Accessing nuclear structure at colliders via high-energy isobar collisions

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isoQuant SFB1225

OUTLINE

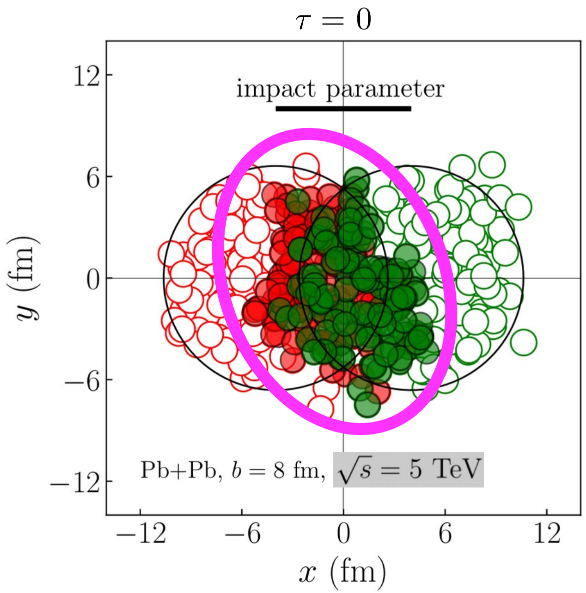
1 – Nuclear structure input to high-energy nuclear collisions.

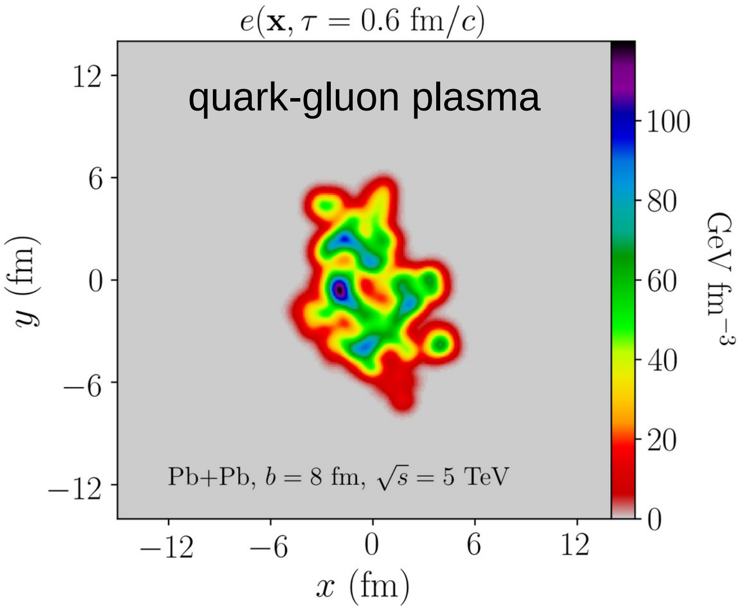
2 – Nuclear shapes in high-energy isobar collisions.

3 – Prospects.

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

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).

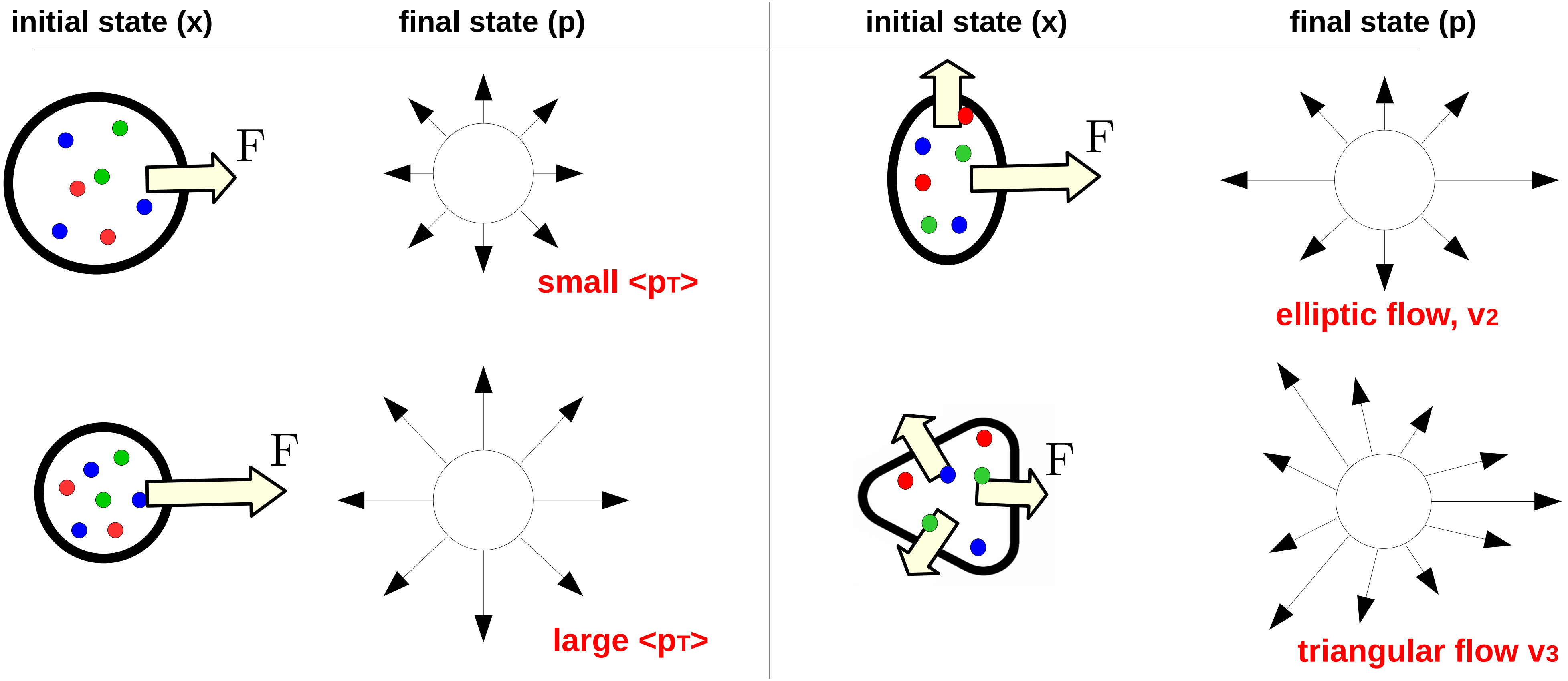
[Gardim, Giacalone, Luzum, Ollitrault, Nature Phys. **16** (2020) 6, 615-619]

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

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

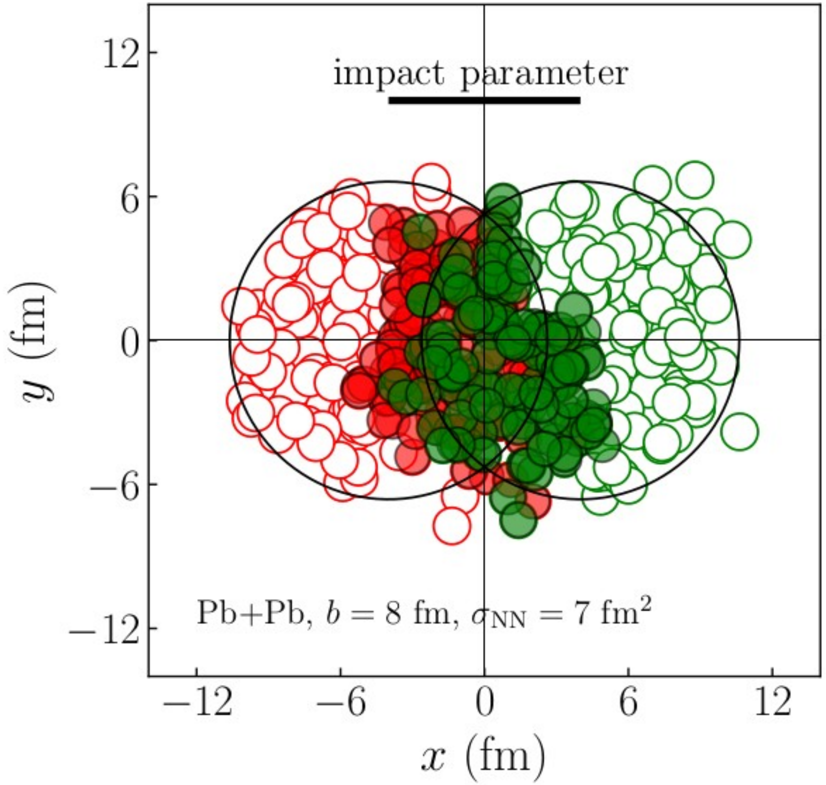
$$F = -\nabla P$$

[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.



High-energy model

Scattering occurs mainly within nucleons.

Interaction acts as a “quantum measurement” of the positions of the nucleons.

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

FULL PROBLEM

$$H|\psi\rangle = E|\psi\rangle$$

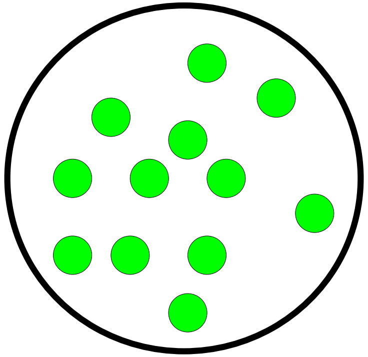
INDEPENDENT PARTICLE PROBLEM

$$h_i|\phi_k^i\rangle = \varepsilon_k^i|\phi_k^i\rangle$$

$$h_i = \frac{p_i^2}{2m} + V(r_i)$$

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

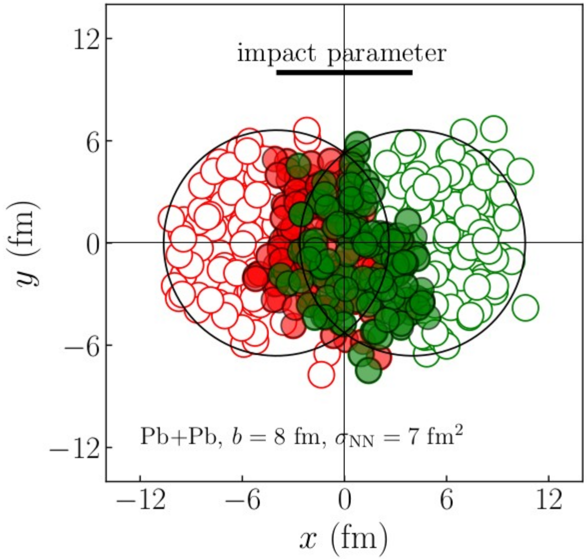
Woods-Saxon

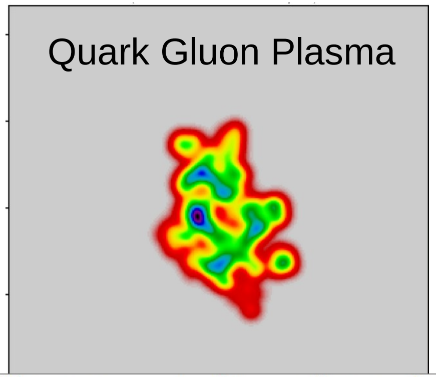


More realistic: Potential generated from effective nucleon-nucleon interaction (Gogny force, Skyrme force, etc.) in "Energy Density Functional" theory.

Mean-field-based approach at the heart of MC Glauber model for ‘spherical’ ions.

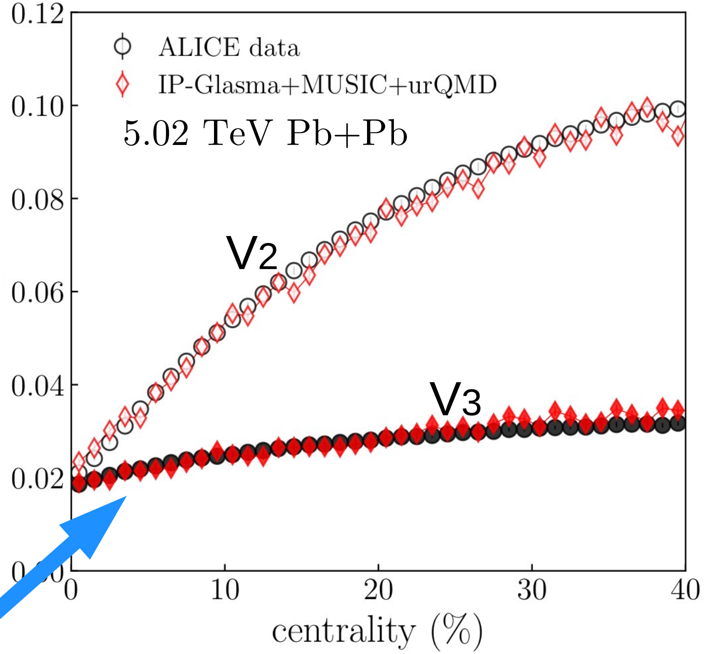
Nucleus-nucleus interaction does not modify the shape of the interaction region on large scales.





$$T^{00}(\mathbf{x})\ [\mathrm{GeV/fm^3}] \propto Q_A^2(\mathbf{x})Q_B^2(\mathbf{x})$$

[Schenke, Shen, Tribedy, PRC **102** (2020) 4, 044905]



precision physics!

Nuclei are in general strongly-correlated systems:

Describing heavy-ion collisions requires *a priori* knowledge of A-body correlation functions, e.g.,

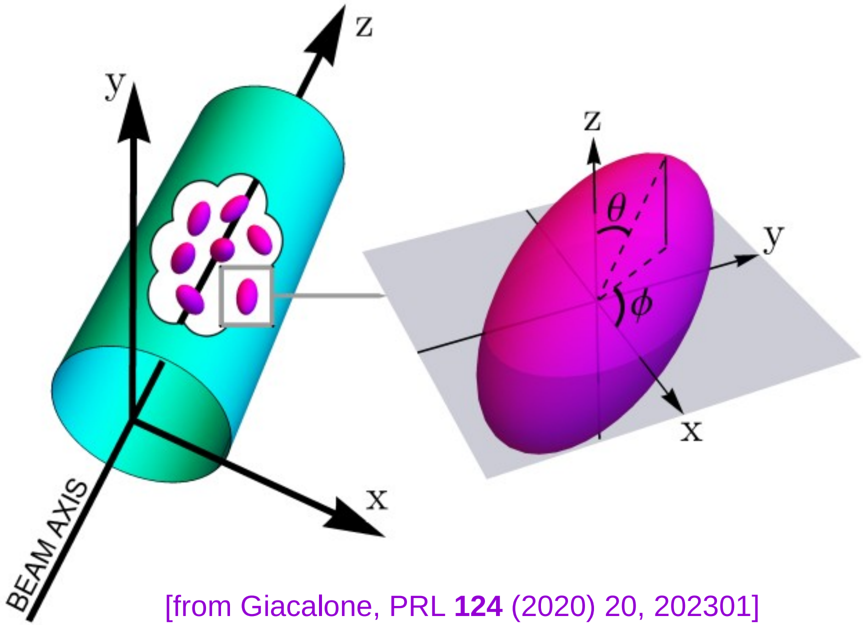
$$\rho_k^{\mathrm{JMNZ}}(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4) \equiv \langle \Psi_k^{\mathrm{JMNZ}} | c^\dagger(\vec{r}_1) c^\dagger(\vec{r}_2) c(\vec{r}_3) c(\vec{r}_4) | \Psi_k^{\mathrm{JMNZ}} \rangle$$

2-body correlation function

Help from low-energy nuclear physics:

Spatial correlations can be conveniently encapsulated in “intrinsic shapes”.

Use 1-body density with a deformed shape.



[from Giacalone, PRL **124** (2020) 20, 202301]

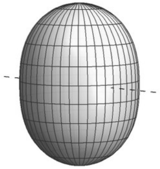
Keep a mean field approach.

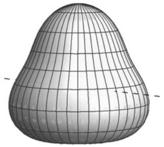
The bag of nucleons is now deformed and with a random orientation.

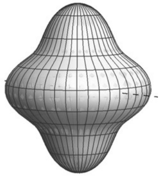
The interaction selects one such orientation.

Generalize the Woods-Saxon profile to include intrinsic deformations:

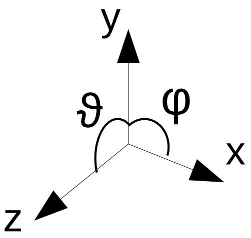
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$

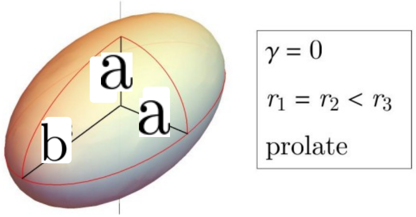


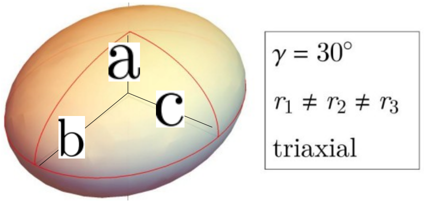


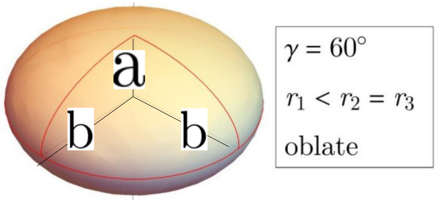


For $\beta_2 > 0$, the nucleus is prolate ($=0$), triaxial ($=30^0$), or oblate ($=60^0$).









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

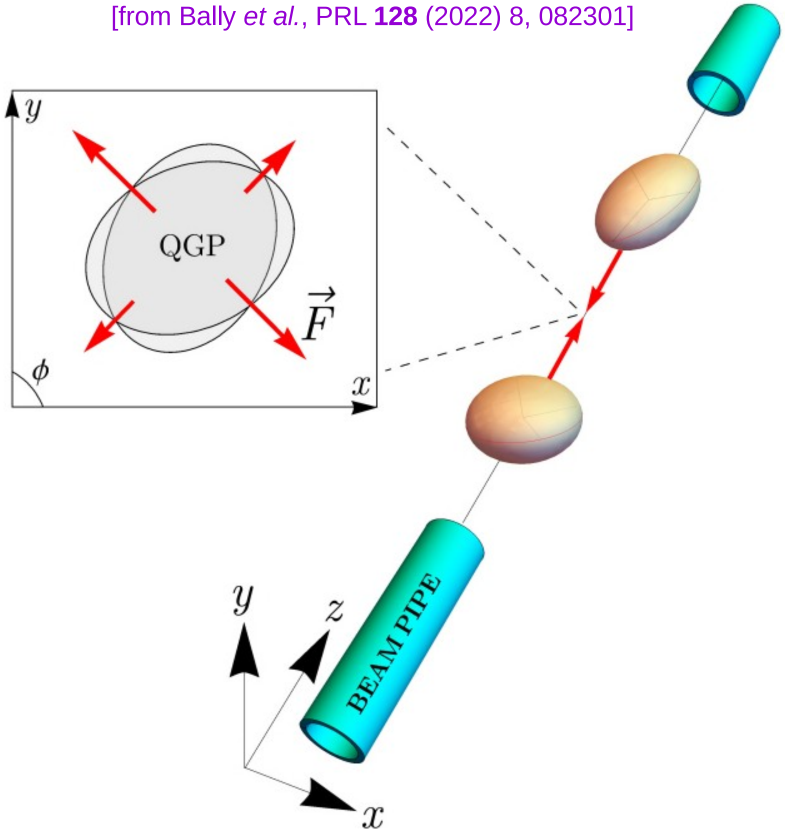
Michael Bender – RBRC Workshop Jan 2022

They will show up as well at high energy.

↓

THIS TALK!

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



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

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 → THIS TALK

(129Xe, 238U, 96Ru, 96Zr → deformed ions)

New questions to address:

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

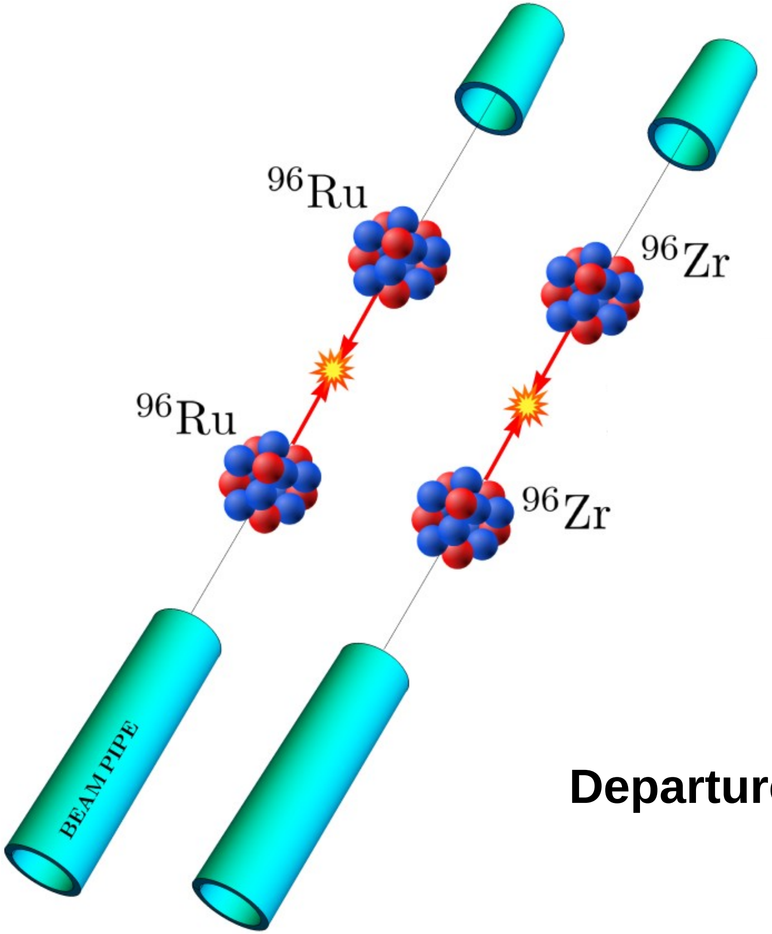
Are low-energy expectations compatible with high-energy observations?

2 – Nuclear shapes in high-energy isobar collisions.

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

Main goal: see effects related to strong magnetic fields. “Complications” arise.

[TALK BY PANOS CHRISTAKOGLOU]



X and Y are isobars.

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

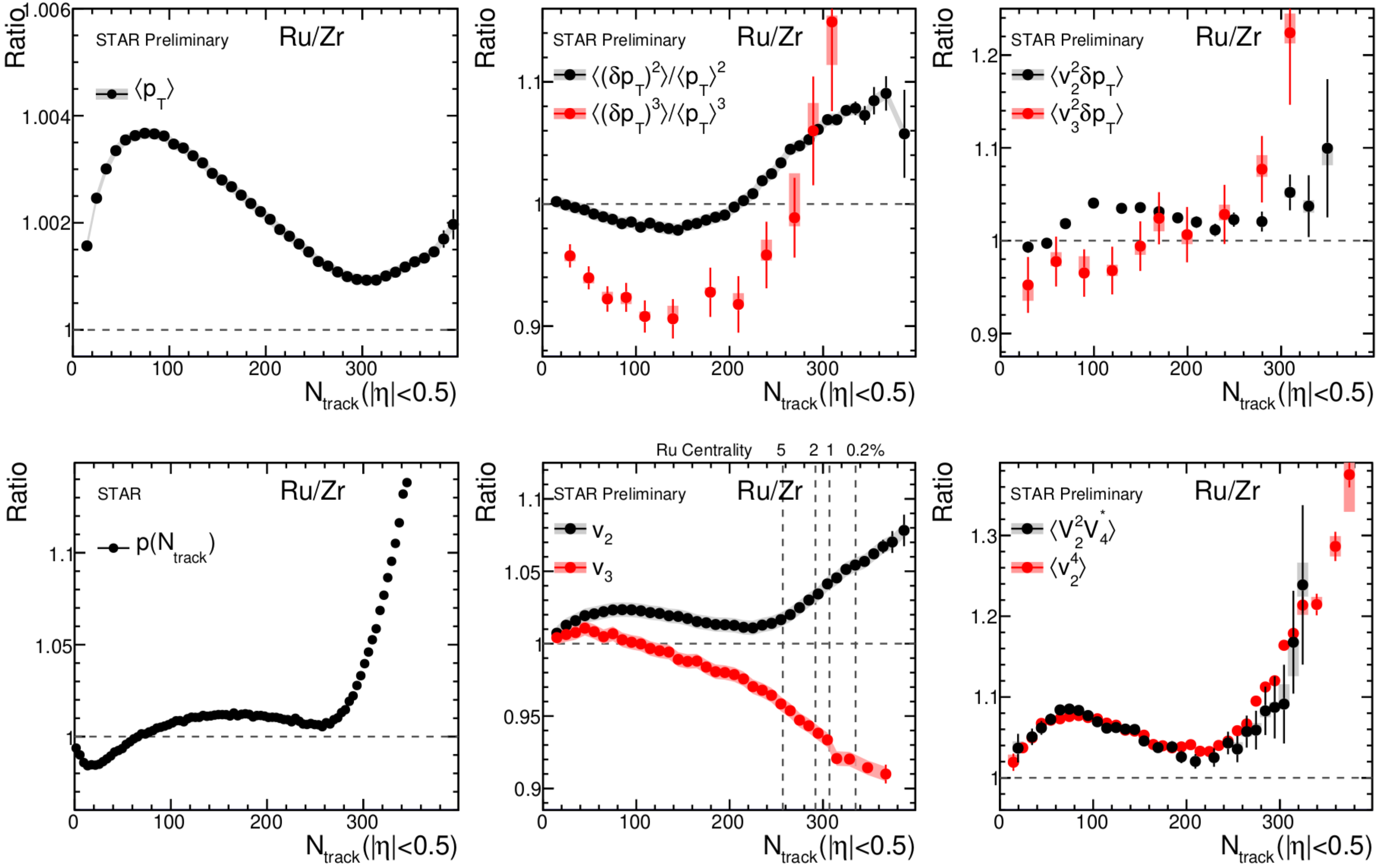
Ratios of observables (O) should be unity…

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

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

Departure from unity is mainly due to nuclear structure.

Extremely precise measurements.


STAR Preliminary
Ru/Zr
⟨p_T⟩
Ratio
N_track(|η|<0.5)
⟨(δp_T)^2⟩/⟨p_T⟩^2
⟨(δp_T)^3⟩/⟨p_T⟩^3
⟨v_2^2δp_T⟩
⟨v_3^2δp_T⟩
STAR
p(N_track)
Ru Centrality 5 2 1 0.2%
v_2
v_3
⟨V_2^2V_4^*⟩
⟨v_2^4⟩

Signature of the quadrupole deformation of ruthenium-96.

In full generality, for quadrupole-deformed nuclei, at fixed multiplicity one has:

$$\langle v_2^2 \rangle = a + b\beta_2^2$$

- a: elliptic flow from fluctuations
- b: response coefficient
- β_2^2: quadrupole deformation

[Giacalone, PRC **99** (2019) 2, 024910]
[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]
[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]
[Jia, PRC **105** (2022) 1, 014905]

Isobar ratio and expand around the fluctuations:

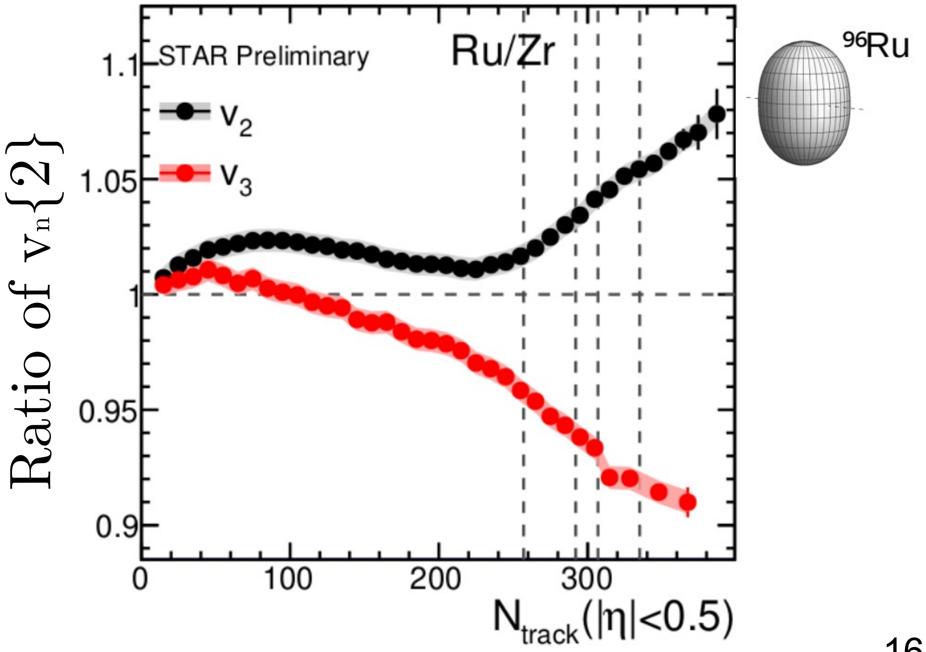
$$\frac{\langle v_2^2 \rangle_{\rm Ru+Ru}}{\langle v_2^2 \rangle_{\rm Zr+Zr}} = 1 + c\left(\beta_{2,\rm Ru}^2 - \beta_{2,\rm Zr}^2\right)$$

- c: positive coeff

Low-energy nuclear physics tells us:

$$\beta_{2,\rm Ru}^2 \gg \beta_{2,\rm Zr}^2$$

Ratio should be above unity.



Signature of the octupole deformation of zirconium-96.

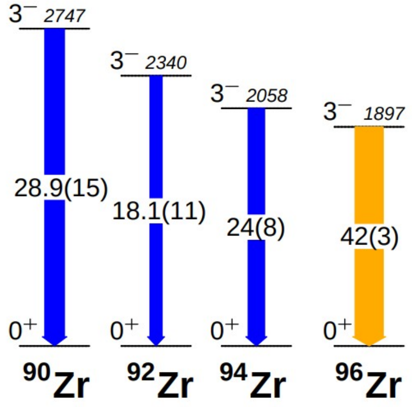
Same logic follows for octupole-deformed nuclei:

$$\frac{\langle v_3^2 \rangle_{\mathrm{Ru+Ru}}}{\langle v_2^2 \rangle_{\mathrm{Zr+Zr}}} = 1 + c\left(\beta_{3,\mathrm{Ru}}^2 - \beta_{3,\mathrm{Zr}}^2\right)$$

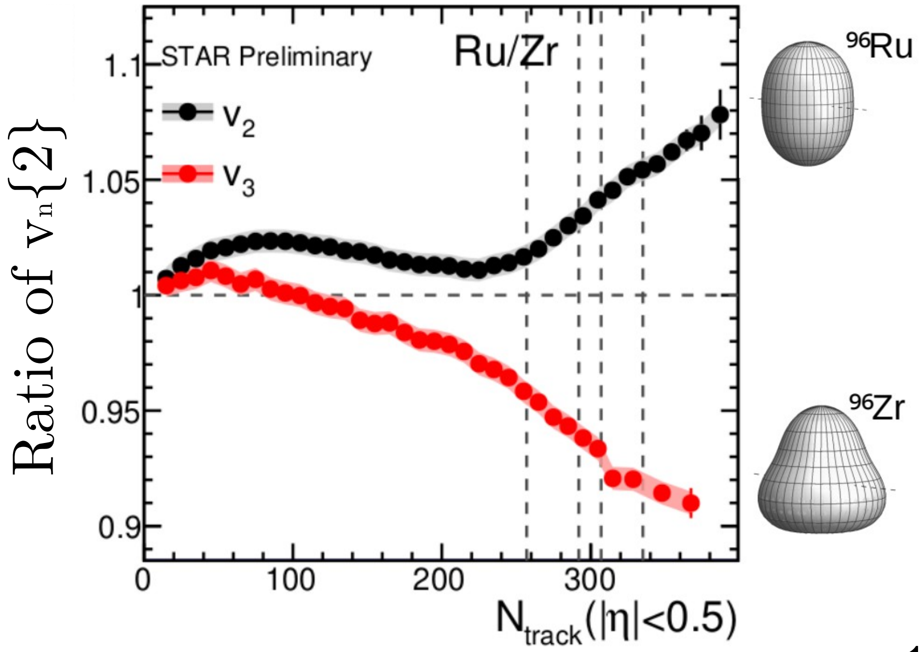
[Jia, Zhang, PRL **128** (2022) 2, 022301]

Significant octupole deformation from low-lying first 3^- state in ^{96}Zr.

No experimental information about ^{96}Ru.



[from M. Zielinska, ESNT workshop]

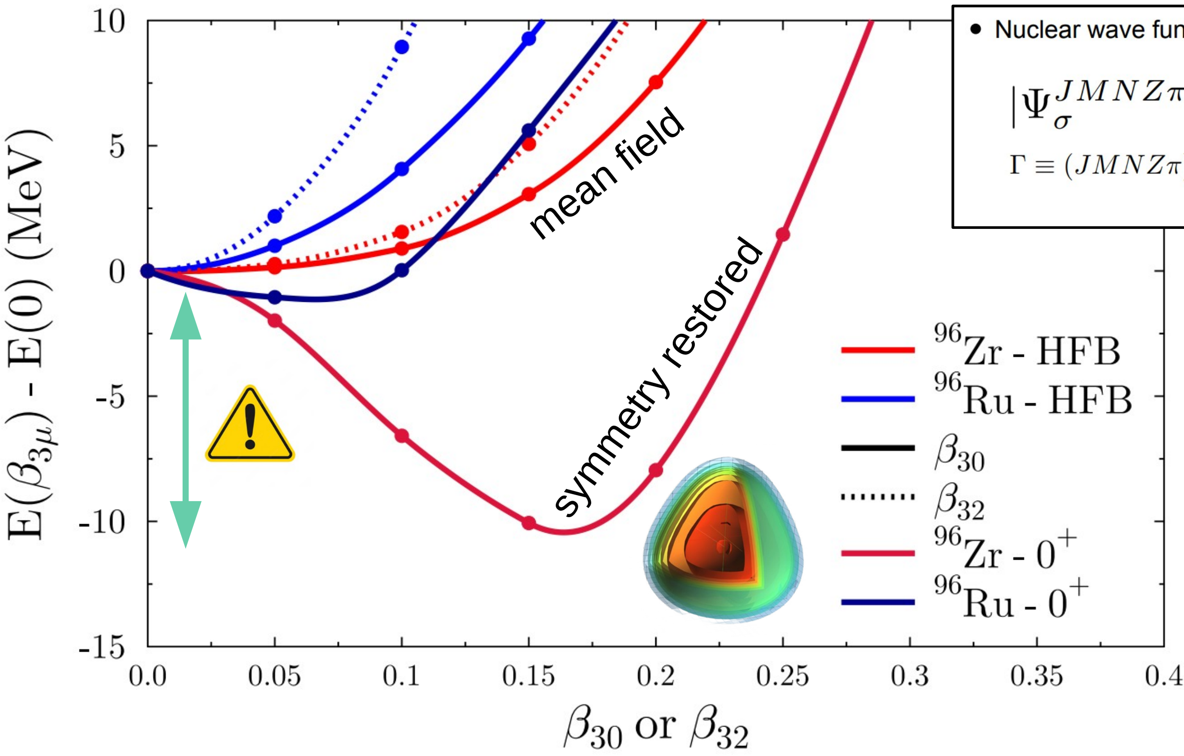


RHIC data immediately implies $\beta_{3,\mathrm{Zr}}^2 \gg \beta_{3,\mathrm{Ru}}^2$

Explanation from nuclear structure theory?

Octupole deformation is a “beyond-mean-field” effect. Emerges from symmetry restoration.

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



- 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

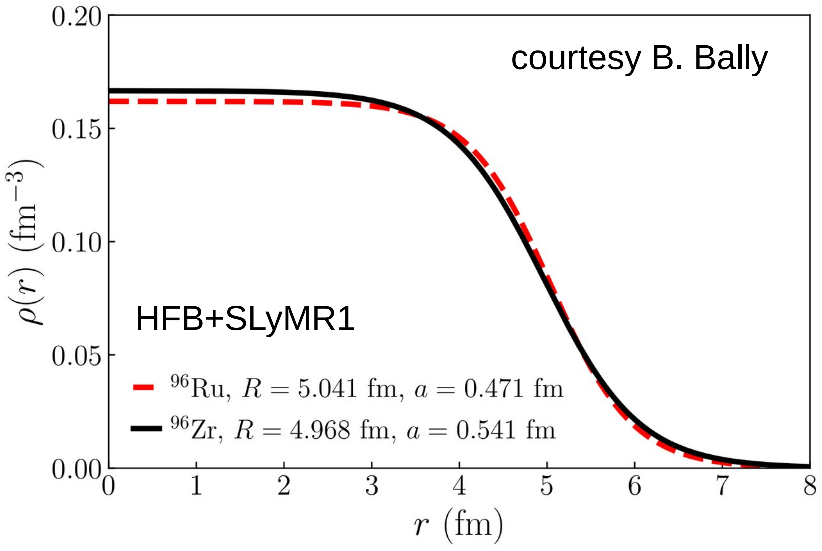
Benjamin Bally (Paris-Saclay)

preliminary results

Preliminary work confirms large octupole deformation in zirconium. $\beta_{3,\mathrm{Zr}}^{2} \gg \beta_{3,\mathrm{Ru}}^{2}$

Large energy gain from symmetry restoration. New challenges in nuclear structure theory.

Signature of skin differences between isobars.



Radial profiles are different:

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

skin thickness

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

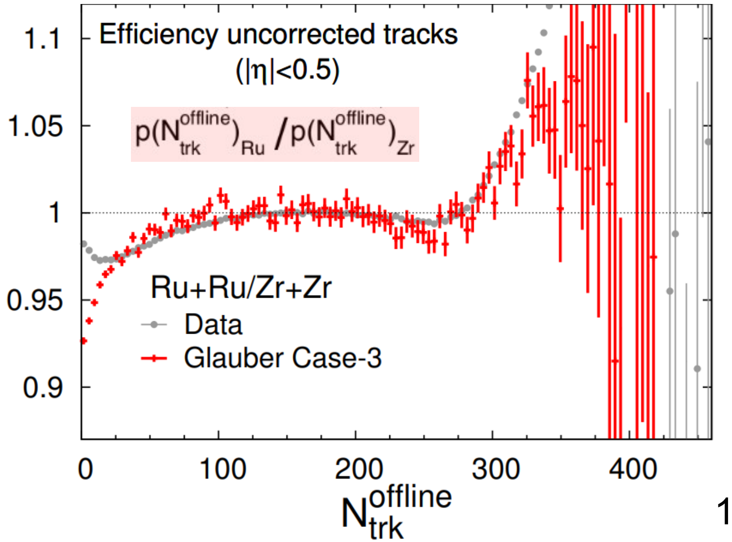
Most immediate evidence: Size differences show up in probabilities of multiplicities.

[Shou *et al.*, PLB **749** (2015) 215-220]

[Li *et al.*, PRC **98** (2018) 5, 054907]

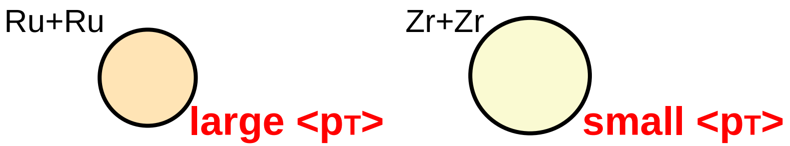
[Li *et al.*, PRL **125** (2020) 22, 222301]

[Xu *et al.*, PLB **819** (2021) 136453]



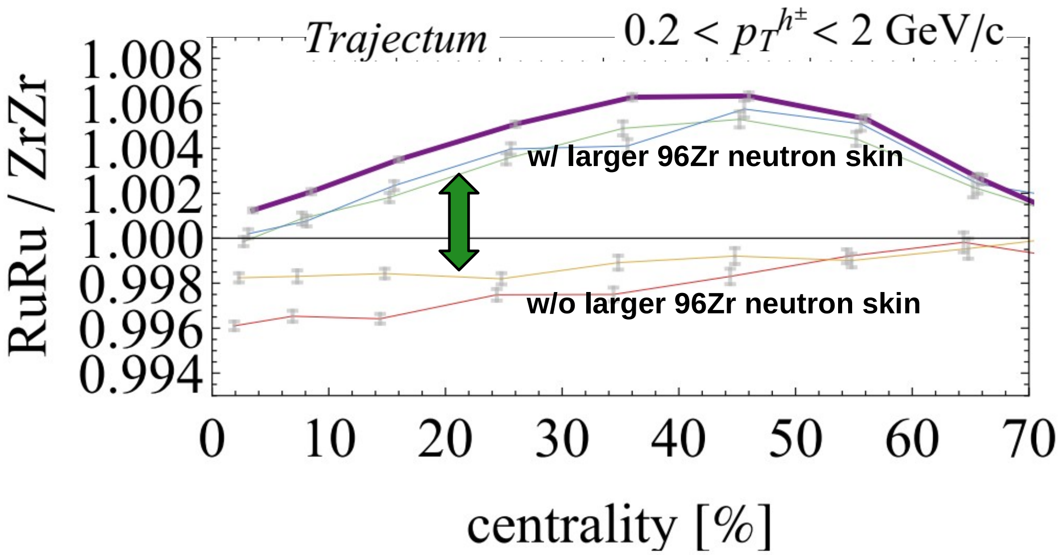
Due to the smaller neutron skin, Ru+Ru systems are more compact. <p_t> is enhanced.

$$F = -\nabla P \quad \Longrightarrow$$

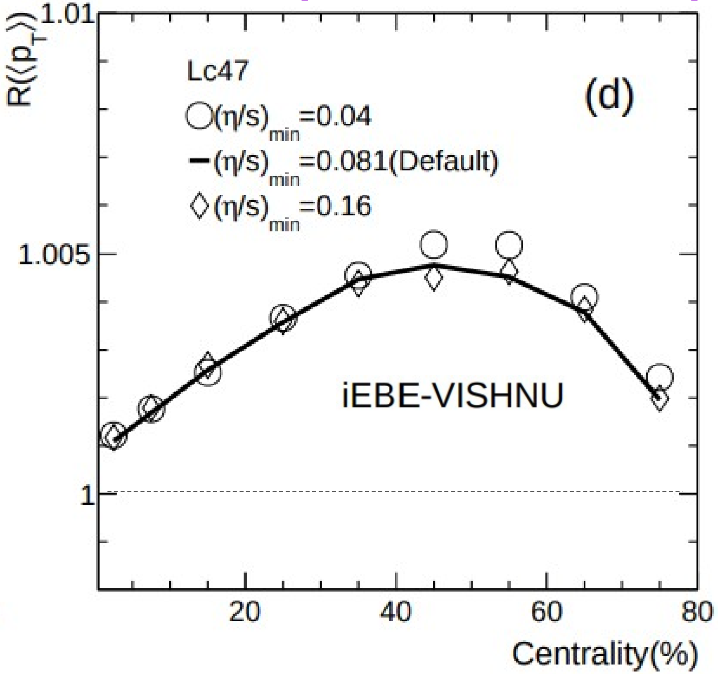


Minor impact from deformations and viscous corrections during hydro.

[Nijs, van der Schee, arXiv:2112.13771]



[Xu *et al.*, arXiv:2111.14812]



Signature of skin thickness in (ratio of) fourth-order cumulant of v_2.

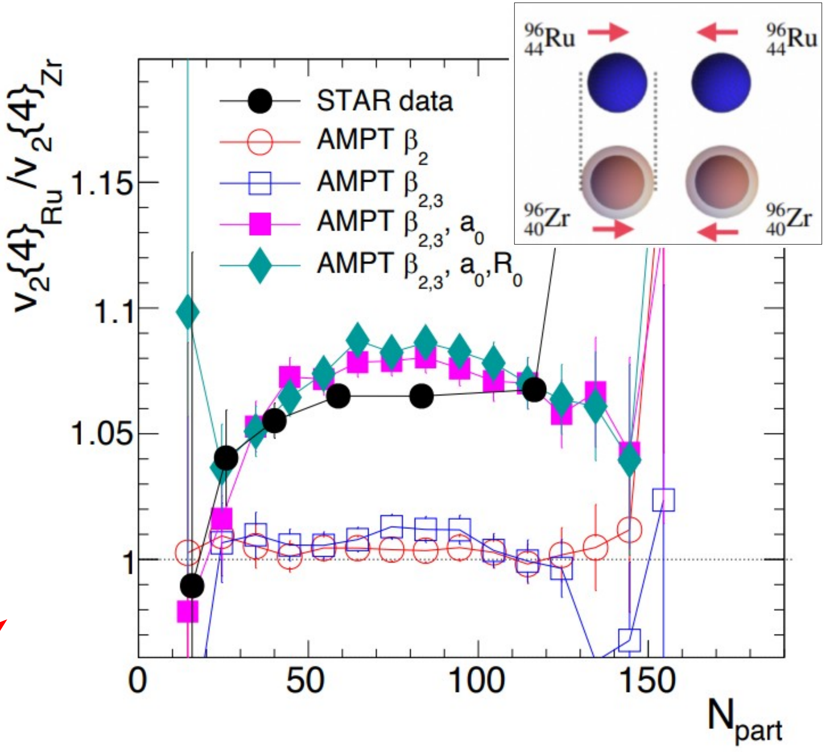
Gaussian model of $V_2=(v_x,v_y)$ fluctuations.
Reaction plane is along x:

$$p(v_{2x}, v_{2y}) = \frac{1}{\pi\delta^2}\exp\left[-\frac{(v_{2x}-v_2^{rp})^2+v_{2y}^2}{\delta^2}\right]$$

Higher-order cumulants isolate elliptic flow
in the reaction plane: [Voloshin *et al.*, PLB **659** (2008) 537-541]

$$v_2\{4\} = v_2\{6\} = \ldots = v_2\{\infty\} = v_2^{rp}$$

[Jia, Giacalone, Zhang, arXiv:2206.10449]



Intrinsic ellipticity:
- sensitive to nuclear thickness
- insensitive to nuclear deformation

More literature on isobars and structure

– Skin thickness from ultra-peripheral collisions. [Xu *et al.*, PRC **105** (2022) 1, L011901]

– Skin thickness from spectators in ultra-central collisions. [Liu *et al.*, PRC **106** (2022) 3, 034913] [Liu *et al.*, PLB **834** (2022) 137441]

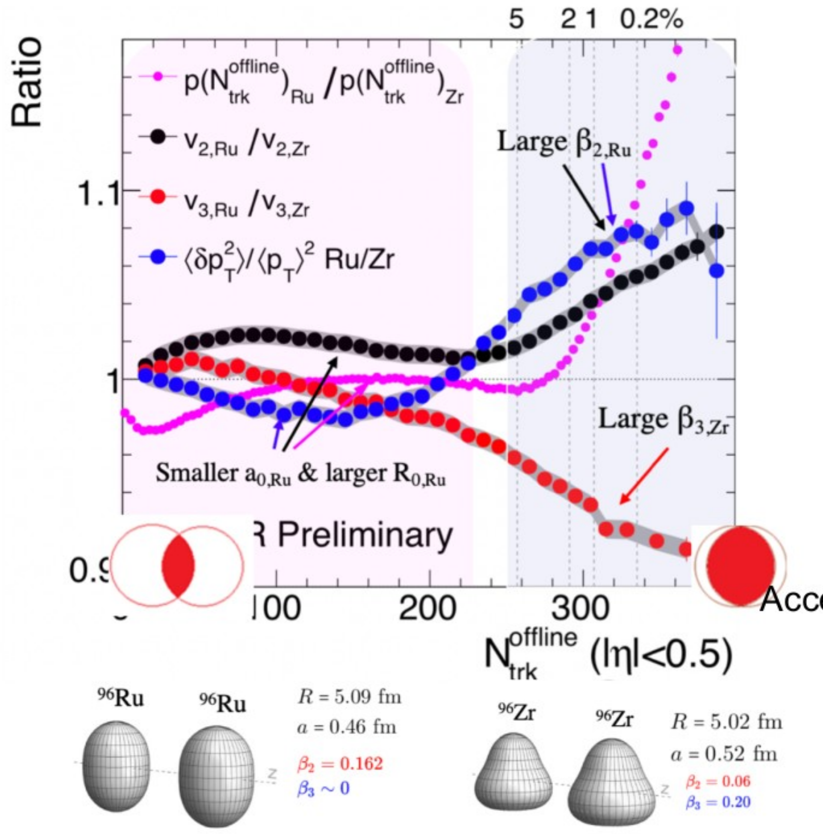
– Longitudinal flow de-correlations. [Nie *et al.*, arXiv:2208.05416]

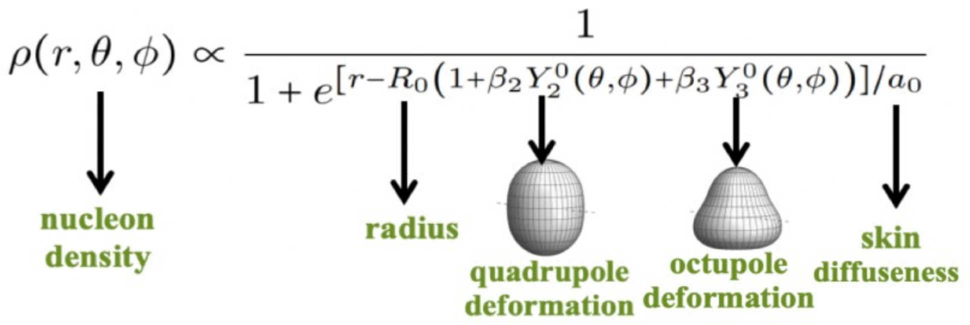
– Nonlinear coupling of flow harmonics. [Jia, Giacalone, Zhang, arXiv:2206.07184] [Zhao *et al.*, arXiv:2204.02387]

– Nuclear mass distribution from J/ψ production. [Zhao, Shi, arXiv:2211.01971]

– Opportunities from isobars in HotQCD Long Range Plan input. [Bally *et al.*, arXiv:2209.11042]

Putting all together. Effect of nuclear structure explains all features of data.





X and Y are isobars, O is an obervable:

$$\frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \stackrel{?}{=} 1 \longrightarrow$$ **Departure from unity from nuclear structure.**

Access structure differences: $R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{Ru}}{\mathcal{O}_{Zr}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$

from J. Jia (HotQCD Town Hall meeting)

Precision phenomenology seems doable.

3 – Prospects.

Ratios of several observables will pin down parameter differences.

[Jia & Zhang, arXiv:2111.15559]

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

observed

high-energy model (hydro)

low-energy model (nuclei)

observed + hydro model ⟶ nuclear model

observed + nuclear model ⟶ hydro model

Generalizes to any isobars, or nuclei close in mass.

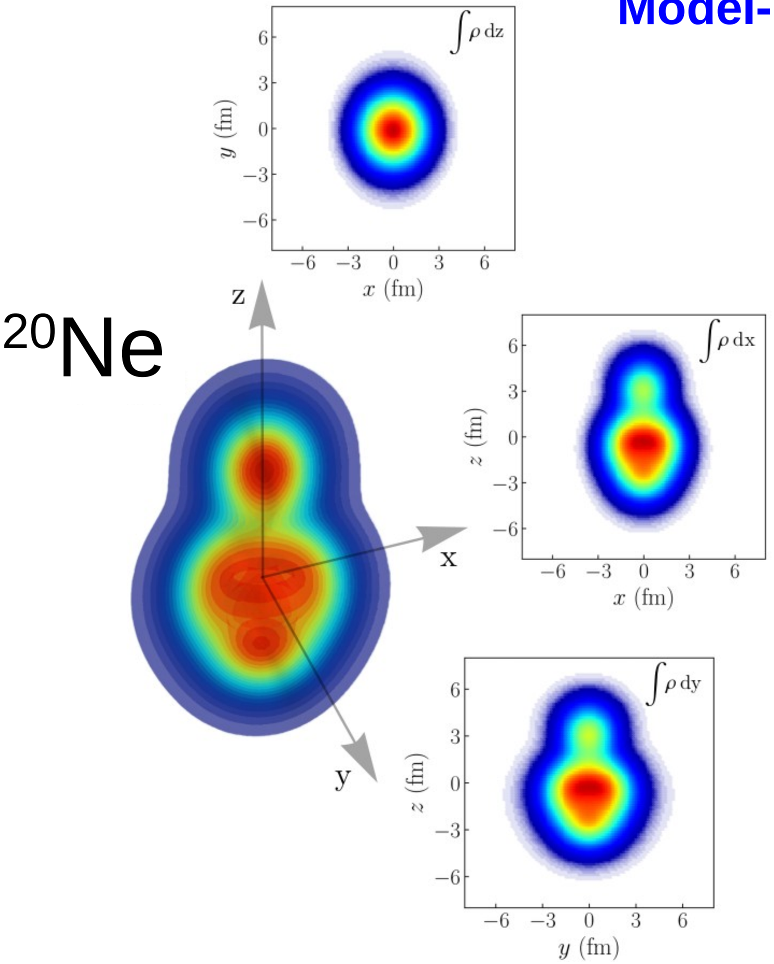
Simple and clean method to assess consistency of nuclear phenomena across energy scales.

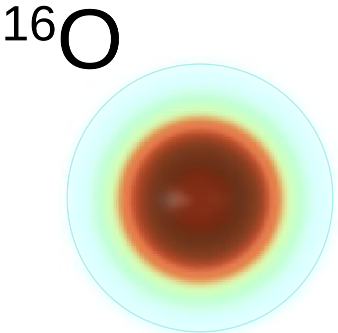
A	isobars	A	isobars	A	isobars
36	Ar, S	106	Pd, Cd	148	Nd, Sm
40	Ca, Ar	108	Pd, Cd	150	Nd, Sm
46	Ca, Ti	110	Pd, Cd	152	Sm, Gd
48	Ca, Ti	112	Cd, Sn	154	Sm, Gd
50	Ti, V, Cr	113	Cd, In	156	Gd, Dy
54	Cr, Fe	114	Cd, Sn	158	Gd, Dy
64	Ni, Zn	115	In, Sn	160	Gd, Dy
70	Zn, Ge	116	Cd, Sn	162	Dy, Er
74	Ge, Se	120	Sn, Te	164	Dy, Er
76	Ge, Se	122	Sn, Te	168	Er, Yb
78	Se, Kr	123	Sb, Te	170	Er, Yb
80	Se, Kr	124	Sn, Te, Xe	174	Yb, Hf
84	Kr, Sr, Mo	126	Te, Xe	176	Yb, Lu, Hf
86	Kr, Sr	128	Te, Xe	180	Hf, W
87	Rb, Sr	130	Te, Xe, Ba	184	W, Os
92	Zr, Nb, Mo	132	Xe, Ba	186	W, Os
94	Zr, Mo	134	Xe, Ba	187	Re, Os
96	Zr, Mo, Ru	136	Xe, Ba, Ce	190	Os, Pt
98	Mo, Ru	138	Ba, La, Ce	192	Os, Pt
100	Mo, Ru	142	Ce, Nd	198	Pt, Hg
102	Ru, Pd	144	Nd, Sm	204	Hg, Pb
104	Ru, Pd	146	Nd, Sm		

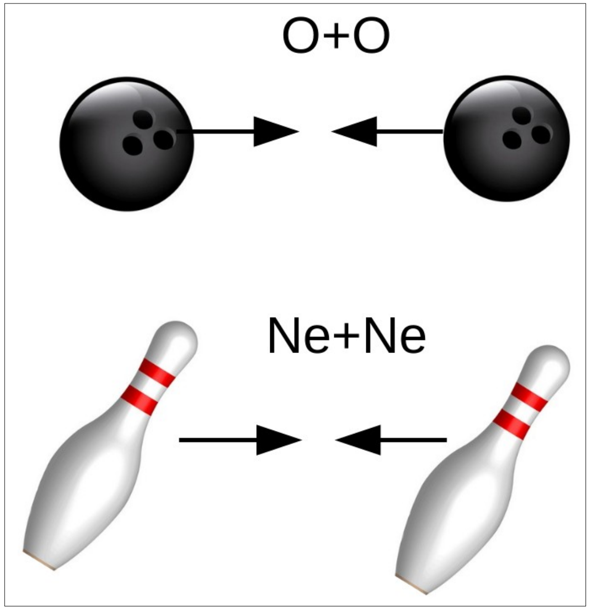
Isobars to understand small systems?

Model-independent evidence of a “geometric” origin of flow?

Exploit bowling-pin-shaped ^{20}Ne.



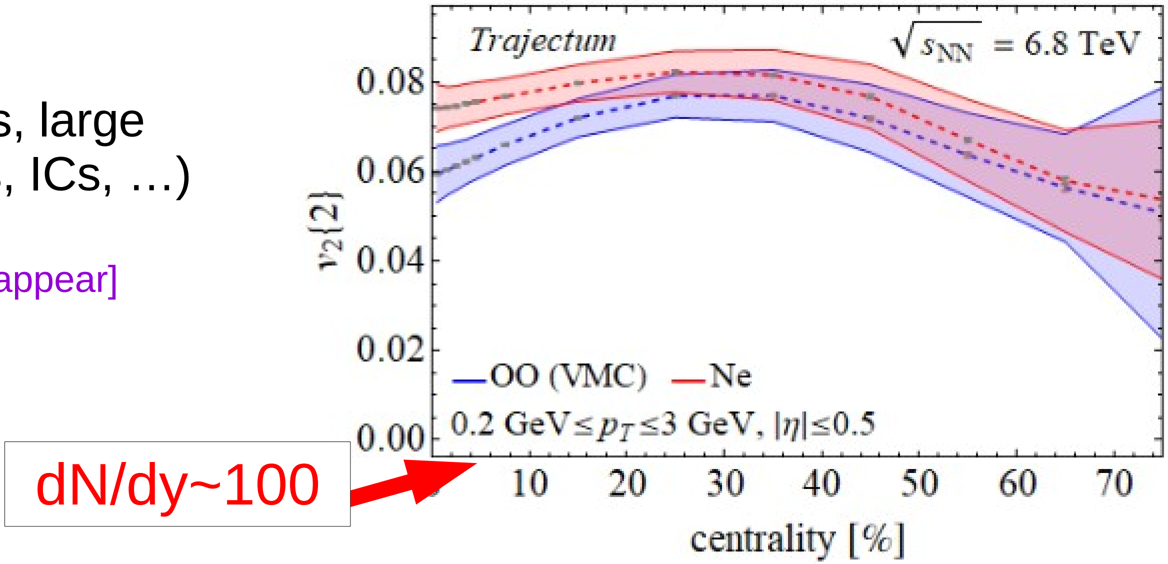




[Oxygen structure: Londardoni *et al.*, PRC **96** (2017) 2, 024326]
[Neon structure: Frosini *et al.*, EPJA **58** (2022) 4, 63]

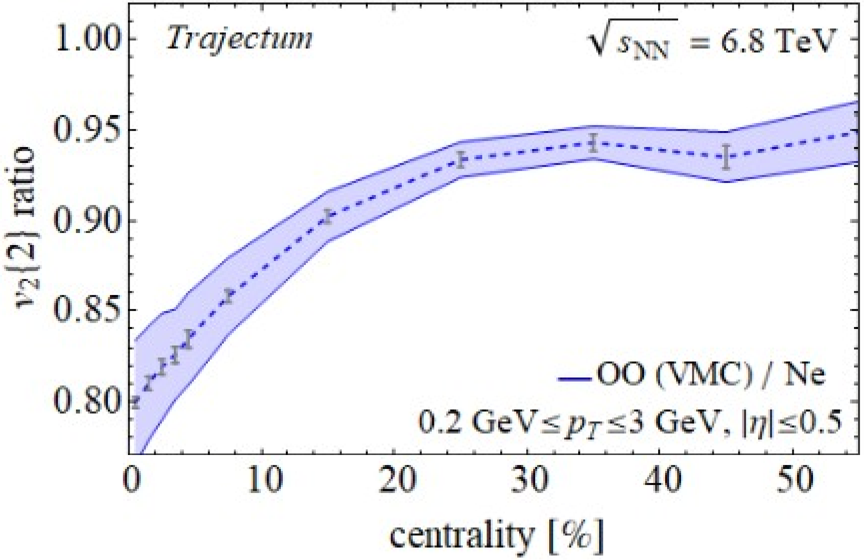
Bands are systematical uncertainties, large variations in parameter space (η/s, ζ/s, ICs, …)

[Giacalone, Nijs, van der Schee, et al., to appear]



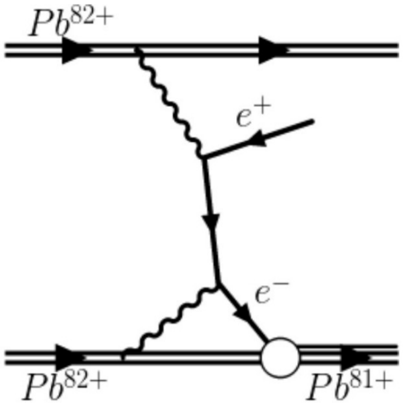
Unprecedented 20% effect on rms v_2.
Systematical uncertainty at % level!
("isobar criterion")

<u>Isolates effect of initial state (structure).</u>
<u>Ideal to test dynamical models.</u>



[TALKS BY XIAOJIAN DU, CLEMENS WERTHMANN]

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



Isobar-like systems to maximize science output?

[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

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?

Method 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]

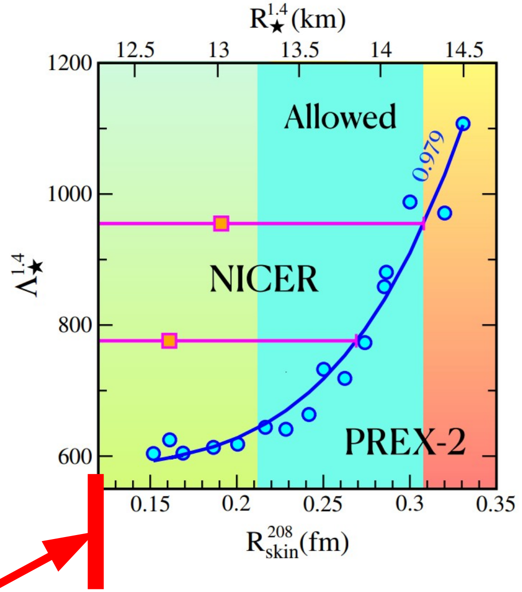
Recent measurements for ^{208}Pb from weak form factor:

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

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

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

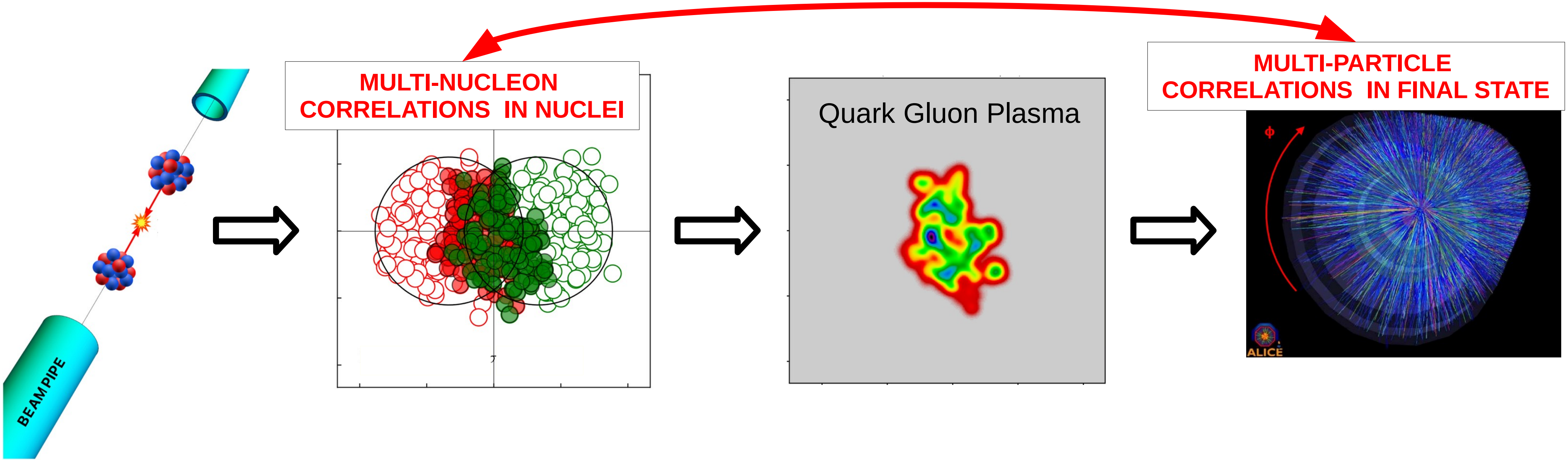
Stiffer EoS than expected.



From NS merger observations.

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

SUMMARY



- High-energy model provides excellent description of heavy-ion data.
- Collective spatial correlations (shapes) in nuclei show up at high energy.
- **Isobar collisions are a precision tool to assess role of nuclear structure.**
- Prospects: ^{20}Ne as an isobar of ^{16}O. More cases 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

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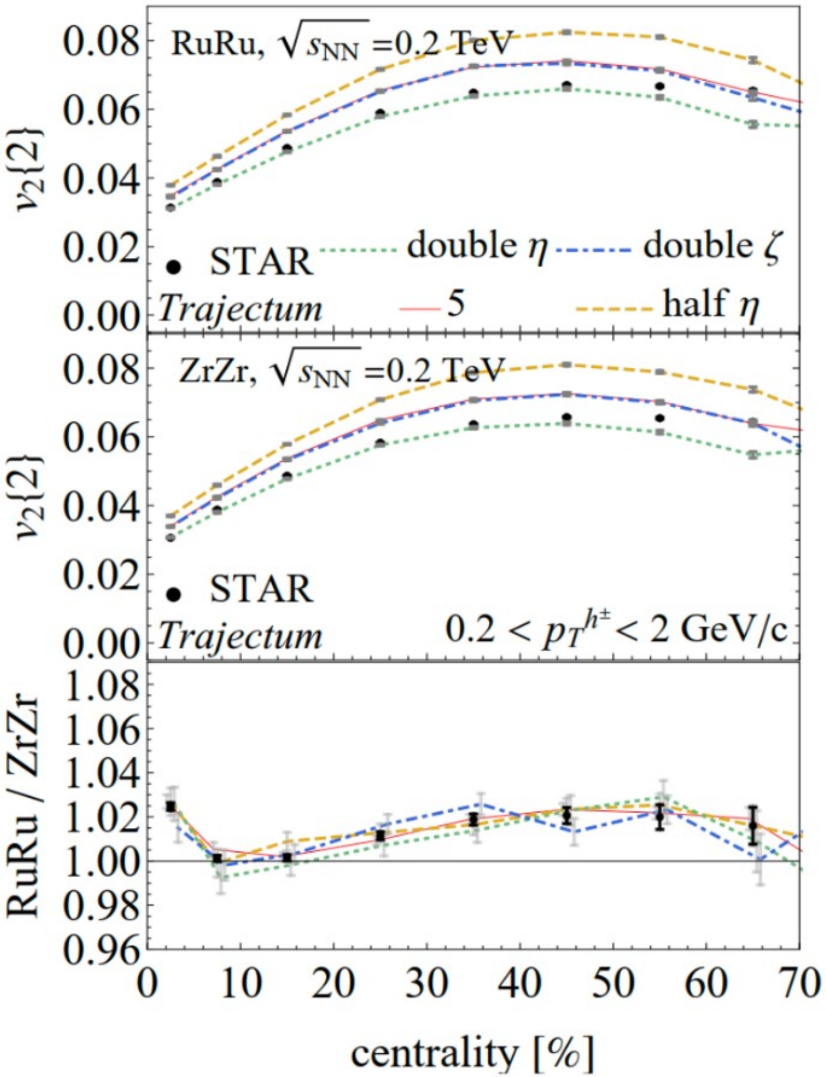
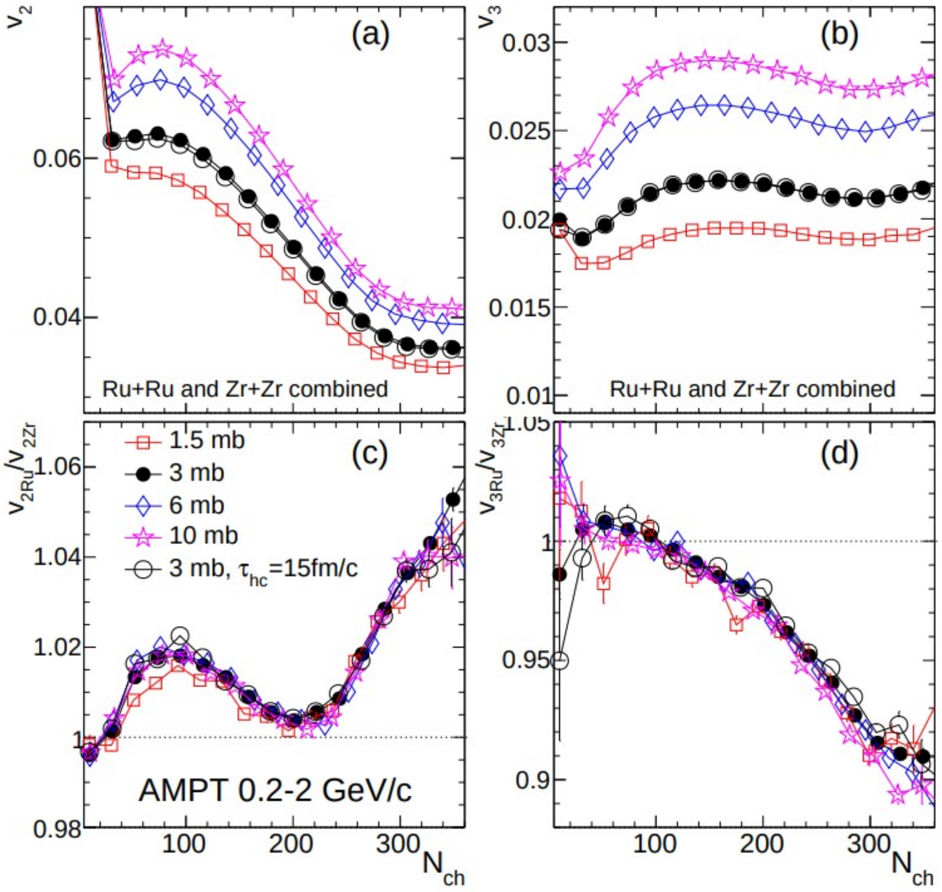
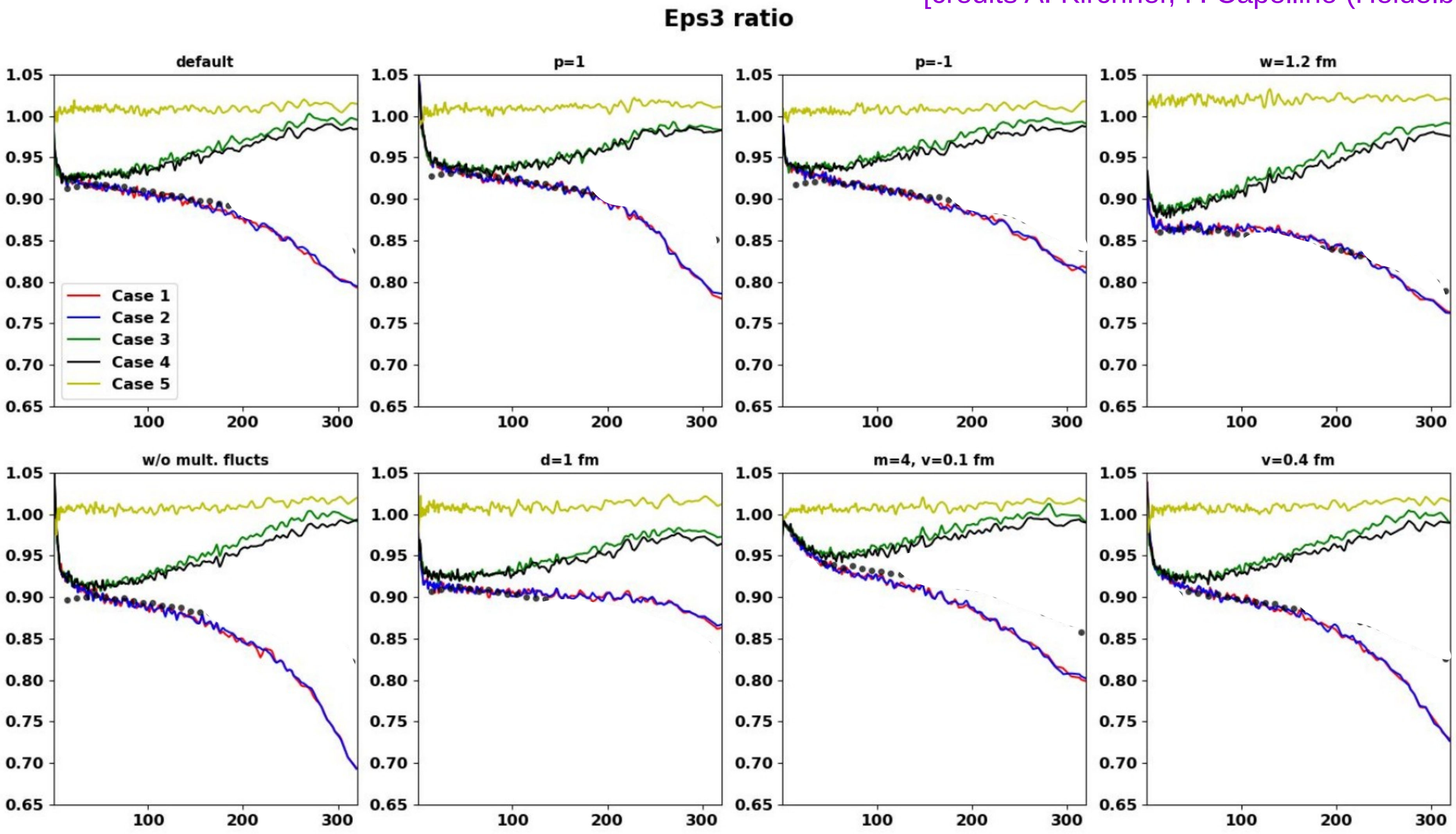
Fuqiang Wang (Purdue)

[Nijs, van der Schee, arXiv:2112.13771]



[Zhang, Bhatta, Jia, PRC **106** (2022) 3, L031901]

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Case 1
Case 2
Case 3
Case 4
Case 5
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0.85
0.80
0.75
0.70
0.65
100
200
300