Nuclear-structure constraints from ultrarelativistic collisions

Applications for nuclear matrix elements?

Matthew Luzum

University of São Paulo

Recommended Values for Neutrinoless Double-Beta Decay Nuclear Matrix Elements
July 15, 2026

Outline

1. Ultrarelativistic nuclear collisions
2. What can be measured?
3. Example 1: Surface deformation parameter extraction
   - Mean field picture: β_2, γ, β_3, neutron skin, ...
4. Example 2: Nuclear EFT coefficient extraction
   - Using Nuclear Lattice Effective Field Theory
5. Connection to nuclear matrix elements
   - NMEs and high-energy observables
6. Summary

Ultrarelativistic nuclear collisions

High-energy nuclear colliders

- Relativistic Heavy Ion Collider (RHIC) *(2000–2026)*
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- Nominal goal: physics at and above confinement scale
- Also sensitive to nuclear structure
- Useful for reducing uncertainties in nuclear matrix elements?
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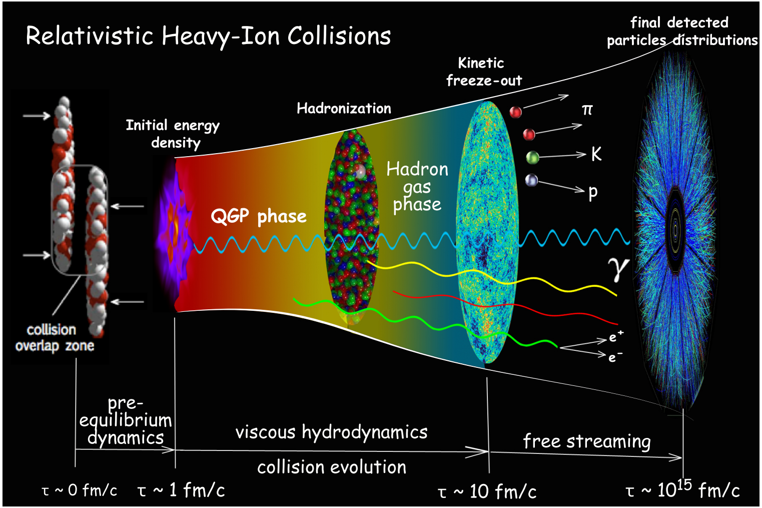

Image: C. Shen

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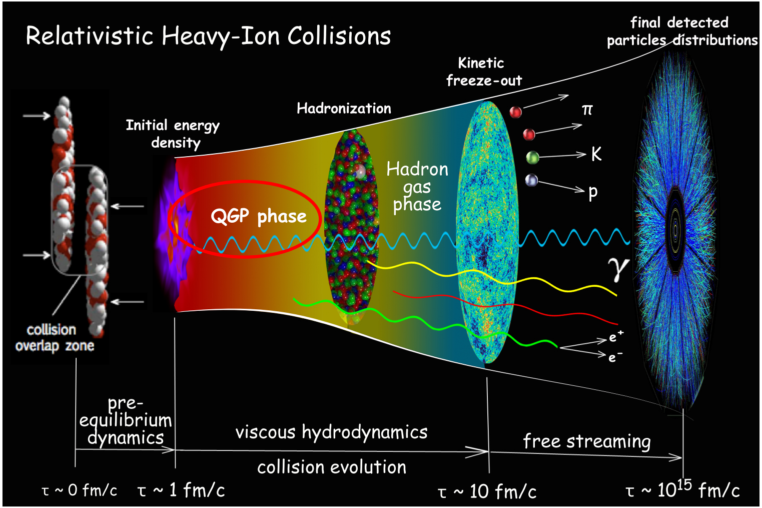

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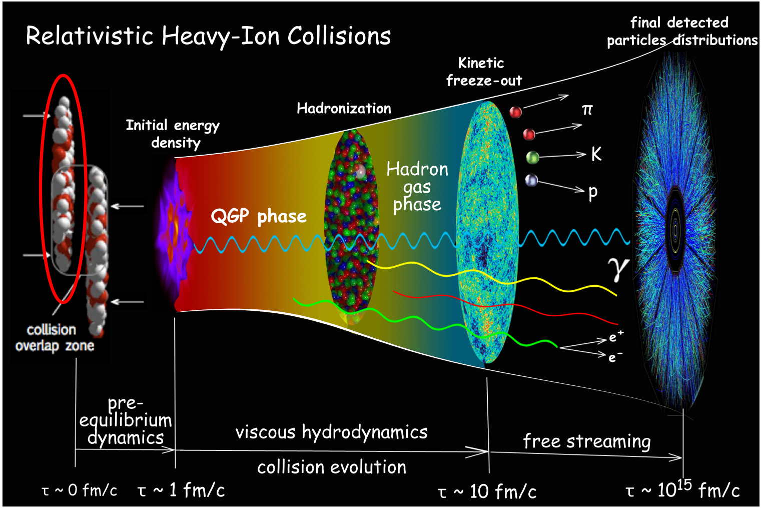

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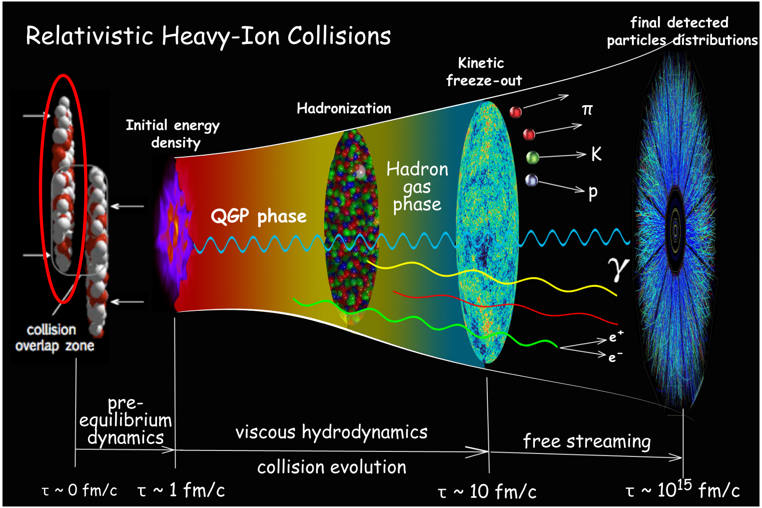

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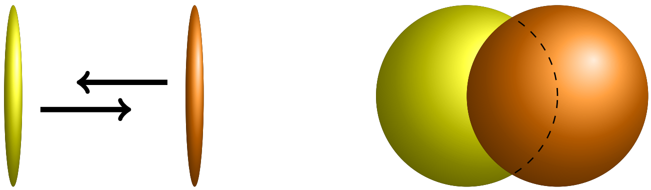
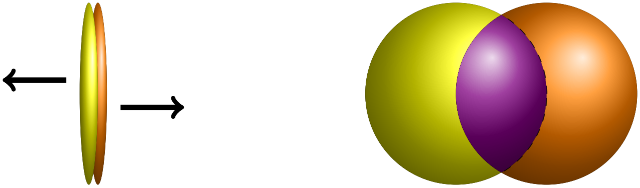
ENERGY/TIME SCALES



- Typical LHC energy: $\sqrt{s_{NN}} \sim 5$ TeV $\implies$ ~ 2.5 TeV per nucleon
- E.g., ^{208}Pb $\implies$ total energy ~ 500 TeV
- Full crossing time of two nuclei: $\sim 2R/\gamma \sim 0.01$ fm/c
- No time for nuclear dynamics — snapshot of nuclear wave function

$$P(\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_A) = |\langle \vec{x}_1, \vec{x}_2, \ldots, \vec{x}_A | \Psi \rangle|^2$$

Energy/time scales



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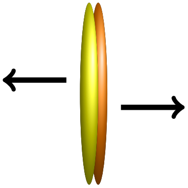

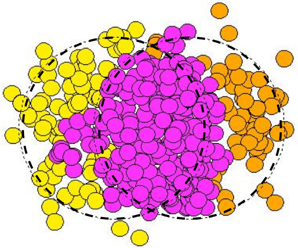

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1. Snapshot of target/projectile nuclei
2. Multi-stage simulation (initial scattering/interactions, hydrodynamics, kinetic theory)
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4. $\sim 10^5$ produced particles for $\sim 10^6$ collisions
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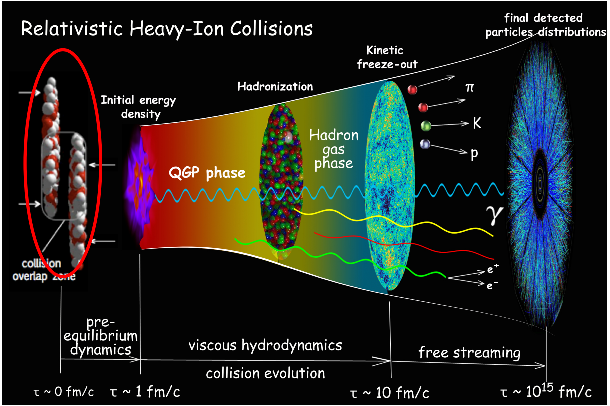

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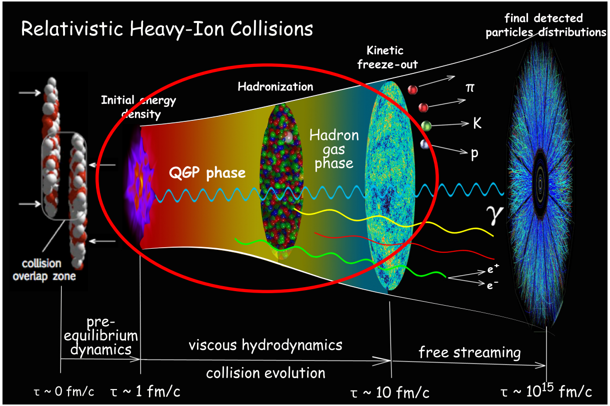

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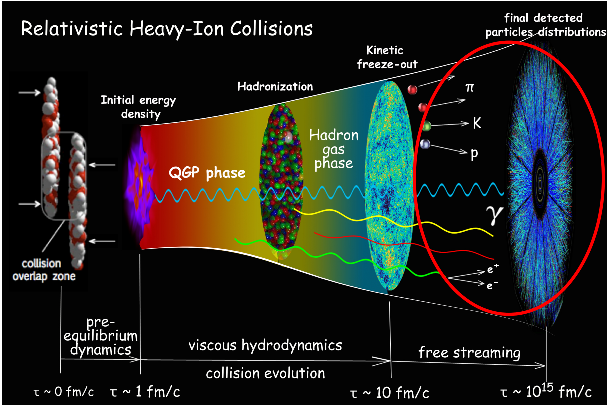

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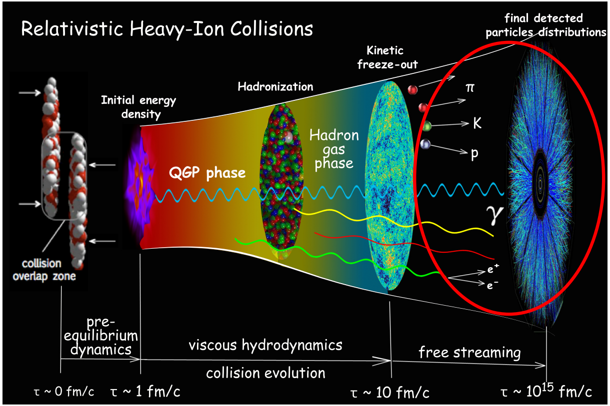

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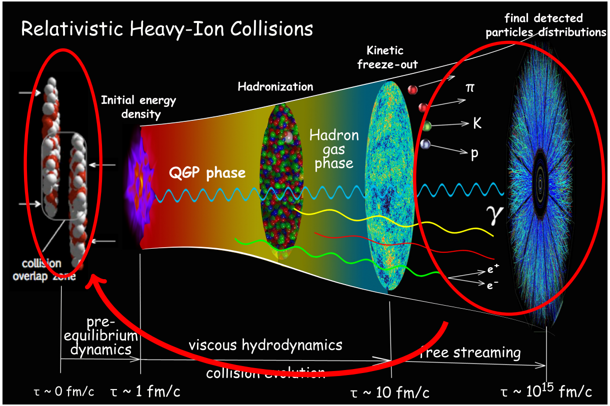

What can be measured?

Sensitivity to nuclear structure — Rules of thumb

- Ground state only (and only stable nuclei)
- Isospin/charge less important – most sensitive to overall matter/baryon density/correlations
- Spin also less important — $P(\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_A)$
- Hierarchy of scales: long-range correlations more important than short-range correlations/structure ("nuclear deformation")
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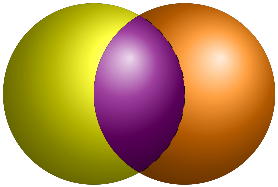
Mean field picture with no long-range correlations

- Step 1 of simulation: Generate target/projectile nuclear configurations
- Simplest case: no long-range correlations (e.g., doubly magic ^{208}Pb)
- Quantum fluctuations still important!
- Sample independent nucleons from Woods-Saxon distribution:

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



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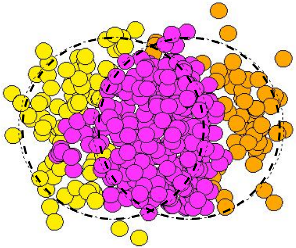

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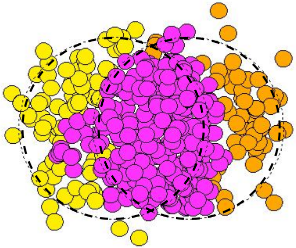

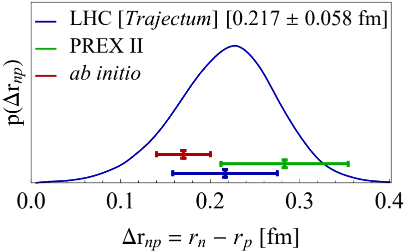

Giacalone, Nijs, van der Schee; Phys.Rev.Lett. 131 (2023) 20, 202302

Deformed nuclei

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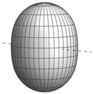

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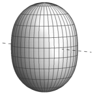

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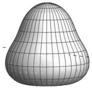

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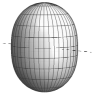

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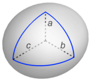
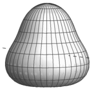


Triaxial



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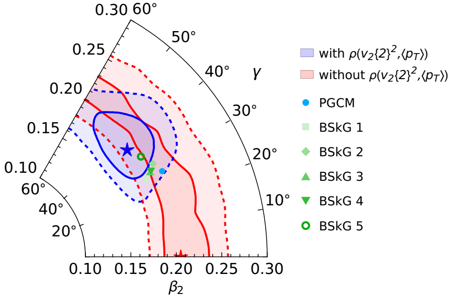
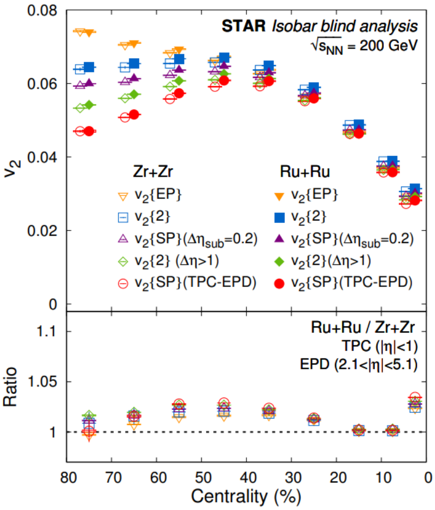


^{129}Xe — Giacalone, Nijs, van der Schee; arXiv:2606.03993

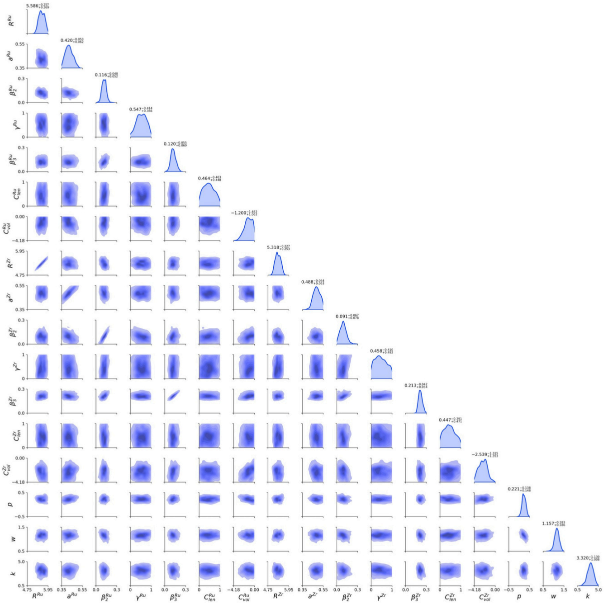
PAIRWISE PROPERTY EXTRACTION

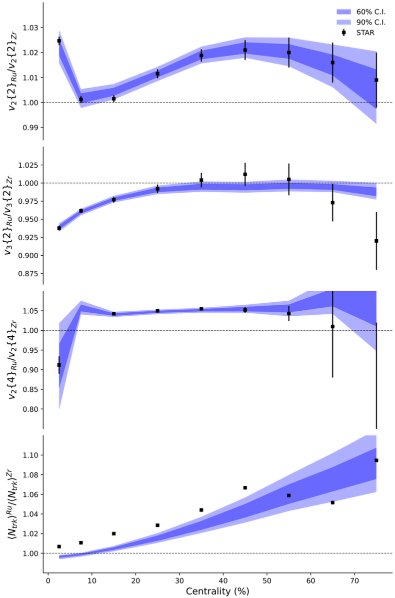
- RHIC: $^{96}_{40}Zr + ^{96}_{40}Zr$ and $^{96}_{44}Ru + ^{96}_{44}Ru$ collisions
- Ratios of measurements for similar mass cancel experimental/theoretical uncertainty
- $\Longrightarrow$ Precise constraint on *relative* properties
- Useful for parent/daughter decay pairs?



STAR Collaboration; Phys. Rev. C 105, 014901 (2022)

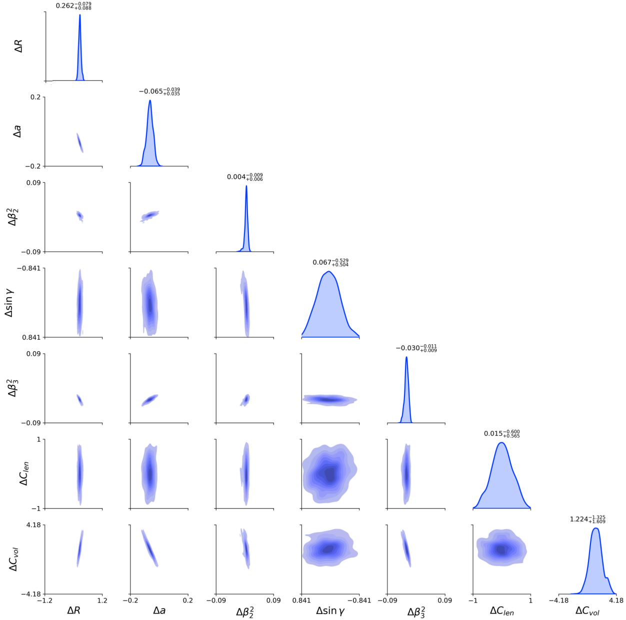
RESULTS (PRELIMINARY ROUGH ESTIMATES)





João Picchetti, ML; work in progress

RELATIVE VALUES (PRELIMINARY ROUGH ESTIMATES)



$$\Delta x_i = x_i^{\mathrm{Ru}} - x_i^{\mathrm{Zr}}$$

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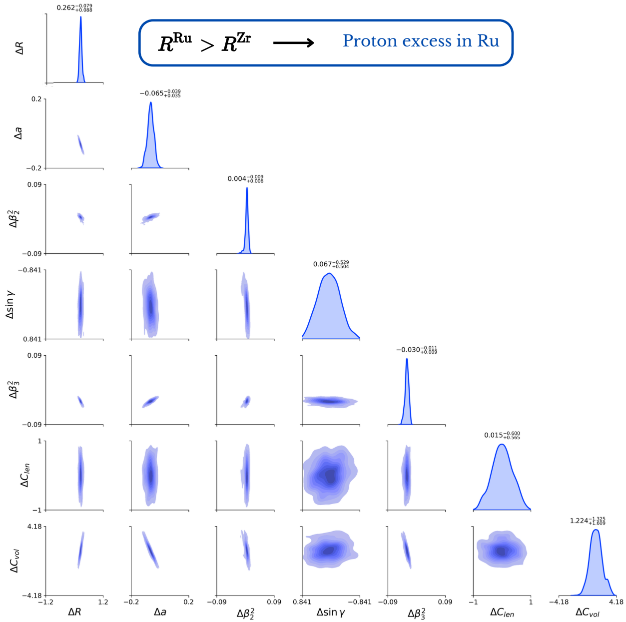

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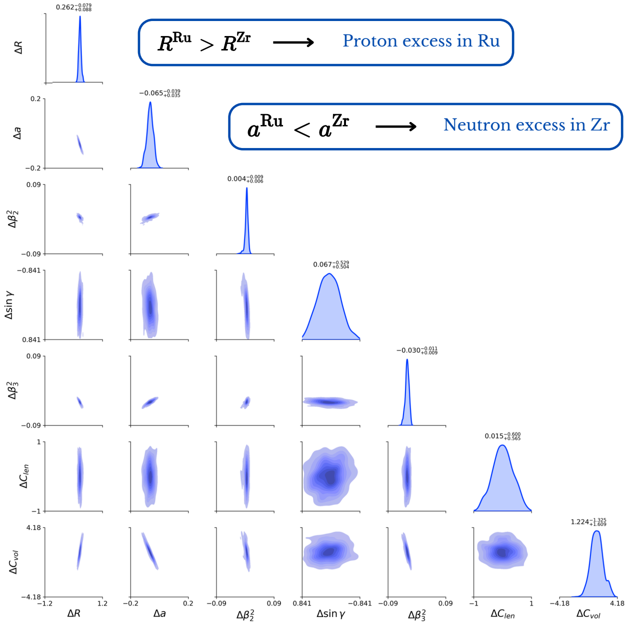

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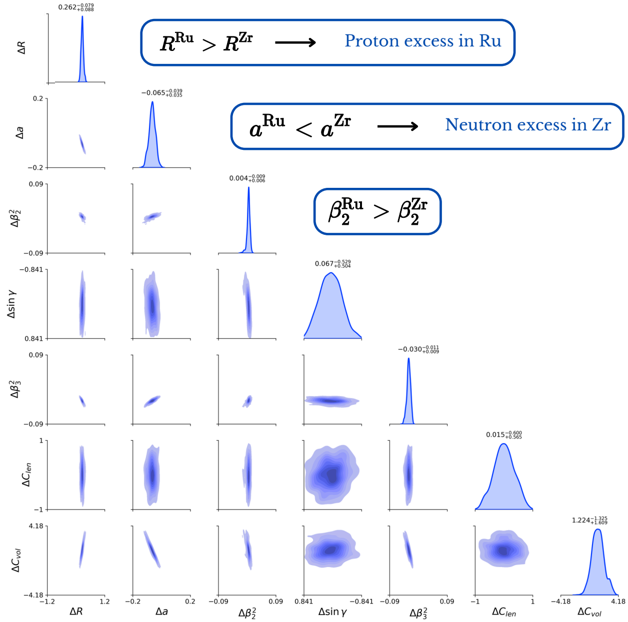
Relative values (Preliminary rough estimates)



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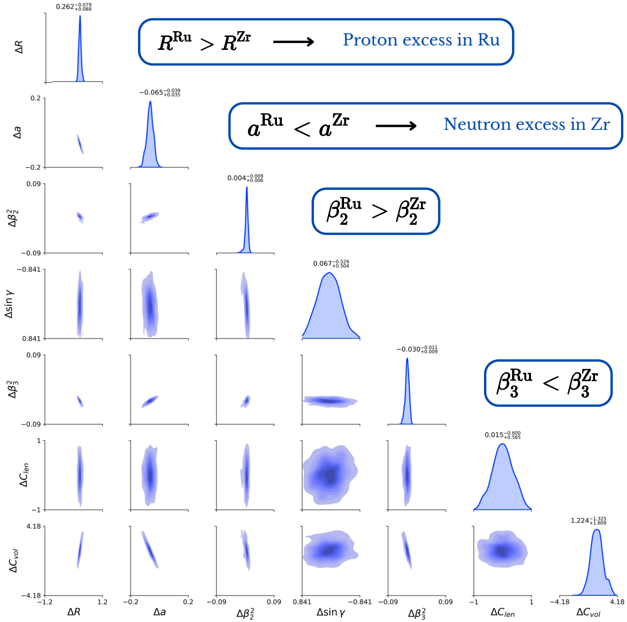

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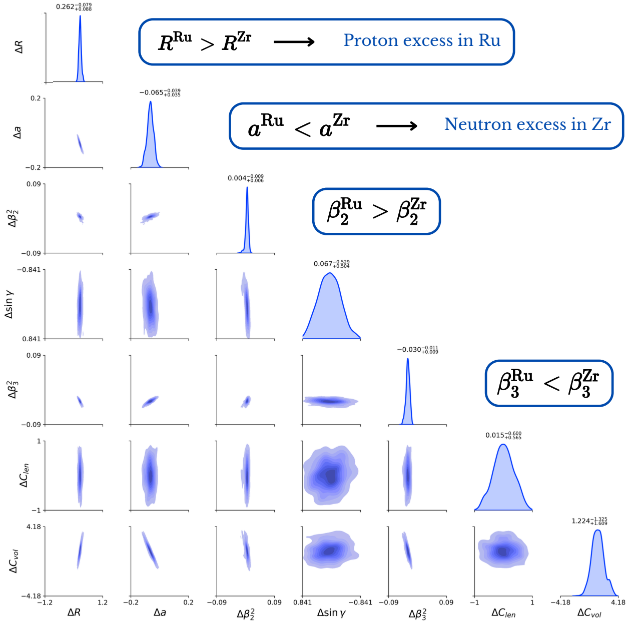

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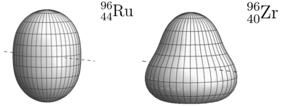
Consistent with spectroscopic measurements

↓

	β_2	β_3
$^{96}_{44}$Ru	0.05 - 0.16	?
$^{96}_{40}$Zr	0.08	0.20 - 0.27



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Model-independent quantities

N-body operators

- "Deformation" parameters model-dependent
- Can instead extract model-independent quantities. *Blaizot, Giacalone, Lovato; arXiv:2512.18926*:

$$\mathcal{B}_n^2(\mathrm{HE}) \equiv \frac{4\pi}{3} \frac{\langle \hat{\mathcal{E}}_n \rangle}{\langle \hat{R}_n \rangle^2}$$

1-body operator

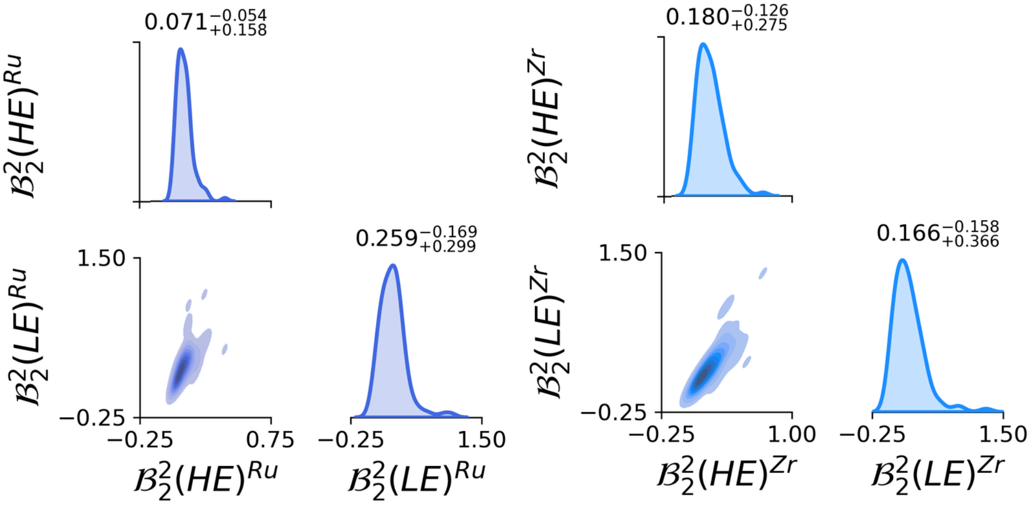
$$\hat{R}_n = (r_\perp^2)^{n/2},$$
$$\langle \hat{R}_n \rangle = \int_{\mathbf{r}} (r_\perp^2)^{n/2} \rho^{(1)}(r),$$

2-body operator

$$\hat{\mathcal{E}}_n(\mathbf{r}_1, \mathbf{r}_2) = r_{1\perp}^n \, r_{2\perp}^n \, e^{in(\phi_1 - \phi_2)},$$
$$\langle \hat{\mathcal{E}}_n \rangle = \int_{\mathbf{r}_1, \mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2) \, r_{1\perp}^n \, r_{2\perp}^n \, e^{in(\phi_1 - \phi_2)}$$

- (Similar to Kumar invariant $\mathcal{B}_2^2(\mathrm{LE})$) *Bofos, Bally, Duguet, Frosini; arXiv:2602.09890*
- (Perhaps could derive other operator tailored for NMEs?)

N-BODY OPERATOR EXPECTATION VALUES



João Picchetti, ML; work in progress

Outline

Nuclear Lattice EFT (^{16}O and ^{20}Ne)

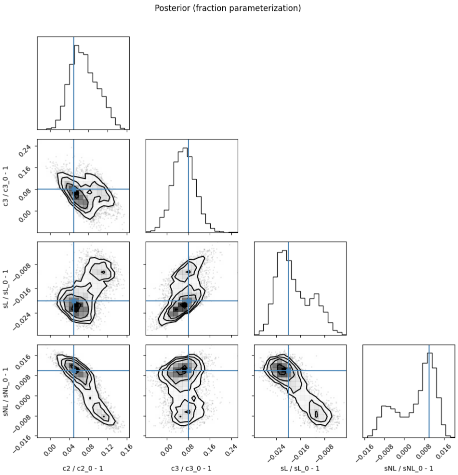
- Nuclear configurations can be generated with Lattice methods
- Simplified LO pionless EFT with SU(4) symmetry (no sign problem):

$$H_{\mathrm{SU}(4)} = H_{\mathrm{free}} + \frac{1}{2!} C_2 \sum_{\boldsymbol{n}} \tilde{\rho}(\boldsymbol{n})^2 + \frac{1}{3!} C_3 \sum_{\boldsymbol{n}} \tilde{\rho}(\boldsymbol{n})^3$$

$$\tilde{\rho}(\boldsymbol{n}) = \sum_i \tilde{a}_i^\dagger(\boldsymbol{n}) \tilde{a}_i(\boldsymbol{n}) + s_L \sum_{|\boldsymbol{n}'-\boldsymbol{n}|=1} \sum_i \tilde{a}_i^\dagger(\boldsymbol{n}') \tilde{a}_i(\boldsymbol{n}')$$

$$\tilde{a}_i(\boldsymbol{n}) = a_i(\boldsymbol{n}) + s_{NL} \sum_{|\boldsymbol{n}'-\boldsymbol{n}|=1} a_i(\boldsymbol{n}')$$

- Vary parameters by reweighting

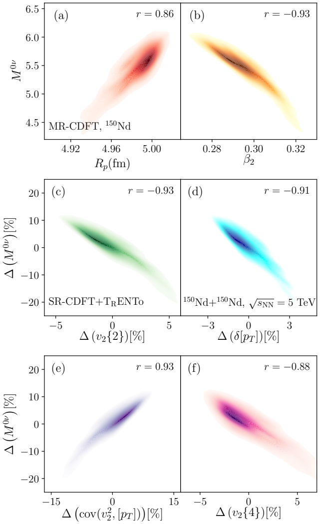


Lu, Li, Elhatisari, Lee, Epelbaum, Meißner; Physics Letters B 797 (2019) 134863

ML; work in progress

Outline

NMEs and high-energy observables



Li, Zhang, Giacalone, Yao; Phys. Rev. Lett. 135, 022301 (2025)

Relation to high-energy observables

- NMEs from CDFT calculations of ^{150}Nd $\rightarrow$ ^{150}Sm
- Well correlated with measureable quantities from high-energy collisions of ^{150}Nd + ^{150}Nd

Summary

- From ultrarelativistic collisions, can extract information about nuclear structure and correlations
- Can be used to constrain nuclear matrix elements
- What is the best way to integrate into matrix element calculations?
  - Posterior distributions for surface deformation parameters? (R, a, β_2, γ, β_3, $\ldots$)
  - Expectation values for certain 2-body, 3-body, . . . operators?
  - More direct integration into nuclear matrix element calculations?
  - Other ideas/suggestions?

Extra Slides