Understanding phenomenological constraints on the transport coefficients of QCD

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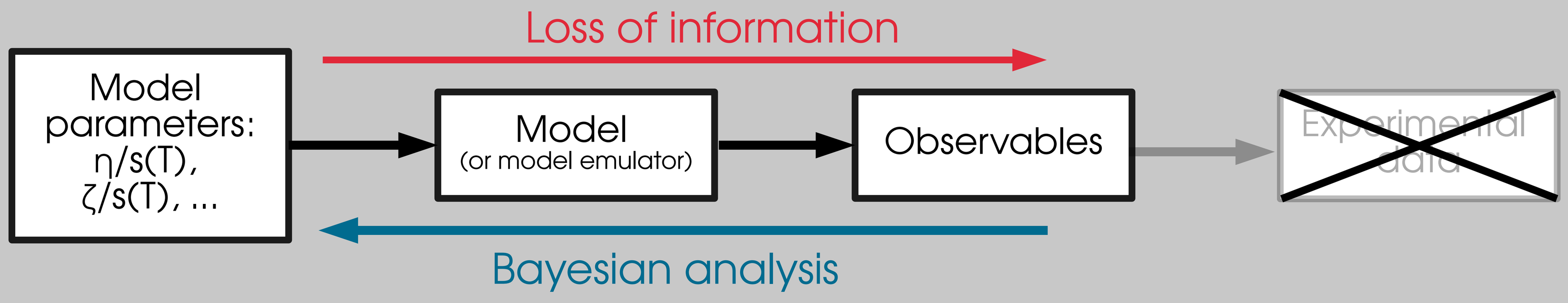
Motivation: shear and bulk viscosity from heavy ion data

- **Shear viscosity η/s** and **bulk viscosity ζ/s:** first order transport coefficients of QCD

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta \quad +\text{2nd order}$$
$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = -\eta\pi^{\mu\nu} \quad +\text{2nd order}$$

- η/s & ζ/s have a **non-trivial temperature-dependence** that heavy ion measurements can help constrain **in the temperature range ~100-500 MeV probed in** A+A collisions at LHC and top RHIC energies

Understanding constraints using model-generated "data"



Why use Bayesian analysis on model calculations?
Controlled setting to understand how observables constrain η/s(T) and ζ/s(T)

Example: peak in bulk viscosity

Perform a Bayesian analysis on hadronic observables computed with a **wide** and a **narrow peak** for ζ/s(T).

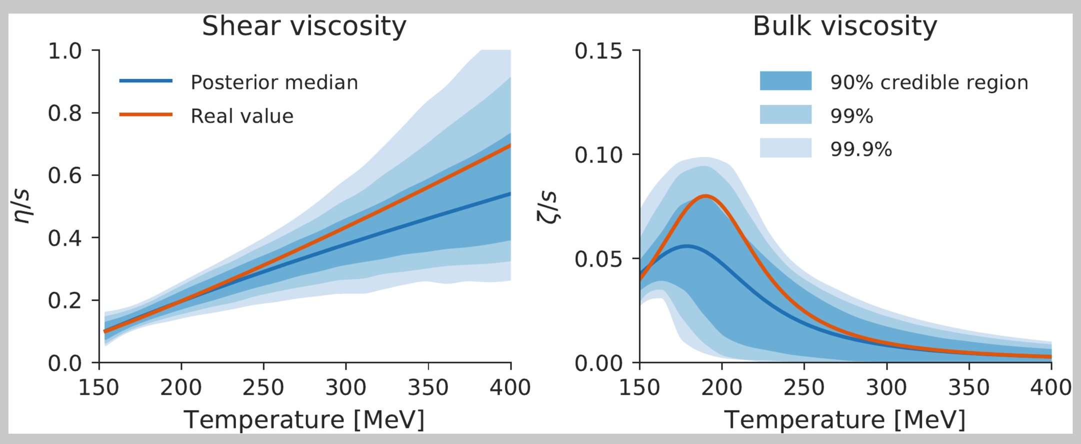
Observables:

$h^\pm : dN/d\eta$, transverse energy E_T, $\langle p_T \rangle$ fluctuations & $v_{2/3/4}$

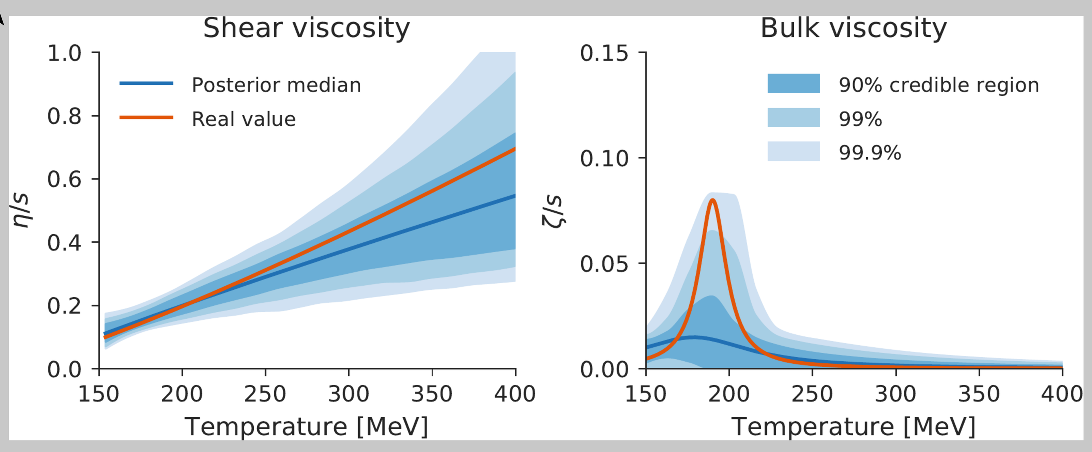
$\pi^\pm, K^\pm, p : dN/dy$ & $\langle p_T \rangle$

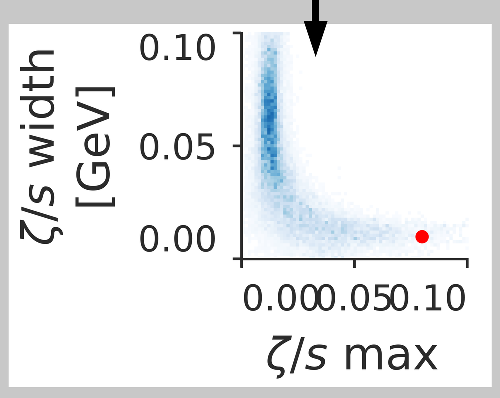
Centralities 0 to 70% in 5% bins; $\sqrt{s_{NN}}$=2.76 & 5.02 TeV

Wide peak recovered



More difficult to constrain a narrow peak in bulk viscosity





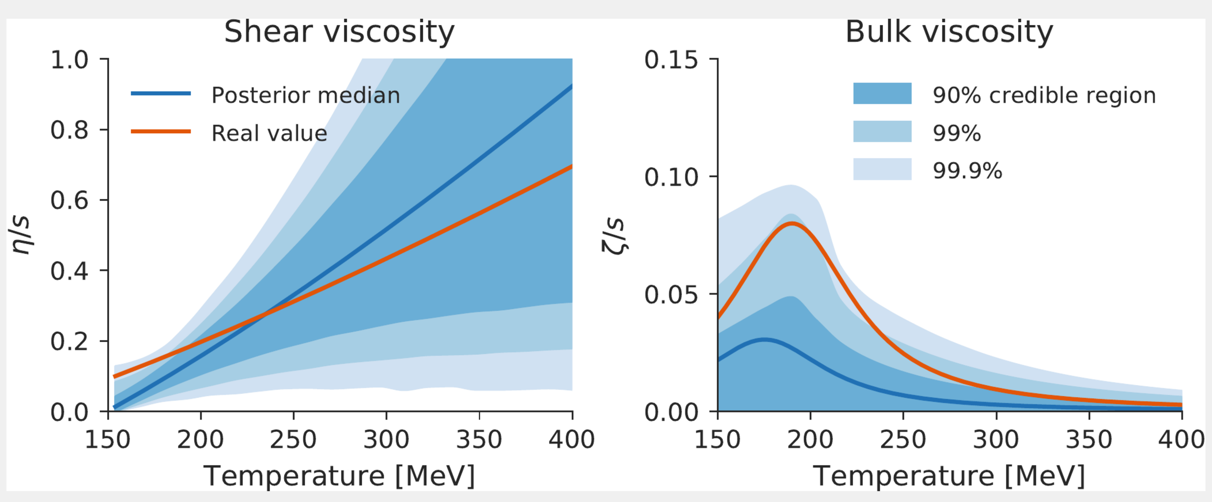
Systematics from viscous corrections, "δf"

Uncertainties in mapping **viscous part of energy-momentum tensor (from hydrodynamics)** to the **momentum distribution of hadrons**

- Stress-test (using IP-Glasma "Scenario 1" set-up):

I. Compute hadronic observables with **14-moments "δf" for shear viscosity & relaxation-time-approx. "δf" for bulk viscosity**

II. Bayesian analysis on observables assuming **Duke"δf" ansatz** $f(\vec{p}) \to z_\Pi f(\vec{p} + (\Lambda_\pi + \Lambda_\Pi)\vec{p})$ (Refs. (1) & (4))



How to reduce "δf" uncertainties on η/s(T) and ζ/s(T)?

- **Method 1**: Better theoretical control, e.g. Refs. (5-9)
- **Method 2:** Parametrize "δf" and constrain with data
- **Method 3:** Choose observables **less dependent on "δf"** viscous corrections

e.g. **transverse energy E_T** almost **independent of "δf"**

Guiding principle: **particle-momentum based observables**, as opposed to e.g. particle-number based

$$T^{\mu\nu}(X) = \sum_h \int \frac{d^3p}{P^0(2\pi)^3} P^\mu P^\nu g_h f_h(P,X)$$

Can such new hadronic observables be measured?

Using Bayesian methods to constrain the viscosities of QCD

Bayesian (**probabilistic**) constraints (Ref. (1)):

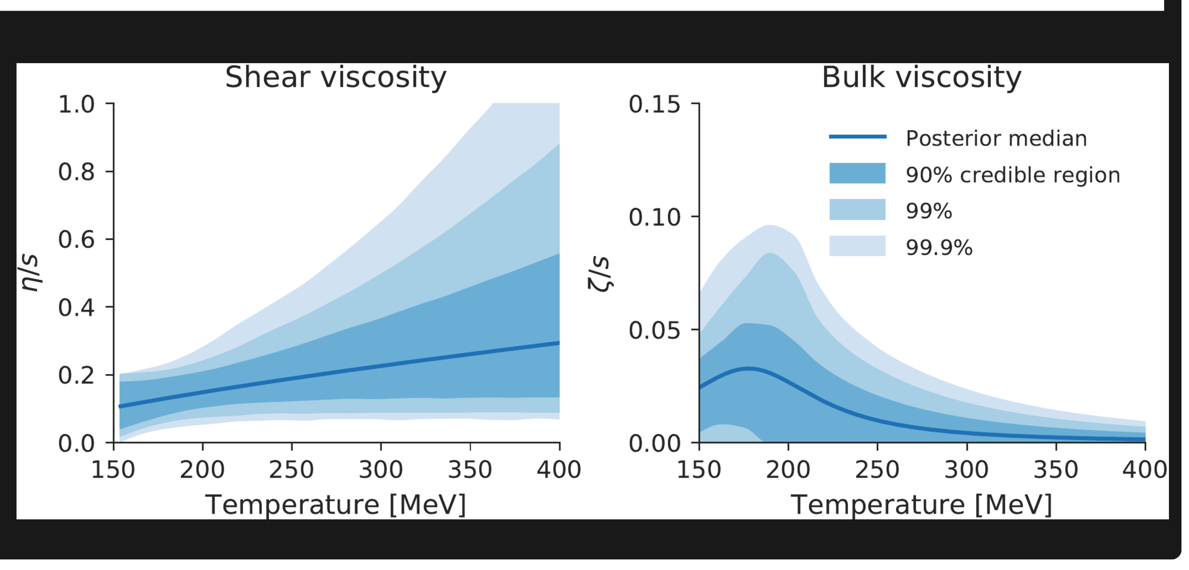
$\vec{C}$=Covariance matrix encoding uncertainties

$\vec{Y}(\eta/s(T), \zeta/s(T), \ldots)$=Model prediction given viscosities & other parameters

$$\text{Likelihood}\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right) \propto \exp\left(-\frac{1}{2}\left[\vec{Y}\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right) - \vec{D}\right]^T C^{-1} \left[\vec{Y}\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right) - \vec{D}\right]\right)$$

$$\text{Constraints on } \frac{\eta}{s} : \int d\left(\text{all parameters except } \frac{\eta}{s}\right) \text{Likelihood}\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right) \otimes \text{Priors}$$

Use **hydrodynamic models** of heavy ion collisions (which describe well hadronic data) **to relate QCD viscosities to measurable observables**



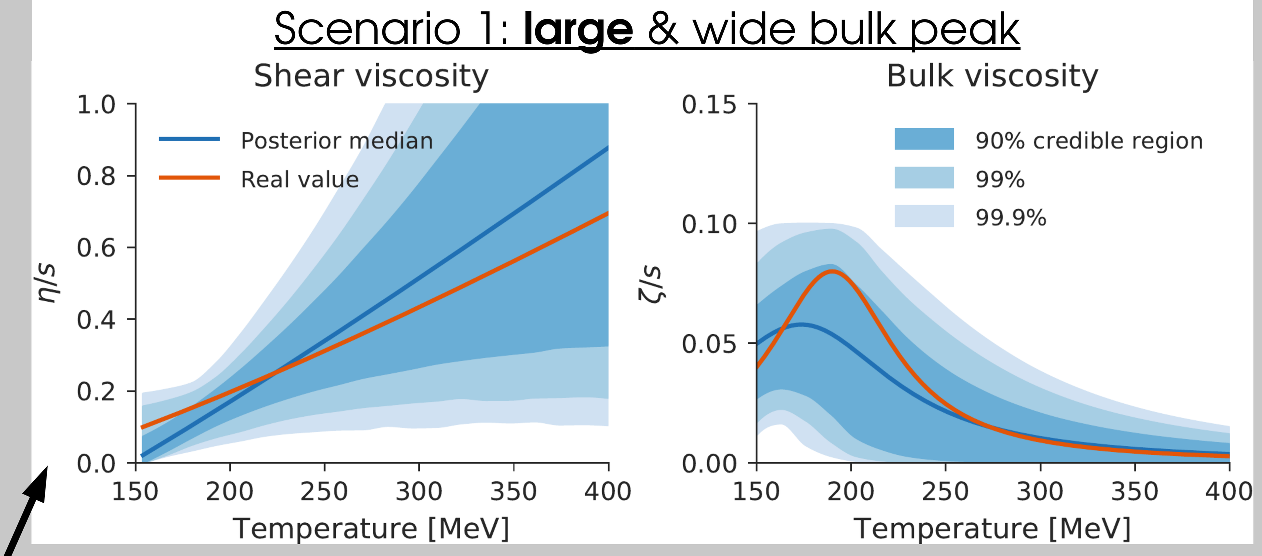
Studying systematics from initial conditions of hydrodynamic model

- **Viscosities** extracted from data **depend on initial conditions**
- Trento as **flexible ansatz** of initial conditions?
- Stress-test:

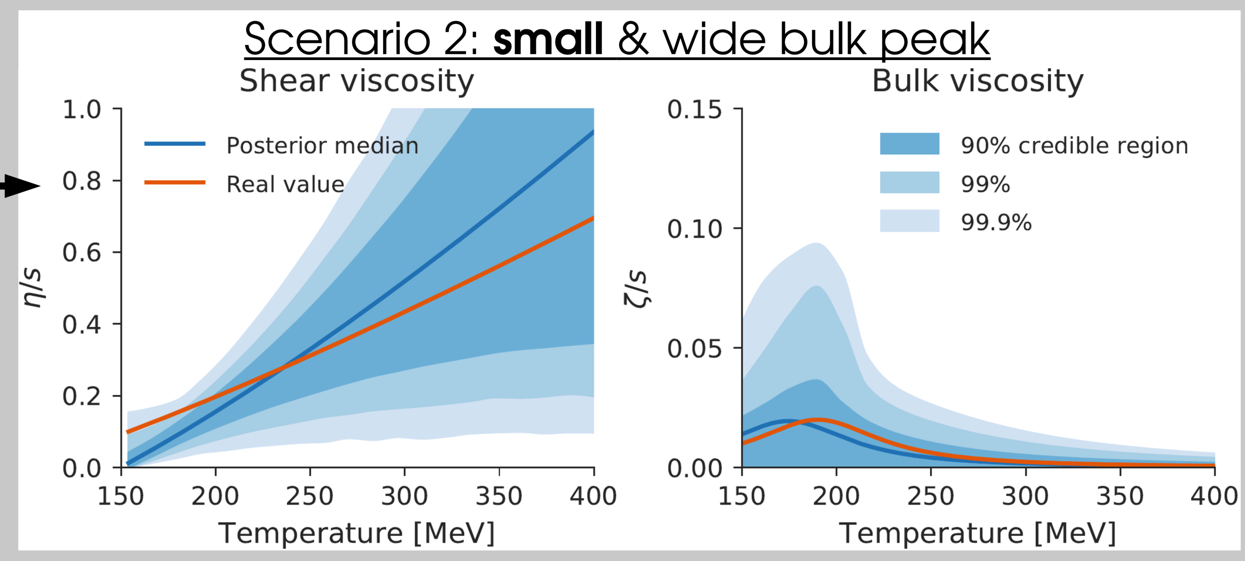
I. Compute hadronic observables from a hydrodynamic model with **IP-Glasma initial conditions** (Ref. (2))

II. **Bayesian analysis** on observables **assuming Trento** initial conditions

Scenario 1: **large** & wide bulk peak

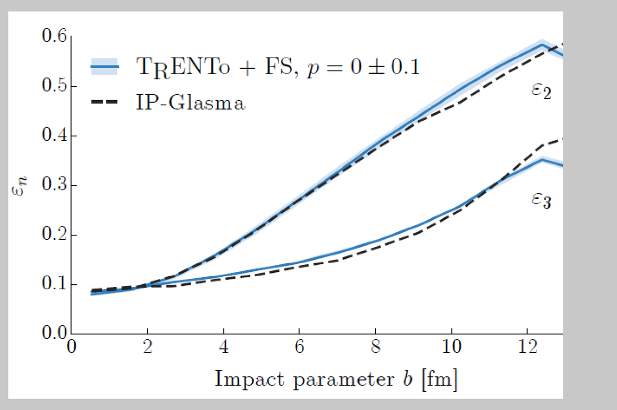


Scenario 2: **small** & wide bulk peak



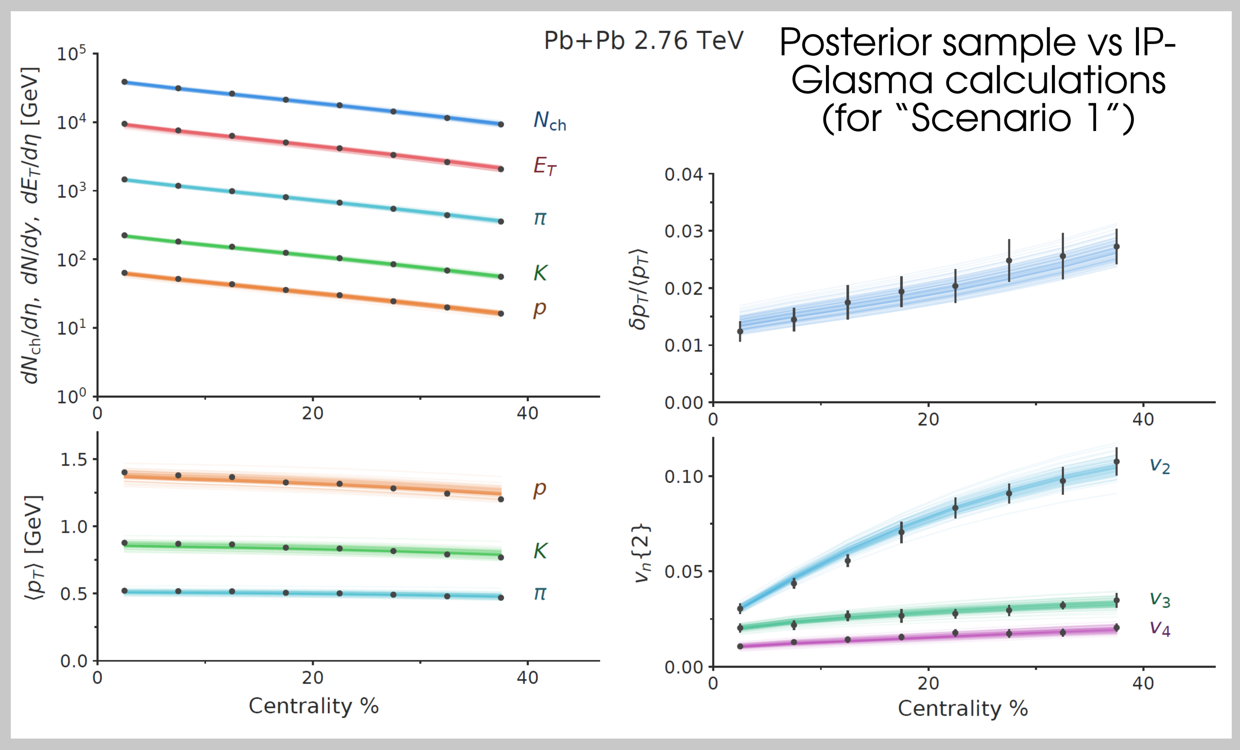
Trento ansatz captures relevant features of IP-Glasma

Consistent with Ref. (3):



Note: uncertainties in Bayesian constraints are larger in this example because fewer centralities and collision energies were used.

Posterior sample vs IP-Glasma calculations (for "Scenario 1")



Summary

- **Bayesian analysis on model calculations** can help **interpret** phenomenological constraints on η/s(T) & ζ/s(T)
- **Constraints are probabilistic** and must be interpreted with care
- Further evidence that the **Trento initial condition** ansatz **captures** the **relevant features** of microscopic models of the early plasma like IP-Glasma
- **Observables** that **minimize theoretical uncertainties** (e.g. "δf") could provide valuable complementary constraints on η/s(T) & ζ/s(T)
- Constraints on **shear viscosity** appear to be **robust** against uncertainties

Outlook

Use methods presented in this work to:
- identify observables that are redundant or complementary
- find observables that can minimize theoretical uncertainties
- conduct additional stress-tests to better understand probabilistic constraints

References

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