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

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June 30, 2023

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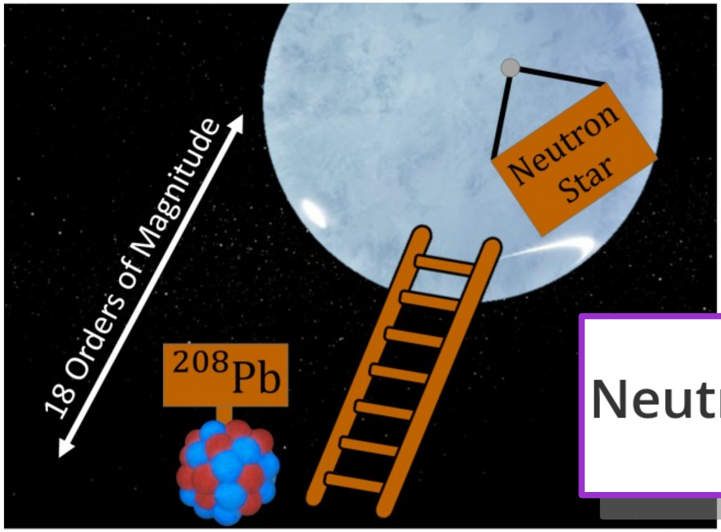
IsoQuant SFB1225

Based on:
arXiv:2305.00015

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



INT WORKSHOP INT-22R-2A

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.

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Nuclear Physics Confronts Relativistic Collisions of Isobars

Heidelberg University, Germany, May 30 – June 3 & October 12 – 14, 2022

Organizers:
Giuliano Giacalone
Jiangyong Jia
Vittorio Somà
You Zhou

Deciphering nuclear phenomenology across energy scales

Organizers:
G. Giacalone, J-Y. Ollitrault, Y. Zhou

20-23 September 2022

Intersection of nuclear structure and high-energy nuclear collisions

Jan 23 - Feb 24 2023

Organizers:
Jiangyong Jia (Stony Brook & BNL)
Giuliano Giacalone (ITP Heidelberg)
Jaki Noronha-Hostler (Urbana-Champaign)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Fuqiang Wang (Purdue)

OUTLINE

1 – Nuclear collisions at high energy.

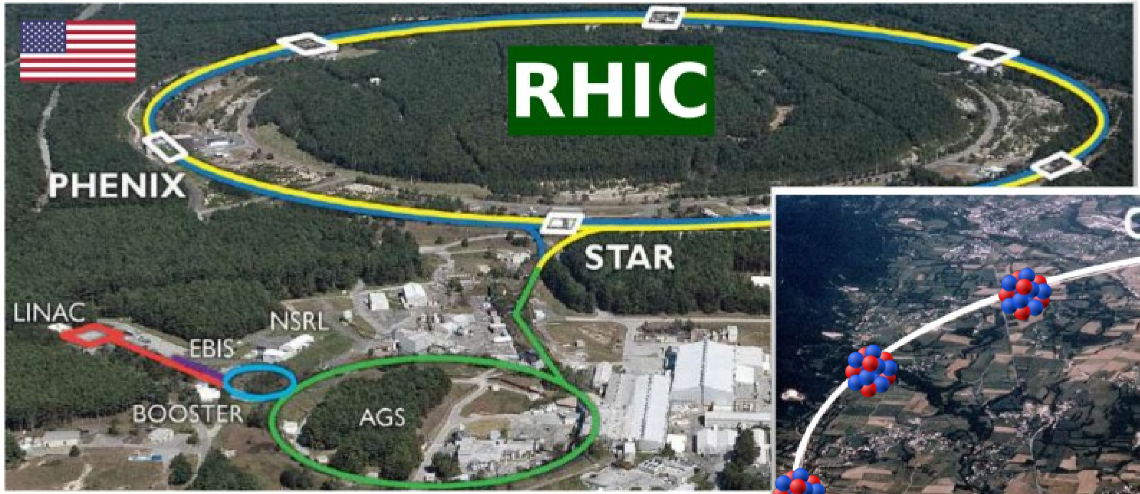
2 – Hydrodynamic model of heavy-ion collisions.

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

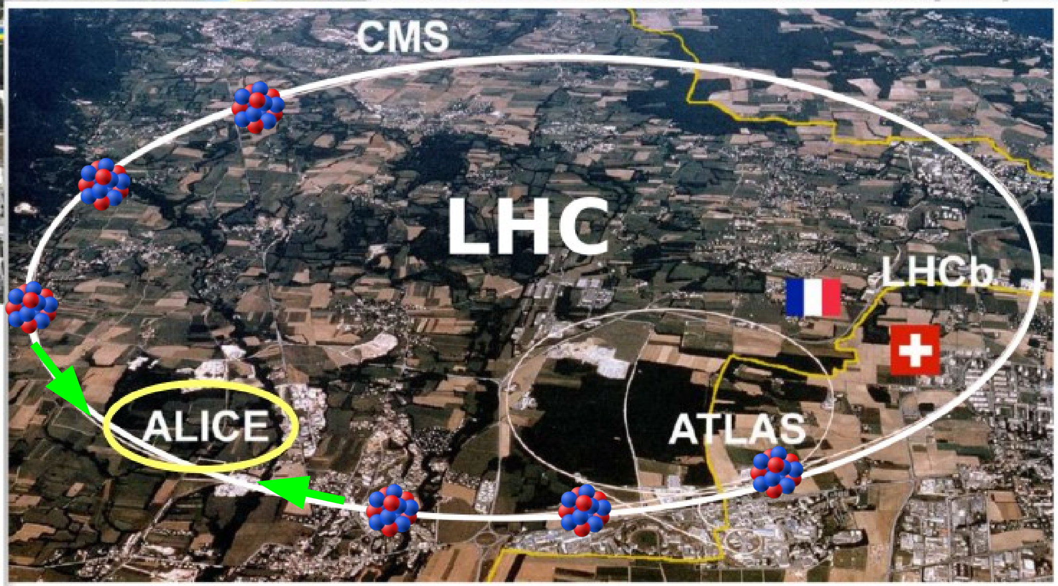
4 – Prospects.

1 – Nuclear collisions at high energy.

Long Island (NY)

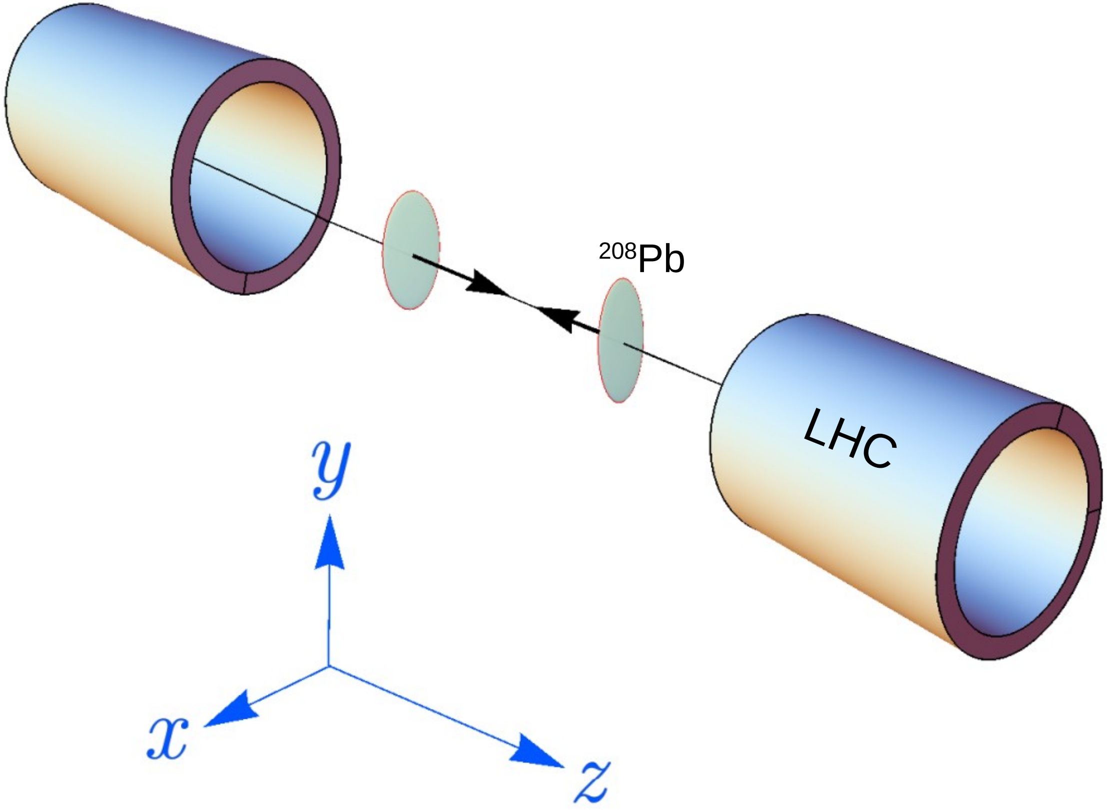


Geneva (CH)



Huge experimental program. The largest colliders in the world.

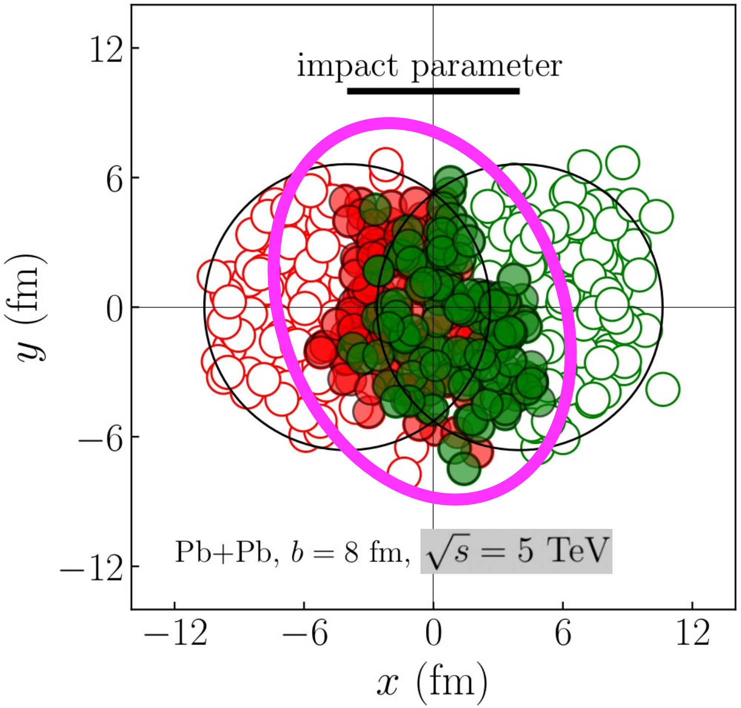
High energy = Nuclei in the lab frame are squeezed in beam direction.

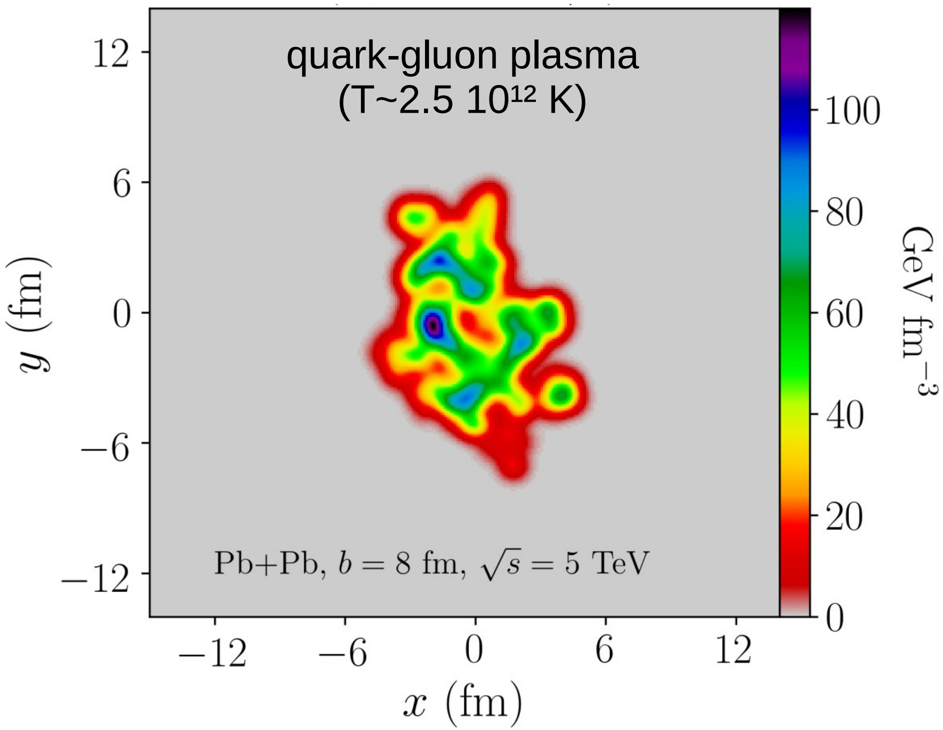


Interaction is instantaneous.

All the relevant dynamics occurs in the plane transverse to the beam.

SNAPSHOT: REPRODUCING THE EARLY UNIVERSE IN THE LAB



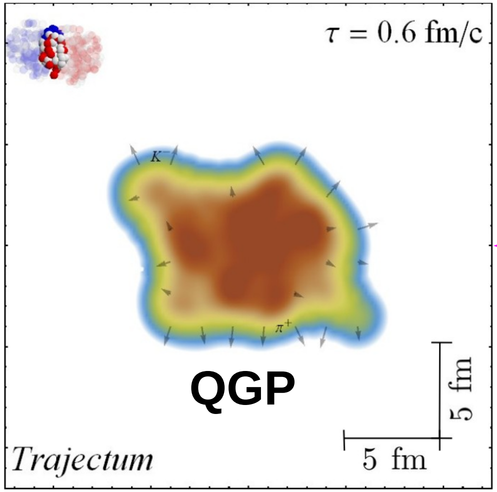


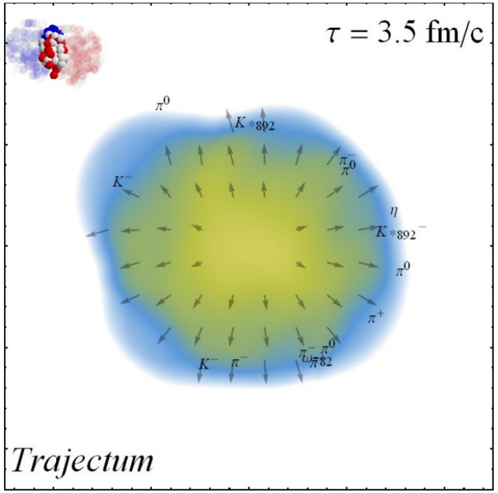
Main goal: characterizing the medium from data.

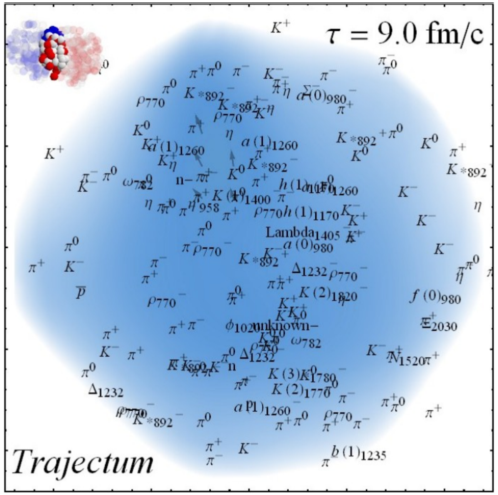
A COLLISION EVENT

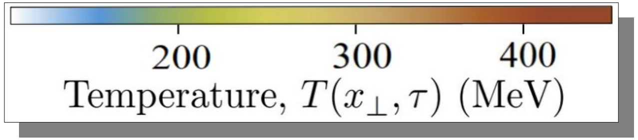
Credits: W. van der Schee

RECONSTRUCTING THE QGP

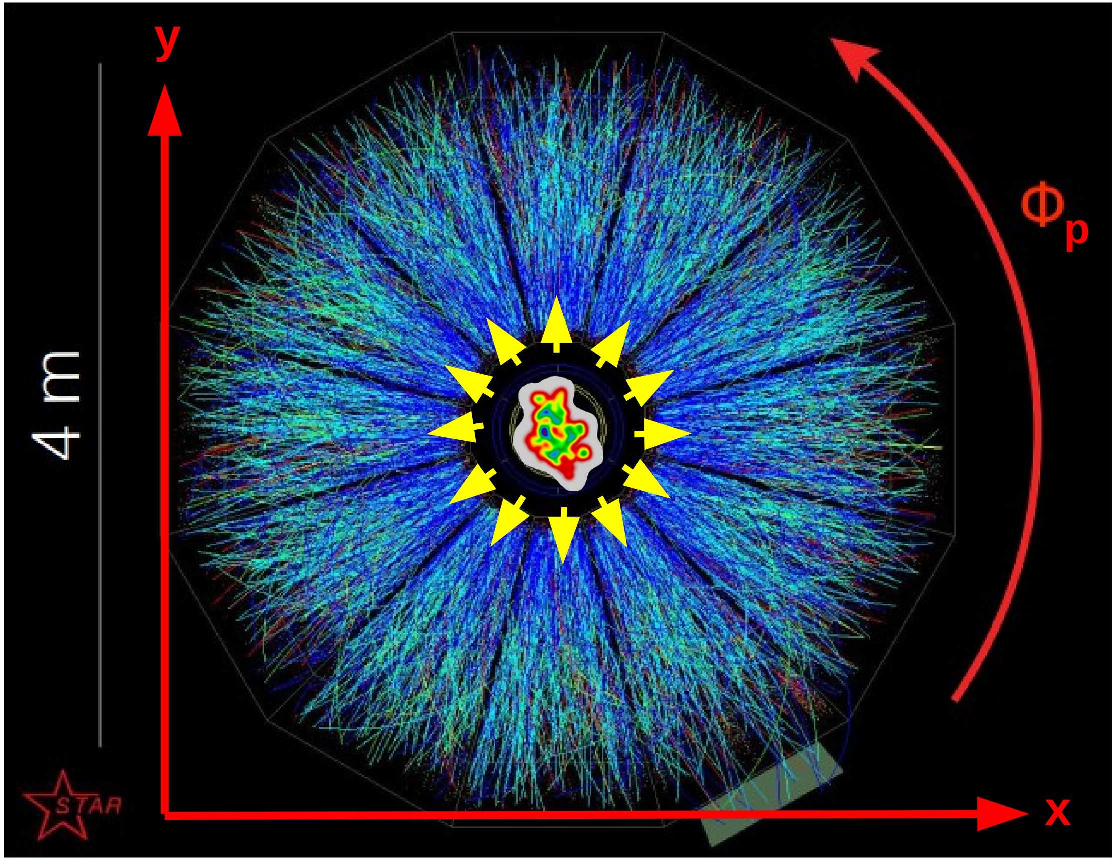








How do we do that? We only observe particles.



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

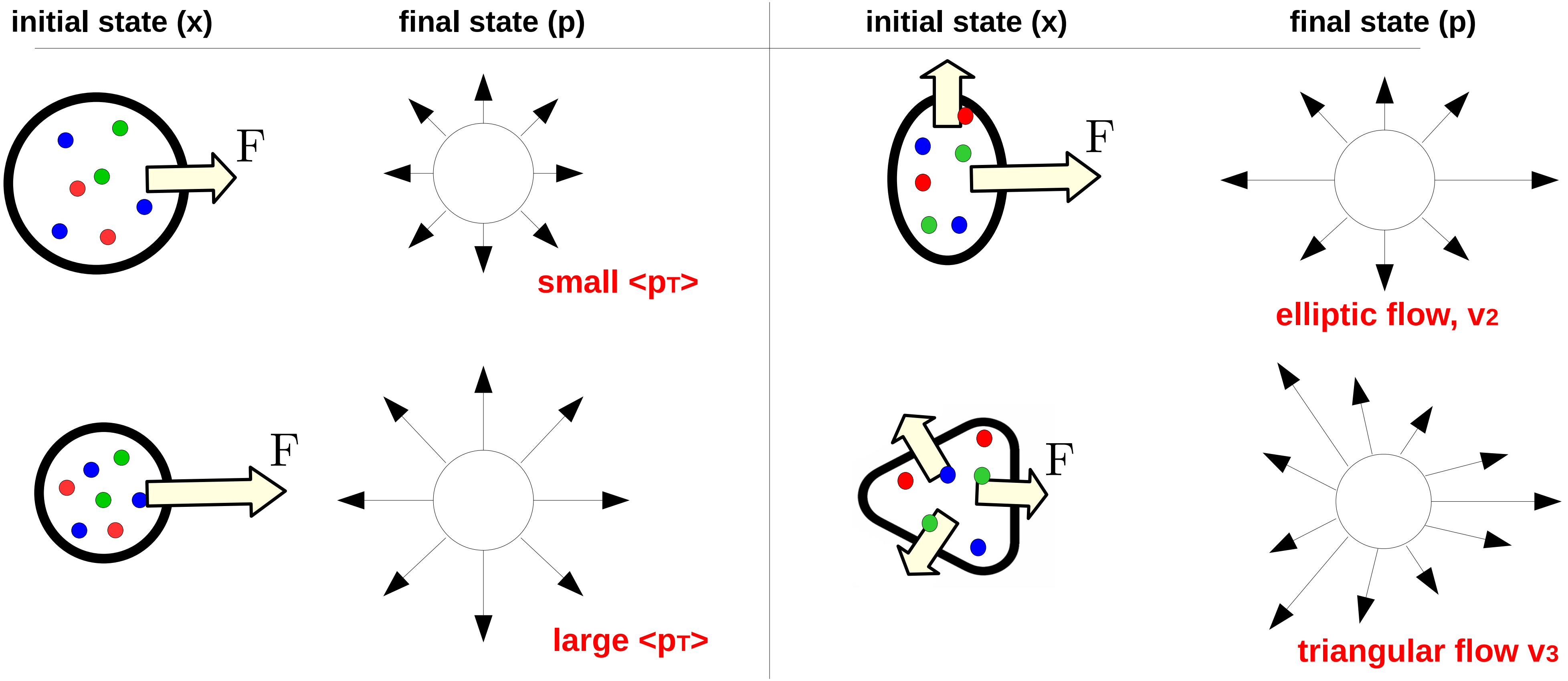
ANISOTROPY OF
AZIMUTHAL DISTRIBUTION

Vast number of observables.

Reconstructing initial-state geometry from final-state observables.

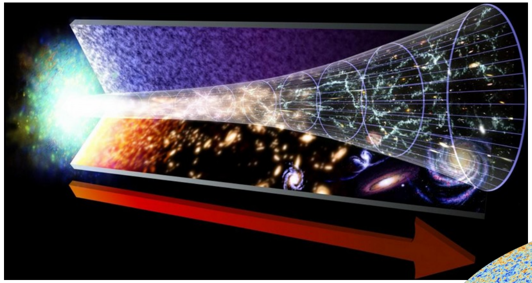
$$F = -\nabla P$$

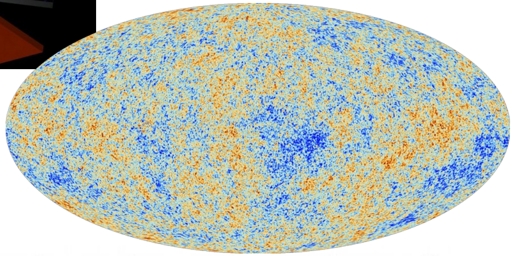
[Ollitrault, PRD **46** (1992) 229-245]
[Broniowski, Chojnacki, Obara, PRC **80** (2009) 051902]
[Alver, Roland, PRC **81** (2010) 054905]

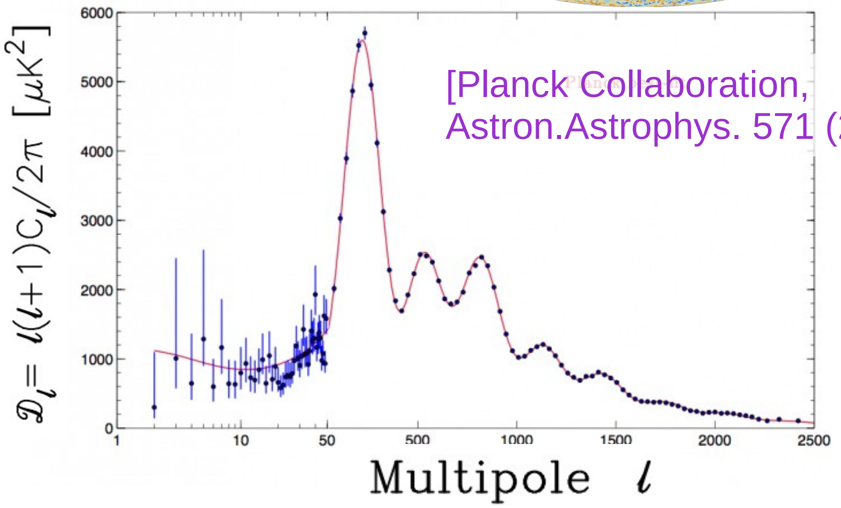


Shape and size of the QGP can be reconstructed from data!

The Big Bang

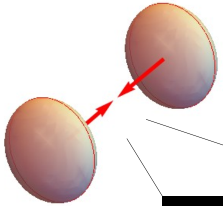


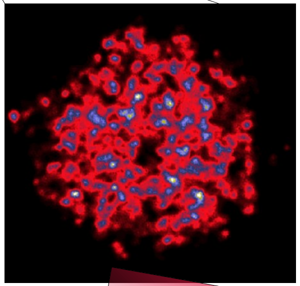


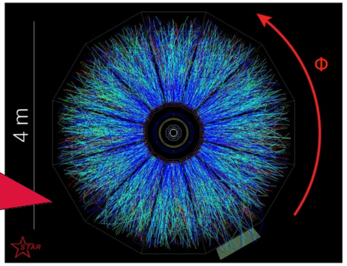


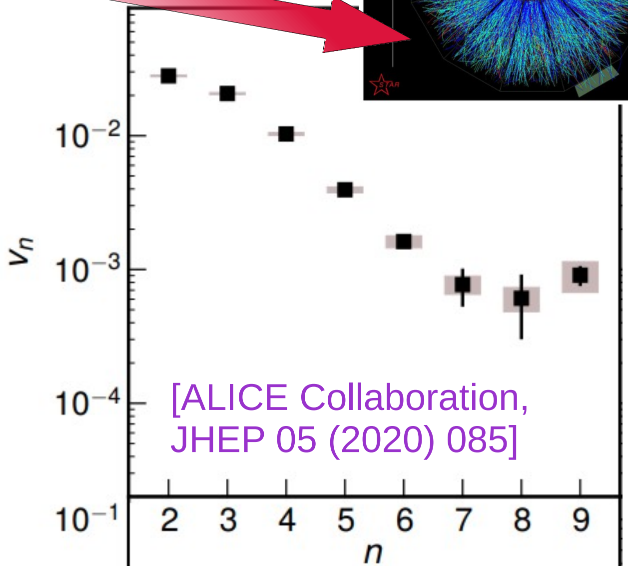
[Planck Collaboration,
Astron.Astrophys. 571 (2014) A16]

The Little Bang(s)









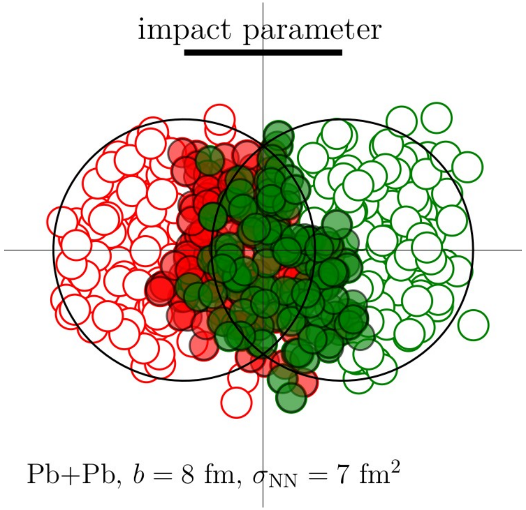
[ALICE Collaboration,
JHEP 05 (2020) 085]

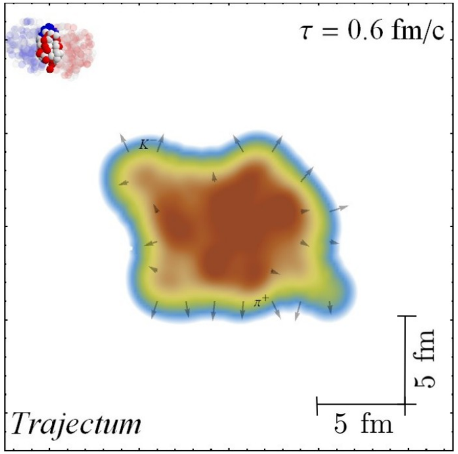
2 – Hydrodynamic model of heavy-ion collisions.

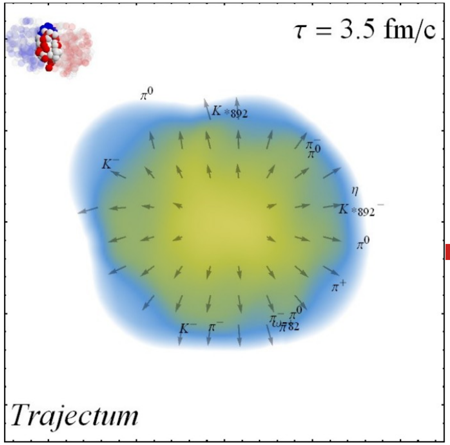
Multi-stage hybrid modeling based on effective descriptions of QCD.

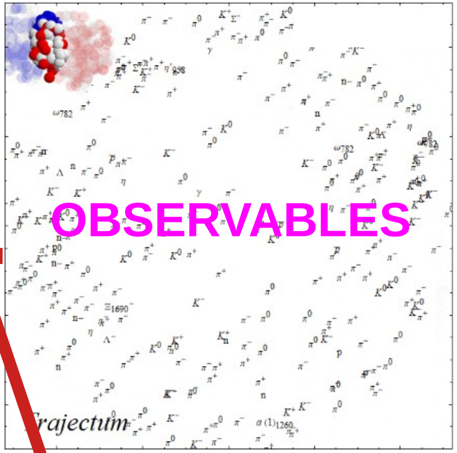
≈ 20-25 model params

NUCLEAR STRUCTURE → **ENERGY DEPOSITION** → **HYDRO EXPANSION** → **HADRONIZATION**









OBSERVABLES

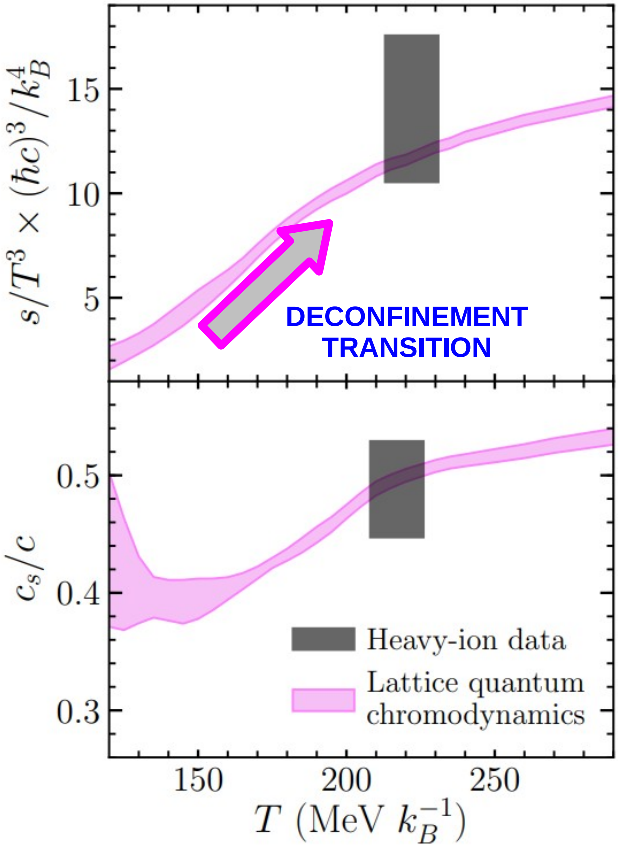
3. **2.** **1.**

NOT DISCUSSED HERE

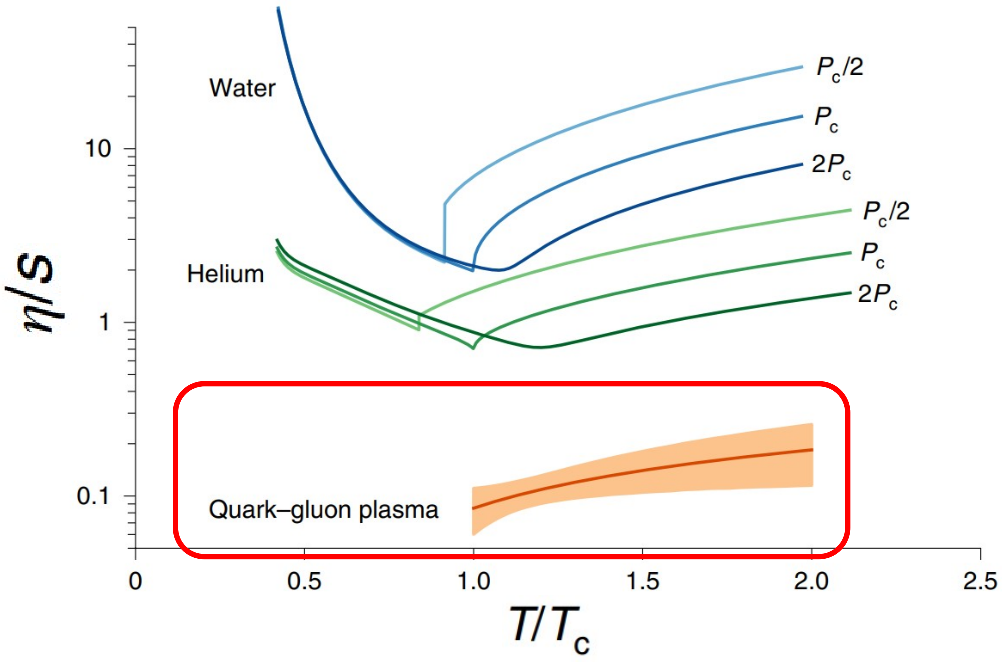
1. Emergent fluid description: $T^{\mu\nu} = (\epsilon + P)u^{\mu}u^{\nu} - Pg^{\mu\nu}$ + transport (η/s, ζ/s, ...)

EQUATION OF STATE FROM LATTICE QCD

[Romatschke & Romatschke, arXiv:1712.05815]



SHEAR VISCOSITY

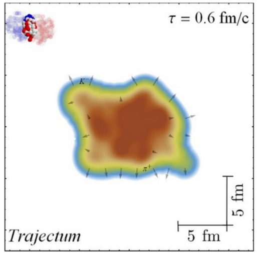


[Gardim *et al.*, Nature Phys. **16** (2020) 6, 615-619]
[HotQCD Collaboration, PRD **90** (2014) 094503]

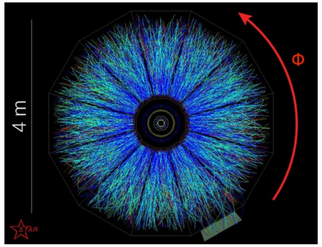
[Bernhard, Moreland, Bass, Nature Phys. **15** (2019) 11, 1113-1117]

Hydrodynamics as a response to the initial geometry.

initial state



HYDRODYNAMIC RESPONSE



final state

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

EXAMPLE

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

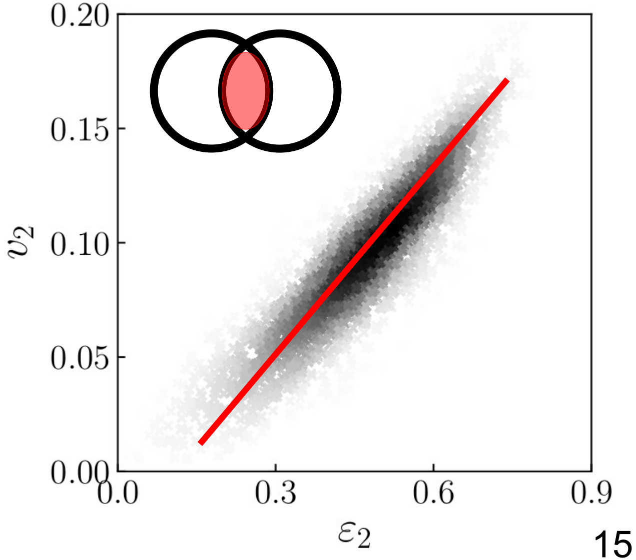
ellipticity of the initial energy density field

HYDRODYNAMIC RESPONSE

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

Elliptic flow of particles in momentum space (observed)

≈ 2000 SIMULATED COLLISIONS

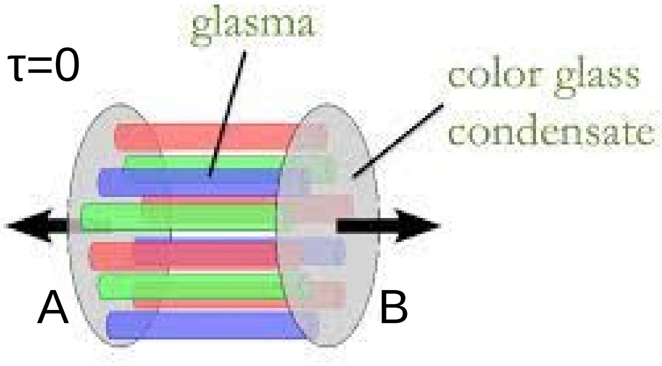


Direct information about the initial state from data.

2. Modeling the initial state. Insights from the effective theory of high-energy QCD.

Glasma = precursor of quark-gluon plasma.

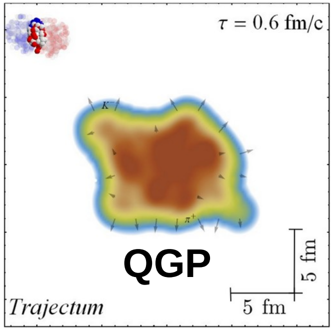
[Lappi, McLerran, NPA **772** (2006) 200-212]
[Gelis, Rept.Prog.Phys. **84** (2021) 5, 056301]



Binary collision scaling for transverse energy density (τ=0):

$$\langle T^{00}\rangle(\mathbf{x}) \;\propto\; t_A(\mathbf{x})t_B(\mathbf{x})$$

Glasma stress-energy tensor — gluon density in nucleus A — gluon density in nucleus B



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

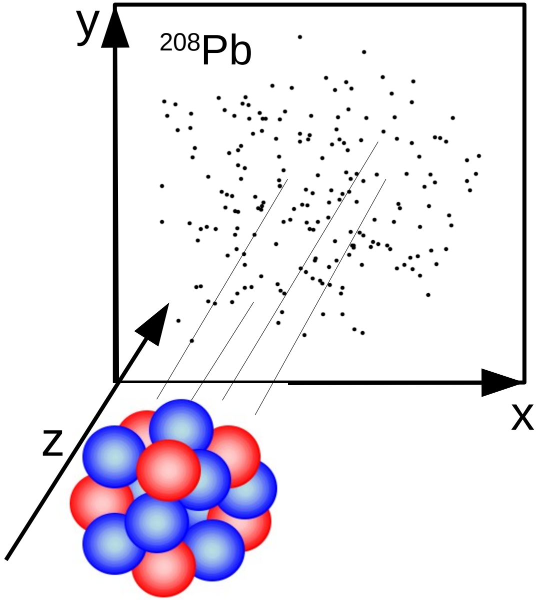
[Moreland, Bernhard, Bass, PRC **92** (2015) 1, 011901]
[Nijs, van der Schee, arXiv:2304.06191]

$$T^{00}(\mathbf{x}) \propto [t_A(\mathbf{x})t_B(\mathbf{x})]^q$$

→ free param

Gluon density for a colliding nucleus as a superposition of nucleons:

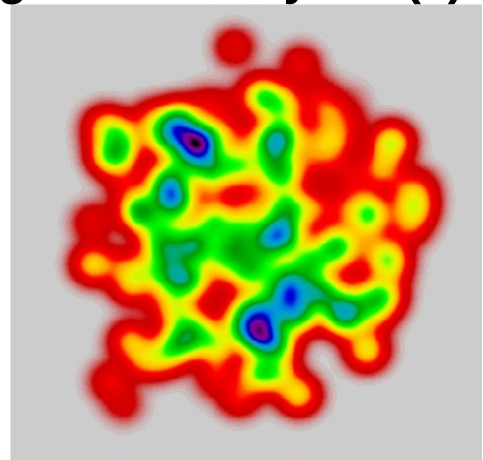
nucleon centers



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

j^{th} nucleon

gluon density $t_A(x)$



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

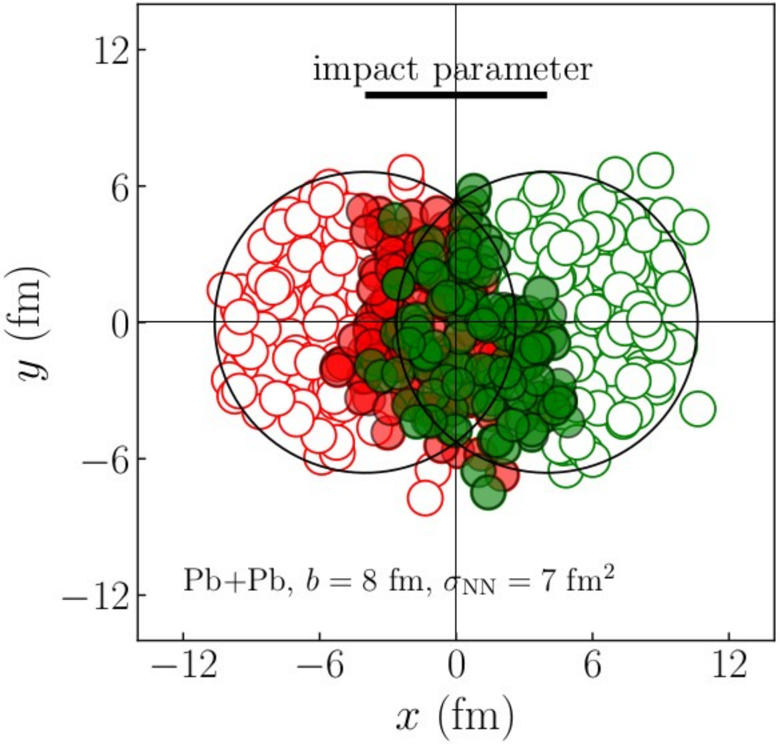
[Schenke, Shen, Tribedy, PRC **102** (2020) 4, 044905]
[Mäntysaari, Schenke, PRL **117** (2016) 5, 052301]

Input from low-energy physics?

Spatial distribution of nucleon centers.

3. Nuclear structure and the "Glauber Monte Carlo" approach.

[Miller *et al.*, Ann.Rev.Nucl.Part.Sci. **57** (2007) 205-243]



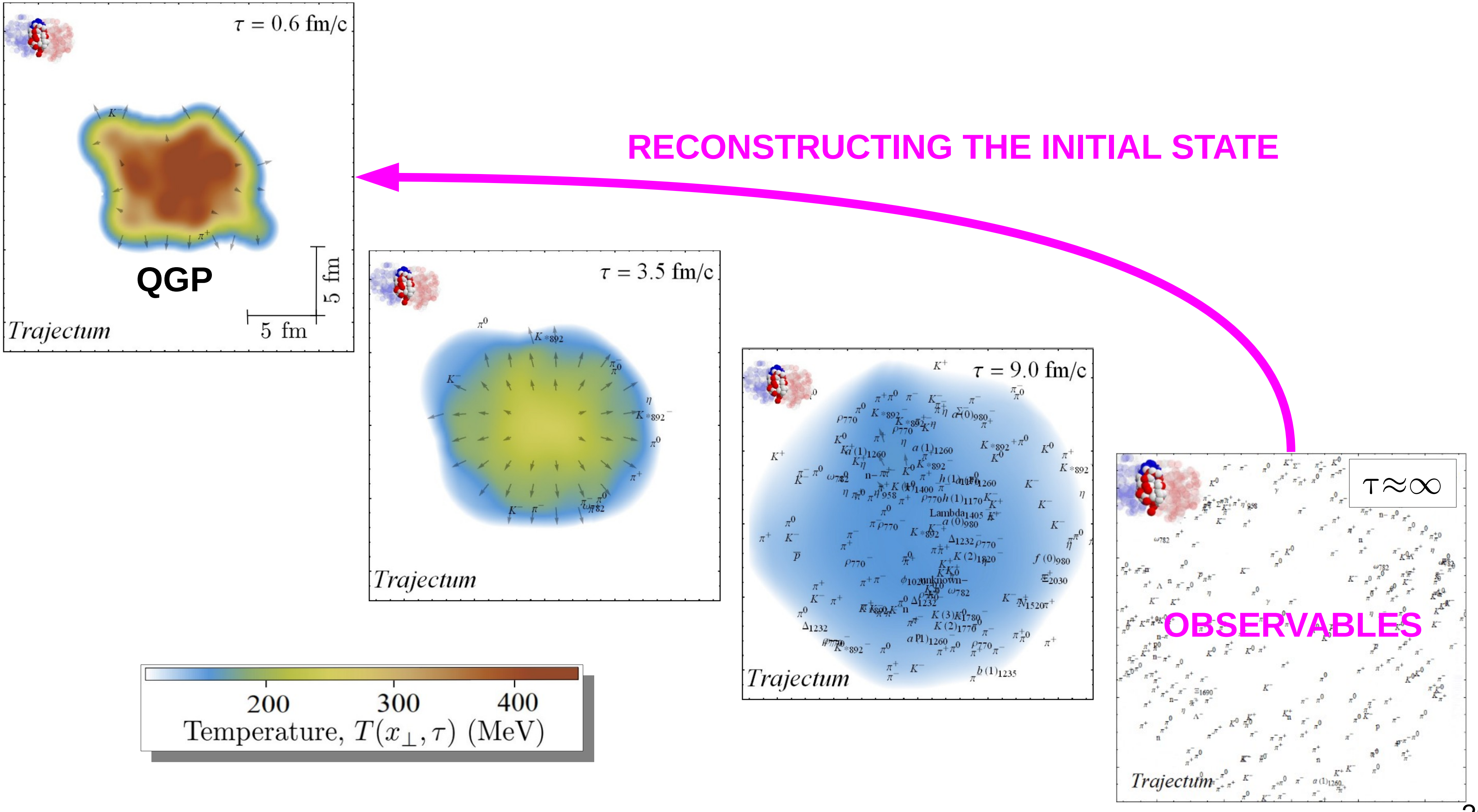
Independent sampling from common density (mean field) is appropriate.

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

We assume it is known.

0 model params as of April 2023 :-)

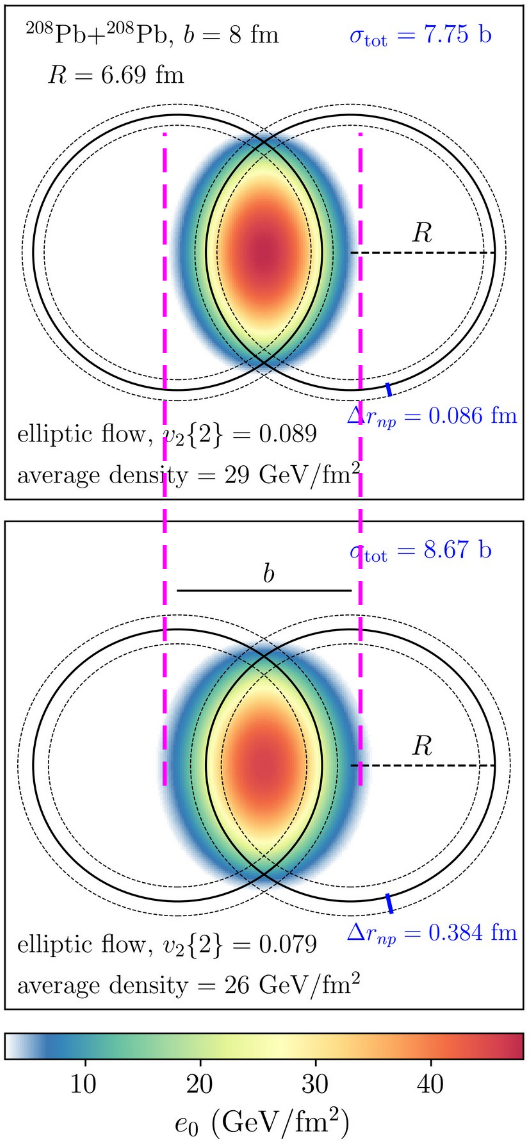
3 – Bayesian inference of the ^{208}Pb neutron skin.


RECONSTRUCTING THE INITIAL STATE
τ = 0.6 fm/c
QGP
5 fm
5 fm
Trajectum
τ = 3.5 fm/c
Trajectum
τ = 9.0 fm/c
Trajectum
τ≈∞
OBSERVABLES
Trajectum
200
300
400
Temperature, T(x⊥, τ) (MeV)

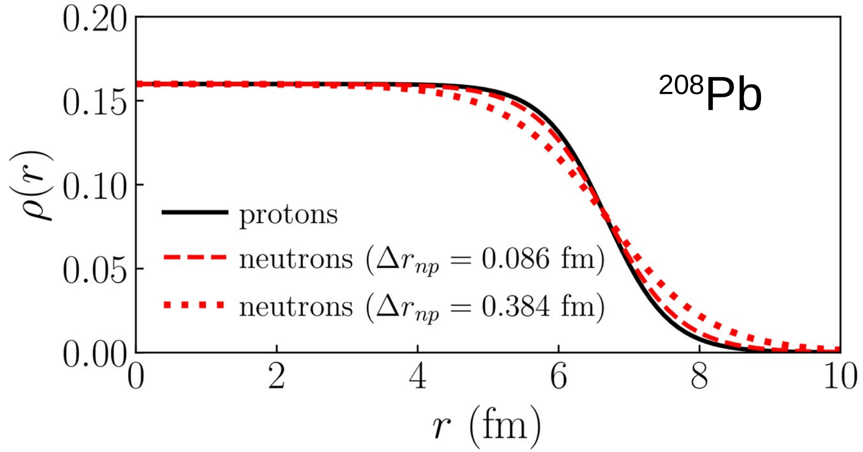
Expected signatures of the neutron skin.

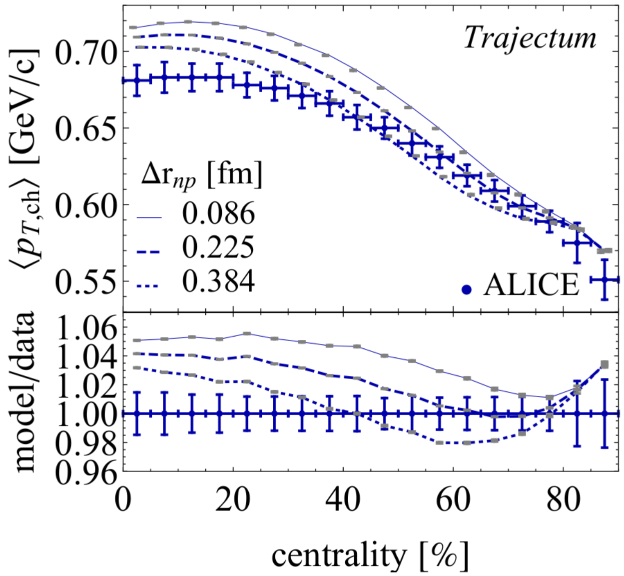
- **Larger skin yields larger system size.**
- **Consequently, fireball density decreases.**
- **Hydro will develop less radial flow.**

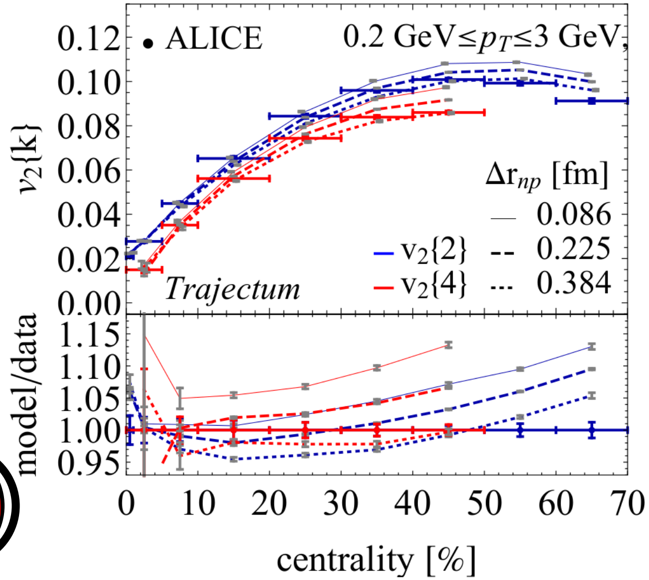
- **Larger skin smears the elliptical shape.**
- **Less elliptic flow will be produced.**

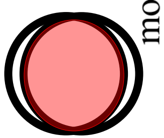


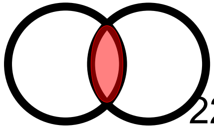
Test on actual observables.





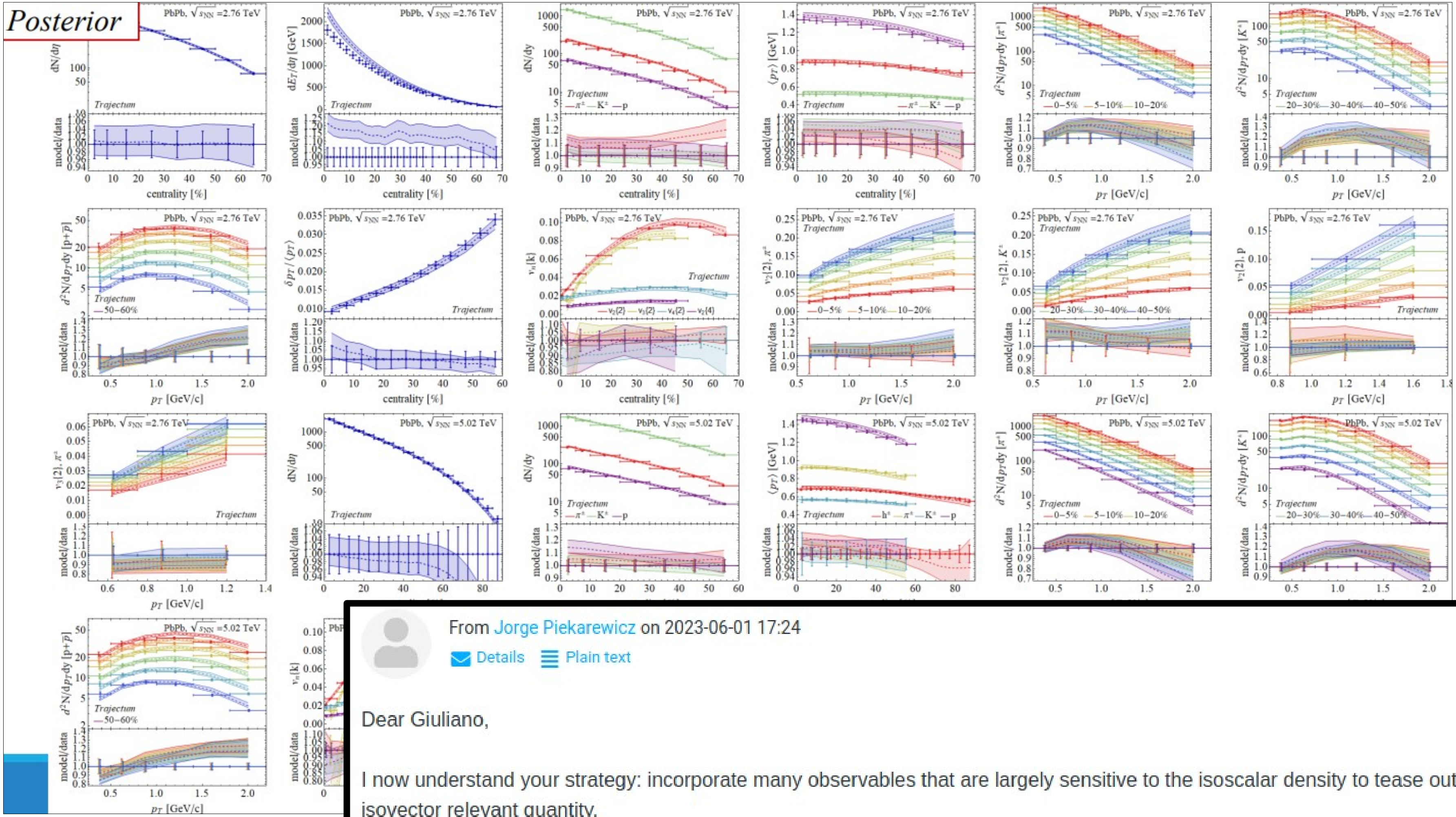






SYSTEMATIC ANALYSIS?

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



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

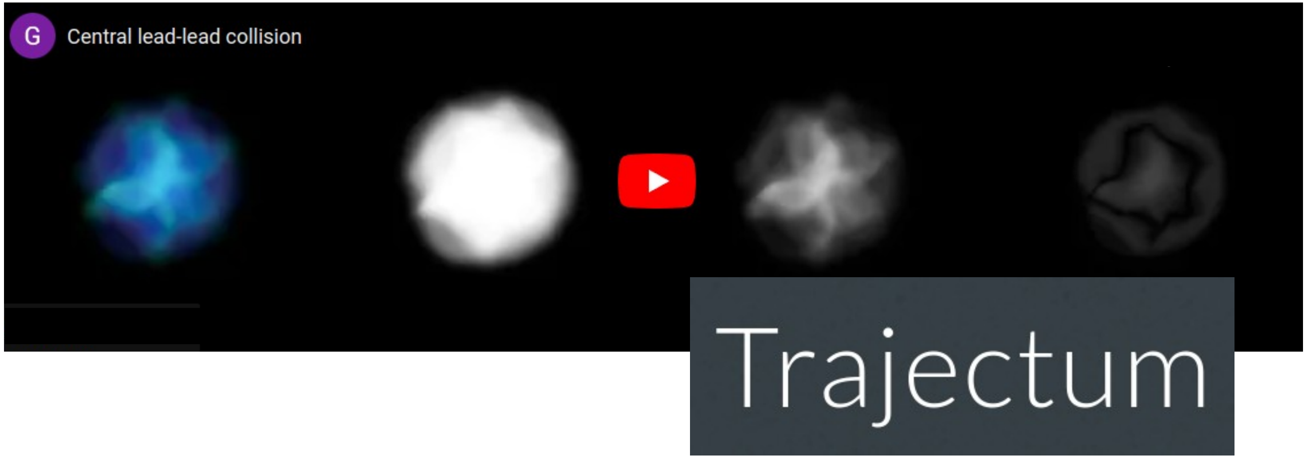
Details   Plain text

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).

[Nijs, van der Schee, Gürsoy, Snellings, PRC **103** (2021) 5, 054909 – PRL **126** (2021) 20, 202301]

OUR STRATEGY: BAYESIAN ANALYSIS

$$\Pr(p \,\&\, D) = \Pr(p) \times \Pr(D|p) = \Pr(D) \times \Pr(p|D)$$
$$\text{prior} \times \text{likelihood} = \text{evidence} \times \text{posterior}$$

Promote neutron diffuseness to a model parameter.

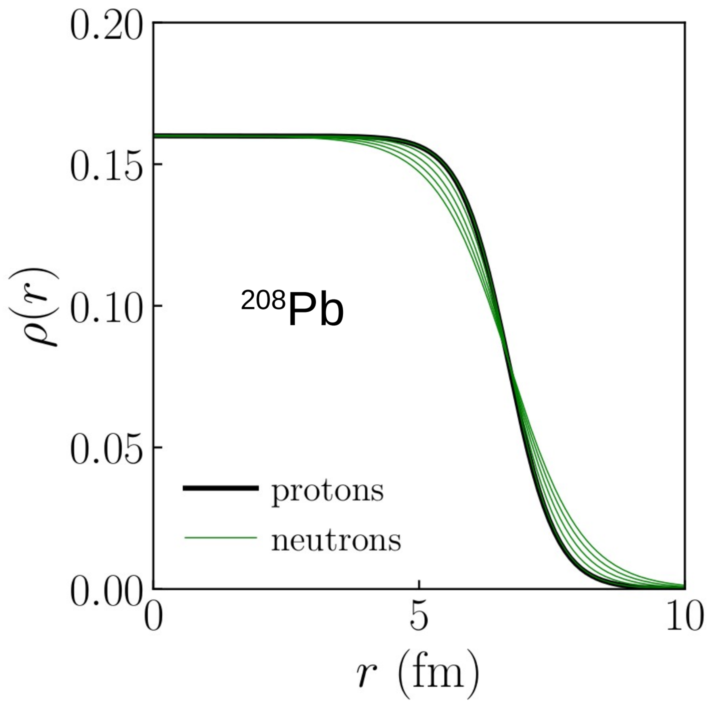
$$\rho(r) \propto \frac{1}{1 + e^{(r-R)/\underline{a}}}$$

Protons: density from low-energy scattering.

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

Neutrons: same R as protons, infer a from data.

[Giacalone, Nijs, van der Schee, arXiv:2305.00015]



Extracting the radial profile – Matter radius.

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

LHC data low-energy data

- 18 tuned DFT Brussels-Skyrme results.

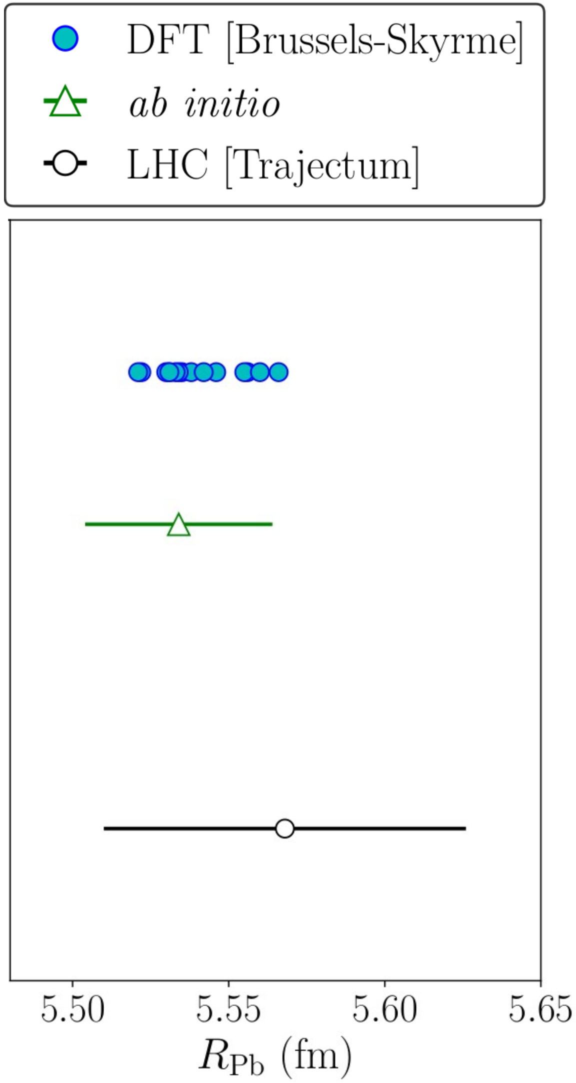
[BSkG2 functional by W. Ryssens]

- $R_{\mathrm{Pb}}(ab\ initio) = 5.534 \pm 0.030\ \mathrm{fm}$

[Hu *et al.*, Nature Phys. **18** (2022) 10, 1196-1200]

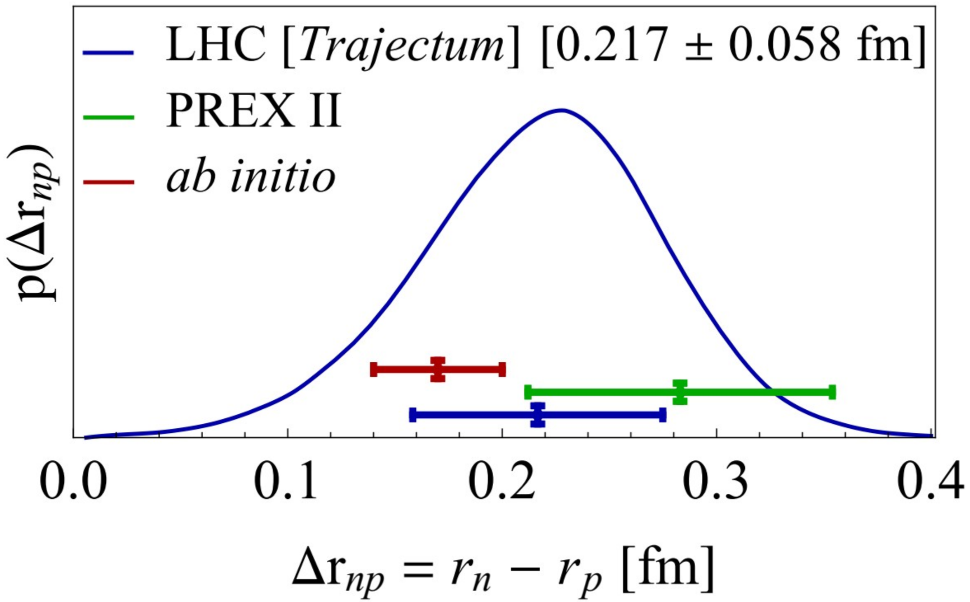
- $R_{\mathrm{Pb}}(\mathrm{LHC}) = 5.568 \pm 0.058\ \mathrm{fm}$

[Giacalone, Nijs, van der Schee, arXiv:2305.00015]

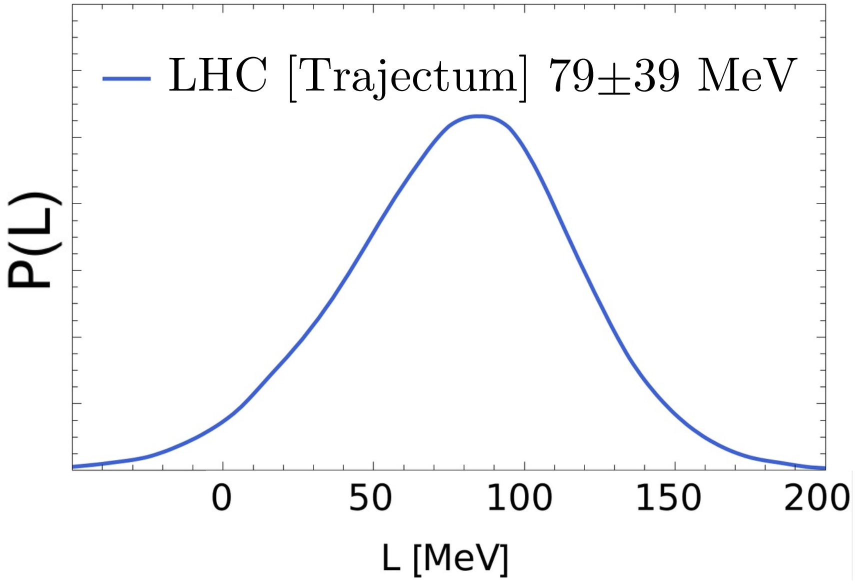


Extracting the radial profile – Neutron skin.

[Giacalone, Nijs, van der Schee, arXiv:2305.00015]



[using Viñas *et al.*, EPJA **50** (2014) 27]



PREX II $0.278 \pm 0.078 \text{ (exp.)} \pm 0.012 \text{ (theo.) fm}$

LHC $0.217 \pm 0.058 \text{(theo.) fm}$

[PREX Collaboration, PRL **126** (2021) 17, 172502]

PREX

- Weak interaction probe.
- Measured quantity is Apv.
- 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}Ru+^{96}Ru and ^{96}Zr+^{96}Zr collisions.

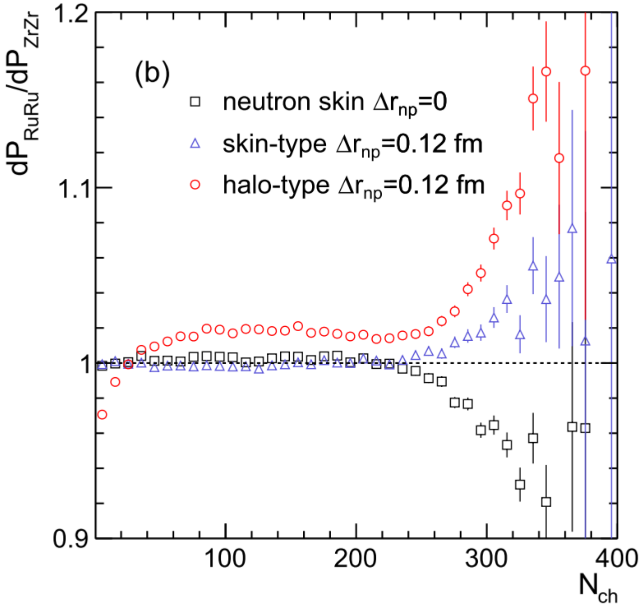
$$\frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_0(R_{0,\mathrm{Ru}} - R_{0,\mathrm{Zr}}) + \underline{c_1(a_{0,\mathrm{Ru}} - a_{0,\mathrm{Zr}})} + c_2(\beta^2_{2,\mathrm{Ru}} - \beta^2_{2,\mathrm{Zr}}) + c_3(\beta^2_{3,\mathrm{Ru}} - \beta^2_{3,\mathrm{Zr}})$$

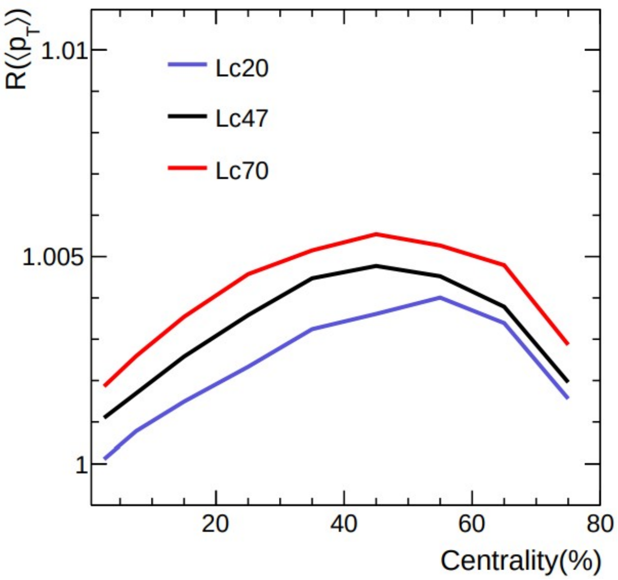
[Jia & Zhang, PRC **107** (2023) 2, L021901]

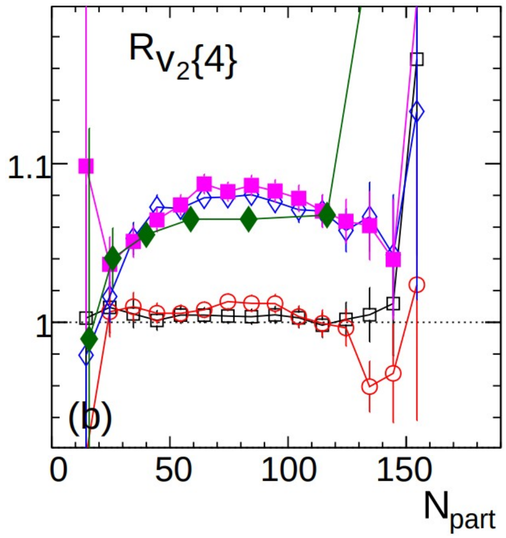
For some observables, ratio between systems is dominated by skin effects.

Multi-system analyses will yield improved constraints.

[Xu *et al.*, PLB **819** (2021) 136453]
[Xu *et al.*, arXiv:2111.14812]
[Giacalone, Jia, Zhang, arXiv:2206.10449]



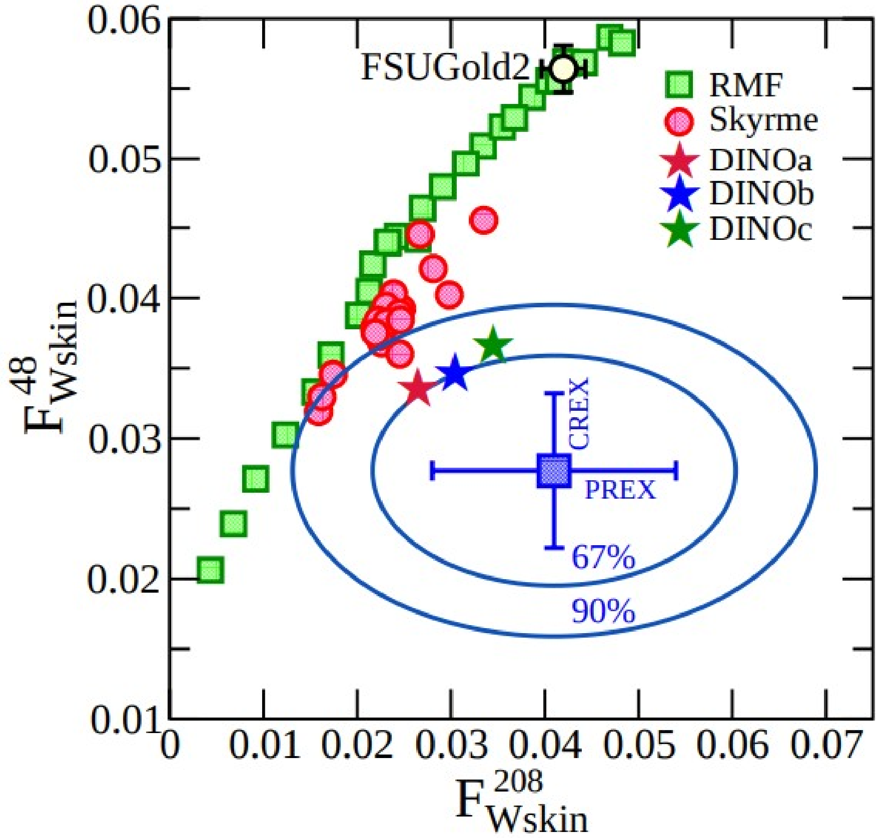




Tension between PREX and CREX results?

[CREX collaboration, PRL **129** (2022) 4, 042501]
[Reinhard, Roca-Maza, Nazarewicz, PRL **127** (2021) 23, 232501 – PRL **129** (2022) 23, 232501]

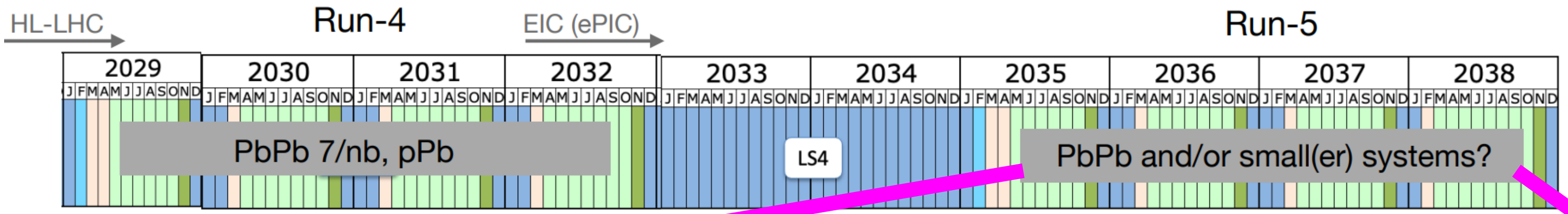
[Reed *et al.*, arXiv:2305.19376]



What about high-energy collisions?

Case for running ^{48}Ca at LHC?

Collisions of additional species @ LHC Run 5?



[https://indico.cern.ch/event/1078695/]

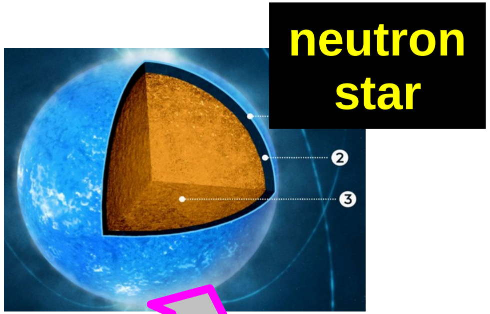
Nucleon-nucleon luminosity: $\mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA}$

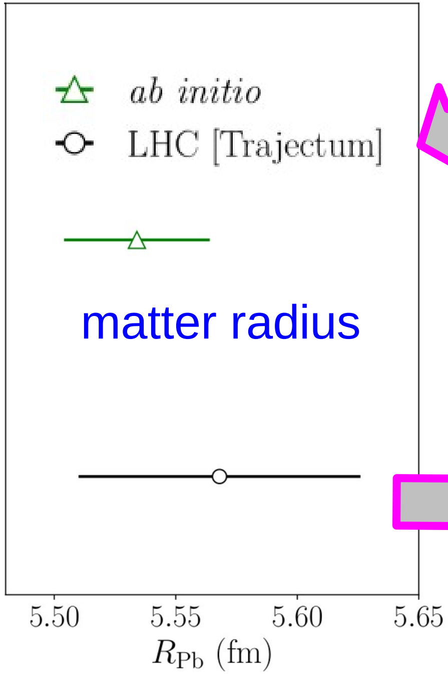
optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathcal{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathcal{L}_{NN}$ (pb^{-1} / month)	409	550	500	510	512	434	242

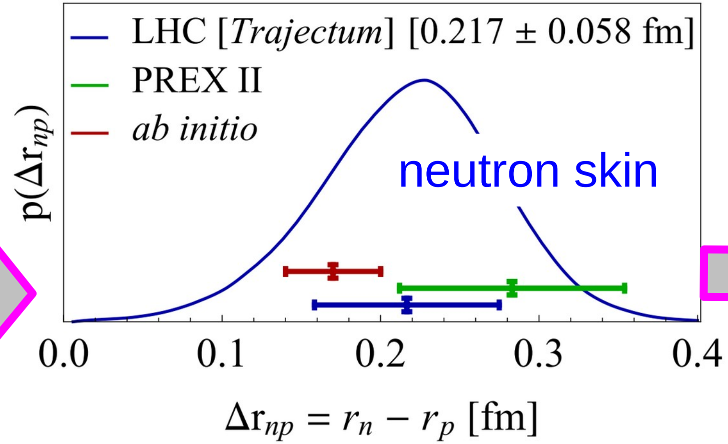
Maximizing impact. ^{48}Ca, ^{136}Xe good candidates for skin studies?

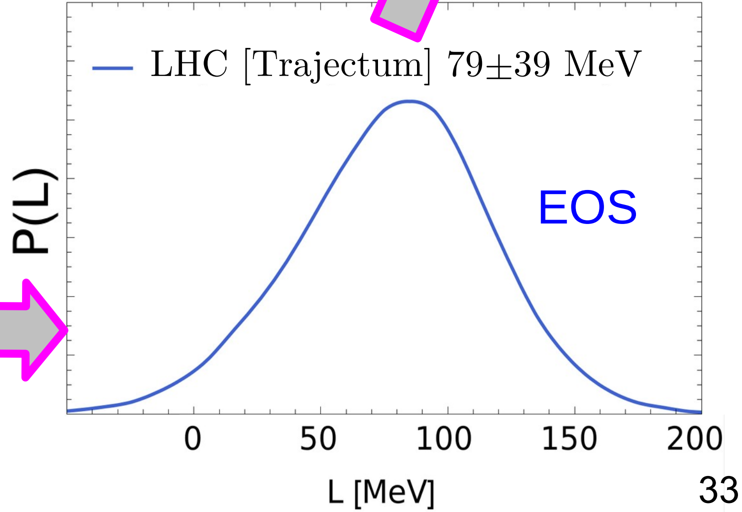
SUMMARY

- **Theory of ultra-relativistic heavy-ion collisions is highly developed.**
- **First reconstruction of the (point-)matter profile of ^{208}Pb from LHC data.**
- **Results consistent with low-energy determinations.**
- **Looking forward to future progress and collaborations.**

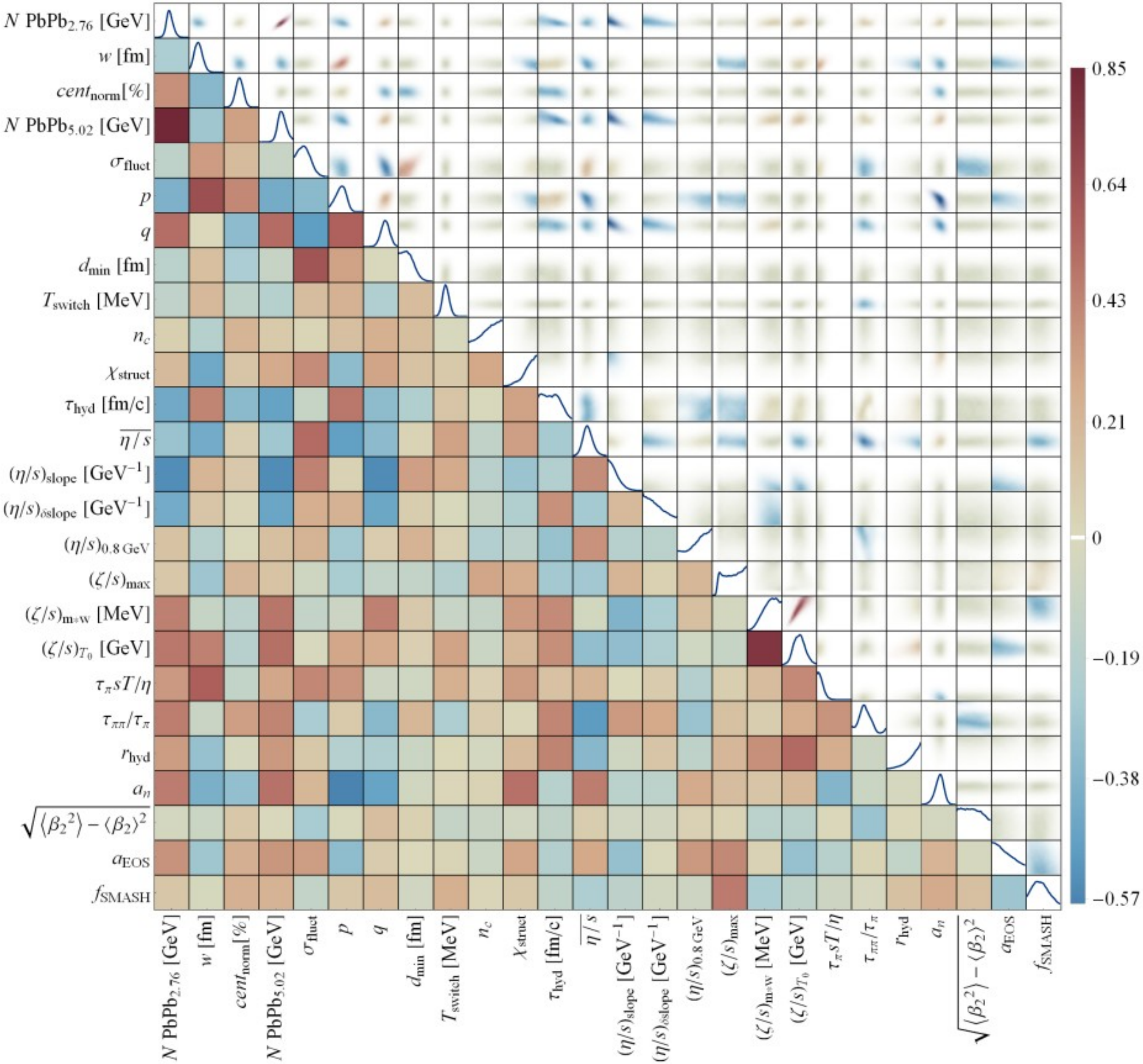






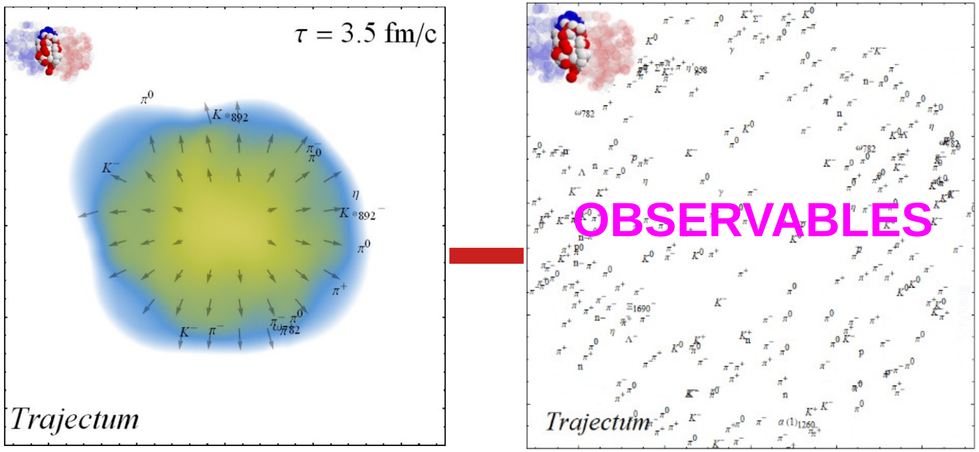


BACKUP



[Giacalone, Nijs, van der Schee, arXiv:2305.00015]

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 Δr_{np} is likely insensitive to theoretical uncertainties in the particlisation of the QGP at the switching temperature [32].

[Giacalone, Nijs, van der Schee, arXiv:2305.00015]