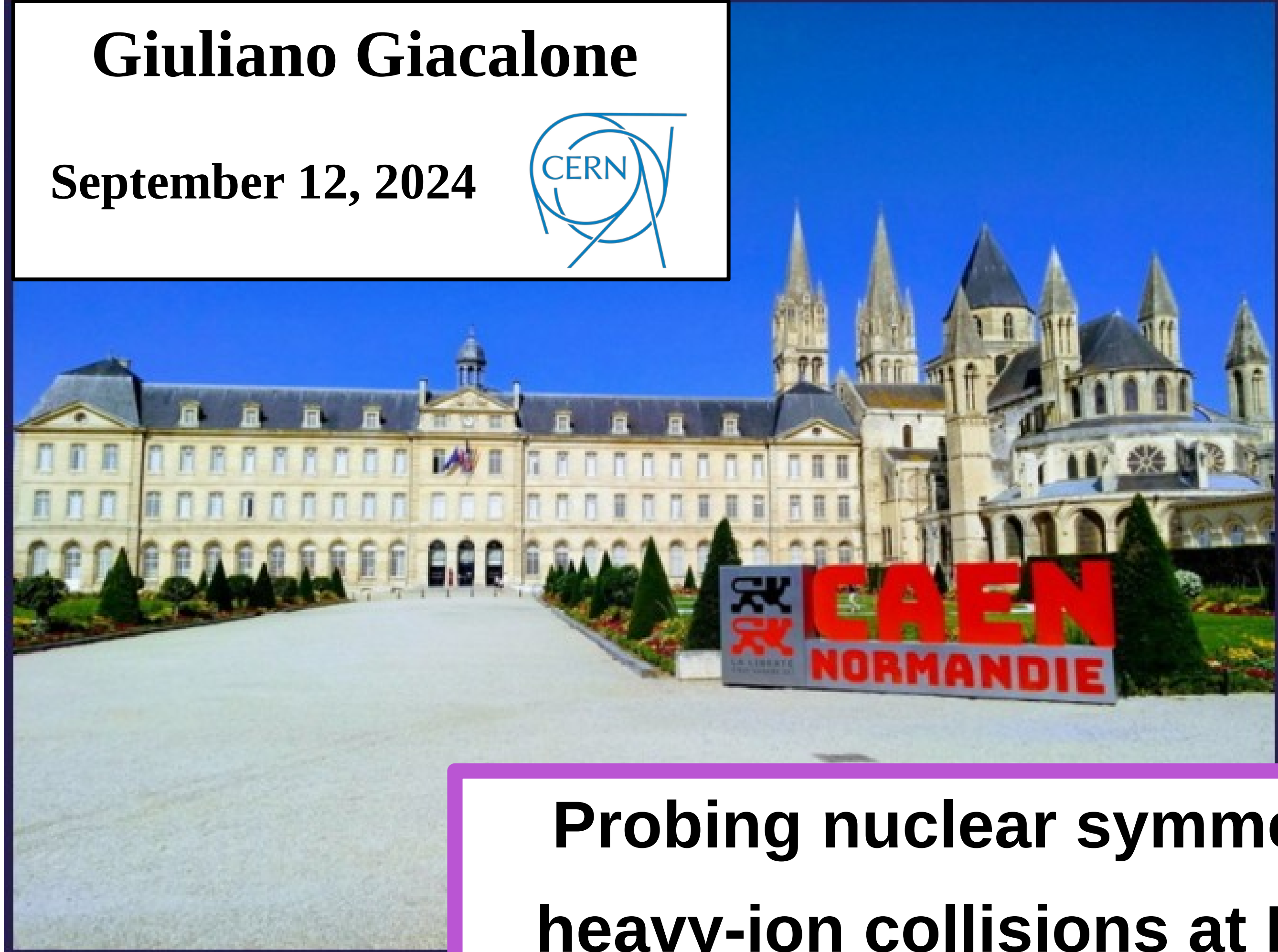
Giuliano Giacalone

September 12, 2024



NUSYM 2024, XIIth International Symposium on Nuclear Symmetry Energy

Probing nuclear symmetry energy in heavy-ion collisions at RHIC and LHC

09–14 set 2024
Caen

OUTLINE

1 – Basics of nuclear collisions at high energy

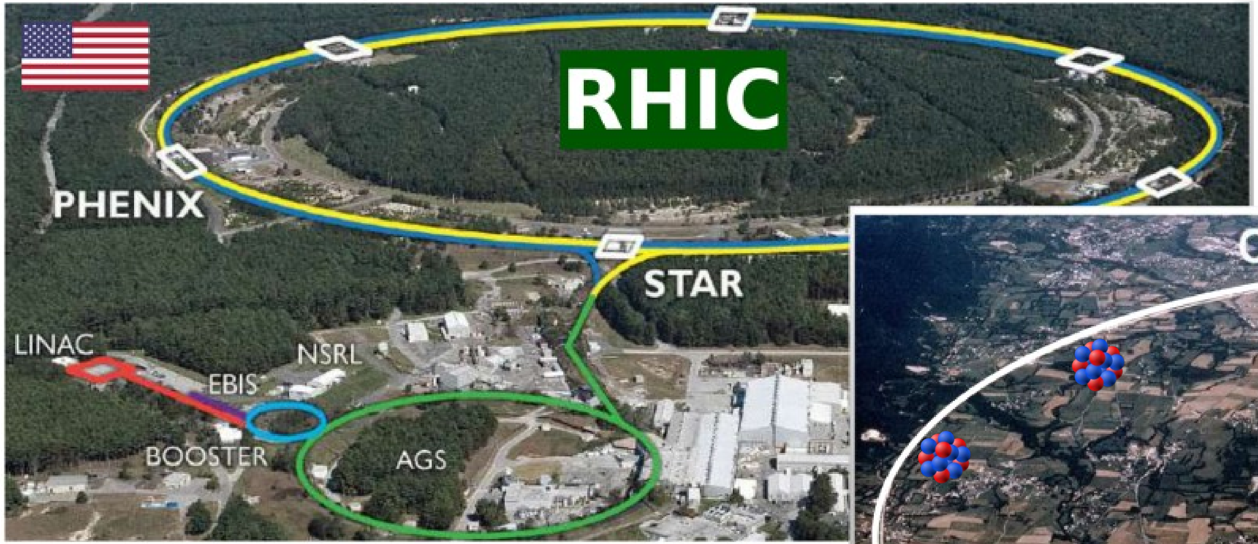
2 – Bayesian inference of the ^{208}Pb neutron skin

3 – Prospects

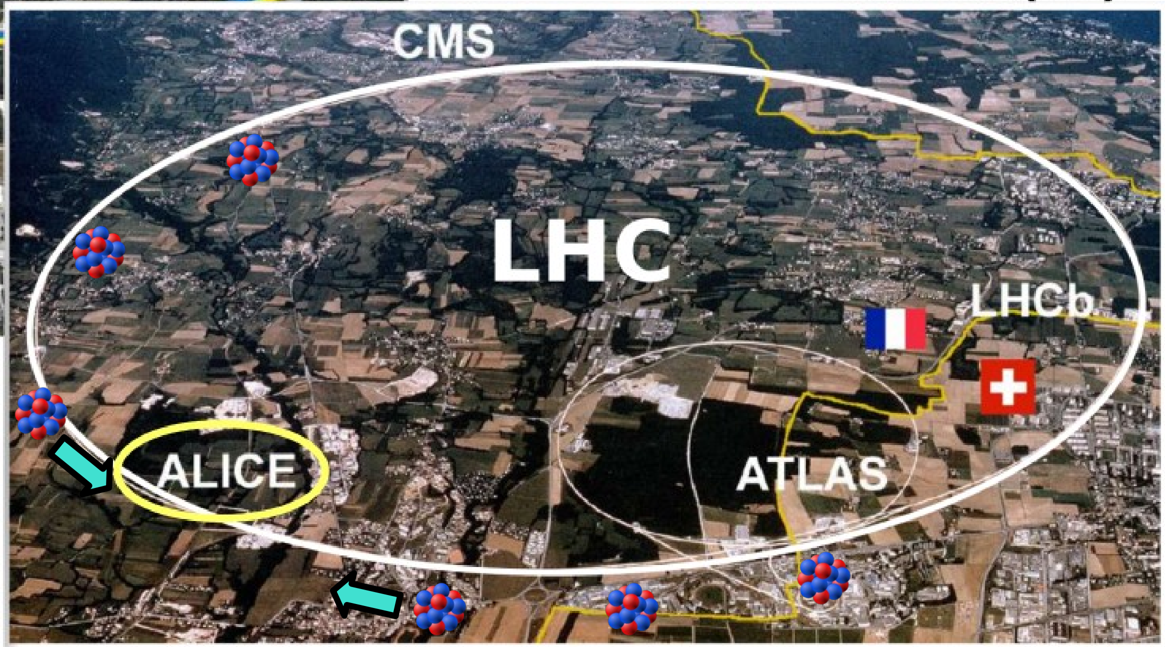
1 – Basics of nuclear collisions at high energy

Ultra-relativistic heavy-ion collisions

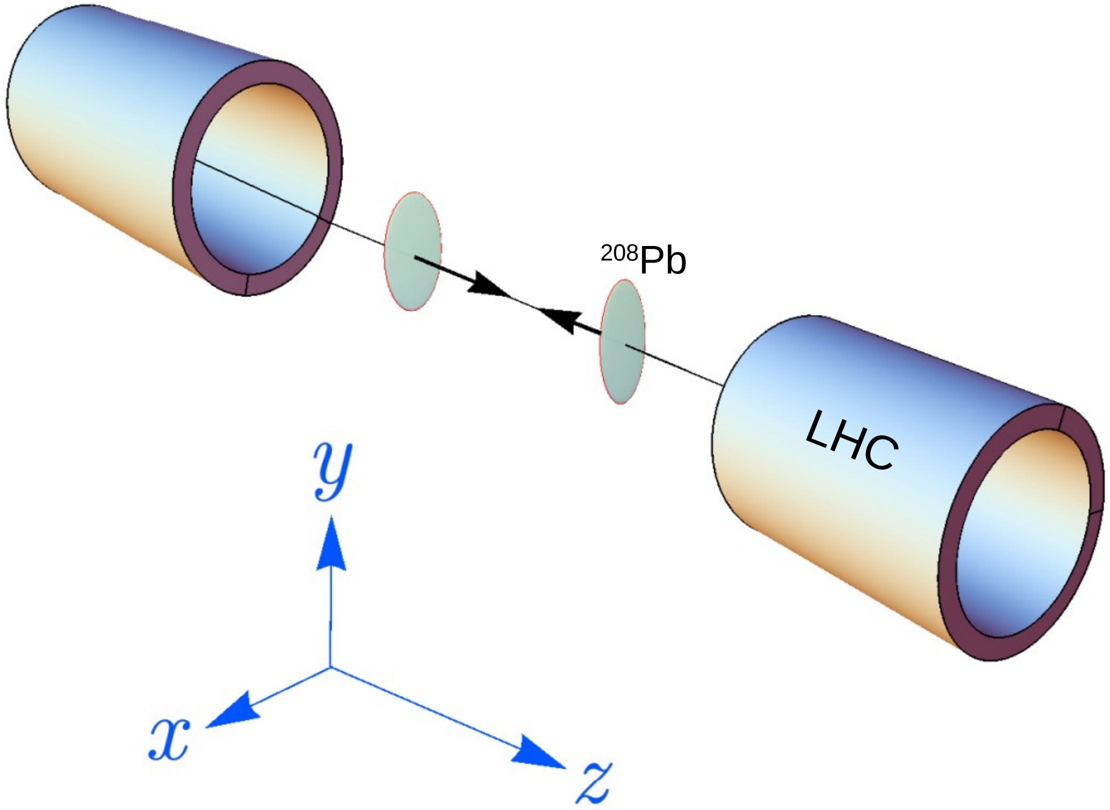
Long Island (NY)



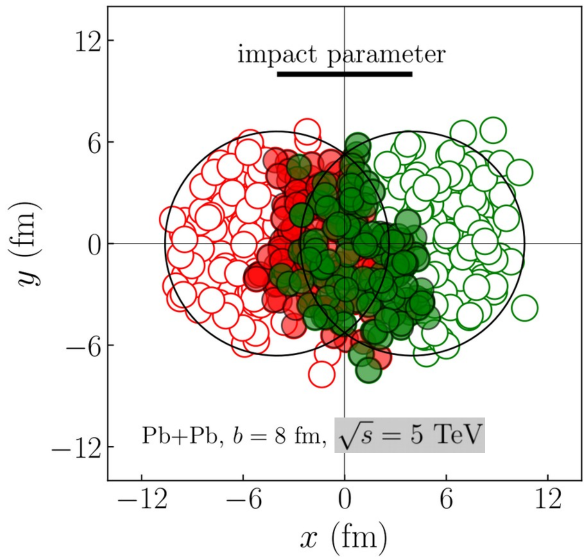
Geneva (CH)

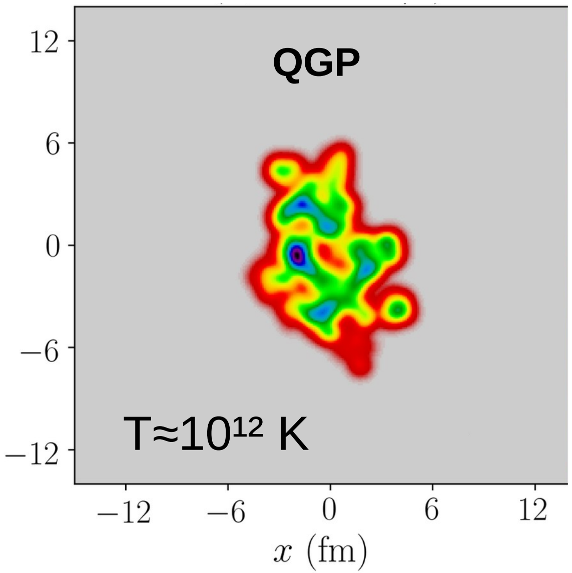


High energy = Nuclei in the lab frame are squeezed in beam direction

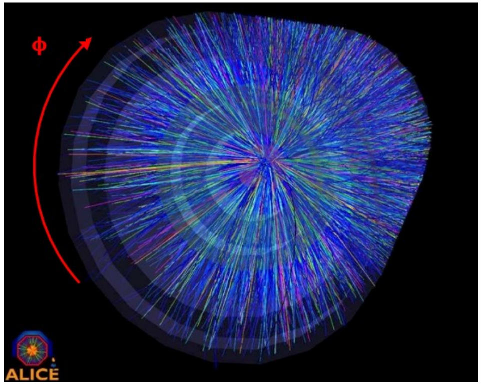


Interaction is instantaneous – Relevant dynamics in the plane transverse to the beam





hydro

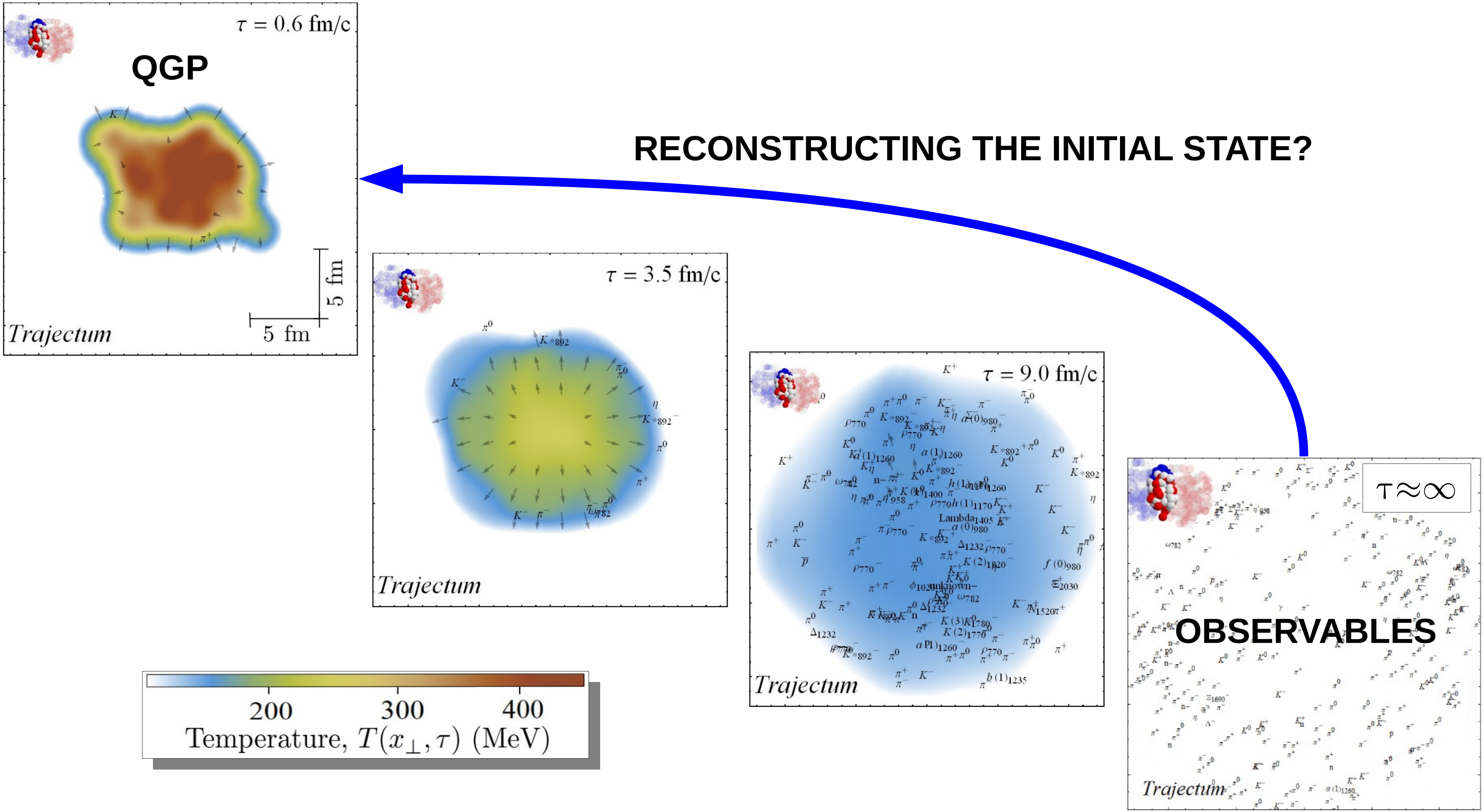


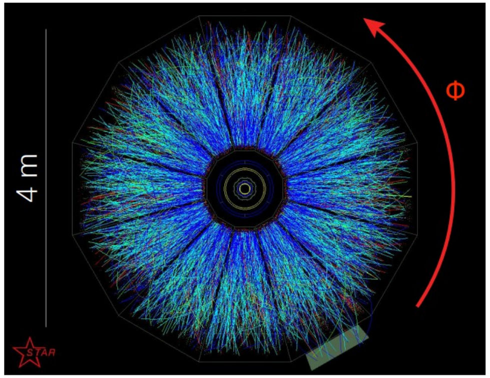
Relativistic fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$

Equation of state from lattice QCD

[HoTQCD collaboration, PRD **90** (2014) 094503]
[Romatschke & Romatschke, arXiv:1712.05815]

Fluid is viscous (η/s **,** ζ/s **, …)**


RECONSTRUCTING THE INITIAL STATE?
QGP
τ = 0.6 fm/c
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)



The art of event-by-event analysis

SPECTRUM

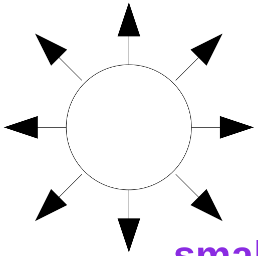
$$\frac{dN_{\mathrm{ch}}}{d\phi p_t dp_t}$$

CHARGED MULTIPLICITY

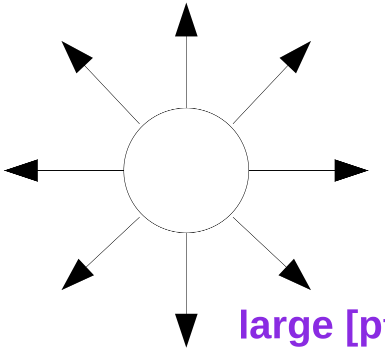
$$N_{\mathrm{ch}} = \int d\phi p_t dp_t \, \frac{dN_{\mathrm{ch}}}{d\phi p_t dp_t}$$

MEAN MOMENTUM

$$[p_t] = \frac{1}{N_{\mathrm{ch}}} \sum_{i=1}^{N_{\mathrm{ch}}} p_{t,i}$$



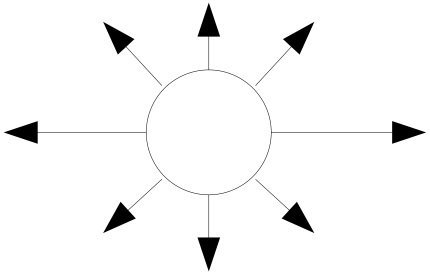
small $[p_T]$



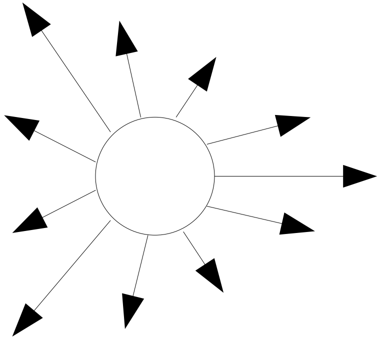
large $[p_T]$

FOURIER HARMONICS

$$V_n = \frac{1}{N_{\mathrm{ch}}} \sum_{i=1}^{N_{\mathrm{ch}}} e^{-in\phi_i}$$



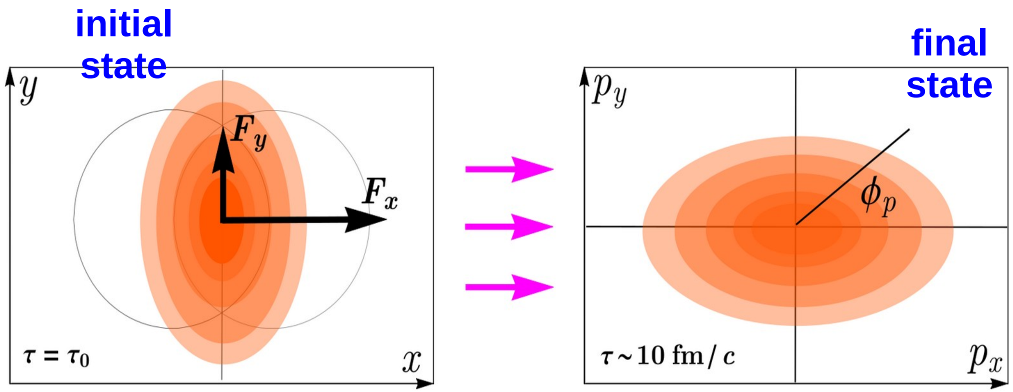
elliptic flow, v_2



triangular flow, v_3

What we see in the final state reflects properties in the initial state

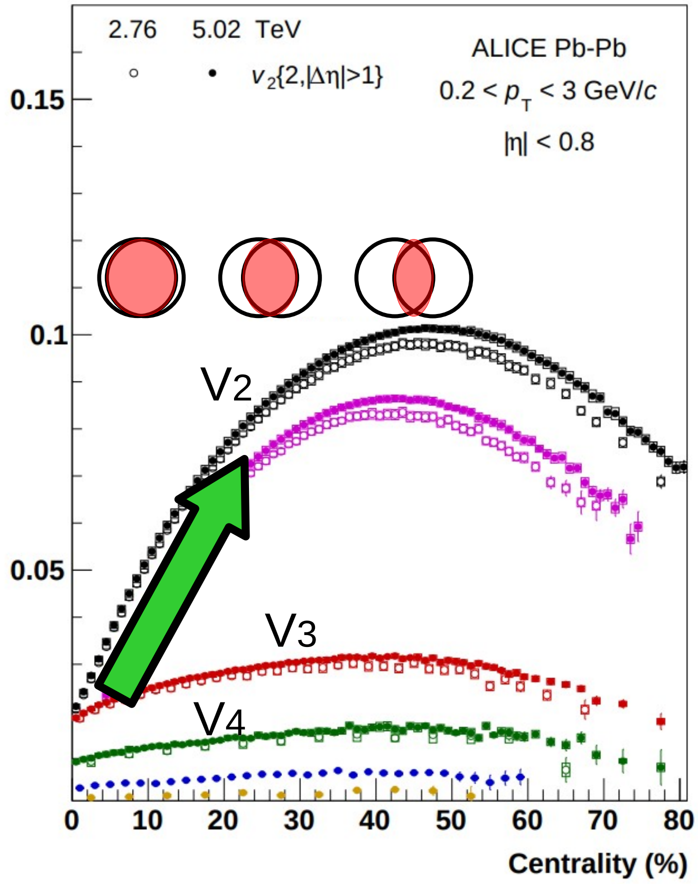
ELLIPTIC FLOW MEASURES THE INITIAL DEFORMATION



$$F = -\nabla P$$

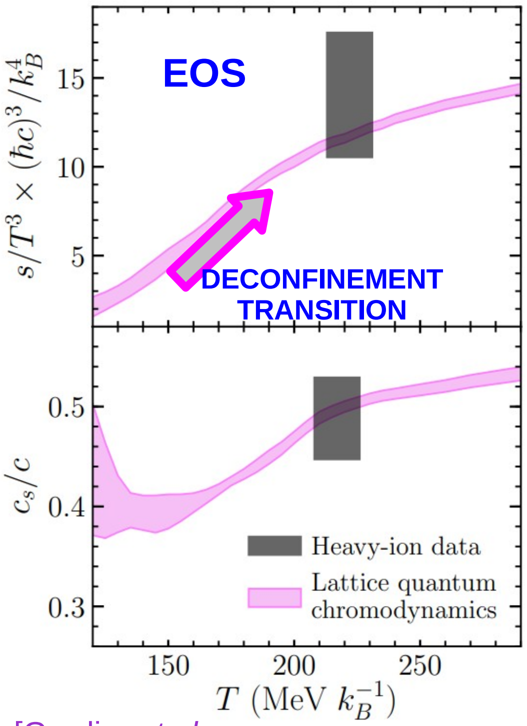
1/R

$$V_2 = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$$

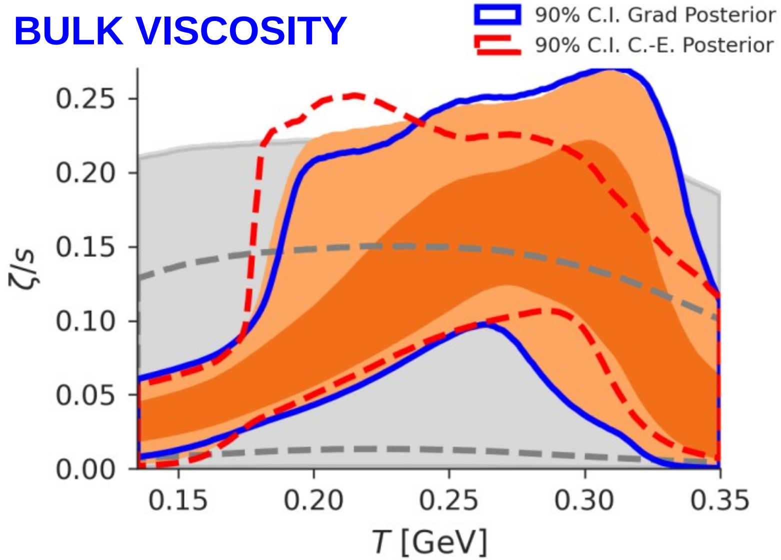


Hydrodynamics preserves information about the initial geometry

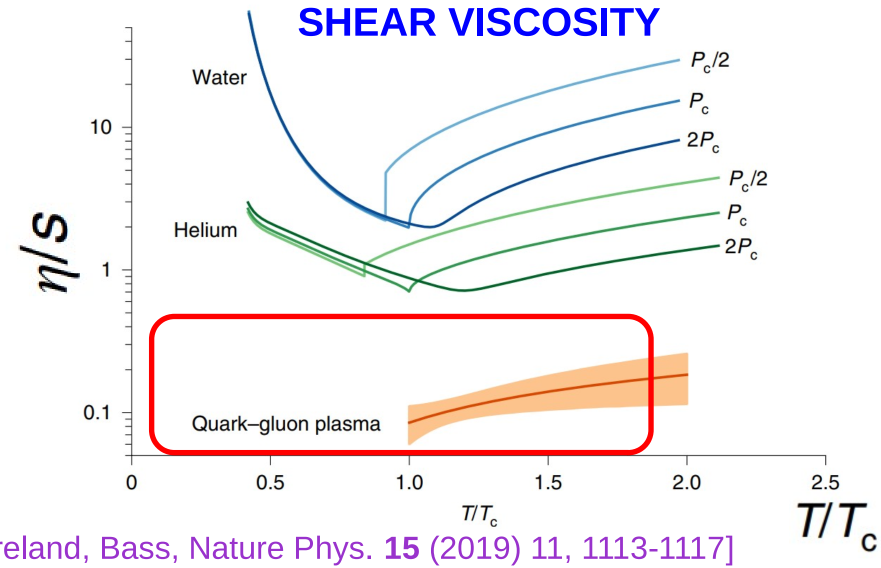
Highly successful program!



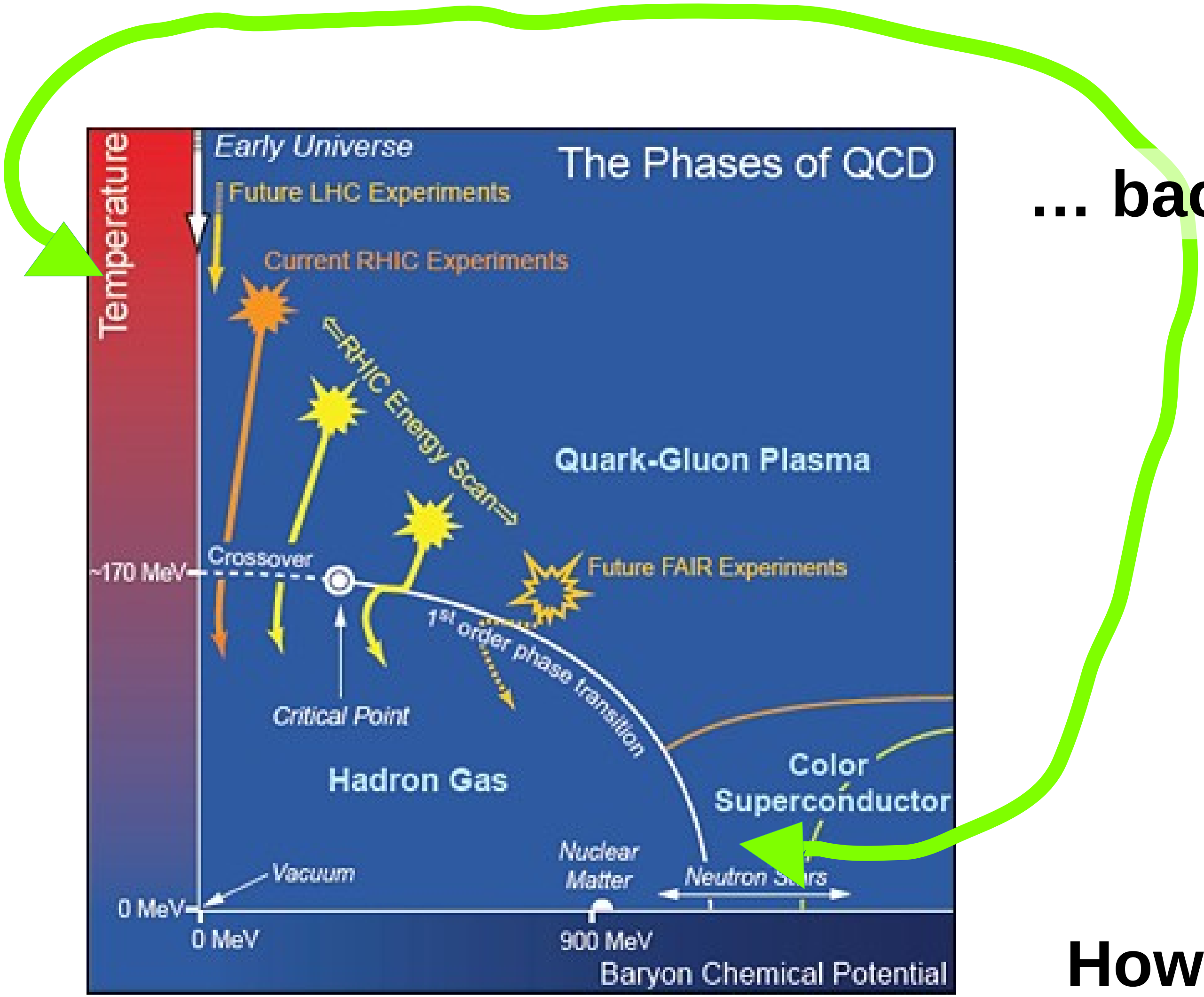
[Gardim *et al.*,
Nature Phys. **16** (2020) 6, 615-619]



[Heffernan *et al.*,
PRL **132** (2024) 25, 252301]



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



… back to this workshop

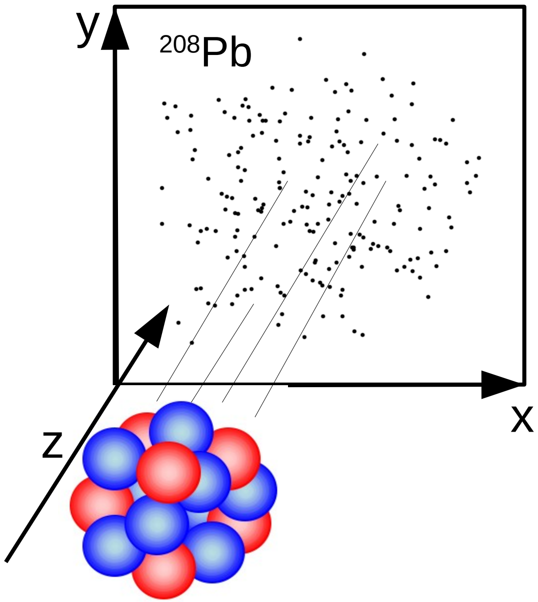
???

How do we connect them?

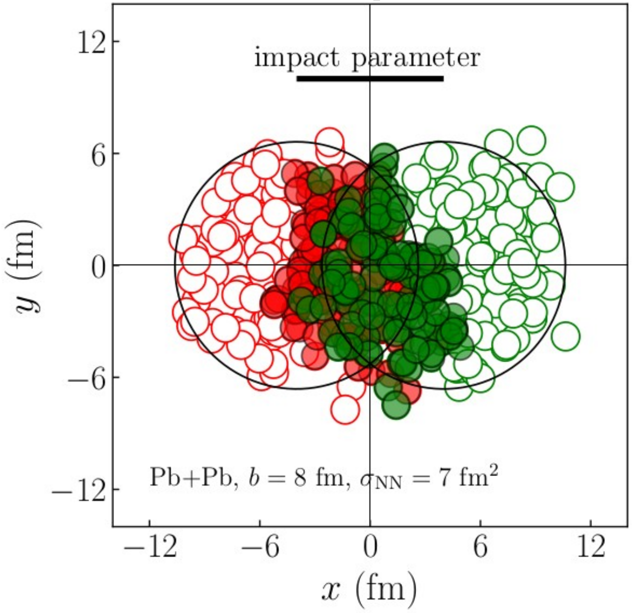
2 – Bayesian inference of the ^{208}Pb neutron skin

How do we probe nuclear matter? We probe nuclear structure

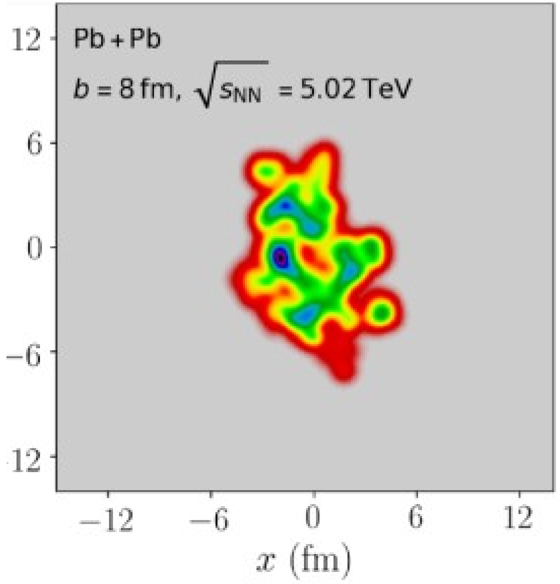
nucleon centers



overlap two nuclei



energy density



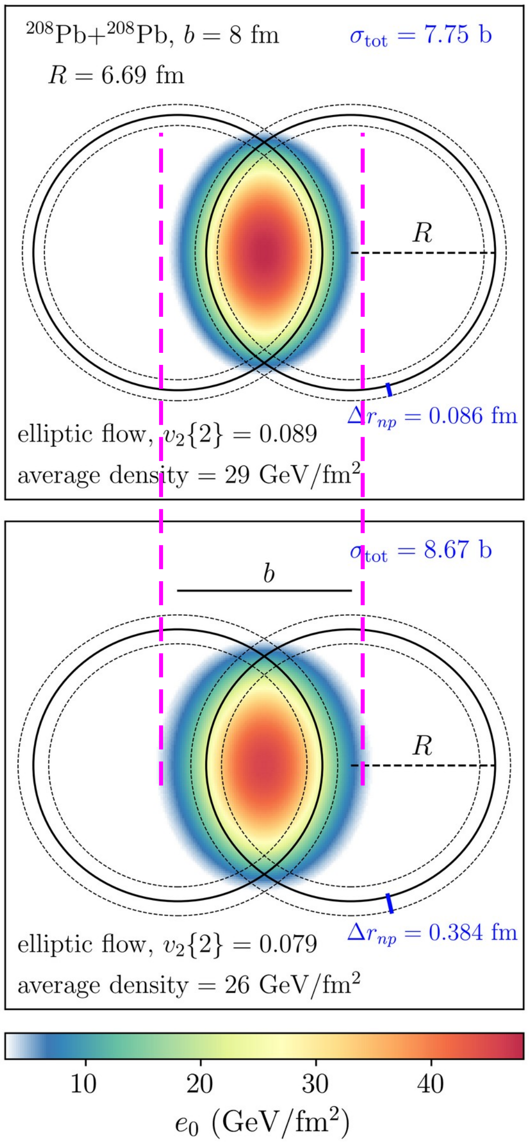
Input is number of nucleons and radial profile

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

Skin thickness is an input of the model!

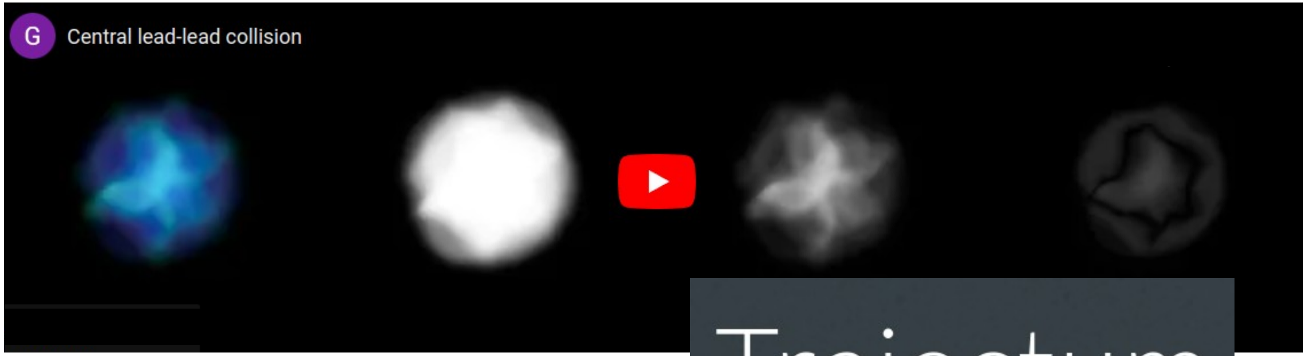
Expected signatures of the neutron skin

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



OUR COMPUTATIONAL FRAMEWORK

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

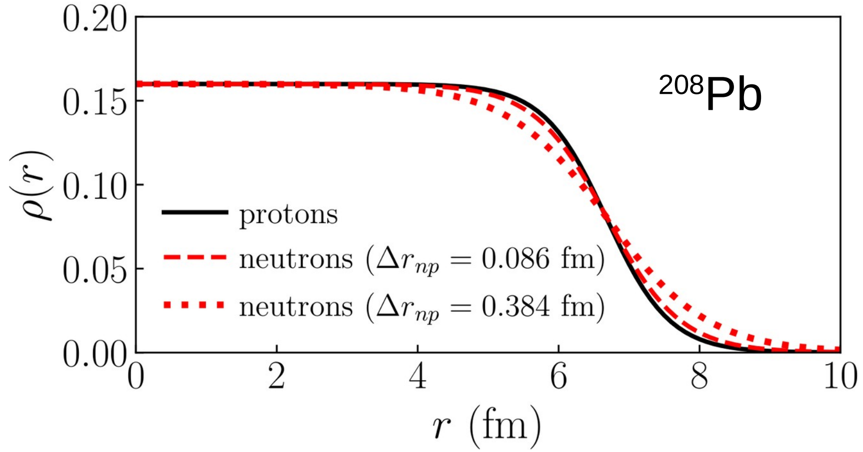


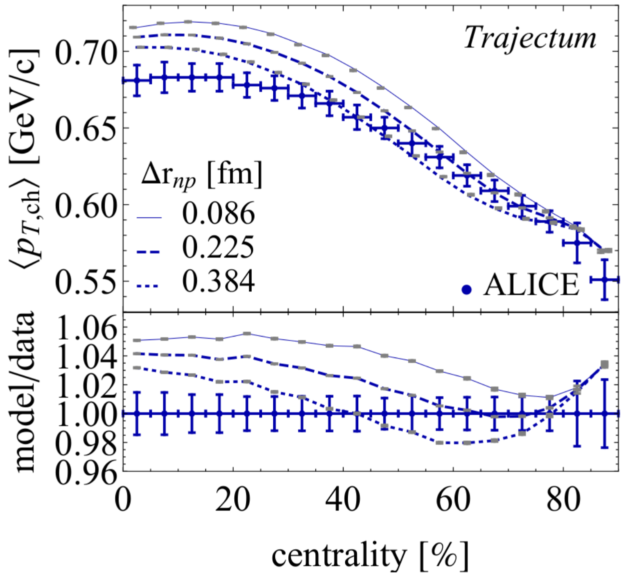
Trajectum

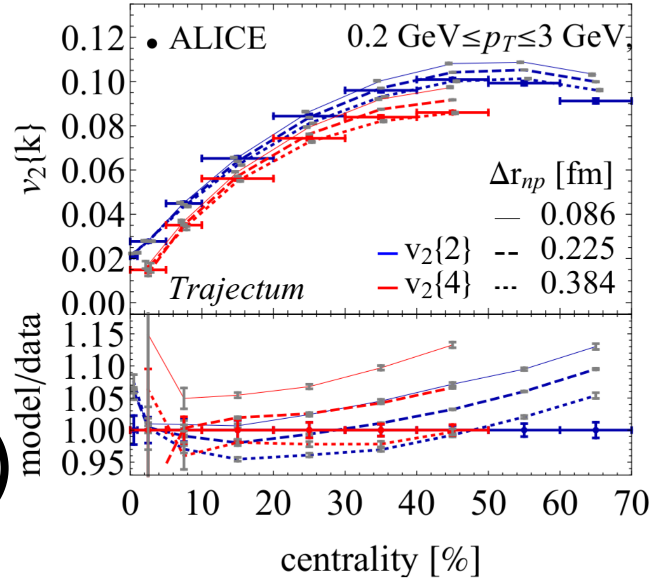
Developed in Utrecht by Govert Nijs (CERN) and Wilke van der Schee (CERN/Utrecht)

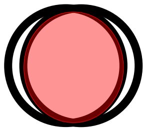
[Nijs, van der Schee, Gürsoy, Snellings, PRC **103** (2021) 5, 054909 – PRL **126** (2021) 20, 202301]

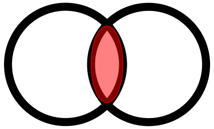
Test on observables in hydro











Promising… global analysis?

OUR STRATEGY: BAYESIAN ANALYSIS

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

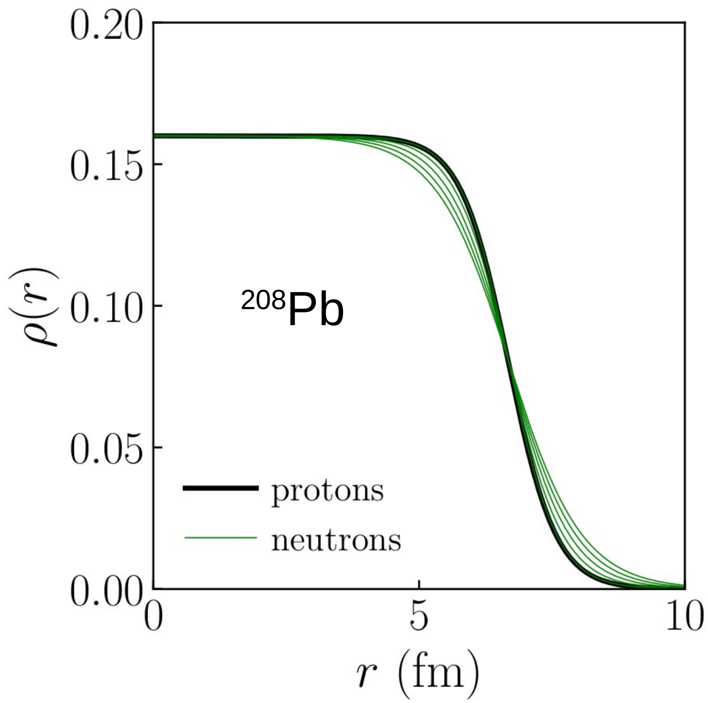
Promote neutron diffuseness to a model parameter

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

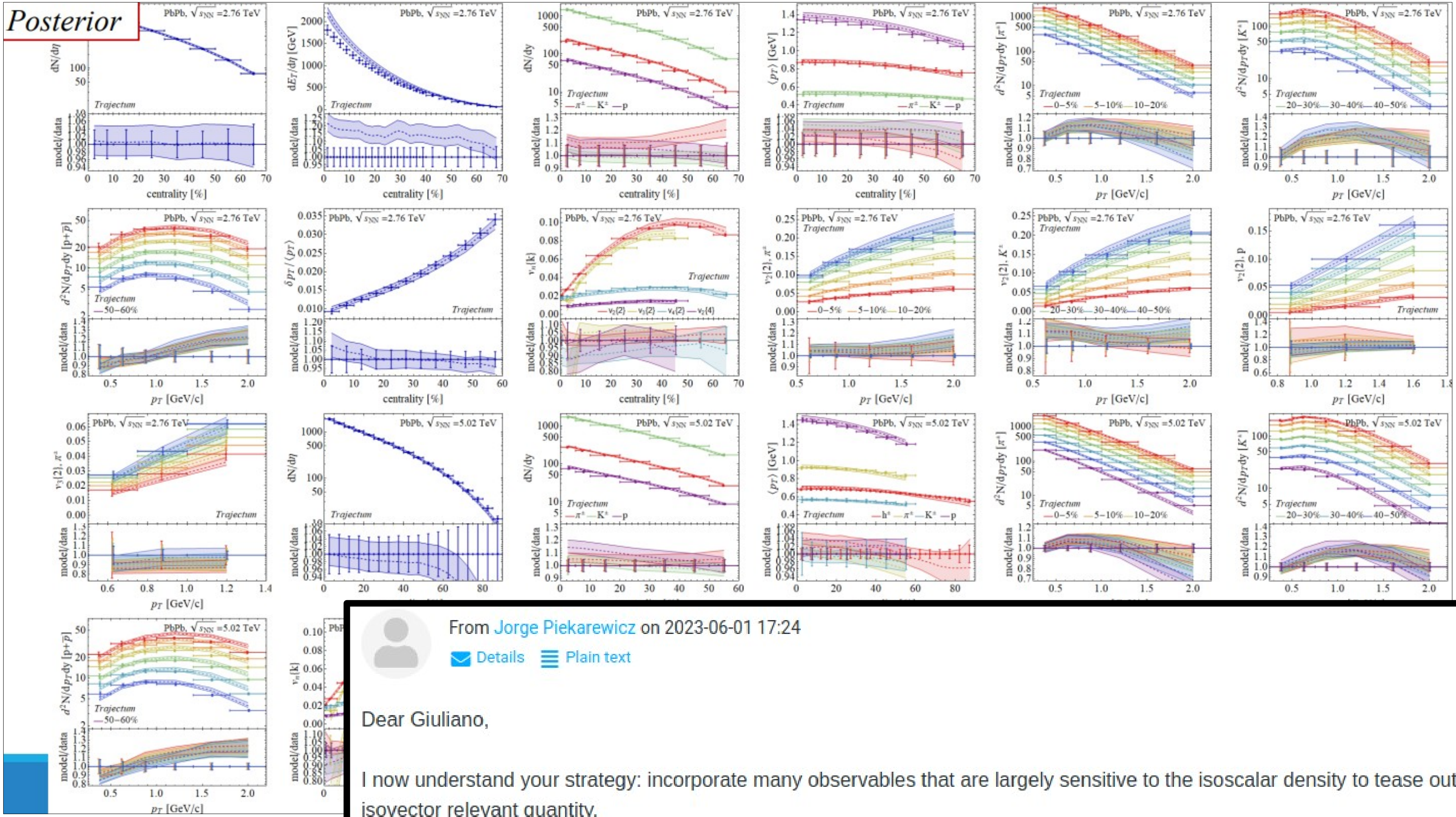
Protons: density from low-energy scattering

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

Neutrons: same R as protons, infer a from data



~ 700 data points on Pb+Pb collisions



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.

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

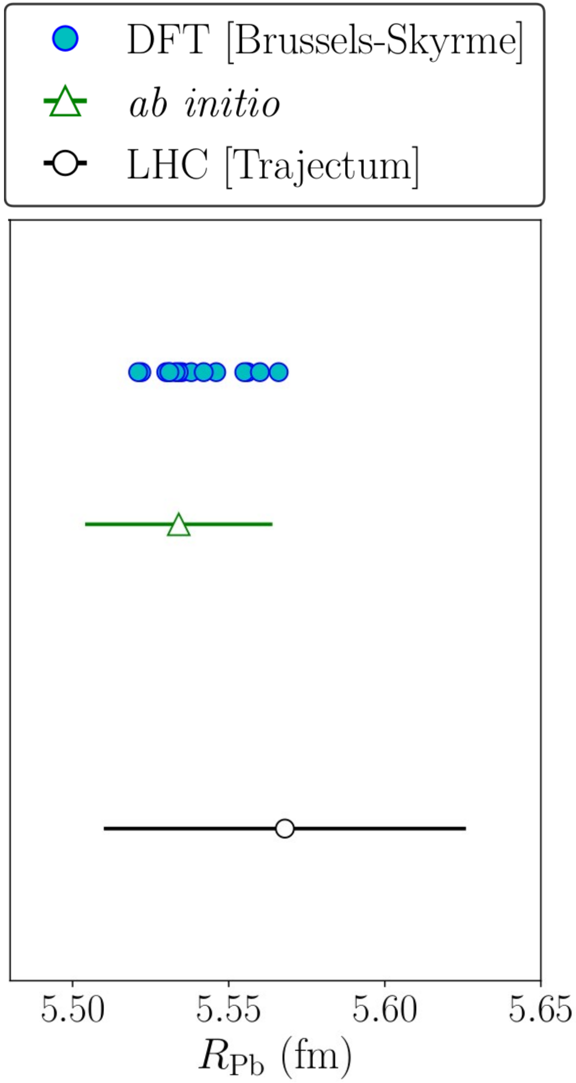
[BSkG2 functional by W. Ryssens]

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

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

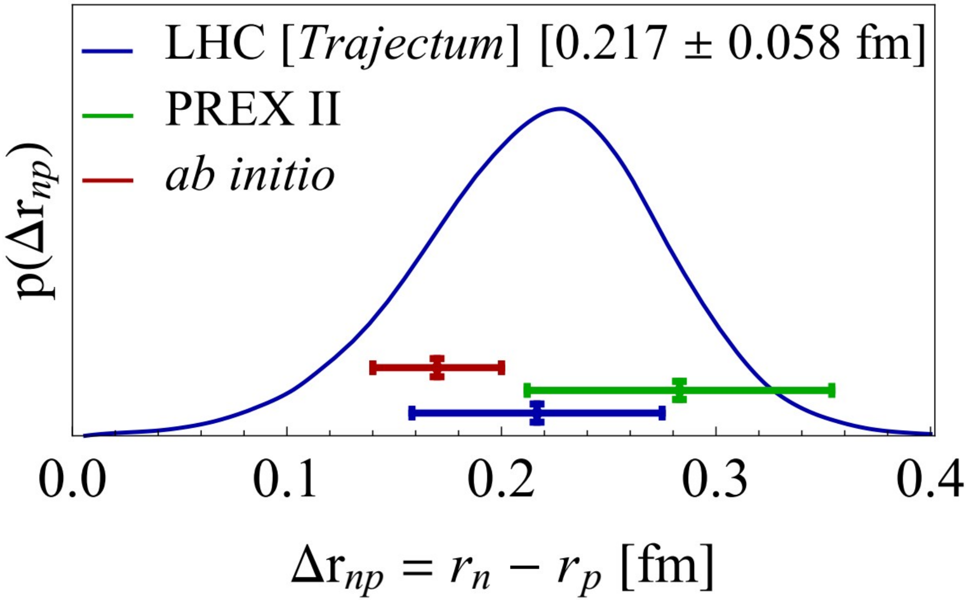
- $R_{\mathrm{Pb}}(\mathrm{LHC}) = 5.568 \pm 0.058\ \mathrm{fm}$

[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]

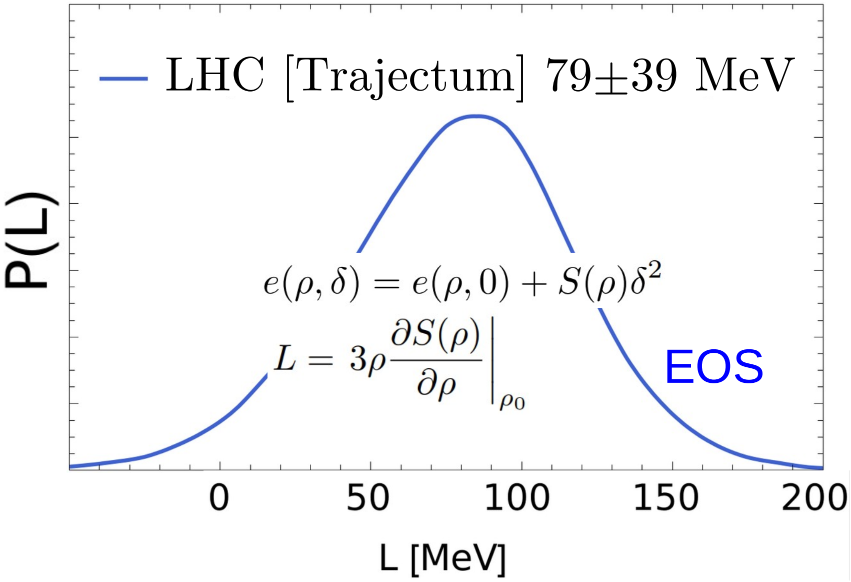


Extracting the radial profile – Neutron skin

[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]



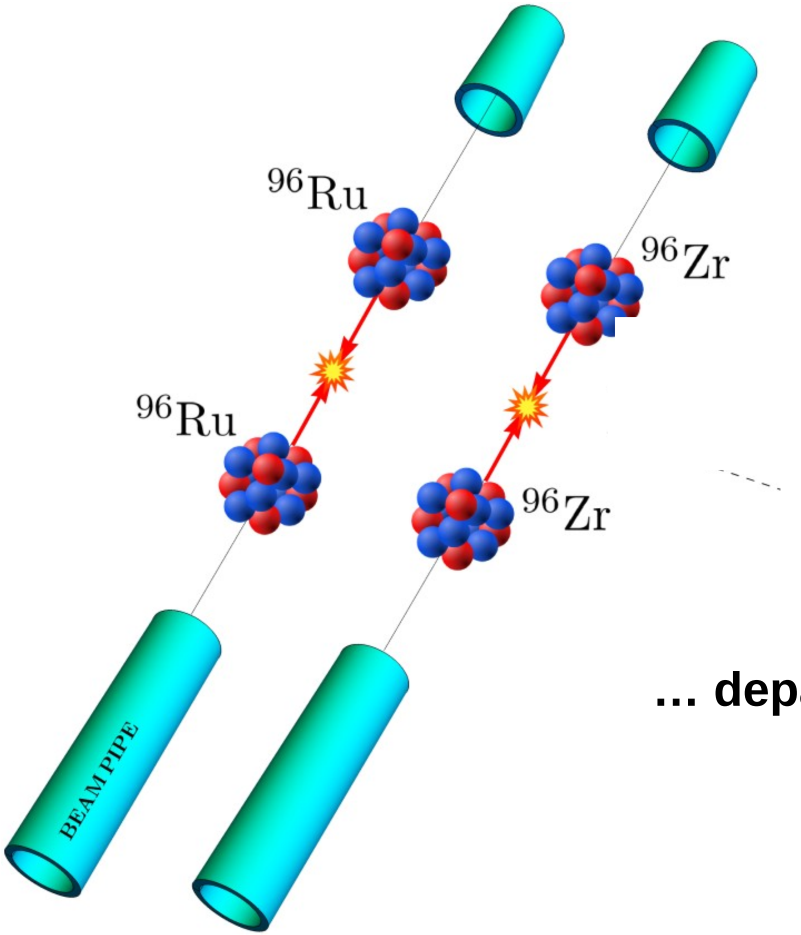
[using Viñas *et al.*, EPJA **50** (2014) 27]



PREX II	$0.278 \pm 0.078\ (\text{exp.}) \pm 0.012\ (\text{theo.})\ \text{fm}$
LHC	$0.217 \pm 0.058 (\text{theo.})\ \text{fm}$

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

How about RHIC data? We can look at isobar collisions



X and Y are isobars

Ratios of observables (O) should be unity…

$$\frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \stackrel{?}{=} 1$$

[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]

… departure from unity mainly due to nuclear structure

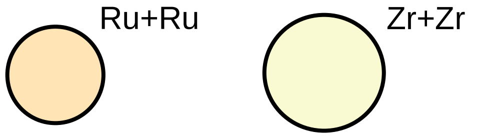
Extremely precise measurements

Accessing the skin difference... Neutrons matter!

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

- 96Zr, more diffuse **due to larger N**
- 96Ru, sharper surface

Ru+Ru systems are more compact...

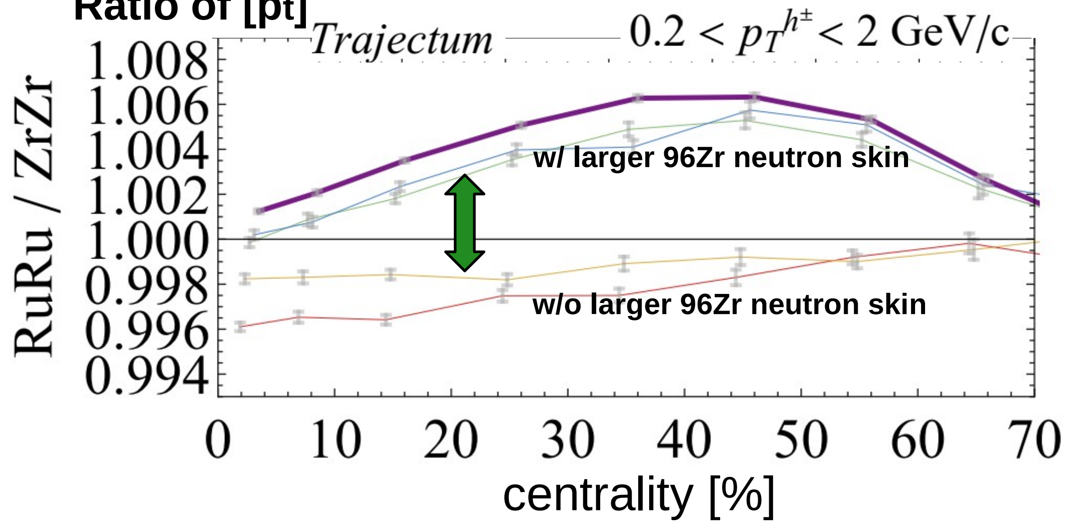


... p_t is enhanced

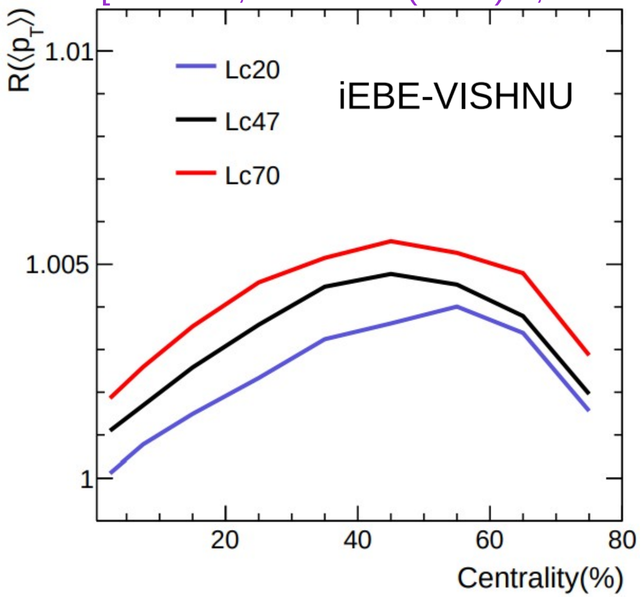
$$F = -\nabla P \rightarrow 1/R$$

[Nijs, van der Schee, SciPost Phys. **15**, 041 (2023)]

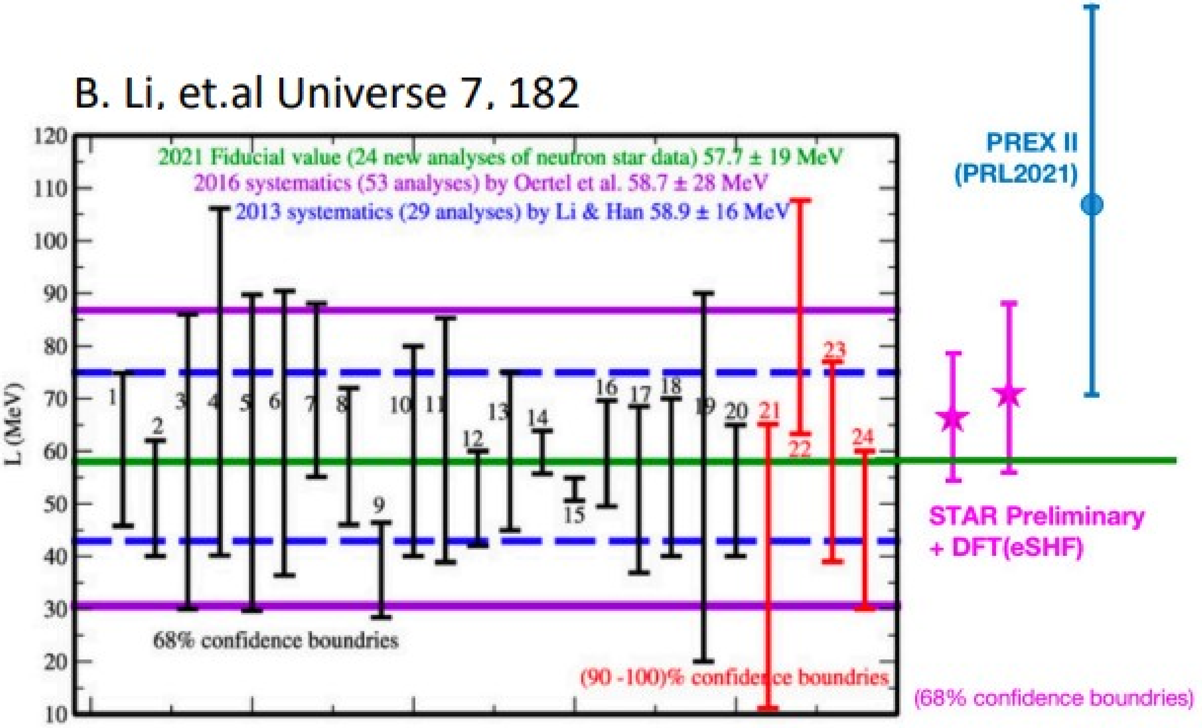
Ratio of [pt]



[Xu *et al.*, PRC 108 (2023) 1, L011902]



Preliminary determinations from STAR data [Haojie Xu]



NB: Bayesian analysis is required for rigorous error validation

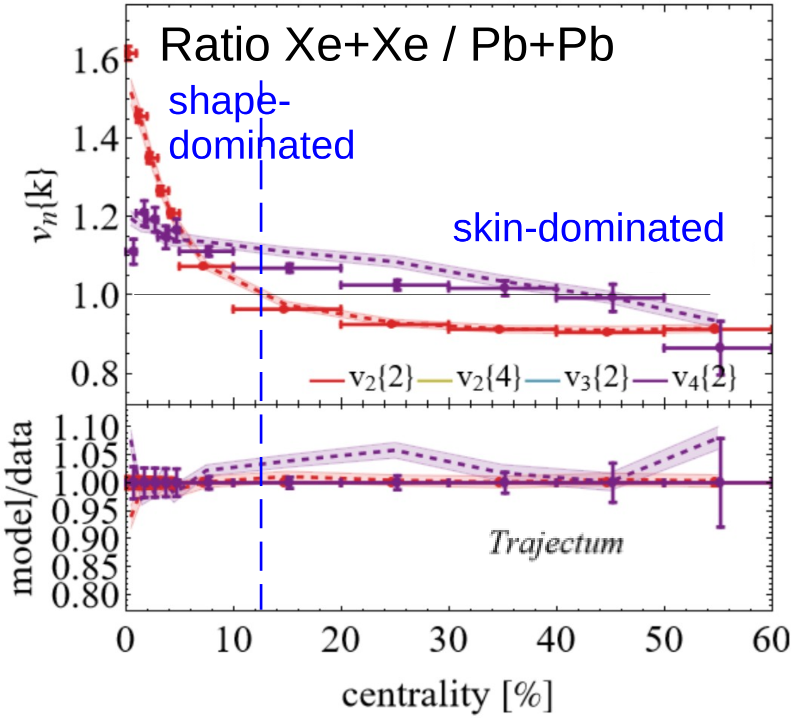
3 – Prospects

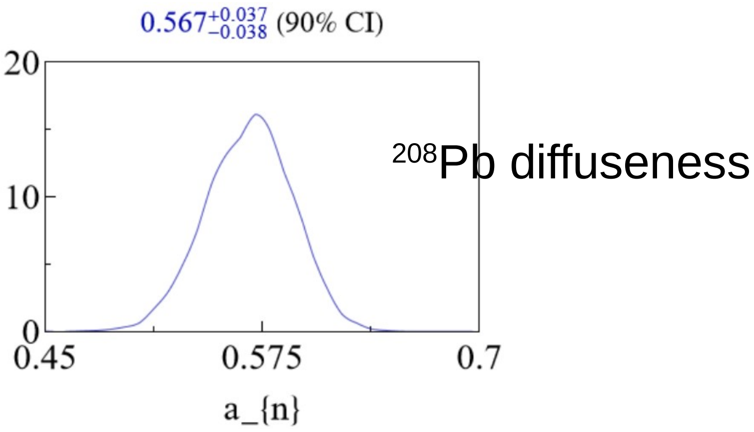
Improved constrains from more than one system

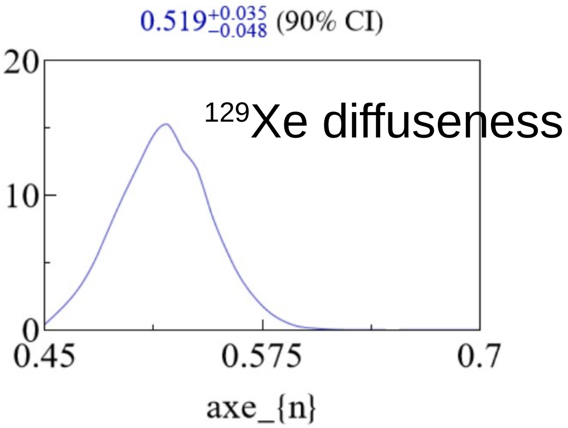
Use Xe+Xe data

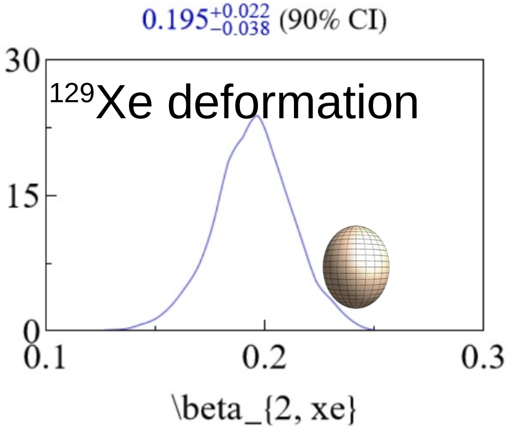
PRELIMINARY RESULTS

[e.g, ALICE collaboration, PLB **784** (2018) 82-95]







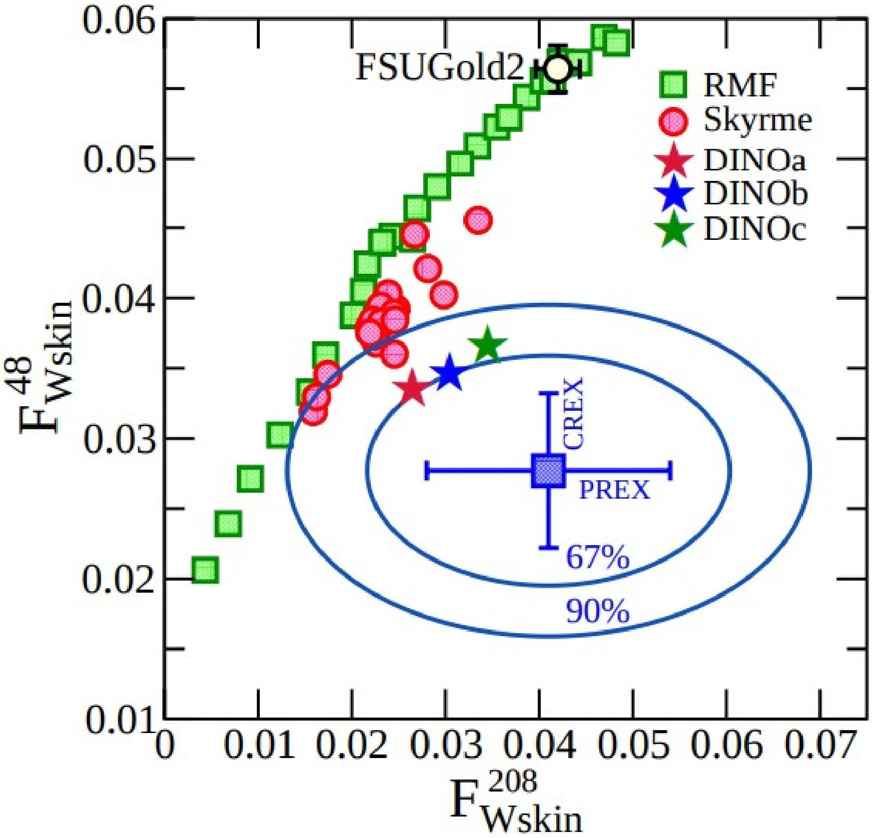


Tension between PREX and CREX results?

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

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

[Reed *et al.*, PRC **109** (2024) 3, 035803]



Case for running ^{48}Ca at LHC?

Isobar pair ^{48}Ca and ^{40}Ca proposed

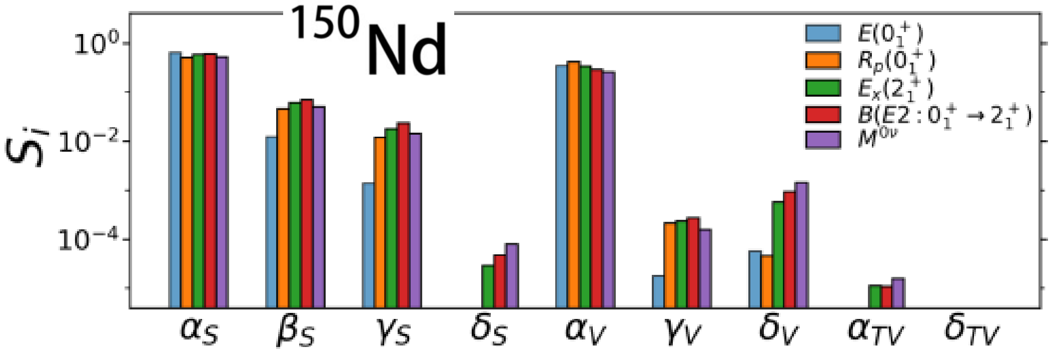
"zero skin" of ^{40}Ca should enable precision extraction of ^{48}Ca skin

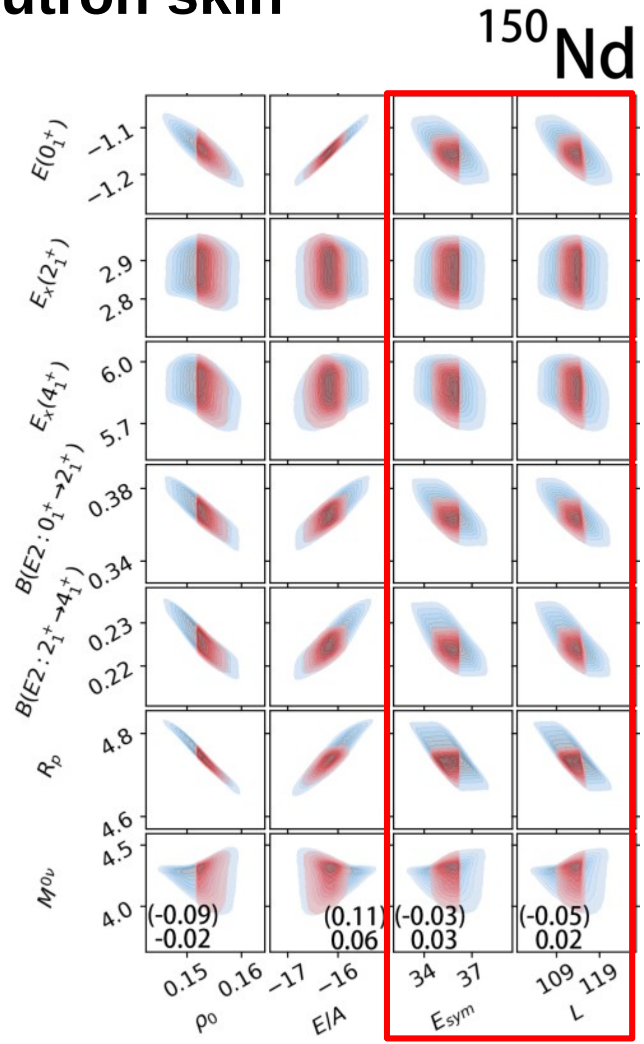
NLEFT calculations in progress… stay tuned

Probing the EOS beyond the neutron skin

Emulator technology and global sensitivity analysis

[Zhang *et al.*, arXiv:2408.13209]



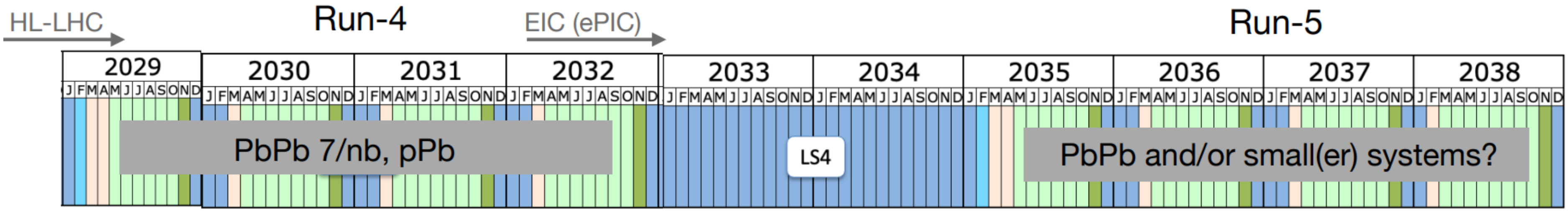


Global sensitivity of RHIC/LHC data to pin down the effective interaction (and L)?

Probing the EOS beyond the symmetry energy?

How about correlations, three-body forces, …. ?

Good cases for additional species @ LHC Run 5? Input is highly timely / wanted



SUMMARY

- **Highly developed understanding of particle production in heavy-ion collisions**
- **Point-matter profile of ^{208}Pb extracted from LHC data – More from other systems soon**
- **Results consistent with low-energy determinations!**
- **Looking forward to future progress and collaborations**