Recent results in particle production and flow from Bayesian analysis

Govert Nijs

June 22, 2023

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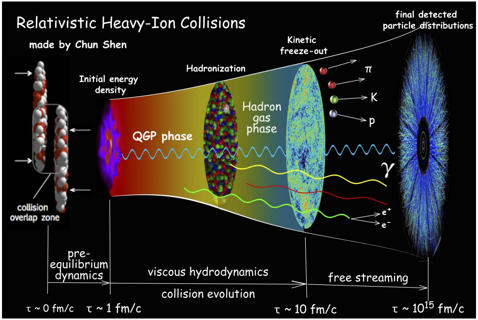
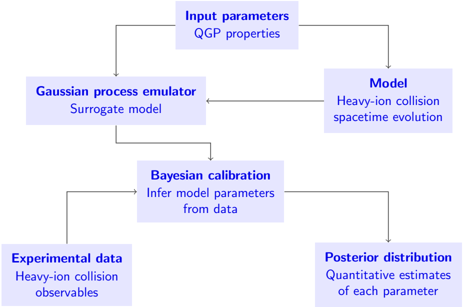
The status of the field

- The general picture of the stages of a heavy ion collision is known.
- Theoretical modelling follows these stages:
  - TRENTo or IP-Glasma for the initial state.
  - Free streaming for the pre-hydrodynamic stage.
  - Viscous hydrodynamics with temperature dependent shear and bulk viscosity.
  - SMASH or UrQMD as a hadronic afterburner.
- Bayesian analysis gives a data-driven approach to understand each stage in more detail.



Bayesian analysis workflow

- In principle, Bayesian analysis is simply a fit to data.
- In practice the process is more complicated:
  - Generate a large number of randomly chosen parameter sets called *design points*.
  - Run the model for each one to obtain the prior.
  - Train the emulator.
  - Run the MCMC to obtain the posterior.
- The posterior then is a list of likely parameter sets.



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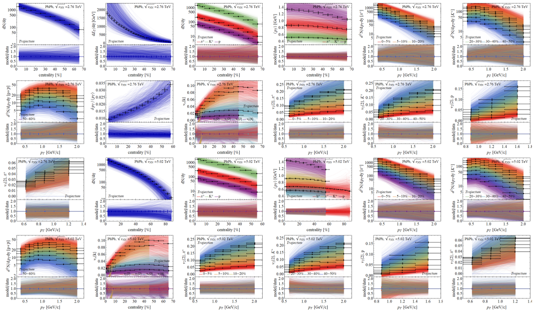

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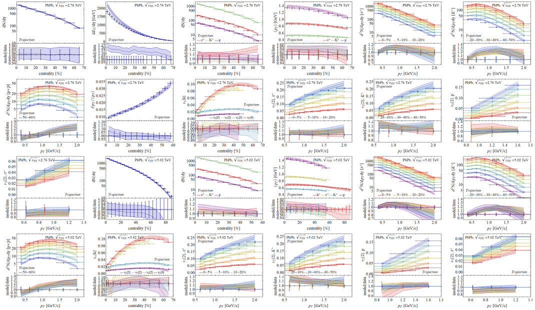

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[GN, van der Schee, 2304.06191; Giacalone, GN, van der Schee, 2305.00015]

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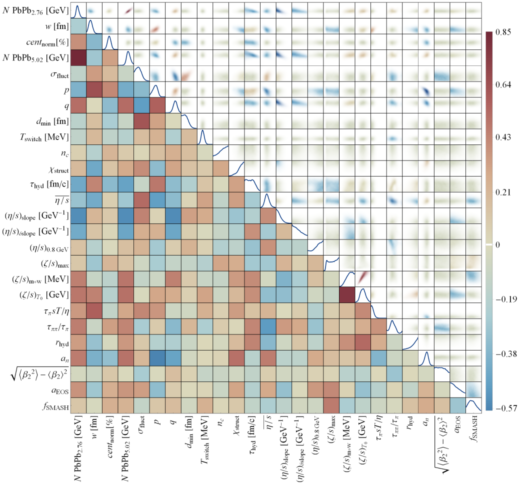
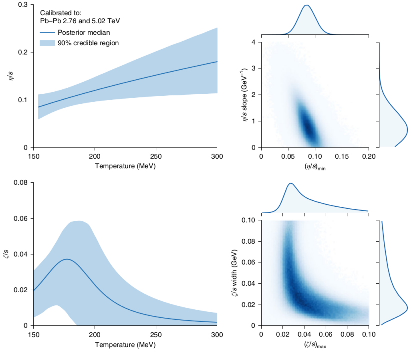


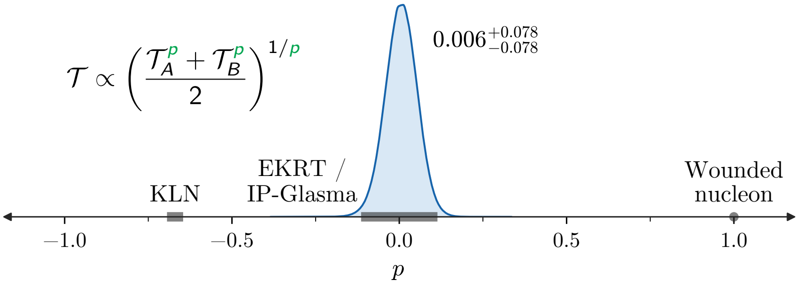
Uses of Bayesian analysis: viscosities

- We know the QGP phase is described by viscous hydrodynamics.
    - We know exactly what the free parameters are, i.e. η/s, ζ/s, ...
- We can use Bayesian analysis to find data-preferred values for these parameters.
- The values of the parameters provide an interface with microscopic theories of the QGP.



Uses of Bayesian analysis: parameterized phenomenology

$$\mathcal{T} \propto \left(\frac{\mathcal{T}_A^p + \mathcal{T}_B^p}{2}\right)^{1/p}$$



- For the initial state, there is no single widely accepted model.
- With a phenomenological model such as TRENTo, aspects of microscopic models can be tested, such as the scaling shown here, parameterized by p.
  - IP-Glasma and EKRT are ruled in.
  - KLN and wounded nucleon are ruled out.

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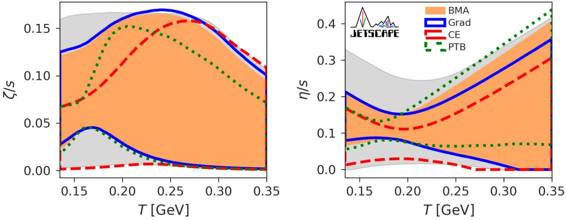
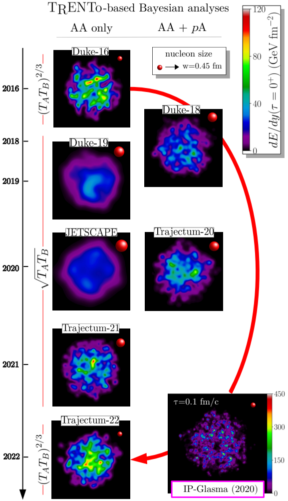
Uses of Bayesian analysis: deciding between models

- One can take this idea a step further, and actually compare different models.
- Here shown are different particlization schemes.
- By taking into account how well each model fits, one can even take a weighted average over models, known as *Bayesian model averaging*.



The history of TRENTo modelling in Bayesian analyses



- The TRENTo model is the most widely used for Bayesian analyses so far.
- Latest iteration has in some sense returned to the first iteration shown.
  - The nucleon has returned to a small size.
  - The energy deposition has gone back to $T^{00} \propto (\mathcal{T}_A \mathcal{T}_B)^{2/3}$.
- In this talk, I will cover this and other progress since 2021, including:
  - Improvements in the pre-hydrodynamic stage.
  - Bayesian analyses using IP-Glasma instead of TRENTo.
  - 3+1D Bayesian analyses.
  - Efforts to connect heavy ion collisions to nuclear structure.

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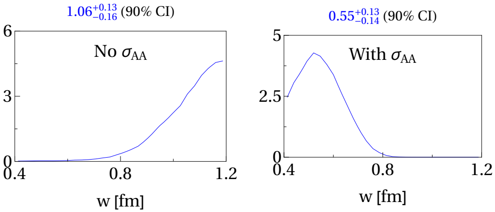
Fitting to the *p*Pb and PbPb cross sections

- In the TRENTo model, the nucleon size is described by the Gaussian radius w.
- Previous analyses favored $w \approx 1$ fm.
  - This leads to a 3σ discrepancy in σ_{PbPb}.
- Fitting to the *p*Pb and PbPb cross sections lowers w to 0.6 fm.
  - σ_{PbPb} discrepancy is reduced to 1σ.
  - Many other observables fit slightly worse.
- Smaller width is now compatible with our knowledge of the proton.



	σ_{PbPb} [b]	$\sigma_{p\text{Pb}}$ [b]
with σ_{AA}	8.02 ± 0.19	2.20 ± 0.06
without σ_{AA}	8.95 ± 0.36	2.48 ± 0.10
ALICE/CMS	7.67 ± 0.24	2.06 ± 0.08

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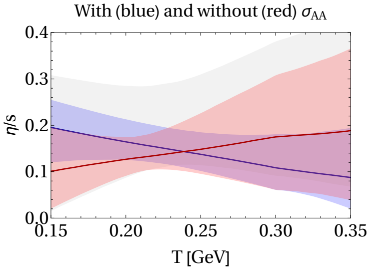
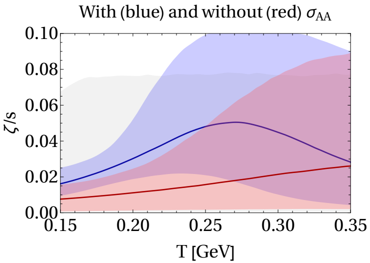
[GN, van der Schee, 2206.13522; ALICE, 2204.10148; ALICE-PUBLIC-2022-004; CMS, 1509.03893]

Implication for viscosities

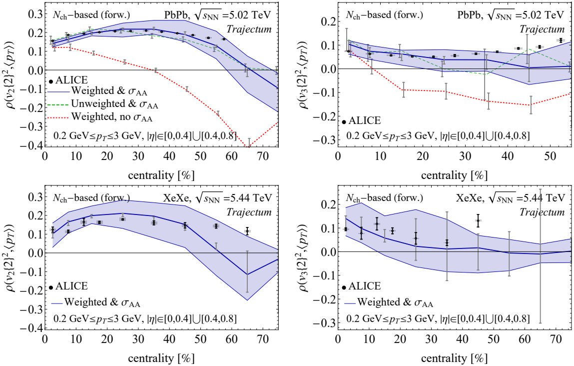




- Including σ_{AA} reverses the preferred slope of specific shear viscosity η/s.
  - Similar findings to IP-Glasma based Bayesian analysis.
- Bulk viscosity ζ/s increases when including σ_{AA}.
  - Smaller nucleons cause larger radial flow.
  - ζ/s increases to compensate so that $\langle p_T \rangle$ agrees with experiment.

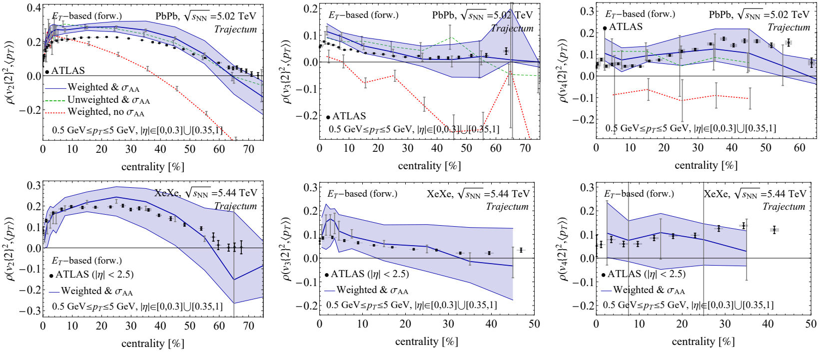
Implication for $\rho(v_2^2, \langle p_T \rangle)$ (ALICE)

- Pearson correlation coefficient $\rho(v_2^2, \langle p_T \rangle)$ between v_2^2 and $\langle p_T \rangle$ is sensitive to the nucleon size.
- Postdiction without fitting to σ_{AA} is qualitatively wrong:
  - $\rho(v_2^2, \langle p_T \rangle)$ goes negative already at 30% centrality.
  - $\rho(v_3^2, \langle p_T \rangle)$ has the wrong sign.
- Fitting to σ_{AA} results in a much improved agreement with ALICE.



[Giacalone, Schenke, Shen, 2111.02908; GN, van der Schee, 2206.13522]

Implication for $\rho(v_2^2, \langle p_T \rangle)$ (ATLAS)



- Still some tension with ATLAS:
  - Kinematic cuts are different.
  - Centrality determination is different.
  - Important to match the precise experimental procedure.

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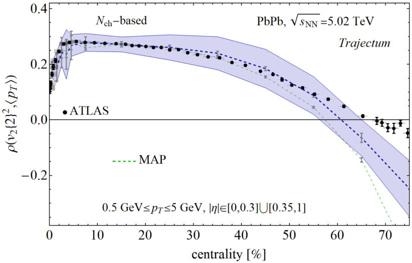
A detailed look at centrality

- Both ALICE and ATLAS determine centrality in the forward region.
- Detectors cannot resolve individual tracks.
  - ALICE signal is proportional to N_{ch}.
  - ATLAS signal is proportional to $\sum E_T$.
- Measurement is sensitive to these details.
- Here we compare using a centrality measurement based on charged tracks.
  - Tracks used have $0.5\,\text{GeV} \leq p_T \leq 5\,\text{GeV}$ and $|\eta| \leq 2.5$.
  - Enables an apples-to-apples comparision between theory and experiment.
  - Price to pay is autocorrelation, but this is present on both sides.



See poster S. Bhatta

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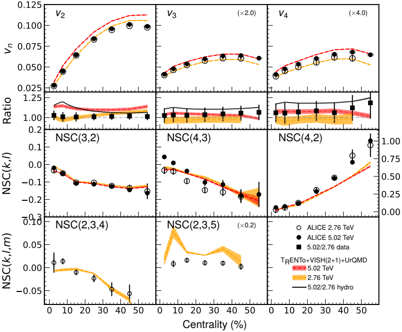
Fitting to ‘difficult’ observables

- We saw that fitting to new observables can lead to new insights.
- Which observables can be used is limited by statistics.
- Jyväskylä group has included several statistically difficult observables in their fit:
    - Normalized symmetric cumulants $NSC(n, m)$.
    - Non-linear flow coefficients $\chi_{k,lm}$.
    - Symmetry plane correlations $\rho_{k,lm}$.
- Latest *Trajectum* fit includes:
    - Normalized symmetric cumulants $NSC(n, m)$.
    - v_2^2–p_T correlator $\rho(v_2^2, \langle p_T \rangle)$.



See poster C. Mordasini

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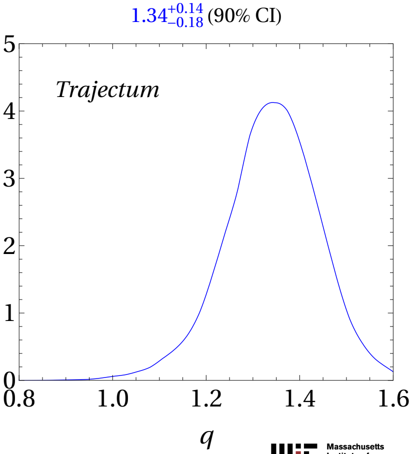
Energy deposition in the initial state

- Nuclear thickness functions $\mathcal{T}_{A/B}$ deposit matter into the initial state energy density $\mathcal{T}$ as follows:

$$\mathcal{T} \propto \left(\frac{\mathcal{T}_A^p + \mathcal{T}_B^p}{2}\right)^{q/p} \stackrel{p\to 0}{=} (\mathcal{T}_A\mathcal{T}_B)^{q/2}.$$

- Previous analyses implicitly set $q = 1$.
- The fit to experimental data favors $q \approx 4/3$.
  - Previous default $q = 1$ is disfavored.
  - Binary scaling $q = 2$ is ruled out.
  - $q = 4/3$ indicates that $\sqrt{\mathcal{T}_A\mathcal{T}_B}$ behaves like an entropy density.



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Comparison to IP-Glasma

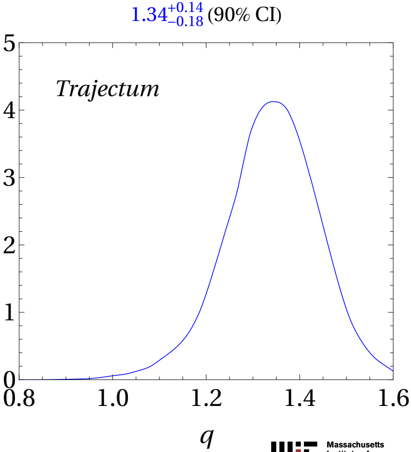
- IP-Glasma scales as follows:

$$\mathcal{T} \propto \frac{\mathcal{T}_A \mathcal{T}_B (2\mathcal{T}_A^2 + 7\mathcal{T}_A\mathcal{T}_B + 2\mathcal{T}_B^2)}{(\mathcal{T}_A + \mathcal{T}_B)^{5/2}}.$$

- This is not a limit of the modified TRENTo formula, but for $\mathcal{T}_A \approx \mathcal{T}_B$ it reduces to

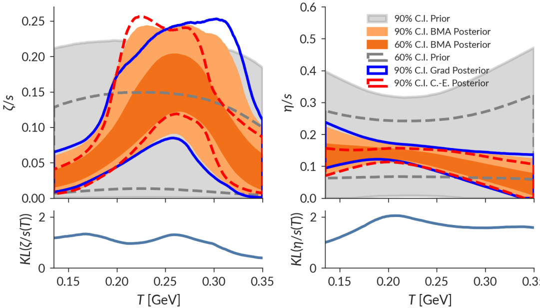
$$\mathcal{T} \propto (\mathcal{T}_A \mathcal{T}_B)^{3/4}.$$

- This corresponds to $q = 1.5$, which is compatible with the posterior.
- In the future, one could explicitly use the full formula and test whether that is preferred.



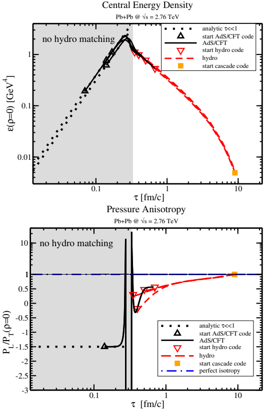
Replacing TRENTo by IP-Glasma

- TRENTo is only a phenomenological model, whereas IP-Glasma is microscopically motivated.
- Results for viscosities are similar to latest analyses using TRENTo.
- Interestingly, the slope of η/s is negative.
  - Also seen in latest TRENTo analysis.
  - Could potentially be related to nucleon size, which is small in both analyses.



Fast hydrodynamization

- AdS/CFT simulations of the initial stage suggest *fast hydrodynamization*:
  - $\pi^{\mu\nu} = 2\eta\sigma^{\mu\nu}$ applies quickly after the initial interaction.
  - By analogy, in a strongly coupled setting we expect $\Pi = -\zeta\nabla \cdot u$ to also apply quickly.
- In free streaming however, the initialization of $\pi^{\mu\nu}$ and Π is qualitatively different.
  - Free streaming absolute value of shear stress $|\pi| \equiv \sqrt{\pi^{\mu}_{\mu}}$ is larger than the strongly coupled result.
  - Free streaming bulk pressure Π is much smaller than the strongly coupled result, and has a different sign.



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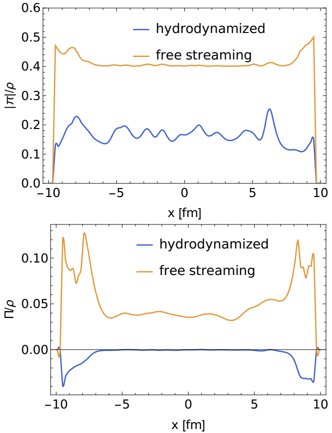
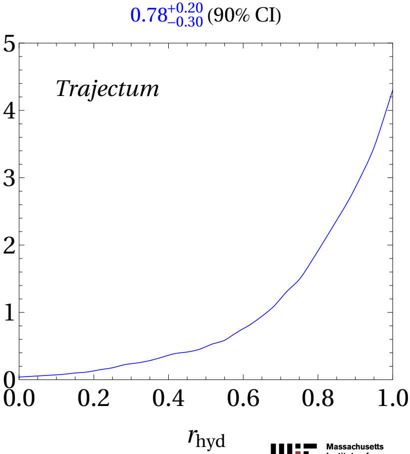


Weak vs. strong coupling in the pre-hydrodynamic stage

- From our two models, we obtain two stress tensors:
  - $T^{\mu\nu}_{\rm fs}$ from free streaming (no interactions).
  - $T^{\mu\nu}_{\rm hyd}$ from the hydrodynamized solution (strong coupling).
- Previous analyses used $T^{\mu\nu}_{\rm fs}$.
- We interpolate with a new parameter $r_{\rm hyd}$:

$$T^{\mu\nu} = r_{\rm hyd}\, T^{\mu\nu}_{\rm hyd} + (1 - r_{\rm hyd})\, T^{\mu\nu}_{\rm fs}.$$

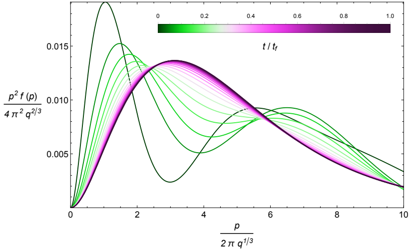
- $r_{\rm hyd} = 1$ is strongly favored over $r_{\rm hyd} = 0$, indicating a preference for strong coupling.



Adiabatic hydrodynamization

See posters K. Boguslavski; A. Mikheev; V. Nugara

- In most microscopic descriptions of the pre-hydrodynamic stage, hydrodynamization is driven by *attractor* solutions.
- Adiabatic hydrodynamization shows promise as a powerful framework to describe attractors.
- Work is ongoing to incorporate such an attractor solution into *Trajectum*, which will result in an updated Bayesian analysis.



See parallel R. Steinhorst Tue. 17:10

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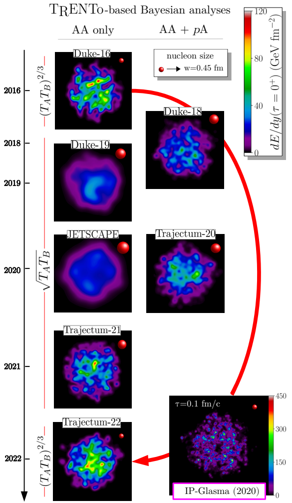
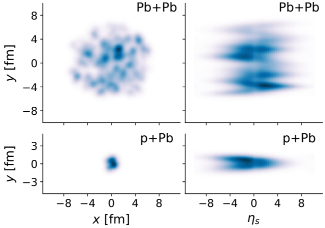
Beyond boost invariance



- We now look at some analyses outside of this timeline.
- Most Bayesian analyses so far have been assuming boost invariance.
- One analysis by the Duke group exists, but it is from 2016.
  - Much progress has happened since then.
  - An update would be timely.

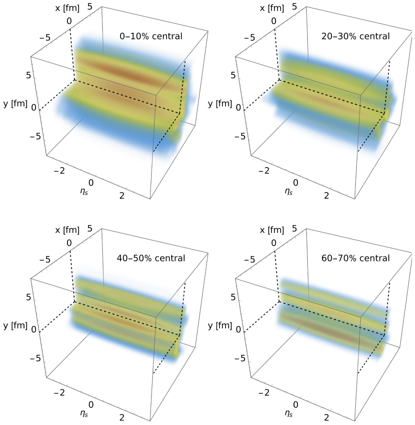


Longitudinal fluctuations

- With *Trajectum*, we took the Duke ansatz and added extra longitudinal fluctuations in energy deposition.
  - Nucleons deposit energy into thickness functions as

$$\mathcal{T}_{A/B} = \sum_{\text{wounded}} \gamma \exp\left(-|\mathbf{x} - \mathbf{x}_i|^2/2w^2\right),$$

    with γ drawn from a Gamma distribution.
  - We replace $\gamma \to \gamma(\eta_s)$, where $\gamma(\eta_s^A)$ and $\gamma(\eta_s^B)$ are correlated as $\exp(-|\eta_s^A - \eta_s^B|/\eta_{\text{corr}})$.
  - The correlation length η_{corr} is a new parameter to be varied in the Bayesian analysis.
- Bayesian analysis is underway!



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[Giacalone, GN, van der Schee, to appear]

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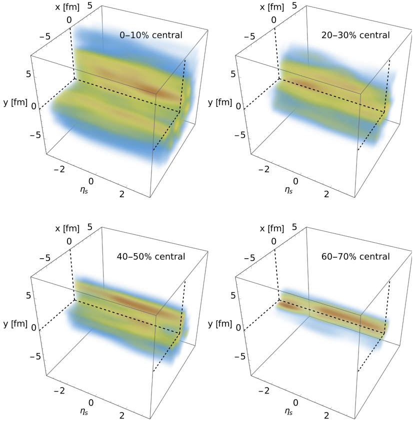

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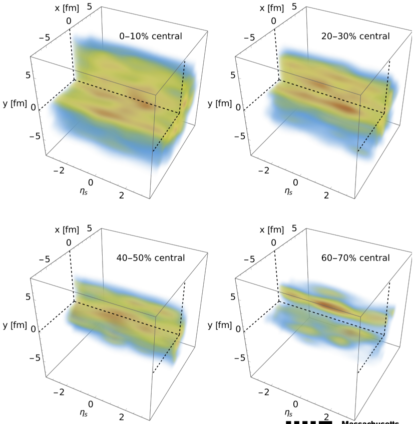

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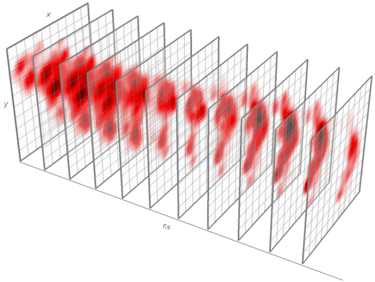
Fireball and fragmentation

- The Duke group extended the TRENTo model to 3+1D by considering a *fireball* part and a *fragmentation* part.
- In the present analysis linearized hydrodynamics was used.
- Full model Bayesian analysis in progress.



See parallel, D. Soeder Tue. 16:10

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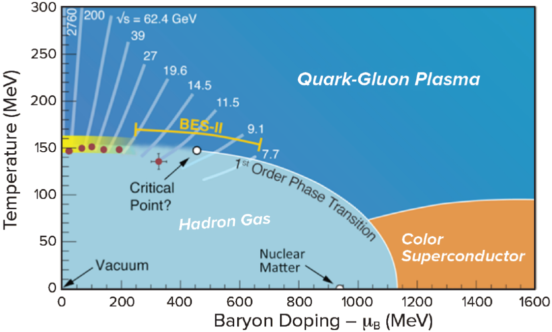
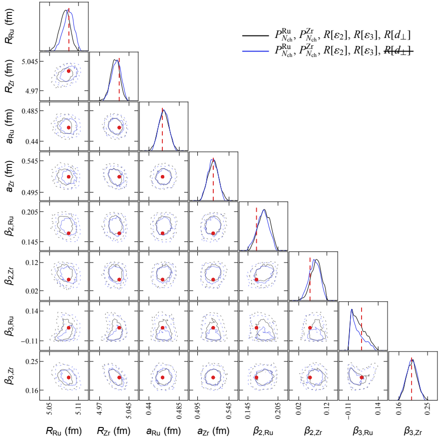
Jumping to the other side of the phase diagram

- Heavy ion collisions take place at $T \gg \mu_B$.
- The nuclei we collide exist at $T \ll \mu_B$.
- The structure of the nuclei leaves an observable imprint in heavy ion collisions.
    - Heavy ion collisions become a new laboratory for dense nuclear matter.
    - Shapes of nuclei can be inferred.
    - We can infer neutron star properties.



Isobars: a first step

- We show a Bayesian fit to *initial state quantities* known to correlate well with $dN/d\eta$, $\langle p_T \rangle$, v_2 and v_3.
- Size R, skin depth a and deformation parameters β_n can be extracted.
- This is a first step:
  - The fit is to the model itself, a *closure test*.
  - Only the initial state is modelled, not a full hydro model.
  - Full hydro for isobars is expensive, would need statistical trick to be viable.



See parallel M. Luzum Tue. 15:20; poster Y. Cheng

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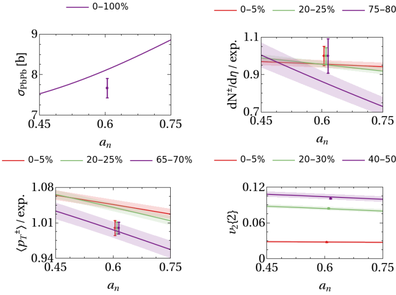
[Cheng, Shi, Ma, Stöcker, Zhou, 2301.03910]

Neutron skin

- In a ^{208}Pb nucleus, neutrons sit further from the center than protons.
  - This is quantified by the *neutron skin*:

$$\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}.$$

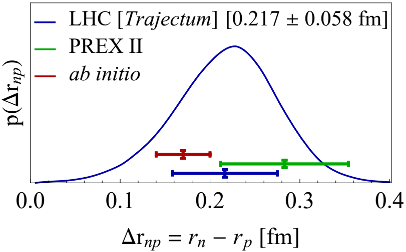
  - The proton distribution is well known from electron scattering.
  - The neutron distribution is harder to pin down.
- We vary the Woods-Saxon skin depth parameter for neutrons a_n in a Bayesian analysis.
  - In the emulator we can see that various observables are sensitive to a_n.

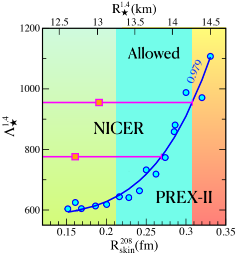


Neutron skin determined from LHC data

- Shown is the posterior for the value of the ^{208}Pb neutron skin.
  - Value obtained is compatible with PREX II and ab initio nuclear theory.
  - Slightly stronger constraint than PREX II ($\Delta r_{np} = 0.283 \pm 0.071$).
- Inferred value for the neutron skin has direct implications for the radius of a 1.4 $M_{\odot}$ neutron star.
- Completely orthogonal method to other measurements.

See plenary G. Giacalone Wed. 9:30





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Outlook

- Many active groups working on Bayesian analysis:
  - Duke,
  - JETSCAPE,
  - *Trajectum*,
  - Jyväskylä,
  - . . .
- Many insights gained from Bayesian analysis:
  - Size of nucleons.
  - Energy deposition in the initial state.
  - Nature of the pre-hydrodynamic stage.
  - Values of viscosities, temperature dependence.
  - Freeze-out prescriptions.
  - . . .
- Many questions are still open, and Bayesian analysis will remain essential to answer them!

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