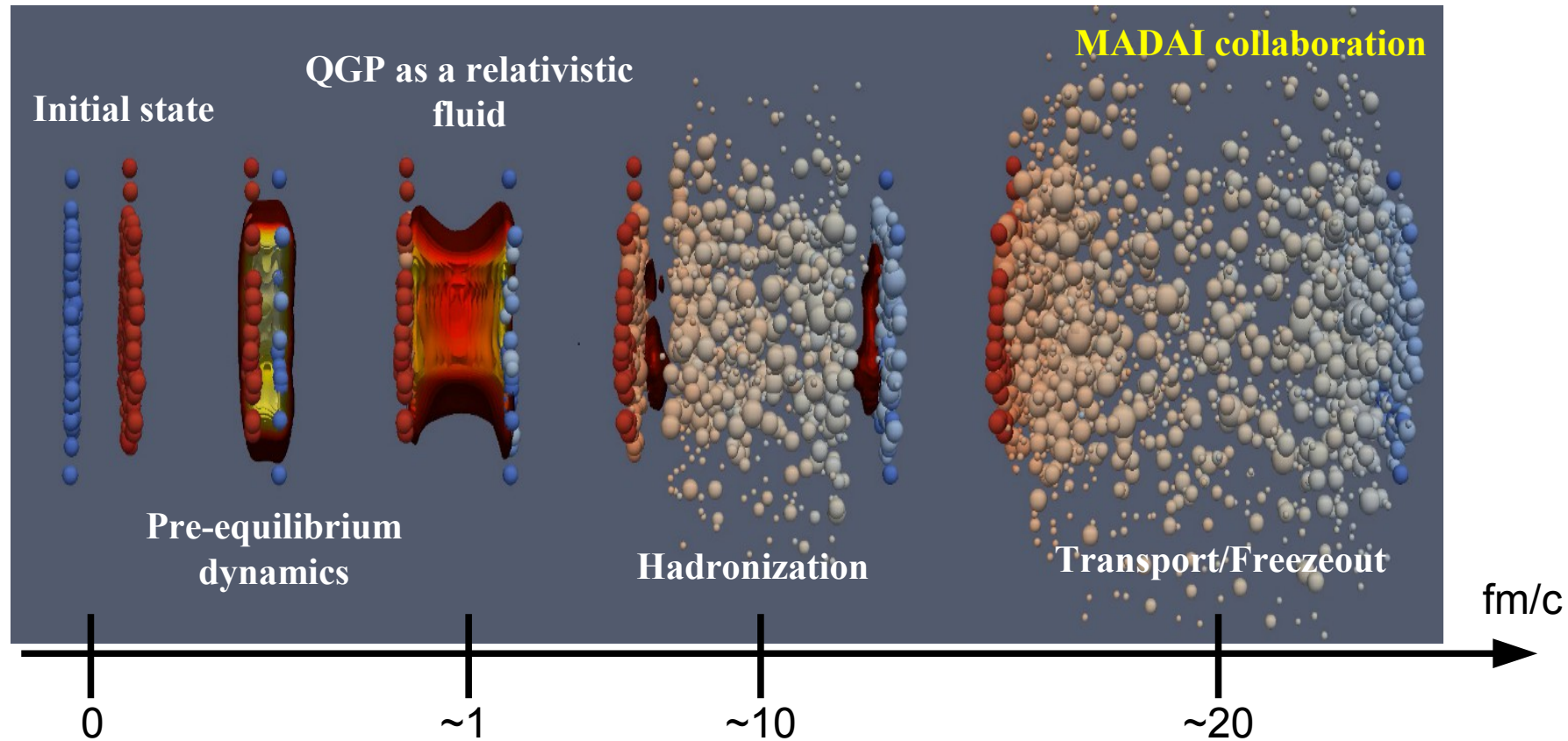
Empirical: Fluid-dynamical modeling of heavy ion collisions works well at RHIC and LHC energies
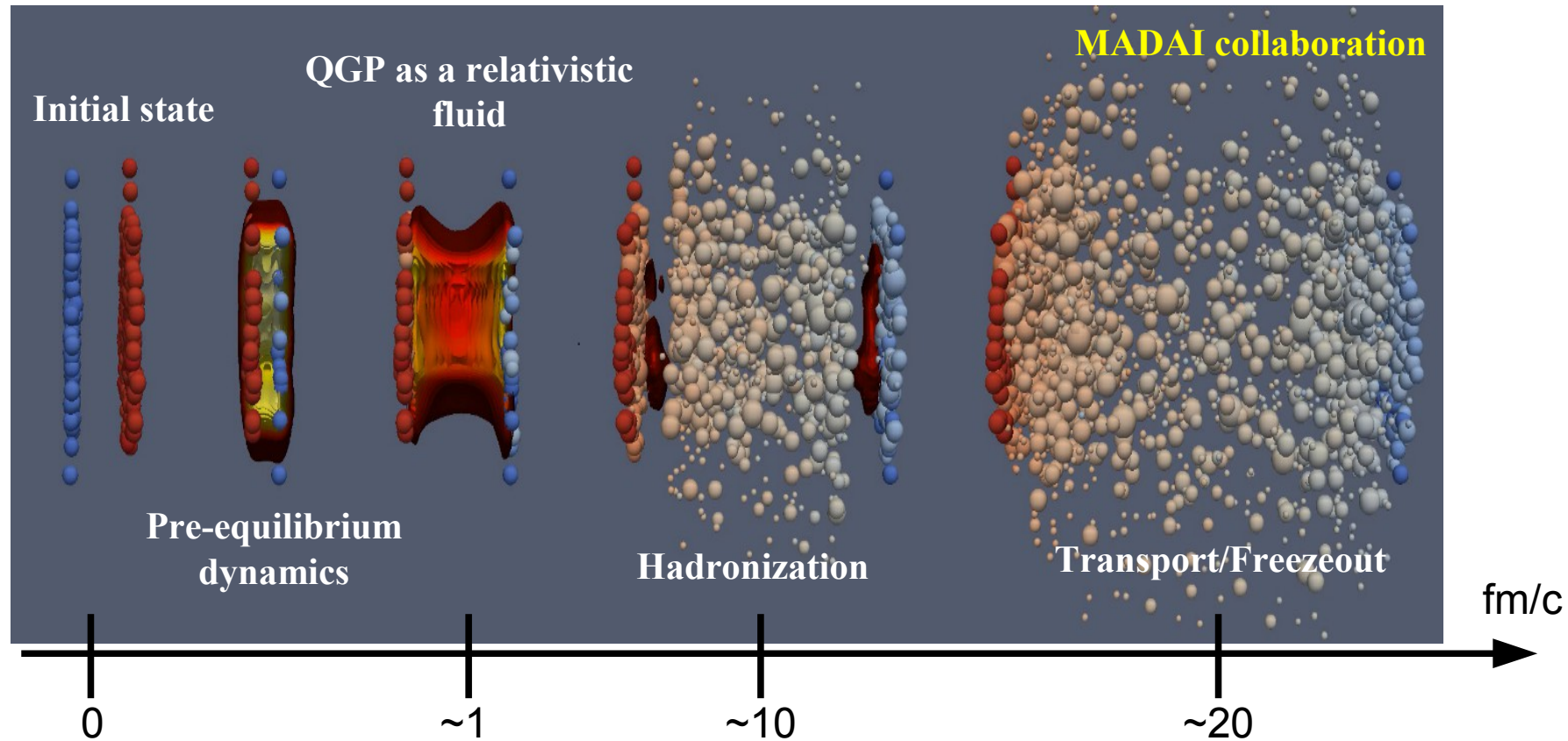
Main assumption: system approaches local equilibrium on very small time scales ~1 fm

Current Theoretical Description

Goal: use all data available to extract transport properties of QCD matter & understand initial state

Bulk QCD matter is only created transiently
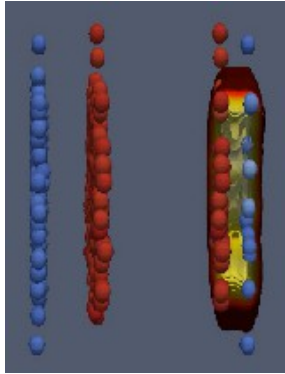Need to reverse-engineer its properties

3

Ingredients of Hydrodynamic model

Initial Condition: $\tau_0,$ $T^{\mu\nu}(\tau_0,\mathbf{r})$, $N^{\mu}(\tau_0,\mathbf{r})$

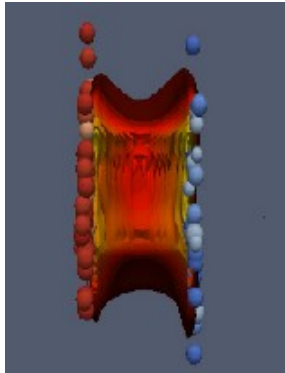Approach to equilibrium, Hydrodynamization
Matching pre-equilibrium phase to hydro
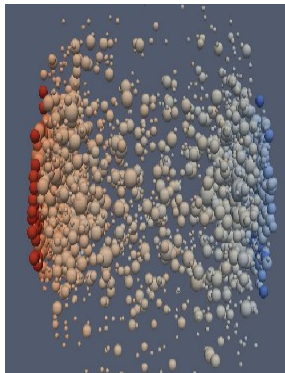
Talks by Kurkela and Chesler (tomorrow)

Fluid-dynamical expansion

(l)QCD EoS: $P(\varepsilon, n_B)$ – includes "hadronization"
transport coeffs.: η, ζ, κ, …

Hadronic Transport

Matching fluid dynamics to transport
hadron resonance gas model – true at T>150 MeV ?

4

Ingredients of Hydrodynamic model

Initial Condition: τ_0, $T^{\mu\nu}(\tau_0, \boldsymbol{r})$, $N^\mu(\tau_0, \boldsymbol{r})$

Approach to equilibrium, Hydrodynamization
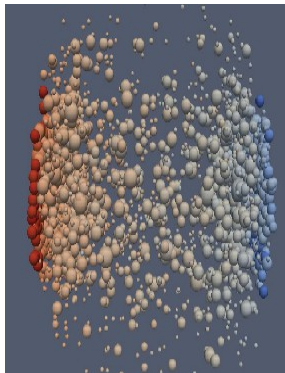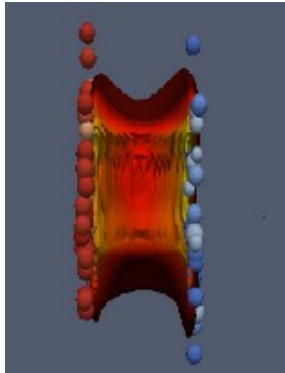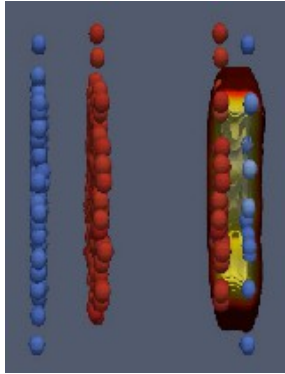Matching pre-equilibrium phase to hydro

Fluid-dynamical expansion

(l)QCD EoS: $P(\varepsilon, n_B)$ – includes "hadronization"
transport coeffs.: η, ζ, κ, ...

Want to extract

Hadronic Transport

Matching fluid dynamics to transport
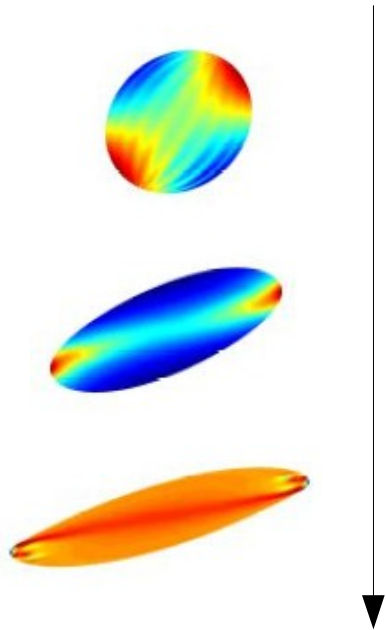hadron resonance gas model – true at T>150 MeV ?

Need to model

5

Progress in extracting transport coefficients

Sources of viscosity and dissipation

Shear viscosity

Resistance to deformation

$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle}$$

Bulk viscosity

Resistance to expansion

$$\Pi = -\zeta\nabla_\mu u^\mu$$

Charge/particle diffusion

$$q^\mu = \kappa\nabla^\mu\frac{\mu_B}{T}$$

very studied

little studied

Not yet … but coming[7]

UrQMD + Hydro + UrQMD
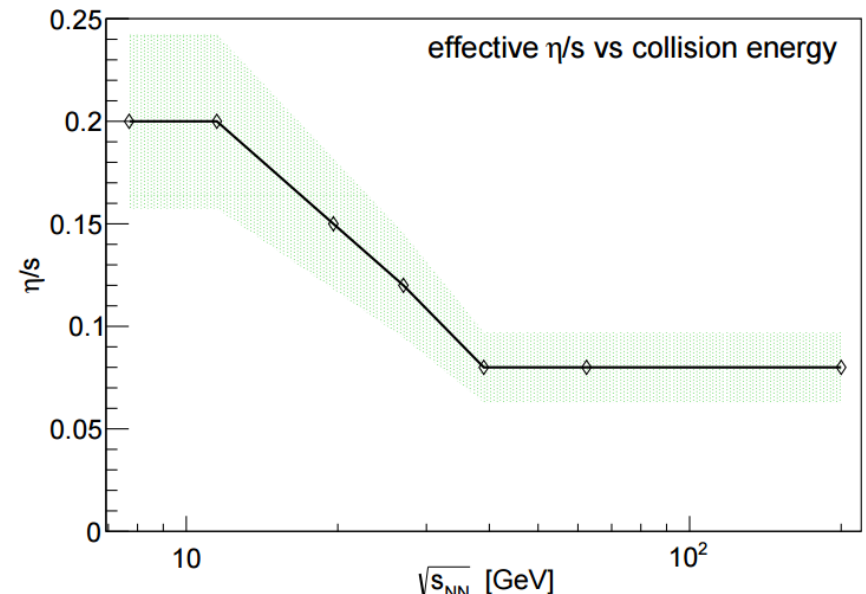
Karpenko *et al*, PRC91 (2015) 6, 064901

Modeling of heavy ion collisions at lower energies

Finite baryon number, isospin, and electric charge must be included

Effective EoS is employed   Steinheimer&Schramm&Stocker, J. Phys. G 38, 035001 (2011).

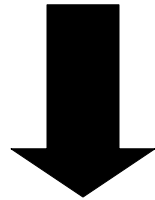**Constant** η/s is extracted separately for each collision energy
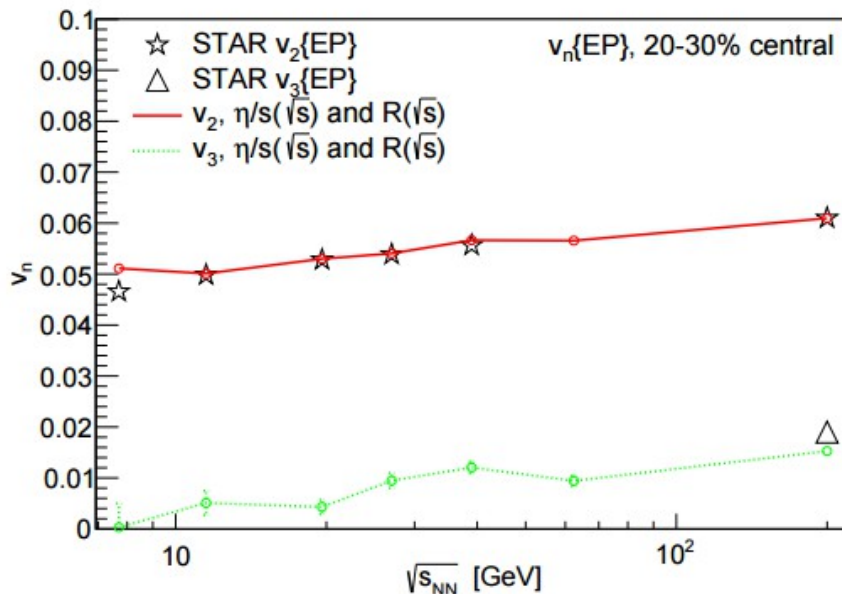
**Good description of
v_2 as a function of energy**

η/s estimated

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η/s is **not** a function of **collision energy**
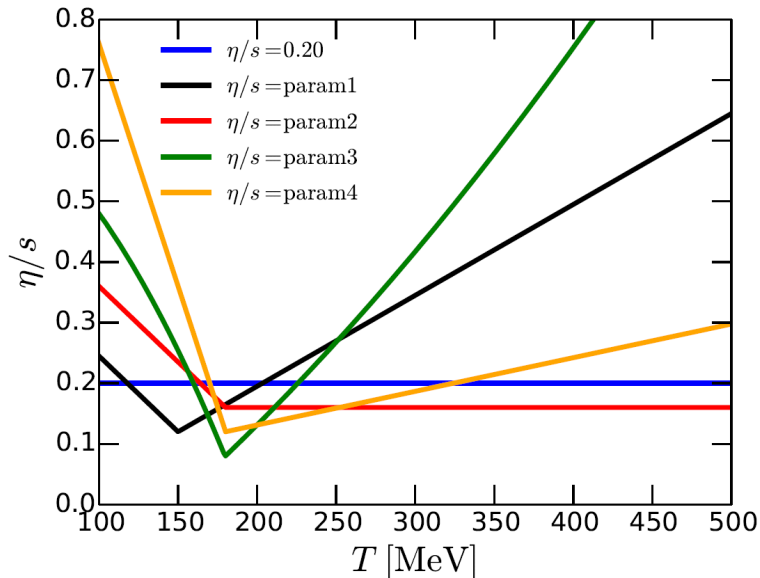
$$\downarrow$$

$$\eta/s(T, \mu_q)$$
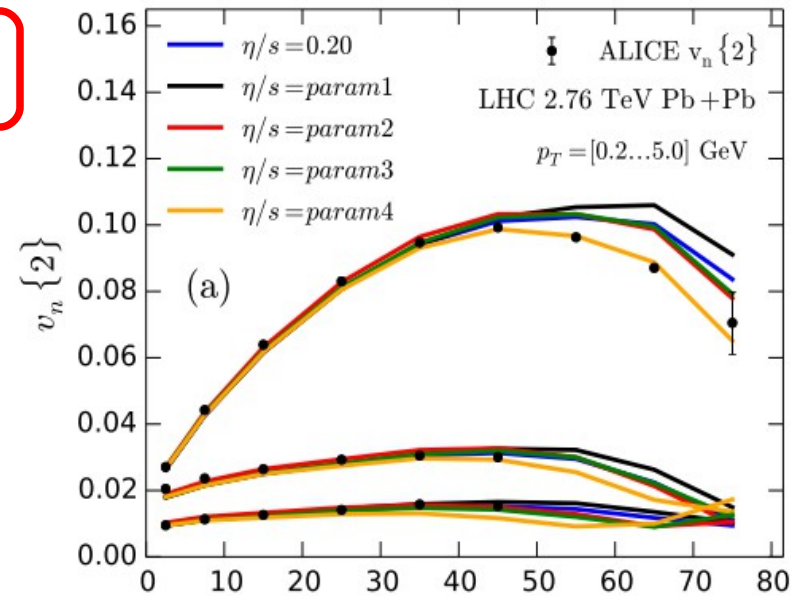
Can we extract it?

EKRT model + second order viscous hydro
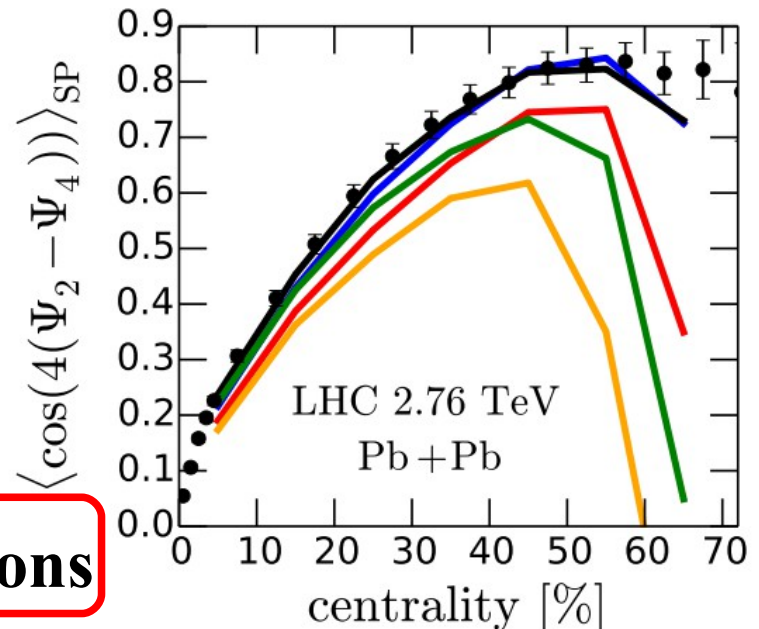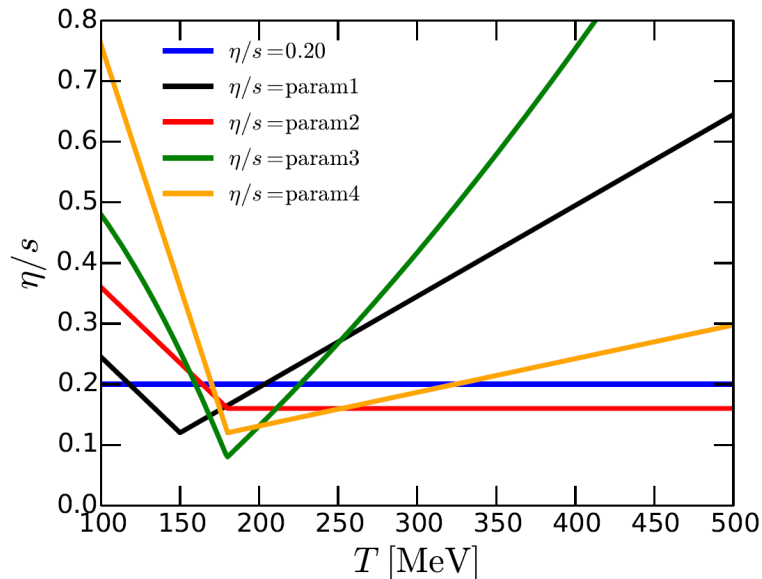
Niemi *et al*, arXiv:1505.02677

talk by
Niemi, Wed.

η/s(T)

Vn

It is necessary to look at more than v₂,₃ to obtain η/s(T)

correlations

EKRT model + second order viscous hydro

Niemi *et al*, arXiv:1505.02677

talk by Niemi, Wed.

$\eta/s(T)$

$$SC(m, n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

It is necessary to look at more than $v_{2,3}$ to obtain η/s(T)
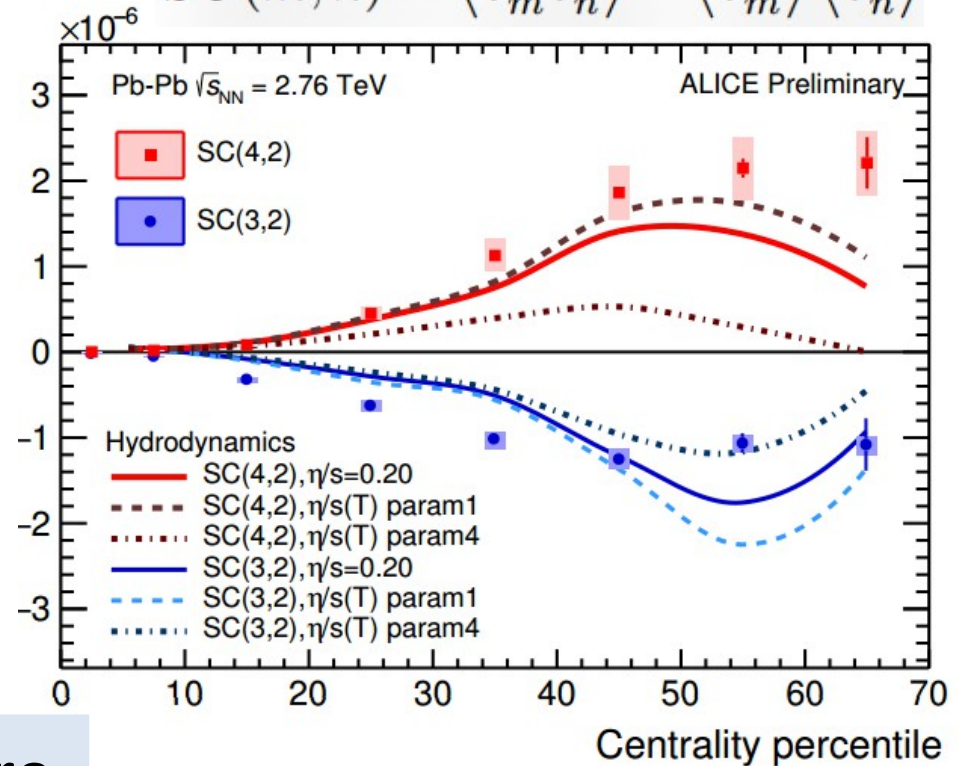
new data Y. Zhou, Wed.

Problems describing this data?

Afterburner? poster by S. Ryu

IP-Glasma + **MUSIC** + **UrQMD**

Ryu *et al*, PRL 115, 132301 (2015)
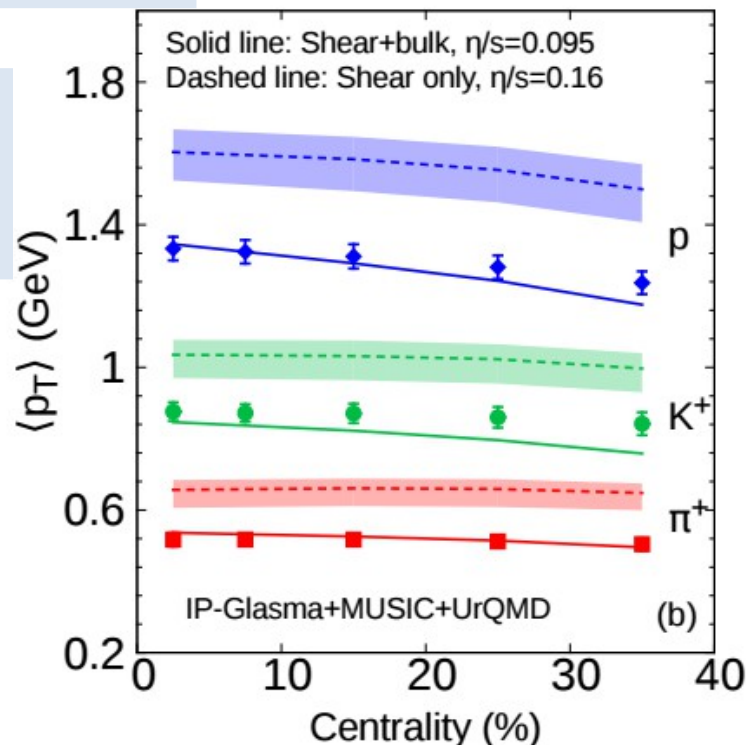
LHC

$\zeta/s(T)$ $\eta/s=0.095$

Importance of bulk viscosity
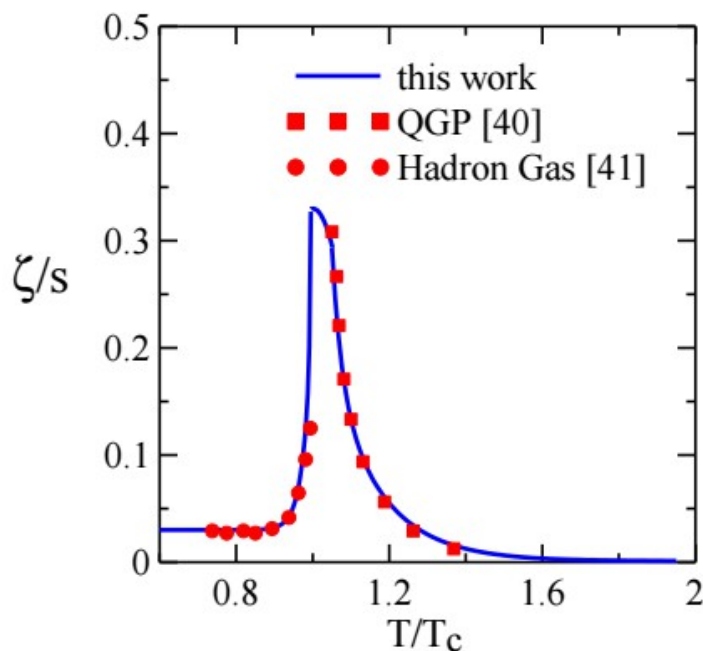
IP-Glasma initial conditions lead to high mean pT

Bulk viscosity reduces mean pT

Value of shear viscosity extracted changes significantly
$\eta/s=0.16 \longrightarrow 0.095$

Good description of direct photons   **Paquet, Wed.**   12

Systematic model-to-data comparison: Global fits

Development of statistical tools to simultaneously vary all parameters in model calculations and extract them from data
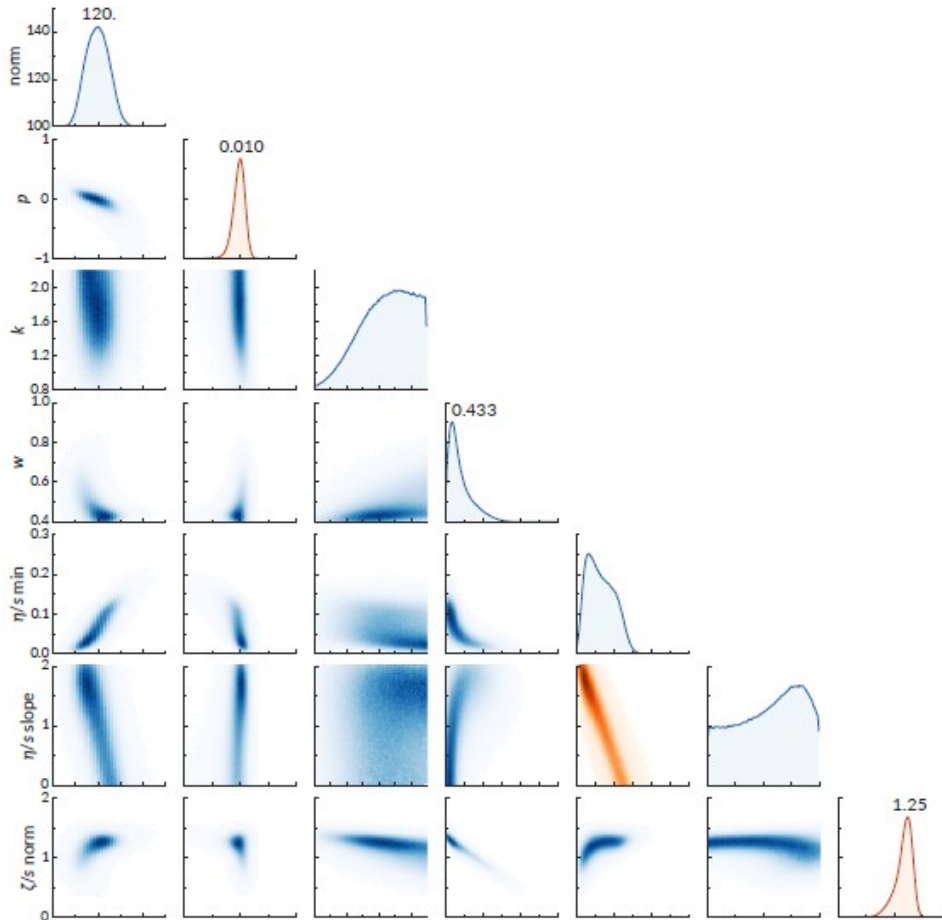

poster by Bernhard

Many model calculations performed randomly in parameter space

Emulator: interpolate between results; Global fits

Diagonal: optimal value of parameters in model

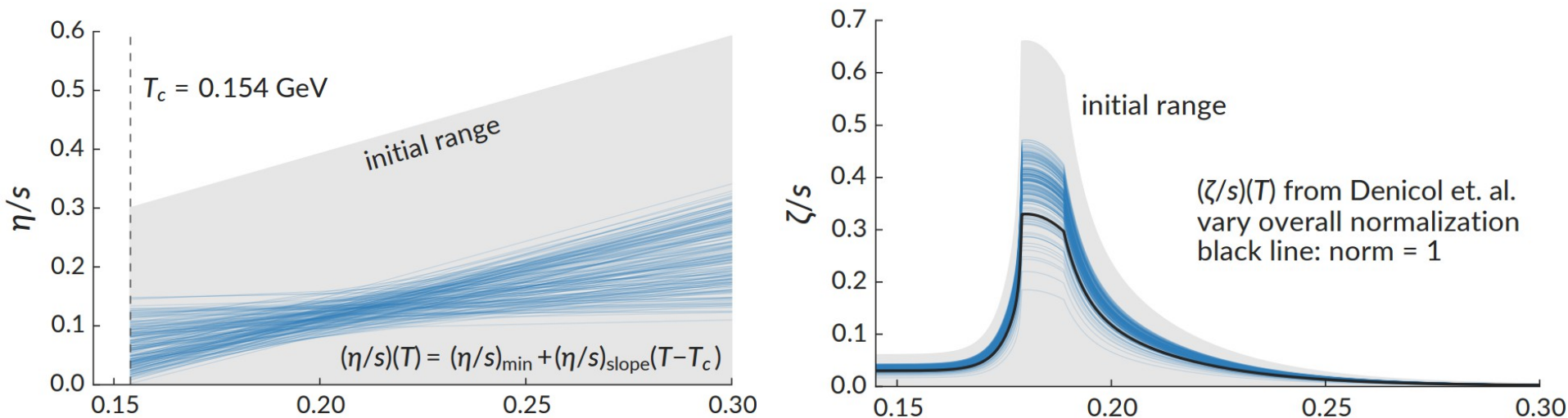**Off diagonal:** correlation between parameters

Outcome: a more systematic extraction of model parameters

Extraction of η/s(T) and ζ/s(T)

Model: Trento initial state + Hydro (bulk&shear) + UrQMD
Very good description of Multiplicity, mean-pT, and Vn

shear not well constrained with just LHC data

finite bulk viscosity is favored

Very similar values of transport coefficients to those found by

the McGill group (PRL 115, 132301 (2015))   14

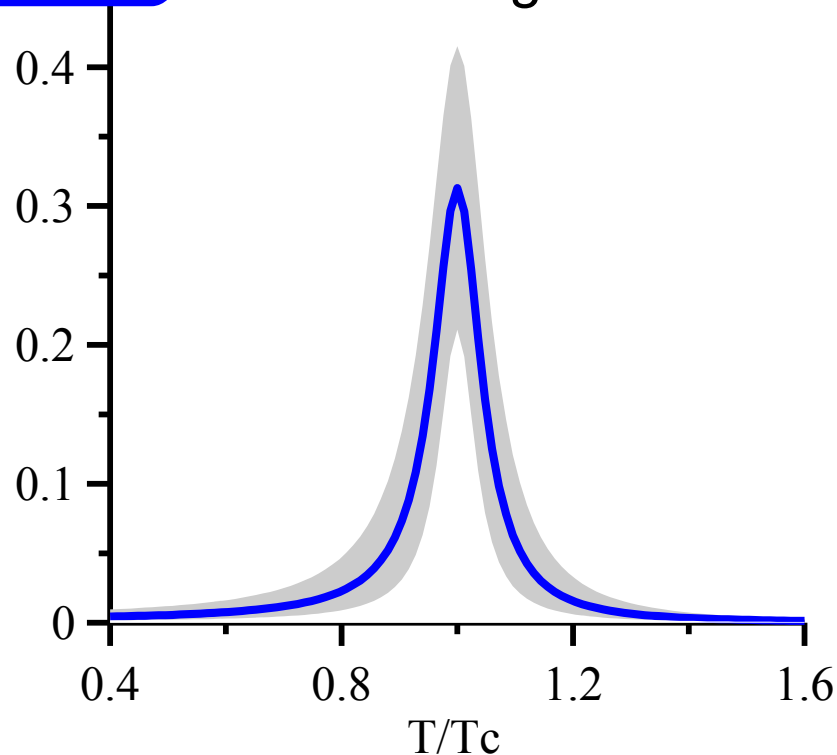# Extraction of $\zeta/s(T)$ and η/s with MADAI Emulator
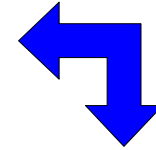
Model: IP-Glasma + MUSIC (bulk&shear) McGill

$\zeta/s(T)$

band = 1 sigma

LHC energy

$\zeta/s(T)$ parametrized as a Breit-Wigner distribution

Parameters extracted

"Tc" = 0.177 ± 0.022 GeV

η/s = 0.077 ± 0.037

large bulk viscosity around "Tc" is favored by data

Consistent with our previous findings (recently confirmed by Duke group)

Parameter optimization: MC-Glauber ICs with pre-flow

Using MADAI tools (see **poster by J. Bernhard, S. Moreland and S.A. Bass** for a more elaborate analysis fitting 8 model parameters simultaneously to LHC Pb+Pb data):
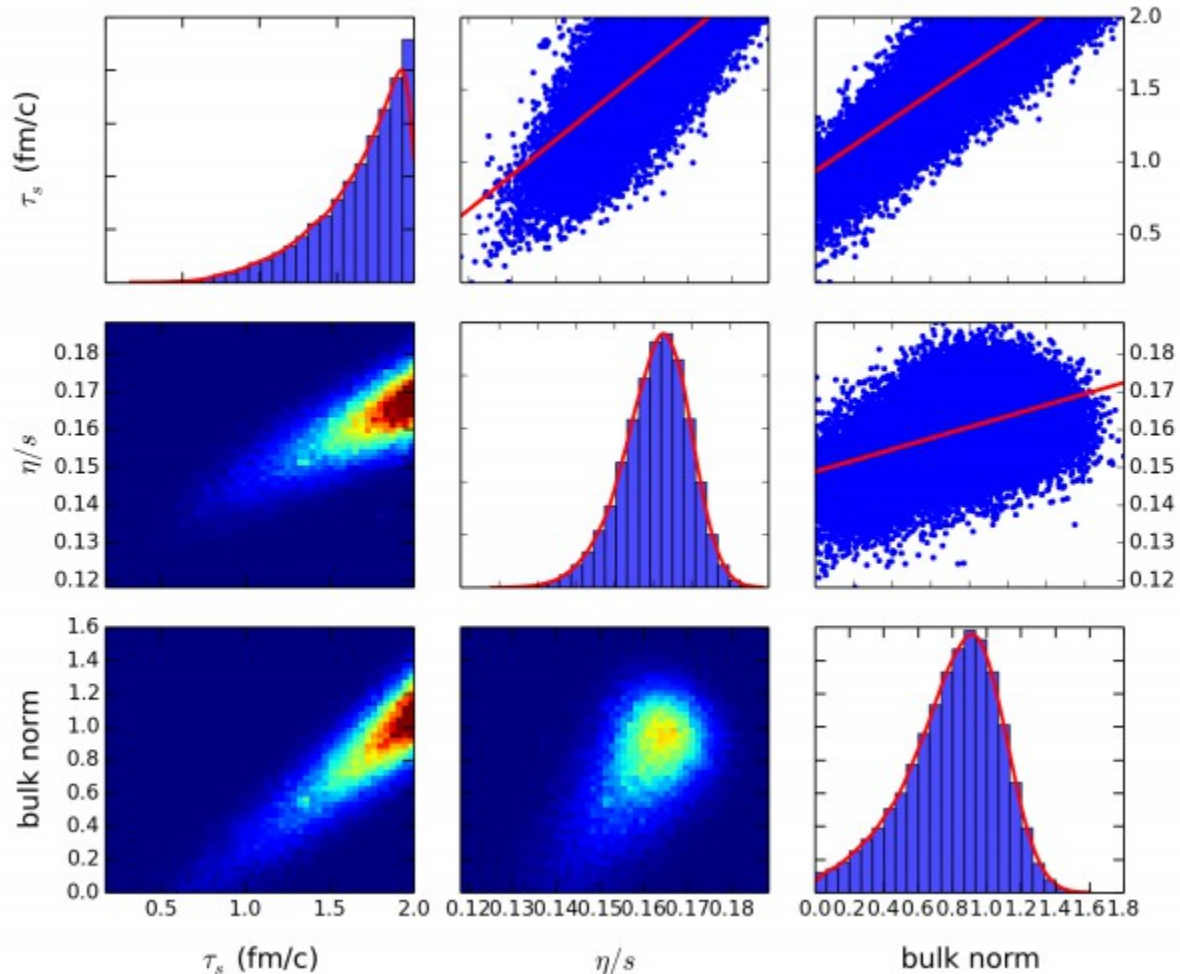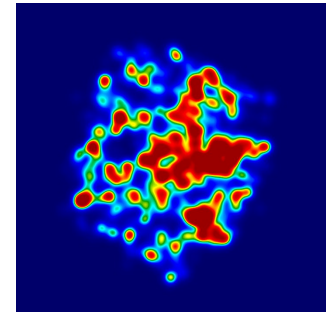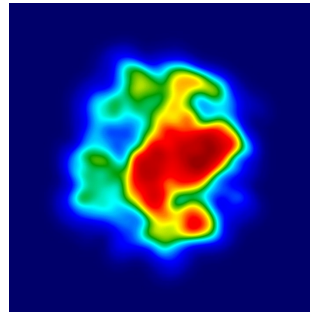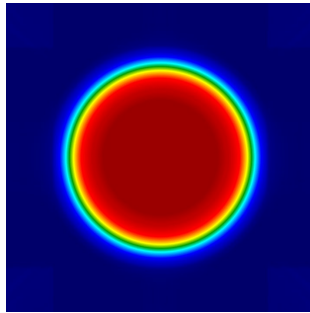
Also using statistical tools. Also finding a nonzero bulk viscosity.
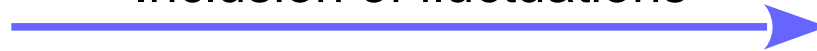
(some) Developments in the model of heavy ion collisions

Evolution of initial state in transverse plane

$\varepsilon(\tau_0, x, y)$
in central
collisions

Inclusion of fluctuations

Understanding of transport coefficients dramatically improved

Important to also understand longitudinal fluctuations

New measurements on fluctuations: models must keep up to date

Beam energy scan: 3+1D model of collision is essential
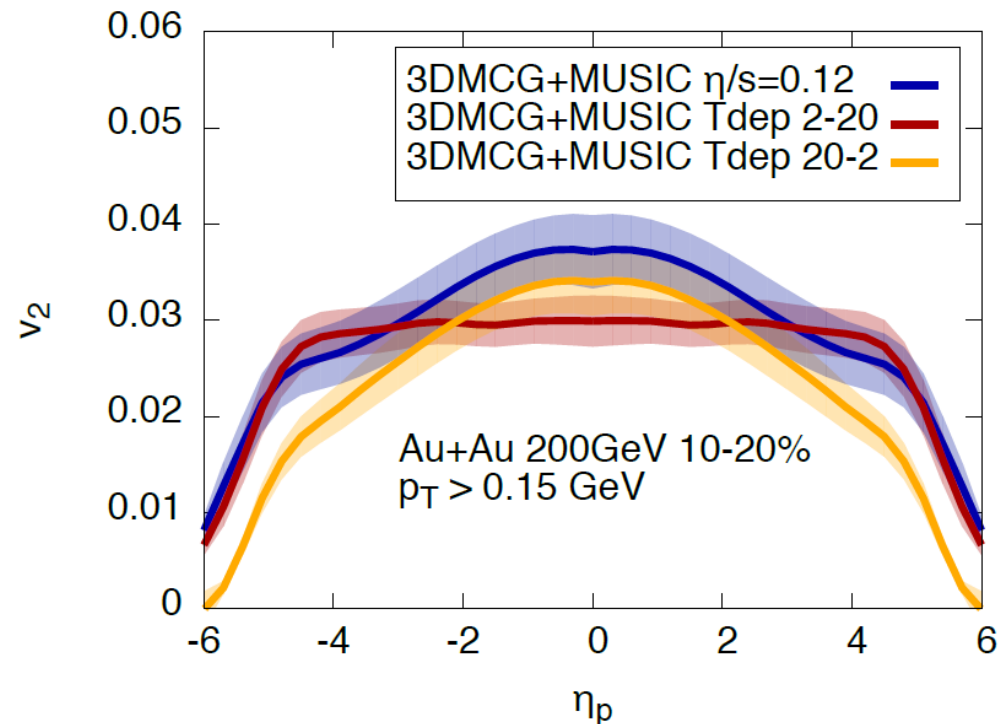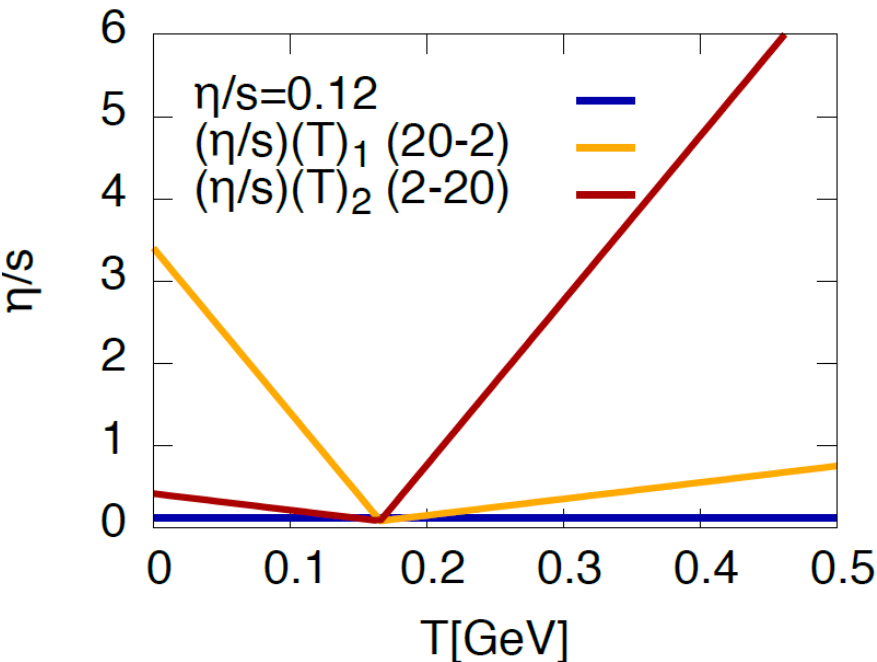
See talks by Schenke and Pang

**How does this affect our understanding of the event
at midrapidity?**

de-correlation of event-planes – L. Pang (Tue.)

3+1D hydro with $\zeta/s(T,\mu)$ and $\eta/s(T,\mu)$

Effect of a temperature dependent η/s on $V_{2,3}(\eta)$

Measurements of flow harmonics at high rapidity can help extract the transport coefficients of QCD
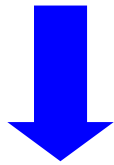
- **Anisotropic Hydrodynamics (aHydro)**

Strickland&Martinez&Florkowski&Ryblewski

Hydrodynamics

$$f_{\mathbf{k}} = f_{\mathbf{k}}^{\mathrm{eq}} + \delta f_{\mathbf{k}}$$

expansion around

local equilibrium

⬇

Momentum anisotropy is treated as a **correction**

Anisotropic Hydrodynamics

$$f_{\mathbf{k}} = f_A\left(\mathbf{k}, T_\perp, \zeta^{\mu\nu}\right) + \delta f_{\mathbf{k}}$$

expansion around

non-equilibrium state

⬇

Momentum anisotropy is "**resummed**" into leading term

We have to understand when hydro breaks down

Do we need a new theory?

20

Validity of Hydro and aHydro?

Comparisons to kinetic theory:

Hydro does OK.

aHydro has a broader

domain of validity

M. Nopoush *et al*, PRD 91 045007 (2015)
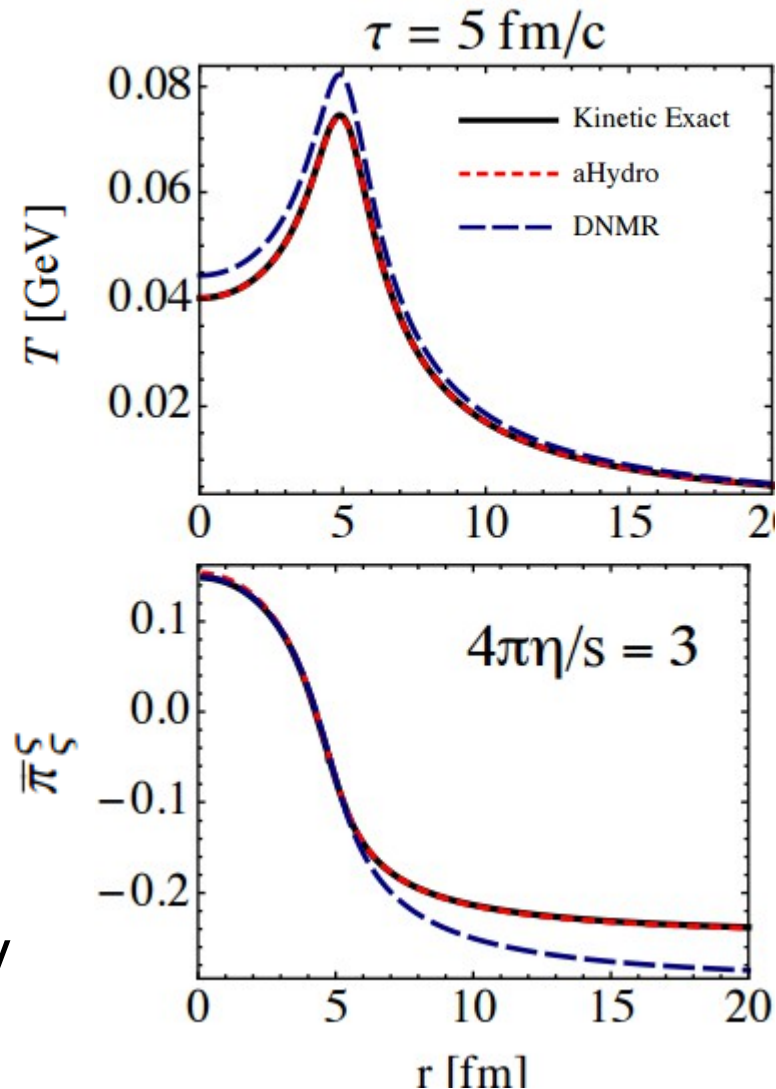G. Denicol *et al*, PRL 113, 202301 (2014)
Florkowski *et al*, PRC88 024903 (2013)
Bazow *et al*, PRC90 054910 (2014)
Tinti *et al*, arXiv:1505.06456

Challenge: aHydro for strongly coupled systems?

Quasi-particle description?

$\tau = 5$ fm/c

— Kinetic Exact
- - - aHydro
- - - DNMR

$4\pi\eta/s = 3$
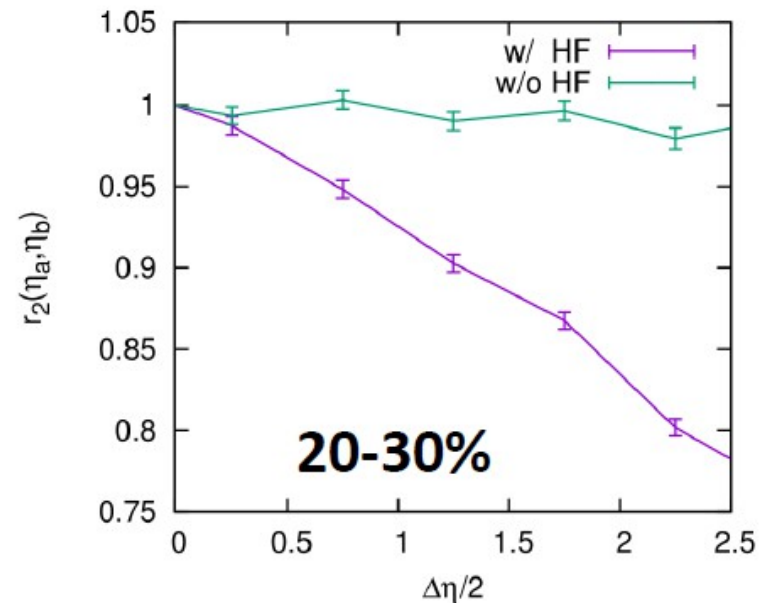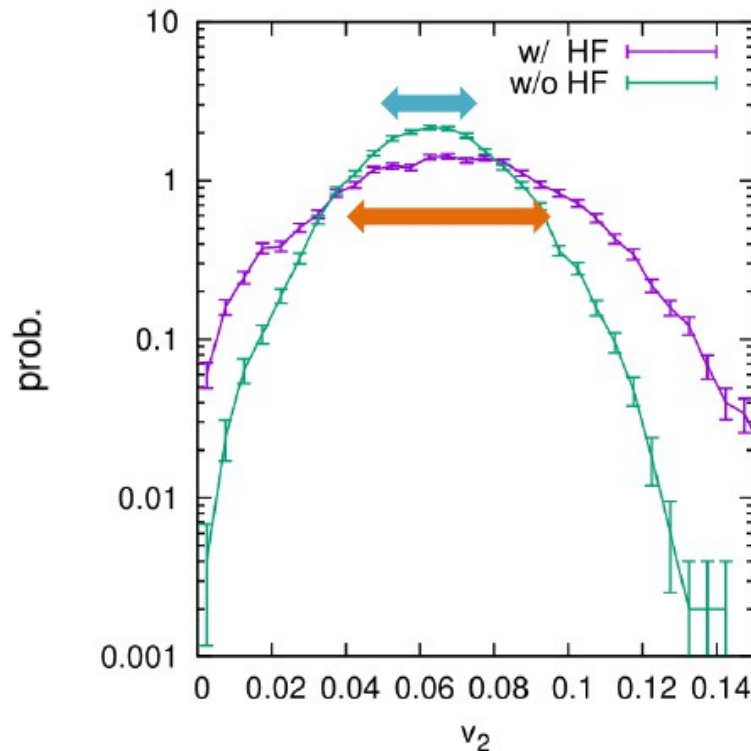
21

Fluctuating hydrodynamics

Hydro is no longer deterministic and is a source of fluctuations

$$\pi^{\mu\nu} = 2\eta\partial^{\langle\mu}u^{\nu\rangle} + \delta\pi^{\mu\nu},$$

usual term **noise term**

Fluctuation-Dissipation Relation

$$\langle\delta\pi^{ij}\delta\pi^{ij}\rangle \sim 4T\eta/V$$

Effect on observables can be large

Summary

✔ Some progress in understanding transport coefficients

Many calculations point to a large bulk viscosity
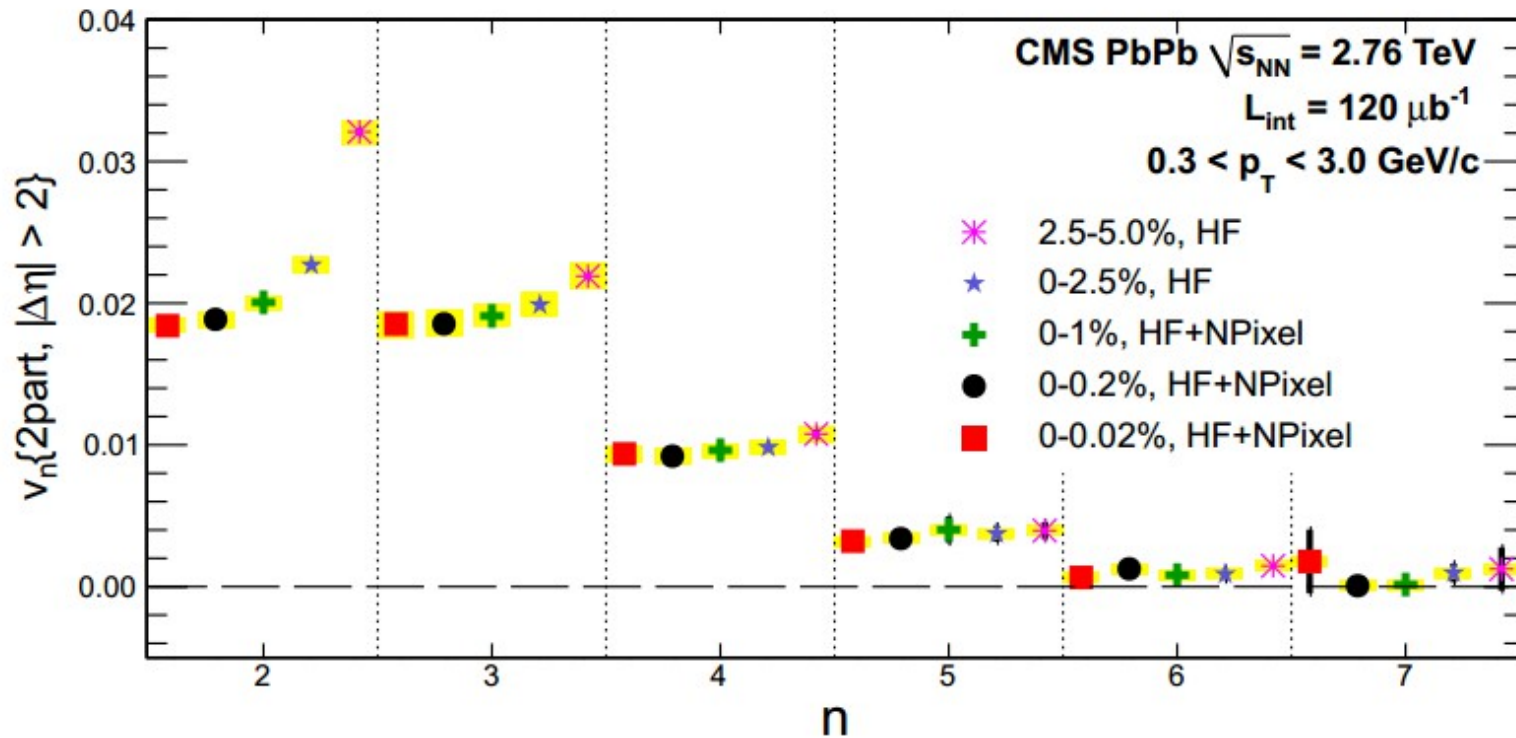
see also poster by Noronha-Hostler

Global fits really getting realistic:

Extracting $\eta/s(T)$ and $\zeta/s(T)$ will be possible in the next few years

✔ Moving torwards a better understanding of longitudial fluctuations

✔ Ahydro getting more quantitative

✔ Fluctuating hydrodynamics?

If(time < T$_{talk}$) {
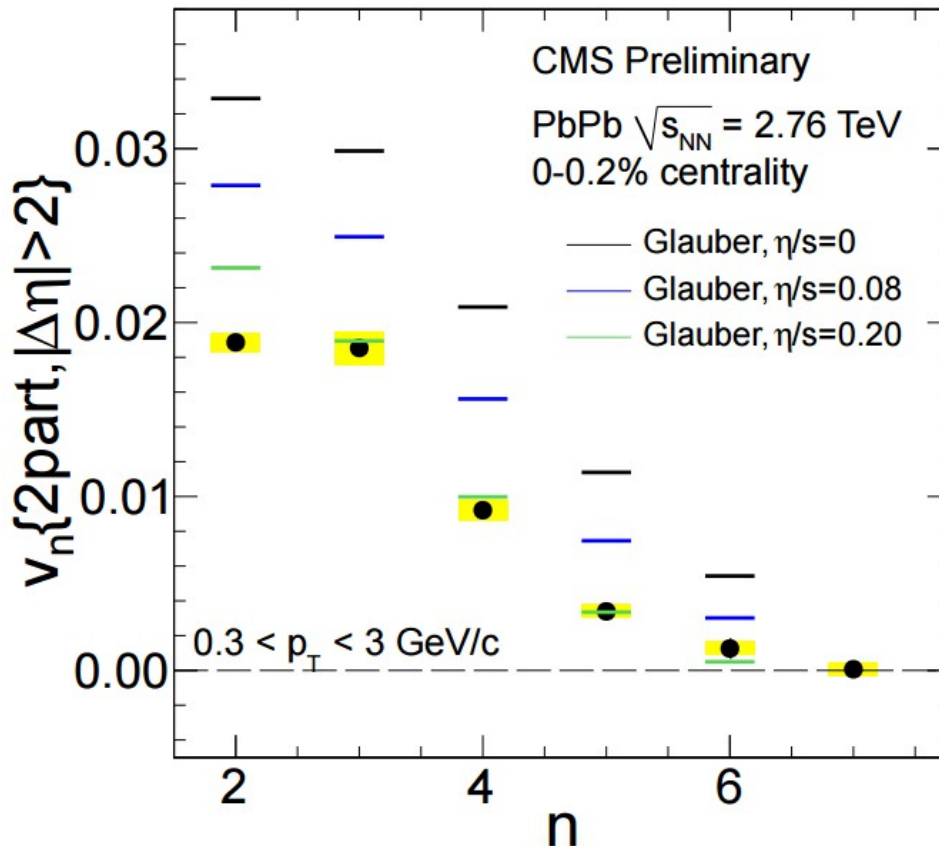
Ultracentral collisions

}

Ultracentral Heavy ion collisions

- **Nonhydrodynamic**(?) behaviour in ultracentral PbPb collisions

CMS Preliminary

PbPb $\sqrt{s_{NN}}$ = 2.76 TeV

0-0.2% centrality

— Glauber, $\eta/s=0$
— Glauber, $\eta/s=0.08$
— Glauber, $\eta/s=0.20$

$0.3 < p_T < 3$ GeV/c

y-axis: $v_n\{2part,|\Delta\eta|>2\}$

x-axis: n

$v_2 \sim v_3$

where is viscous damping?

Hydrodynamic models
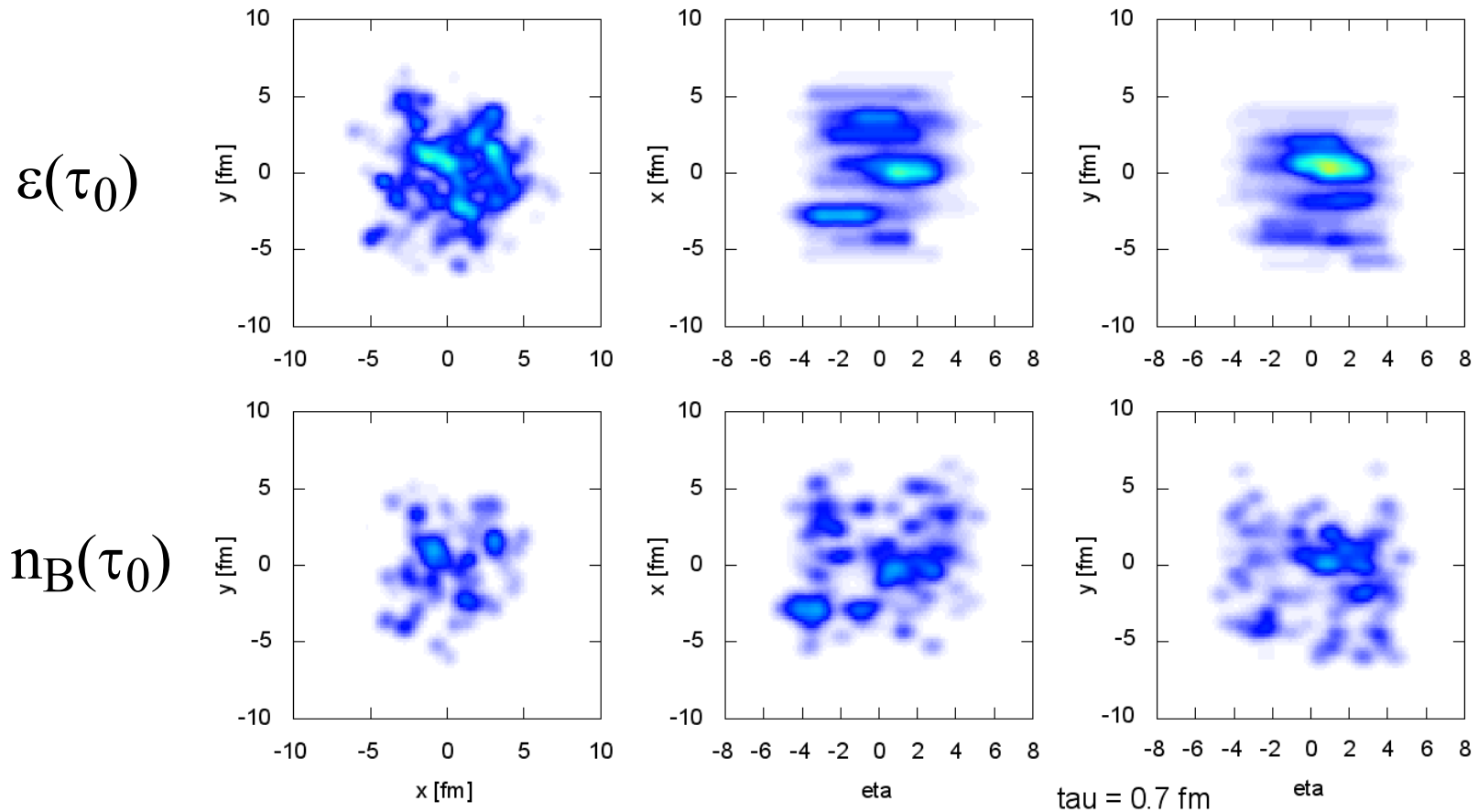always over-predict
the elliptic flow

CMS coll., CMS-PAS-HIN-12-011
Calculations by Luzum, arXiv:1210.6010

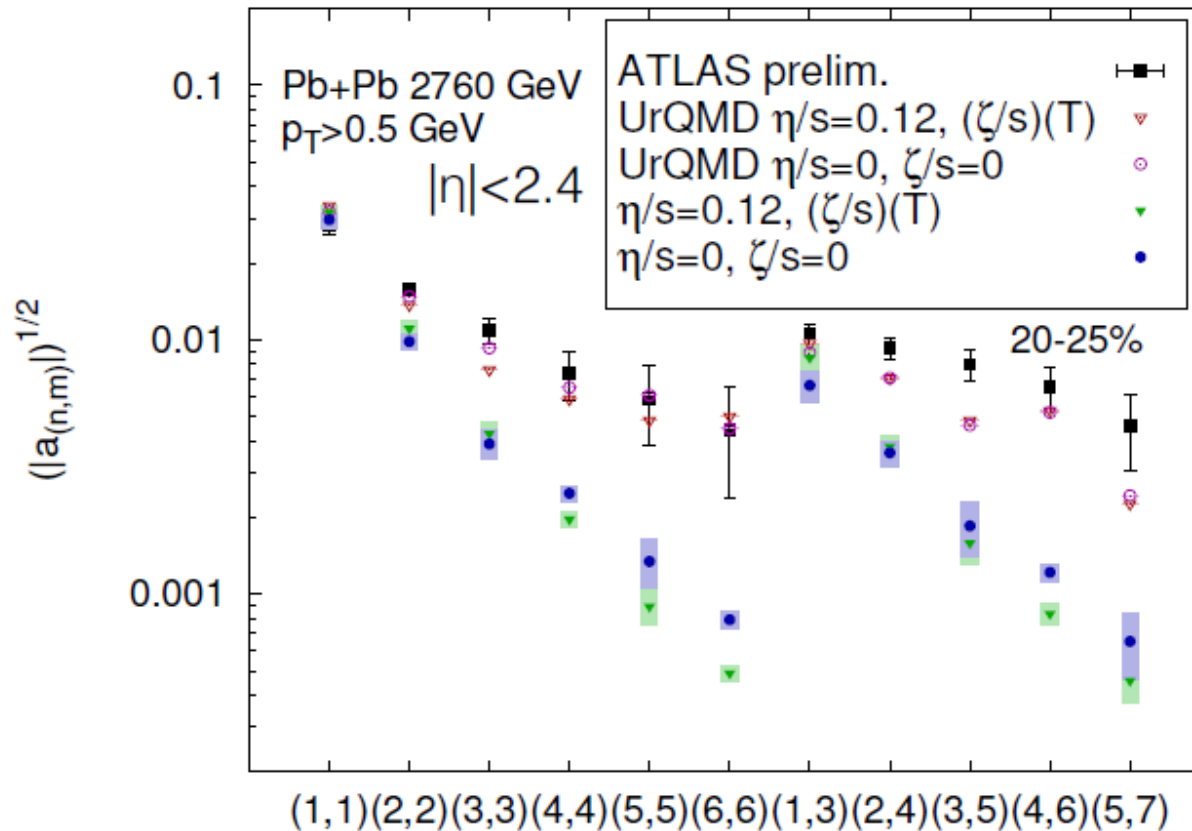So far, all hydro models cannot get this right

Important to understand longitudinal fluctuations

MC-Glauber for valence quarks

Longitudinal profile from qLEXUS model

$\varepsilon(\tau_0)$

$n_B(\tau_0)$

tau = 0.7 fm

Schenke (Wed.)

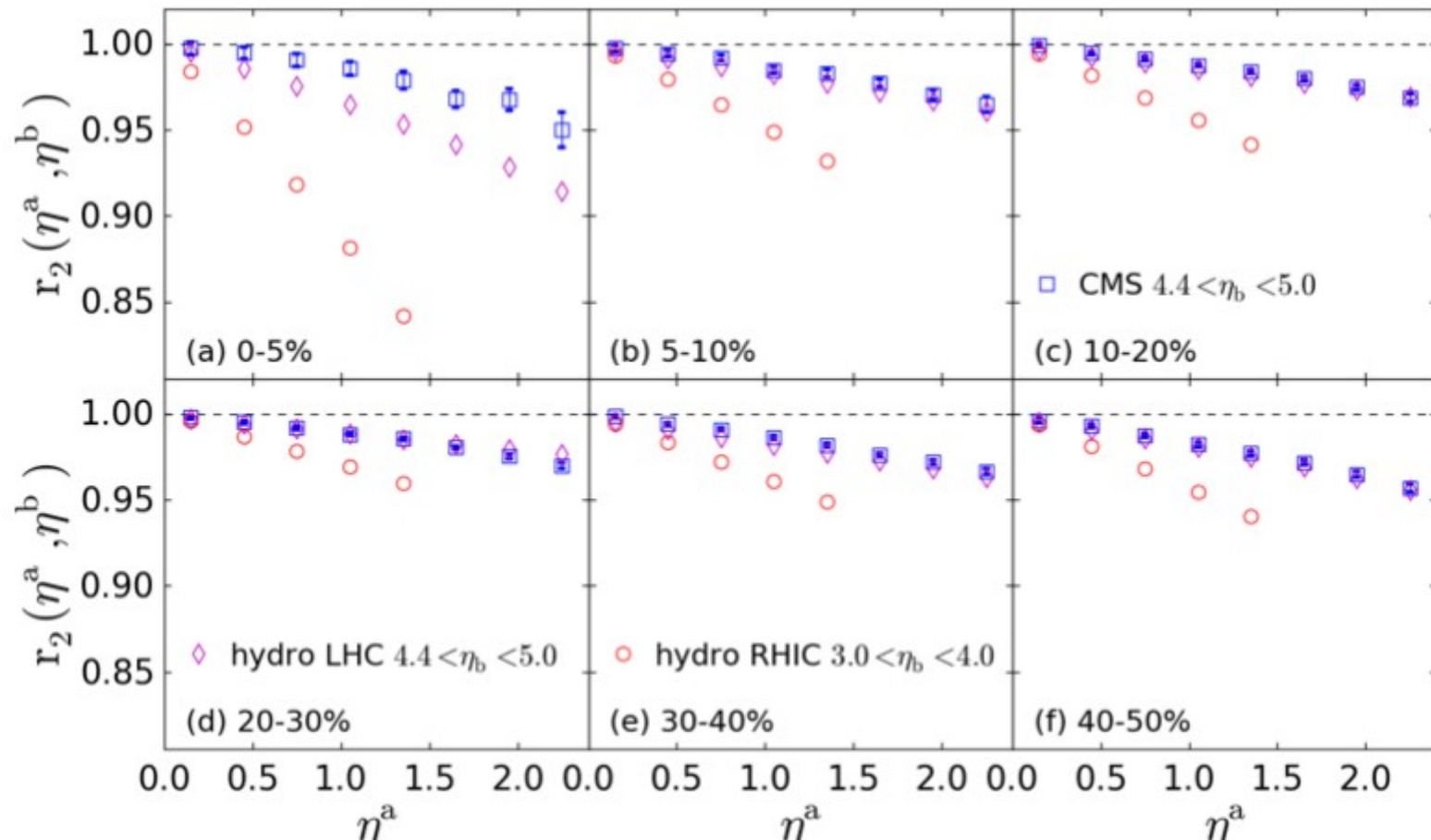- Comparison to some new observables (ATLAS)

Schenke&Monnai   (afterburner by S. Ryu)

Good agreement; mainly due to afterburner.

Same as found by Bozek et al arXiv:1509.04124

- Comparison to some new observables (CMS)

L. Pang – decorrelation of anisotropic flow
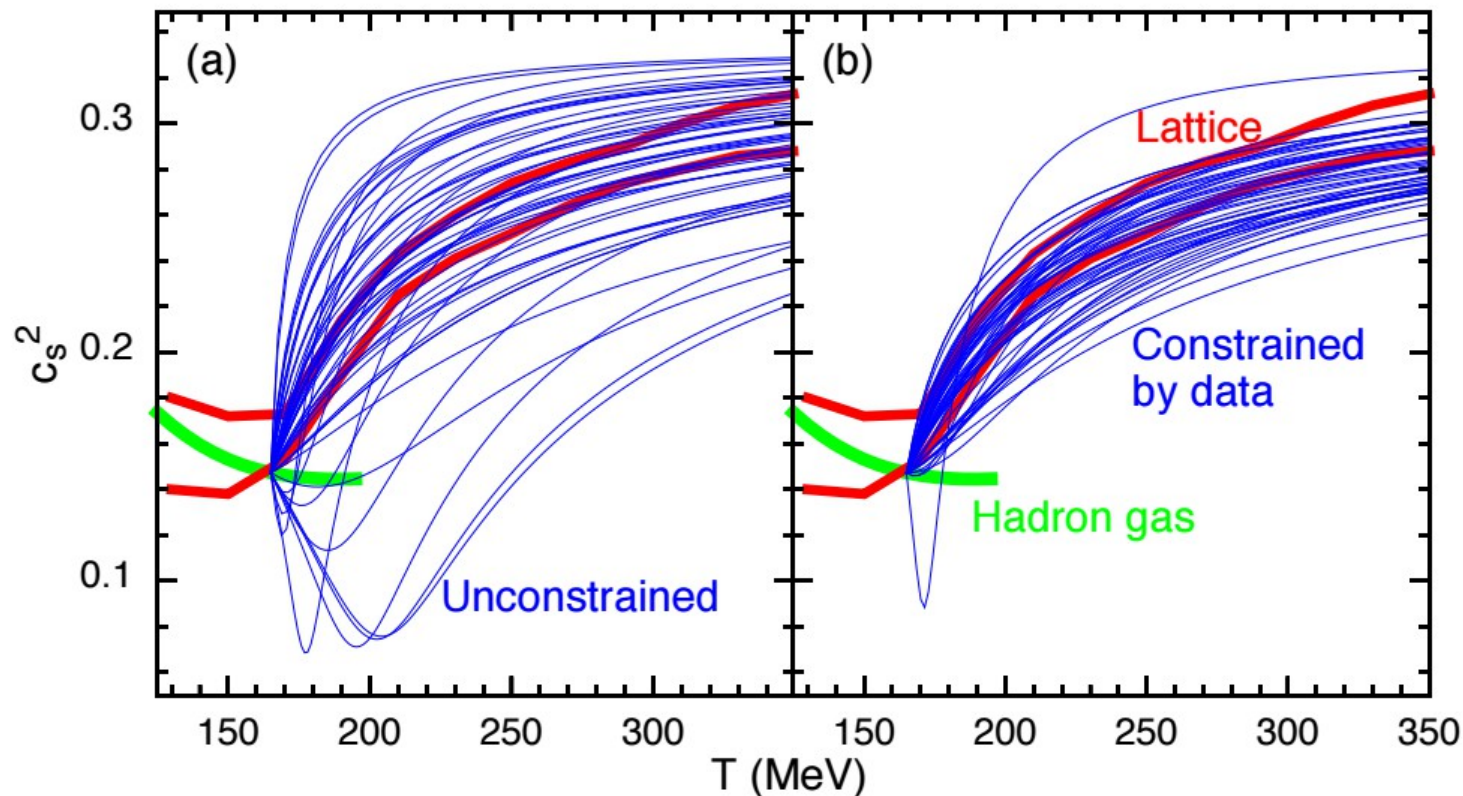

Good agreement, except in central collisions.

See also poster by I. Kozlov

Example: extracting the velocity of sound

Model: 14 parameters – smooth initial state, 3+1D, EoS, viscosity
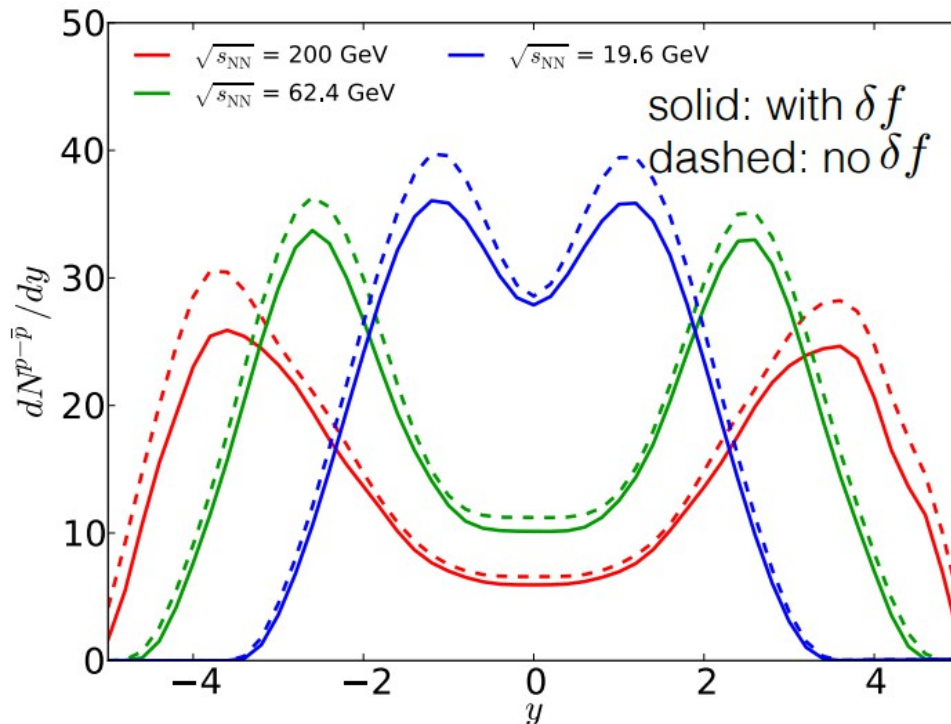

Constrained velocity of sound is in agreement with IQCD

Very good example of the power of such statistical methods

Hydrodynamics with diffusion

C. Shen *et al*, Preliminary

Modeling of heavy ion collisions at lower energies

$$\Delta^{\mu\alpha}\Delta^{\nu\beta}D\pi_{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta$$
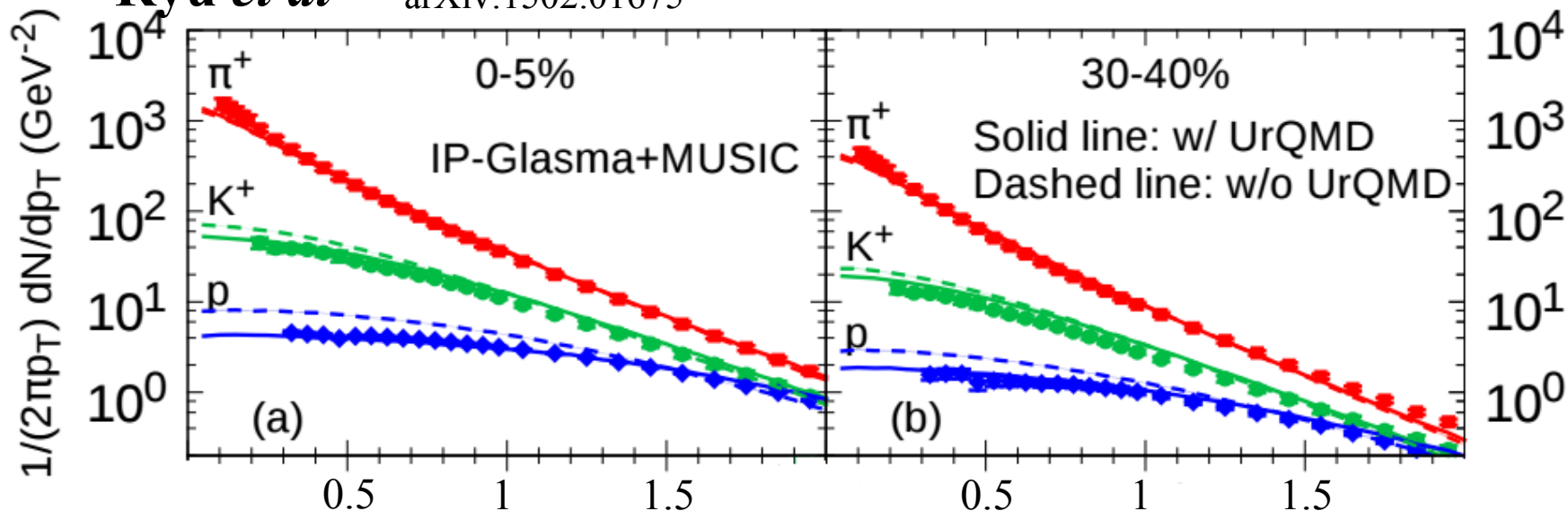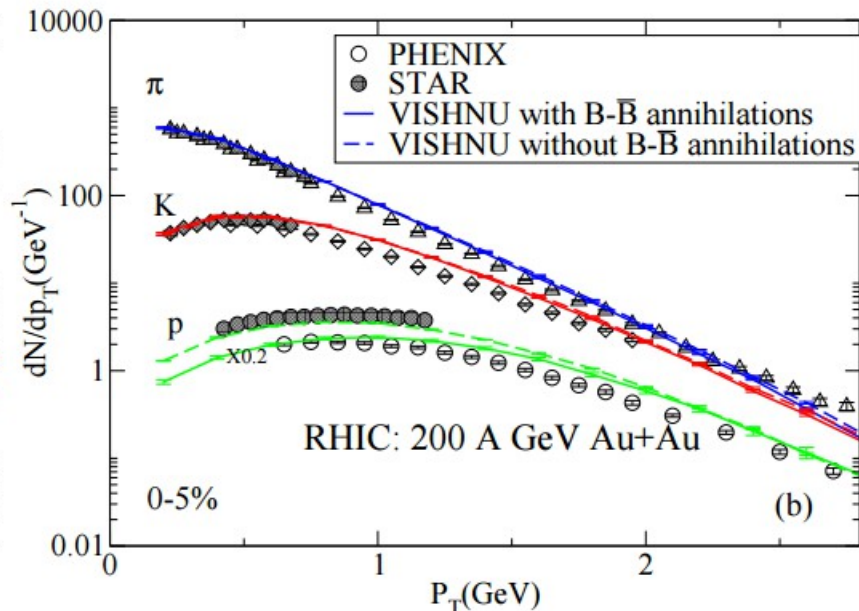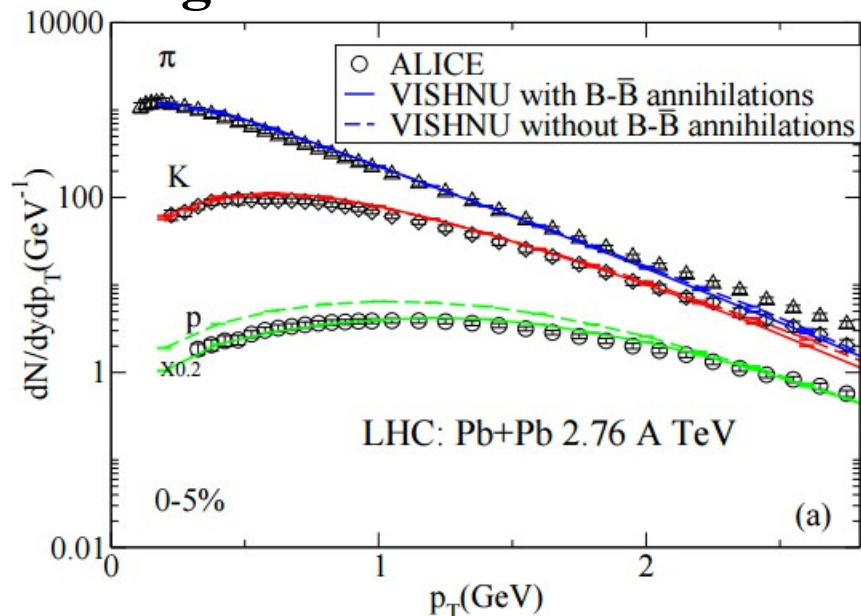
$$\Delta^{\mu\nu}Dq_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa\nabla^\mu\frac{\mu_B}{T}\right) - q^\mu\theta - \frac{3}{5}\sigma^{\mu\nu}q_\nu$$

Effect on multiplicity can be large

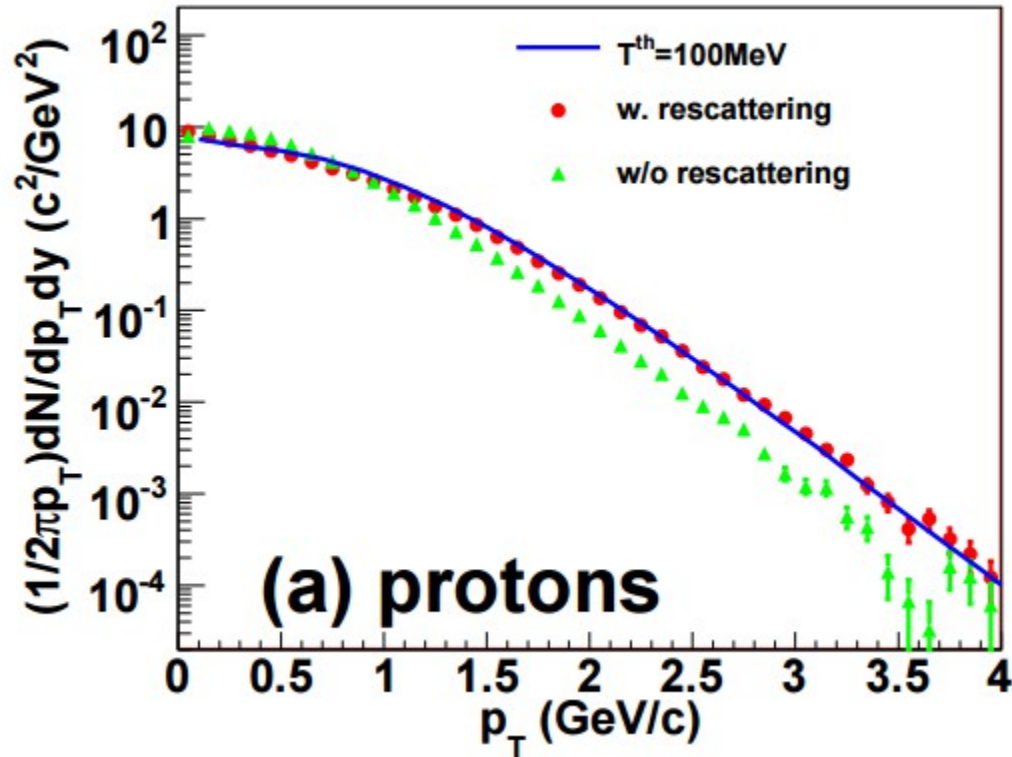**Can we use RHIC and SPS data to understand this transport coefficient?**

Maybe we will know the answer soon

30

Song *et al*   arXiv:1311.0157

Ryu *et al*   arXiv:1502.01675

Both calculations show an important effect from annihilation as first shown by Steinheimer&Aichelin&Bleicher arXiv:1203.5302

But Hirano *et al* does not see it ...   arXiv:0710.5795

(a) protons

And is still able to describe protons and multi-strange hadrons ...   arXiv:1505.05961

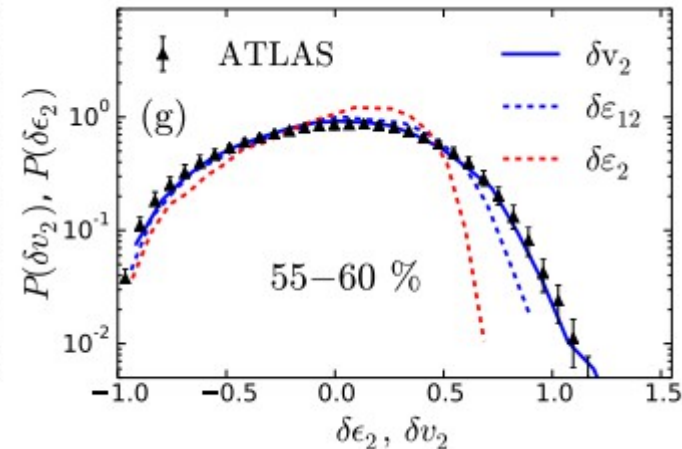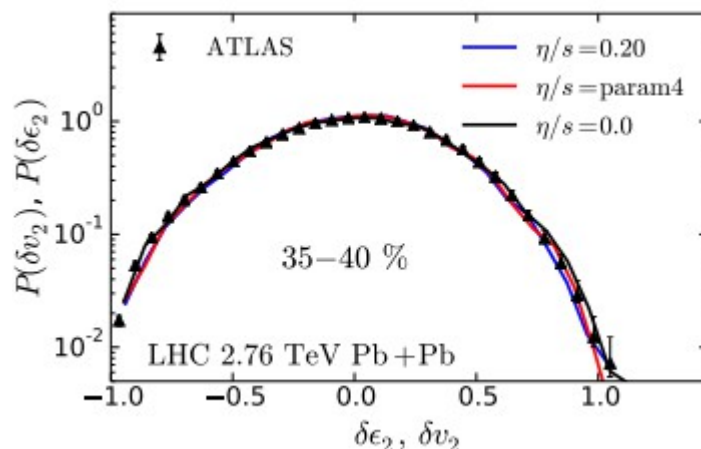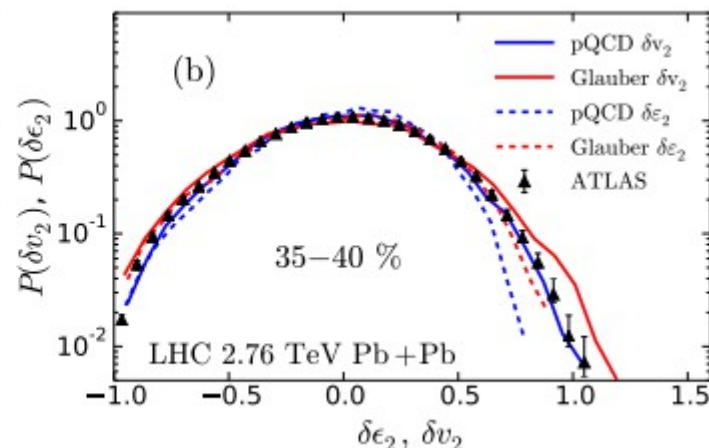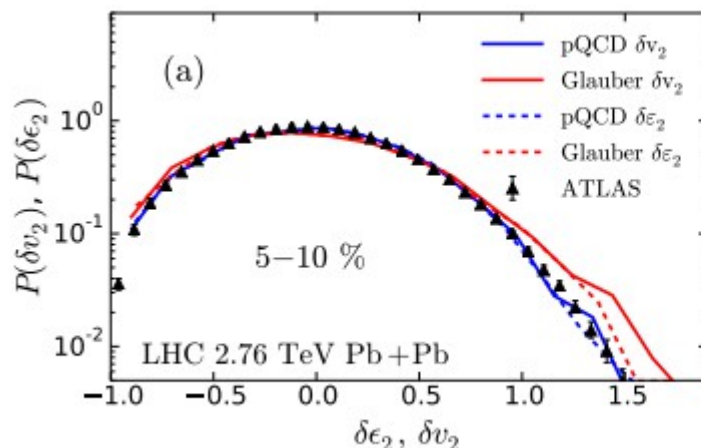## Why? Is hadronic transport under control?

EKRT model: NLO-improved pQCD + saturation

Niemi *et al*, arXiv:1505.02677

talk by Niemi, Wed.

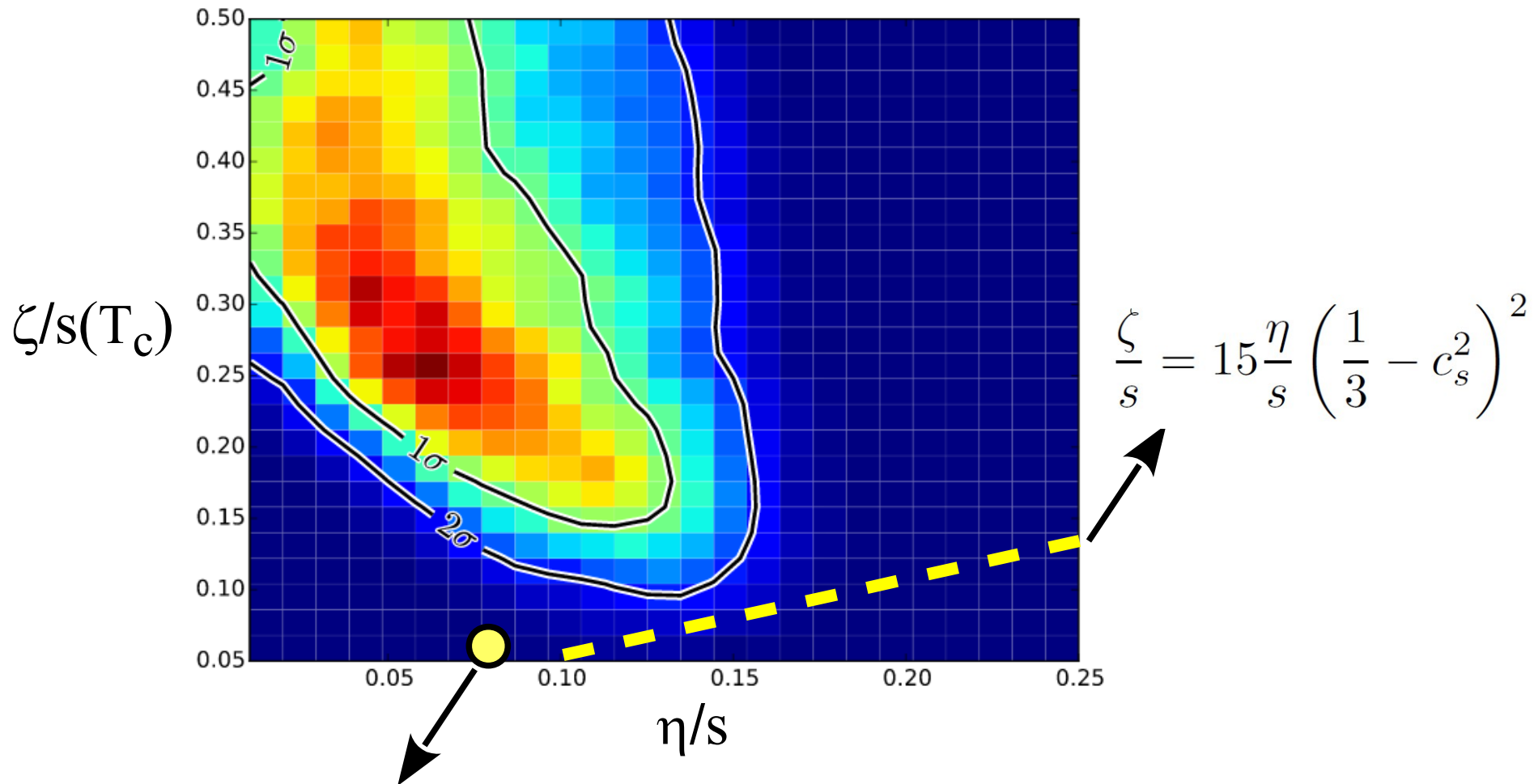**Also able to describe event-by-event distributions of flow**

Central

Peripheral

Only EKRT and IP-Glasma describe this data (maybe Trento as well?)

Correlation between Bulk and Shear

Increasing ζ/s leads to a reduction of η/s $\longleftrightarrow$ flow harmonics

$$\frac{\zeta}{s} = 15\frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

non-conformal holography prediction Finazzo *et al*, arXiv:1412.2968

Value of ζ is much larger than expected