Nuclear Deformation in High Energy Nuclear Collisions

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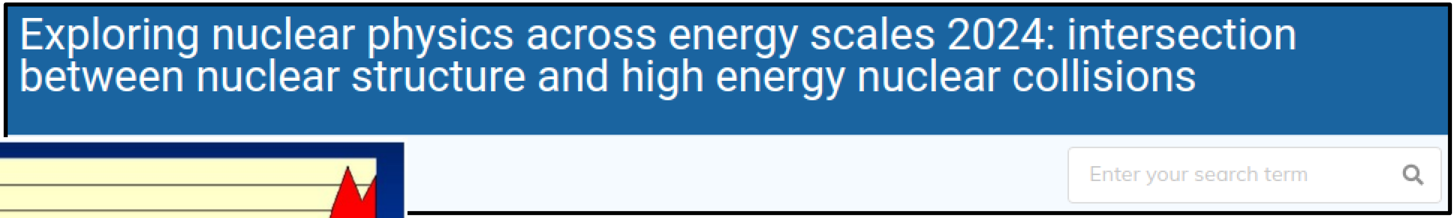
April 17, 2024



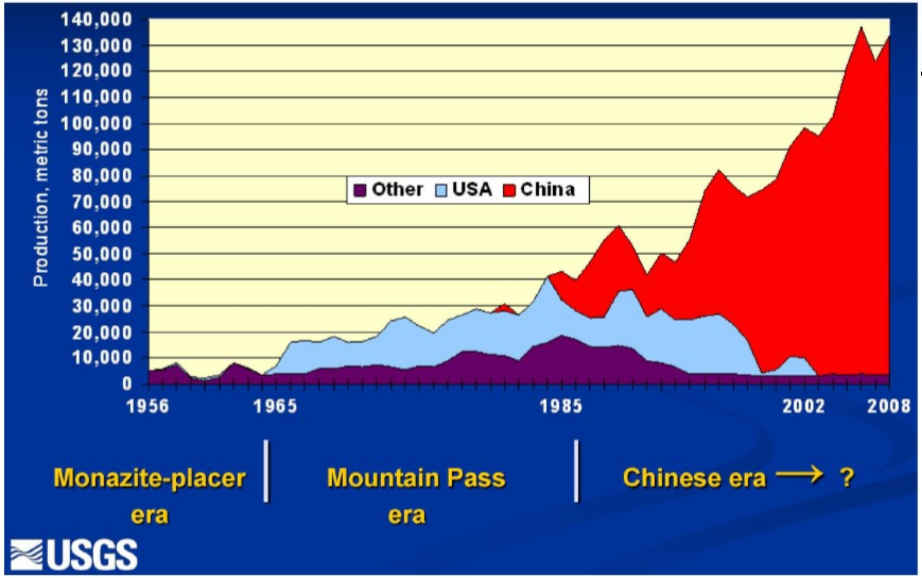
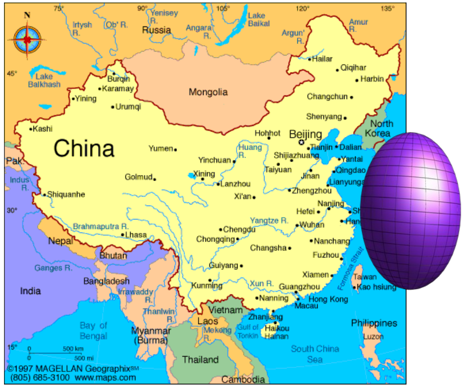


Figure 1. Global rare-earth-oxide production trends.



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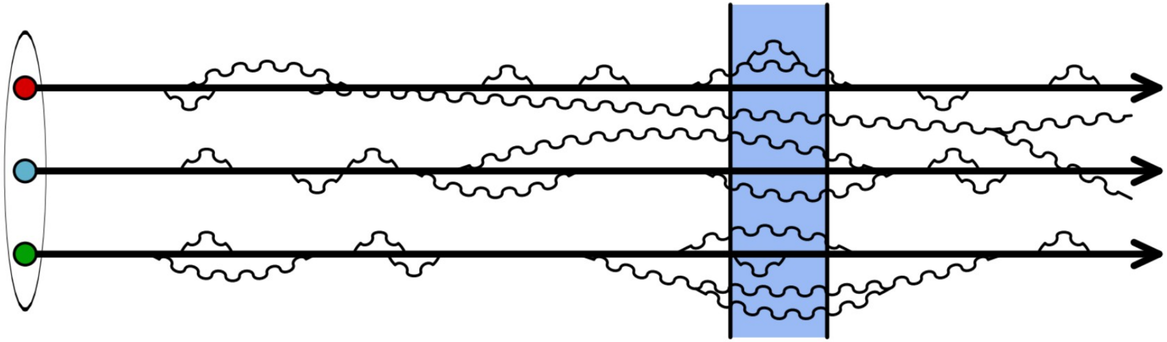
OUTLINE

1 – Role of nuclear deformation in heavy-ion collisions

2 – Implementations of nuclear deformation in high energy collisions

3 – Studying and exploiting nuclear deformation at high energy

1 – Role of nuclear deformation in heavy-ion collisions



[Gelis, IJMPE **24** (2015) 10, 1530008]

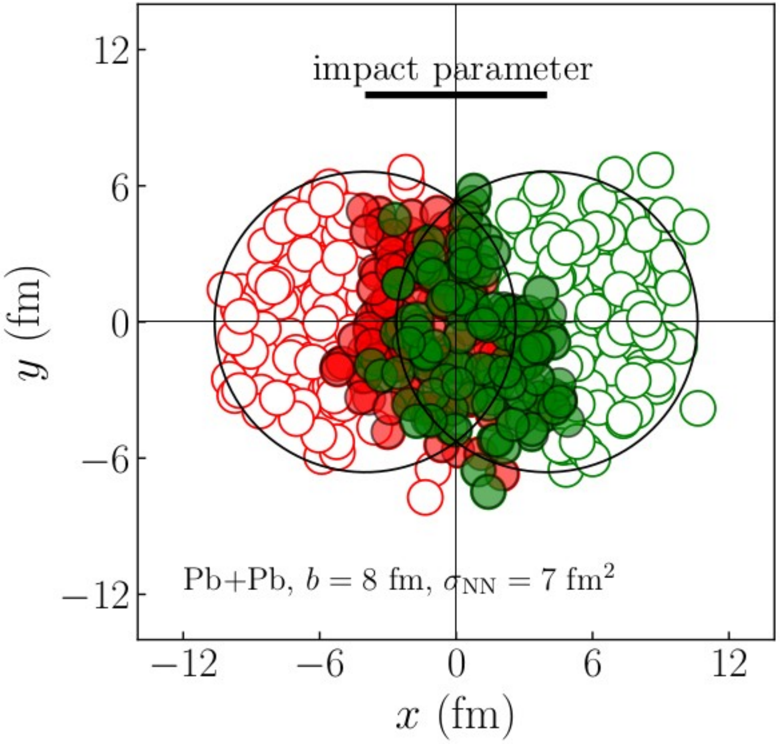
a QCD description of high energy collisions between hadrons may be feasible, provided we can provide "snapshots" of their partonic content at the time of the collision.

$$\text{transition probability from hadrons to X} \approx \sum_{\substack{\text{partons}\\ \{q,g\}}} \text{probability to find } \{q,g\} \text{ in } \{h_1,h_2\} \otimes \left| \sum \text{Amplitudes } \{q,g\} \to X \right|^2$$

called *initial state factorization*. Roughly speaking, the physical motivation for such a factorization is that the neglected terms are interferences between a hard process that occurs on the timescale of the collision and a process internal to one of the projectiles, happening on much longer timescales.

Snapshots of atomic nuclei

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



“snapshot”
of the nucleon positions

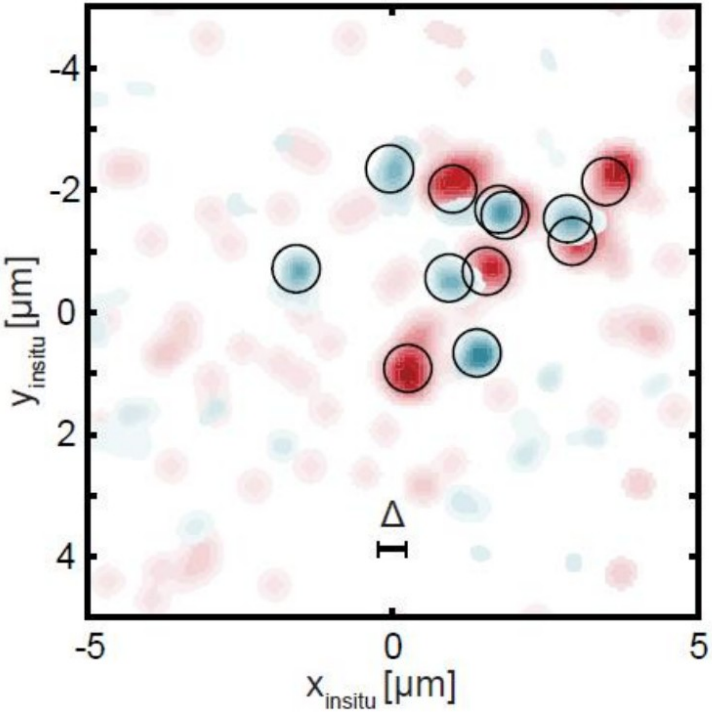
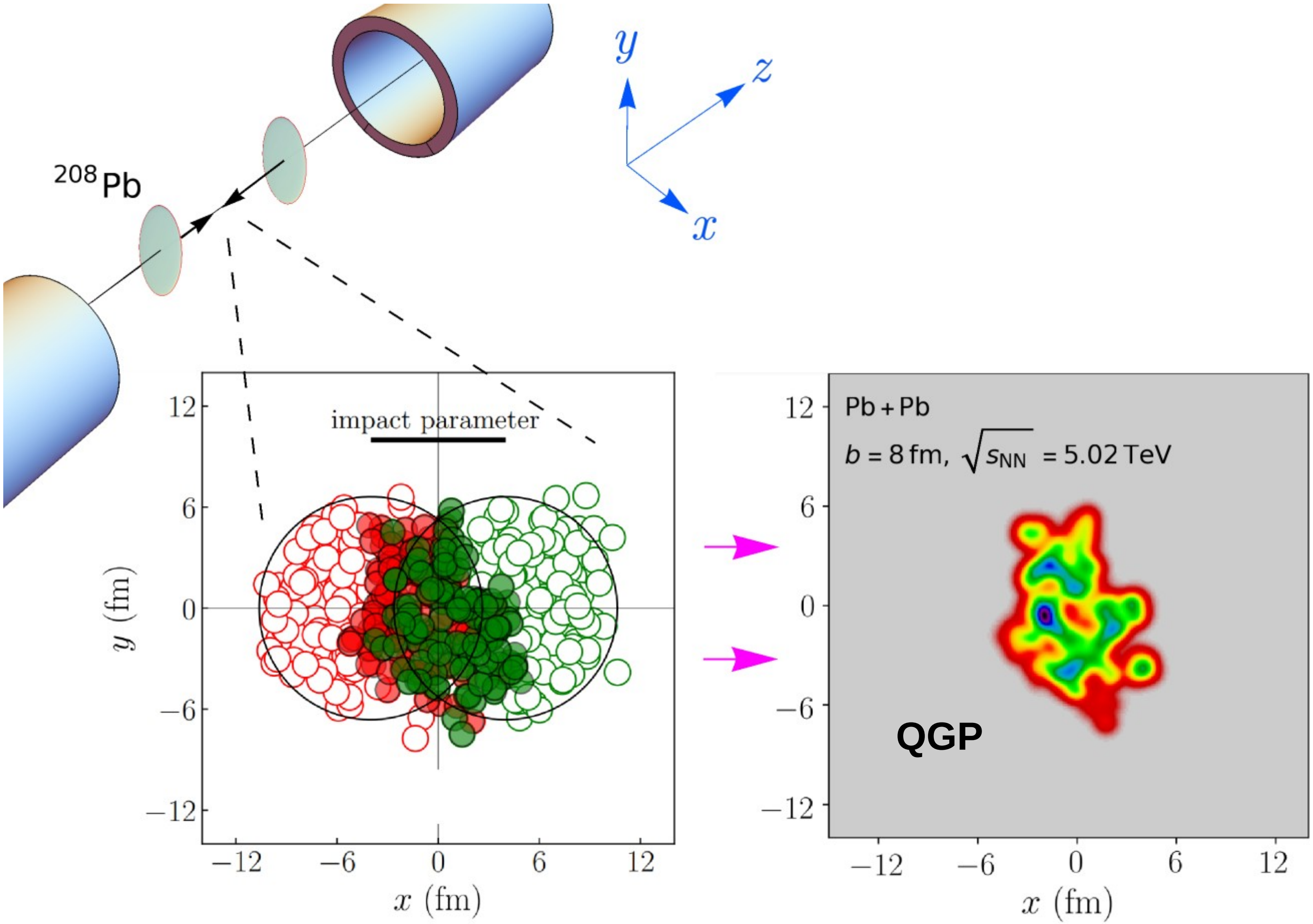


Image of collapsed wave function of 10 Li atoms
[from S. Brandstetter (PI Heidelberg)]



^{208}Pb
y
z
x
impact parameter
y (fm)
x (fm)
12
6
0
−6
−12
Pb + Pb
b = 8 fm, $\sqrt{s_{NN}}$ = 5.02 TeV
QGP

ANALYTICAL INSIGHTS

– **THICKNESS FUNCTION:** $$t(\mathbf{x}) = \sum_{i=1}^{A} \underline{g(\mathbf{x};\mathbf{x}_i, w)}$$

Nucleon “form factor” at high energy.
w = nucleon size.

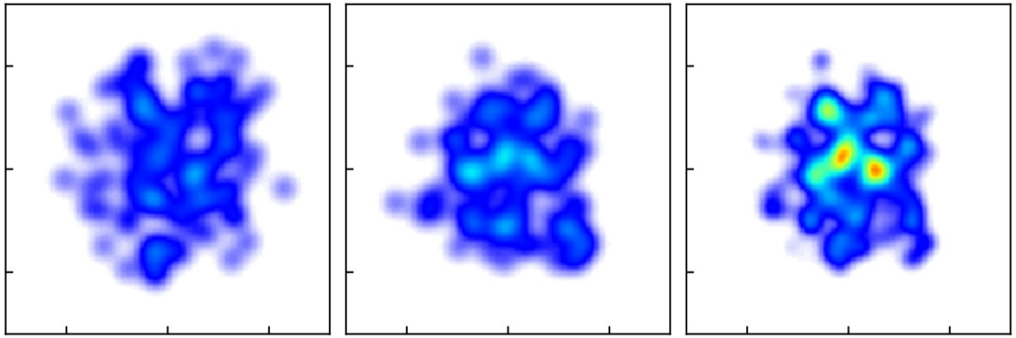
– **ENERGY DEPOSITION:**

$$\lim_{\tau\to 0^+} \tau e(\mathbf{x}) \propto \left(\frac{t_A(\mathbf{x})+t_B(\mathbf{x})}{2}\right)^{q/p} \xrightarrow[p=0]{} [t_A(\mathbf{x})t_B(\mathbf{x})]^{q/2} \xrightarrow[q=2]{} \underline{t_A(\mathbf{x})t_B(\mathbf{x})}$$

IP-Glasma (τ=0)
“IP-Jazma”
“binary collisions”
…

– **TAKE HEAD-ON COLLISIONS (b=0).**

nucleus A ⋆ nucleus B → energy density



DENSITY CORRELATIONS IN THE OVERLAP REGION

$$\langle \epsilon(\mathbf{x}) \rangle_{\rm ev} = A^2 \left(\int_{\xi_i} P_{1\perp}(\xi_i) g(\mathbf{x} - \xi_i) \right)^2$$

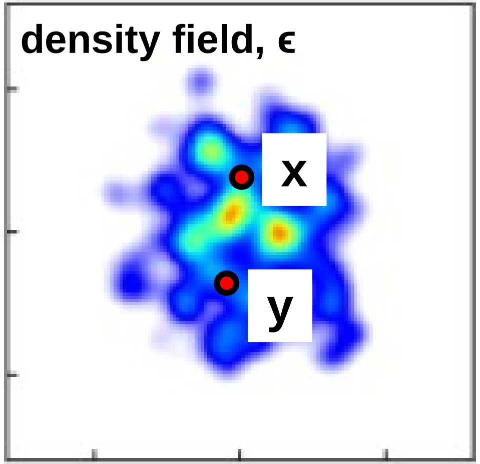
$$\langle \epsilon(\mathbf{x}) \epsilon(\mathbf{y}) \rangle_{\rm ev} = \left(A \int_{\xi_i} P_{1\perp}(\xi_i) g(\mathbf{x} - \xi_i) g(\mathbf{y} - \xi_i) \right.$$

ENERGY DENSITY

$$\left. + (A^2 - A) \int_{\xi_i \neq \xi_j} P_{2\perp}(\xi_i, \xi_j) g(\mathbf{x} - \xi_i) g(\mathbf{y} - \xi_j) \right)^2$$

NUCLEAR STRUCTURE

NUCLEON STRUCTURE



[Giacalone, EPJA **59** (2023) 12, 297]

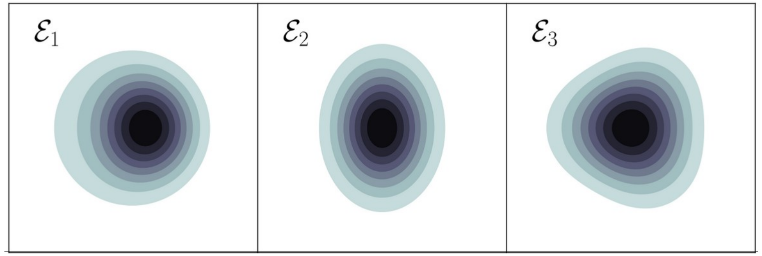
nuclear *n*-body density:
(⊥ = integrated over “z”)

$$P_n(\mathbf{r}_1, \ldots, \mathbf{r}_n) = \sum_{s,t} \int d\mathbf{r}_{n+1} \ldots d\mathbf{r}_A |\Psi_A|^2$$

GROUND STATE

BONUS: CONNECTION TO EXPERIMENTAL OBSERVATIONS

– **ECCENTRICITY:** $$\mathcal{E}_n = -\frac{\int_{\mathbf{x}} \epsilon(\mathbf{x})\ |\mathbf{x}|^n e^{in\phi_x}}{\int_{\mathbf{x}} \epsilon(\mathbf{x})\ |\mathbf{x}|^n}$$



– **PERTURBATIVE EXPANSION:** $$\epsilon(\mathbf{x}) = \langle \epsilon(\mathbf{x}) \rangle + \delta\epsilon(\mathbf{x})$$

[Blaizot, Broniowski, Ollitrault, PLB **738** (2014) 166-171]

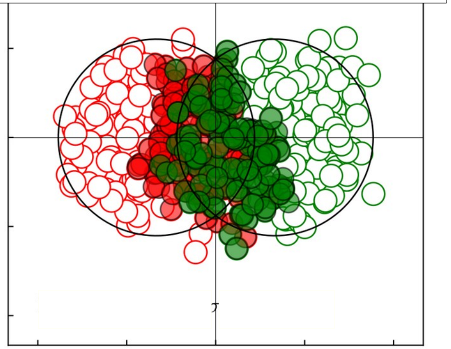
– **MEAN SQUARED ANISOTROPY:**

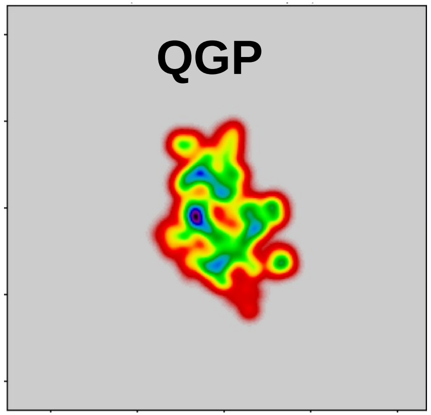
$$P_{2\perp}(\xi_i, \xi_j)$$ **TWO-NUCLEON DENSITY**

INITIAL STATE **FINAL STATE**

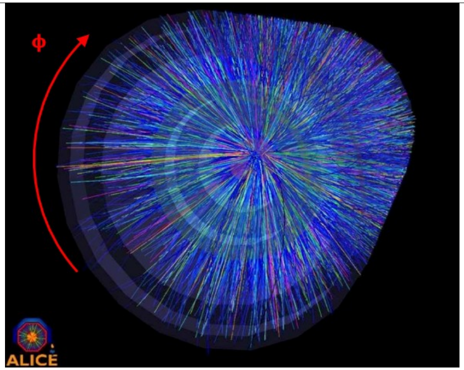
$$\langle \mathcal{E}_n \mathcal{E}_n^* \rangle = \frac{\int_{\mathbf{x},\mathbf{y}} |\mathbf{x}|^n |\mathbf{y}|^n e^{in(\phi_x - \phi_y)} \langle \epsilon(\mathbf{x}) \epsilon(\mathbf{y}) \rangle}{\left(\int_{\mathbf{x}} \langle \epsilon(\mathbf{x}) \rangle |\mathbf{x}|^n \right)^2} \propto \langle V_n V_n^* \rangle$$

MULTI-NUCLEON CORRELATIONS IN NUCLEI





MULTI-PARTICLE CORRELATIONS IN FINAL STATE



Recent reviews:
[Ollitrault, EPJA **59** (2023) 10, 236]
[Giacalone, EPJA **59** (2023) 12, 297]

1-nucleon density

$$P_1(\mathrm{r}_1) = \sum_{s,t} \int d^3\mathrm{r}_2 \dots d^3\mathrm{r}_A |\Psi_A(\mathrm{r}_1 \dots \mathrm{r}_A)|^2$$

2-nucleon density

$$P_2(\mathrm{r}_1, \mathrm{r}_2) = \sum_{s,t} \int d^3\mathrm{r}_3 \dots d^3\mathrm{r}_A |\Psi_A(\mathrm{r}_1 \dots \mathrm{r}_A)|^2$$

3-nucleon density

$$P_3(\mathrm{r}_1, \mathrm{r}_2, \mathrm{r}_3) = \sum_{s,t} \int d^3\mathrm{r}_4 \dots d^3\mathrm{r}_A |\Psi_A(\mathrm{r}_1 \dots \mathrm{r}_A)|^2$$

MEAN TRANSVERSE MOMENTUM

1 particle

$$\langle [p_t] \rangle_{\rm ev} = \left\langle \frac{1}{N_{\rm ch}} \sum_{i=1}^{N_{\rm ch}} p_{t,i} \right\rangle_{\rm ev}$$

MEAN SQUARED ANISOTROPY

2 particles

$$v_n^2 = \langle V_n V_n^* \rangle_{\rm ev} = \left\langle \frac{\sum_{i\neq j} e^{in(\phi_i - \phi_j)}}{N_{\rm ch,ev}(N_{\rm ch,ev}-1)} \right\rangle_{\rm ev}$$

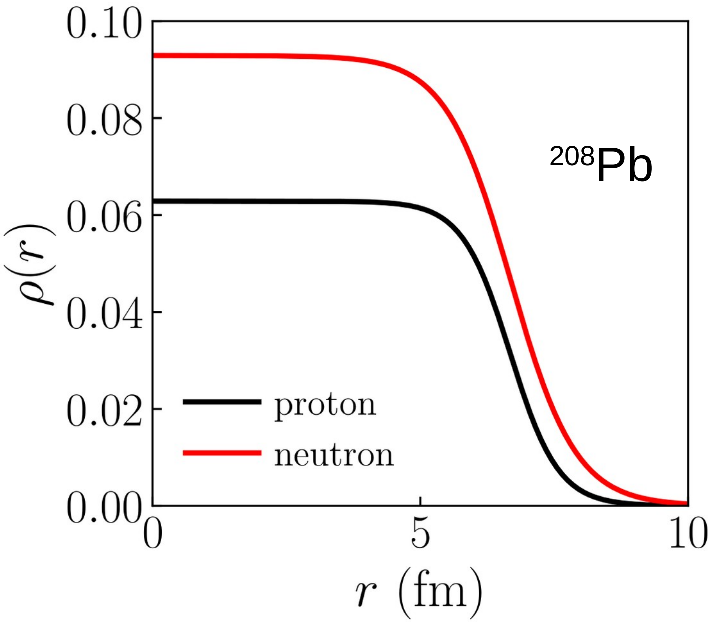
MOMENTUM-ANISOTROPY CORRELATION

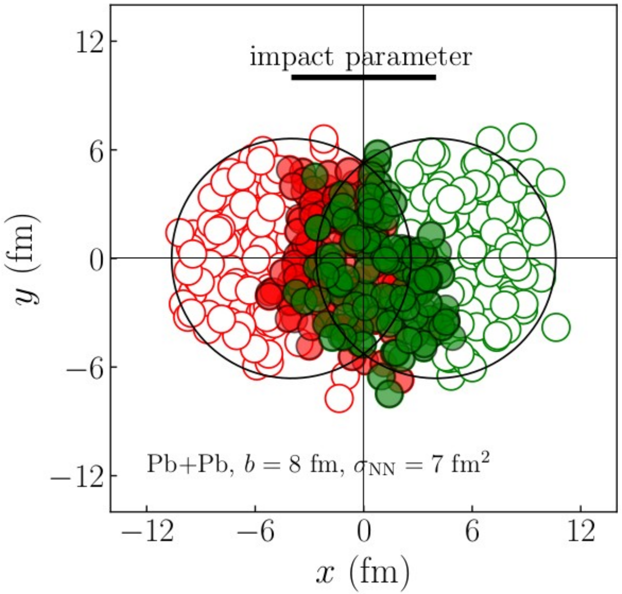
3 particles

$$\mathrm{cov}([p_t], v_n^2) = \left\langle \frac{\sum_{i\neq j\neq k} (p_i - \langle [p_t]_{\rm ev} \rangle) e^{in(\phi_j - \phi_k)}}{N_{\rm ch,ev}(N_{\rm ch,ev}-1)(N_{\rm ch,ev}-2)} \right\rangle_{\rm ev}$$

Independent fermions: $h_i = \frac{p_i^2}{2m} + V(r_i) \longrightarrow P_A(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A) = P_1(\mathbf{r}_1)P_1(\mathbf{r}_2)\ldots P_1(\mathbf{r}_A)$

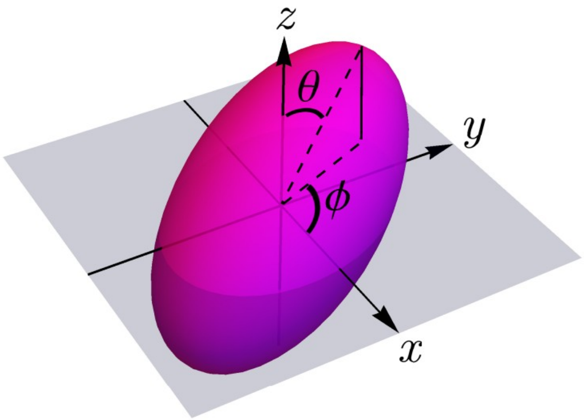
All information in the one-body density: $P_1(r) \propto \frac{1}{1+e^{(r-R)/a}}$ **e.g. Woods-Saxon**



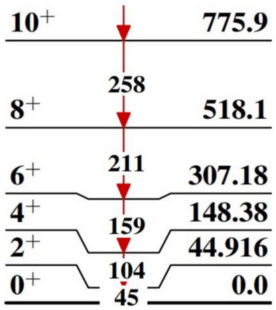


Information from nuclear structure = radial profile + number of nucleons

However, nuclei display strong spatial correlations = shapes

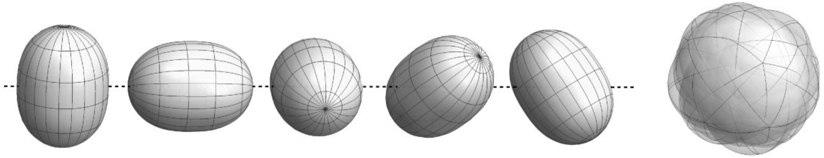


$^{238}_{92}\mathrm{U}$ **E = B J(J+1)**



Correlations from random rotation of an intrinsic deformed object

$$P_1(\mathbf{r}_1) = \int_{\Omega} \rho_{\Omega}(\mathbf{r}_1)$$

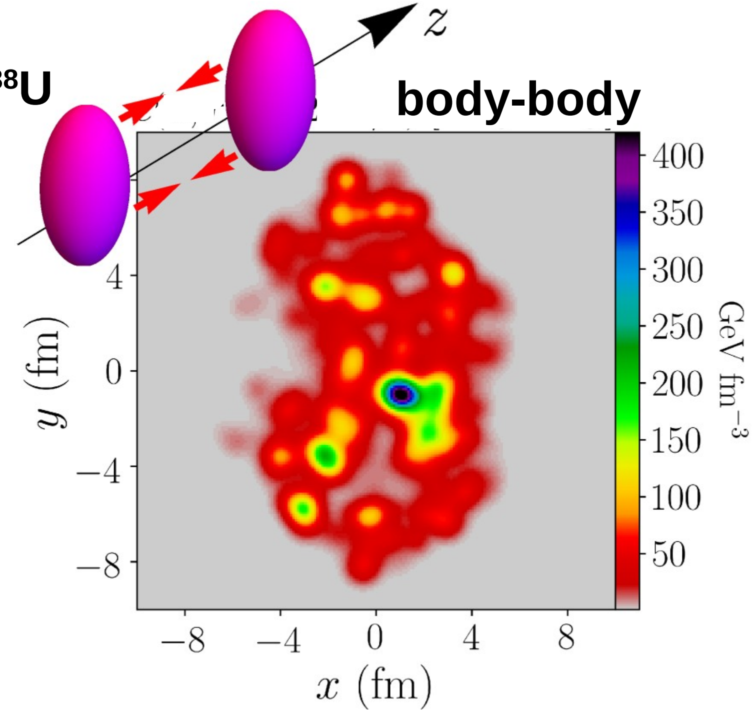


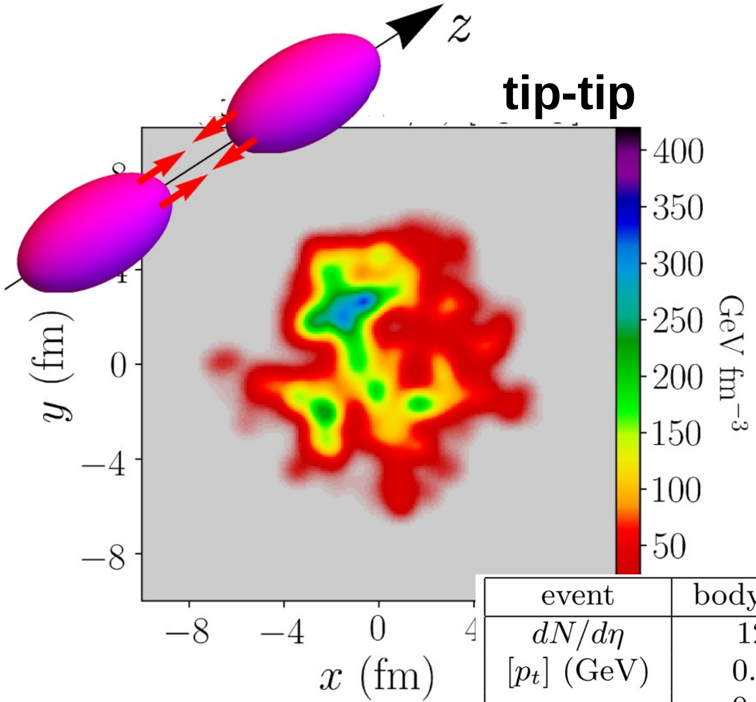
EULER ANGLES

[STAR collaboration, arXiv:2401.06625]

$$P_2(\mathbf{r}_1, \mathbf{r}_2) = \int_{\Omega} \rho_{\Omega}(\mathbf{r}_1)\rho_{\Omega}(\mathbf{r}_2) \neq P_1(\mathbf{r}_1)P_1(\mathbf{r}_2)$$

DEFORMATION

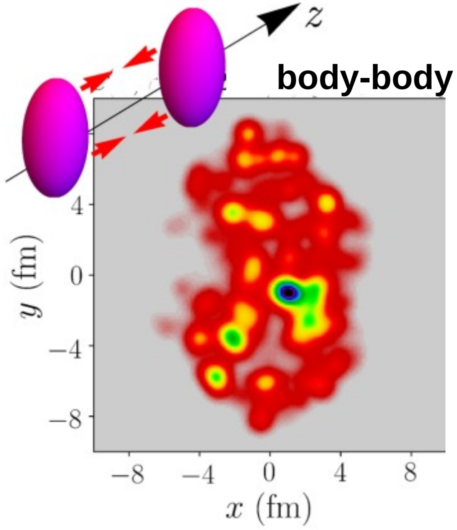


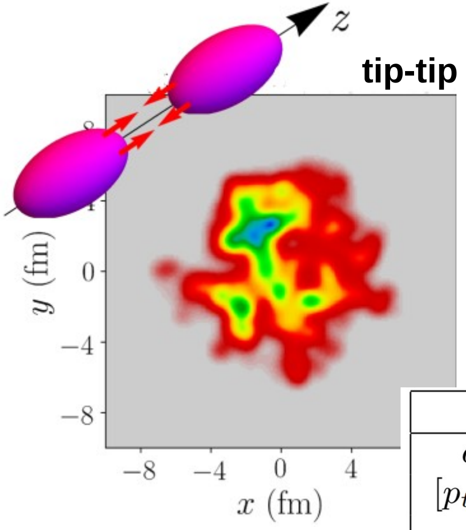


LARGE-SCALE FLUCTUATIONS!

event	body-body	tip-tip
$dN/d\eta$	1296	1280
$[p_t]$ (GeV)	0.587	0.651
v_2	0.083	0.027

"Seeing" the deformation of ^{238}U





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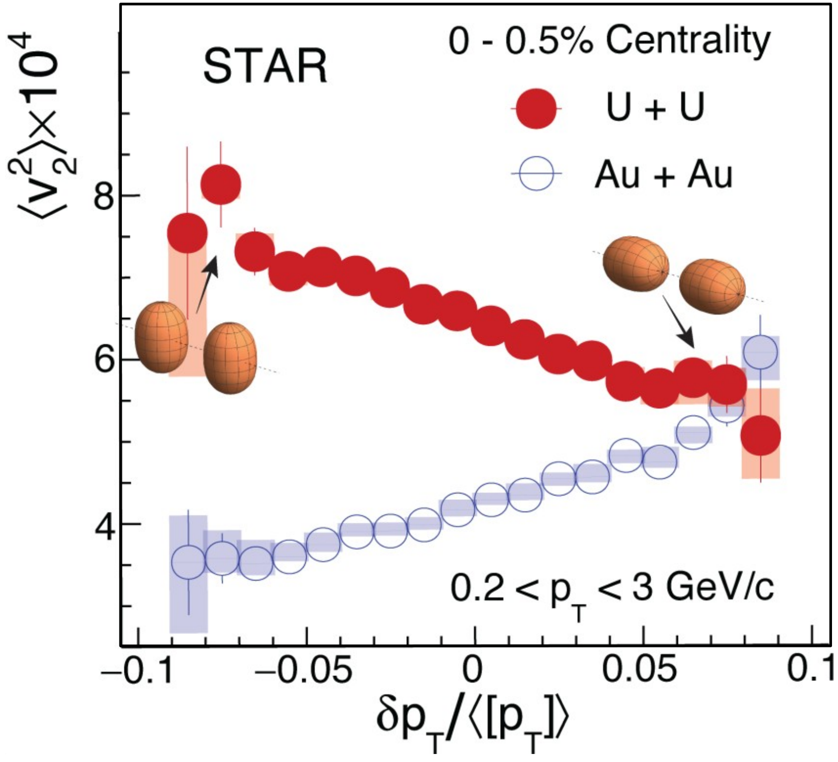
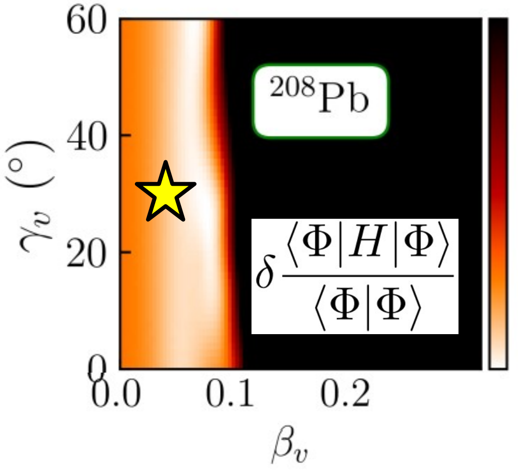
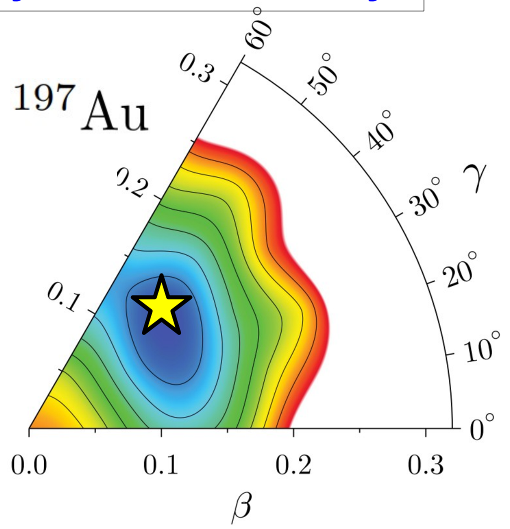
[STAR collaboration, arXiv:2401.06625]

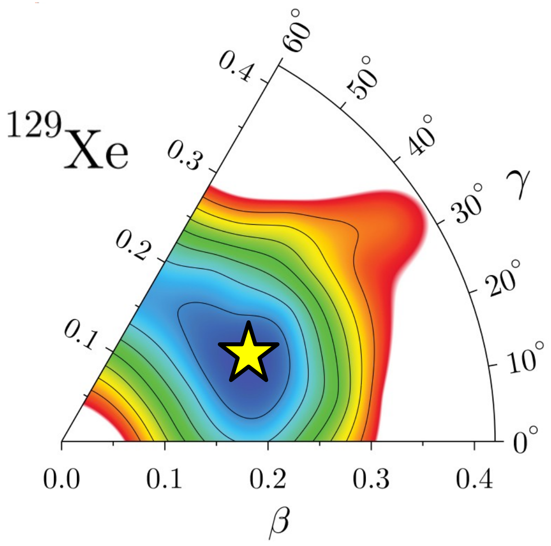


2 – Implementations of nuclear deformation in high energy collisions

Implementation from energy density functional theory







Intrinsic one-body density from mean-field states

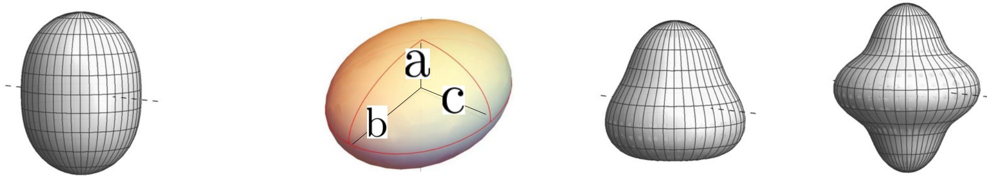
$$\rho(\mathbf{r}) = \sum_{s,t} \langle \Phi(\vec{\beta})| \, a^{\dagger}_{s,t}(\mathbf{r}) a_{s,t}(\mathbf{r}') \, |\Phi(\vec{\beta})\rangle \Big|_{\mathbf{r}=\mathbf{r}'}$$

[Bally *et al.*, PRL **128** (2022) 8, 082301]
[Bally, Giacalone, Bender, EPJA **58** (2022) 9, 187]
[Bally, Giacalone, Bender EPJA **59** (2023) 3, 58]
[Ryssens *et al.*, PRL **130** (2023) 21, 212302]

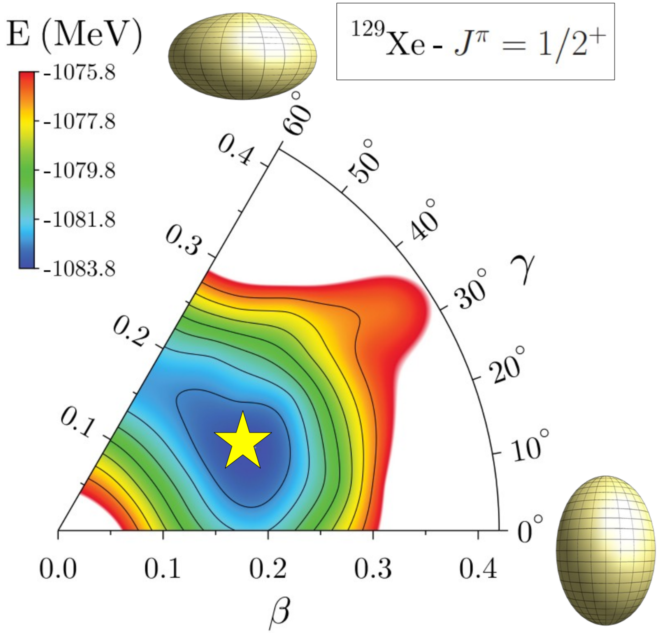
Fit some appropriate function

$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left([r-R(\theta,\phi)]/a\right)} \;, \quad R(\theta,\phi) = R_0\left[1+\underline{\beta_2}\left(\cos\gamma Y_{20}(\theta)+\sin\underline{\gamma}Y_{22}(\theta,\phi)\right)+\underline{\beta_3}Y_{30}(\theta)+\underline{\beta_4}Y_{40}(\theta)\right]$$

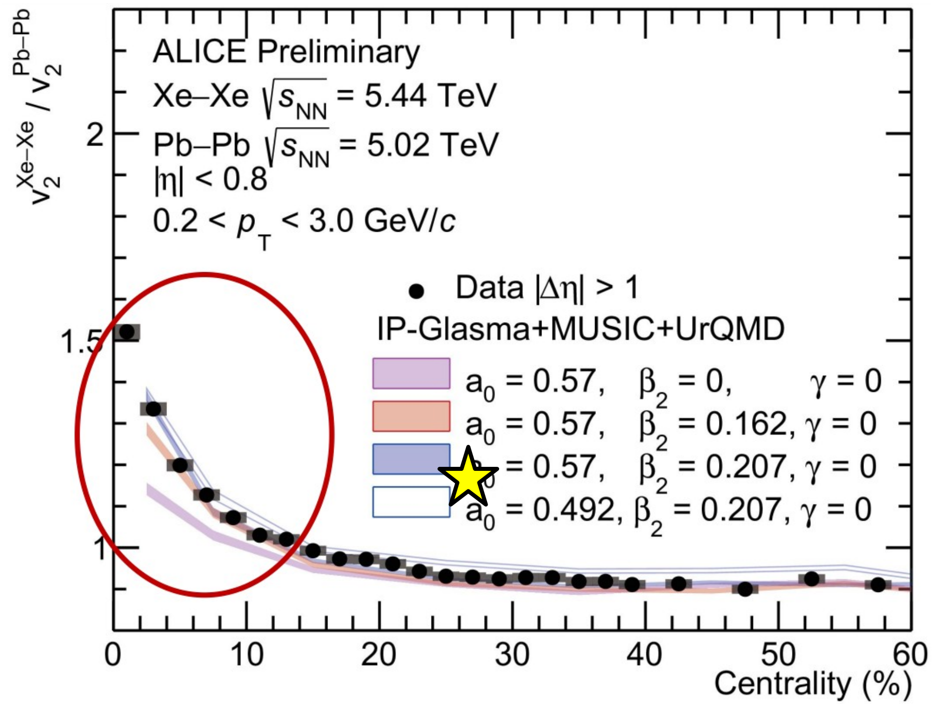
e.g. Woods-Saxon



Deformation of ^{129}Xe at the LHC



[Bally *et al.*, PRL **128** (2022) 8, 082301]
[Jia, PRC **105** (2022) 4, 044905]



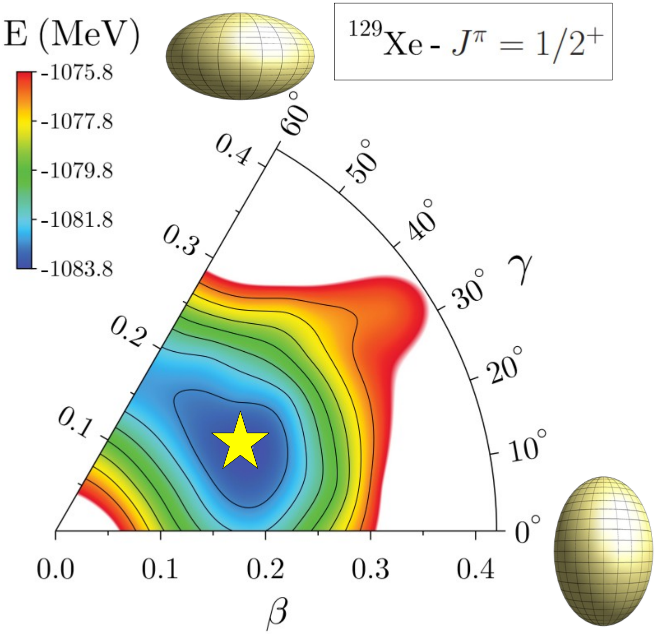
NUCLEAR TWO-BODY DENSITY

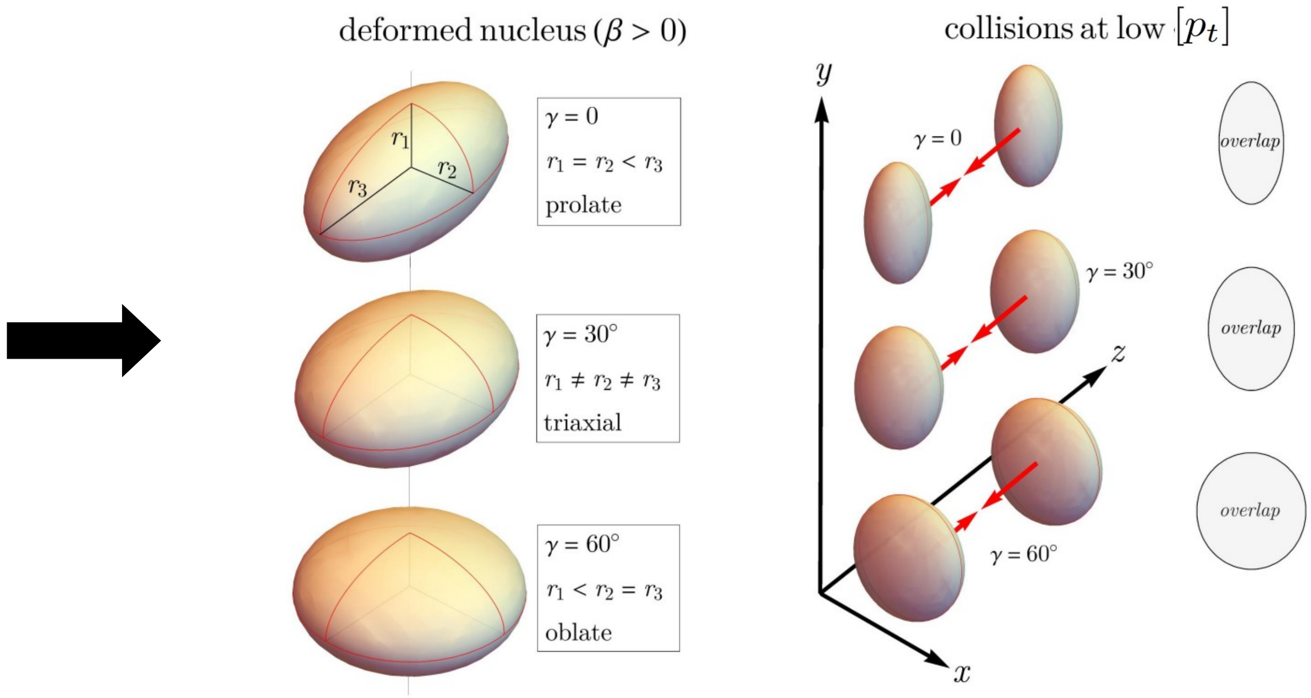
$$P_2(\mathrm{r}_1, \mathrm{r}_2) = \sum_{s,t} \int d^3\mathrm{r}_3 \dots d^3\mathrm{r}_A |\Psi_A(\mathrm{r}_1 \dots \mathrm{r}_A)|^2$$

MEAN SQUARED ANISOTROPY

$$v_n^2 = \langle V_n V_n^* \rangle_{\mathrm{ev}} = \left\langle \frac{\sum_{i \neq j} e^{in(\phi_i - \phi_j)}}{N_{\mathrm{ch,ev}}(N_{\mathrm{ch,ev}} - 1)} \right\rangle_{\mathrm{ev}}$$

Evidence of triaxiality in ^{129}Xe

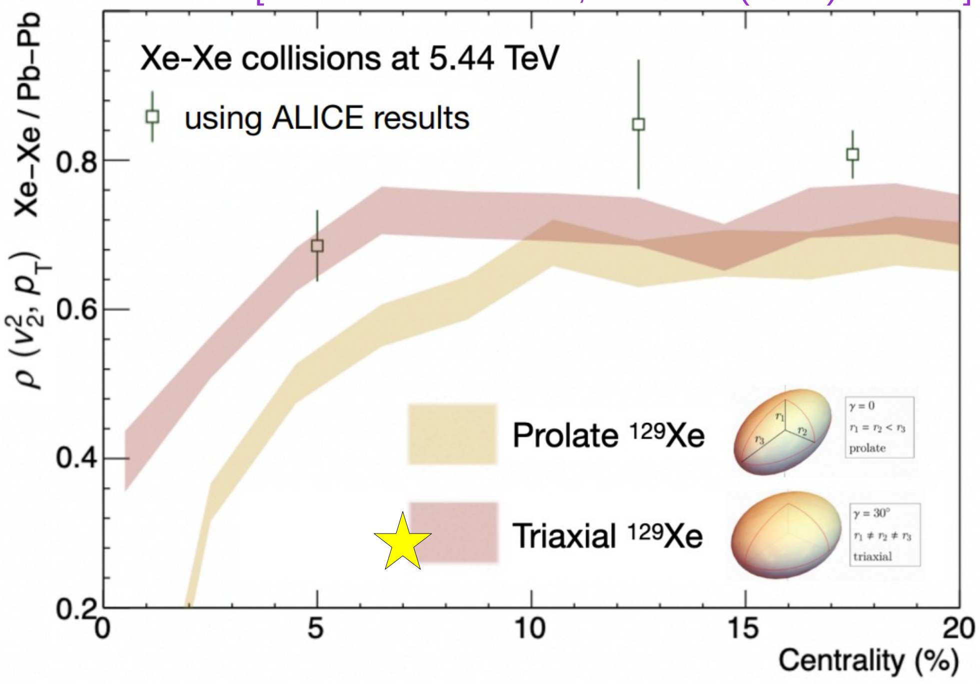




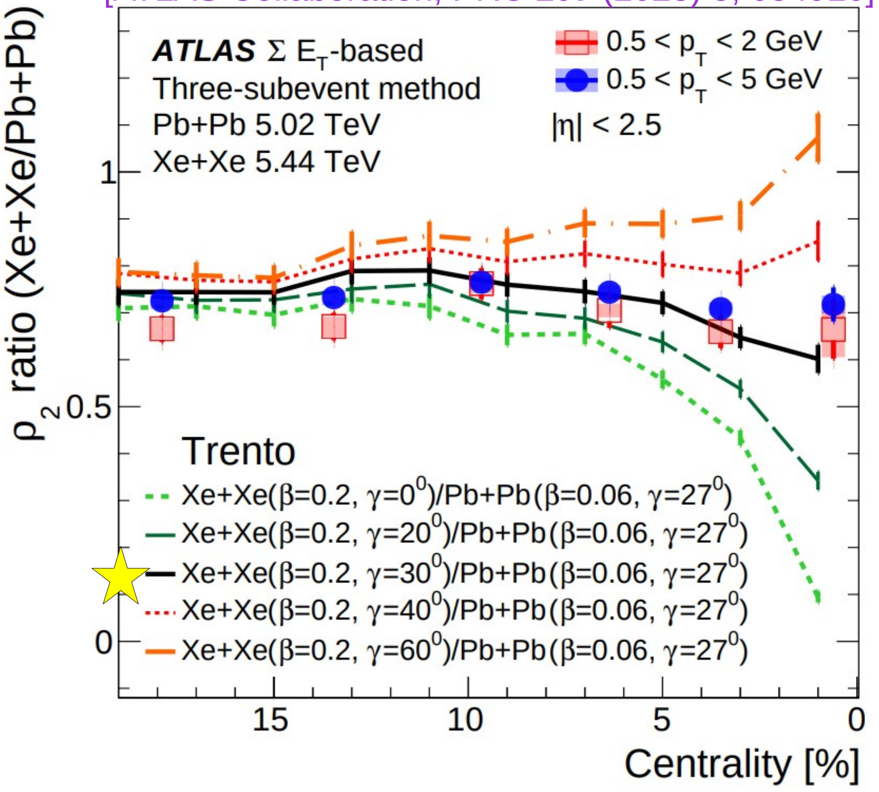
[Bally *et al.*, PRL **128** (2022) 8, 082301]

Probing three-body correlations

[ALICE Collaboration, PLB **834** (2022) 137393]



[ATLAS Collaboration, PRC **107** (2023) 5, 054910]



NUCLEAR THREE-BODY DENSITY

$$P_3(\mathrm{r}_1,\mathrm{r}_2,\mathrm{r}_3) = \sum_{s,t}\int d^3\mathrm{r}_4 \dots d^3\mathrm{r}_A |\Psi_A(\mathrm{r}_1\dots\mathrm{r}_A)|^2$$

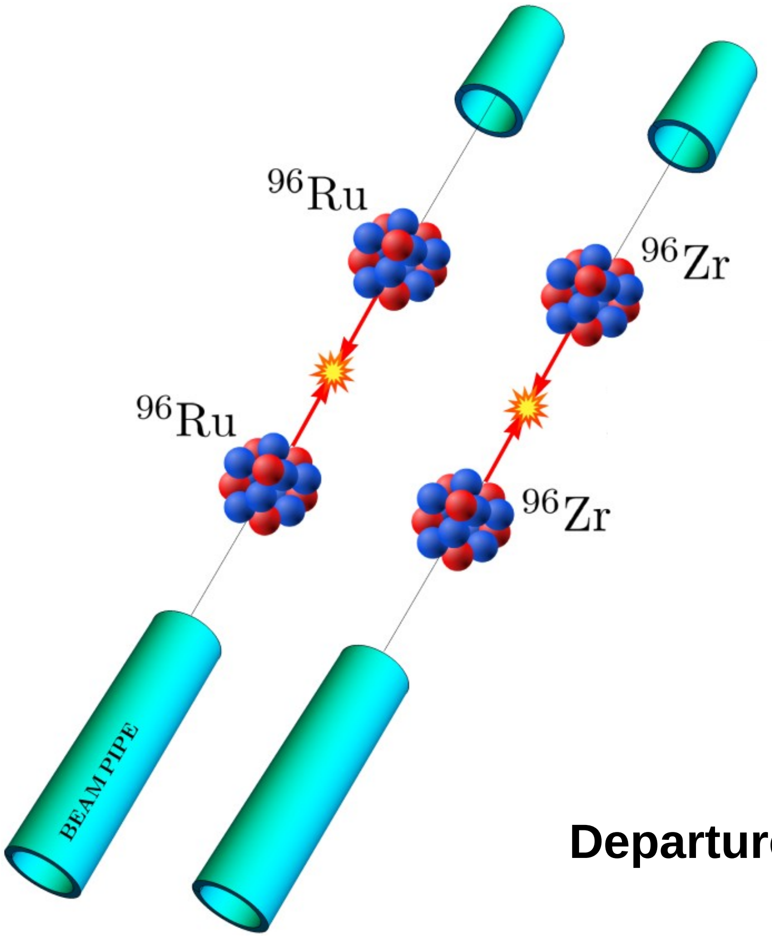
[Jia, PRC **105** (2022) 4, 044905]
[Giacalone, EPJA **59** (2023) 12, 297]

MOMENTUM-ANISOTROPY CORRELATION

$$\rho_n \propto \mathrm{cov}([p_t], v_n^2) = \left\langle \frac{\sum_{i\neq j\neq k}(p_i - \langle [p_t]_{\mathrm{ev}}\rangle)e^{in(\phi_j-\phi_k)}}{N_{\mathrm{ch,ev}}(N_{\mathrm{ch,ev}}-1)(N_{\mathrm{ch,ev}}-2)} \right\rangle_{\mathrm{ev}}$$

$$\rho_n \propto -\cos(3\gamma)\beta_2^3$$

Breakthrough of 2021: data from "isobar collisions" is released.



TALK BY J. JIA

X and Y are isobars.

X+X collisions produce QGP with same properties as Y+Y collisions.

Ratios of observables (O) should be unity…

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

[STAR collaboration, PRC **105** (2022) 1, 014901]
[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]

Departure from unity is mainly due to nuclear structure.

Extremely precise measurements.

Quadrupole and octupole deformations

$$\langle v_n^2 \rangle = a + b\beta_n^2$$

spherical baseline

QGP response

deformation

[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]
[Jia, PRC **105** (2022) 1, 014905]
[Jia, Zhang, PRL **128** (2022) 2, 022301]

Isobar ratio and Taylor expand around unity:

$$\frac{\langle v_n^2 \rangle_{\mathrm{Ru+Ru}}}{\langle v_n^2 \rangle_{\mathrm{Zr+Zr}}} = 1 + c\left(\beta_{n,\mathrm{Ru}}^2 - \beta_{n,\mathrm{Zr}}^2\right)$$

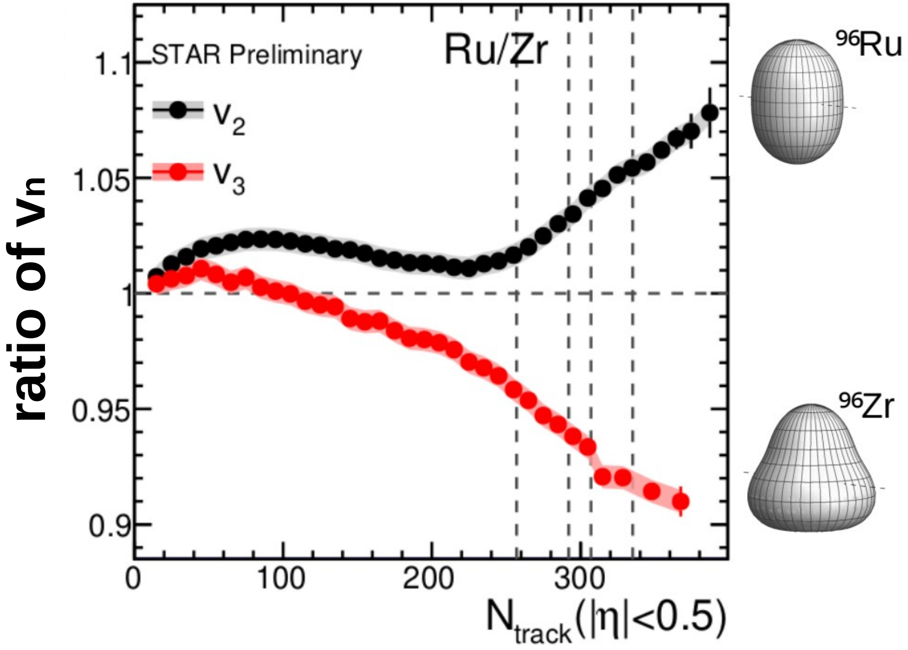
positive coeff

Low-energy nuclear physics: $\beta_{2,\mathrm{Ru}}^2 \gg \beta_{2,\mathrm{Zr}}^2$

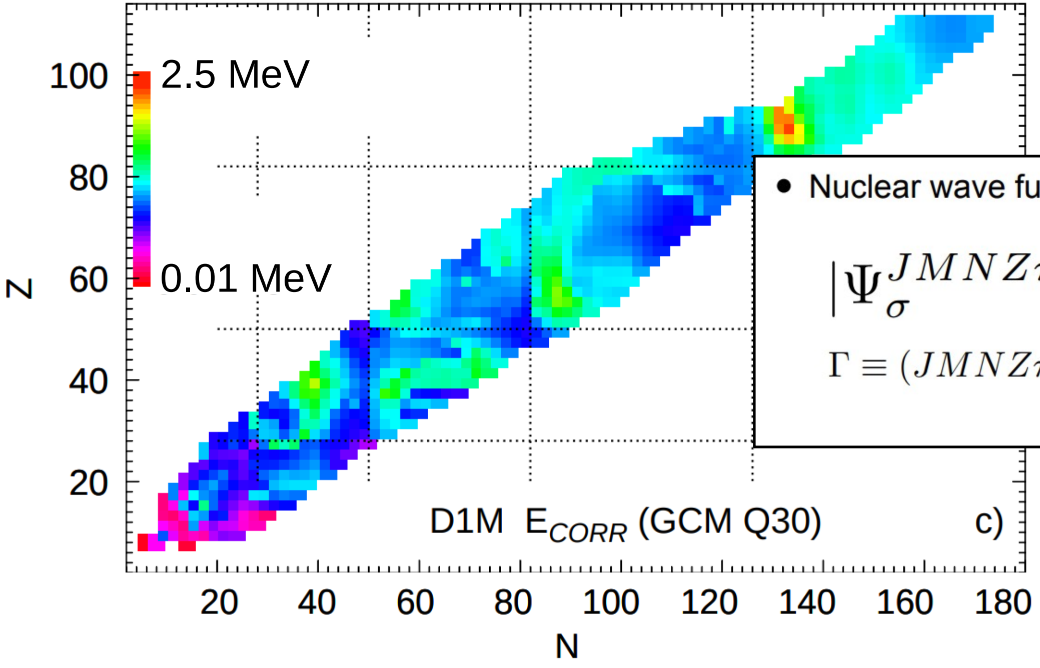
TALK BY M. ZIELIŃSKA

RHIC data: $\beta_{2,\mathrm{Ru}}^2 \gg \beta_{2,\mathrm{Zr}}^2$ $\boxed{\beta_{3,\mathrm{Zr}}^2 \gg \beta_{3,\mathrm{Ru}}^2}$

[STAR collaboration, PRC **105** (2022) 1, 014901]



Octupole requires correlations “beyond mean field”. A feature of the 2-body density.



- Nuclear wave functions : Generator Coordinate Method (GCM) ansatz

$$|\Psi_\sigma^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} P^J_{MK} P^N P^Z P^\pi |\Phi(q)\rangle$$

$$\Gamma \equiv (JMNZ\pi)$$

MIXING **PROJECTION** **DEFORMED MF STATE**

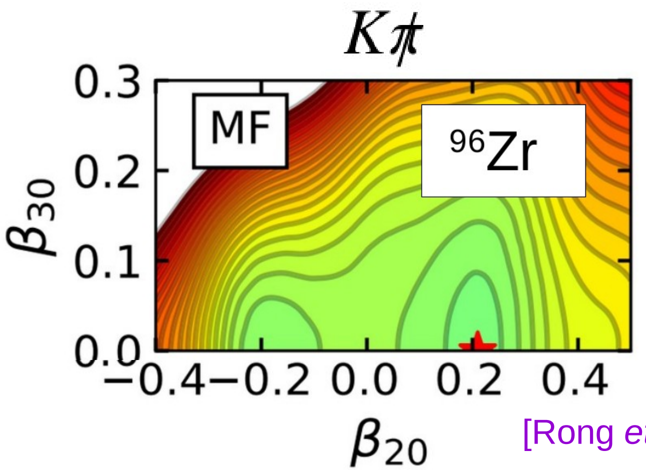
[Bertsch, Robledo, J. Phys. G **42** (2015) 5, 055109]

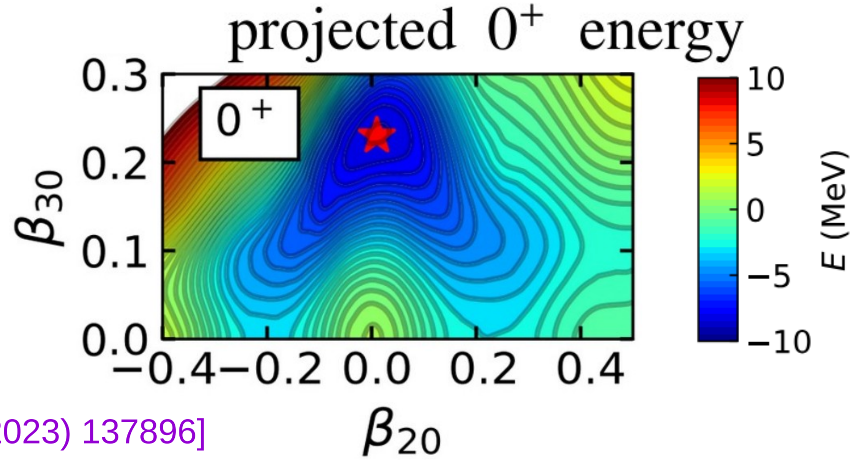
TALK BY D. VRETENAR

But how do we sample it?

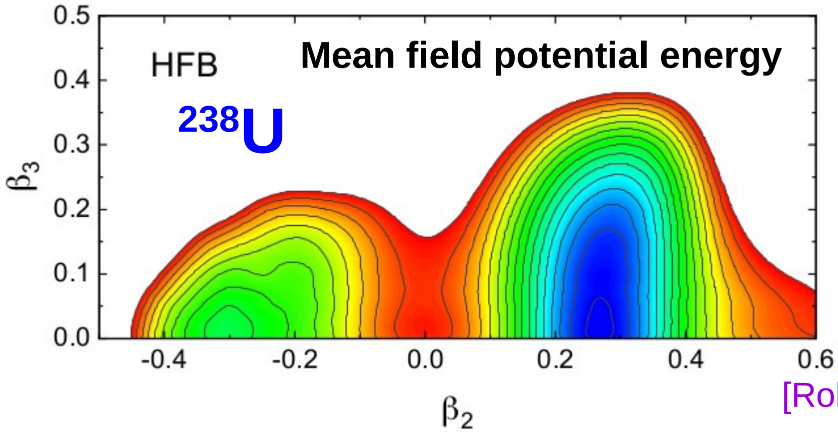
Evaluate mean field state at the maximum of g² / minimum of projected energy. Sample nucleons.

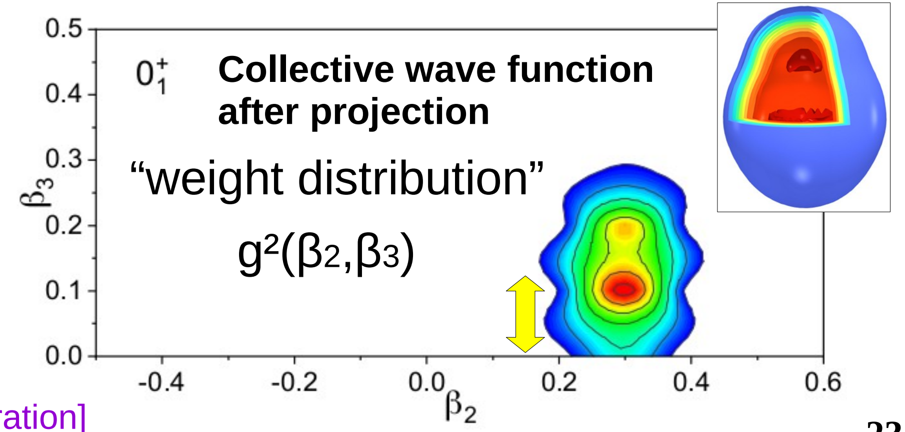
[Bally *et al.*, PRL **128** (2022) 8, 082301]
[Bally, Giacalone, Bender EPJA **59** (2023) 3, 58]





[Rong *et al.*, PLB **840** (2023) 137896]





[Robledo *et al.*, in preparation]

Implementation from zero-point fluctuations

TALK BY P. RING

$$|\Psi(t)\rangle = |0\rangle + \sum_n c_n |n\rangle \mathrm{e}^{-i\omega_n t}$$

$$\rho(\mathbf{r},t) = \langle\Psi(t)| \sum_{i=1}^{A} \delta(\mathbf{r}-\mathbf{r}_i) |\Psi(t)\rangle$$

To leading order in the perturbation:

$$\rho(\mathbf{r},t) = \rho_0(\mathbf{r}) + \sum_n \left\{ c_n \delta\rho^n(\mathbf{r}) e^{-i\omega_n t} + \mathrm{c.c.} \right\}$$

[Ring, Schuck, Nuclear Many Body Problem]

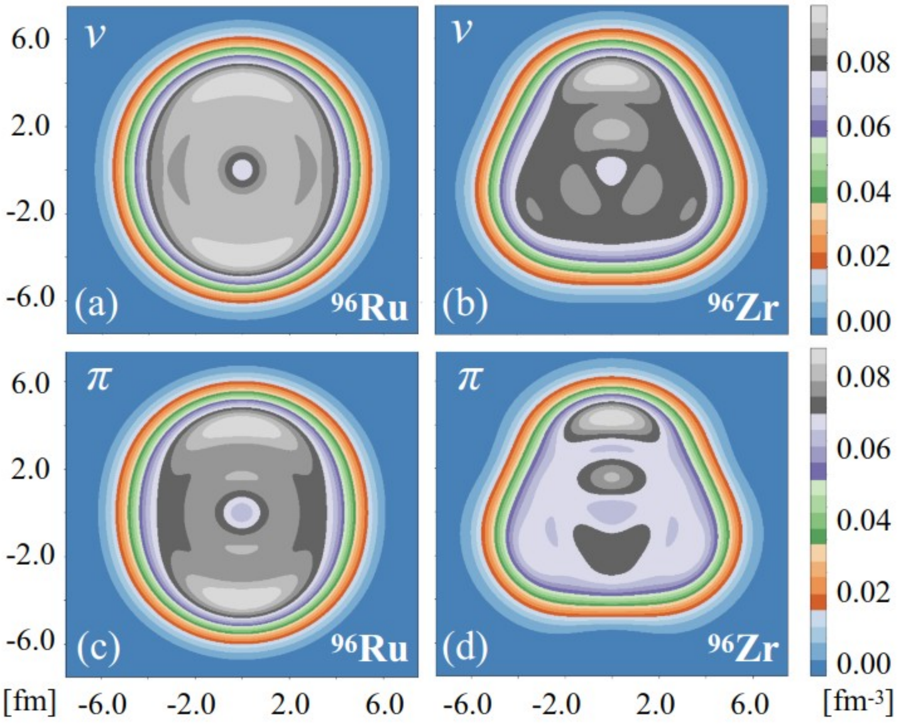
Transition densities computed within relativistic nuclear effective theory

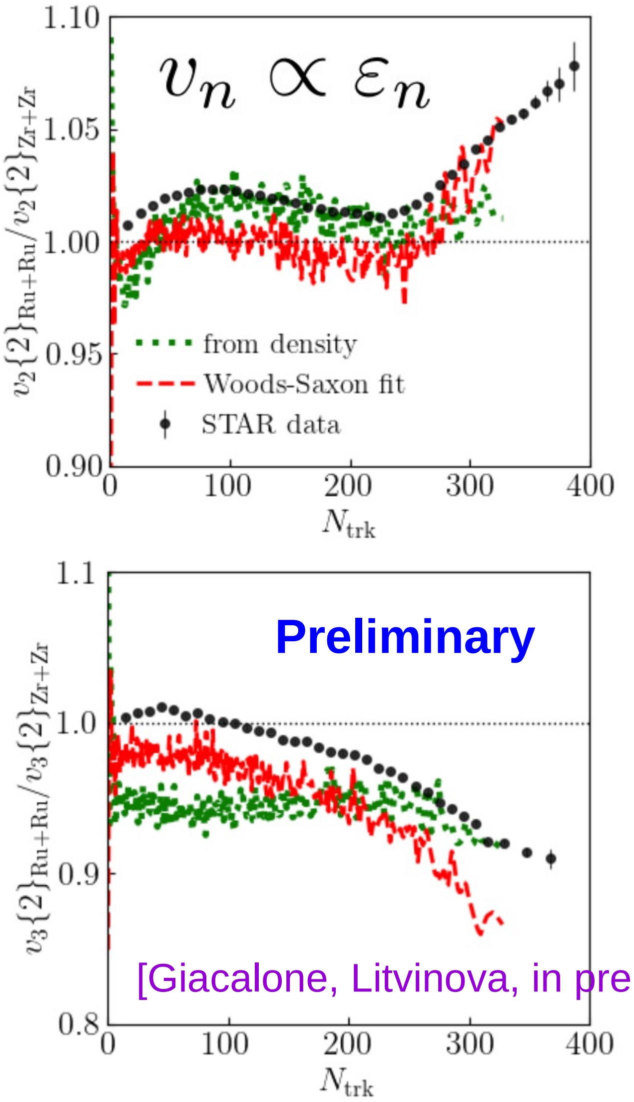
Equations-of-Motion Method and the Extended Shell Model

D. J. ROWE
Rev. Mod. Phys. **40**, 153 – Published 1 January 1968

[Litvinova, Schuck, PRC **107** (2023) 2, 029903]

The dominant softness of ^{96}Ru is of the quadrupole character, with the lowest quadrupole state at ≈833 (880) keV in the experiment [9] (theory), which is well separated from the higher excited states. In ^{96}Zr, the lowest 2_1^+ and 3_1^- states which define the dominant fluctuation shape are nearly degenerate, appearing at the energies ≈1751 (1790) keV and ≈1897 (1990) keV

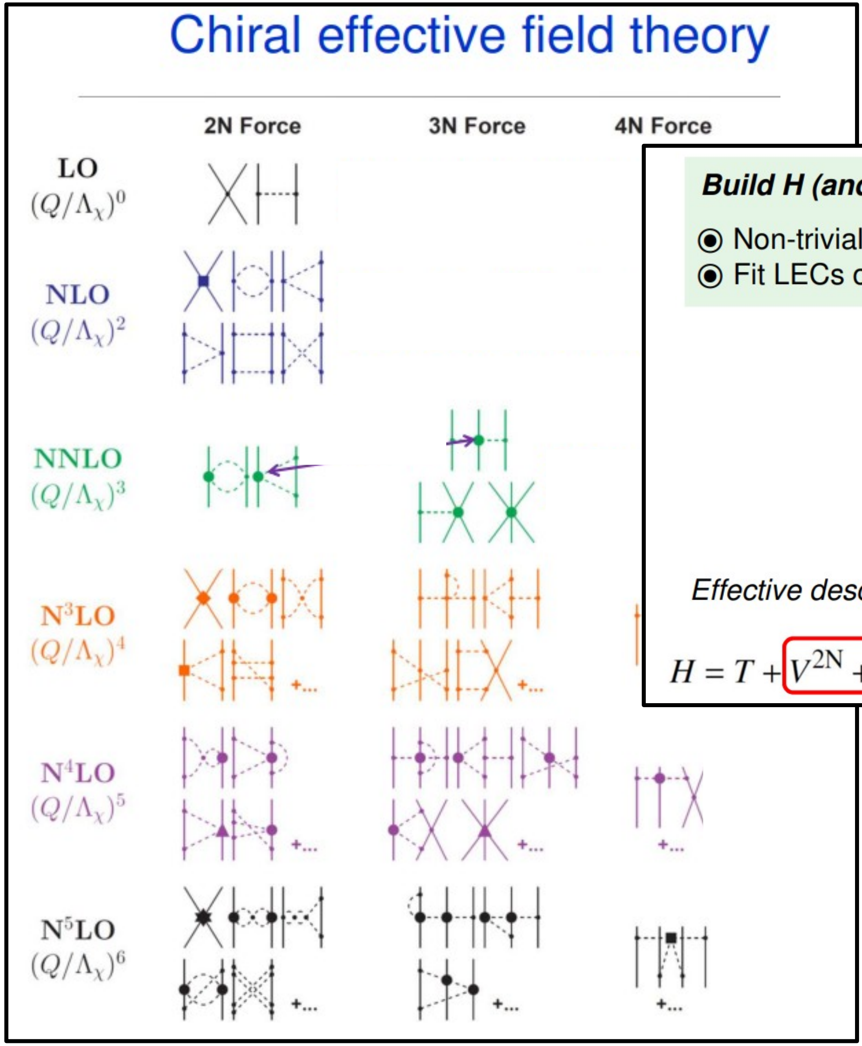




[Giacalone, Litvinova, in preparation]

Implementation from *ab initio* approaches

TALK BY B. BALLY



[T. Duguet, ESNT workshop, Sep 2022]

Build H (and other operators) with χEFT at various orders

- ◉ Non-trivial formal task whose difficulty increases with order (e.g. **3N at N²LO, 4N at N³LO**…)
- ◉ Fit LECs of mode-2k tensors to experimental data (or lattice QCD) in A = k-body systems

Organization = power counting
Importance of interaction terms

A-body Schrödinger Equation

$$H|\Psi_k^A\rangle = E_k^A|\Psi_k^A\rangle$$

Effective description = *A*-body operator in principle

[Weinberg, Gasser, Leutwyler, van Kolck, ..]

$$H = T + \boxed{V^{2N} + V^{3N}} + V^{4N} + \ldots + V^{AN}$$

Describing nuclear systems:

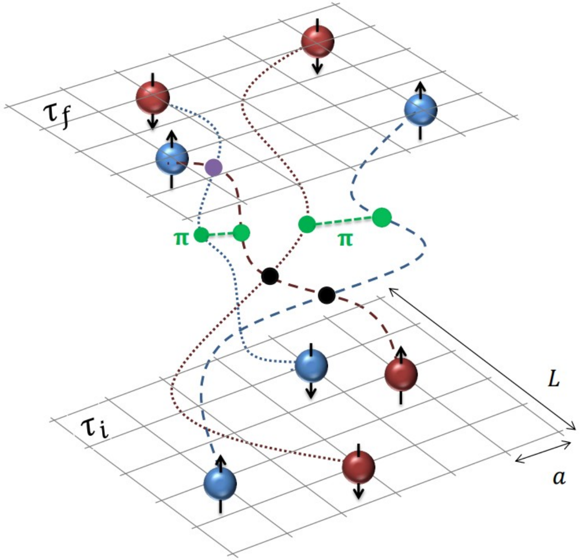
1) Consistently (from a single theoretical rationale?)
2) Systematically (complete phenomenology?)
3) Accurately enough (relevant to experimental uncertainty?)
4) From inter-nucleon interactions (right balance between reductionism/emergence?)
5) Rooted in QCD (sound connection to underlying EFT?)

Opportunities from O+O

1 – Variational Monte Carlo – Auxiliary Field Diffusion Monte Carlo (VMC-AFDMC)

MC solution of Schrödinger eq. from time evolution of trial wave function.

[Lonardoni *et al*., PRC **97** (2018) 4, 044318]
[Lim *et al*., PRC **99** (2019) 4, 044904]



2 – Nuclear Lattice Effective Field Theory (NLEFT)

MC solution of Schrödinger eq. on a lattice.

TALK BY U. MEISSNER

[Lu *et al*., PLB **797** (2019) 134863]
[Summerfield *et al*., PRC **104** (2021) 4, L041901]

→ **sampled nucleons include up to A-body correlations**

3 – *ab initio* Projected Generator Coordinate Method (*ab initio* PGCM)

Wave function from variational calculation
(as in density functional theory).

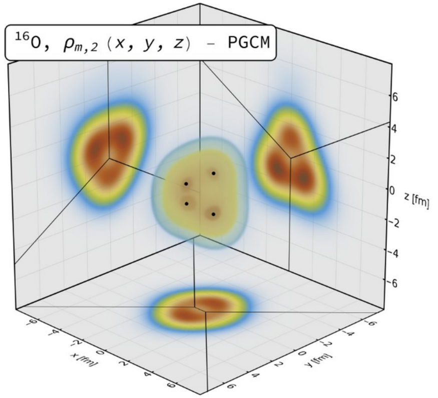
Provides a deformed density.

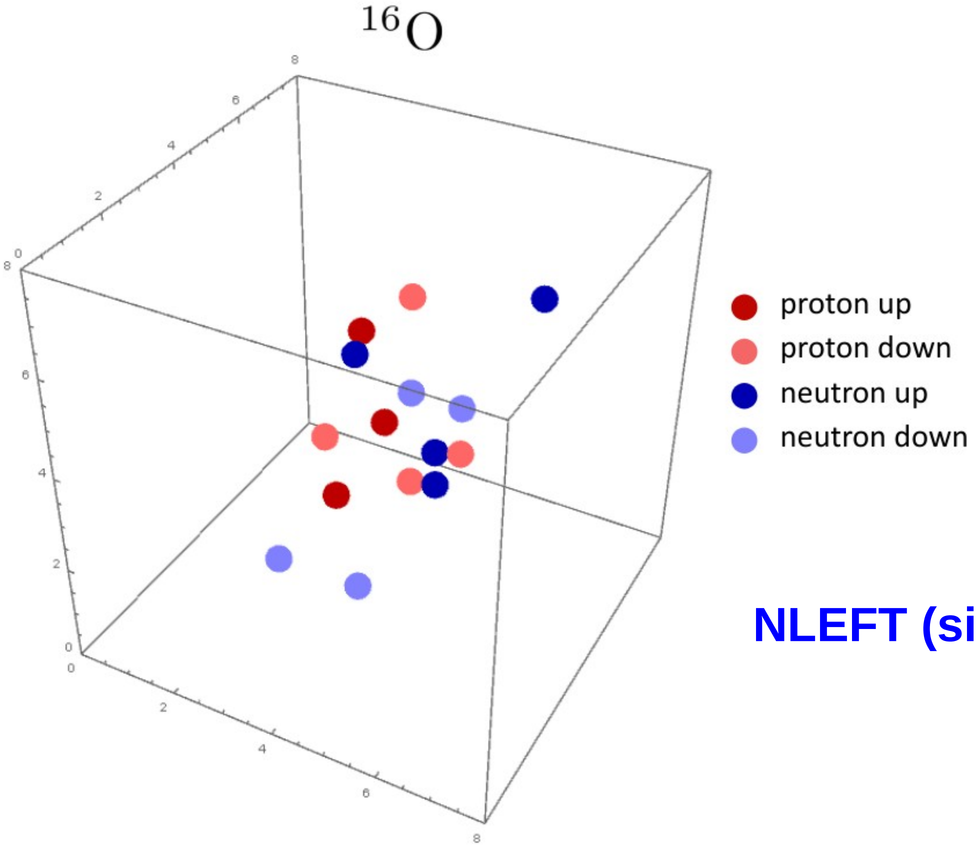
$$\delta \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} = 0$$

[Frosini *et al*., EPJA **58** (2022) 4, 62
EPJA **58** (2022) 4, 63
EPJA **58** (2022) 4, 64]

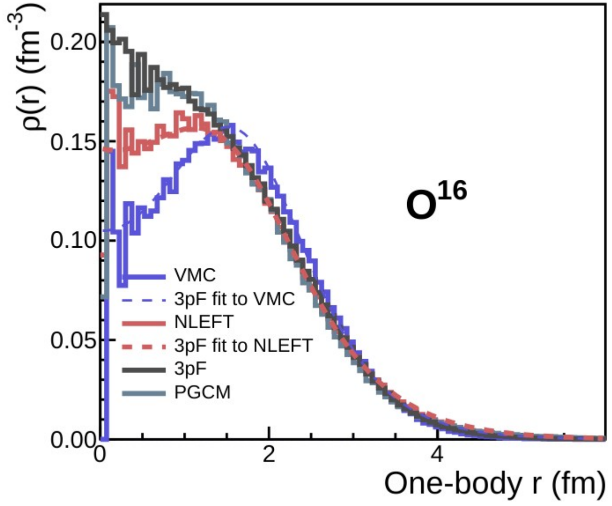
TALK BY B. BALLY

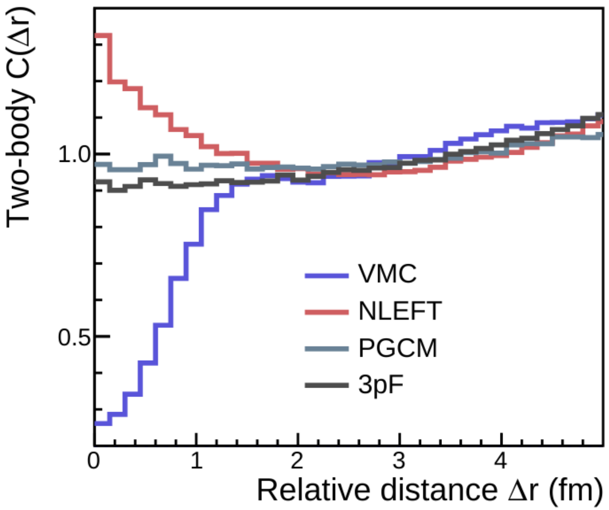
Deformations?





NLEFT (similar for VMC)

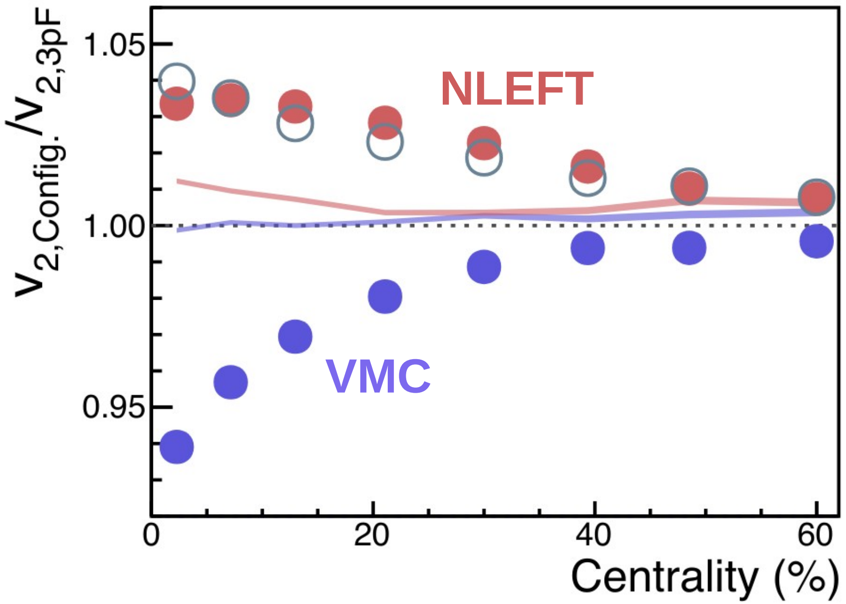




VMC has strongest clustering/short-range correlations

[Zhang *et al.*, 2404.08385]

[Broniowski, Rybczyński, PRC **100** (2019) 6, 064912]



Oxygen-oxygen collisions will discern models of clustering and short-range correlations.

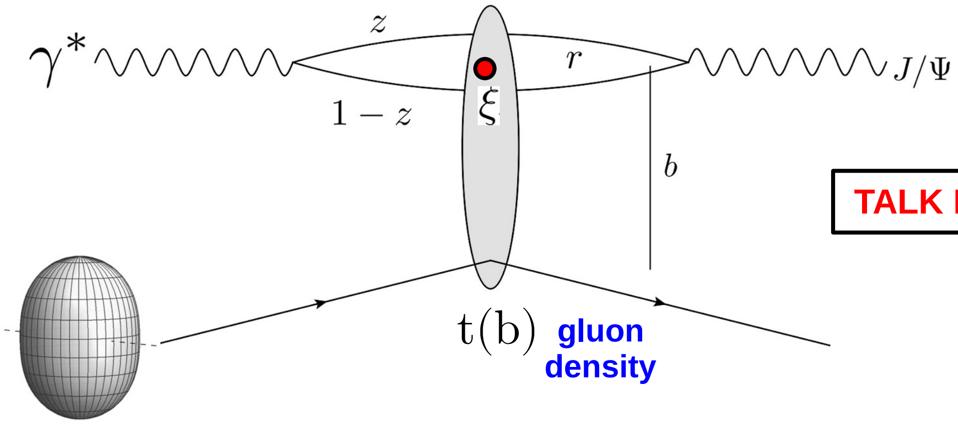
3 – Studying and exploiting nuclear deformation at high energy

1 2 3 4

EIC (or UPC) program – Same paradigm?

[Mäntysaari *et al.*, PRL **131** (2023) 6, 062301]

1



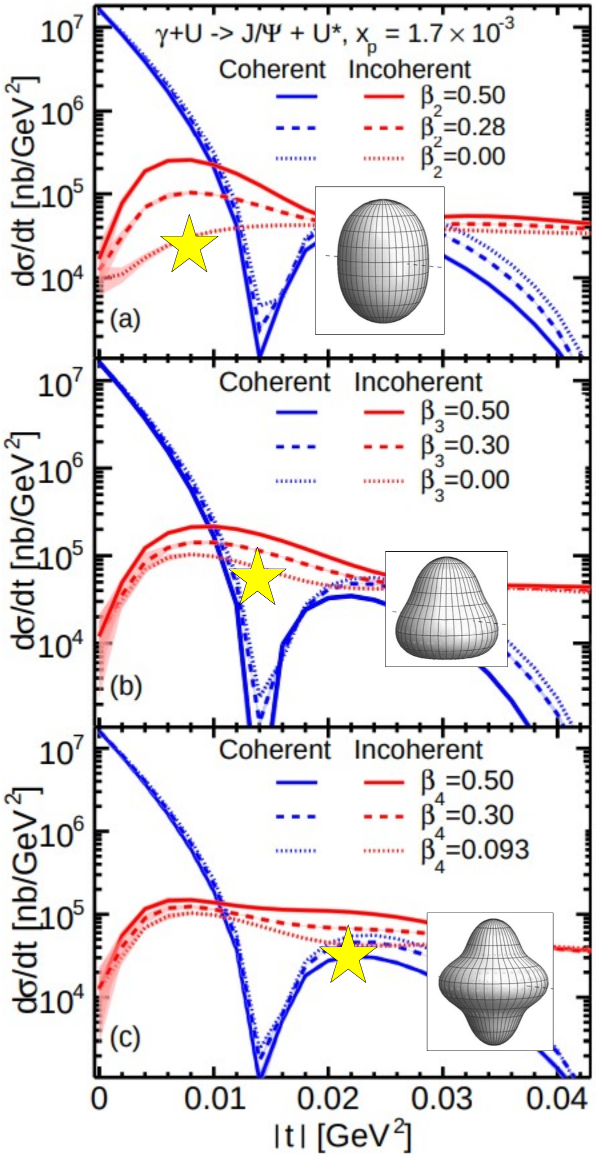
TALK BY Z. XU

Amplitude: $\mathcal{A}^{\gamma^* A\to VA} \propto \int_{\mathbf{b}} e^{-i\mathbf{b}\cdot\mathbf{\Delta}}\, t(\mathbf{b})$ **(- Δ² = t)**

→ $|\langle \mathcal{A}(|t|)\rangle|^2 \longrightarrow \int_{\xi_i} P_{1\perp}(\xi_i) e^{-i\Delta\cdot\xi_i}$ **(coherent)**

→ $\langle\, |\mathcal{A}|^2(|t|)\,\rangle \longrightarrow \int_{\xi_i\neq\xi_j} P_{2\perp}(\xi_i,\xi_j) e^{-i\mathbf{\Delta}\cdot(\xi_i-\xi_j)}$ **(incoherent)**

[Caldwell, Kowalski, PRC **81** (2010) 025203]
[Giacalone, EPJA **59** (2023) 12, 297]



2

Consistency of nuclear phenomena across scales

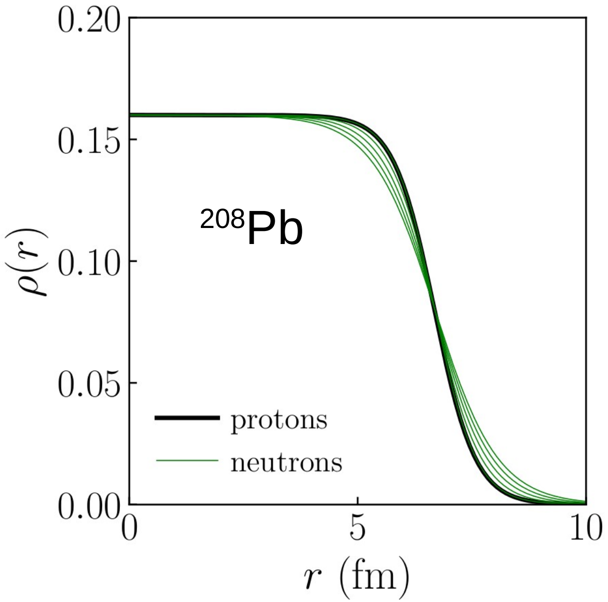
BAYESIAN ANALYSIS

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

[e.g. Paquet, arXiv:2310.17618]

Beautiful example and opportunity: The neutron distribution of ^{208}Pb is poorly known.

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



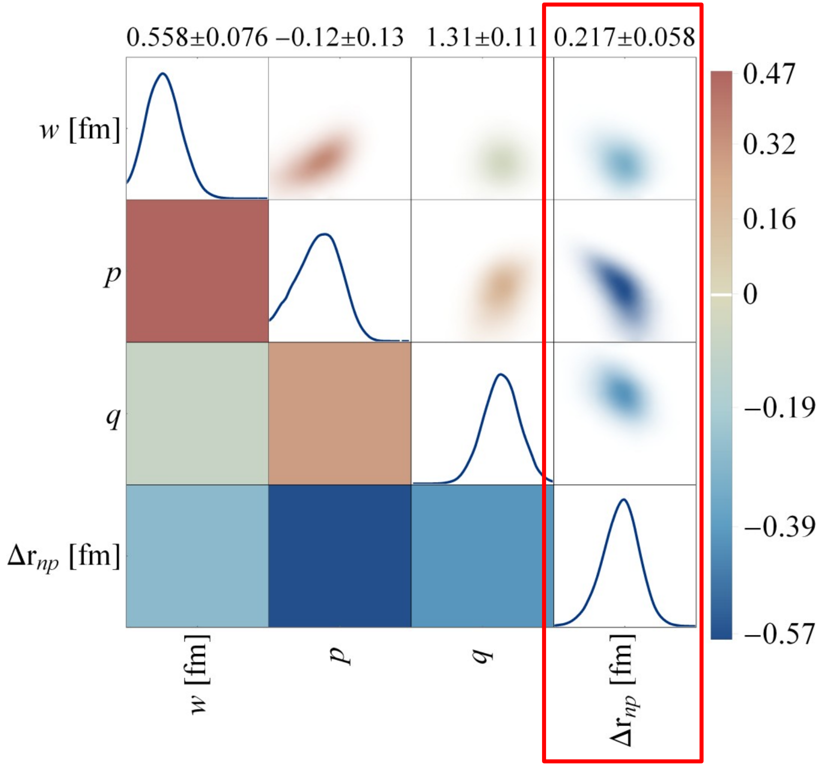
Protons: density from low-energy scattering.

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

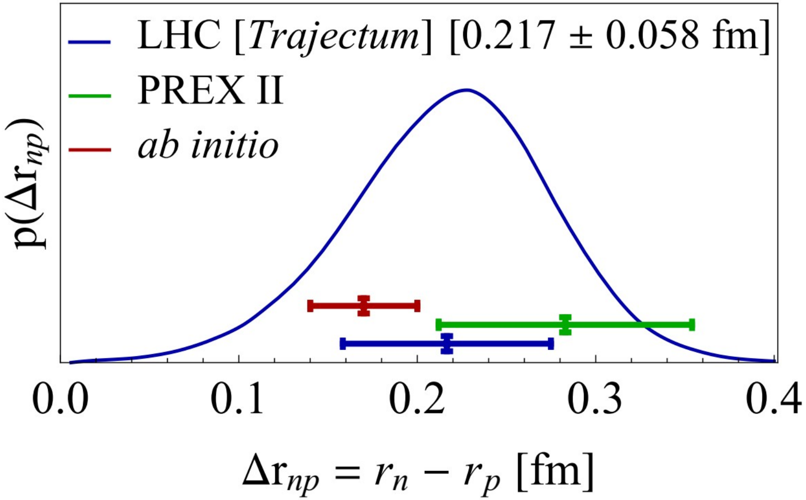
Neutrons: same R as protons, infer a from LHC data.

Correlation between nuclear properties and initial-state parameters

TALK BY G. NIJS



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



[PREX Collaboration, PRL **126** (2021) 17, 172502]
[Hu *et al.*, Nature Phys. 18 (2022) 10, 1196-1200]

Generalize to deformation parameters - Refining initial-state model

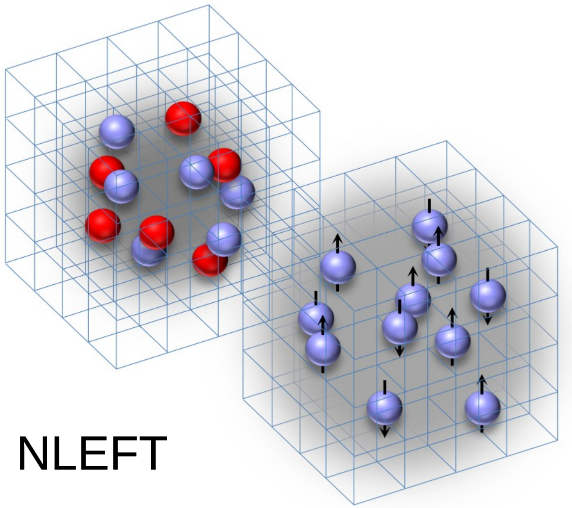
3

arXiv:2402.05995

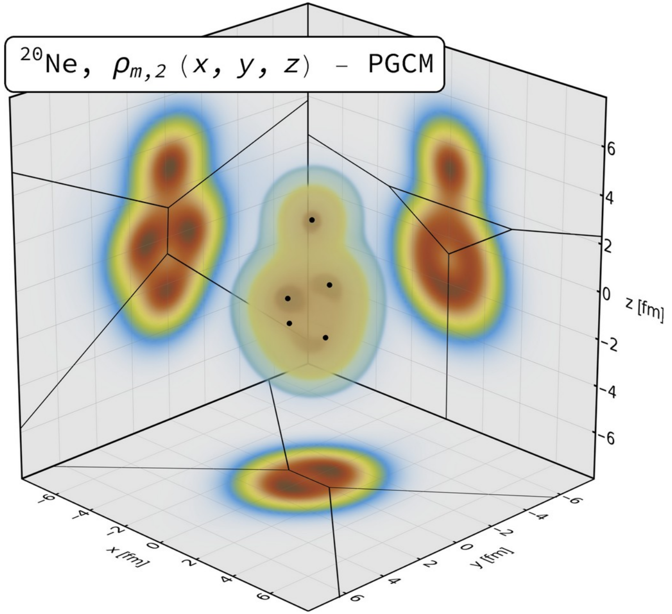
CERN-TH-2024-021

The unexpected uses of a bowling pin: exploiting ^{20}Ne isotopes for precision characterizations of collectivity in small systems

Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]



NLEFT

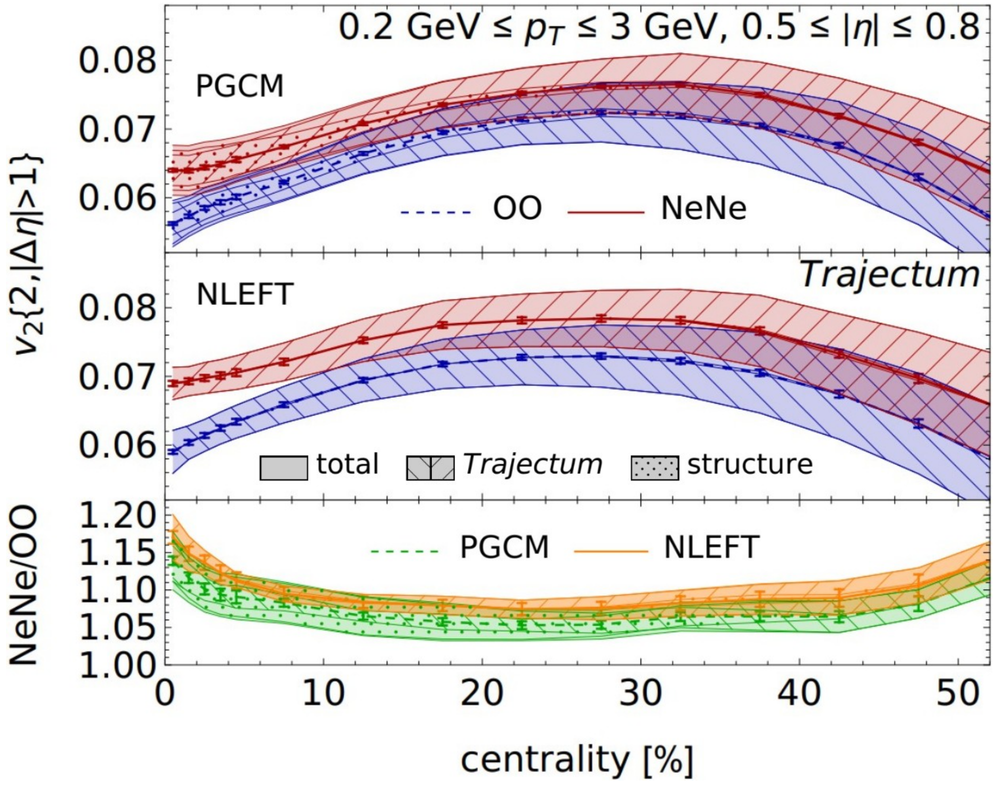


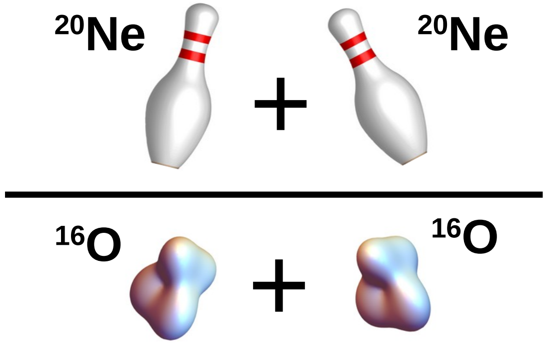
Ancillary files (details):

- NLEFT_dmin_0.5fm_negativeweights_Ne.h5
- NLEFT_dmin_0.5fm_negativeweights_O.h5
- NLEFT_dmin_0.5fm_positiveweights_Ne.h5
- NLEFT_dmin_0.5fm_positiveweights_O.h5
- PGCM_clustered_dmin0_Ne.h5
- PGCM_clustered_dmin0_O.h5
- PGCM_uniform_dmin0_Ne.h5
- PGCM_uniform_dmin0_O.h5

Error cancellations – Quantitative predictions for a small system

$dN_{ch}/d\eta \approx 150$





Theory with reliable systematic error:

$$\frac{v_2\{2\}_{\text{NeNe}}}{v_2\{2\}_{\text{OO}}} = \begin{cases} 1.170(8)_{\text{stat.}}(30)^{\textit{Traj.}}_{\text{syst.}}(0)^{\text{str.}}_{\text{syst.}} & \text{(NLEFT)} \\ 1.139(6)_{\text{stat.}}(27)^{\textit{Traj.}}_{\text{syst.}}(28)^{\text{str.}}_{\text{syst.}} & \text{(PGCM),} \end{cases}$$

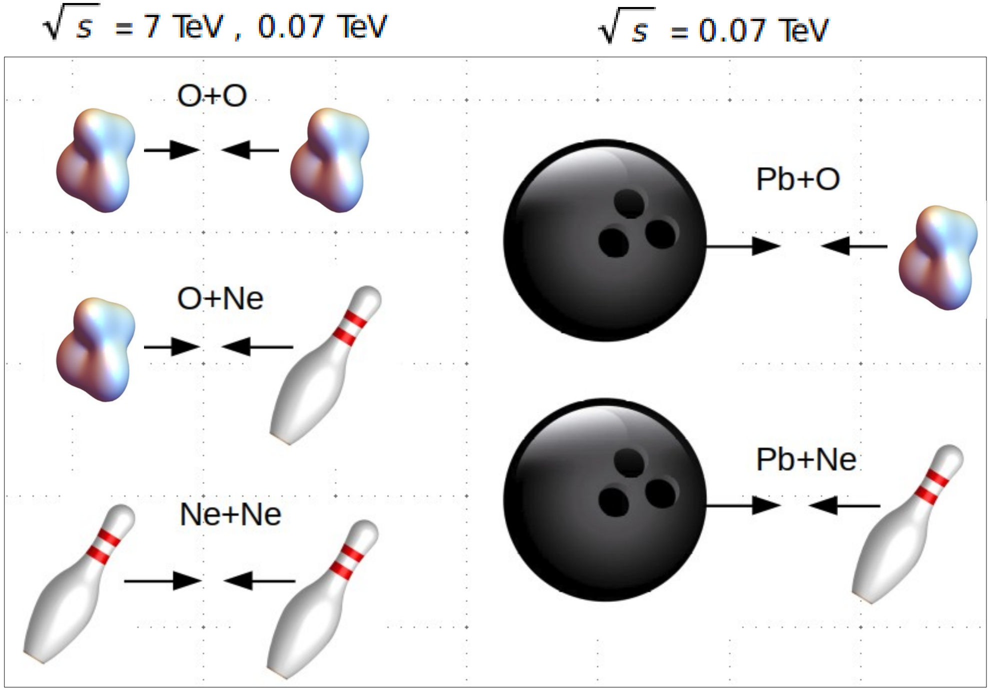
TALK BY G. NIJS

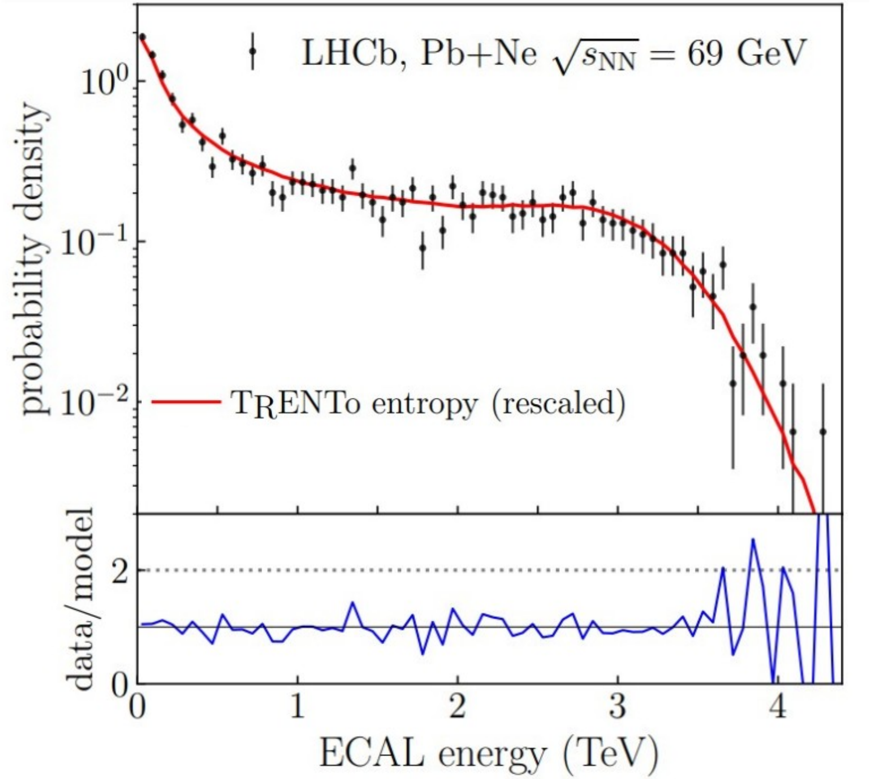
Systematics are from hydrodynamics. Ideal to test physics beyond "standard model".

The unexpected uses of a bowling pin – SMOG2

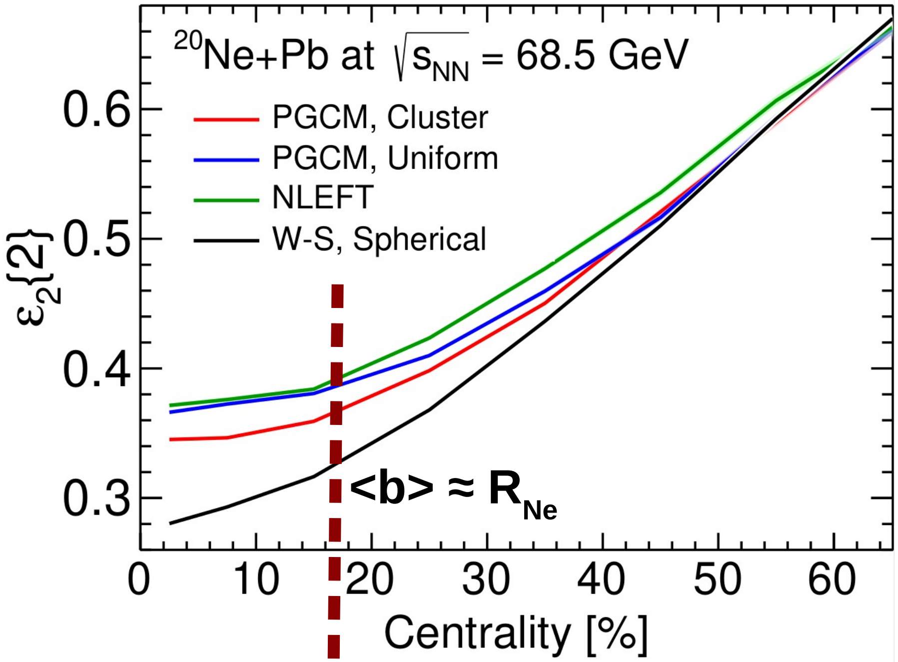
TALK BY G. GRAZIANI

[LHCb Collaboration, JINST **17** (2022) 05, P05009]

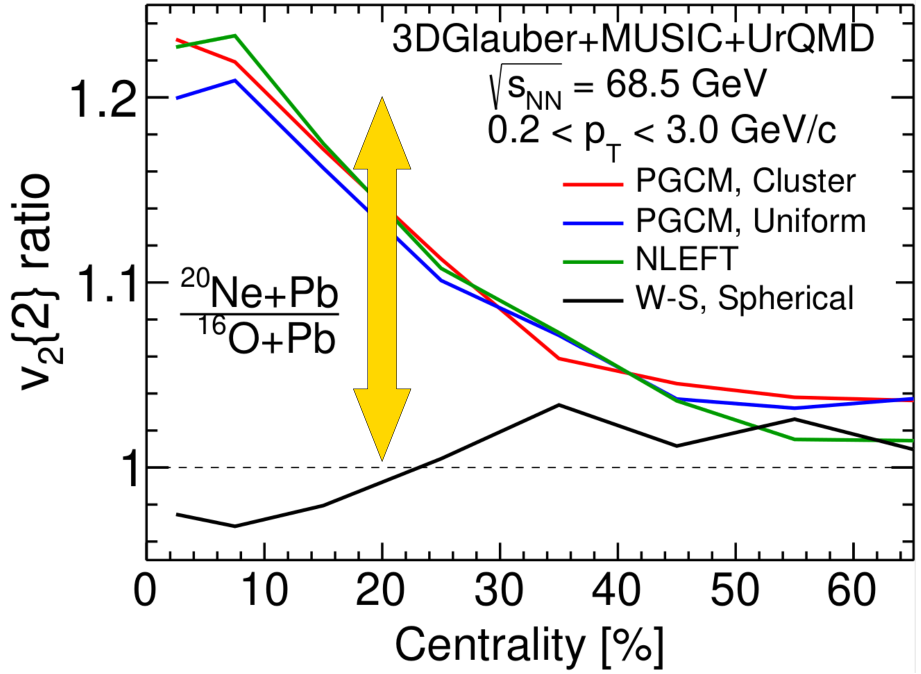




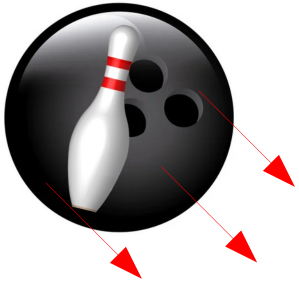
For deformed nuclei, flat eccentricity up to ~20% centrality



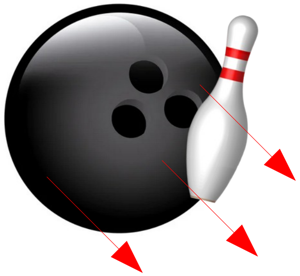
[W. Zhao et al., in preparation]



on-target



off-target

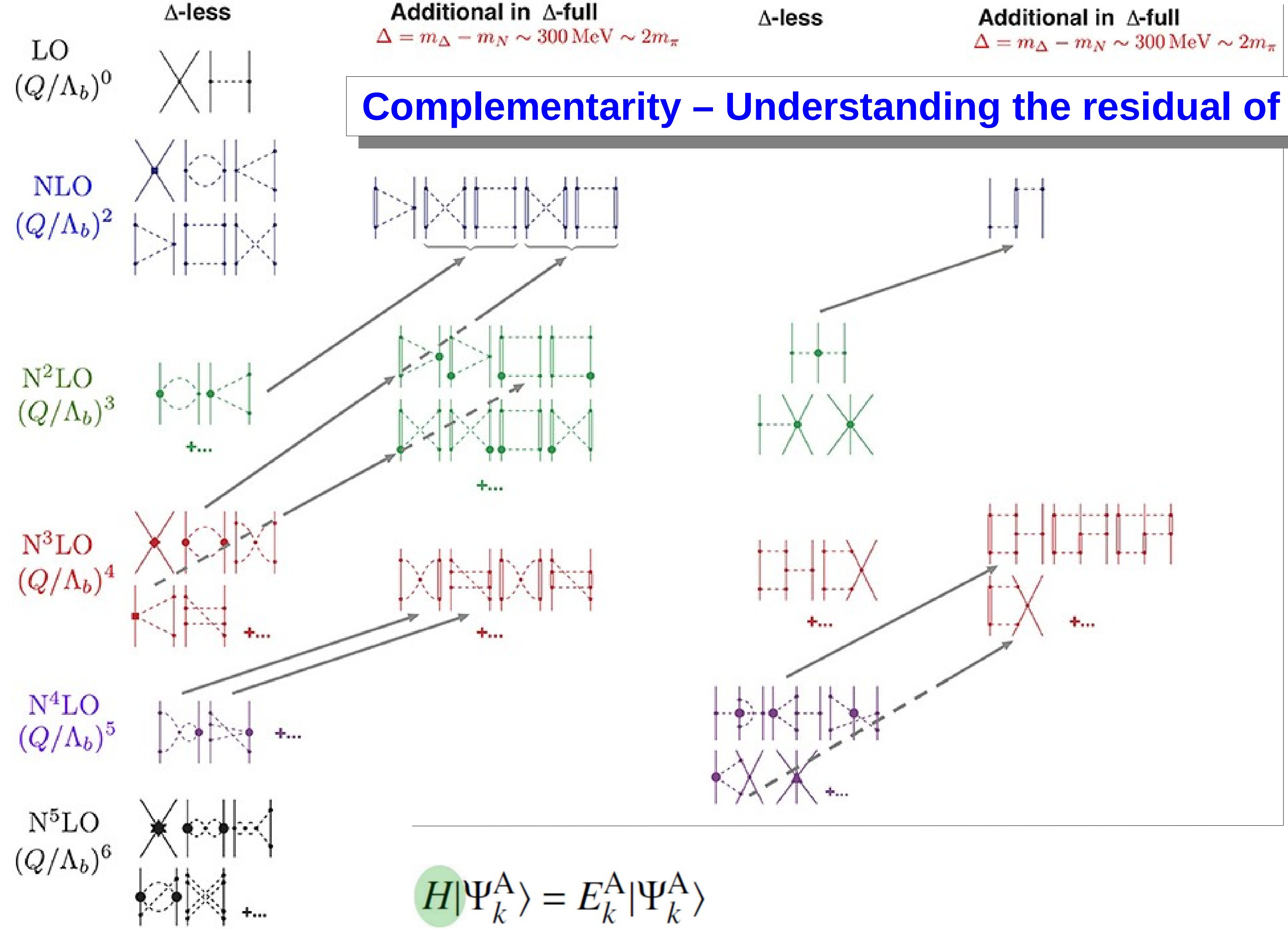


Signal is gigantic.

Unique potential of SMOG2 for imaging nuclei.

4

Complementarity – Understanding the residual of QCD

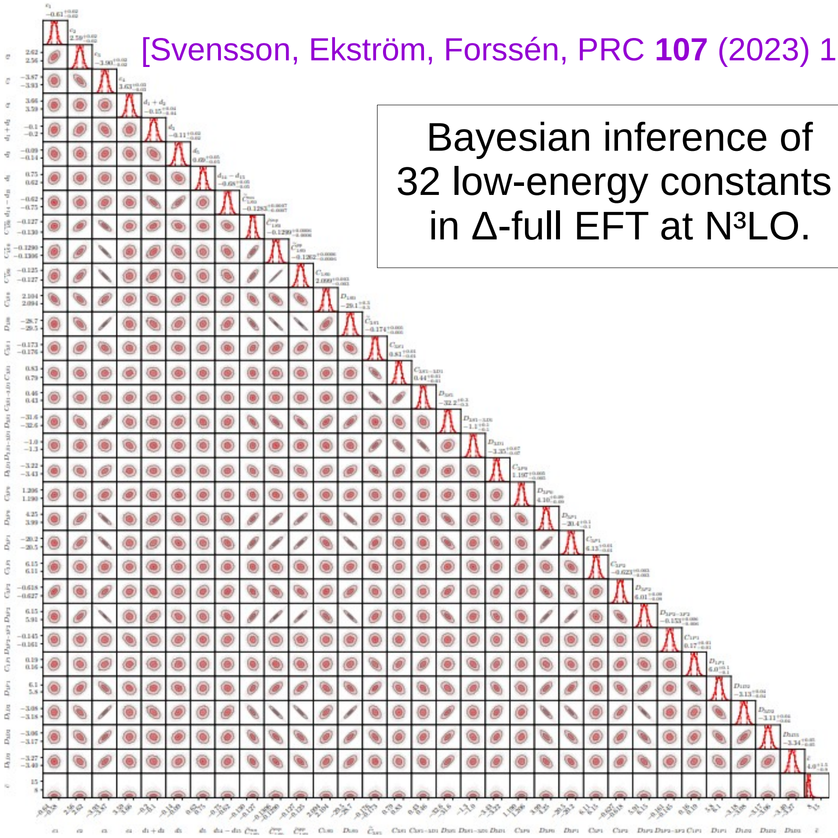


$$H|\Psi_k^A\rangle = E_k^A|\Psi_k^A\rangle$$

High-energy collisions and the quest for nuclear interactions

TALKS BY K. GODBEY, X. ZHANG

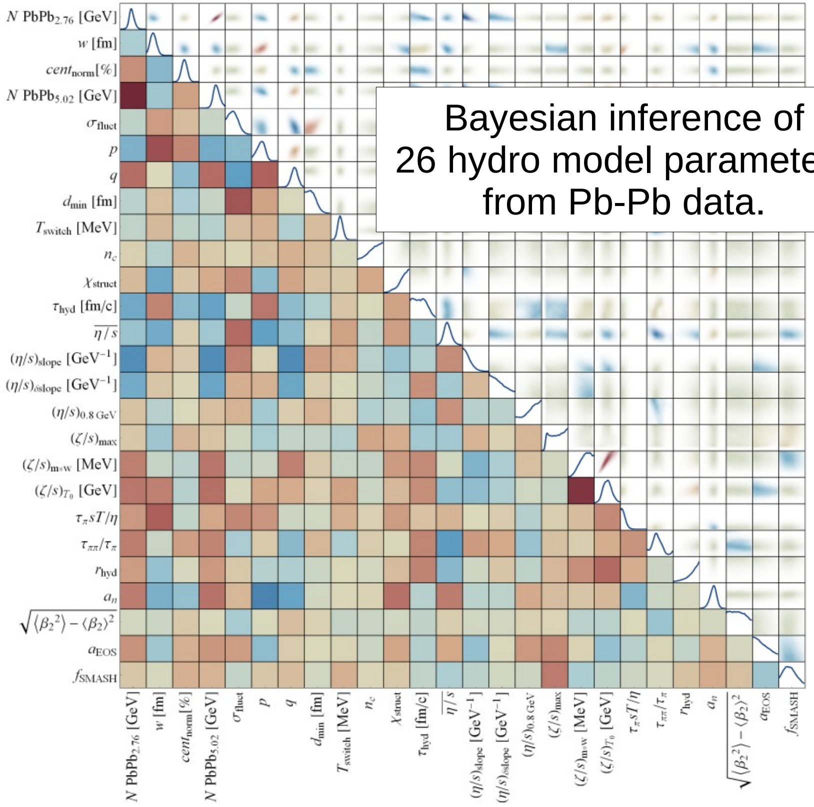
[Svensson, Ekström, Forssén, PRC **107** (2023) 1, 014001]



Bayesian inference of
32 low-energy constants
in Δ-full EFT at N³LO.

↔

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



Bayesian inference of
26 hydro model parameters
from Pb-Pb data.

TALK BY G. NIJS

Reconstructing the strong nuclear force

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

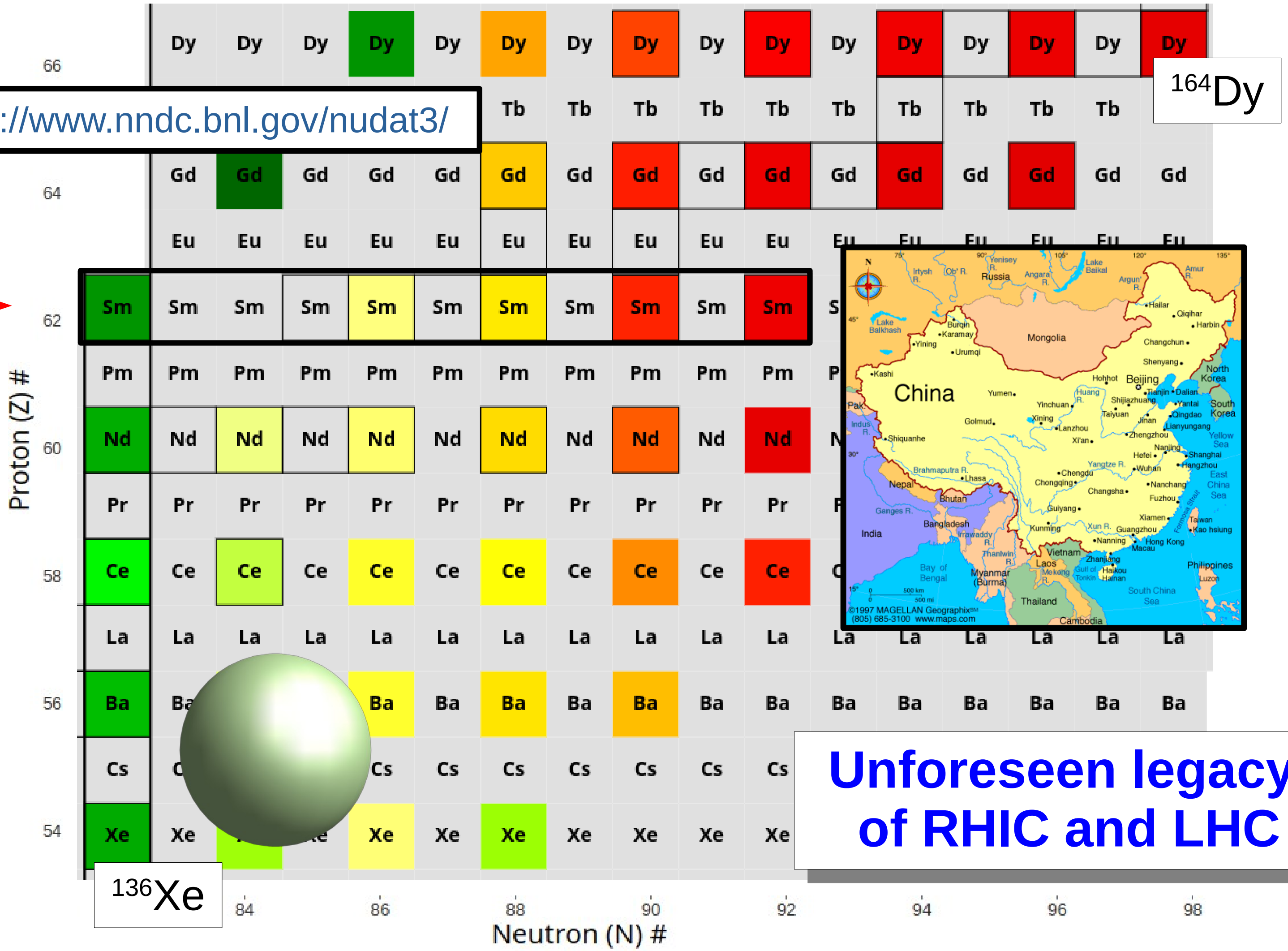
$$\tilde{\rho}(\mathbf{n}) = \sum_i \tilde{a}_i^\dagger(\mathbf{n}) \tilde{a}_i(\mathbf{n}) + s_L \sum_{|\mathbf{n}'-\mathbf{n}|=1} \sum_i \tilde{a}_i^\dagger(\mathbf{n}') \tilde{a}_i(\mathbf{n}')$$

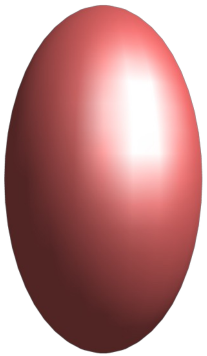
$$\tilde{a}_i(\mathbf{n}) = a_i(\mathbf{n}) + s_{NL} \sum_{|\mathbf{n}'-\mathbf{n}|=1} a_i(\mathbf{n}')$$

Parameters can be extracted from LHC and RHIC data on 16O collisions

Is it important? Different nuclei offering different sensitivities?

from https://www.nndc.bnl.gov/nudat3/





Unforeseen legacy of RHIC and LHC