New constraints for QCD matter from improved Bayesian parameter estimation

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Significant progress has happened in modeling heavy-ion collisions.

**Color Glass Condensate** + **Causal Hydrodynamics** + **Hadronic Gas Cascade**

The multi-stage phenomenological models contain 10 to 20 parameters,

Two most interesting ones are $\eta/s$ and $\zeta/s$.

It is essential to include independent new observables and improve the precision of the measurements.
New flow harmonic observables in Bayesian analysis

\[ \frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos [n(\varphi - \psi_n)] \]

Flow harmonics, \((v_n, \psi_n)\), depend on the initial state parameters, transport coefficients \((\eta/s, \zeta/s, \ldots)\), ...

<table>
<thead>
<tr>
<th>Observable</th>
<th>Inputs of the analysis (e.g. (\rightarrow))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-harmonic observables [1, 2]</td>
<td>(v_2{2}, \ldots, v_7{2})</td>
</tr>
<tr>
<td>Symmetric cumulants [3]</td>
<td>NSC((2, 3)), NSC((2, 4)), NSC((3, 4))</td>
</tr>
<tr>
<td>Higher-order symmetric cumulants [4]</td>
<td>NSC((2, 3, 4)), NSC((2, 3, 5))</td>
</tr>
<tr>
<td>Symmetry plane correlations [2,5]</td>
<td>(\rho_{4,22}, \rho_{5,23}, \rho_{6,222}, \rho_{6,33})</td>
</tr>
<tr>
<td>Non-linear mode couplings [2,6]</td>
<td>(\chi_{4,22}, \chi_{5,23}, \chi_{6,222}, \chi_{6,33})</td>
</tr>
</tbody>
</table>

We use the same model, $T_{\text{ren}} + \text{VISH}(2+1) + \text{UrQMD}$ for Pb–Pb collision, as Ref. [1] to manifest the importance of including the new observables and improving the accuracy.

**Significant improvement in uncertainties, especially in bulk viscosity.**

The energy dependence of $v_2$.

- Deviation from simulation and data in NSC(2,4) and NSC(2,3,5).
- Poor agreement for $v_6$, $v_7$, $v_8$, $v_9$, especially $v_8$.
- Wrong energy ordering for $\rho_{6,222}$.
Higher harmonics, higher order observables have more sensitivity to $\eta/s$ and $\zeta/s$.

Summary: • Higher-order transport coefficients are very sensitive to the higher-order flow observables, revealing the importance of their precision measurements. • Including the latest flow harmonic measurements, we have improved the uncertainty of estimated values for $\eta/s$ and $\zeta/s$. • Despite using the new observables as inputs to extract model parameters, there are remaining discrepancies between model and experimental measurements.
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### MAP Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range</th>
<th>MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(2.76 TeV)</td>
<td>Overall normalization (2.76 TeV)</td>
<td>[11.152, 18.960]</td>
<td>14.373</td>
</tr>
<tr>
<td>N(5.02 TeV)</td>
<td>Overall normalization (5.02 TeV)</td>
<td>[16.542, 25]</td>
<td>21.044</td>
</tr>
<tr>
<td>$p$</td>
<td>Entropy deposition parameter</td>
<td>[0.0042, 0.0098]</td>
<td>0.0056</td>
</tr>
<tr>
<td>$\sigma_k$</td>
<td>Std. dev. of nucleon multiplicity fluctuations</td>
<td>[0.5518, 1.2852]</td>
<td>1.0468</td>
</tr>
<tr>
<td>$d_{\text{min}}^3$</td>
<td>Minimum volume per nucleon</td>
<td>[0.8893, 1.5243]</td>
<td>1.23673</td>
</tr>
<tr>
<td>$\tau_{\text{fs}}$</td>
<td>Free-streaming time</td>
<td>[0.03, 1.5]</td>
<td>0.71</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Temperature of const. $\eta/s(T), T &lt; T_c$</td>
<td>[0.135, 0.165]</td>
<td>0.141</td>
</tr>
<tr>
<td>$\eta/s(T_c)$</td>
<td>Minimum $\eta/s(T)$</td>
<td>[0, 0.2]</td>
<td>0.093</td>
</tr>
<tr>
<td>$(\eta/s)_{\text{slope}}$</td>
<td>Slope of $\eta/s(T)$ above $T_c$</td>
<td>[0, 4]</td>
<td>0.8024</td>
</tr>
<tr>
<td>$(\eta/s)_{\text{curve}}$</td>
<td>Curvature of $\eta/s(T)$ above $T_c$</td>
<td>$[-1.3, 1]$</td>
<td>0.1568</td>
</tr>
<tr>
<td>$(\zeta/s)_{\text{peak}}$</td>
<td>Temperature of $\zeta/s(T)$ maximum</td>
<td>[0.15, 0.2]</td>
<td>0.1889</td>
</tr>
<tr>
<td>$(\zeta/s)_{\text{max}}$</td>
<td>Maximum $\zeta/s(T)$</td>
<td>[0, 0.1]</td>
<td>0.01844</td>
</tr>
<tr>
<td>$(\zeta/s)_{\text{width}}$</td>
<td>Width of $\zeta/s(T)$ peak</td>
<td>[0, 0.1]</td>
<td>0.04252</td>
</tr>
<tr>
<td>$T_{\text{switch}}$</td>
<td>Switching / particlization temperature</td>
<td>[0.135, 0.165]</td>
<td>0.1595</td>
</tr>
</tbody>
</table>

\[
(\eta/s)(T) = (\eta/s)(T_c) + (\eta/s)_{\text{slope}}(T - T_c) \left( \frac{T}{T_c} \right)^{(\eta/s)_{\text{curve}}}, \quad \frac{(\zeta/s)(T)}{1 + \left( \frac{T - (\zeta/s)_{\text{peak}}}{(\zeta/s)_{\text{width}}} \right)^2}.
\]
MAP parametrization

ALICE PbPb

TRENTo+VISH(2+1)+UrQMD

\[
\begin{align*}
\text{dN}_{\text{ch}}/d\eta & \quad \text{100} \\
\text{p} & \quad \text{10} \\
\pi \times 0.5 & \quad \text{10} \\
K & \quad \text{10} \\
\text{Charged} & \quad \text{10} \\
\text{5.02 TeV} & \quad \text{10} \\
\text{2.76 TeV} & \quad \text{10}
\end{align*}
\]

\[
\begin{align*}
\text{Ratio} & \quad \text{0} \\
\text{Centrality (%)} & \quad \text{0} \\
\text{Centrality (%)} & \quad \text{0}
\end{align*}
\]
Posterior distribution

N(2.76 TeV) 14.1 ± 1.2
N(5.02 TeV) 20.2 ± 1.8

p 0.006 ± 0.002
w [fm] 0.8 ± 0.1

d [fm] min 1.27 ± 0.23
fs [fm/c] 0.89 ± 0.38
slope [GeV/s] 0.145 ± 0.014

Tc [GeV] 0.106 ± 0.030

crv [GeV/s] 0.159 ± 0.005

T switch [GeV] 1.30 ± 0.15

model sys 0.09 ± 0.09

Slope [GeV/s] 0.135 ± 0.013

Width [GeV] 0.043 ± 0.030

0.0 0.2 0.4