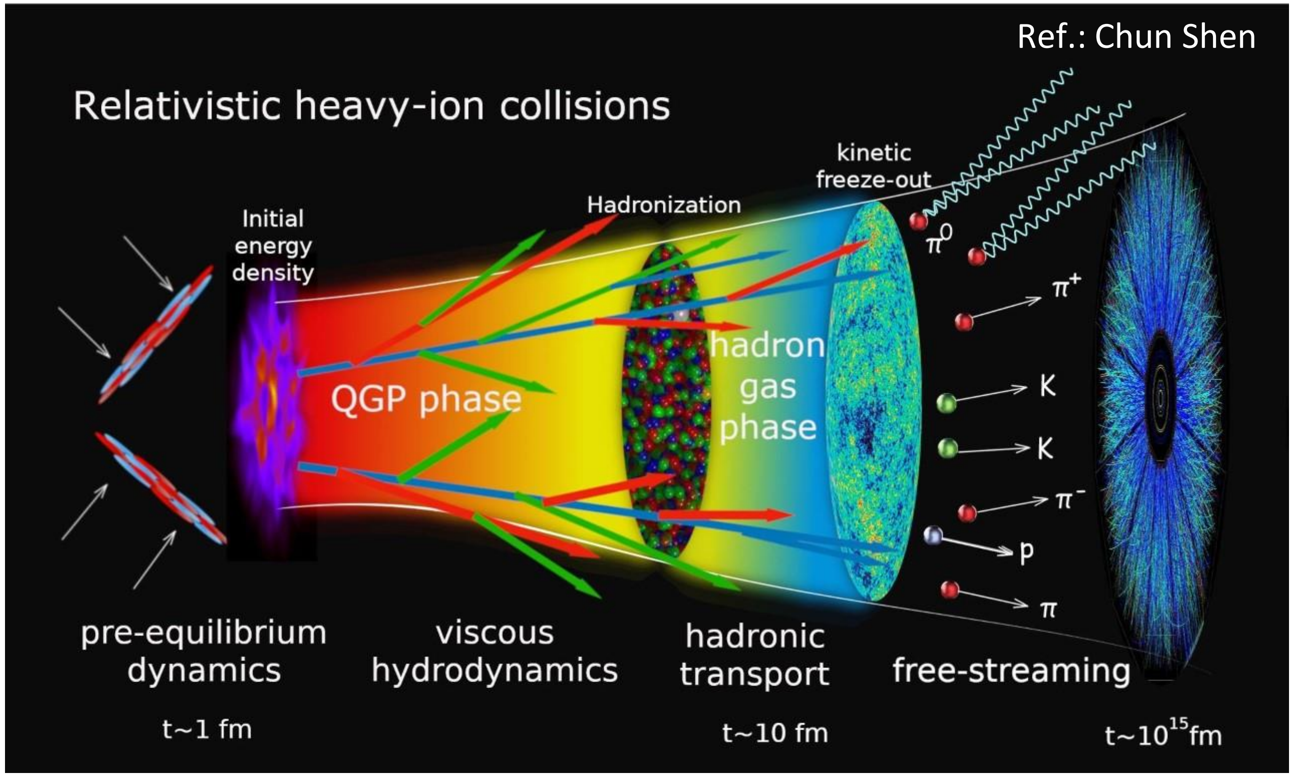
Multi-system Bayesian constraints on the transport coefficients of QCD

Jean-François Paquet (Duke University),
for the JETSCAPE Collaboration

November 5, 2019

Hard & soft sectors of heavy ion collisions



- Soft hadrons:
  carry most of the plasma's energy-momentum
- Hard partons:
  complementary probes of plasma
- Asymmetric interdependency:
  hard sector depends heavily on soft sector

- **Working Group within JETSCAPE focused on Bayesian analysis of soft hadrons**:
  Steffen Bass, JFP, Yingru Xu (Duke), **Weiyao Ke** (Duke/LBNL)
  Charles Gale, Matthew Heffernan (McGill)
  Lipei Du, **Derek Everett**, Michael McNelis, Ulrich Heinz (OSU), Gojko Vujanovic (WSU/OSU)
  Matthew Luzum (USP), Chun Shen (WSU/BNL), Abhijit Majumder (WSU)

Modelling the soft sector

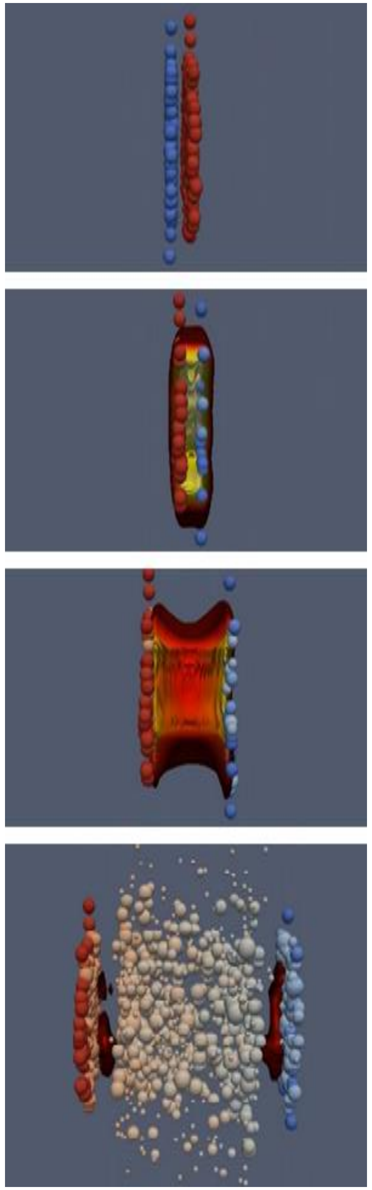


Figure ref.: J. Bernhard, H. Petersen, MADAI Collaboration

$\tau = "0^+"$: Nuclei collide

- Trento ansatz used to parametrize the energy deposition

Ref.: Moreland, Bernhard, Bass (2015) PRC92,011901

$\tau \sim 0.1$ fm: "Pre-equilibrium phase"

- Free-streaming

Ref.: Everett (2018), https://github.com/derekeverett/freestream-milne

$\tau \sim 1$ fm: Beginning of "hydrodynamic phase"

- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Equation of state: hadron resonance gas + lattice QCD [HotQCD Collaboration (2014) PRD90,094503]
- Shear and bulk viscosity

MUSIC ref.: Schenke, Jeon, Gale (2010) PRC82,014903; (2011) PRL106,042301; Paquet, Shen, Denicol, Luzum, Schenke, Jeon, Gale (2016) PRC93,044906

Hadron resonance gas + lattice combination: https://github.com/j-f-paquet/eos_maker

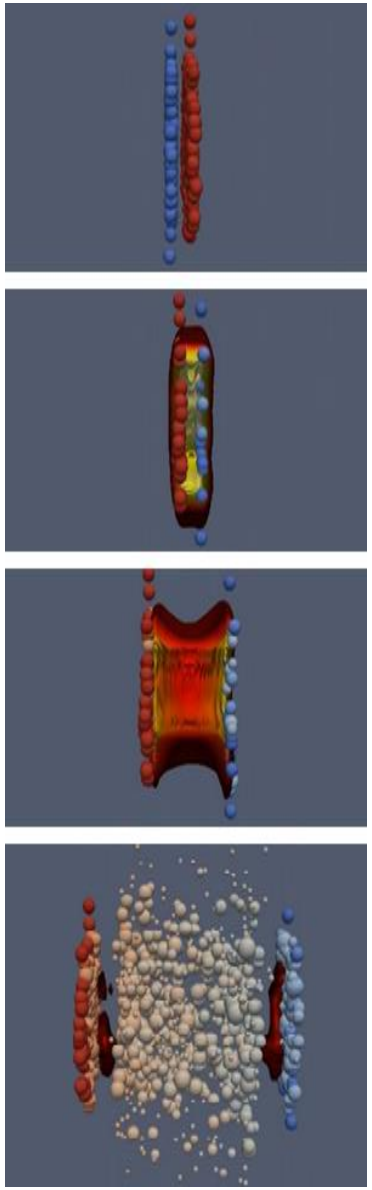
$\tau \sim 10$ fm: End of "hydrodynamic phase"

- Fluid converted to hadrons [iS3D]
- Hadronic interactions with SMASH hadronic transport

iS3D ref.: McNelis, Everett, Golden & Heinz, in preparation; https://github.com/derekeverett/iS3D

SMASH ref.: Weil, Steinberg, Staudenmaier, Pang, Oliinychenko, Mohs, Kretz, Kehrenberg, Goldschmidt, Bäuchle, Auvinen, Attems, Petersen (2016) PRC94, 054905
https://smash-transport.github.io/

Modelling the soft sector



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$\tau = "0^+"$: Nuclei collide

- Trento ansatz used to parametrize the energy deposition
- 5 parameters: (i-iii) nucleon width, fluctuation & minimum distance, (iv) transparency parameter, (v) normalization

$\tau \sim 0.1$ fm: "Pre-equilibrium phase"

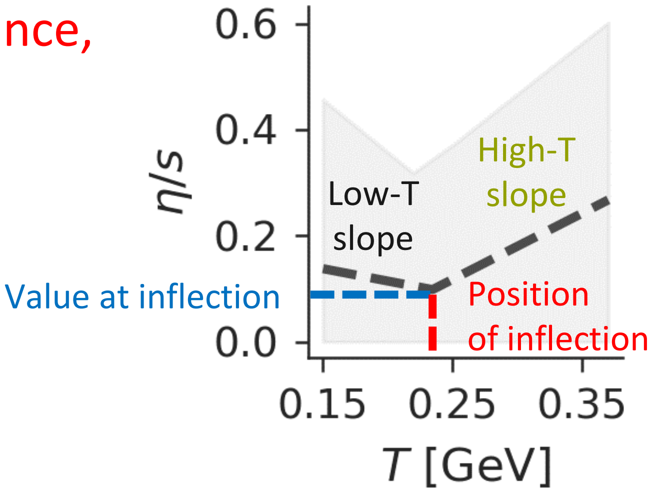
- Free-streaming
- Free-streaming time is a parameter

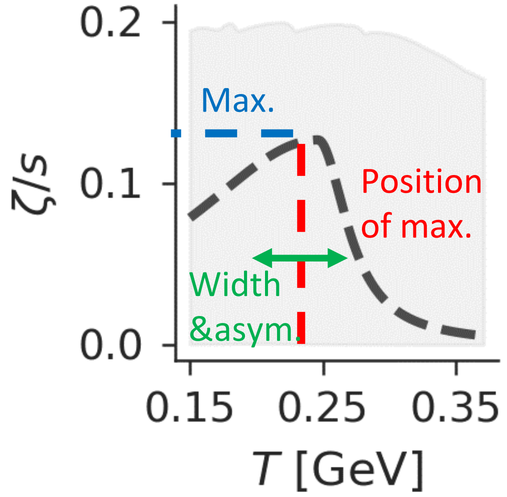
$\tau \sim 1$ fm: Beginning of "hydrodynamic phase"

- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Equation of state: hadron resonance gas + lattice QCD [HotQCD]
- Shear and bulk viscosity: $\frac{\eta}{s}(T)$ and $\frac{\zeta}{s}(T)$ parametrized

$\tau \sim 10$ fm: End of "hydrodynamic phase"

- Fluid converted to hadrons [iS3D]: Cooper-Frye at temperature T_{sw}
- Viscous corrections in Cooper-Frye: 4 different models
- Hadronic interactions with SMASH hadronic transport





Model & validation

- JETSCAPE Framework wraps together all the individual physics code:
  (i) Trento, (ii) OSU’s free-streaming, (iii) hydrodynamics [MUSIC], (iv) OSU’s Cooper-Frye [iS3D], & (v) afterburner [SMASH]

- Provide state-of-the-art simulation of the soft sector of heavy ion collisions

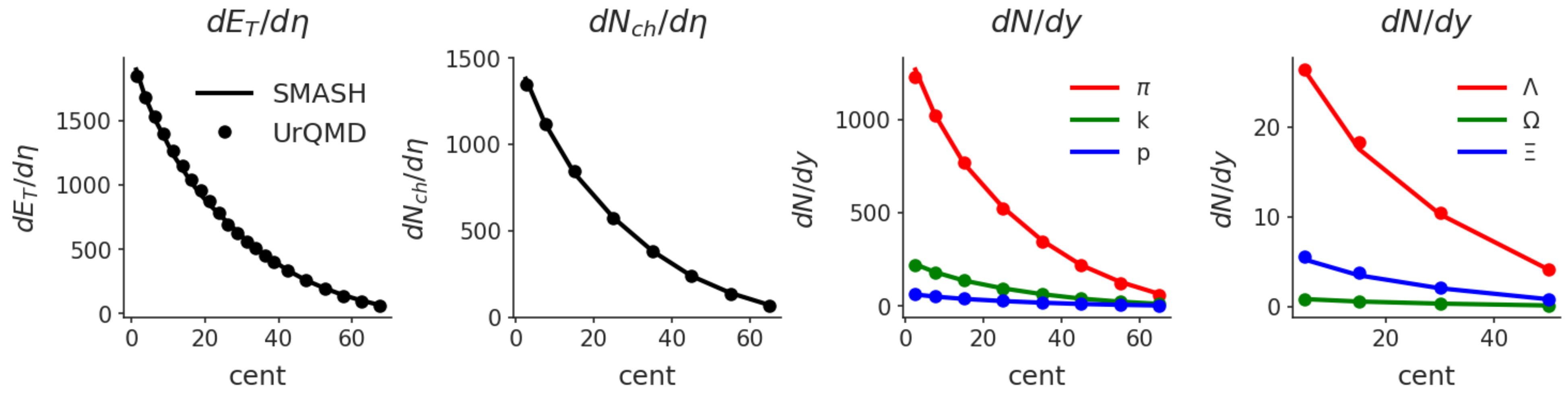
- Systematic & extensive validation

Model & validation

- JETSCAPE Framework wraps together all the individual physics code: (i) Trento, (ii) OSU's free-streaming, (iii) hydrodynamics [MUSIC], (iv) OSU's Cooper-Frye [iS3D], & (v) afterburner [SMASH]

- Provide state-of-the-art simulation of the soft sector of heavy ion collisions

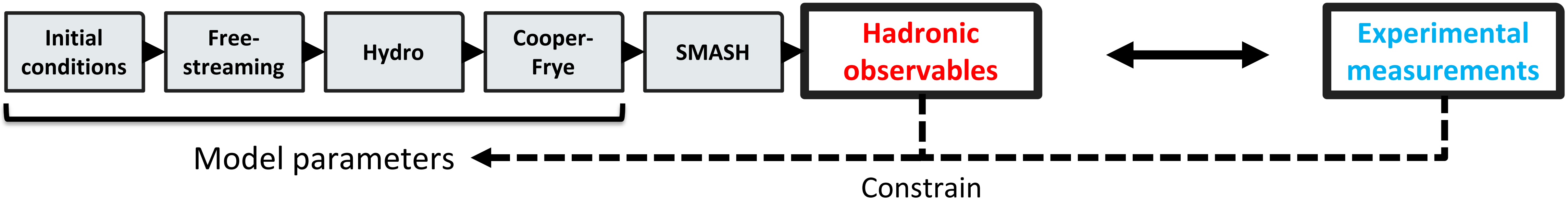
- Systematic & extensive validation lead to important results, e.g. comparison of SMASH and UrQMD **[Solid lines: SMASH ; Points: UrQMD]**



Only works if hadron species in hydro's equation of state and in Cooper-Frye is consistent with SMASH/UrQMD's hadron content

Bayesian analysis

- Model predicts hadronic observables given model parameters (initial conditions, viscosities, ...)



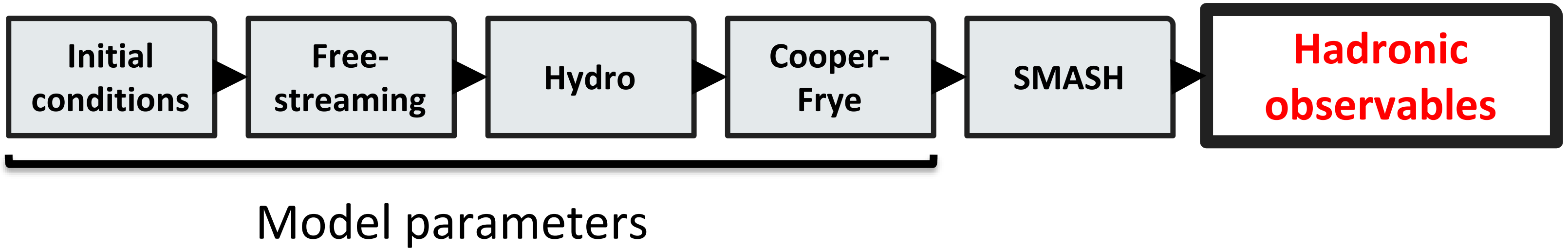
- **Bayesian analysis:** systematically **propagate model&data uncertainties** to model parameters

Probability of model parameter $\propto e^{-\chi^2}$

$$\chi^2 \sim \sum \frac{(calculation - measurement)^2}{\sigma^2_{calculation} + \sigma^2_{experiment}}$$

Emulator

- Model predicts hadronic observables given model parameters (initial conditions, viscosities, ...)
- Model is slow: would take **years** to perform Bayesian analysis directly from model
- Solution: emulator



Emulator

I. Sample parameter space
II. Compute hadronic observables for all sampled parameter
III. Emulator interpolates hadronic observables between sampled parameters

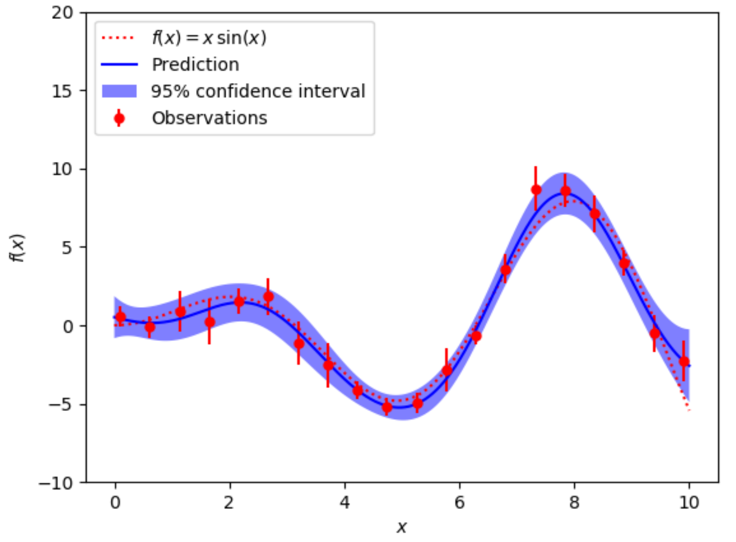


Figure ref: https://scikit-learn.org/stable/auto_examples/gaussian_process/plot_gpr_noisy_targets.html

Emulator

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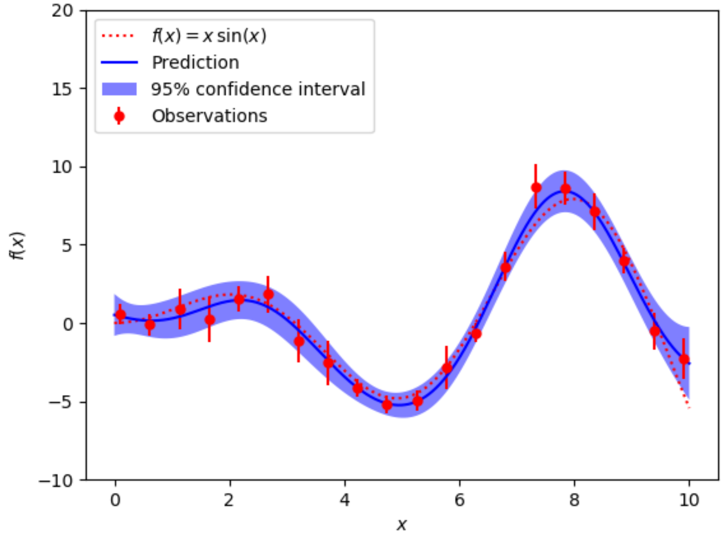

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- Emulators must be validated to insure it provides a good representation of the physics model
- Emulators **always** have a certain level of uncertainty

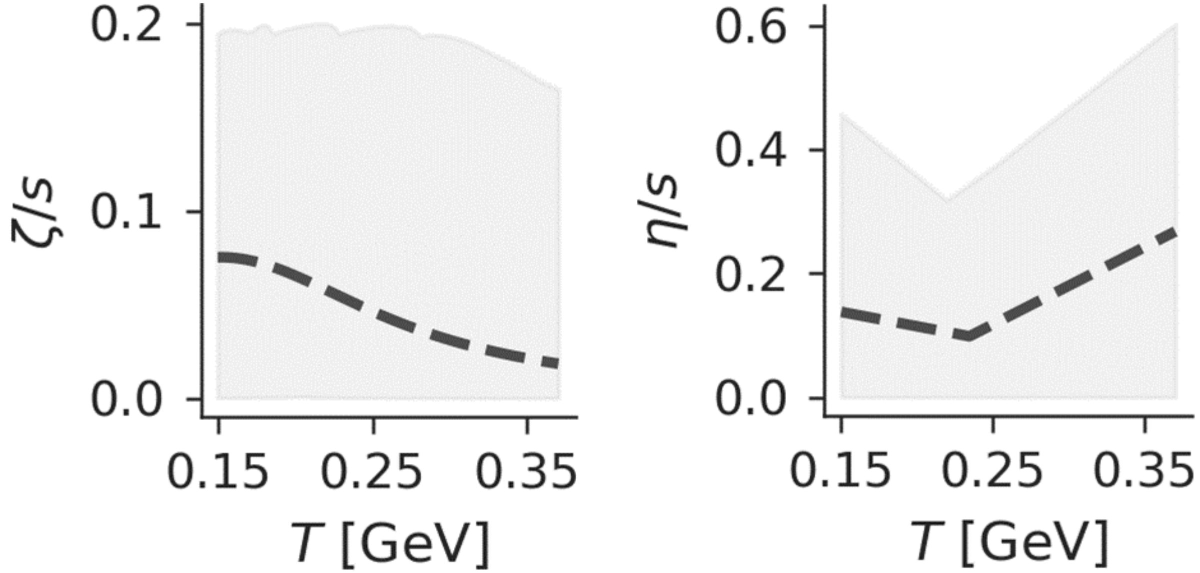
Validating the Bayesian analysis: closure tests

Validating the analysis: closure tests

- **Bayesian analysis can & should be validated** before comparisons with experimental data

Closure test

I. **Choose** a set of model parameters
II. Calculate hadronic observables: identified hadron dN/dy & $\langle p_T \rangle$, $v_{2/3/4}\{2\}$
III. Perform Bayesian analysis on calculated hadronic observables with **known parameters** and compare



Grey region: all possible values of viscosity known to the emulator

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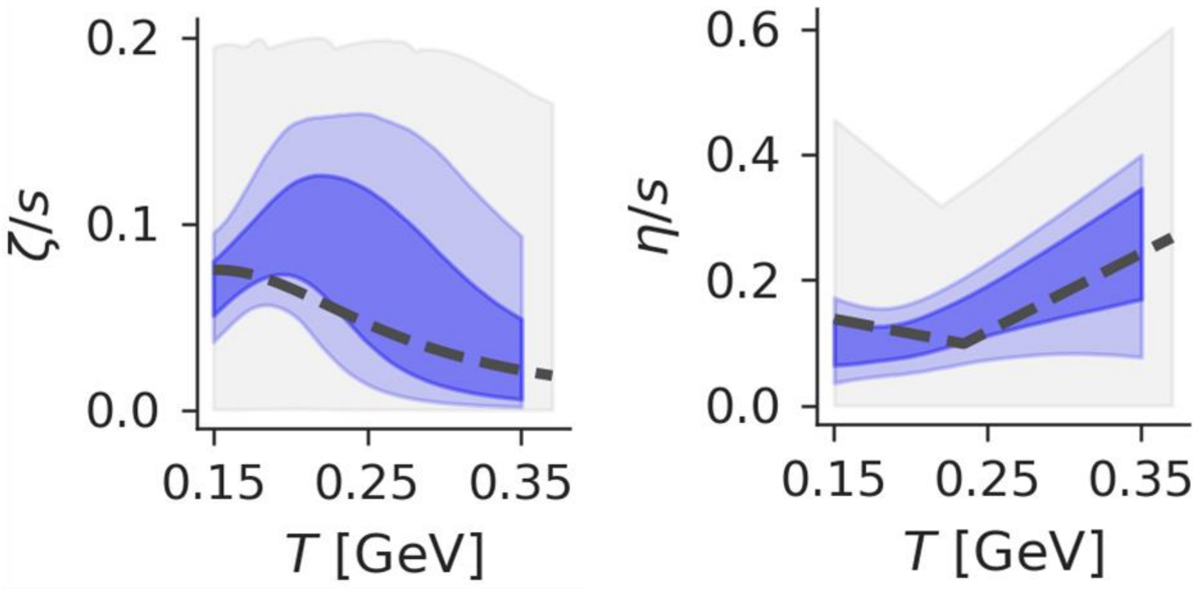

Grey region: all possible values of viscosity known to the emulator

Dark & light blue: 60% & 90% confidence intervals of the Bayesian analysis

Bayesian analysis on data: PbPb@2760 GeV

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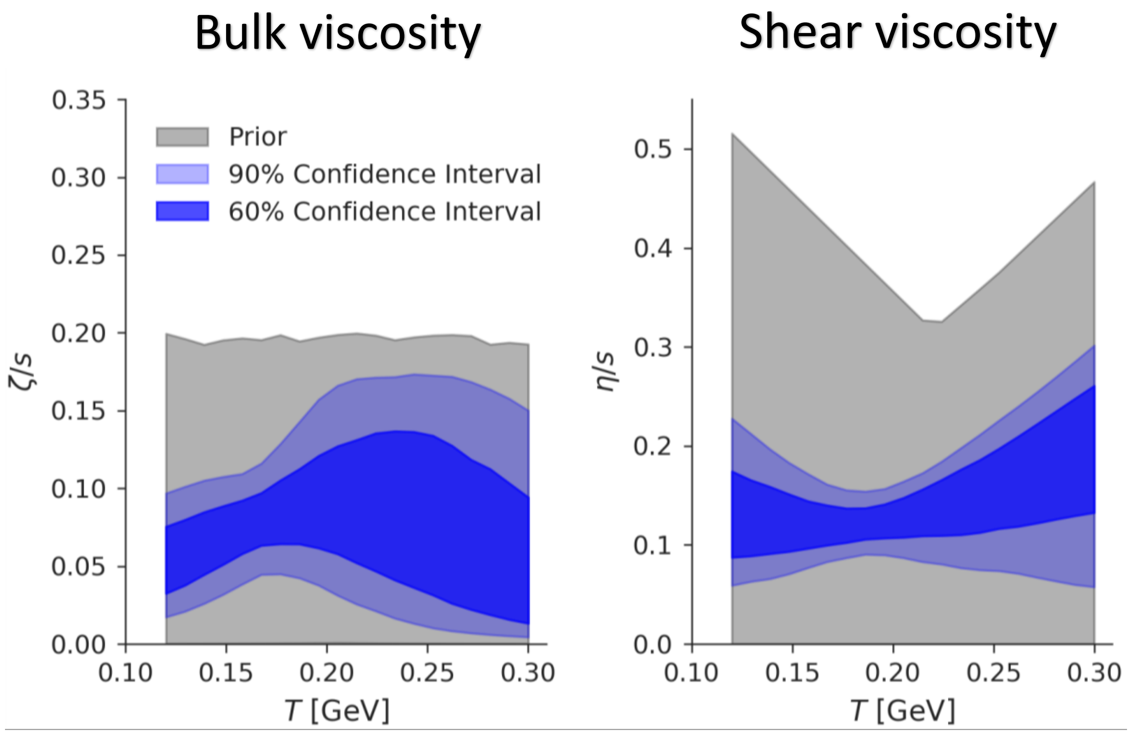
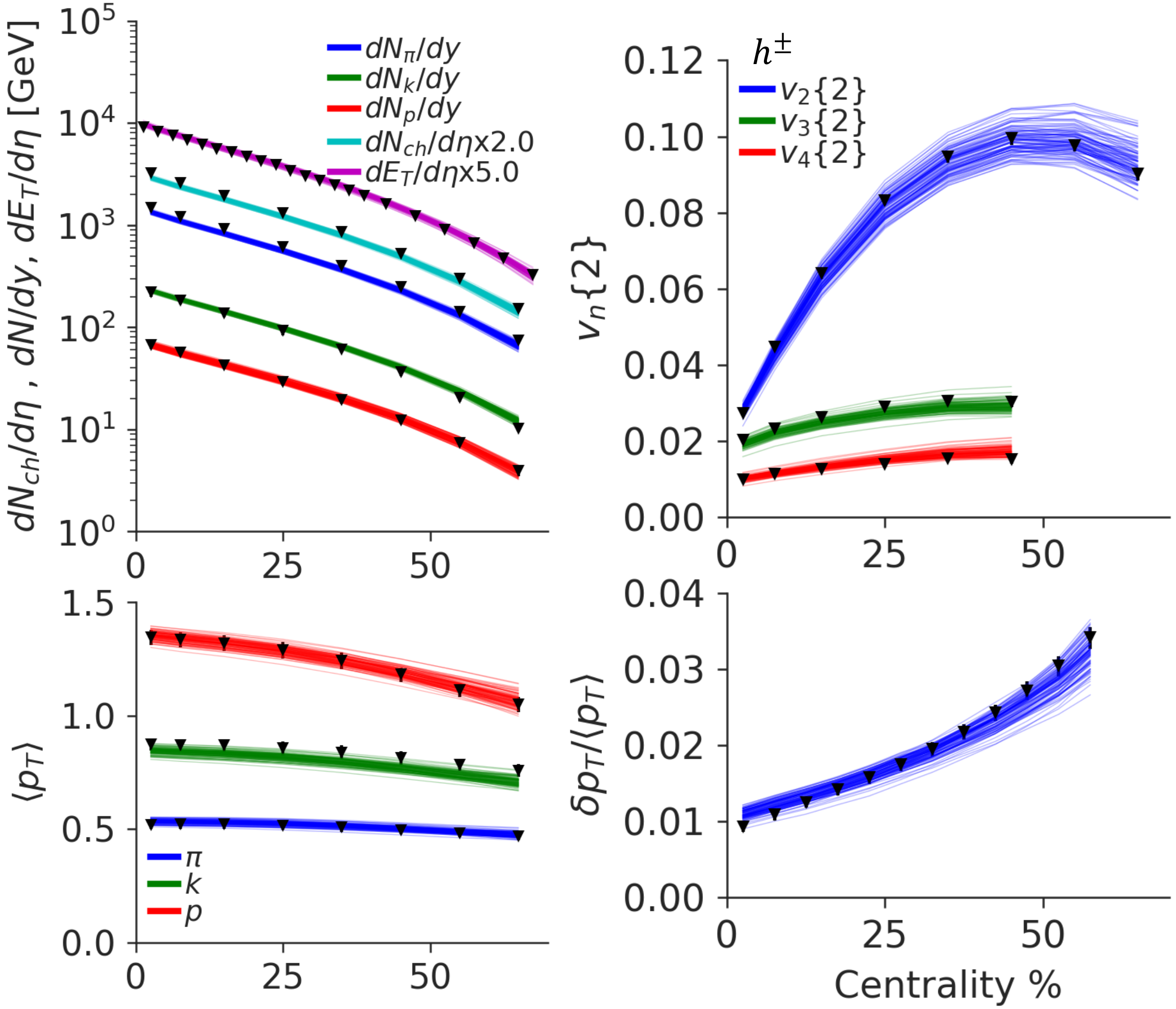
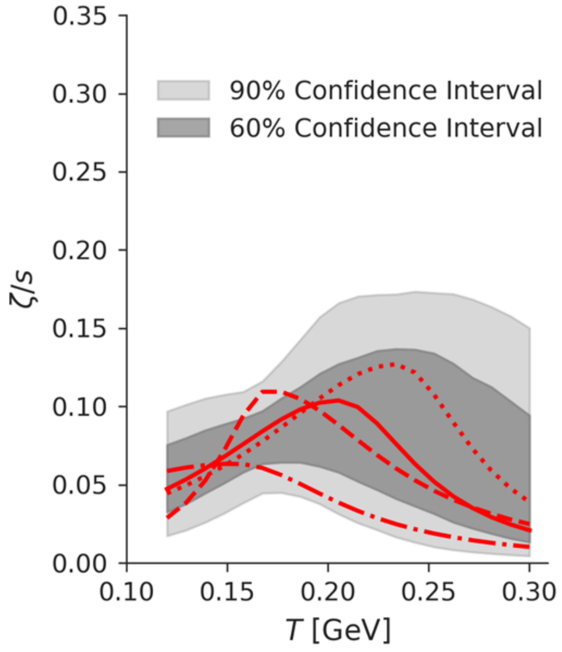




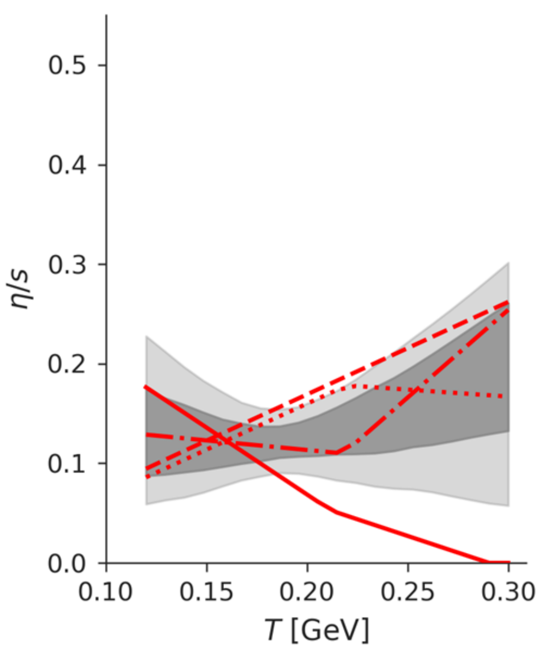
[All measurements from ALICE]

Bayesian analysis: PbPb@2760 GeV

Bulk viscosity

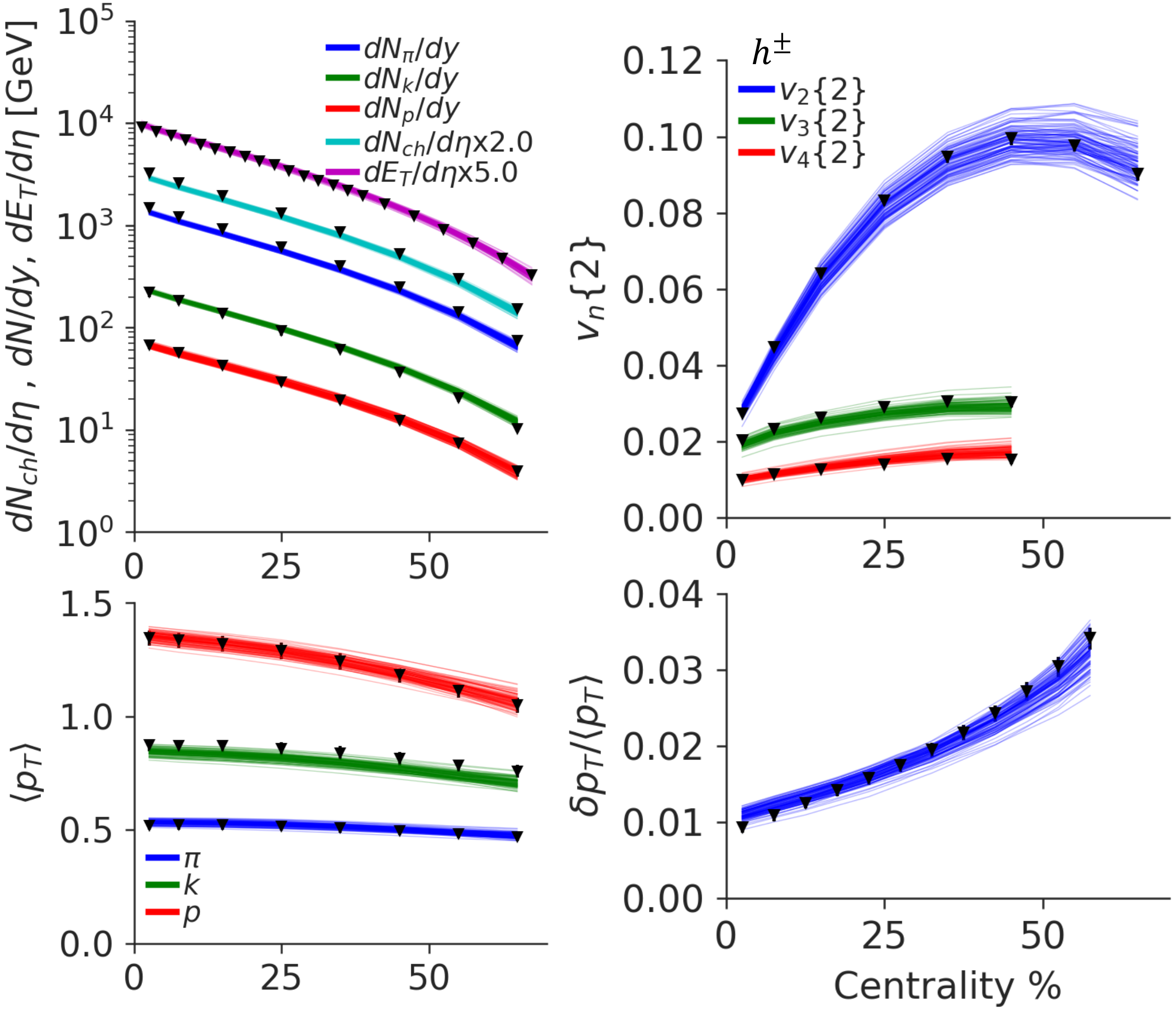


Shear viscosity



Red lines:

samples of temperature dependence of $\frac{\zeta}{s}(T)$ and $\frac{\eta}{s}(T)$ consistent with data & uncertainties



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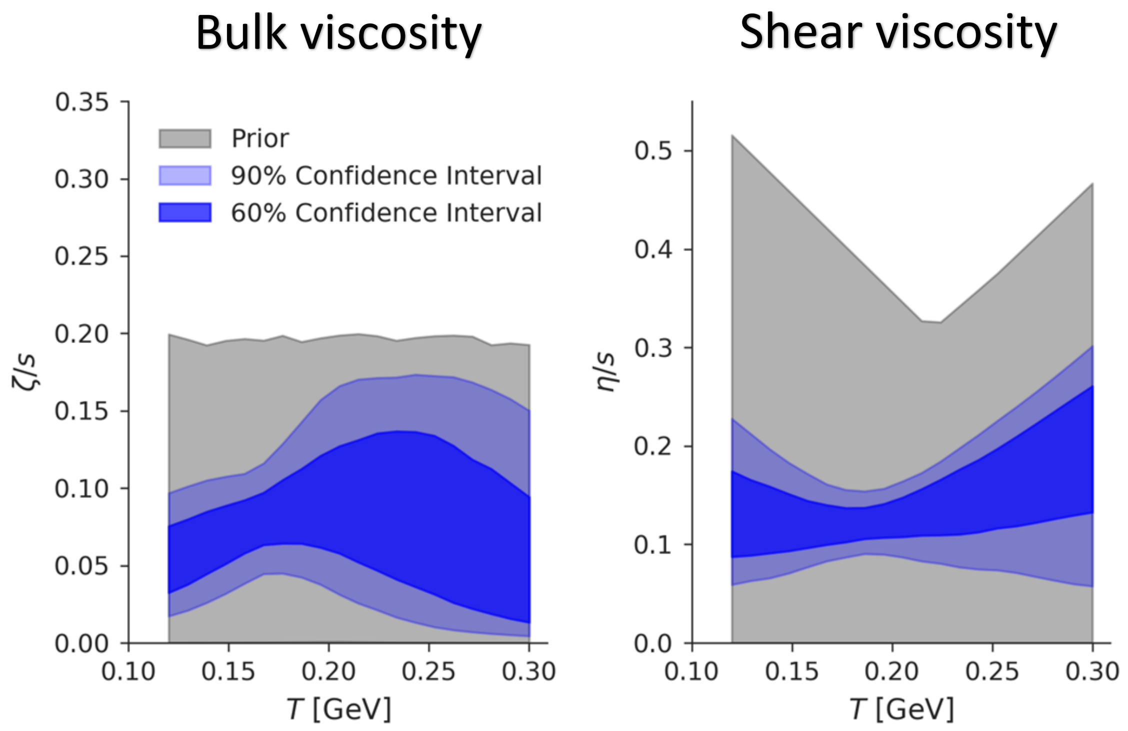
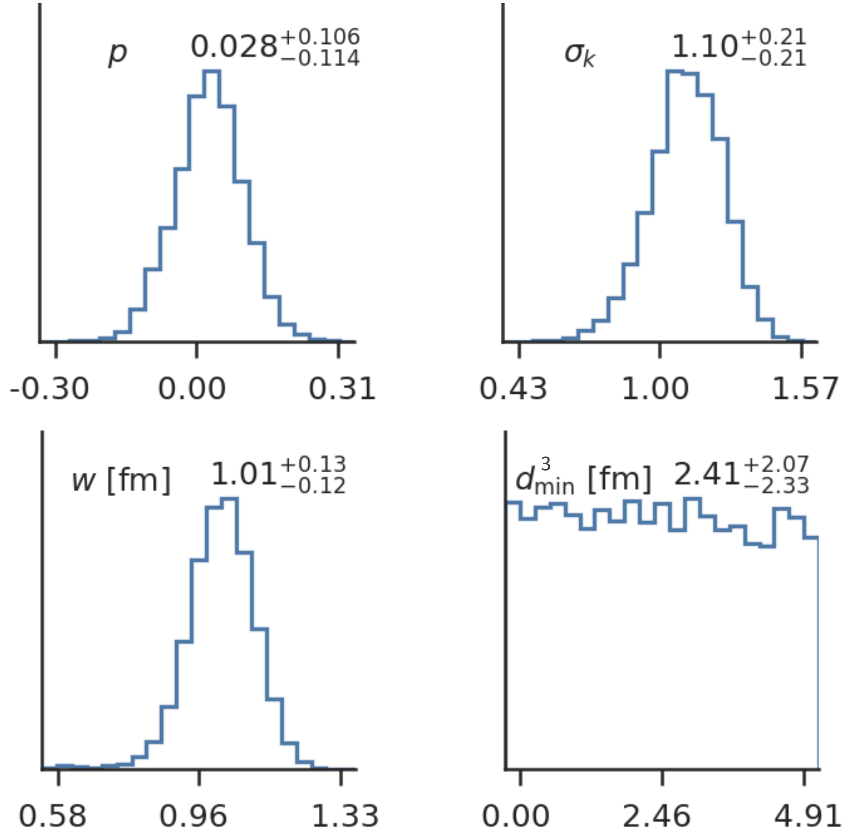
Bayesian analysis: PbPb@2760 GeV



Note: posterior for viscosities is marginalized over all other parameters

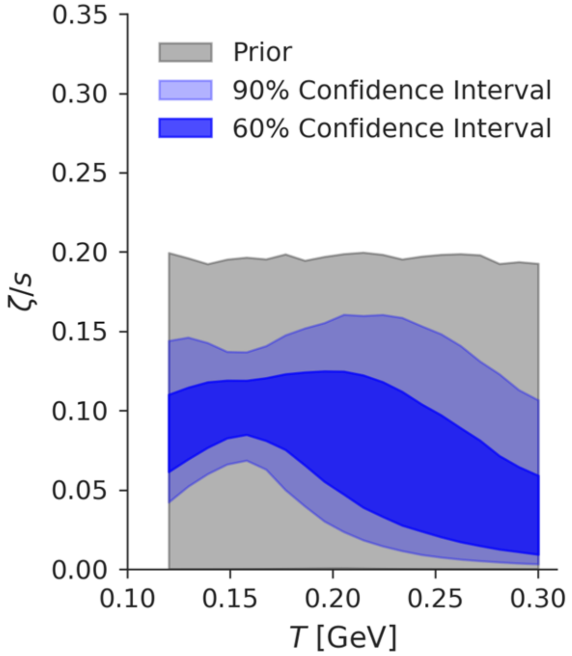


Posteriors for initial condition parameters

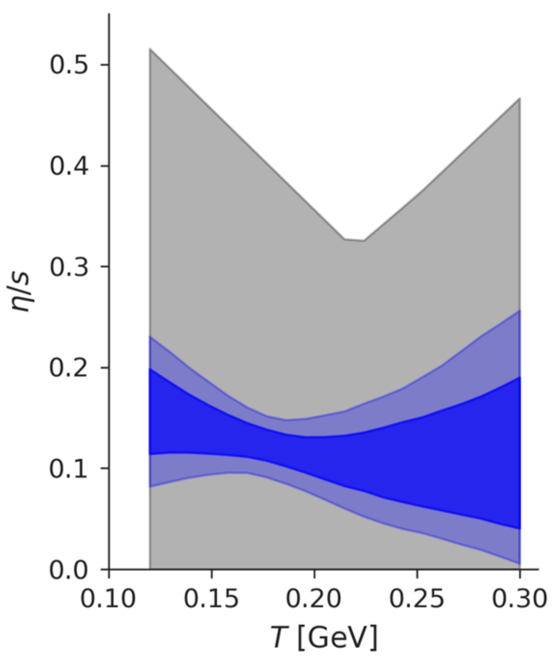
Bayesian analysis on data: adding AuAu@200 GeV

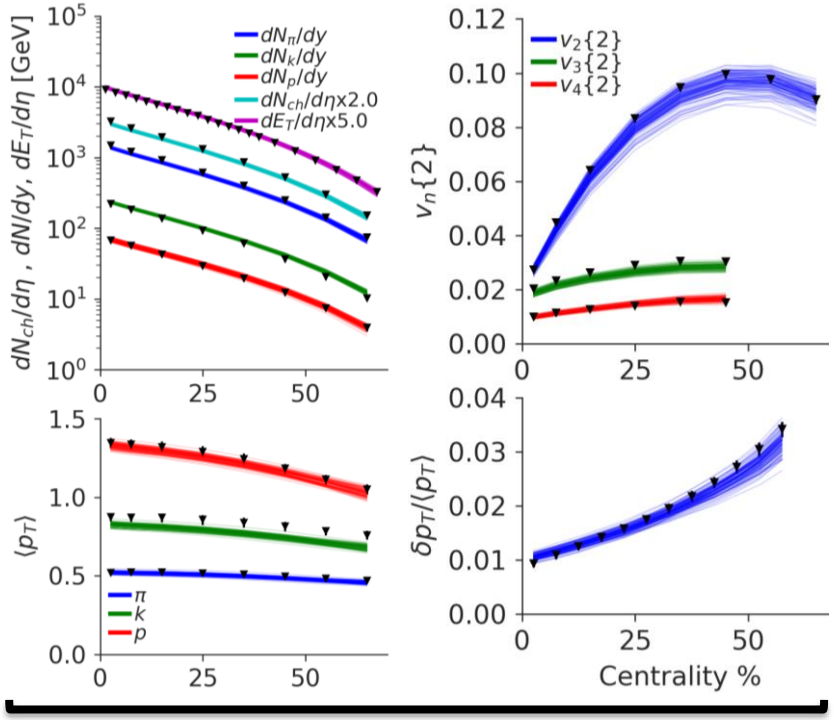
Combined analysis: RHIC & LHC data

Bulk viscosity

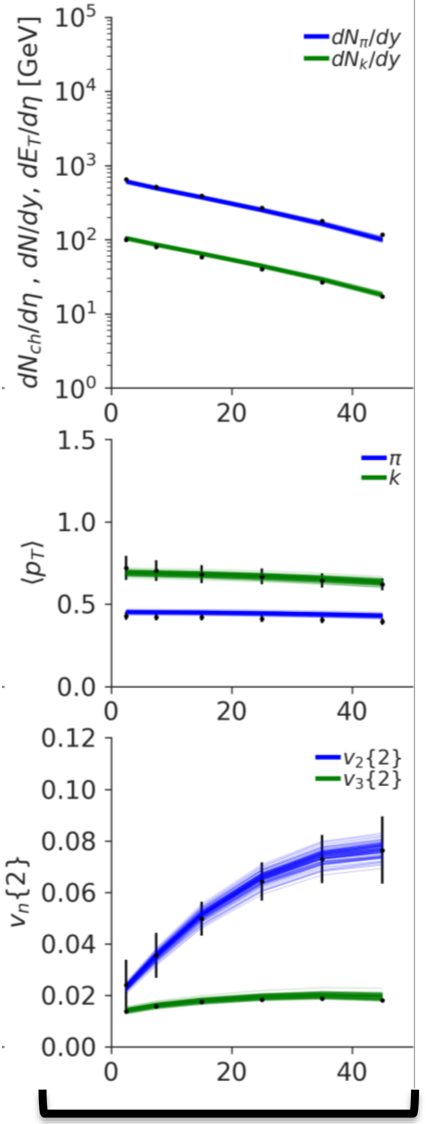


Shear viscosity





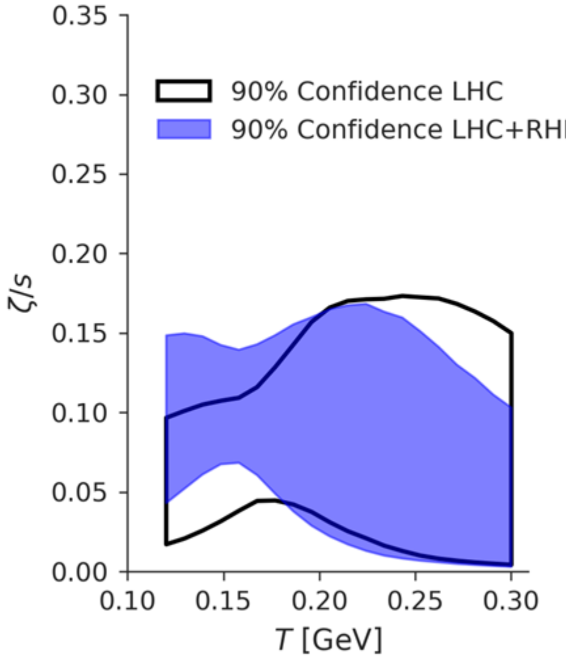
PbPb $\sqrt{s_{NN}}$=2760 GeV
[All measurements from ALICE]



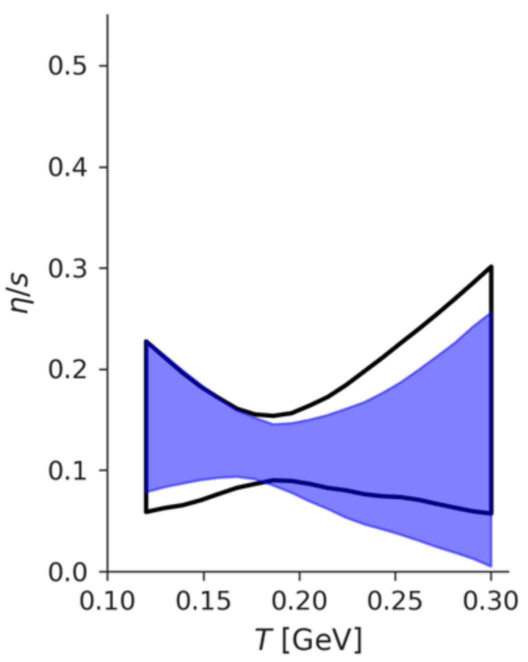
AuAu
$\sqrt{s_{NN}}$=200 GeV
[All measurements from STAR]

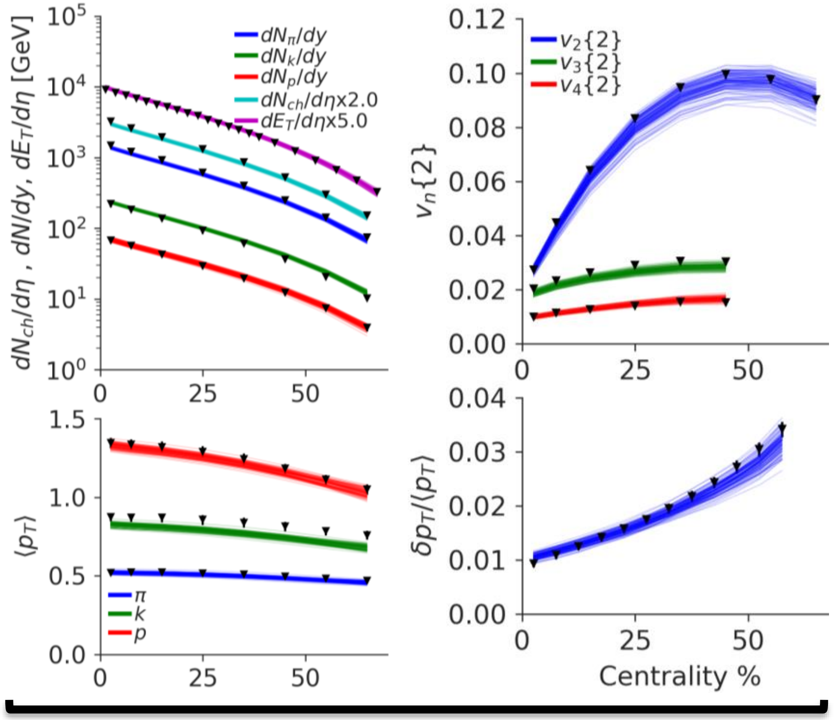
Combined analysis: RHIC & LHC data

Bulk viscosity



Shear viscosity





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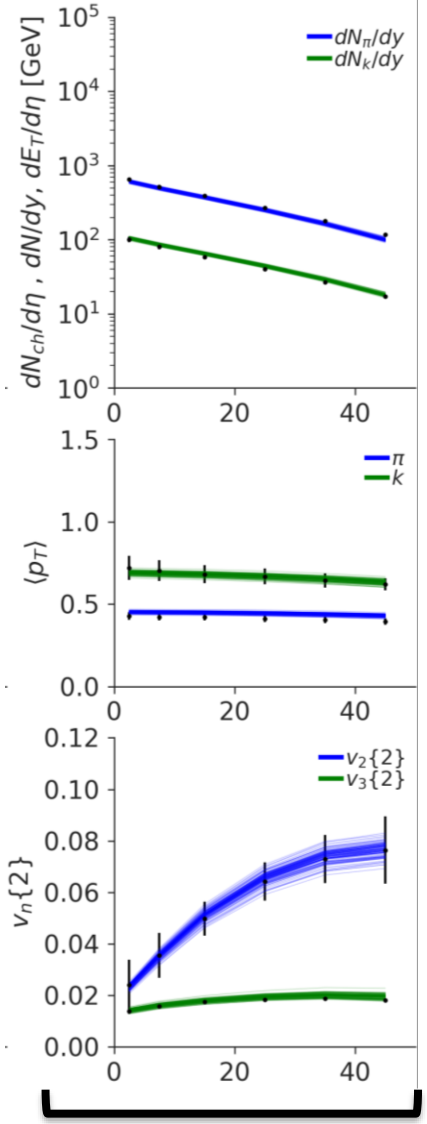

AuAu
$\sqrt{s_{NN}}$=200 GeV
[All measurements from STAR]

Theoretical uncertainty: viscous corrections

From fluid to particles: Viscous corrections

- Hydrodynamics is a coarse-grained description
- Momentum distribution of hadrons corresponding to fluid’s energy-momentum tensor?

Fluid description	Hadronic momentum distribution
Ideal hydrodynamics & local thermal equilibrium	Equilibrium: Fermi-Dirac (baryons), Bose-Einstein (mesons)
Viscous hydrodynamics & deviation from equilibrium	14 moments approximation?

From fluid to particles: Viscous corrections

- Hydrodynamics is a coarse-grained description
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Fluid description	Hadronic momentum distribution
Ideal hydrodynamics & local thermal equilibrium	Equilibrium: Fermi-Dirac (baryons), Bose-Einstein (mesons)
Viscous hydrodynamics & deviation from equilibrium	?

Different ansätze to map energy-momentum tensor to hadron momentum distributions:

- 14 Moments (Grad):

$$f_n = f_{n,thermal} + \delta f_n; \; \delta f_n = f_{n,\mathrm{eq}} \bar{f}_{n,\mathrm{eq}} \left(c_T \, m_n^2 + c_E (u \cdot p)^2 + c_\pi^{<\mu\nu>} p_{\langle\mu} p_{\nu\rangle} \right)$$

- Chapman-Enskog - Relaxation Time Approximation (R.T.A.):

$$f_n = f_{n,thermal} + \delta f_n; \quad \delta f_n = f_{n,\mathrm{eq}} \bar{f}_{n,\mathrm{eq}} \left[\frac{\Pi}{\beta_\Pi} \left(\frac{(u \cdot p)\mathcal{F}}{T^2} + \frac{(-p \cdot \Delta \cdot p)}{3(u \cdot p) T} \right) + \frac{\pi_{\mu\nu} p^{\langle\mu} p^{\nu\rangle}}{2\beta_\pi (u \cdot p) T} \right],$$

See:
McNelis, Everett, Golden & Heinz, in preparation;
McNelis, APS DNP2019,
and references therein

- Pratt-McNelis:

$$f_n = \mathcal{Z}_n \, g_n \left[\exp \left(\frac{\sqrt{p_i' p_i' + m_n^2}}{T + \beta_\Pi^{-1} \Pi \mathcal{F}} \right) + \Theta_n \right]^{-1}$$

- Pratt-Bernhard:

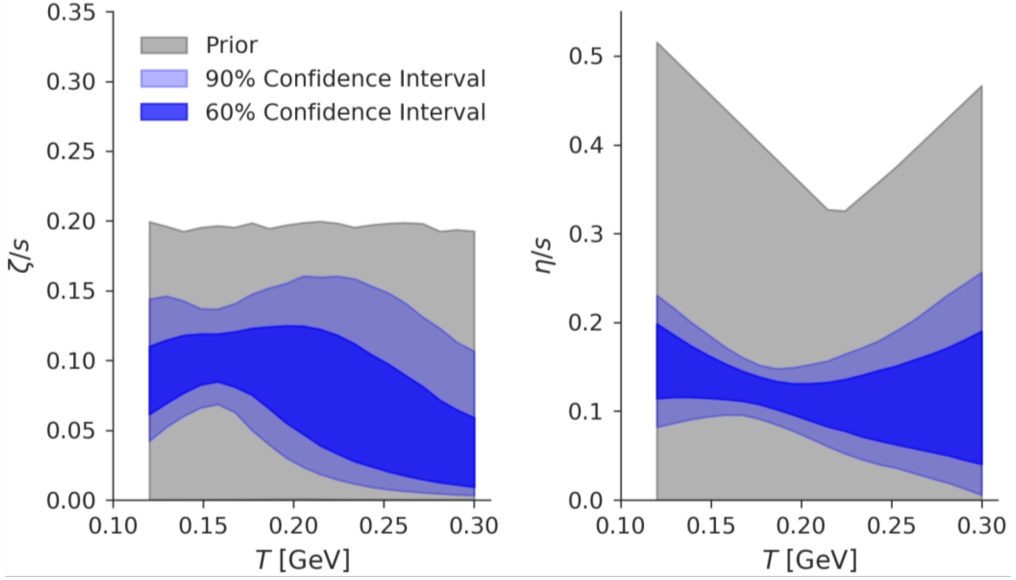
$$f_n = \frac{z_\Pi}{\det \Lambda} g_n \left[\exp \left(\frac{\sqrt{p_i' p_i' + m_n^2}}{T} \right) + \Theta_n \right]^{-1}$$

$$p_i = \Lambda_{ij} p_j'$$

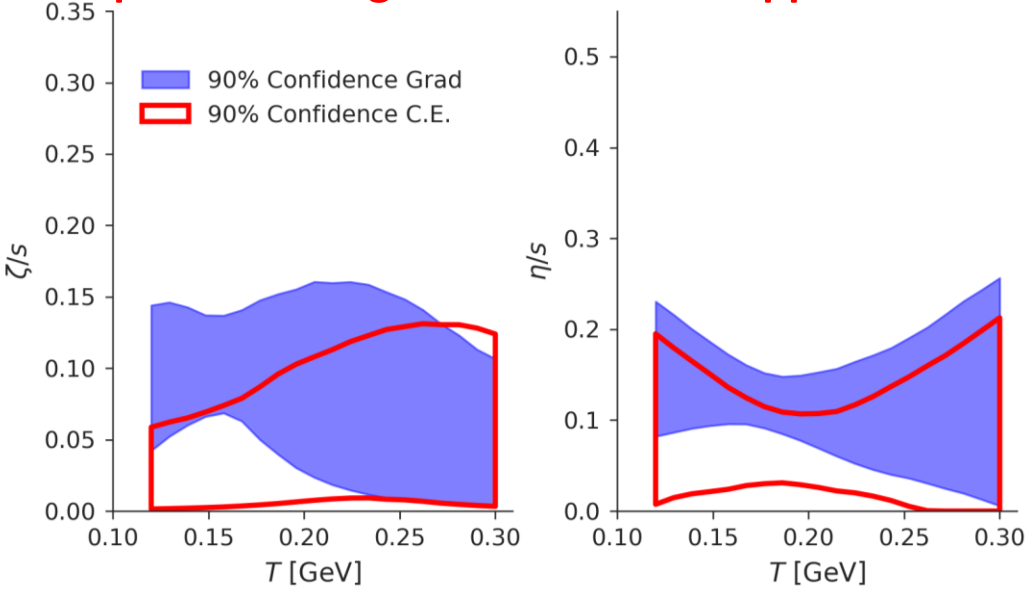
$$\Lambda_{ij} = (1 + \lambda_\Pi) \delta_{ij} + \frac{\pi_{ij}}{2\beta_\pi}$$

Viscous corrections to momentum distribution

14 Moments (Grad)



Chapman–Enskog Relaxation Time Approximation



Pb-Pb

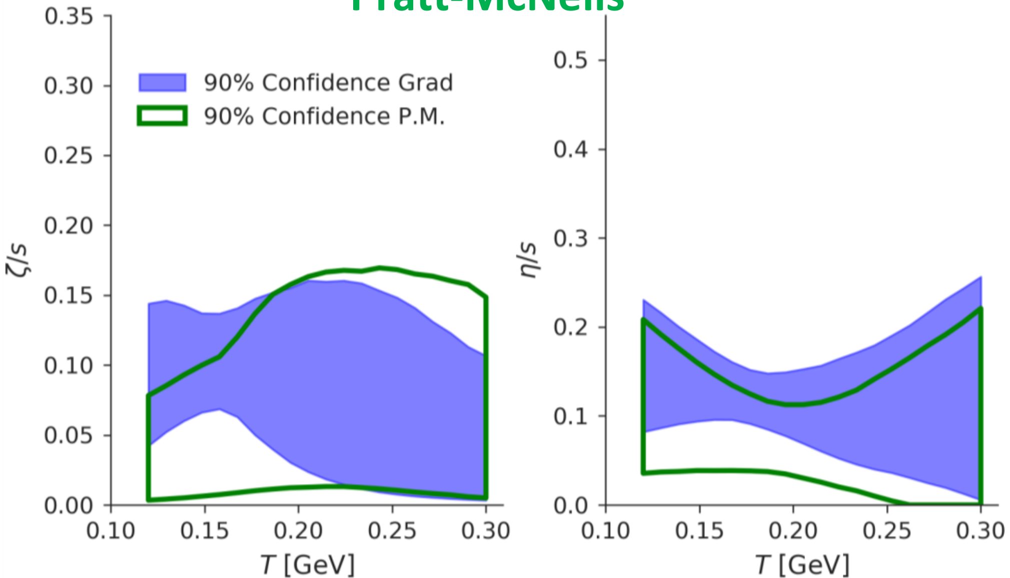
$\sqrt{s_{NN}}$=2760 GeV

&

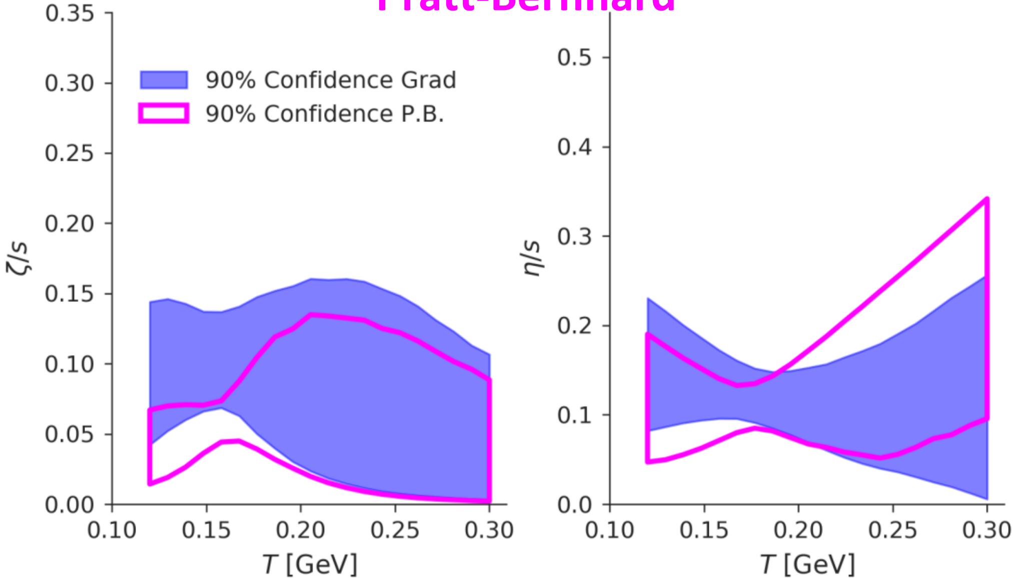
Au-Au

$\sqrt{s_{NN}}$=200 GeV

Pratt-McNelis

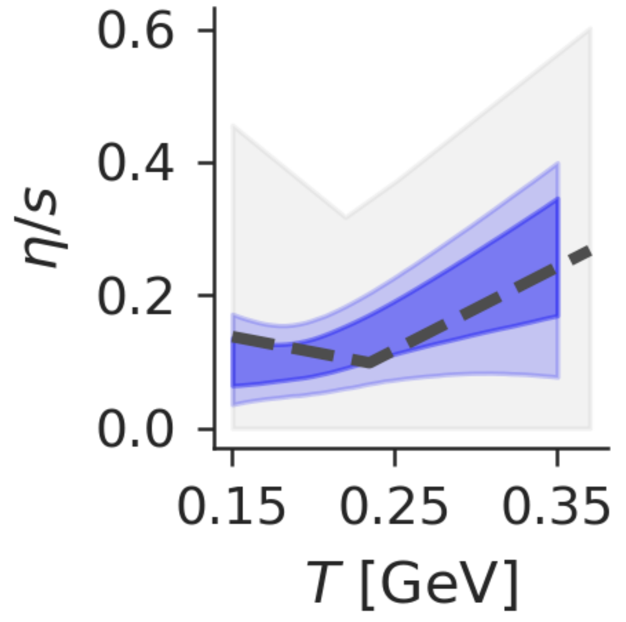


Pratt-Bernhard

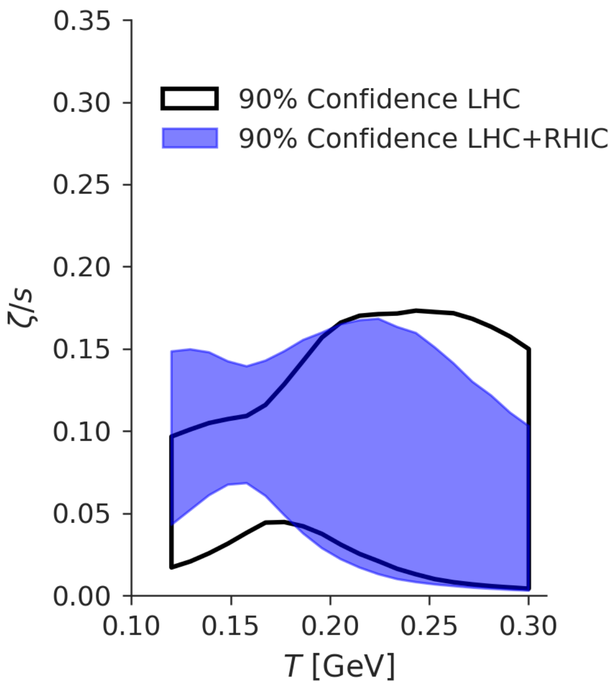


Summary

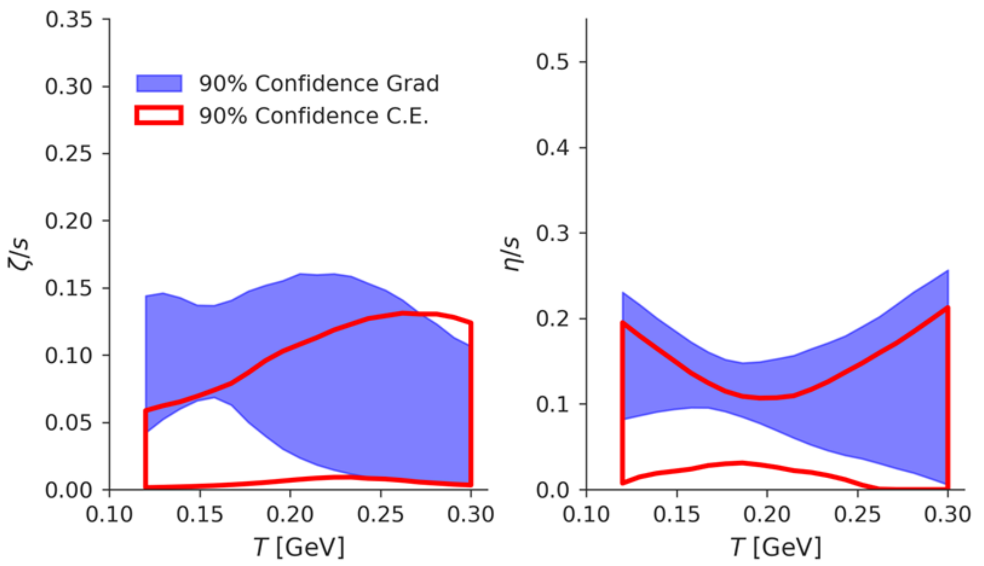
- **Closure tests are powerful tools to validate Bayesian analyses**



- **RHIC data complement LHC's**



- **Non-negligible uncertainties from hydrodynamics to particle transition ("viscous corrections")**



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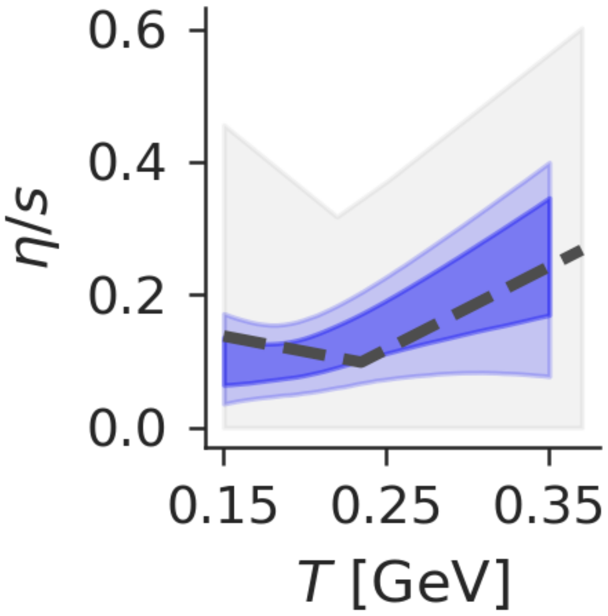

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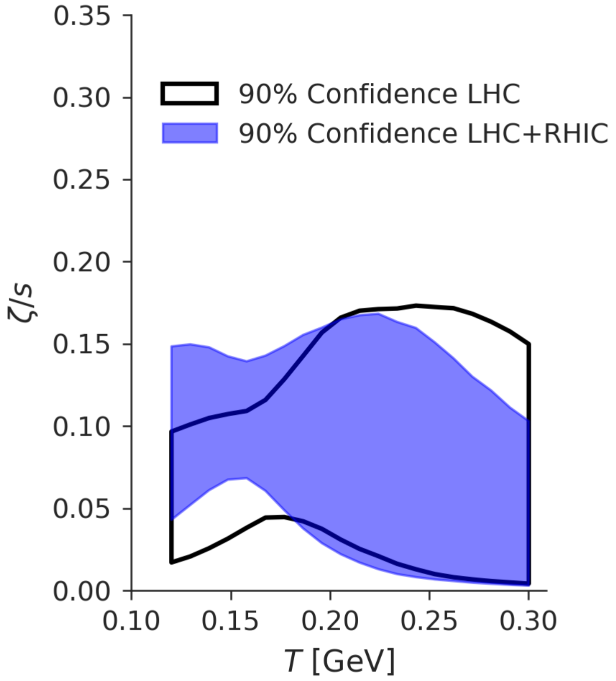

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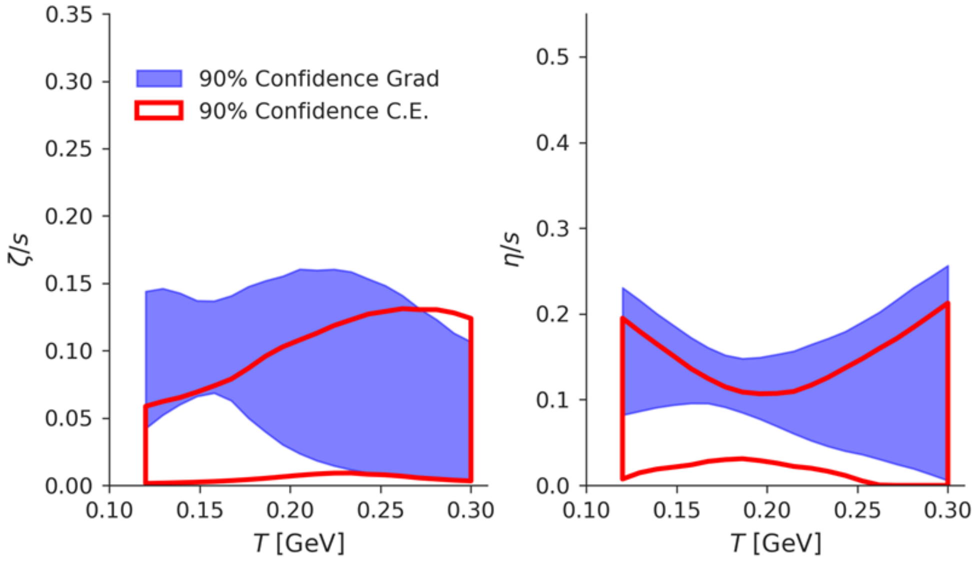

And this is only the beginning:
more systems; more observables; more flexible model; revisit viscous corrections; …

Acknowledgements

The JETSCAPE Collaboration

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U.S. DEPARTMENT OF ENERGY | Office of Science

J.-F.P. was supported by the U.S. Department of Energy (DOE) under award number DE-FG02-05ER41367 and by the National Science Foundation (NSF) under award number ACI-1550300

Computational resources from XSEDE & TACC

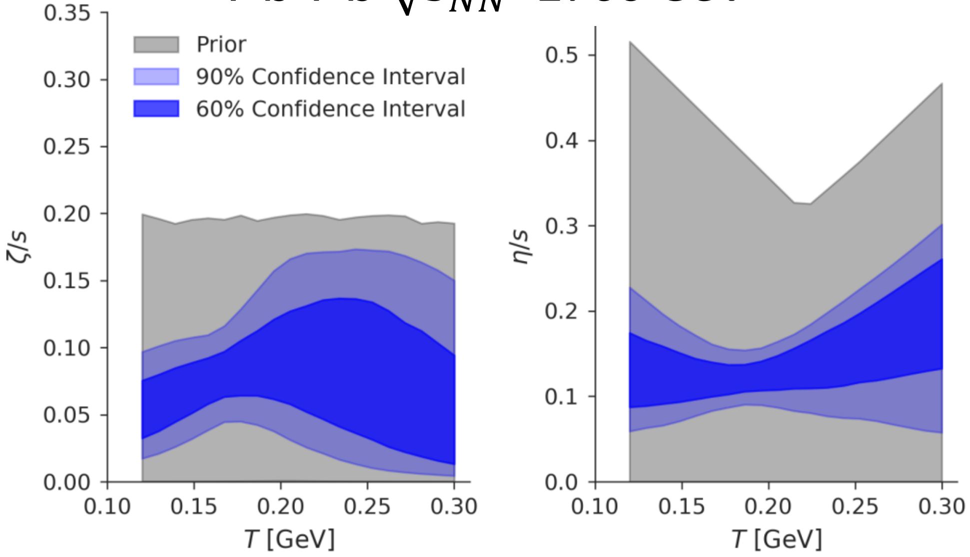
XSEDE
Extreme Science and Engineering Discovery Environment

Questions?

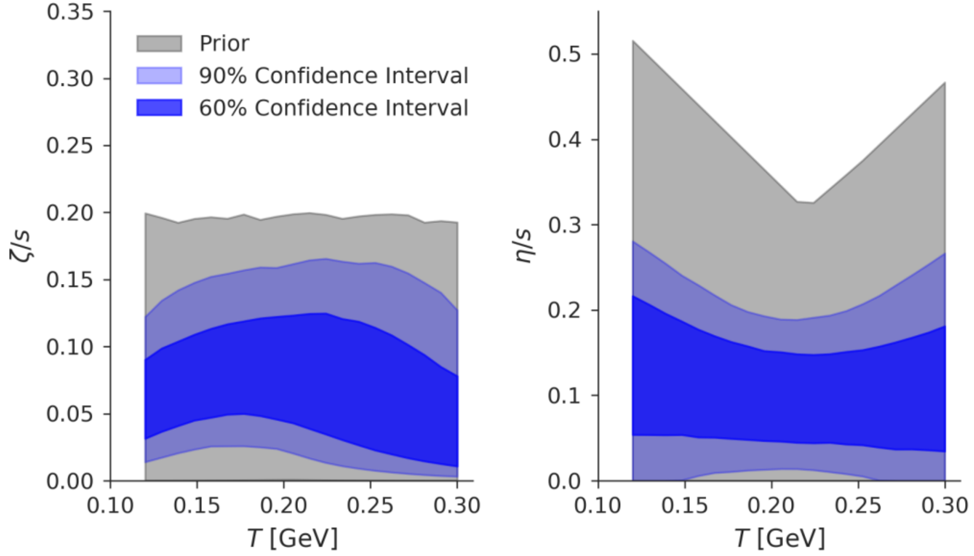
Backup

Combined analysis: RHIC & LHC data

Pb-Pb $\sqrt{s_{NN}}$=2760 GeV



Au-Au $\sqrt{s_{NN}}$=200 GeV



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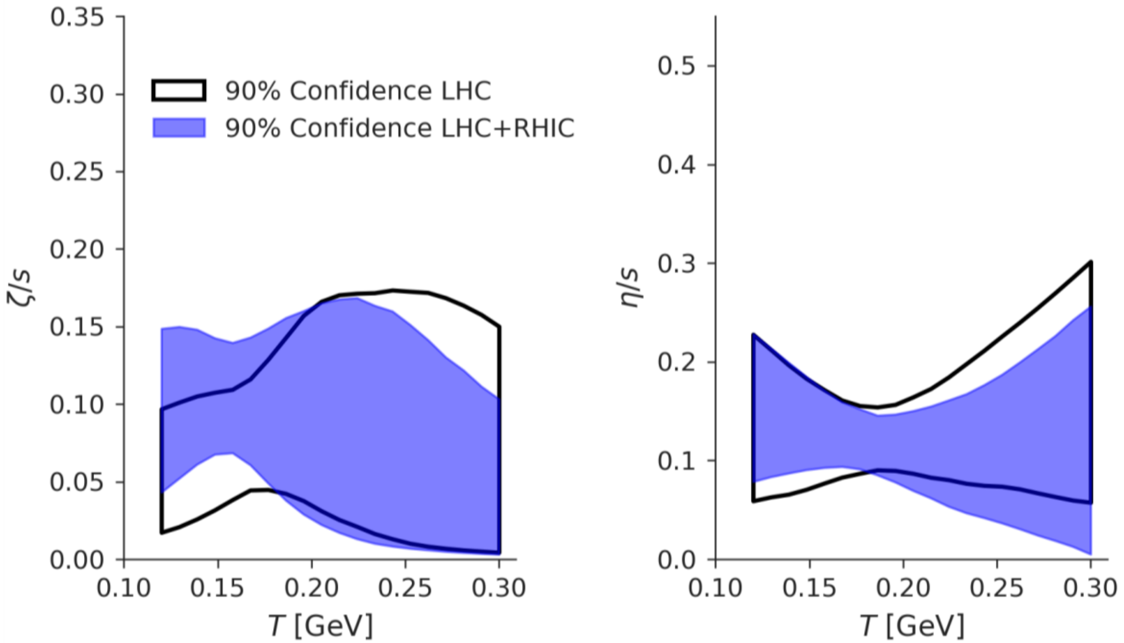
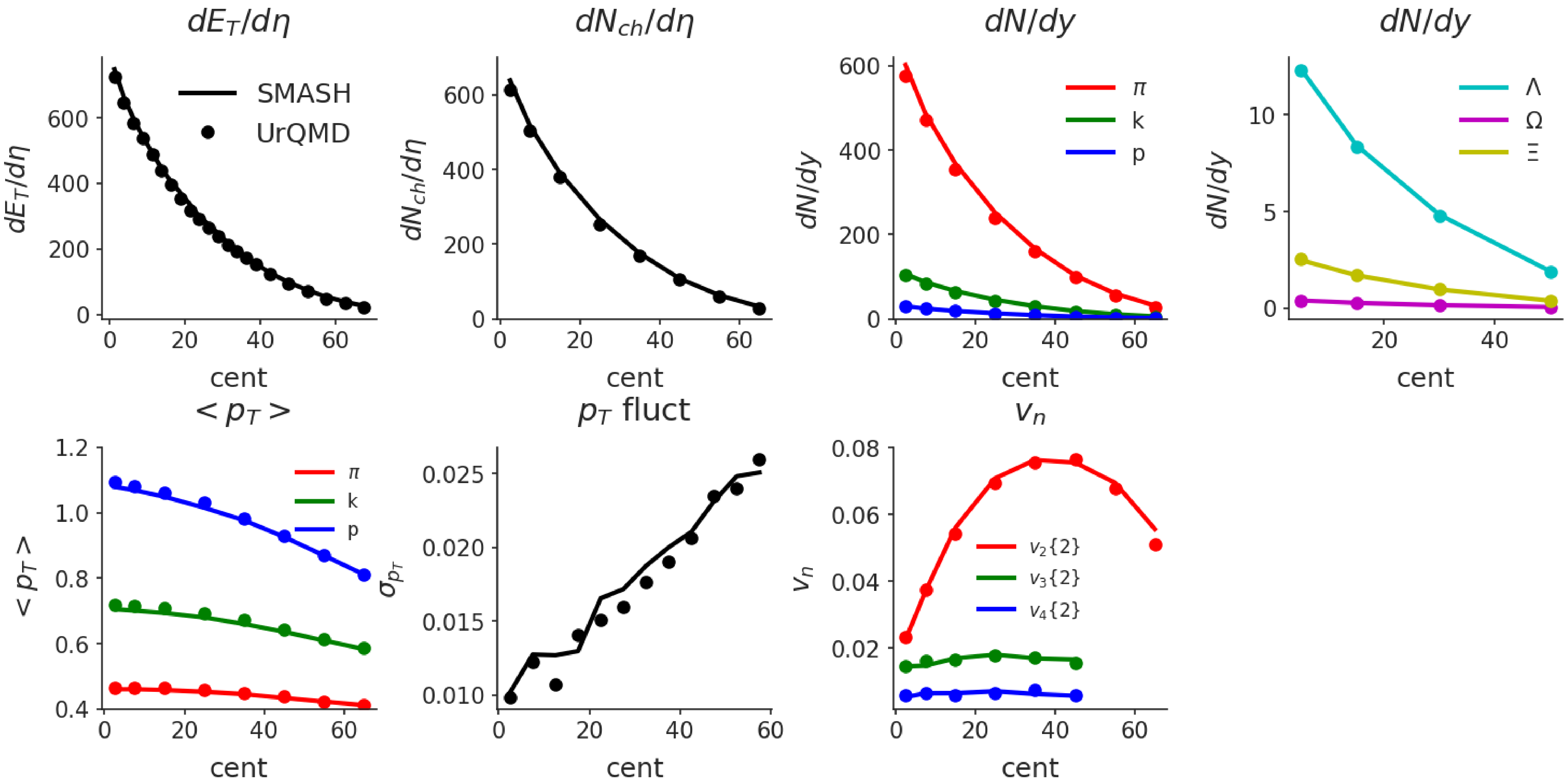
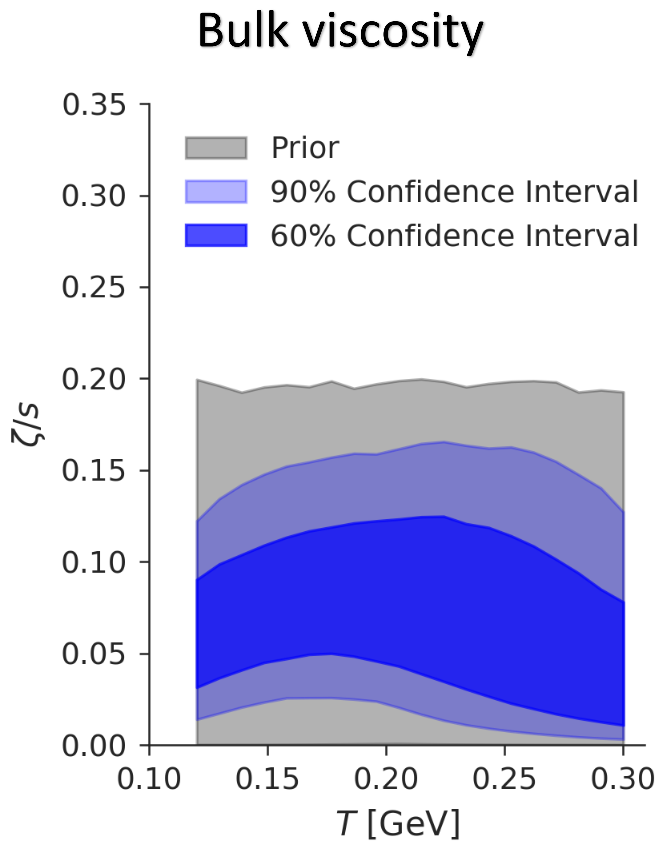
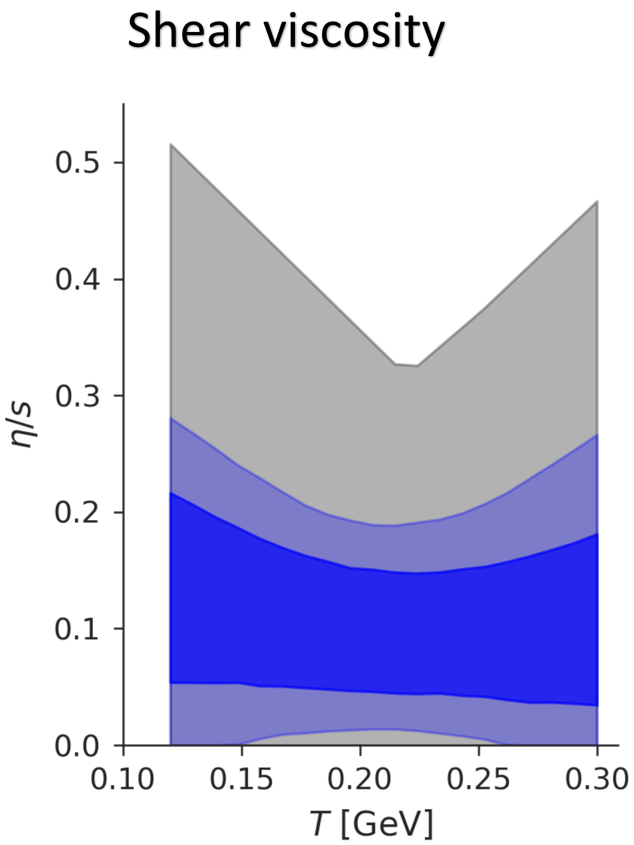


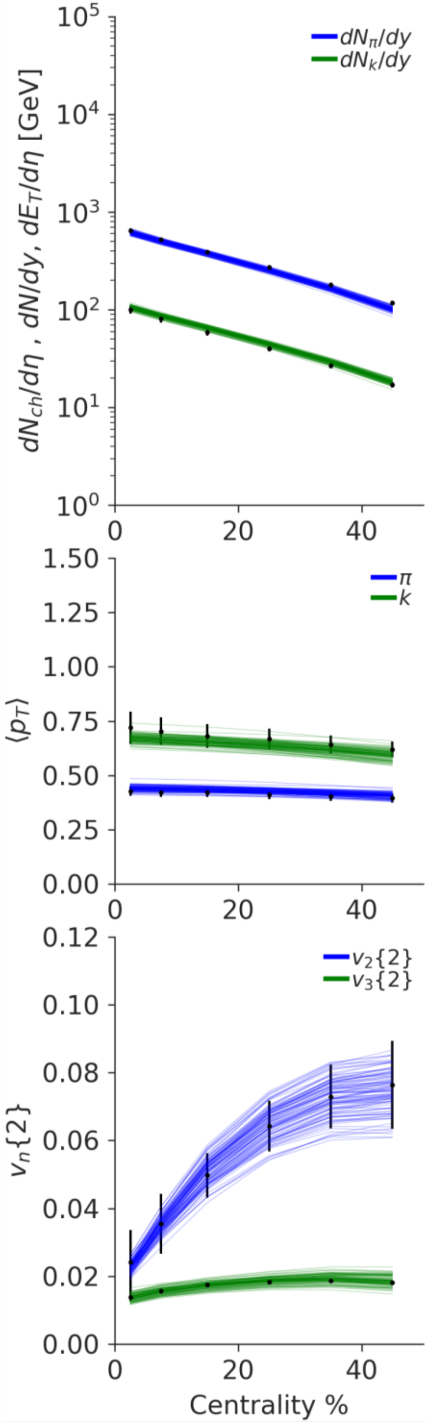
SMASH vs UrQMD as afterburner



Bayesian analysis: AuAu@200 GeV







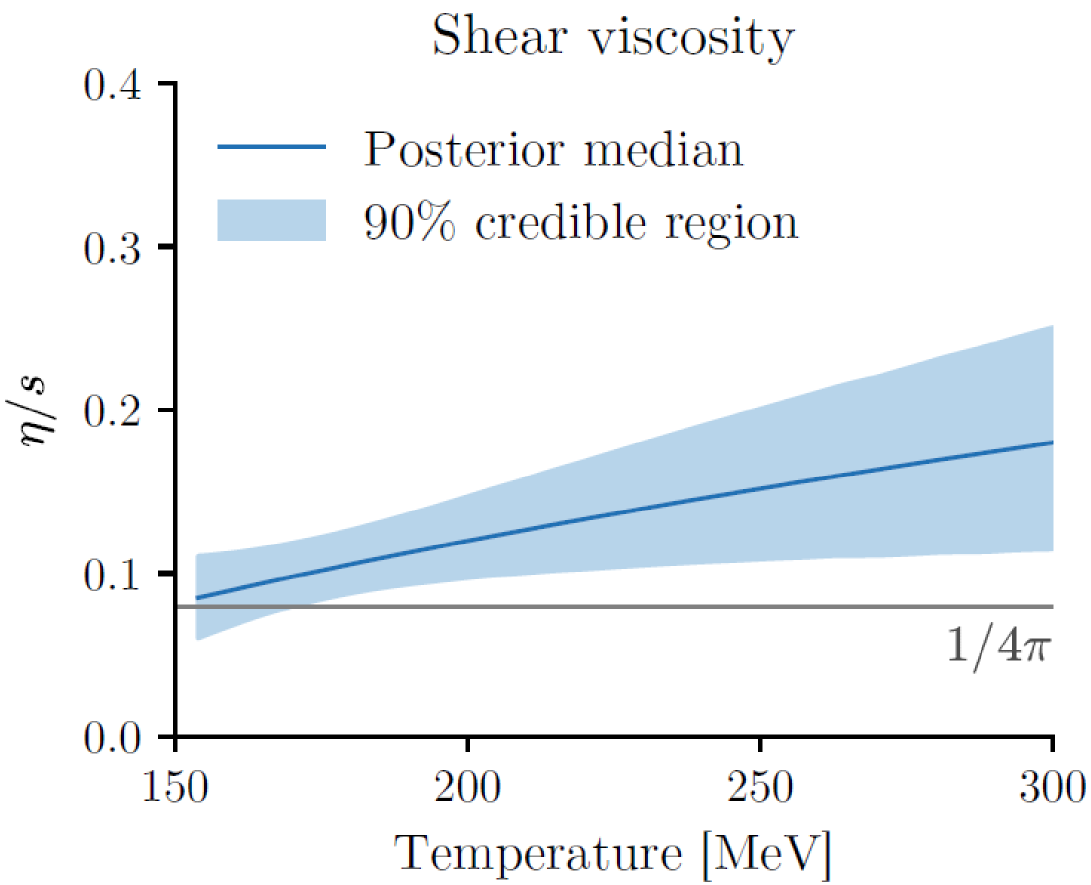
Current analysis vs Duke's previous analysis

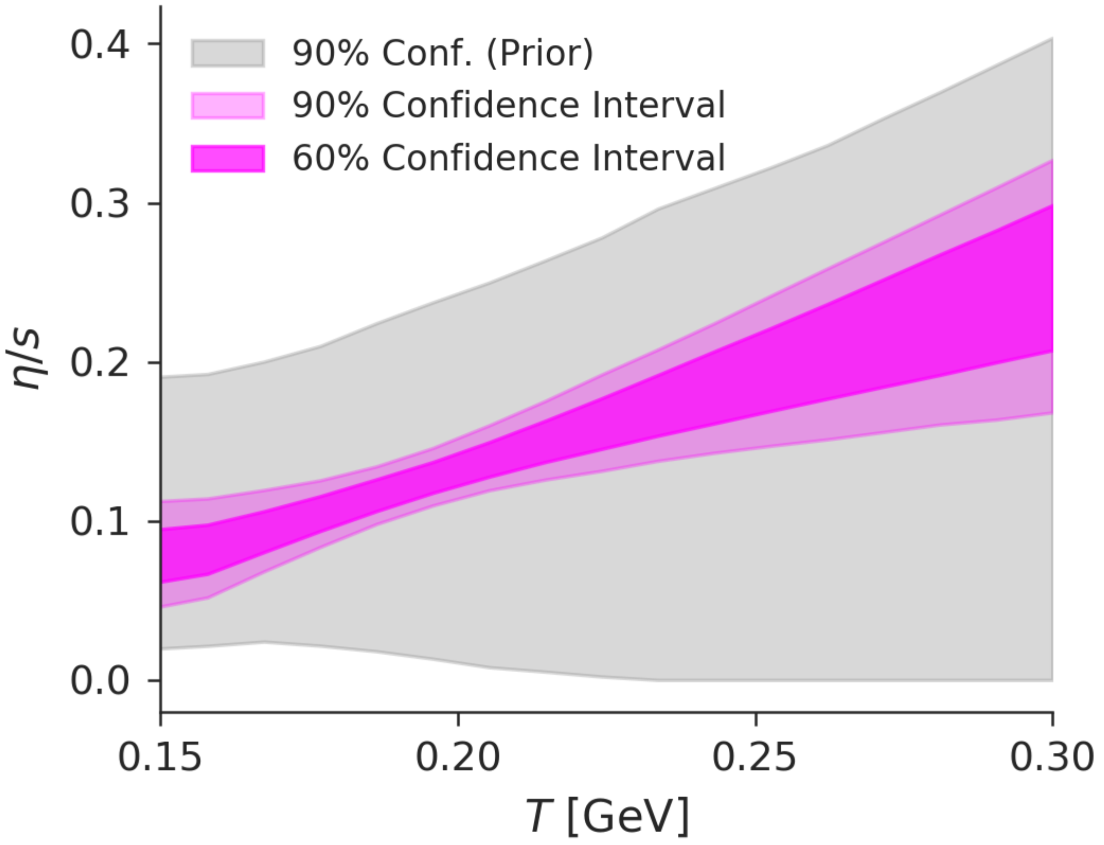
- Difference 1: sigma meson

σ	$dN_{\rm ch}/d\eta$	$dE_T/d\eta$ [GeV]	Pion dN/dy	Pion $\bar{p}_T$ [GeV]
None	579	743	531	0.54
m = 800 MeV	583	754	534	0.55
m = 475 MeV	615	777	569	0.54

Current analysis vs Duke's previous analysis

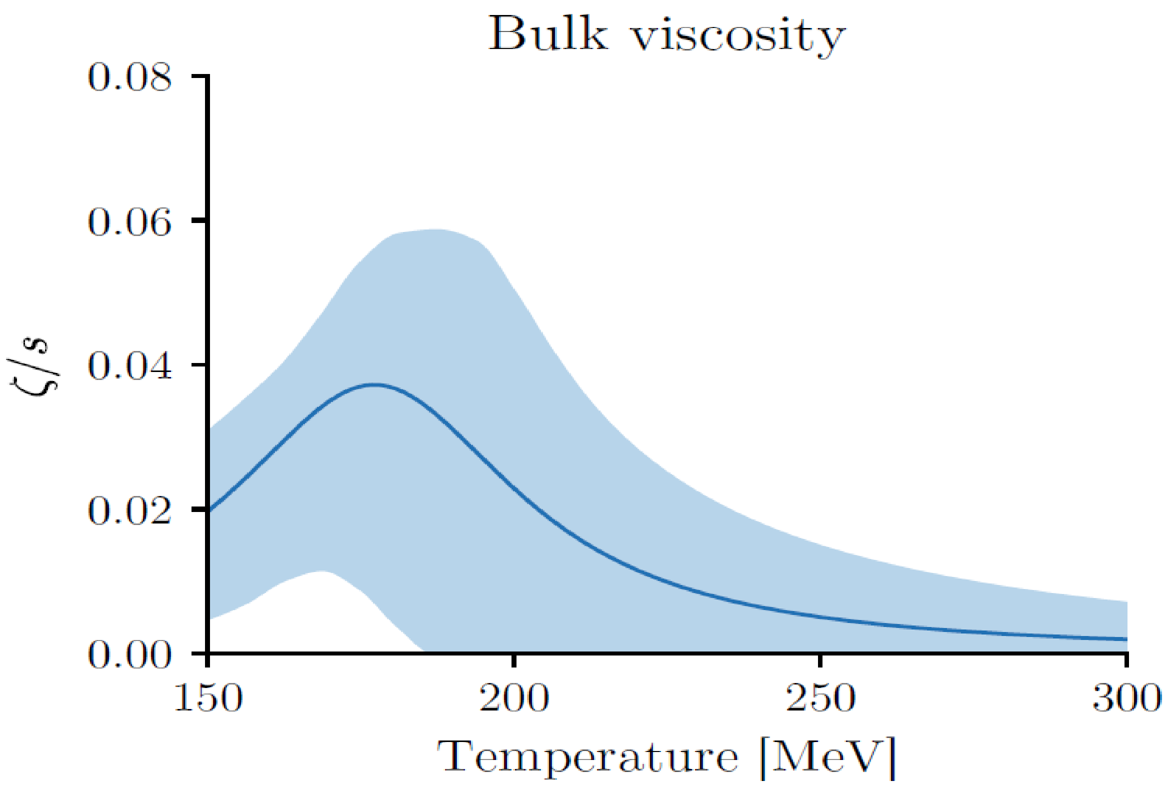
- Differences: parametrization of viscosities - shear

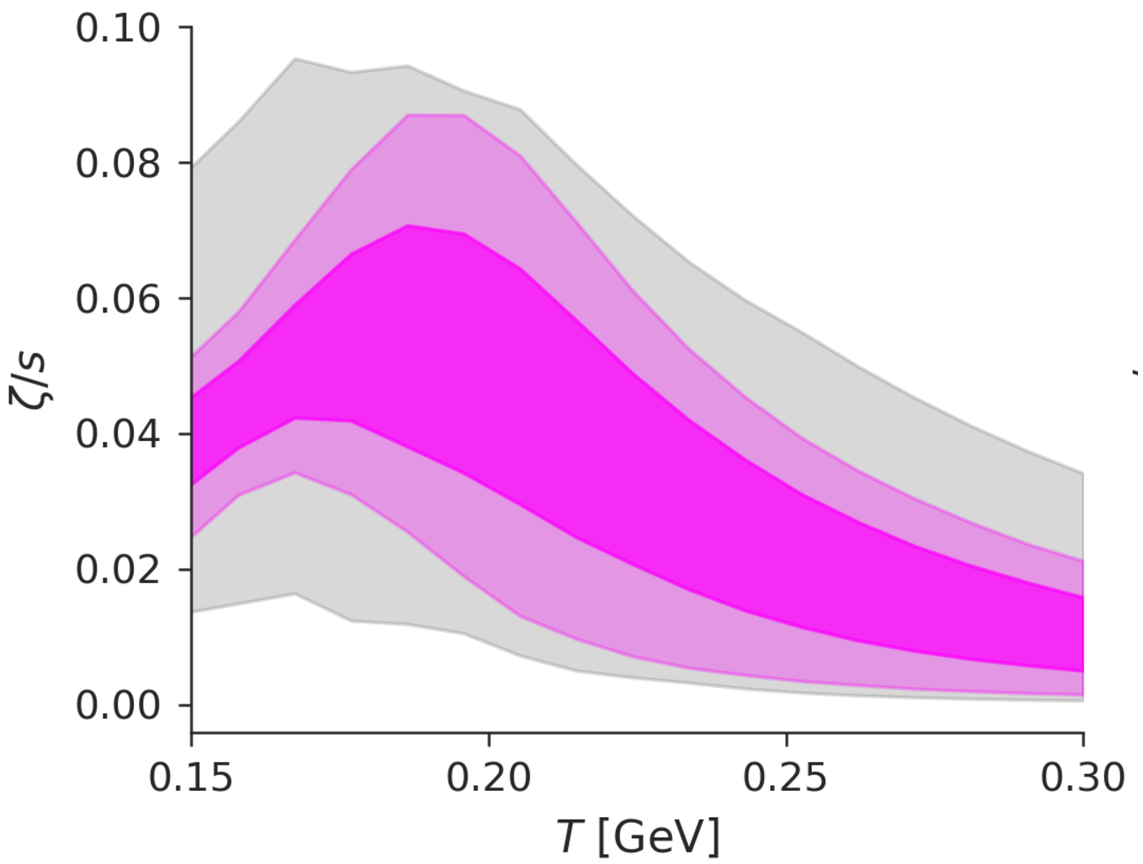




Current analysis vs Duke's previous analysis

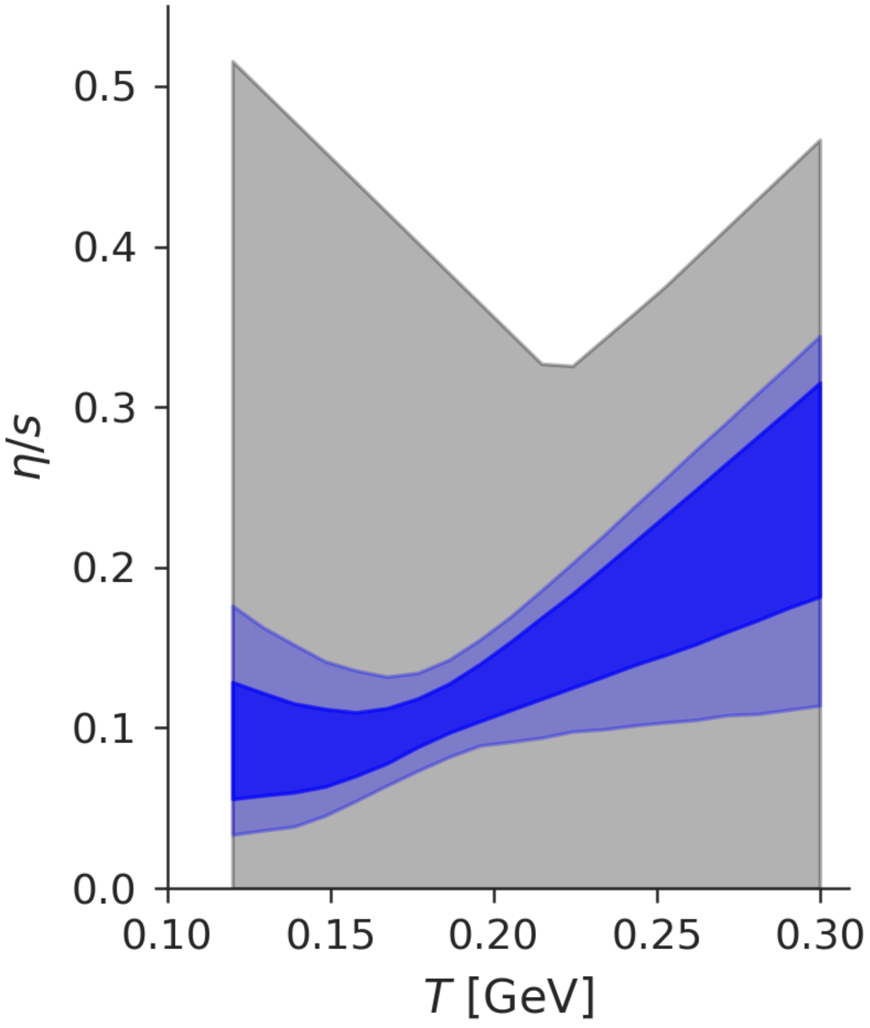
- Differences: parametrization of viscosities - bulk

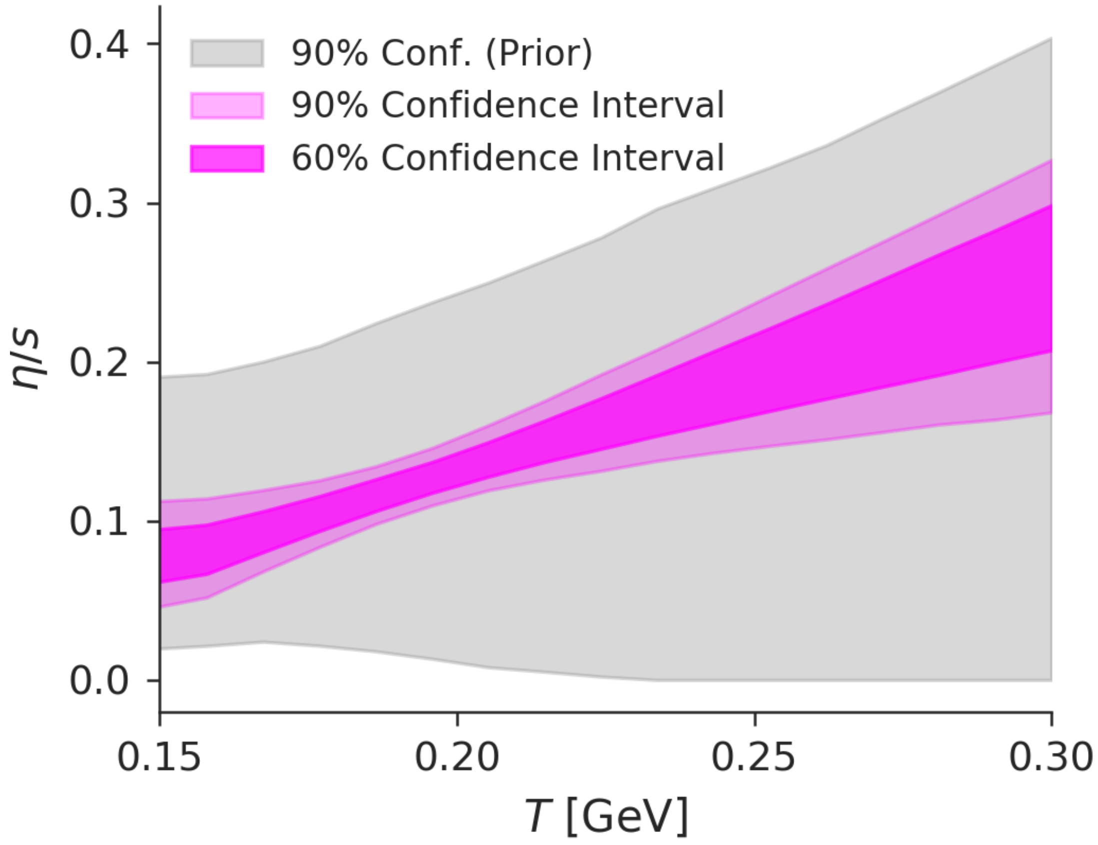




Current analysis vs Duke's previous analysis

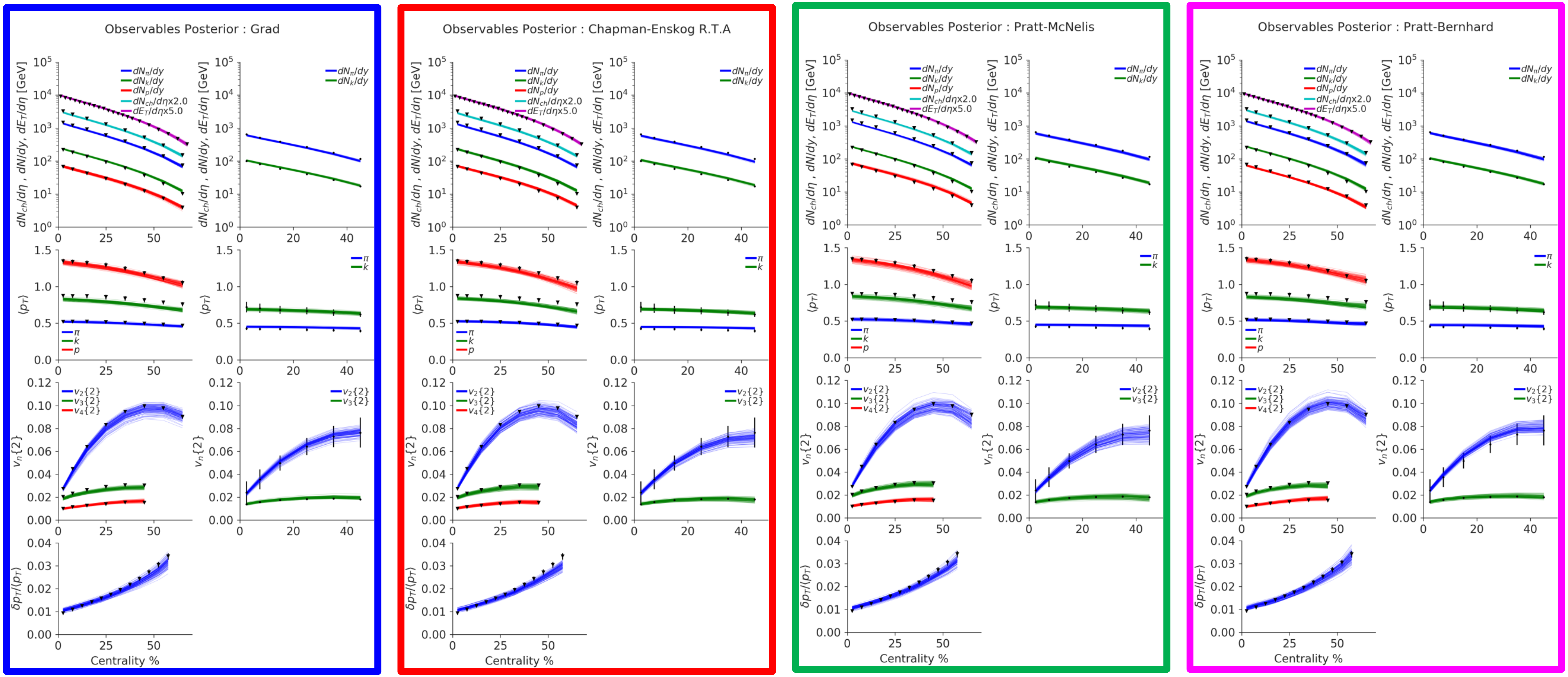
- Differences: parametrization of viscosities





Viscous corrections and data

[Measurements from ALICE and STAR]



Modelling the soft sector

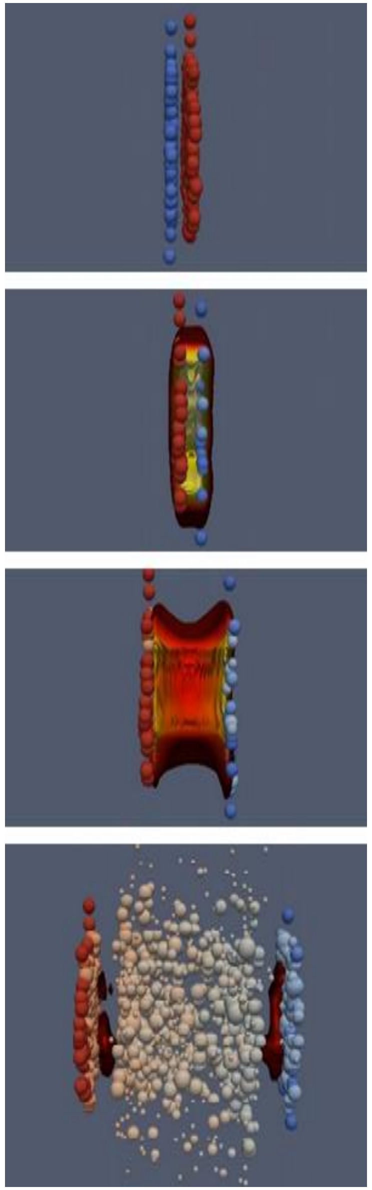


Figure ref.: J. Bernhard, H. Petersen, MADAI Collaboration

$\tau = "0^+"$: Nuclei collide

- Trento ansatz used to parametrize the energy deposition
- 5 parameters: (i-iii) nucleon width, fluctuation & minimum distance, (iv) transparency parameter, (v) normalization

$\tau \sim 0.1$ fm: "Pre-equilibrium phase"

- Free-streaming
- Free-streaming time is a parameter

$\tau \sim 1$ fm: Beginning of "hydrodynamic phase"

- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Equation of state: hadron resonance gas + lattice QCD [HotQCD]
- Shear and bulk viscosity: $\frac{\zeta}{s}(T)$ and $\frac{\eta}{s}(T)$ parametrized
- Shear relaxation time varied: $\tau_\pi = b_\pi \eta/(\epsilon + P)$; $b_\pi \in [2,8]$

$\tau \sim 10$ fm: End of "hydrodynamic phase"

- Fluid converted to hadrons [iS3D]: Cooper-Frye at temperature T_{sw}
- Viscous corrections in Cooper-Frye: 4 different models
- Hadronic interactions with SMASH hadronic transport