New constraints for QCD matter from improved Bayesian parameter estimation

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Quark Matter
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Introduction

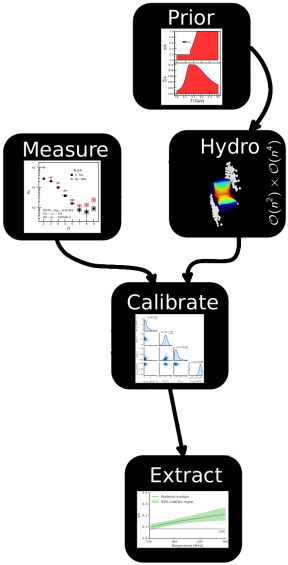
Significant progress has happened in modeling heavy-ion collisions.

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

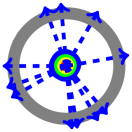
The multi-stage phenomenological models contain 10 to 20 parameters,

Two most interesting ones are η/s and ζ/s.

It is essential to include independent new observables and improve the precision of the measurements.



New flow harmonic observables in Bayesian analysis



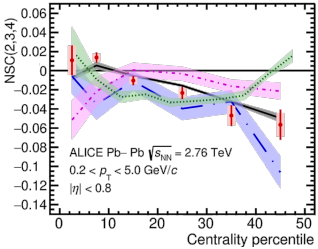
$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos\left[n(\varphi - \psi_n)\right]$$

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

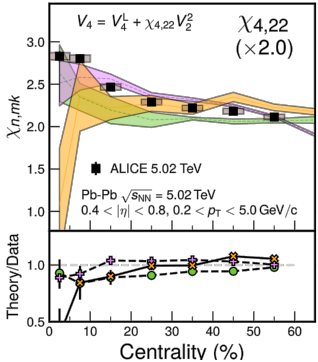
Observable	**Inputs of the analysis** (e.g. →)
Single-harmonic observables [1, 2]	$v_2\{2\}, \ldots, v_7\{2\}$
Symmetric cumulants [3]	$\mathrm{NSC}(2,3)$, $\mathrm{NSC}(2,4)$, $\mathrm{NSC}(3,4)$
Higher-order symmetric cumulants [4]	$\mathrm{NSC}(2,3,4)$, $\mathrm{NSC}(2,3,5)$
Symmetry plane correlations [2,5]	$\rho_{4,22}$, $\rho_{5,23}$, $\rho_{6,222}$, $\rho_{6,33}$
Non-linear mode couplings [2,6]	$\chi_{4,22}$, $\chi_{5,23}$, $\chi_{6,222}$, $\chi_{6,33}$

[1] Borghini, et al., PRC 64 (2001) 054901, ALICE Collaboration, PRL, 107 (2011) 032301, ALICE Collaboration, PRL, 116 (2016) 13, 132302.
[2] ALICE Collaboration, JHEP 05 (2020) 085, ALICE Collaboration, 773 (2017) 68-80.
[3] Bilandzic, et al., PRC 89 (6) (2014) 064904, ALICE Collaboration, PRC 97 (2018) 2, 024906, PRL, 117 (2016) 182301.
[4] Mordasini, et al., PRC 102 (2) (2020) 024907, ALICE Collaboration, PRL, 127 (2021) 9, 092302.
[5] Bhalerao, et al., PLB, 742 (2015) 94-98, Yan, et al. PLB, 744 (2015) 82-87, (see poster T07_1).
[6] Qiu, et al., PLB, 717 (2012) 261-265, ATLAS Collaboration, PRC, 90 (2014) 2, 024905.

Ref. [4]



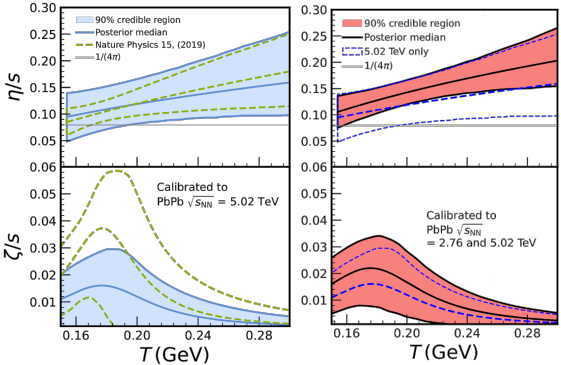
Ref. [2]

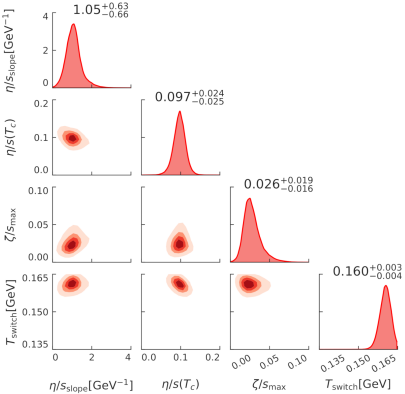


Shear and Bulk viscosity in the light of new observables

- We use the same model, T$_R$ENTo + VISH(2+1) + 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.

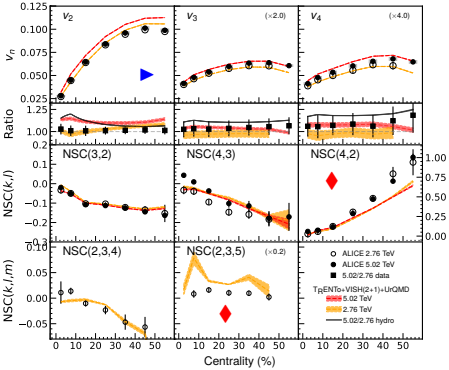


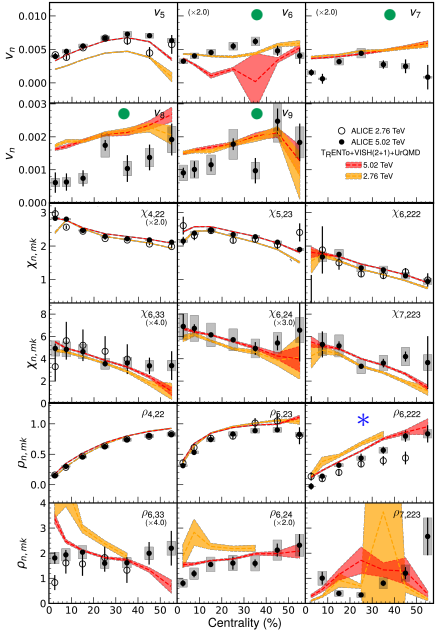


[1] Bernhard, et al., Nature Phys. 15 (2019) 11, 1113-1117.

Maximum A Posteriori parametrization

Overall agreement, with only few discrepancies



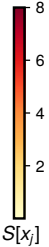


- ▶ The energy dependence of v_2.
- ♦ Deviation from simulation and data in NSC$(2,4)$ and NSC$(2,3,5)$.
- ● Poor agreement for v_6, v_7, v_8, v_9, especially v_8.
- ∗ Wrong energy ordering for $\rho_{6,222}$.

Sensitivity of the input parameters

Sensitivity of an observable $\hat{O}$ to the parameter x_i, $S[x_i] := |\hat{O}(\vec{x}') - \hat{O}(\vec{x})|/\delta\hat{O}(\vec{x})$ **[JETSCAPE, PRC, 103, 054904 (2021)]**

	$dN_{ch}/d\eta$	$dN_{p^\pm}/d\eta$	$\langle p_{T,\pi^\pm}\rangle$	$\langle p_{T,K^\pm}\rangle$	$\langle p_{T,p^\pm}\rangle$	v_2	v_3	v_4	v_5	$\chi_{4,22}$	$\chi_{5,23}$	$\chi_{6,222}$	$\chi_{6,33}$	$\rho_{4,22}$	$\rho_{5,23}$	$\rho_{6,222}$	$\rho_{6,33}$	NSC(3, 2)	NSC(4, 2)	NSC(4, 3)	NSC(2, 3, 4)*	NSC(2, 3, 5)*	NSC(2, 4, 6)*
τ_{fs}	0.00	0.17	1.05	1.01	0.85	0.60	1.42	2.36	3.94	0.09	0.77	0.30	1.46	1.25	1.26	1.98	1.44	0.65	6.25	12	30	2.07	40
$(\eta/s)_{slope}$	0.00	0.14	0.19	0.19	0.18	0.49	1.43	2.10	3.30	0.26	0.13	0.81	0.85	1.74	1.37	3.03	1.36	0.70	7.02	1.70	34	30	1.06
T_c	0.00	0.25	0.03	0.03	0.04	0.18	0.46	0.48	0.37	0.32	0.55	0.83	0.93	0.80	0.40	0.45	0.61	0.41	3.53	1.44	4.46	7.15	0.21
$\eta/s(T_c)$	0.00	0.08	0.22	0.21	0.14	1.65	3.29	4.87	6.00	0.95	3.84	2.92	5.44	2.53	1.27	2.85	2.76	1.61	15	9.80	22	29	14
$(\eta/s)_{crv}$	0.00	0.17	0.05	0.05	0.05	0.19	0.38	0.53	0.69	0.20	0.36	0.55	0.69	0.40	0.40	0.73	0.75	0.13	1.81	4.72	2.20	8.41	6.17
$(\zeta/s)_{peak}$	0.01	0.44	1.16	1.01	0.73	2.26	2.67	3.79	6.40	0.59	0.32	1.48	1.11	0.34	1.59	1.04	1.15	1.49	1.49	2.57	3.74	2.04	15
$(\zeta/s)_{max}$	0.00	0.07	1.05	0.96	0.77	0.37	0.13	0.12	0.37	0.20	0.01	0.53	1.12	0.52	0.64	1.26	0.59	0.44	1.43	3.00	3.02	1.58	2.91
$(\zeta/s)_{width}$	0.00	0.01	0.20	0.15	0.07	0.19	0.04	0.09	0.33	0.09	0.26	0.40	1.69	0.39	1.66	1.55	1.35	0.38	1.41	1.21	1.77	23	19
T_{switch}	0.01	1.34	0.25	0.21	0.16	1.30	3.51	4.64	5.86	0.77	0.45	2.03	3.34	3.95	2.42	1.98	1.00	1.96	17	13	4.08	0.47	6.22



Higher harmonics, higher order observables have more sensitivity to η/s and ζ/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 η/s and ζ/s. ● Despite using the new observables as inputs to extract model parameters, there are remaining discrepancies between model and experimental measurements.

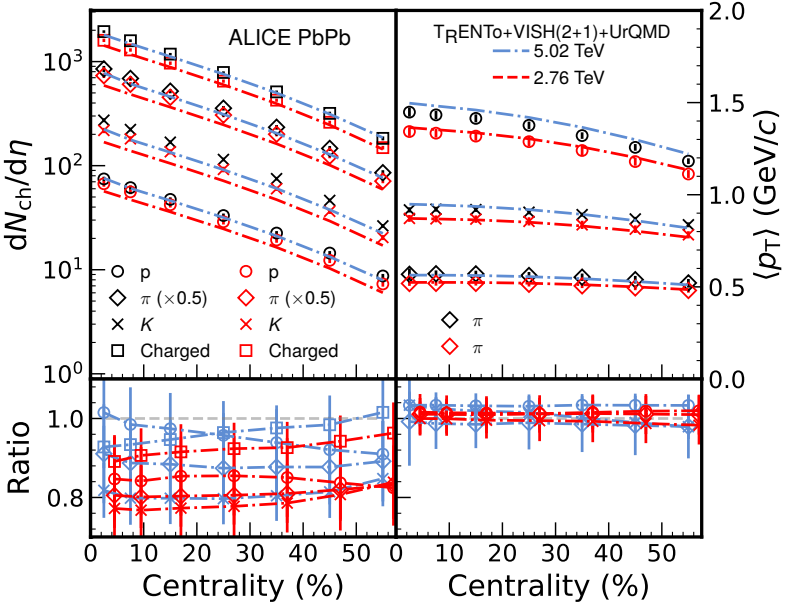
Backup Slides

MAP parameters

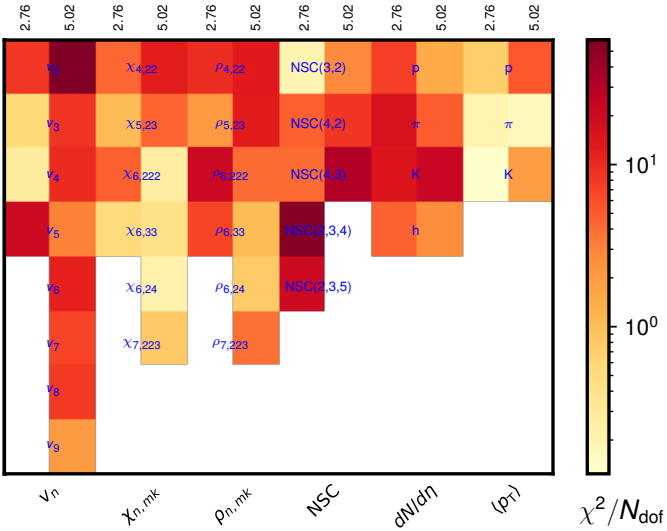
Parameter	Description	Range	MAP
N(2.76 TeV)	Overall normalization (2.76 TeV)	[11.152, 18.960]	14.373
N(5.02 TeV)	Overall normalization (5.02 TeV)	[16.542, 25]	21.044
p	Entropy deposition parameter	[0.0042 , 0.0098]	0.0056
σ_k	Std. dev. of nucleon multiplicity fluctuations	[0.5518, 1.2852]	1.0468
$d^3_{\rm min}$	Minimum volume per nucleon	$[0.889^3, 1.524^3]$	1.2367^3
$\tau_{\rm fs}$	Free-streaming time	[0.03, 1.5]	0.71
T_c	Temperature of const. $\eta/s(T)$, $T < T_c$	[0.135, 0.165]	0.141
$\eta/s(T_c)$	Minimum $\eta/s(T)$	[0, 0.2]	0.093
$(\eta/s)_{\rm slope}$	Slope of $\eta/s(T)$ above T_c	[0, 4]	0.8024
$(\eta/s)_{\rm curve}$	Curvature of $\eta/s(T)$ above T_c	$[-1.3, 1]$	0.1568
$(\zeta/s)_{\rm peak}$	Temperature of $\zeta/s(T)$ maximum	[0.15, 0.2]	0.1889
$(\zeta/s)_{\rm max}$	Maximum $\zeta/s(T)$	[0, 0.1]	0.01844
$(\zeta/s)_{\rm width}$	Width of $\zeta/s(T)$ peak	[0, 0.1]	0.04252
$T_{\rm switch}$	Switching / particlization temperature	[0.135, 0.165]	0.1595

$$(\eta/s)(T) = (\eta/s)(T_c) + (\eta/s)_{\rm slope}(T - T_c)\left(\frac{T}{T_c}\right)^{(\eta/s)_{\rm curve}}, \qquad (\zeta/s)(T) = \frac{(\zeta/s)_{\rm max}}{1 + \left(\frac{T-(\zeta/s)_{T_{\rm peak}}}{(\zeta/s)_{\rm width}}\right)^2}.$$

MAP parametrization



Chi-square


2.76
5.02
v_2
v_3
v_4
v_5
v_6
v_7
v_8
v_9
$\chi_{4,22}$
$\chi_{5,23}$
$\chi_{6,222}$
$\chi_{6,33}$
$\chi_{6,24}$
$\chi_{7,223}$
$\rho_{4,22}$
$\rho_{5,23}$
$\rho_{6,222}$
$\rho_{6,33}$
$\rho_{6,24}$
$\rho_{7,223}$
NSC(3,2)
NSC(4,2)
NSC(4,3)
NSC(2,3,4)
NSC(2,3,5)
p
π
K
h
10^1
10^0
v_n
$\chi_{n,mk}$
$\rho_{n,mk}$
NSC
dN/dη
$\langle p_T \rangle$
χ^2/N_{dof}

Posterior distribution