The effect of the equation of state on η/s of strongly interacting matter

Jussi Auvinen

Institute of Physics Belgrade

in collaboration with
Kari J. Eskola, Pasi Huovinen, Harri Niemi, Risto Paatelainen
and Peter Petreczky

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Equations of state

Old baseline:

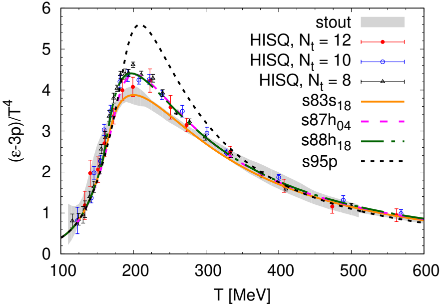
P. Huovinen and P. Petreczky, Nucl. Phys. A **837**, 26 (2010)

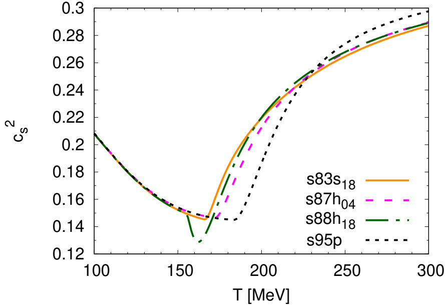
- **s95p**: $M < 2$ GeV particles from 2004 PDG summary tables for the hadron gas part, lattice data for high T: Phys. Rev. D **80**, 014504 (2009); Phys. Rev. D **77**, 014511 (2008)

New parametrizations:

J. Auvinen, K. J. Eskola, P. Huovinen, H. Niemi, R. Paatelainen, P. Petreczky, PRC **102**, 044911 (2020) [arXiv:2006.12499 [nucl-th]]

- s83s$_{18}$: HG: 2018 PDG, lattice: stout action PLB **730**, 99 (2014), JHEP **1011**, 077 (2010)
- s87h$_{04}$: HG: 2004 PDG, lattice: HISQ action PRD **90**, 094503 (2014), PRD **97**, 014510 (2018)
- s88h$_{18}$: HG: 2018 PDG, lattice: HISQ action PRD **90**, 094503 (2014), PRD **97**, 014510 (2018)





EKRT+hydrodynamics model

- Initial energy density from the EKRT minijet saturation model

  Paatelainen et al., Phys. Rev. C **87**, no. 4, 044904 (2013); Phys. Lett. B **731**, 126 (2014)

  $$\epsilon(\vec{r}_T, \tau_s(\vec{r}_T)) = \frac{K_{\rm sat}}{\pi}[p_{sat}(\vec{r}_T, K_{\rm sat})]^4;\ \tau_s(\vec{r}_T) = 1/p_{\rm sat}(\vec{r}_T, K_{\rm sat})$$

  For each centrality class, produce a number of energy density profiles, convert to entropy density via EoS, and average over events

- 2+1D viscous hydrodynamics with a temperature dependent shear viscosity coefficent η/s Niemi et al., PRC **93**, 024907 (2016)

  $$(\eta/s)(T) = S_{\rm HG}(T_{\rm H} - T) + (\eta/s)_{\rm min},\ T < T_{\rm H}$$
  $$(\eta/s)(T) = (\eta/s)_{\rm min},\ T_{\rm H} \le T \le T_{\rm H} + W_{\rm min}$$
  $$(\eta/s)(T) = S_{\rm QGP}(T - T_{\rm H} - W_{\rm min}) + (\eta/s)_{\rm min},\ T > T_{\rm H} + W_{\rm min}$$

- Kinetic decoupling temperature $T_{\rm dec}$ and chemical freeze-out temperature $T_{\rm chem}$ are also free parameters

Bayesian analysis

Model parameters (input): $\vec{x} = (x_1, ..., x_n)$

$(K_{\mathrm{sat}},\ (\eta/s)_{\mathrm{min}},\ T_{\mathrm{H}},\ W_{\mathrm{min}},\ S_{\mathrm{HG}},\ S_{\mathrm{QGP}},\ T_{\mathrm{dec}},\ T_{\mathrm{chem}})$

$\Downarrow$

Model output $\vec{y} = (y_1, ..., y_m) \Leftrightarrow$ Experimental values $\vec{y}^{\,\mathrm{exp}}$

$(dN/dy,\ \langle p_T \rangle,\ v_2)$

Bayes' theorem:

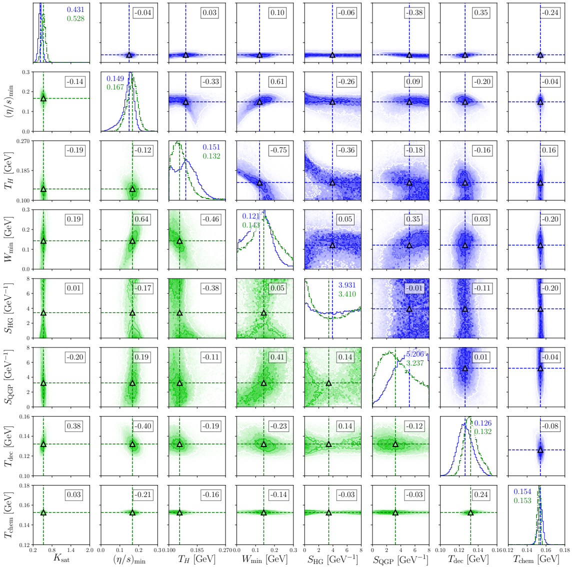
$$\boxed{\text{Posterior probability} \propto \text{Likelihood} \cdot \text{Prior knowledge}}$$

- Prior knowledge: Range of input parameter values to investigate
- Likelihood: $\mathcal{L}(\vec{x}) \propto \exp\left(-\frac{1}{2}(\vec{y}(\vec{x}) - \vec{y}^{\,\mathrm{exp}})\Sigma^{-1}(\vec{y}(\vec{x}) - \vec{y}^{\,\mathrm{exp}})^T\right)$, where Σ is the covariance matrix representing the uncertainties

Use Markov chain Monte Carlo to sample the posterior probability

- Random walk in input parameter space, constrained by the prior
- Use Gaussian process (GP) emulator to estimate model output for likelihood computations

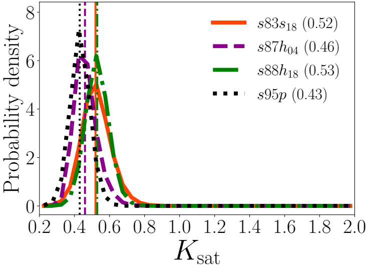
Example illustration of posterior probability distributions



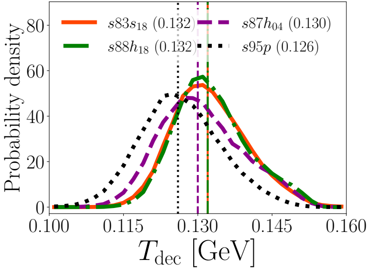
s88h_{18}

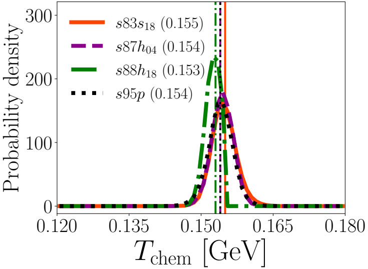
s95p

Posterior distribution comparisons

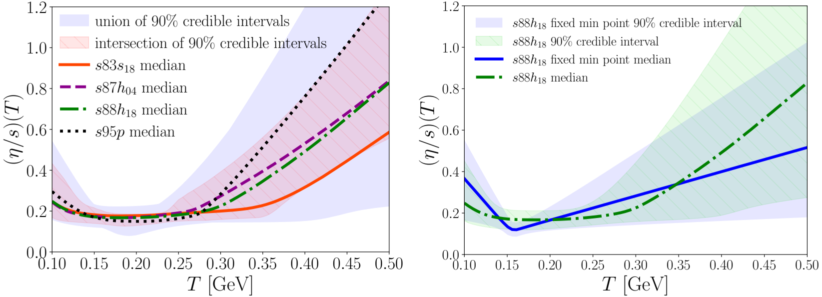


- Initial state parameter K_{sat} and the decoupling temperatures quite well constrained, $K_{\mathrm{sat}} \approx 0.5$ consistent with earlier studies
- No significant differences between EoSs





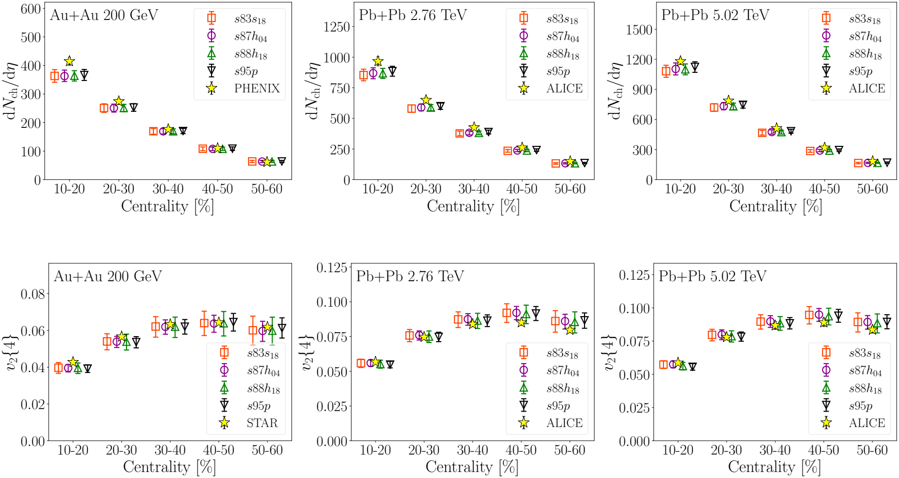
Posterior $(\eta/s)(T)$



- Tightest constraints on η/s in the temperature range $T \approx 150$–220 MeV, where η/s is approximately constant
- All EoSs: $0.08 < \eta/s < 0.23$; $s83s_{18}$ and $s88h_{18}$: $0.12 < \eta/s < 0.23$
- Reducing the constant-value plateau to a point ($W_{\min} \approx 0$) leads to a smaller η/s minimum value
- Differences due to equations of state within uncertainties

Backup: Emulator predictions for posterior points

Charged particle multiplicity and $v_2\{4\}$



Backup: Emulator predictions for posterior points

Identified particle multiplicity and $\langle p_T \rangle$ at $\sqrt{s_{NN}} = 2.76$ TeV