Determination of the neutron skin of $^{208}$Pb from ultrarelativistic nuclear collisions

Giuliano Giacalone

Institut für Theoretische Physik (ITP)
Universität Heidelberg

June 30, 2023

Based on:
arXiv:2305.00015

In collaboration with:
Govert Nijs (MIT)
Wilke van der Schee (CERN/Utrecht)

Neutron Rich Matter on Heaven and Earth
June 26, 2023 - June 30, 2023
Recent focus: connecting low-energy nuclear structure to high-energy nuclear collisions.
OUTLINE

1 – Nuclear collisions at high energy.

2 – Hydrodynamic model of heavy-ion collisions.

3 – Bayesian inference of the $^{208}$Pb neutron skin.

4 – Prospects.
1 – Nuclear collisions at high energy.
Huge experimental program. The largest colliders in the world.
All the relevant dynamics occurs in the plane transverse to the beam.

High energy = Nuclei in the lab frame are squeezed in beam direction.

Interaction is instantaneous.

All the relevant dynamics occurs in the plane transverse to the beam.
SNAPSHOT: REPRODUCING THE EARLY UNIVERSE IN THE LAB

Main goal: characterizing the medium from data.
Observables

τ ≈ ∞

Reconstructing the QGP

Credits: W. van der Schee
How do we do that? We only observe particles.

Low-momentum hadron spectra.

\[ \frac{d^2N}{dp_T d\phi} = \frac{dN}{2\pi dp_T} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Phi_n)) \right) \]

EXPLOSIVENESS OF THE EXPANSION

Vast number of observables.

ANISOTROPY OF AZIMUTHAL DISTRIBUTION
Reconstructing initial-state geometry from final-state observables.

\[ F = -\nabla P. \]

Shape and size of the QGP can be reconstructed from data!

References:
- Ollitrault, PRD 46 (1992) 229-245
- Broniowski, Chojnacki, Obara, PRC 80 (2009) 051902
- Alver, Roland, PRC 81 (2010) 054905
The Big Bang

The Little Bang(s)


[ALICE Collaboration, JHEP 05 (2020) 085]
2 – Hydrodynamic model of heavy-ion collisions.
Multi-stage hybrid modeling based on effective descriptions of QCD.

\[ \approx 20-25 \text{ model params} \]

1. Not discussed here

OBSERVABLES

\begin{itemize}
  \item Pb+Pb, \( b = 8 \text{ fm}, \sigma_{NN} = 7 \text{ fm}^2 \)
  \item \( \tau = 0.6 \text{ fm/c} \)
  \item \( \tau = 3.5 \text{ fm/c} \)
\end{itemize}
1. Emergent fluid description: \[ T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \text{transport} \left( \frac{\eta}{s}, \frac{\zeta}{s}, \ldots \right) \]

EQUATION OF STATE FROM LATTICE QCD

\[
s/T^3 \times (\hbar c)^3/k_B^4 \]

DECONFINEMENT TRANSITION

\[
\epsilon_s/c
\]

Heavy-ion data
Lattice quantum chromodynamics

\[
T (\text{MeV} k_B^{-1})
\]

[Romatschke & Romatschke, arXiv:1712.05815]

SHEAR VISCOSITY

[HotQCD Collaboration, PRD 90 (2014) 094503]

[Romatschke & Romatschke, arXiv:1712.05815]


[Romatschke & Romatschke, arXiv:1712.05815]
Hydrodynamics as a response to the initial geometry.

Initial state: [Image]

Final state: [Image]

Hydrodynamic response

EXAMPLE

\[ \varepsilon_2 \propto \int \epsilon(\phi, r) e^{i2\phi} \]

Ellipticity of the initial energy density field

\[ v_2 \propto \int \frac{dN}{d\phi_p} e^{i2\phi_p} \]

Elliptic flow of particles in momentum space (observed)

Direct information about the initial state from data.

[see e.g. Giacalone, arXiv:2101.00168, Chapter 3]

\[ \approx 2000 \text{ SIMULATED COLLISIONS} \]
2. Modeling the initial state. Insights from the effective theory of high-energy QCD.

**Glasma = precursor of quark-gluon plasma.**


Binary collision scaling for transverse energy density ($\tau=0$):

$$\left\langle T^{00} \right\rangle (x) \propto t_A(x)t_B(x)$$

Glasma stress-energy tensor

Gluon density in nucleus A

Gluon density in nucleus B

Phenomenological variations to have more flexibility, e.g.,


$$T^{00}(x) \propto [t_A(x)t_B(x)]^q \quad \text{free param}$$
Gluon density for a colliding nucleus as a superposition of nucleons:

\[ t_A(x) = \sum_j g(x; x_j, w) \]

Nucleon form factor in principle constrained by electron-proton or electron-nucleus scattering.

[Schenke, Shen, Tribedy, PRC 102 (2020) 4, 044905]
[Mäntysaari, Schenke, PRL 117 (2016) 5, 052301]

Input from low-energy physics?

Spatial distribution of nucleon centers.
3. Nuclear structure and the “Glauber Monte Carlo” approach.


Independent sampling from common density (mean field) is appropriate.

\[ \rho(r) \propto \frac{1}{1 + e^{(r-R)/a}} \]

We assume it is known.

0 model params as of April 2023 :-)

\[ Pb+Pb, \ b = 8 \text{ fm}, \sigma_{NN} = 7 \text{ fm}^2 \]
3 – Bayesian inference of the $^{208}$Pb neutron skin.
OBSERVABLES

$	au = 0.6 \text{ fm/c}$

$\tau = 3.5 \text{ fm/c}$

$\tau = 9.0 \text{ fm/c}$

RECONSTRUCTING THE INITIAL STATE

QGP

Temperature, $T(x_\perp, \tau)$ (MeV)
Expected signatures of the neutron skin.

- Larger skin yields larger system size.
- Consequently, fireball density decreases.
- Hydro will develop less radial flow.
- Larger skin smears the elliptical shape.
- Less elliptic flow will be produced.
Test on actual observables.

SYSTEMATIC ANALYSIS?
20 years later: hydrodynamic model constrained via global statistical analyses.

From Jorge Piekarewicz on 2023-06-01 17:24

Dear Giuliano,

I now understand your strategy: incorporate many observables that are largely sensitive to the isoscalar density to tease out the isovector relevant quantity.
OUR COMPUTATIONAL FRAMEWORK

https://sites.google.com/view/govertnijs/trajectum?authuser=0


Developed by Govert Nijs (MIT) and Wilke van der Schee (CERN/Utrecht).
OUR STRATEGY: BAYESIAN ANALYSIS

\[ Pr(p & D) = Pr(p) \times Pr(D|p) = Pr(D) \times Pr(p|D) \]

prior \times likelihood = evidence \times posterior

Promote neutron diffuseness to a model parameter.

\[ \rho(r) \propto \frac{1}{1 + e^{(r-R)/a}} \]

**Protons:** density from low-energy scattering.

[Zenihiro et al., PRC 82 (2010) 044611]

**Neutrons:** same R as protons, infer \( a \) from data.

Extracting the radial profile – Matter radius.

\[ R_{\text{Pb}}^2 = \frac{1}{208} \left( 126 \langle r_n^2 \rangle + 82 \langle r_p^2 \rangle \right) \]

- 18 tuned DFT Brussels-Skyrme results. [BSkG2 functional by W. Ryssens]

- \( R_{\text{Pb}}(\text{ab initio}) = 5.534 \pm 0.030 \) fm [Hu et al., Nature Phys. 18 (2022) 10, 1196-1200]

- \( R_{\text{Pb}}(\text{LHC}) = 5.568 \pm 0.058 \) fm [Giacalone, Nijs, van der Schee, arXiv:2305.00015]
Extracting the radial profile – Neutron skin.

\[ \Delta r_{np} = r_n - r_p \text{ [fm]} \]

- **LHC [Trajectum]**: \( 0.217 \pm 0.058 \text{ fm} \)
- **PREX II**: \( 0.278 \pm 0.078 \text{ (exp.)} \pm 0.012 \text{ (theo.) fm} \)
- **LHC** [using Viñas et al., EPJA 50 (2014) 27]: \( 79 \pm 39 \text{ MeV} \)

\[ \text{P(L)} \]

\[ L \text{ [MeV]} \]

**PREX II** [Giacalone, Nijs, van der Schee, arXiv:2305.00015]

**LHC** [PREX Collaboration, PRL 126 (2021) 17, 172502]
- Weak interaction probe.
- Measured quantity is $A_{pv}$.
- Global analysis of neutron diffuseness within density functional theory.
- Nuclear one-body density and skin from nuclear models.
- Claimed theory error very small: 0.012 fm. Systematic analysis is underway?
- Measurement is statistics-limited.

---

**LHC (Trajectum)**

- Strong interaction probe.
- Lots of measured quantities.
- Global analysis of neutron diffuseness in hydrodynamic model.
- Nuclear forces are never invoked. Inference of one-body density from data.
- Theory error is about 0.060 fm. Systematic analysis is underway.
- Statistical uncertainty is negligible. Theory error dominates.

---

**COMPLEMENTARY DETERMINATIONS**
4 – Prospects.
Recently, focus on skin signatures in “isobar” $^{96}\text{Ru}+^{96}\text{Ru}$ and $^{96}\text{Zr}+^{96}\text{Zr}$ collisions.

$$\frac{O_{\text{Ru}}}{O_{\text{Zr}}} \approx 1 + c_0(R_{0,\text{Ru}} - R_{0,\text{Zr}}) + c_1(a_{0,\text{Ru}} - a_{0,\text{Zr}}) + c_2(\beta_{2,\text{Ru}}^2 - \beta_{2,\text{Zr}}^2) + c_3(\beta_{3,\text{Ru}}^2 - \beta_{3,\text{Zr}}^2)$$

[Jia & Zhang, PRC 107 (2023) 2, L021901]

For some observables, ratio between systems is dominated by skin effects.

Multi-system analyses will yield improved constraints.

[Xu et al., PLB 819 (2021) 136453]
[Xu et al., arXiv:2111.14812]
Tension between PREX and CREX results?

[CREX collaboration, PRL 129 (2022) 4, 042501]

What about high-energy collisions?

Case for running $^{48}$Ca at LHC?
Collisions of additional species @ LHC Run 5?

Maximizing impact. $^{48}$Ca, $^{136}$Xe good candidates for skin studies?
SUMMARY

- Theory of ultra-relativistic heavy-ion collisions is highly developed.
- First reconstruction of the (point-)matter profile of $^{208}\text{Pb}$ from LHC data.
- Results consistent with low-energy determinations.
- Looking forward to future progress and collaborations.
BACKUP
DETAILED MECHANISM OF QGP HADRONIZATION IS POORLY UNDERSTOOD.

Skin extraction is however robust.

targeting a subset of $p_T$-integrated-only observables, corresponding to 233 ALICE data points, we obtain $\Delta r_{np} = 0.216 \pm 0.057$ fm. This suggests that the extraction of $\Delta r_{np}$ is likely insensitive to theoretical uncertainties in the partciliation of the QGP at the switching temperature [32].