Bayesian characterization of the initial state and QGP medium

Jonah E. Bernhard
J. Scott Moreland
Steffen A. Bass

Goal

Perform a **systematic model-to-data comparison** using an event-by-event heavy-ion collision model.

Simultaneously tune all model parameters to optimally reproduce experimental data.

Extract **probability distributions** for each parameter.

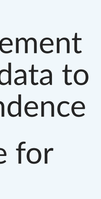
More information about the methodology
J. E. Bernhard *et. al.*, PRC 91 054910, 1502.0039.
S. Pratt *et. al.*, PRL 114 202301, 1501.04042.
J. Novak *et. al.*, PRC 89 034917, 1303.5769.
D. Higdon *et. al.*, J. Amer. Stat. Assoc. 103 570.

Input parameters

norm	initial condition normalization
p	entropy deposition parameter
k	nucleon fluctuation parameter
w	Gaussian nucleon width
η/s min	shear viscosity at T_c = 0.154 GeV
η/s slope	slope of shear viscosity above T_c
ζ/s norm	bulk viscosity normalization
$T_{\rm switch}$	hydro to UrQMD switching temp.

$O(10^2)$ semi-random, space-filling parameter points.
Vary all parameters simultaneously.

Model



Initial conditions
TRENTo (parametric model)

J. S. Moreland, J. E. Bernhard, and S. A. Bass, PRC 92 011901, 1412.4708.

$$\frac{dS}{dy} \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p} = \begin{cases} (T_A+T_B)/2 & p=+1 \\ \sqrt{T_A T_B} & p=0 \\ 2\,T_A T_B/(T_A+T_B) & p=-1 \end{cases}$$

p = tunable entropy deposition parameter
see J. Scott Moreland's poster

Hydro
event-by-event VISH2+1
HotQCD EOS
T-dependent shear & bulk

H. Song and U. W. Heinz, PRC 77 064901, 0712.3715.
C. Shen *et. al.*, CPC 2015, 1409.8164.
HotQCD collaboration, PRD 90 094503, 1407.6387.
G. S. Denicol *et. al.*, PRC 80 064901, 0903.3595.

Particlization
OSU Cooper-Frye sampler

C. Shen *et. al.*, CPC 2015, 1409.8164.
Z. Qiu, 1308.2182.

Hadronic phase
UrQMD

S. A. Bass *et. al.*, Prog. Part. Nucl. Phys. 41 225.
M. Bleicher *et. al.*, JPG 25 1859.

Gaussian process emulator

non-parametric interpolation / fast surrogate to full model

C. E. Rasmussen and C. K. I. Williams, *Gaussian Processes for Machine Learning* (2006).

MCMC

(Markov chain Monte Carlo)

random walk through parameter space weighted by posterior probability

Bayes' theorem
posterior ∝ likelihood × prior

probability of parameters given model and data
probability of observing experimental data given proposal parameters
initial knowledge of parameters

after many steps, chain equilibrates to

Experimental data

ALICE collaboration
Pb+Pb collisions at $\sqrt{s}$ = 2.76 TeV

yields and mean p_T: PRC 88 044910, 1303.0737.
flows: PRL 107 032301, 1105.3865.

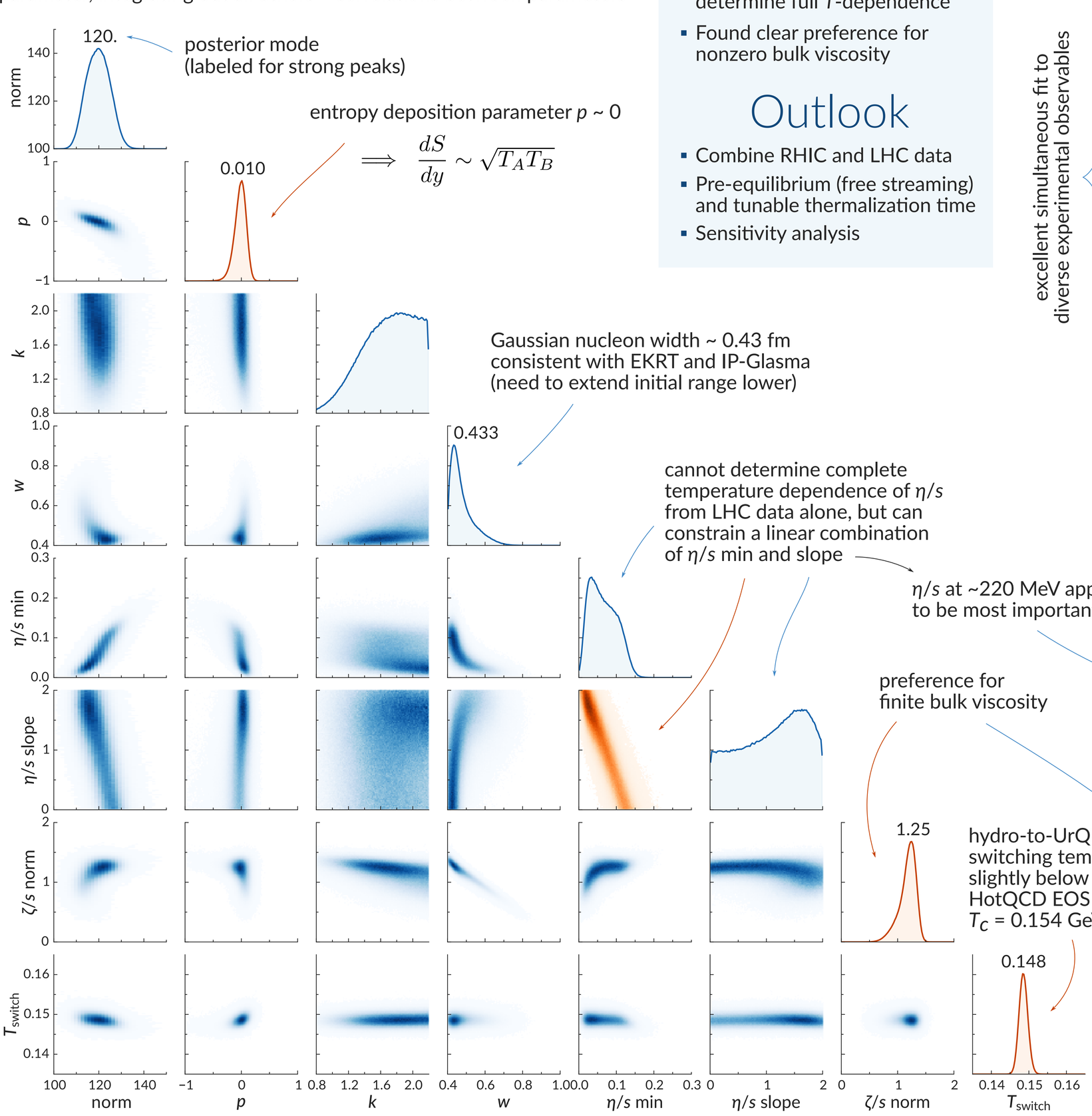
Posterior distribution

Draw random samples from MCMC chain

Posterior samples

Diagonals
probability distributions of each parameter, integrating out all others

Off-diagonals
pairwise probabilities showing correlations between parameters



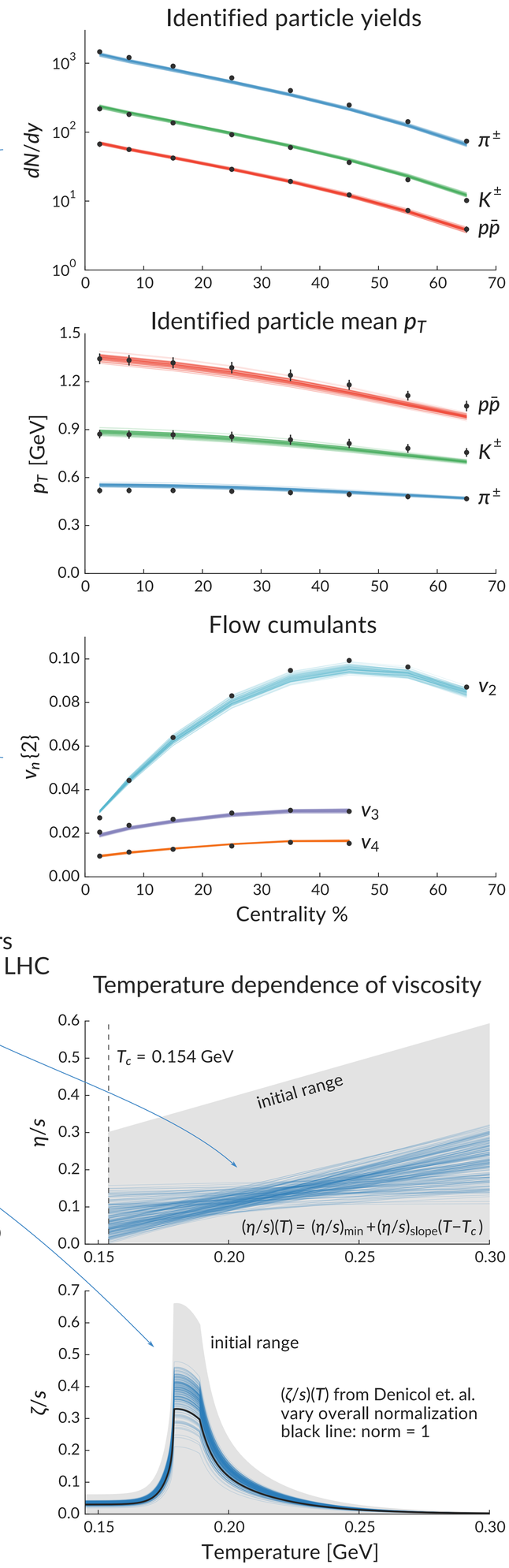
Key results

- Determined scaling of initial entropy deposition
- Extracted new measurement of $(\eta/s)(T)$; need RHIC data to determine full T-dependence
- Found clear preference for nonzero bulk viscosity

Outlook

- Combine RHIC and LHC data
- Pre-equilibrium (free streaming) and tunable thermalization time
- Sensitivity analysis

excellent simultaneous fit to diverse experimental observables



Temperature dependence of viscosity

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