The role of theory in understanding experimental heavy ion data

Govert Nijs

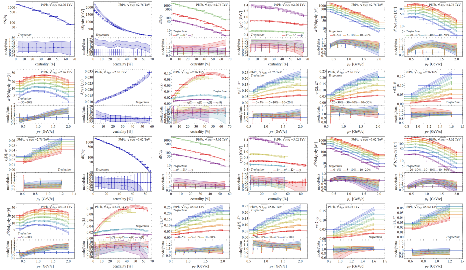
February 16, 2025

Based on:

- GN, van der Schee, 2312.04623
- Giacalone, GN, van der Schee, 2305.00015
- Giacalone, Bally, GN, Shen, Duguet, Ebran, Elhatisari, Frosini, Lähde, Lee, Lu, Ma, Meißner, Noronha-Hostler, Plumberg, Rodríguez, Roth, van der Schee, Somà, 2402.05995

A wealth of data

- Experiments have provided us with a wealth of data.
- However, it is not easy to infer quantities of theoretical interest directly from the data points.
- Over the past decade, *bayesian analysis* has helped bridge this gap.



- Requirements:
  - Theoretical models able to describe most aspects of collisions *simultaneously*.
  - Extensive computing facilities.
- Deliverables:
  - Theoretical quantities of interest, *including uncertainties*.
  - Predictions for observables not fitted to, *including systematic uncertainties*.

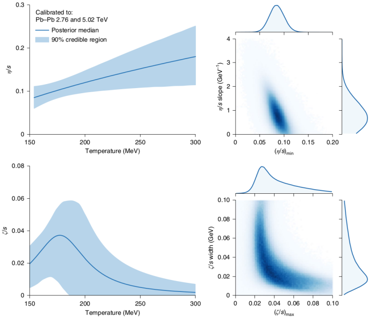
[GN, van der Schee, 2304.06191]

Theoretical modeling in heavy ions

- As mentioned, we need models able to describe most aspects of collisions *simultaneously*.
- Developing these models requires interaction with many fields:
  - Lattice QCD for the equation of state.
  - AdS/CFT for the shear viscosity.
  - Jet physics for hard probes.
  - Machine learning for Bayesian analyses.
  - ...
- Recently, this started to also include nuclear structure.
- The connection goes both ways:
  - We can use heavy ion data to extract interesting nuclear structure data.
  - We can exploit differently shaped nuclei to manipulate the shape of the QGP we produce.

Extraction of quantities of interest

- Using Bayesian analysis, we are able to extract important model parameters.
- Examples shown:
  - The temperature-dependent shear and bulk viscosities.
  - The neutron skin of ^{208}Pb.
  - The jet quenching parameter.
- Bayesian analysis not only gives us the best fit values, but also uncertainties.



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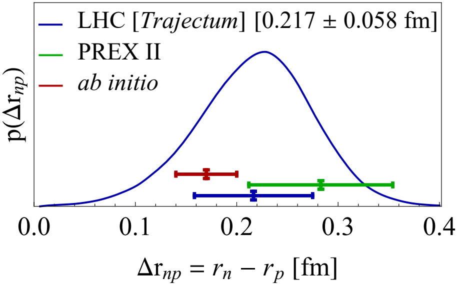

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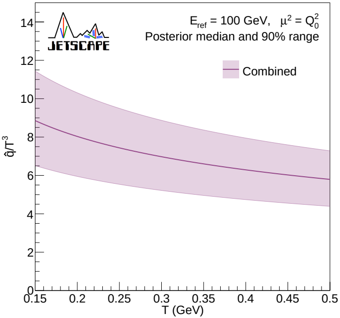
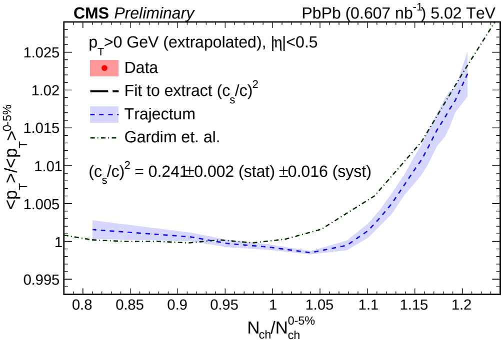


[Bernhard, Moreland, Bass, *Nature Phys.* **15**, 1113-1117 (2019); Giacalone, GN, van der Schee, 2305.00015; JETSCAPE, 2408.08247]

Using Bayesian analysis to make quantitative predictions

- The posterior parameter values can be used to make predictions for new observables.
  - This includes *systematic uncertainty* from the parameter estimation.
- Here shown is the prediction for ultracentral $\langle p_T \rangle$.



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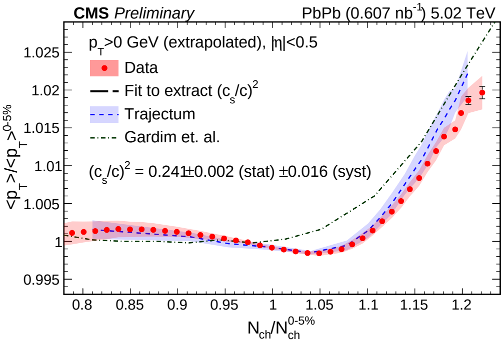
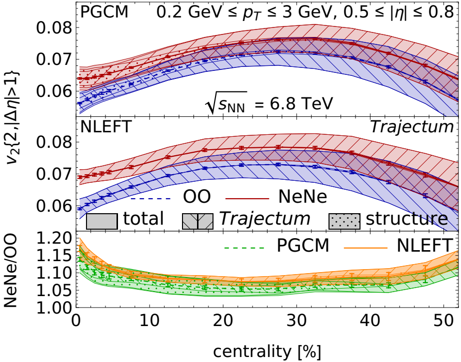
- Here shown is the prediction for ultracentral $\langle p_T \rangle$.
- Precise agreement between theory and experiment.



Identifying new opportunities

- Detailed analysis of systematic uncertainties can identify observables under good theoretical control.
- In the case shown, the $v_2\{2\}$ ratio between ^{20}Ne and ^{16}O reaches percent level precision.
- This identifies new opportunities to explore small systems.



0–1%	$v_2\{2\}_{\mathrm{NeNe}}/v_2\{2\}_{\mathrm{OO}}$
NLEFT	$1.170(8)_{\mathrm{stat.}}(30)^{Traj.}_{\mathrm{syst.}}(0)^{\mathrm{str.}}_{\mathrm{syst.}}$
PGCM	$1.139(6)_{\mathrm{stat.}}(27)^{Traj.}_{\mathrm{syst.}}(28)^{\mathrm{str.}}_{\mathrm{syst.}}$

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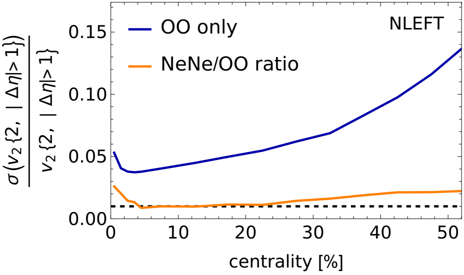

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