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

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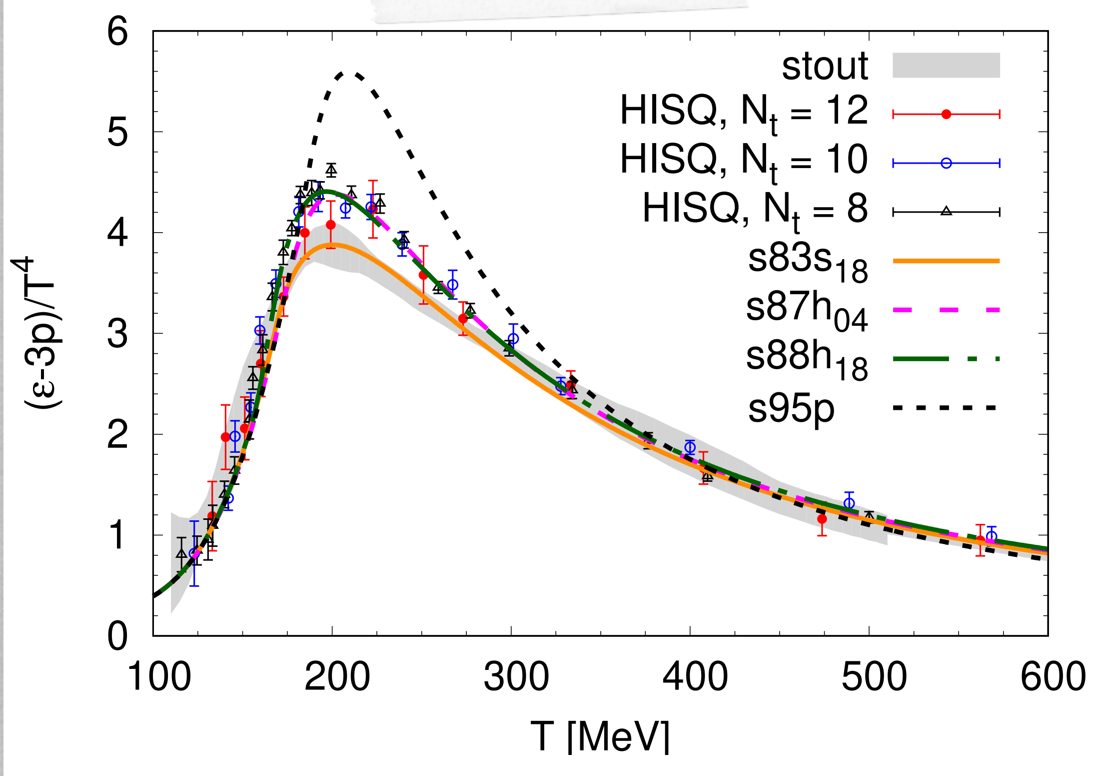
Phys. Rev. C **102**, 044911 (2020) [arXiv:2006.12499]

1. Three new equations of state

- Serve as updates for the well-known **s95p** EoS [1]
- Match hadron resonance gas at low T, lattice data at high T
- Each parametrization uses different PDG summary tables for HRG and/or different lattice data, labeled as "stout" or "HISQ" based on the discretization scheme

Name	PDG	Lattice data
s83s18	2018	stout [2]
s87h04	2004	HISQ [3]
s88h18	2018	HISQ [3]



Trace anomaly comparison

2. Bayesian analysis with Gaussian process emulator

Model input (parameters): $\vec{x} = (x_1, \ldots, x_n)$ $[K_{\rm sat}, (\eta/s)_{\rm min}, T_{\rm H}, W_{\rm min}, S_{\rm HG}, S_{\rm QGP}, T_{\rm dec}, T_{\rm chem}]$

Model output $\vec{y} = (y_1, \ldots, y_m) \Leftrightarrow$ Experimental values $\vec{y}^{\rm exp}$ $[dN/dy, \langle p_T \rangle, v_2]$

Bayes' theorem: Posterior probability $\propto$ Likelihood · Prior knowledge

Prior knowledge: Range of input parameter values to investigate

Likelihood: $\mathcal{L}(\vec{x}) \propto \exp\left(-\frac{1}{2}(\vec{y}(\vec{x}) - \vec{y}^{\rm exp})\Sigma^{-1}(\vec{y}(\vec{x}) - \vec{y}^{\rm exp})^T\right)$

where Σ is the covariance matrix representing the uncertainties

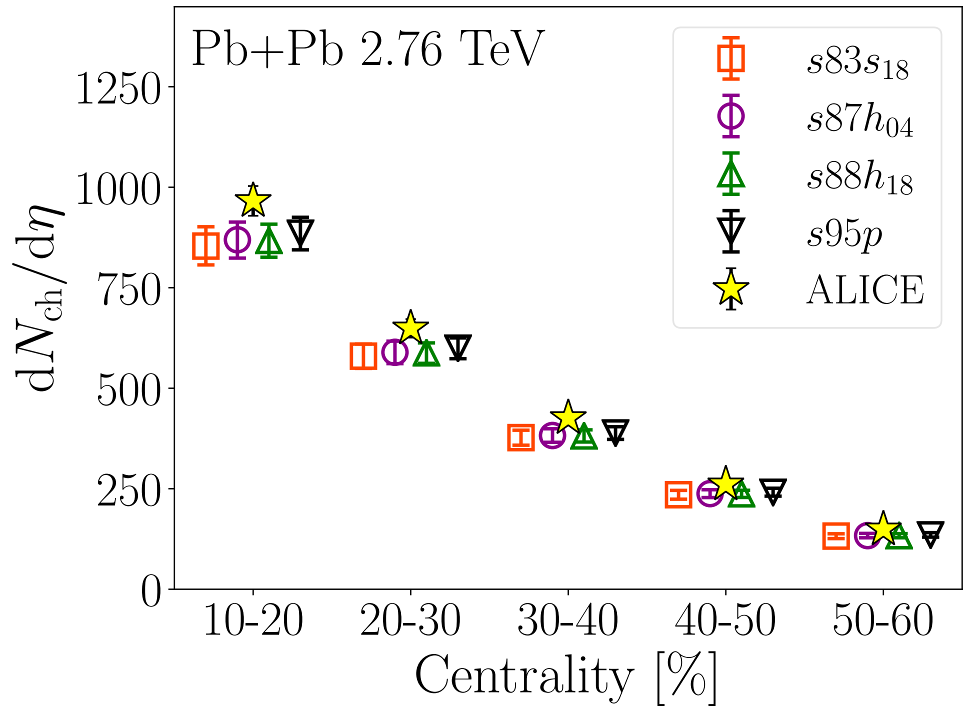
Use Gaussian Process (GP) emulator to quickly estimate $\vec{y}(\vec{x})$:

We establish a GP covariance matrix $\mathcal{C}_{A,B} = \{c(\vec{a}, \vec{b})\}, \vec{a} \in A, \vec{b} \in B$, by defining the covariance function

$$c(\vec{a}, \vec{b}) = \theta_0 \exp\left(-\sum_{i=1}^{n} \frac{(a_i - b_i)^2}{2\theta_i^2}\right) + \theta_{\rm noise}\delta_{\vec{a}\vec{b}}.$$

Knowing a set of model outputs U for a set of parameter combinations T, we can derive the GP conditional predictive mean and the associated covariance as $y^{\rm GP}(\vec{x}_0) = \mathcal{C}_{0,T}\mathcal{C}_{T,T}^{-1}U; \sigma^{\rm GP}(\vec{x}_0)^2 = \mathcal{C}_{0,0} - \mathcal{C}_{0,T}\mathcal{C}_{T,T}^{-1}\mathcal{C}_{T,0}$

Similar to [4], we use Markov chain Monte Carlo to sample the posterior probability: Random walk in input parameter space, constrained by the prior



Emulator estimates for posterior samples

3. Modeling the heavy ion collision

Initial energy density from the EKRT minijet saturation model [5]:

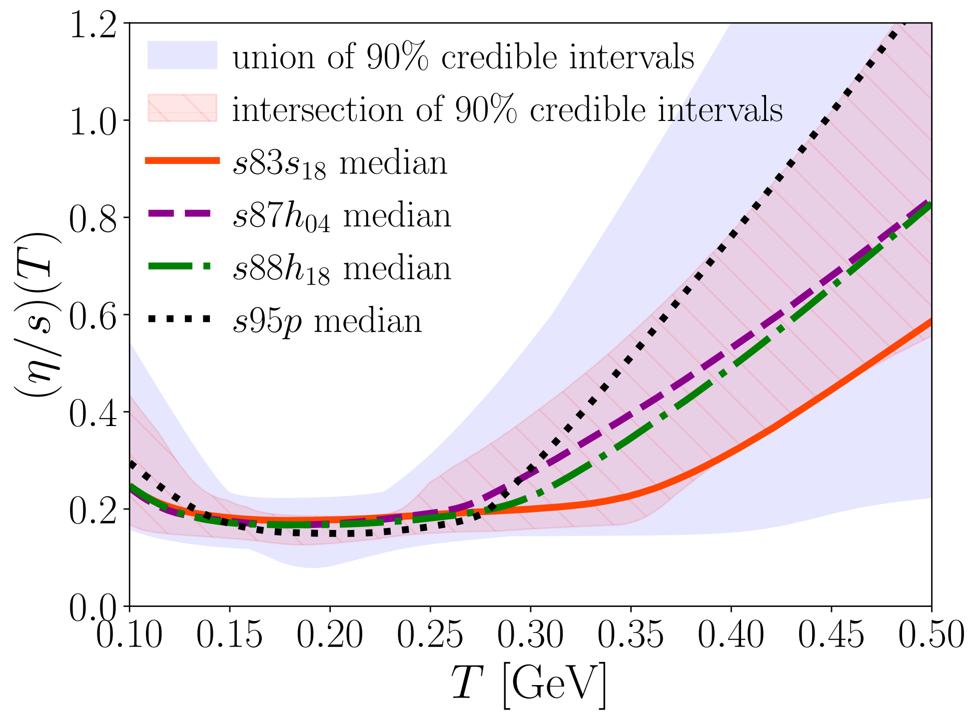
$$\epsilon(\vec{r}_T, \tau_s(\vec{r}_T)) = \frac{K_{\rm sat}}{\pi}[p_{sat}(\vec{r}_T, K_{\rm sat})]^4; \ \tau_s(\vec{r}_T) = 1/p_{\rm sat}(\vec{r}_T, K_{\rm sat})$$

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 [6] with a temperature dependent shear viscosity coefficent η/s

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

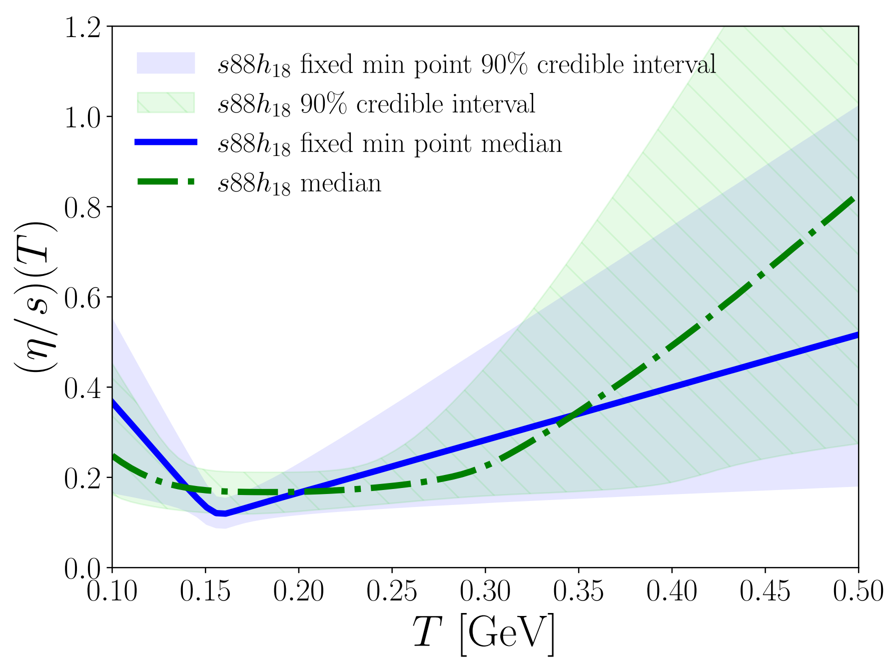
Kinetic decoupling temperature $T_{\rm dec}$ and chemical freeze-out temperature $T_{\rm chem}$ are also adjustable parameters



Uncertainties of $(\eta/s)(T)$

4. Summary of the results

- Tightest constraints on η/s in the temperature range $T \approx 150$--220 MeV; η/s approximately constant in this interval
- Accounting for all four EoSs: $0.08 < \eta/s < 0.23$
- Only s83s18 and s88h18: $0.12 < \eta/s < 0.23$
- Restricting the η/s minimum to a point leads to a smaller minimum value
- Differences due to equations of state within uncertainties



Minimum point vs. plateau

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