Nuclear structure for high-energy nuclear collisions

– exploring nuclear phenomena across energy scales –

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November 8th 2022

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On-line seminar series V on "RHIC Beam Energy Scan" Fall 2022

Intersection of nuclear structure and high-energy nuclear collisions: a new research direction.

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

https://esnt.cea.fr/Phocea/Page/index.php?id=107 **Sep 20th - Sep 23rd 2022**

Organizers:
Giuliano Giacalone (ITP Heidelberg)
Jean-Yves Ollitrault (IPhT Saclay)
You Zhou (Niels Bohr Institute)

Intersection of nuclear structure and high-energy nuclear collisions

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

Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

→ Next Initial Stages conference (Copenhagen, 2023) will have a track related to nuclear structure.

→ Input for Nuclear Physics LRP in the US, arXiv link

→ Contributed input to NUPECC LRP 2024 [with Y. Zhou (NBI Copenhagen)]

OUTLINE

1 – Nuclear structure input to high-energy nuclear collisions.

2 – Nuclear shapes in high-energy nuclear experiments.

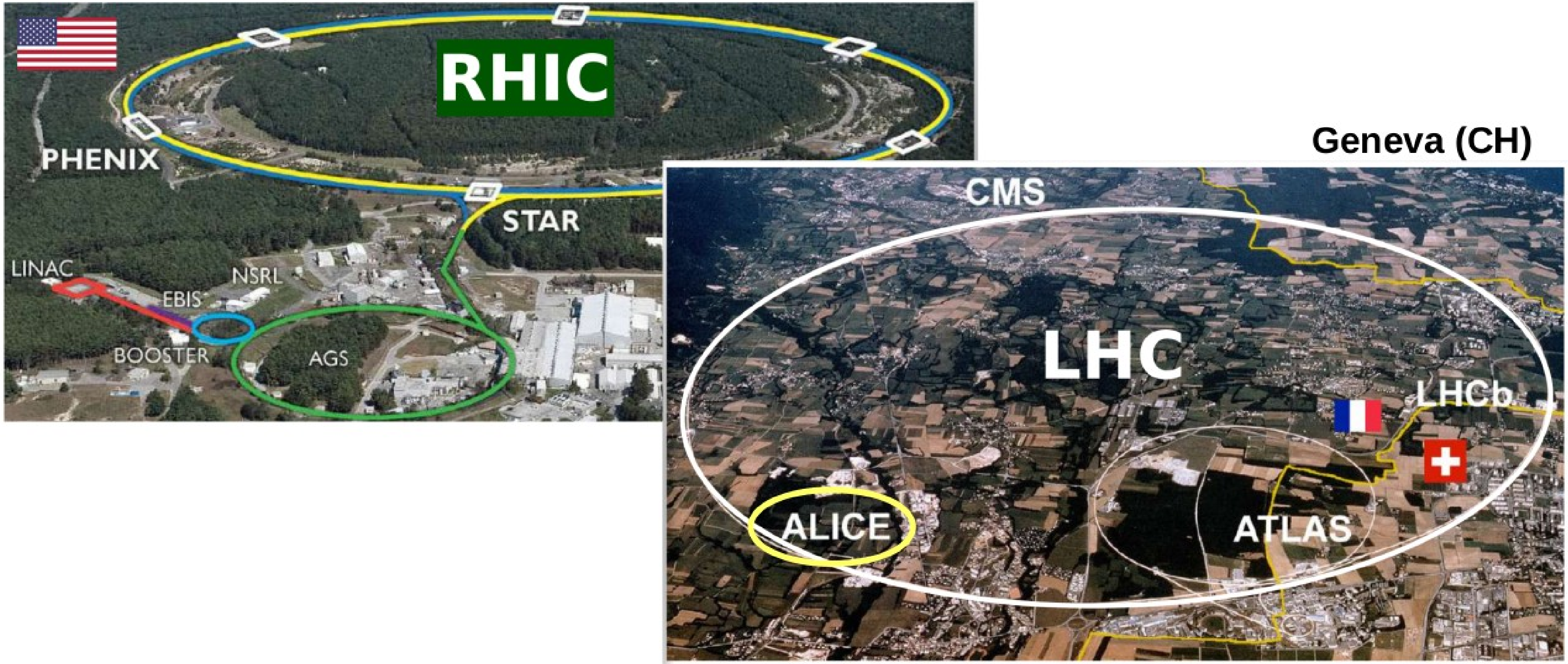
3 – Prospects: theory and experiment.

1 – Nuclear structure input to high-energy nuclear collisions.

HIGH ENERGY NUCLEAR PHYSICS

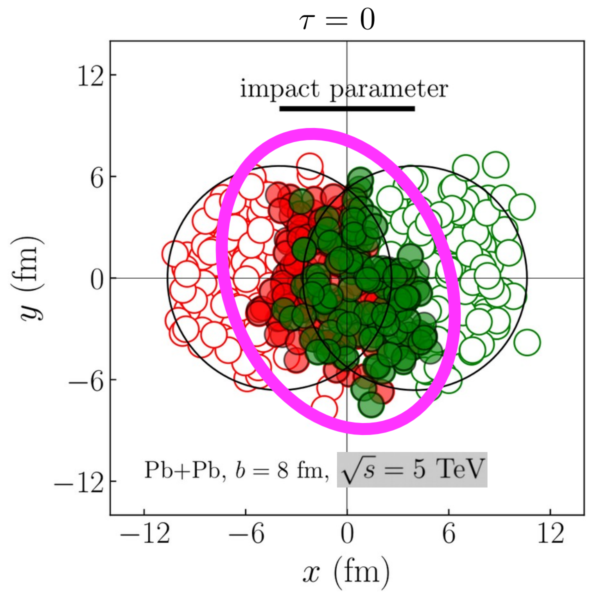
Long Island (NY)

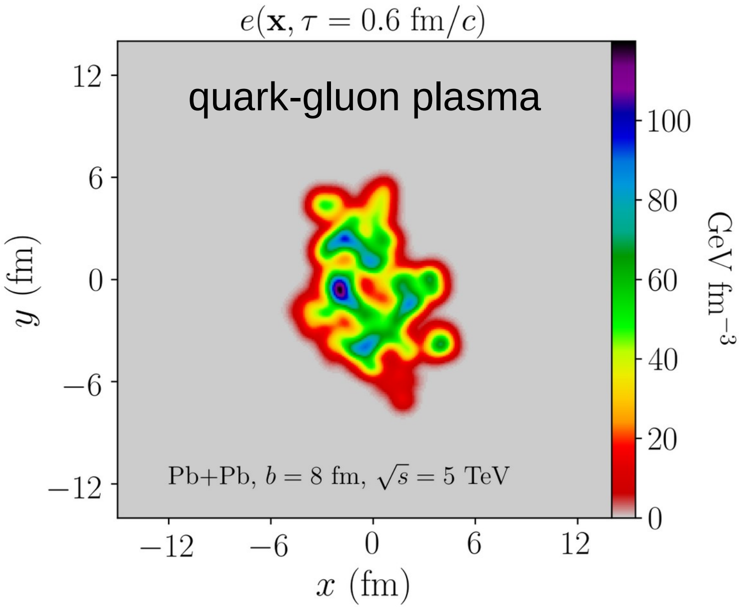
Geneva (CH)



- Great program of high-energy nuclear collisions (~2k experimentalists involved).
- Nuclei collided ~1 month/year @ LHC.
- RHIC is dedicated to nuclear collisions (shutdown ~2026).

THE EARLY UNIVERSE IN THE LAB





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

[Romatschke & Romatschke, arXiv:1712.05815]

Equation of state from lattice QCD. Large number of DOF (~40): QGP.

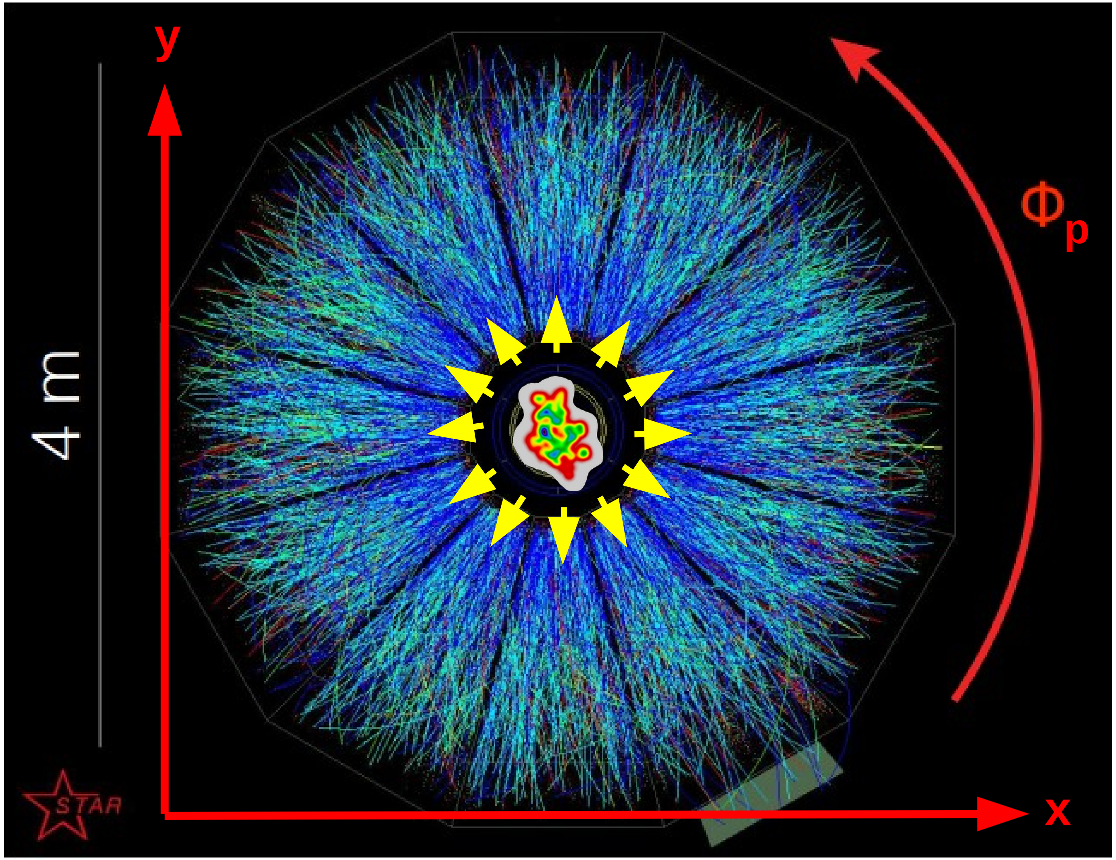
[HoTQCD collaboration, PRD **90** (2014) 094503]

Relevant temperature at top LHC energy: ≈ 220 MeV (2.6 x 10^{12} K).

[Gardim, Giacalone, Luzum, Ollitrault, Nature Phys. **16** (2020) 6, 615-619]

Main goals: understanding initial condition/transport properties/hadronization.

How do we “reconstruct” the QGP from the particle distributions?



Hydrodynamics describes the motion of the bulk of the produced particles.

They sit at low momenta and follow the collective expansion of the system.

$$\frac{d^2N}{dp_{\mathrm{T}}d\phi} = \frac{dN}{2\pi dp_{\mathrm{T}}}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)$$

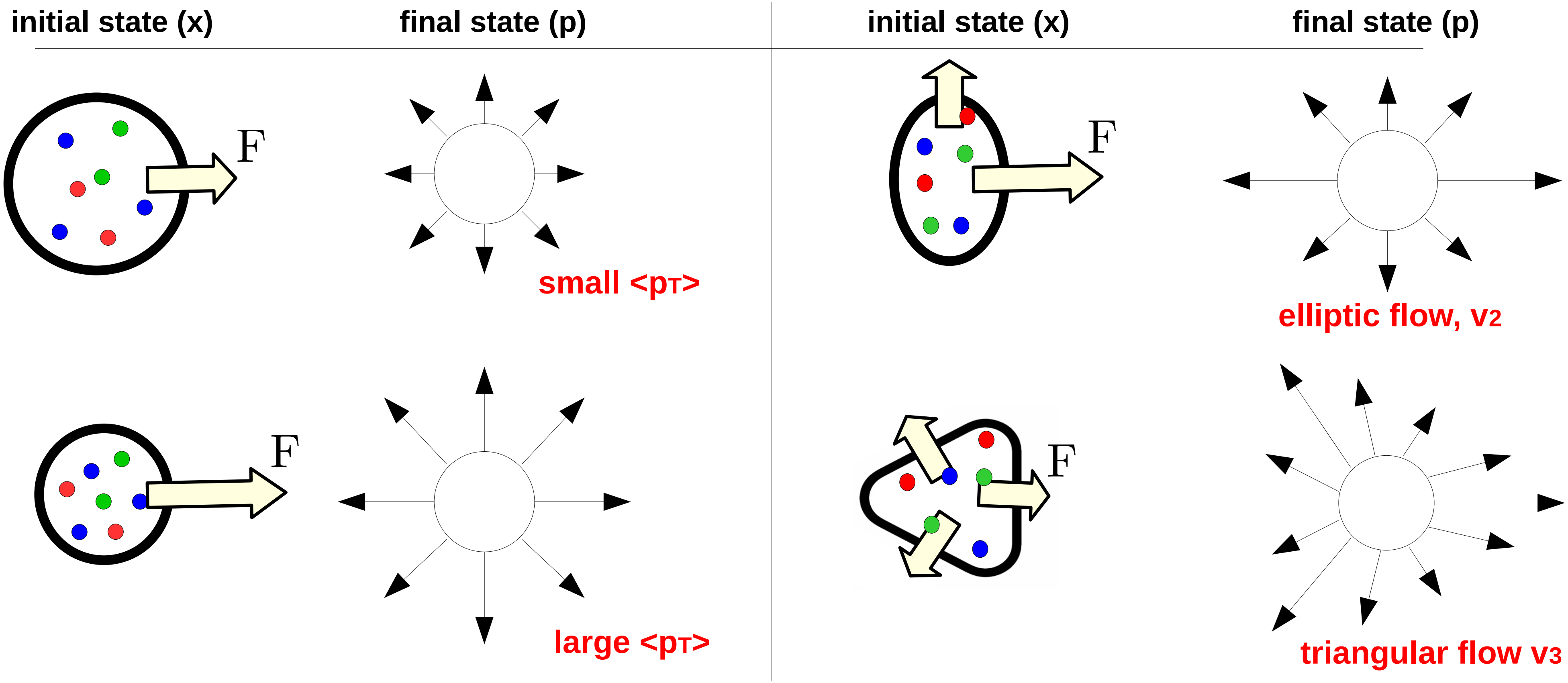
EXPLOSIVENESS OF THE EXPANSION

ANISOTROPY OF AZIMUTHAL DISTRIBUTION

Mapping initial-state geometry to final-state observables via pressure-gradient force.

$$F = -\nabla P$$

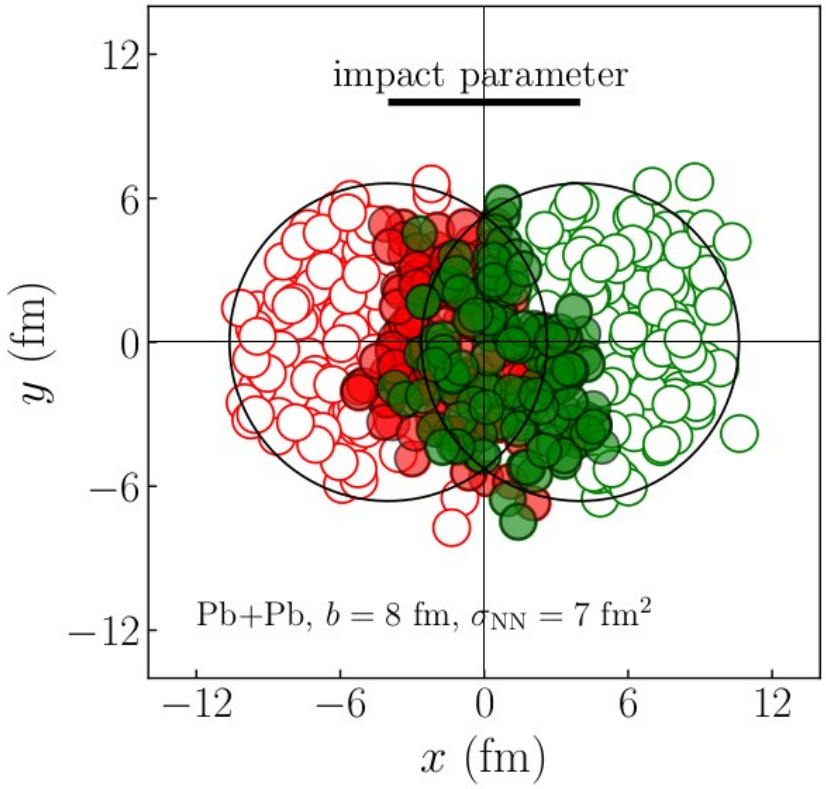
[Ollitrault, PRD **46** (1992) 229-245]



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

Formation of QGP starts with an input from nuclear structure.

We want to understand this connection from experiments.



High-energy model

Scattering occurs mainly within nucleons.

Interaction acts as a "quantum measurement" of the positions of the nucleons. (resolution dictated by momentum transfer 1-10 GeV ~ 0.01-0.1 fm)

Origin of nucleon positions: for “spherical” systems like 208Pb, independent sampling in common potential (mean field) is appropriate.

INDEPENDENT PARTICLE PROBLEM

FULL PROBLEM

$$H|\psi\rangle = E|\psi\rangle \longrightarrow \begin{aligned} h_i|\phi_k^i\rangle &= \varepsilon_k^i|\phi_k^i\rangle \\ h_i &= \frac{p_i^2}{2m} + V(r_i) \end{aligned}$$

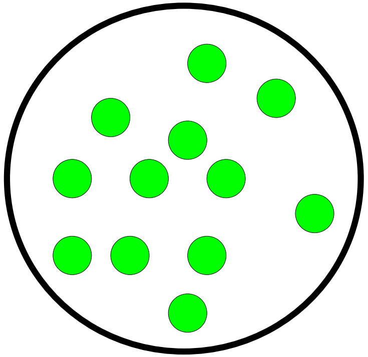
$$V(r_i) = -\frac{V_0}{1+\exp\left(\frac{r_i - R}{a}\right)}$$

Woods-Saxon

Nuclear state from variational equation with Ansatz of independent Fermions.

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

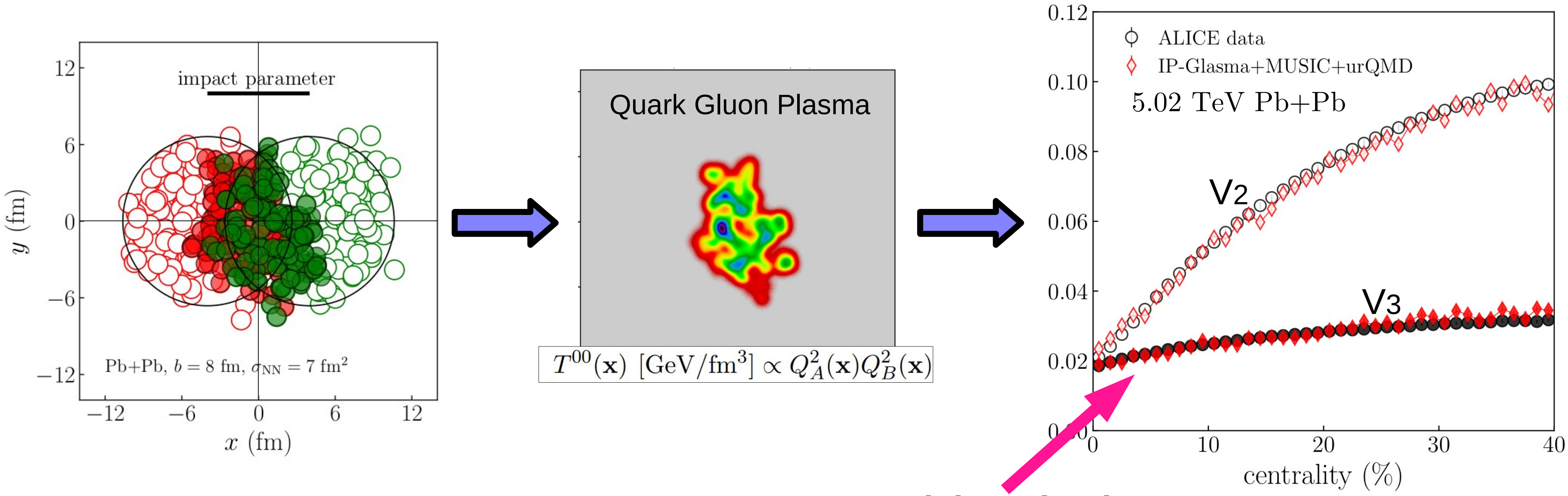
Slater determinant
(+ pairing)



More realistic: Potential generated from effective nucleon-nucleon interaction (Gogny force, Skyrme force, etc.), in “Energy Density Functional” theory.

Mean-field-based approach works at high energy (justifies the MC Glauber approach).

Nucleus-nucleus interaction does not modify the shape of the interaction region on large scales.

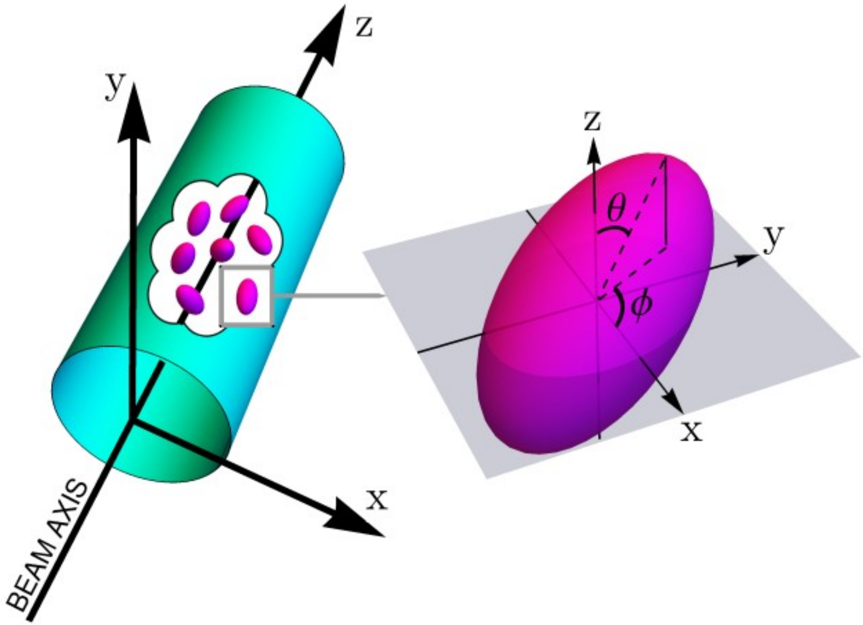


precision physics!

Now, nuclei are in general strongly-correlated systems:
Describing heavy-ion collisions requires *a priori* knowledge of A-body correlation functions, e.g.,

$$\rho_k^{\mathrm{JMNZ}}(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4) \equiv \langle \Psi_k^{\mathrm{JMNZ}} | c^\dagger(\vec{r}_1) c^\dagger(\vec{r}_2) c(\vec{r}_3) c(\vec{r}_4) | \Psi_k^{\mathrm{JMNZ}} \rangle$$ **2-body correlation function**

Help from low-energy nuclear physics:
Spatial correlations can be conveniently encapsulated in "intrinsic shapes".
Instead of A-body correlation functions, use 1-body density with a deformed shape.



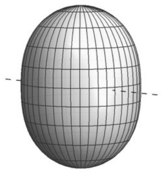
Keep a mean field approach.

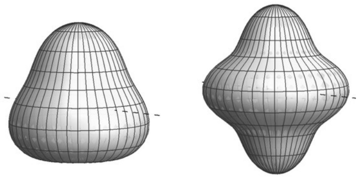
The bag of nucleons is now deformed and with a random orientation.

The interaction selects one such orientation.

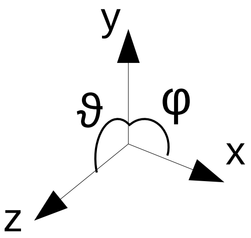
Generalize the Woods-Saxon profile to include intrinsic deformations:

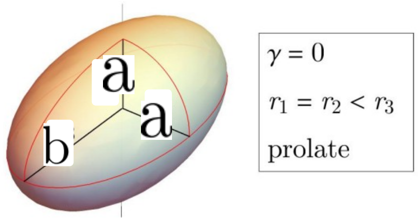
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \;, \quad R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$

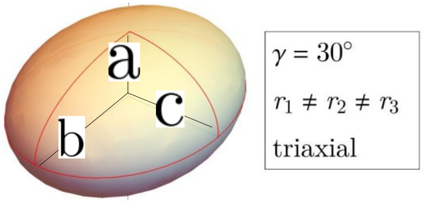


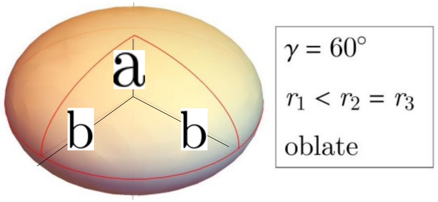


For $\beta_2>0$, the nucleus is prolate ($\gamma=0$), triaxial ($\gamma=30^0$), or oblate ($\gamma=60^0$).









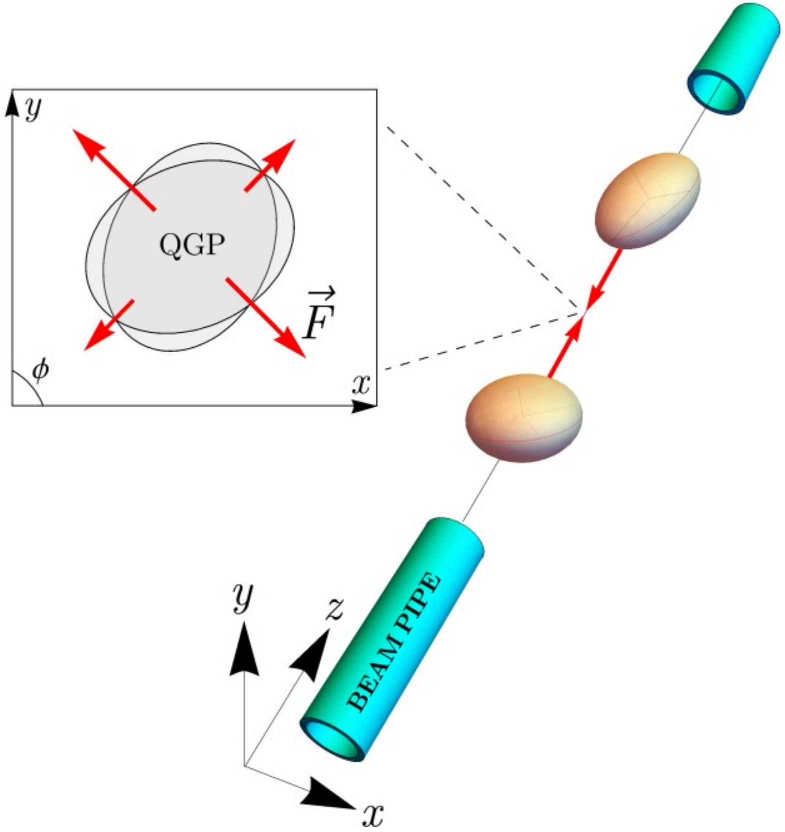
Intrinsic shapes are non-observable for direct measurements, but they leave their fingerprint on virtually all nuclear observables and phenomena

Michael Bender – RBRC Workshop Jan 2022

They will show up as well at high energy.

↓

THIS TALK!



2 – Nuclear shapes in high-energy nuclear experiments.

Species that have been collided so far (excludes p-A, d-A, He-A):

LHC

@ 2.76-5.02 TeV

- 208Pb, main species → "spherical baseline"
- 129Xe, data released in 2018

RHIC

@ 200 GeV

- 197Au, main species
- 238U, data released in 2015
- 96Ru, 96Zr, data released in 2021

(- 63Cu, very old data set)

(129Xe through 63Cu) → deformed ions

New questions to address:

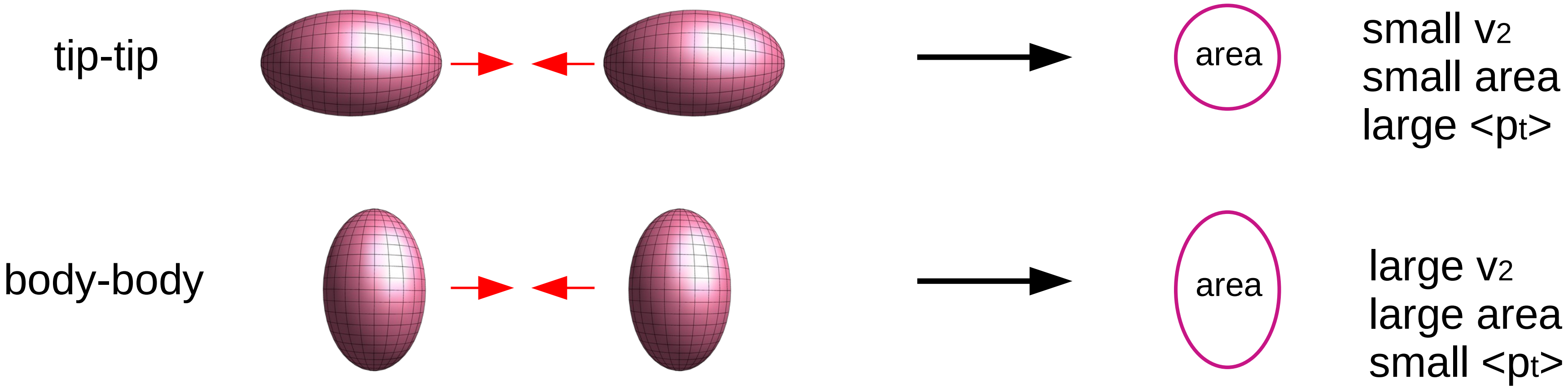
Testing high-energy model via crosscheck of nuclear deformation effects.

Are low-energy expectations compatible with high-energy observations?

HOW TO DO THAT? GOOD PROBE IS SHAPE-SIZE CORRELATION.

A new "classical phenomenon".

[Giacalone, PRL **124** (2020) 20, 202301
PRC **102** (2020) 2, 024901]



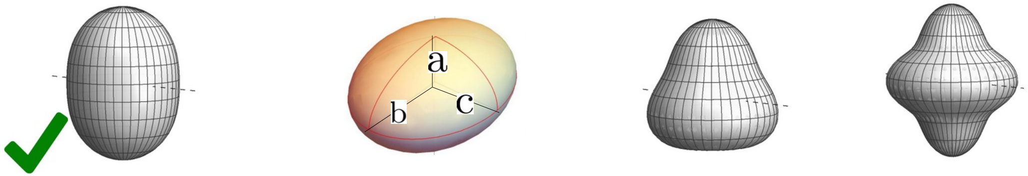
CENTRAL COLLISIONS OF (PROLATE) DEFORMED IONS

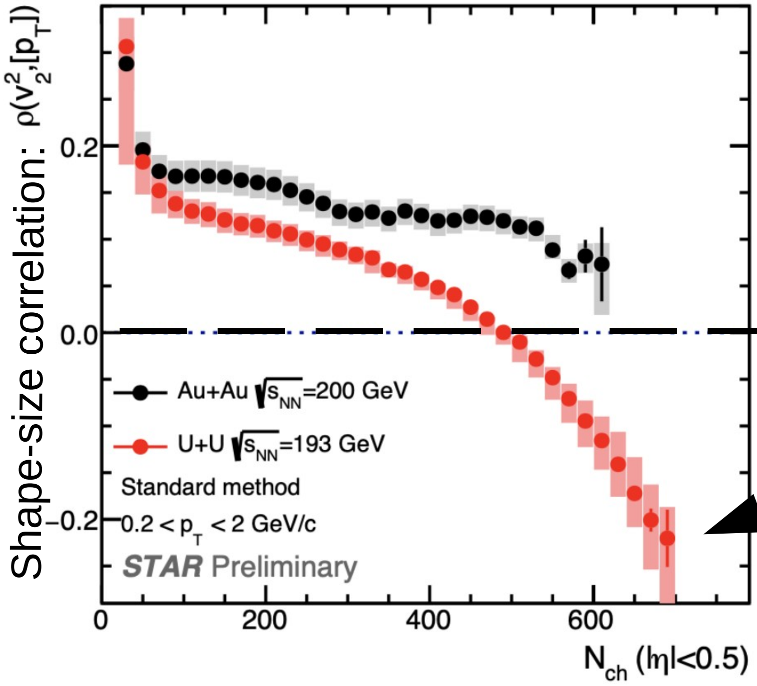
The ellipticity of the quark-gluon plasma is positively correlated with its area.

Deformation yields a negative correlation between v_2 and the $\langle p_t \rangle$.

Signature of the strong prolate deformation of uranium-238.

$$R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma}Y_{20}(\Theta)+\sin\underline{\gamma}Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$

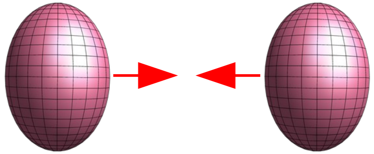




Shape is correlated with size

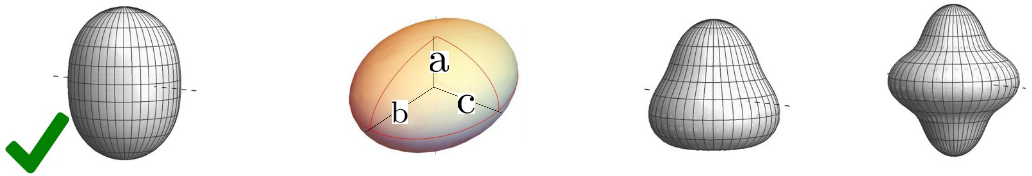
v_2 is anti-correlated with <p_t>

Limit of fully-overlapping shapes.



Signature of the hexadecapole deformation of uranium-238.

$$R(\Theta,\Phi) = R_0\left[1 + \underline{\beta_2}\left(\cos\gamma Y_{20}(\Theta) + \sin\underline{\gamma} Y_{22}(\Theta,\Phi)\right) + \underline{\beta_3} Y_{30}(\Theta) + \underline{\beta_4} Y_{40}(\Theta)\right]$$



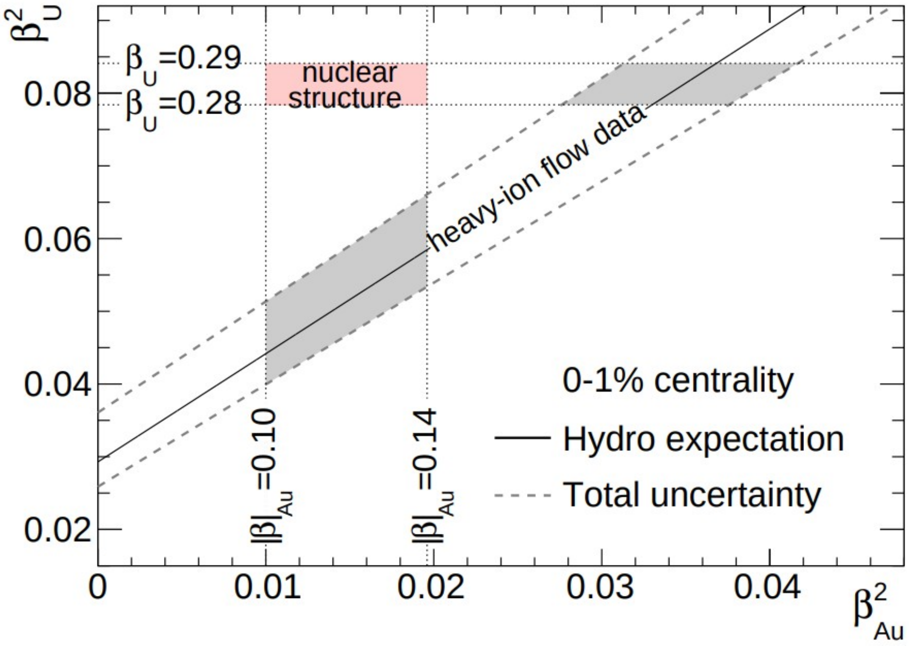
Circumstantial evidence of the failure of hydrodynamics in reproducing v_2 data from U+U collisions at RHIC.

$$\langle v_2^2 \rangle = a + b\beta^2$$

$$\downarrow$$

$$\beta_Y^2 = \left(\frac{r_{v_2^2} r_a - 1}{\frac{b_Y}{a_Y}}\right) + \left(r_{v_2^2} r_b\right)\beta_X^2$$

[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]



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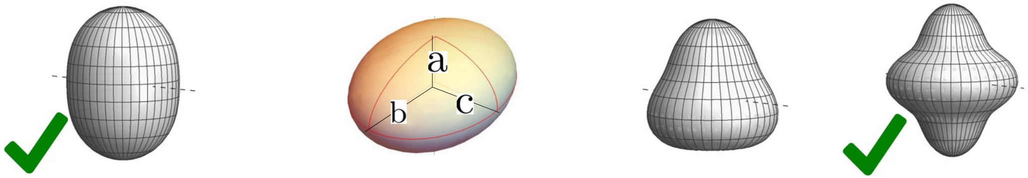


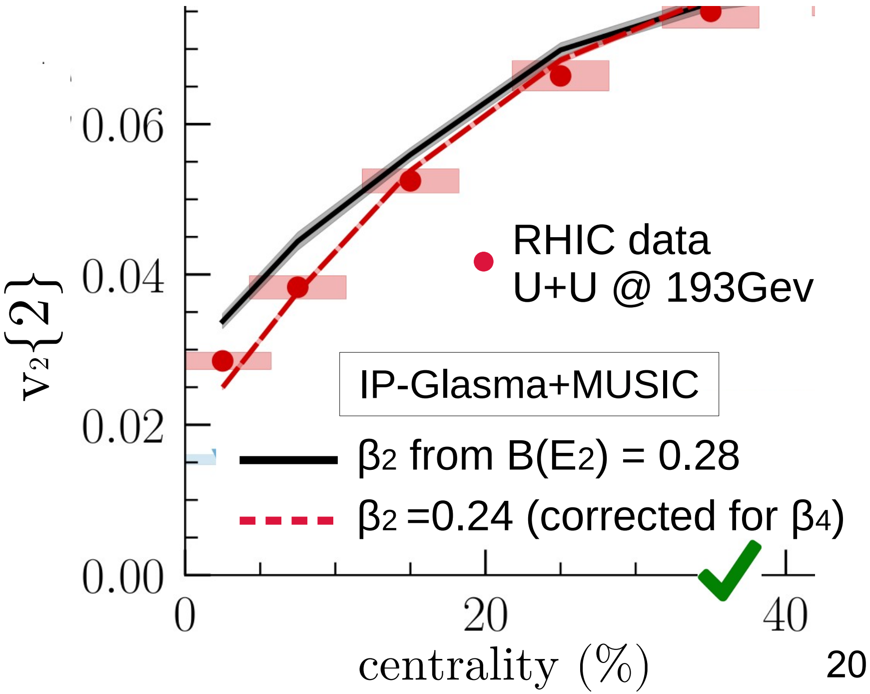
[Ryssens, Giacalone, Schenke, Shen, in preparation]

Recently pointed out by W. Ryssens (Brussels).

For large quadrupole deformation, coupling with hexadecapole adds a substantial correction.

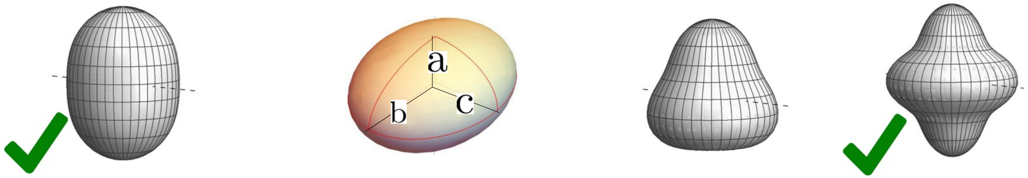
$$\beta_2 = \beta_2^{\rm WS} + \mathcal{O}[a] + \mathcal{O}[(\beta_2^{\rm WS})^2] + \underline{\mathcal{O}[\beta_4^{\rm WS}\beta_2^{\rm WS}]}$$

The coefficient to implement in Woods-Saxon profile is lower than that reported in low-energy data tables.



Signature of the triaxial deformation of xenon-129.

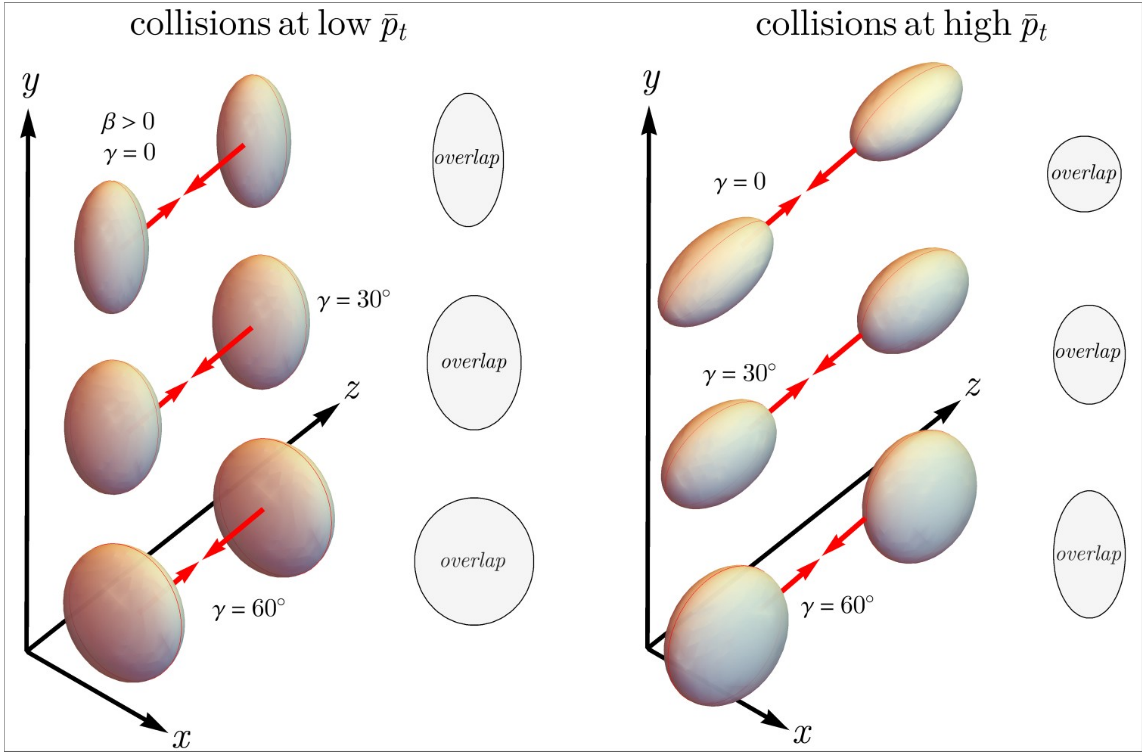
$$R(\Theta,\Phi) = R_0\left[1 + \beta_2\left(\cos\gamma Y_{20}(\Theta) + \sin\gamma Y_{22}(\Theta,\Phi)\right) + \beta_3 Y_{30}(\Theta) + \beta_4 Y_{40}(\Theta)\right]$$



Shape-size correlation is sensitive to the triaxiality, γ.

$$\rho_2 \propto -\cos(3\gamma)\beta_2^3$$

[see e.g. Jia, PRC **105** (2022) 4, 044905]



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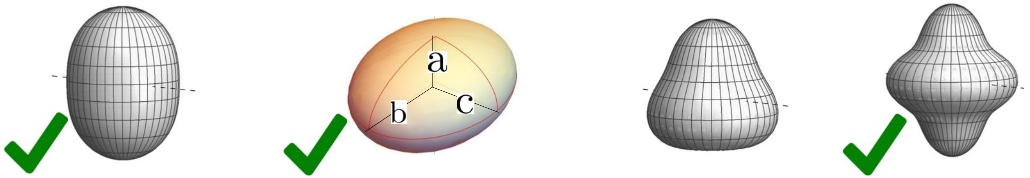
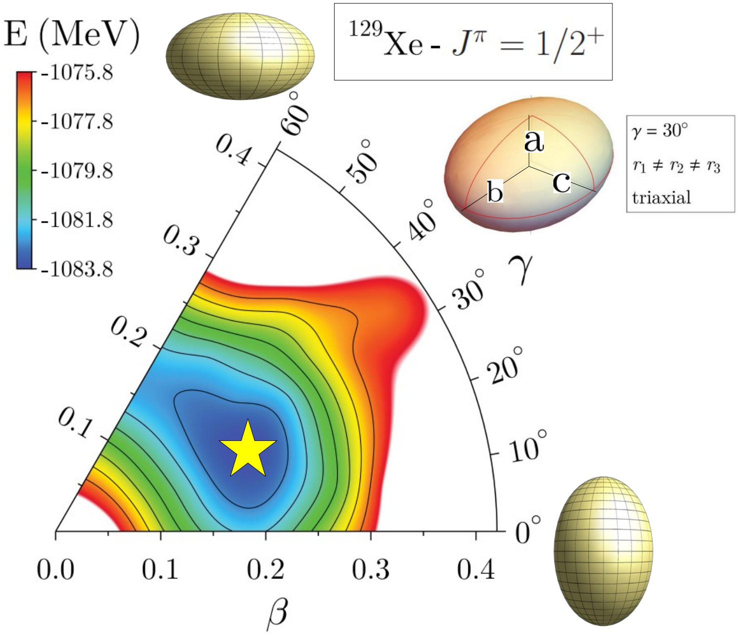
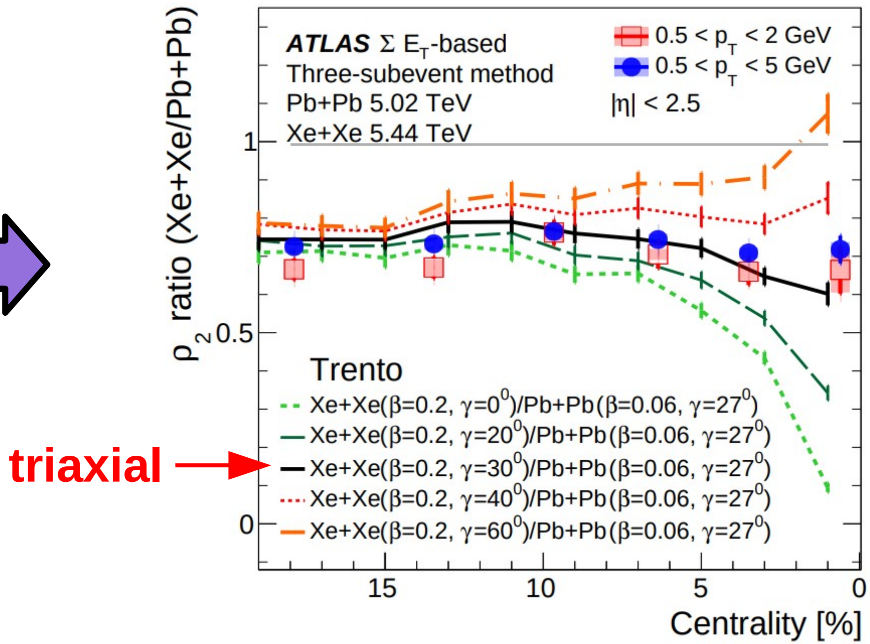


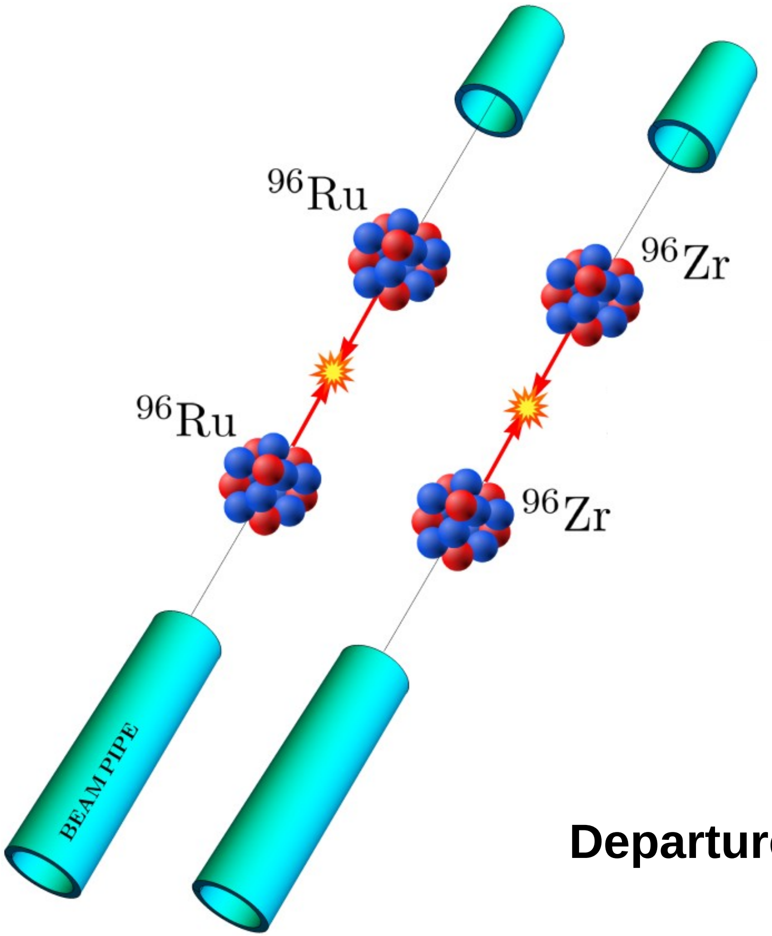


[Bally et al., PRL **128** (2022) 8, 082301]

[ATLAS collaboration, arXiv:2205.00039]



Breakthrough of 2021: data from “isobar collisions” is released.



X and Y are isobars.

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

Ratios of observables (O) should be unity…

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

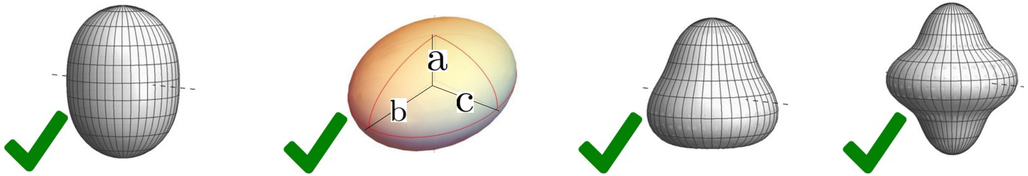
[STAR collaboration, PRC **105** (2022) 1, 014901]
[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]

Departure from unity is mainly due to nuclear structure.

Extremely precise measurements.

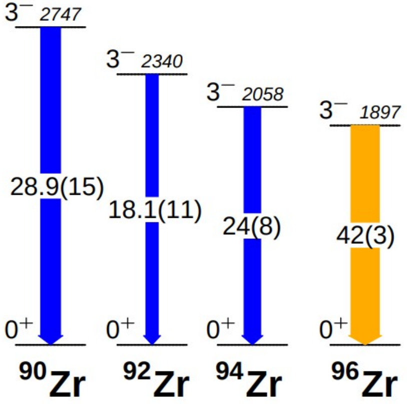
Signature of the octupole deformation of zirconium-96.

$$R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\gamma Y_{20}(\Theta)+\sin\underline{\gamma} Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$

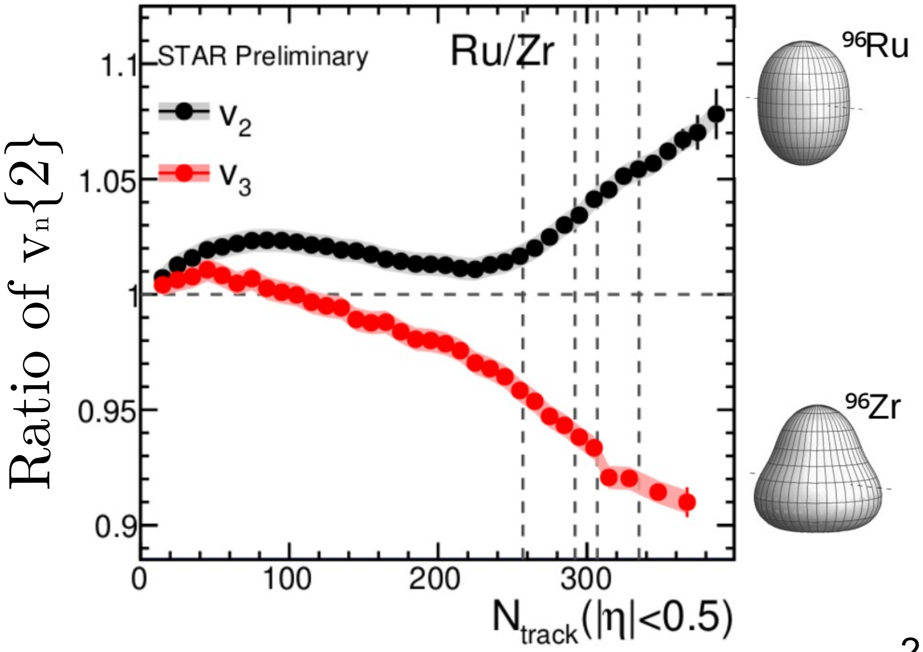


Signature of octupole deformation.

Octupole deformation of ^{96}Zr expected from low-lying first 3^- state.



[from M. Zielinska, ESNT workshop]

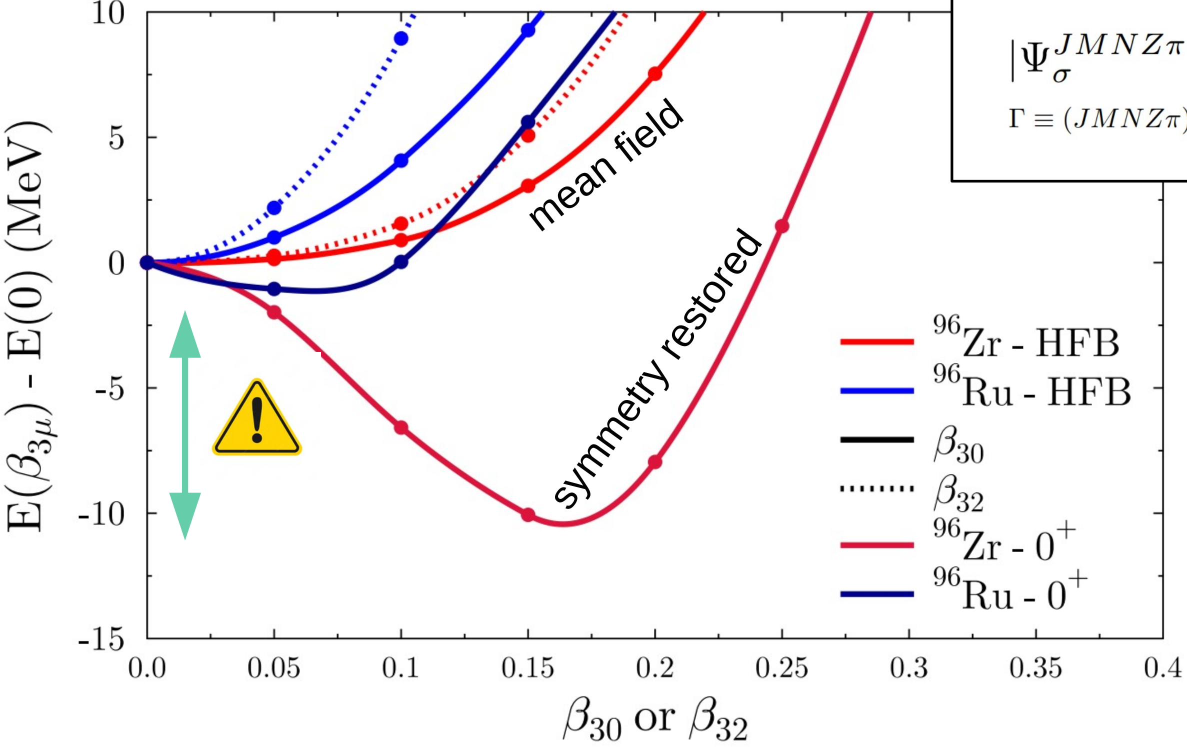


Very clean manifestation at RHIC.

Explanation from nuclear structure theory?

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

Octupole deformation is a beyond-mean-field effect emerging from symmetry restoration.



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

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

$\Gamma \equiv (JMNZ\pi)$

WEIGHTS — PROJECTION — DEFORMED MF STATE

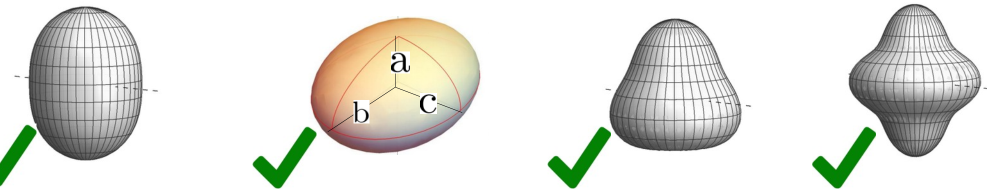
ExtreMe Matter Institute EMMI
EMMI Rapid Reaction Task Force
Nuclear Physics Confronts Relativistic Collisions of Isobars
Heidelberg University, Germany, May 30 – June 3 & October 12 – 14, 2022

Benjamin Bally (Paris-Saclay)
preliminary results

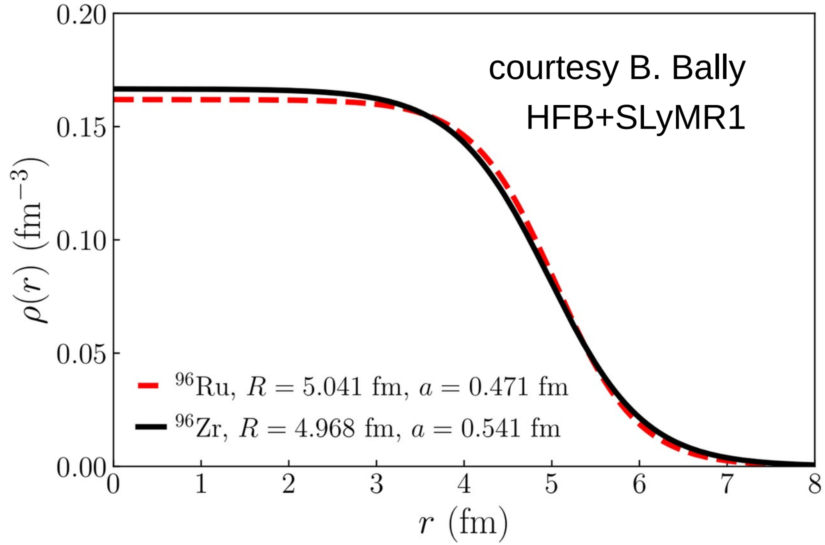
Preliminary work confirms large octupole deformation. Huge energy gain from symmetry restoration.
New phenomena in nuclear structure theory.

BONUS: Signature of skin differences between isobars.

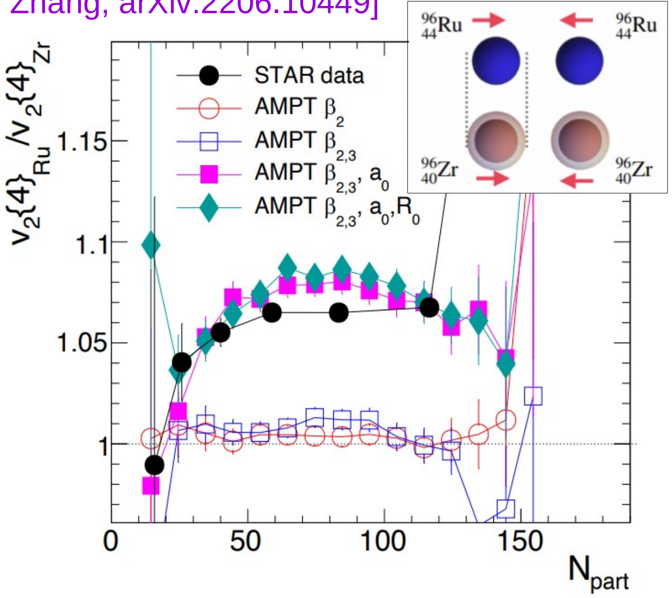
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$



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



[Jia, Giacalone, Zhang, arXiv:2206.10449]



We can isolate the difference, Δa.

see also [Nijs, van der Schee, arXiv:2112.13771]
[Xu *et al.*, arXiv:2111.14812] [Xu *et al.*, PLB **819**, 136453 (2021)]

Answers to the initial questions:

- Expectations from low-energy nuclear physics confirmed in high-energy data.
- Quadrupole, triaxiality, octupole (?), hexadecapole, radial profile differences between isobars.
- **Great confidence that high-energy model is appropriate.** ✓
- **No clear indication of modifications of nuclear geometry from enhanced gluon fluctuations (Lorentz boost).** ✓

3 – Prospects: theory and experiment

Determination of nuclear structure parameters within high-energy model.

From isobars, ratios of observable have simple scaling with parameters.
Ratios of several observables will pin down parameter differences.

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

[Jia & Zhang, arXiv:2111.15559]

This generalizes to any isobars, or pairs of nuclei close in mass.

In addition, extract nuclear structure from Bayesian analyses of high-energy data.

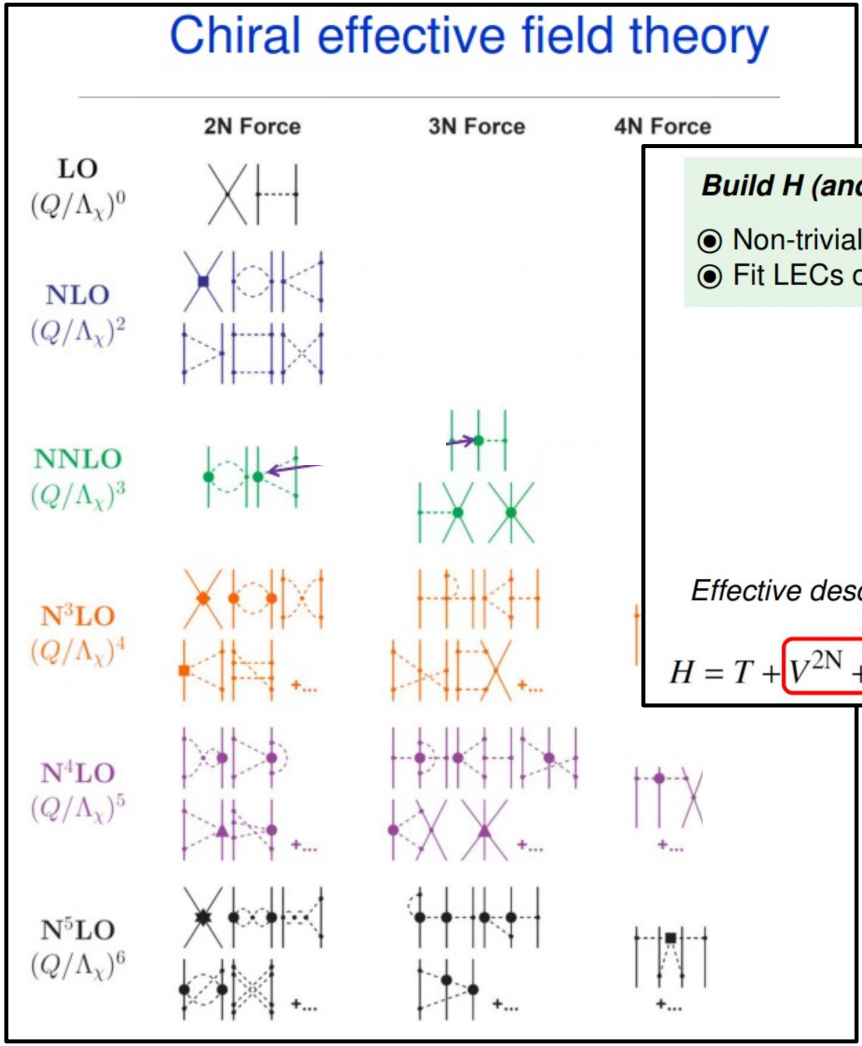
[see e.g. Matt Luzum, ESNT workshop]

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

Promote deformations and skin parameters as model parameters.

Strong dependence of observables implies posterior distribution can be extracted.

Going beyond shapes: connection with *ab initio* approaches.



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

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

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

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?)

[from Thomas Duguet, ESNT workshop]

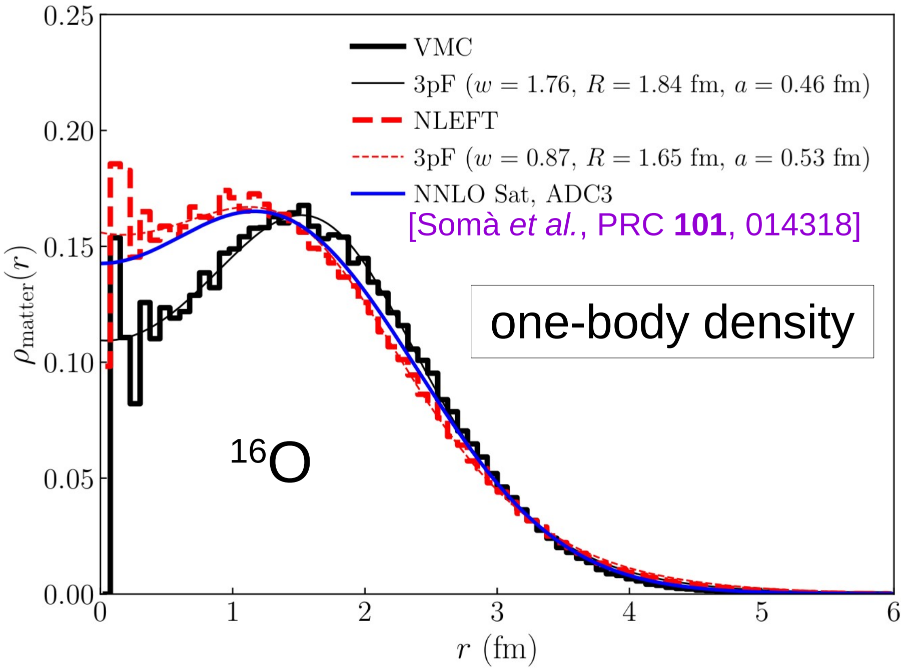
Going beyond shapes: connection with *ab initio* approaches.

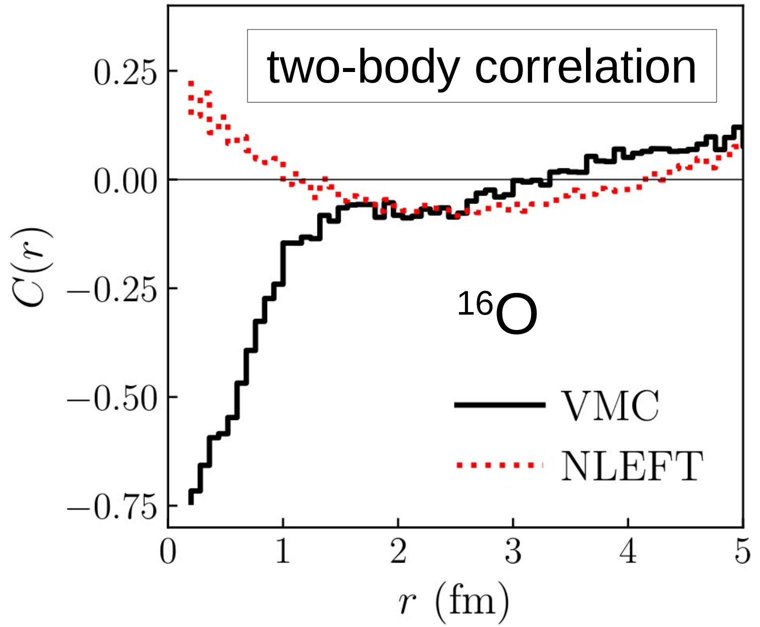
Oxygen-oxygen collisions are ideal for the purpose.

- 6000 configurations from **cluster Variational Monte Carlo (VMC)** simulations.
Interaction: AV18+UIX (not an EFT) with a repulsive core. [Londardoni *et al.*, PRC **96** (2017) 2, 024326]

- 15359 configurations from **Nuclear Lattice Effective Field Theory (NLEFT)**.
Interaction: pionless chiral EFT. Pin-hole algorithm to determine nucleon positions.

[Summerfield *et al.*, PRC **104** (2021) 4, L041901]

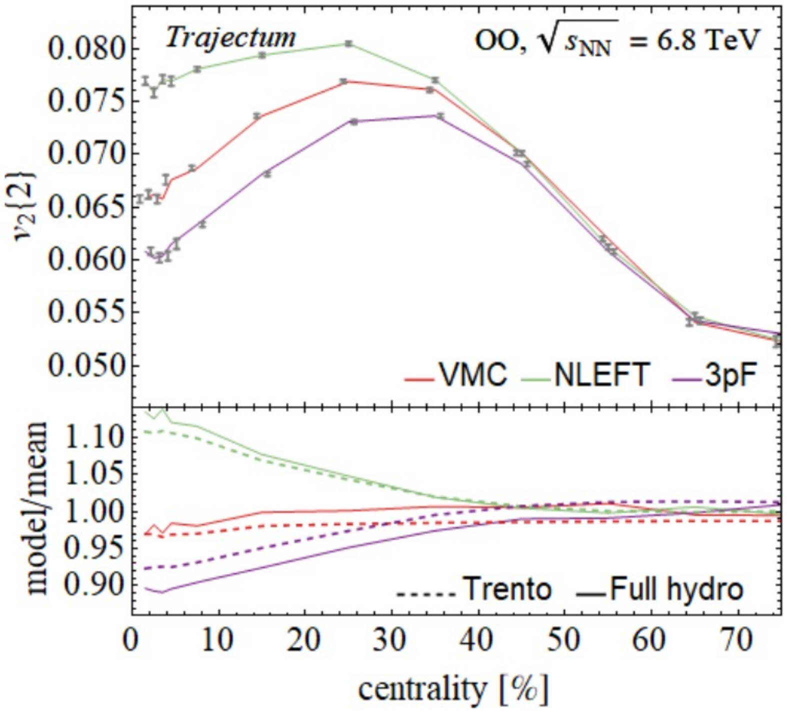


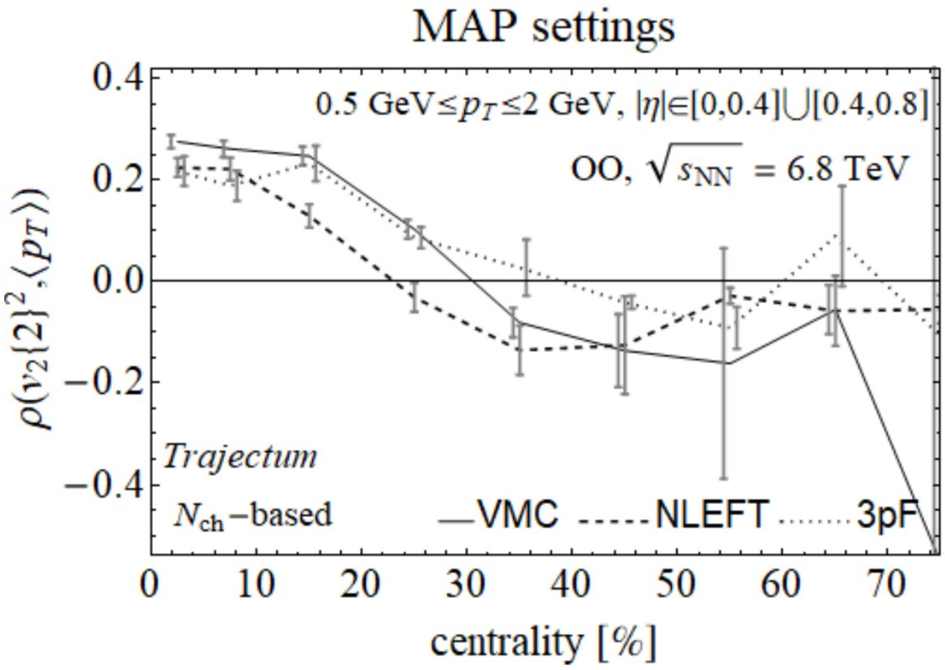


Study of shape-size correlations in oxygen collisions.

Different predictions from different frameworks… why?
Different interaction or many-body solution? Role of short-range physics?

[Giacalone, Lee, Nijs, van der Schee, in preparation]

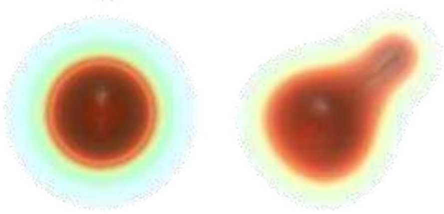




A new tool to test effective theories of QCD for nuclei.

LHC – Run3 and Run4 (2023-2032)

Case study: Impact of neon-neon collisions on small system program at LHC?



^{16}O ^{20}Ne

Strong geometry effects in a small system.
Essentially as dramatic as U+U vs Au+Au.

dN/dy ~ 100

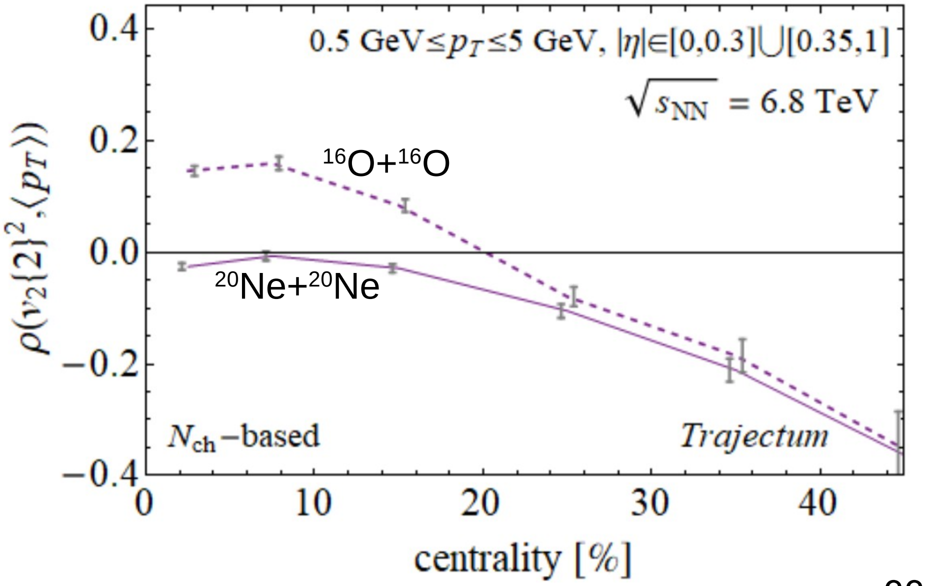
Extreme structure to test “hydro” response.

⇕

Nucleus amenable to *ab-initio* description.

[Saclay group + Giacalone, Nijs, van der Schee, in preparation]

Trajectum preliminary, MAP values

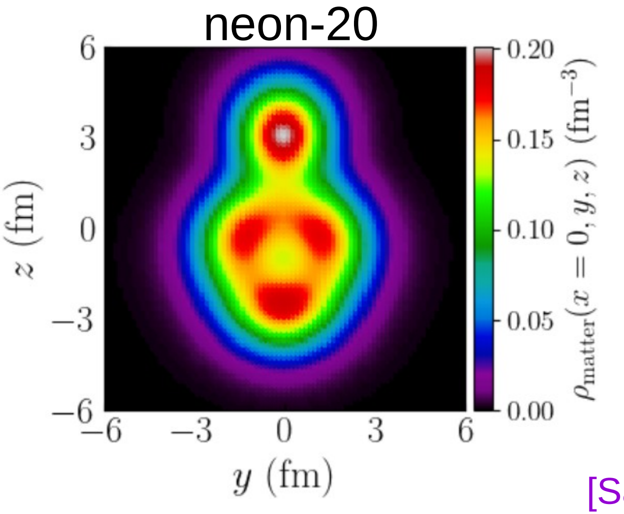


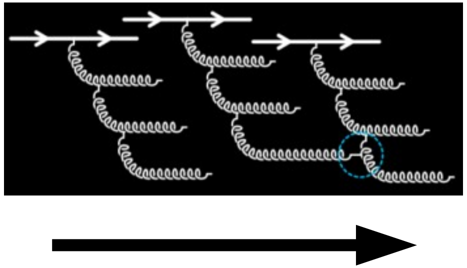
LHC – Run3 and Run4 (2023-2032)

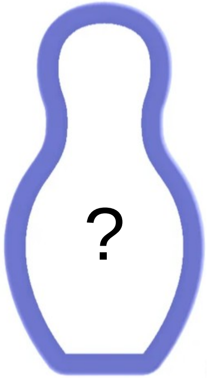
Case study: Impact of neon-neon collisions on small system program at LHC?

Role of small-x evolution? Melting of clusters?

x~0.01







x~0.0001

[Saclay group + Giacalone, Schenke, Schlichting, Singh, in progress]

1 – [20]Ne in SMOG system of LHCb. Collider + fixed-target at the same time.
Collisions at sqrt(s)=7000 GeV and sqrt(s)=70 GeV.

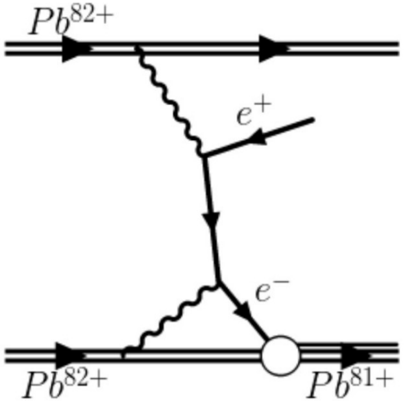
2 – FOCAL upgrade of ALICE. "Dilute-dense" Ne+Ne, one small-*x*, one large-*x*.

Role of quarks and gluons (QCD) for nuclear structure?

LHC – Run5 and Run6 (beyond 2032)

Possibility of collisions of additional species @ LHC Run 5 and Run 6?

Maximizing impact for both low- and high-energy communities?



[from Alexander Kalweit, ESNT workshop]

[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

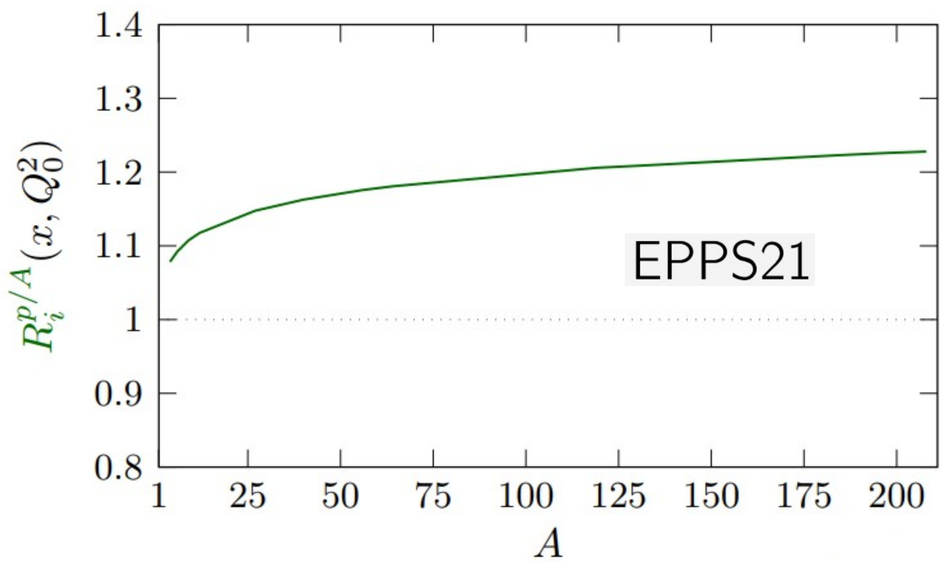
EIC (beyond 2032)

Effects of nuclear shapes should be assessed.

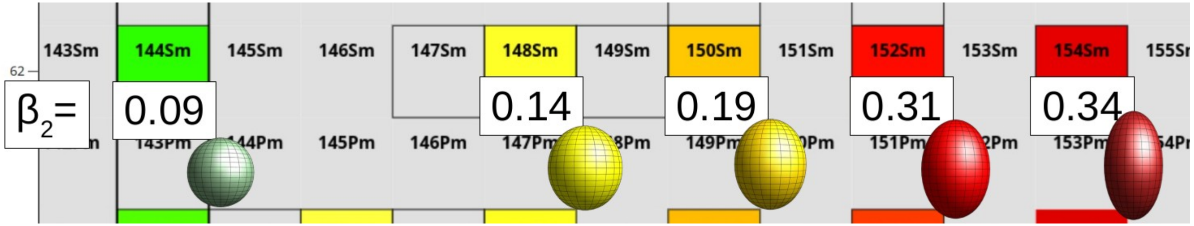
[from Petja Paakkinen, ESNT workshop]

- Define nuclear PDFs in terms of

$$\underbrace{f_i^{p/A}(x,Q^2)}_{\text{bound-proton PDF}} = \overbrace{R_i^{p/A}}^{\text{nuclear modification}}(x,Q^2)\,\underbrace{f_i^{p}(x,Q^2)}_{\text{free-proton PDF}}$$



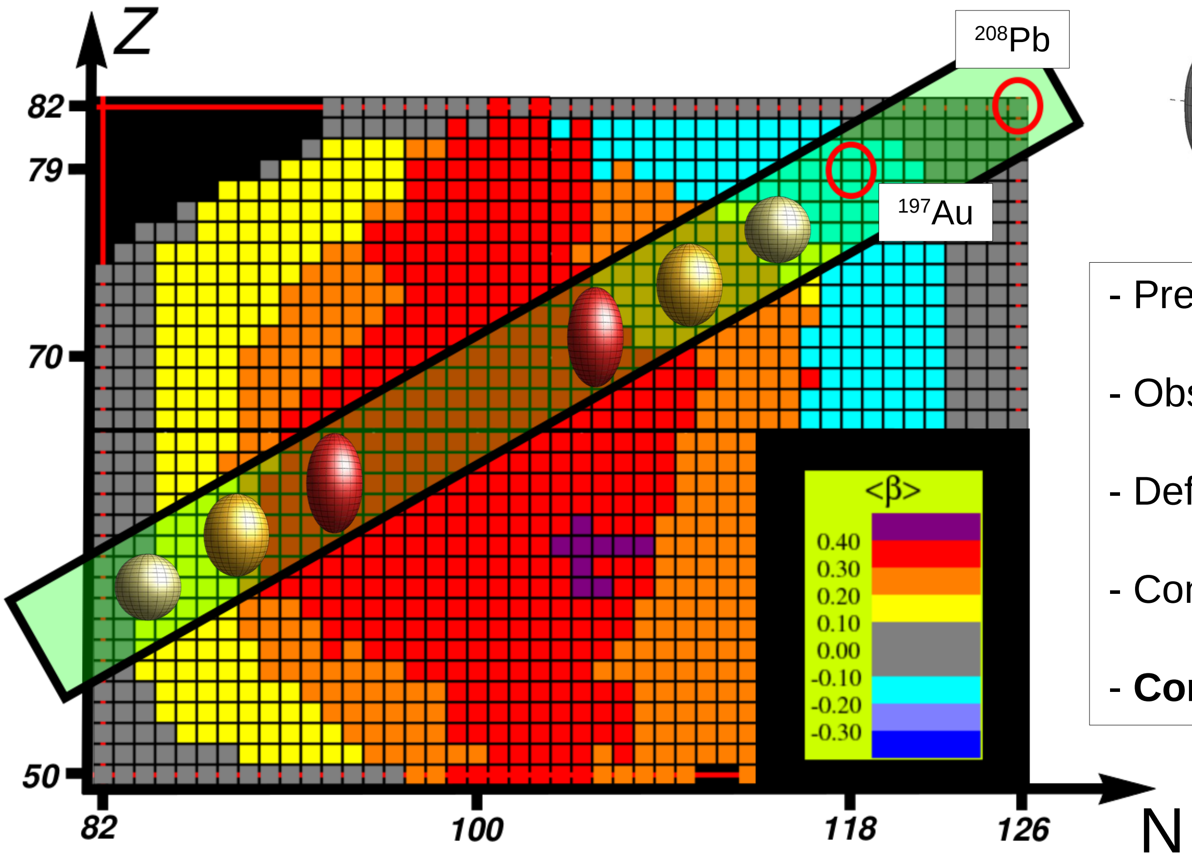
Suggestion: Samarium isotopic chain. Same A (within 7%) but completely different shapes.

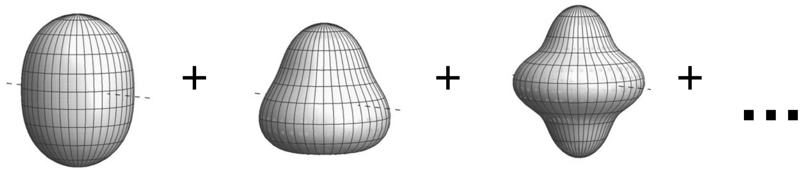


RHIC (after sPHENIX?)

Shut down is imminent. Still worth pointing out new realizations/opportunities.

The ultimate nuclear shape experiment: Exploration of rare earth nuclei.

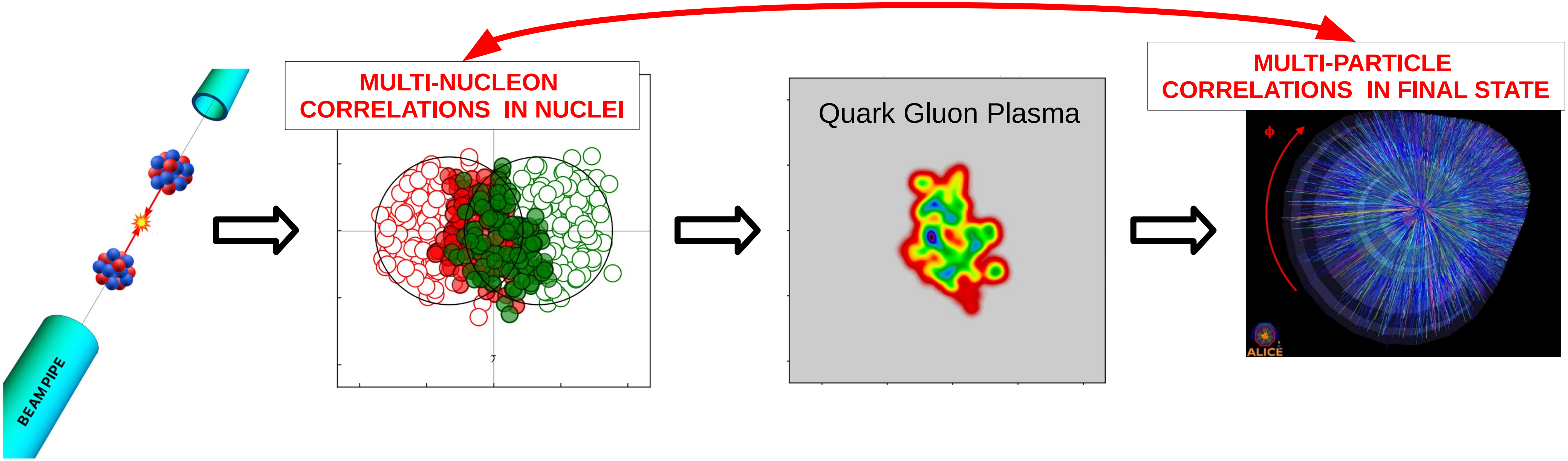




- Precise determination of relative deformations.
- Observation of small triaxial deformations.
- Deformations beyond hexadecapole (β_4).
- Complementary constraints for *ab-initio* theories.
- **Complementary knowledge about nuclei.**

LEGACY?

SUMMARY



- High-energy model coupled with mean-field description of nuclei provides excellent description of heavy-ion data.
- Collective spatial correlations (shapes) in nuclei show up clearly at high energy.
- Prospect theory: improved initial conditions and synergy with *ab-initio* nuclear theory.
- Prospect experiments: many opportunities to be discussed/investigated.

THANK YOU!

Intersection of nuclear structure and high-energy nuclear collisions

https://www.int.washington.edu/programs-and-workshops/23-1a

Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

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

BONUS: Neutron skin estimates from high-energy collisions? Two methods.

Difference in diffuseness gives access to neutron skin difference. Use isobars.
^{208}Pb, ^{48}Ca … can high-energy nuclear physics contribute to these efforts?

[Jia & Zhang, arXiv:2111.15559]

Nice results from STAR in an individual system: $\Delta r_{np}[\,^{197}\mathrm{Au}\,] = 0.17 \pm 0.03\ (\mathrm{stat.}) \pm 0.08\ (\mathrm{syst.})\ \mathrm{fm}$
Consistent with low-energy nuclear theory.

[STAR Collaboration, arXiv:2204.01625]

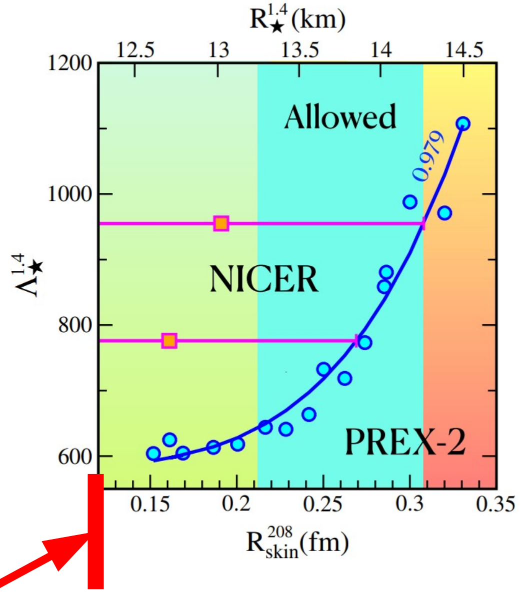
Recent measurements for ^{208}Pb from weak form factor:

$$\Delta r_{np} = 0.283 \pm 0.071\ \mathrm{fm}$$

$$L = (106 \pm 37)\ \mathrm{MeV}$$

[PREX-II experiment,
PRL **126** (2021) 17, 172502]

Stiffer EoS than expected.



From NS merger observations.

[Reed et al., PRL **126** (2021) 17, 172503]
[Fattoyev et al., PRL **120** (2018) 17, 172702]