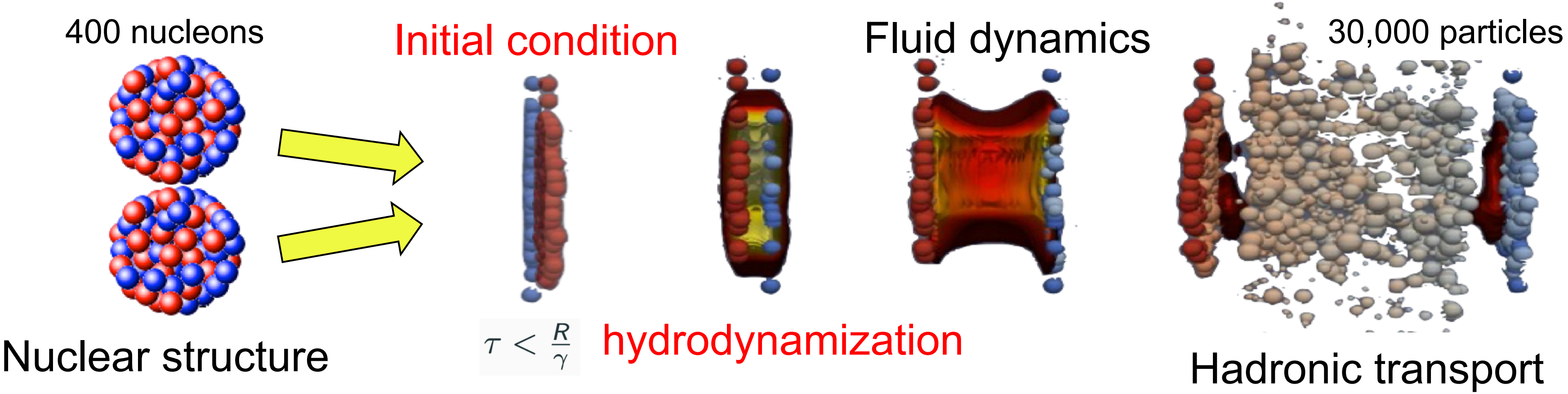
Opportunities in small systems and connection to nuclear structure

Jiangyong Jia Stony Brook University and BNL

based partially on arXiv:2209.11042

Imaging the initial condition of heavy-ion collisions and nuclear structure across the nuclide chart

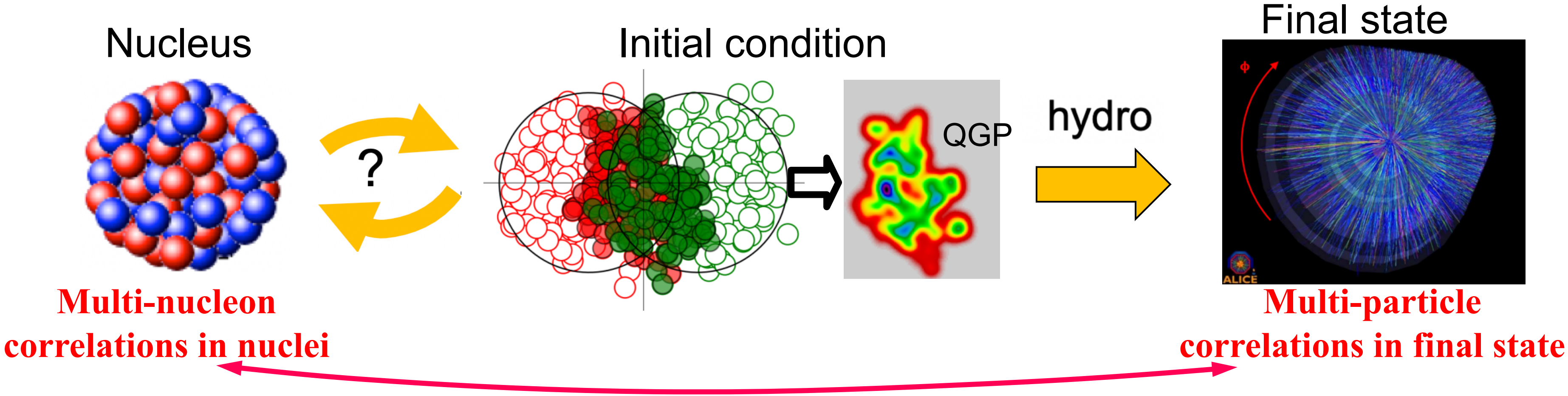
Initial condition and emergence of collectivity



Challenge: A lack of control on the **initial condition** and **hydrodynamization** process from which collectivity emerges, limits the precision on the extraction of QGP transport properties and exploration of QCD phase diagram. Proposal: Collisions of carefully-selected species across nuclear charts to 1) understand how heavy-ion initial condition is shaped from structure of nuclei, and in turn improve constraints on QGP properties and provide new insights on nuclear structure, 2) stress-test the emergence of collectivity by going to small systems in a more systematic way. 3) Future data from a well-motivated system scan, isobars in particular, is necessary for precision heavy ion physics.

Imaging nuclear structure and initial condition

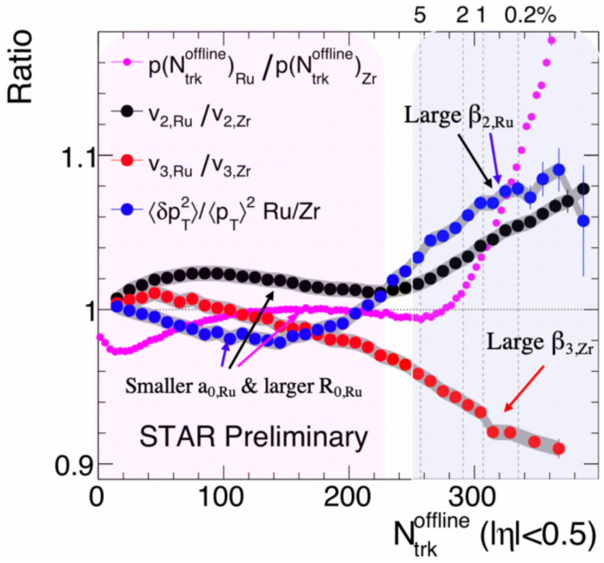
Atomic nuclei are strongly-correlated systems exhibiting rich structures in their shapes and radial distributions. These structures impact the initial condition and dynamics of high energy collisions, where, due to short crossing time and abundant particle production, nuclear structure becomes easy to access. Main advantage: nucleon configurations are probed on an event-by-event basis via multi-particle correlations



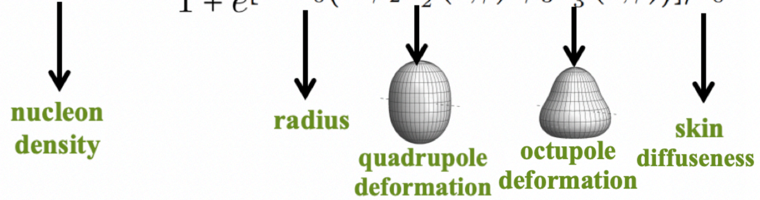
Once the response of initial condition to nuclear structure is established, high-energy colliders will be a new tool to reveal the collective structure in atomic nuclei.

How impact of nuclear structure shows up?

Nuclear structure influences show up ubiquitously in comparison of data between different collision species. Best example: Isobars collisions (96Ru vs 96Zr) are a precision tool to access nucleon distributions.



$$\rho(r,\theta,\phi) \propto \frac{1}{1+e^{[r-R_0(1+\beta_2 Y_2^0(\theta,\phi)+\beta_3 Y_3^0(\theta,\phi))]/a_0}}$$



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.**

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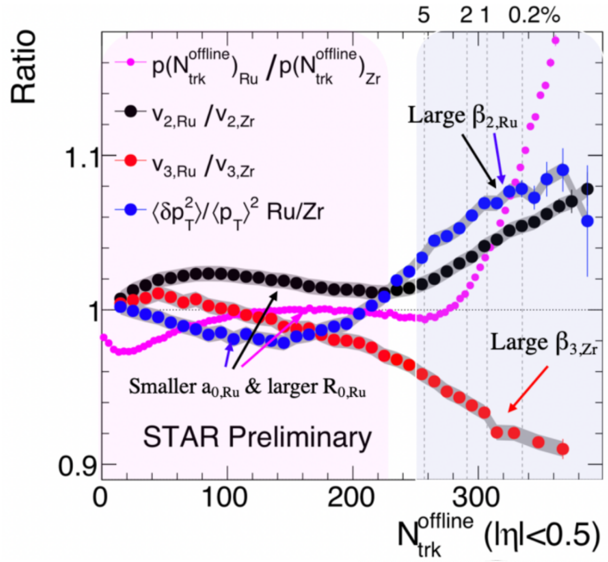

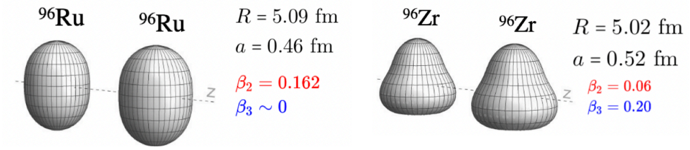

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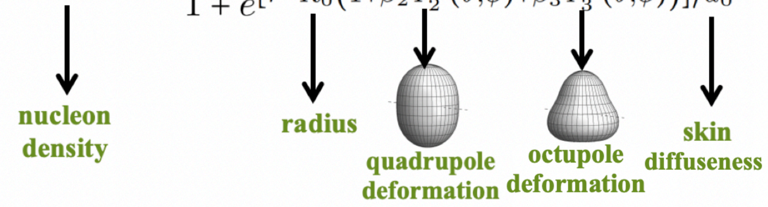

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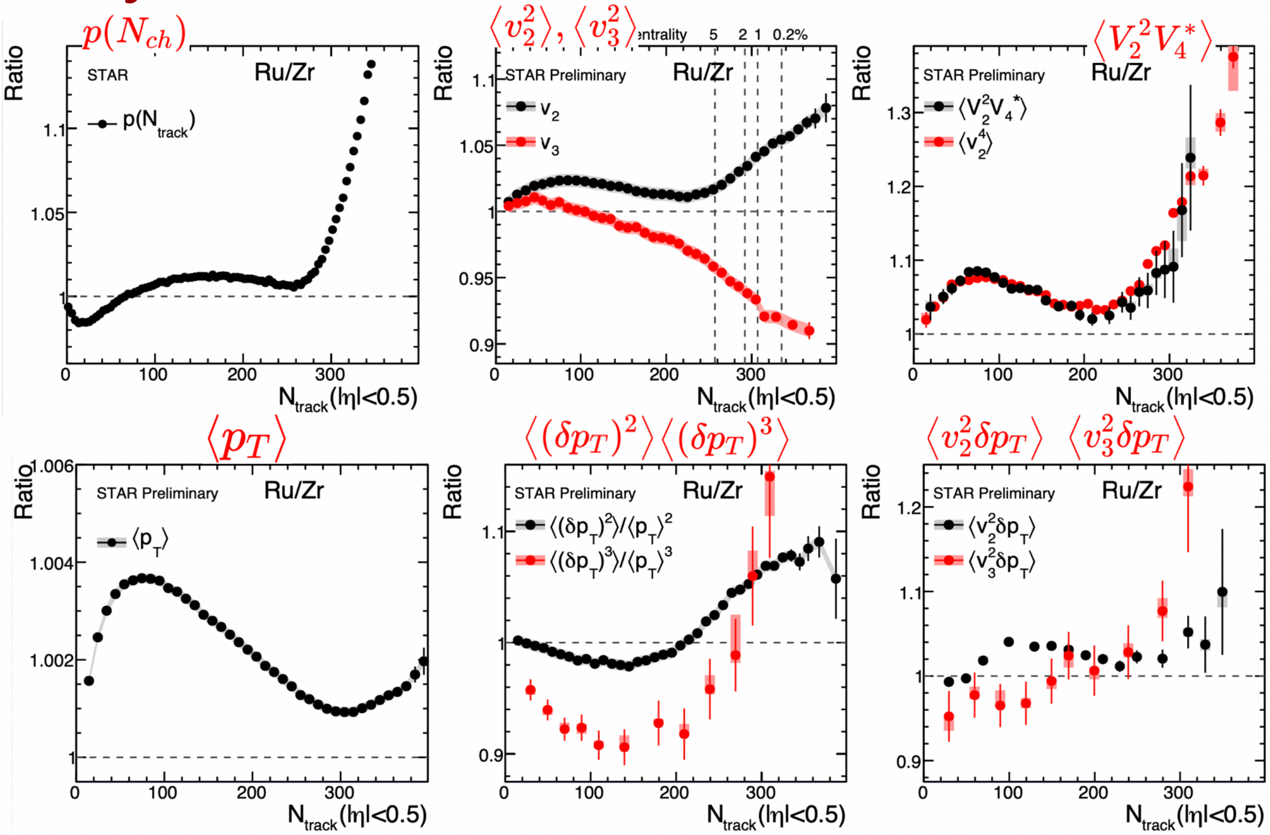
Access structure differences: $\boxed{R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{Ru}}{\mathcal{O}_{Zr}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a}$

Access neutron skin: $\Delta r_{np} = \langle r_n \rangle^{1/2} - \langle r_p \rangle^{1/2}$

$$\Delta r_{np,Ru} - \Delta r_{np,Zr} \propto (R_0 \Delta R_0 - \overbrace{R_{0p}\Delta R_{0p}) + 7/3\pi^2(a\Delta a}^{\text{charge}} - a_p \Delta a_p)$$

$$\underbrace{\Delta R_0 - R_{0p}\Delta R_{0p}) + 7/3\pi^2(a\Delta}_{\text{mass}}$$

Many more observables show sensitivity

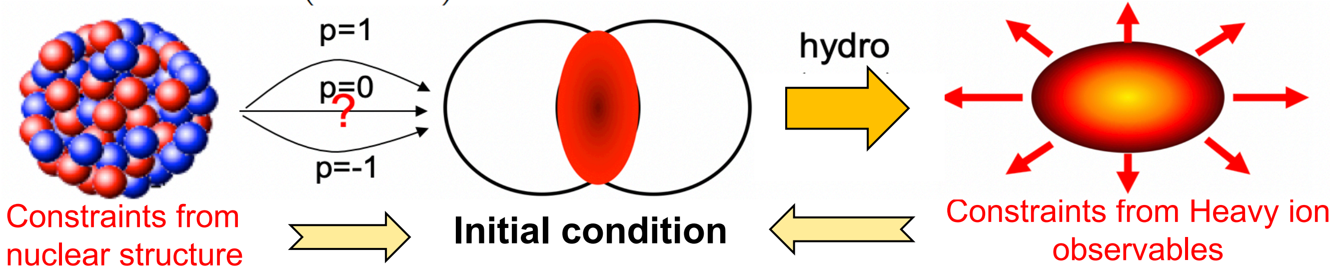


We can ask the same question for isobar ratios for hard probes

US nuclear community should explore the interdisciplinary connection between HI initial condition and structure of atomic nuclei by collisions of well-motivated species across the nuclear chart at the LHC

Energy deposition mechanism:

$$T \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{q/p}$$



Impact on heavy-ion collision program.

heavy-ion initial condition via lever-arm of nuclear structure

Key limitation in the extraction of QGP transport properties

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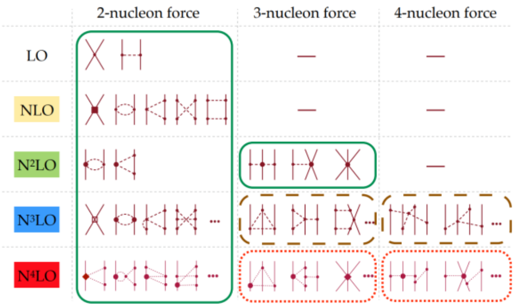

Impact on nuclear structure program.
Emergence of correlations from ab-initio description of the strong force, rapid progress expected in the next LRP period.
High-energy colliders are the right laboratory.

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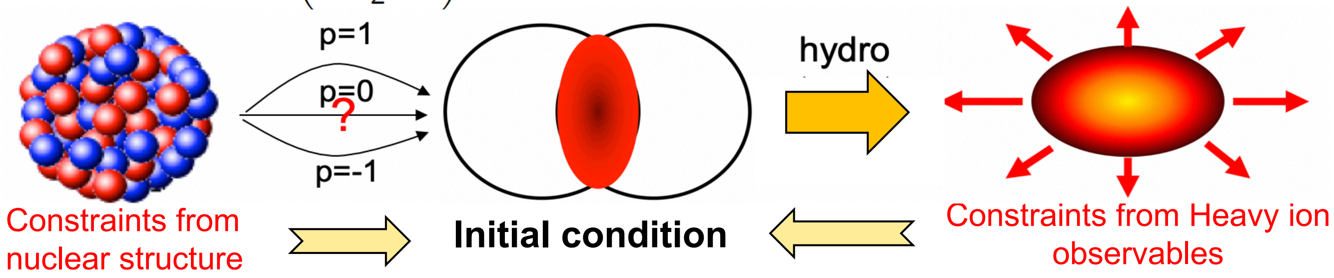

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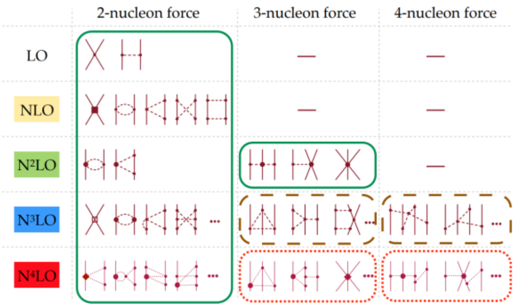

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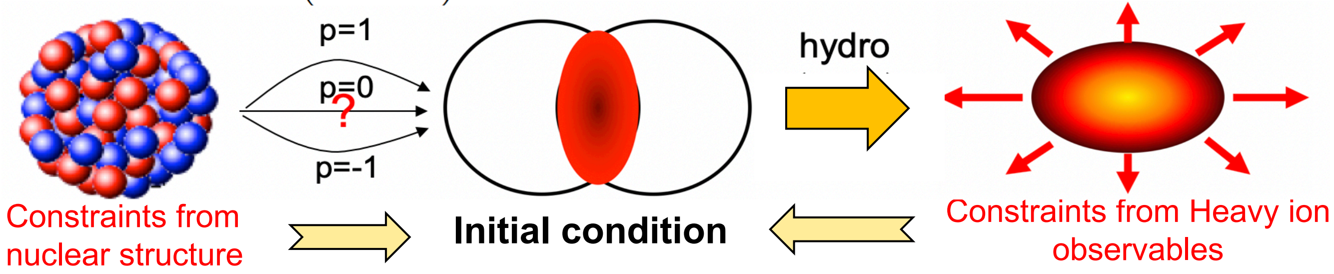
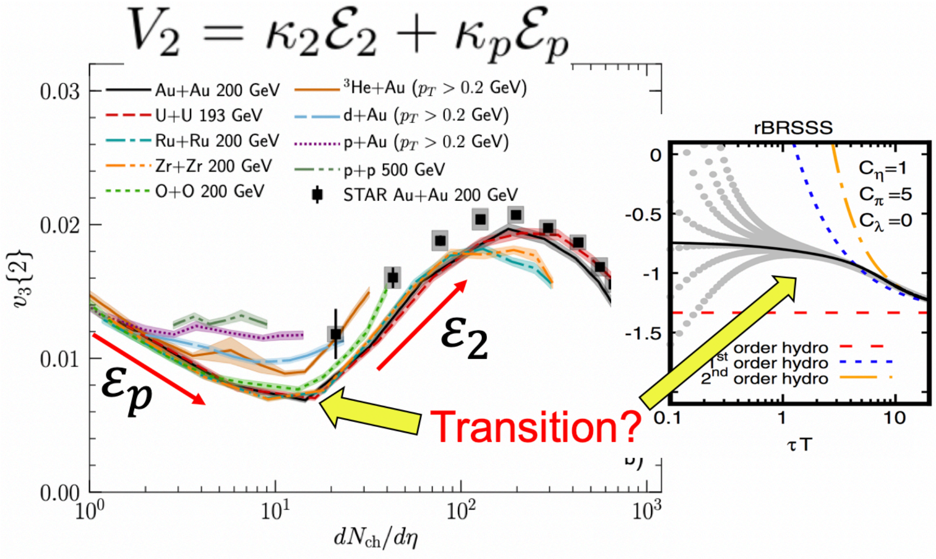


Proposals are under discussion. LHC 2025+ (to be defined) and/or before end of RHIC (opportuntistically), see e.g. the outcome of a recent Task Force Organized by EMMI, and a white paper arXiv:2209.11042

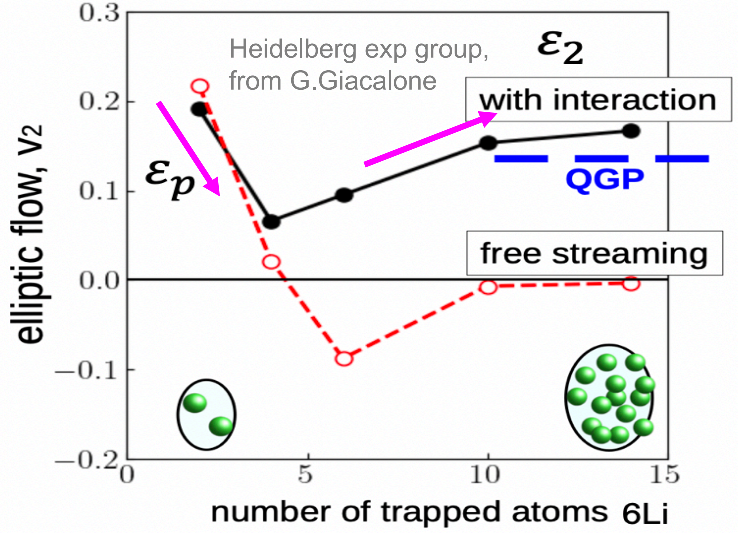
Emergence of collectivity

Status: Long-range collectivity is ubiquitous in AA, pA , pp, and γA collisions. Seems we can not switch it off. Challenge: On the other hand, we do not know what drives this collectivity, initial momentum anisotropy, geometry-driven transport or hydrodynamics, role of nucleon structure? Experimentally, we don't know how non-hydro modes die off + non-flow subtraction systematics.

Unable to see yet interplay between geometry-driven response and initial momentum anisotropy in HI



But clearly seen in cold atomic system by varying number of atoms

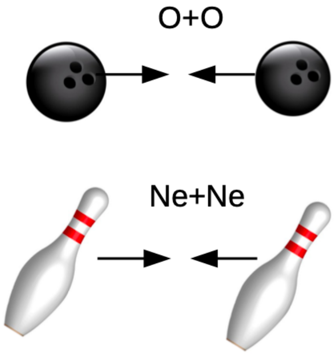


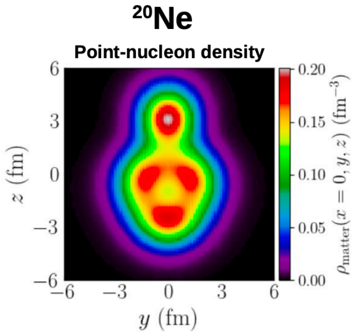
Emergence of collectivity

Opportunities: New data with capability to explore $\sqrt{s_{NN}}$ and rapidity dependences, including OO/dAu/pAu at RHIC and OO at LHC (e.g. resolve PHENIX/STAR v_3 difference). But unclear the extent to which we can separate non-hydro modes (ε_p and transport) and hydrodynamics with only these systems. Proposal: stress-test collectivity via small isobar or isobar-like pairs with different but controlled geometry

One example:

Structure of 16O and 20Ne relatively well-controlled via ab-initial approach





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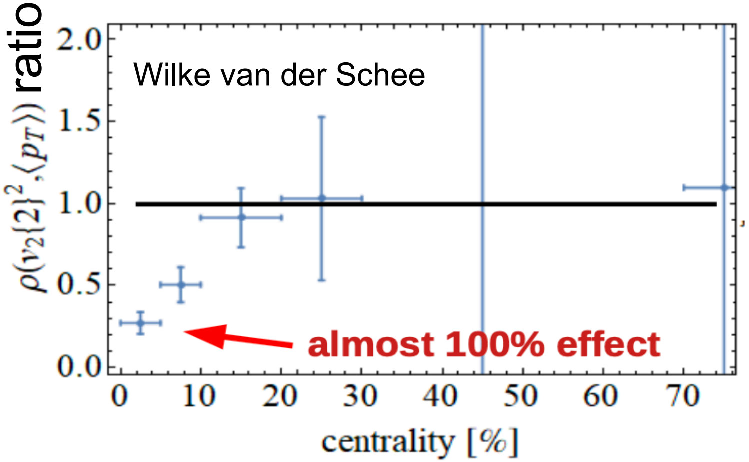
^{20}Ne has the most extreme shape: β_2~0.7. Use NeNe/OO to observe "strong" geometric effects at dN/dy~100.



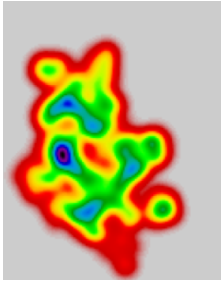
Exploiting the lever-arm provided by nuclear structure

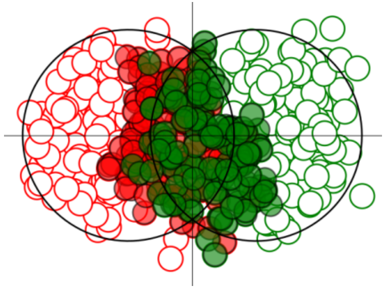
Flow observable = k ⊗ initial condition (structure)

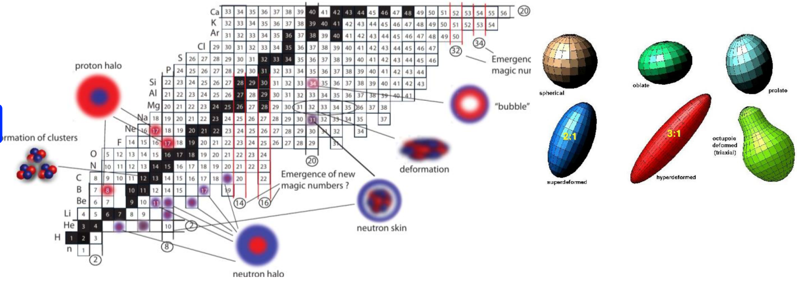
QGP response,
a smooth function of N+Z

Structure of colliding nuclei,
non-monotonic function of N and Z

QGP

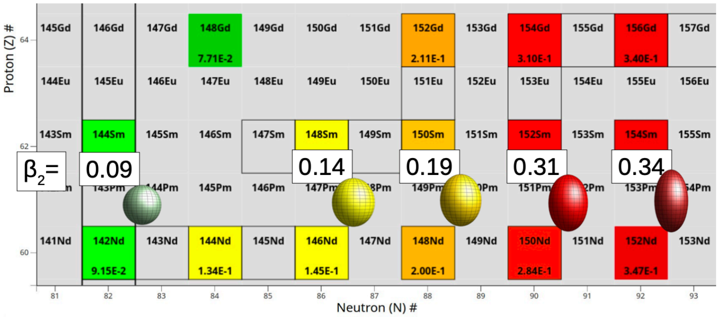






IC and NS via shape evolution of $^{144-154}$Sm isotopic chain

Transition from nearly-spherical to well-deformed nuclei when mass increases by less than 7%: 1) Use large level-arm in nuclear shape to probe the initial condition 2) Use HI collisions to access many-body nucleon correlations leading to such shape evolution

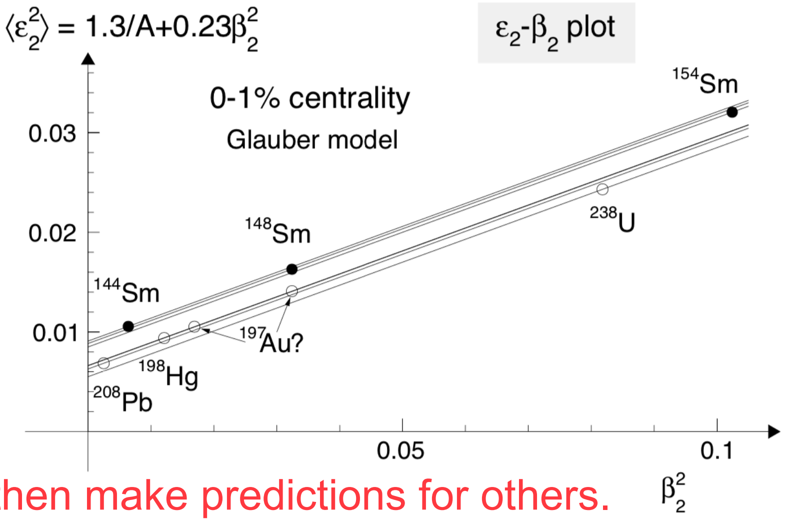


$$\langle \epsilon_2^2 \rangle = a' + b'\beta_2^2$$
$$\langle v_2^2 \rangle = a + b\beta_2^2$$

In central collisions

$$a' = \langle \varepsilon_2^2 \rangle_{|\beta_2=0} \propto 1/A$$
$$a = \langle v_2^2 \rangle_{|\beta_2=0} \propto 1/A$$

b', b are ~ independent of system



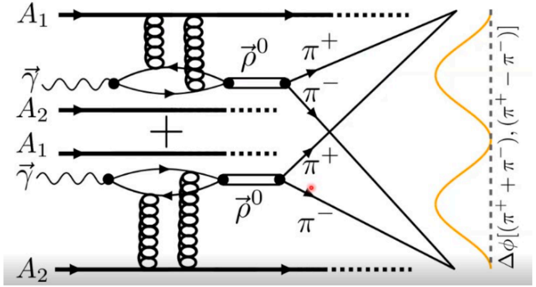
Systems with similar A falls on the same curve.

Fix a and b with two isobar systems with known β_2, then make predictions for others.

Impact of having both AuAu and PbPb at the same collider

1) Cross-calibrate nuclear structure & heavy-ion initial condition of ^{197}Au with ^{208}Pb
   → 197Au has large deformation and smaller skin → small irreducible uncertainties for hard probes.
2) Allow more direct comparison with results from Pb+Pb collisions at LHC.
3) Extract neutron skin, fundamental importance to nuclear physics.

Photo-nuclear in UPC



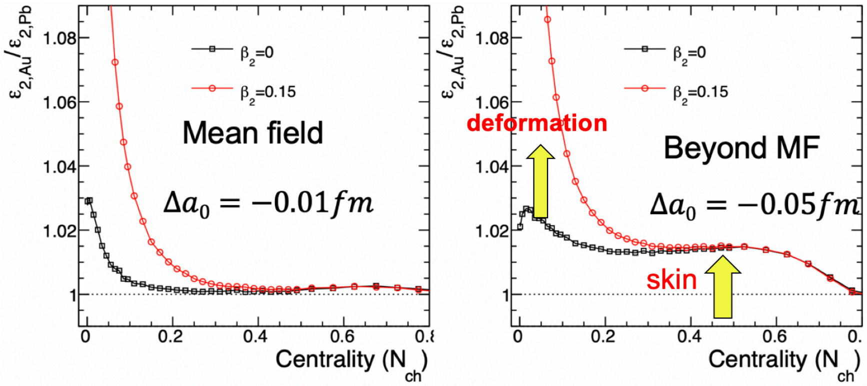
Neutron skin: STAR: 2204.01625

$0.44 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$ fm for ^{238}U

$0.17 \pm 0.03(\text{stat.}) \pm 0.08(\text{syst.})$ fm for ^{197}Au

2 DFTs (MF and beyond MF) give same neutron skin but different a_0

$\Delta r_{np,\,Au} = 0.17 fm$
$\Delta r_{np,\,Pb} = 0.19 fm$



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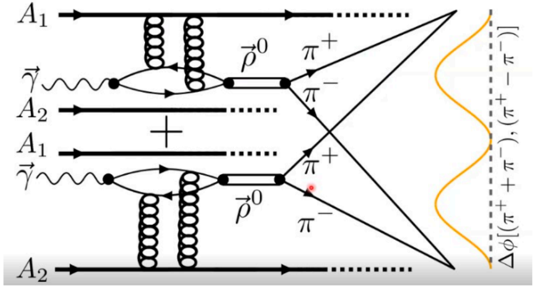

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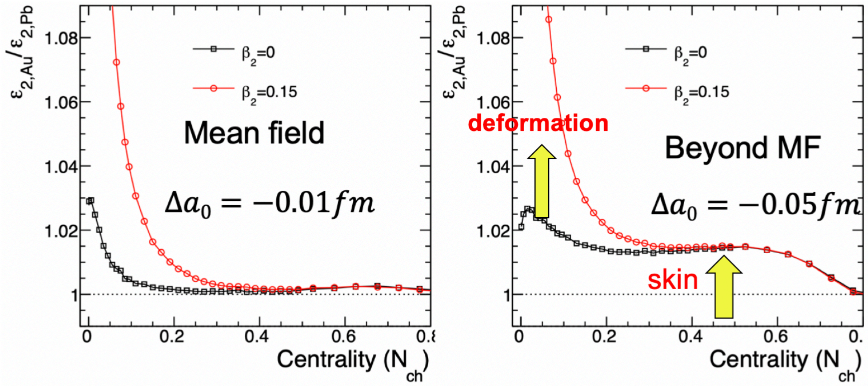


Isobars are good tool for neutron skin:

^{208}Pb and ^{48}Ca are targeted by PREX and CREX

Neutron skin of ^{48}Ca is easy to get from ^{40}Ca+^{40}Ca and ^{48}Ca+^{48}Ca: ➡

We know:

$$\sqrt{\langle r_p^2 \rangle}(^{48}\text{Ca}) = \sqrt{\langle r_p^2 \rangle}(^{40}\text{Ca})$$

$$\sqrt{\langle r_p^2 \rangle}(^{40}\text{Ca}) \approx \sqrt{\langle r_n^2 \rangle}(^{40}\text{Ca})$$

➡

$$\Delta_{\text{np}}(^{48}\text{Ca}) - \Delta_{\text{np}}(^{40}\text{Ca}) \simeq \Delta_{\text{np}}(^{48}\text{Ca})$$

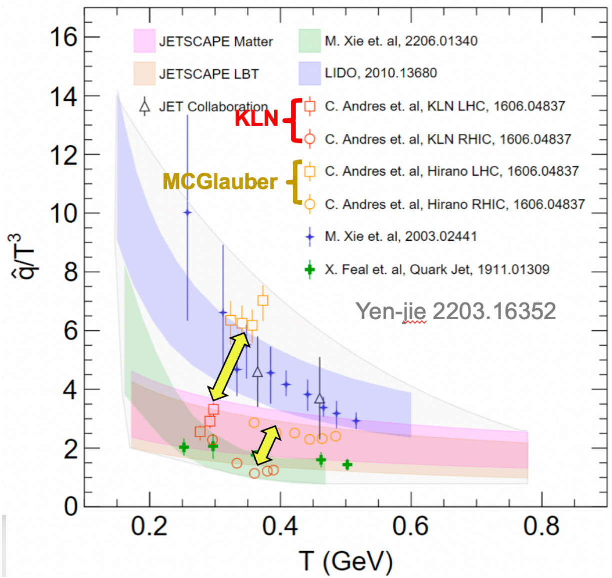
$$\propto \bar{R}_0 \Delta R_0 + 7/3\pi^2 \bar{a} \Delta a$$

Impact on initial condition for hard probes

Isobar ratios of hard probes (h,jets,jet-v_2 etc) allow us to vary initial condition (nPDF and parton transverse spatial distribution) while canceling jet quenching effect.

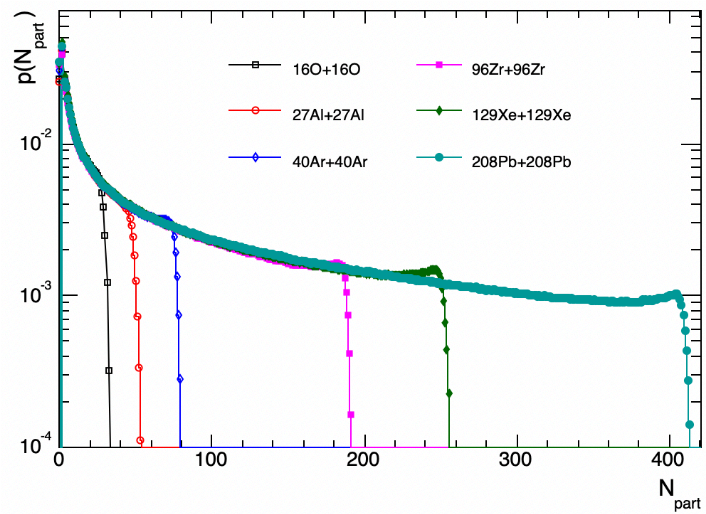
Rapidity and energy dependence of isobar ratios will further constrain nPDF, valuable information for EIC.

Significant sensitivity of $\hat{q}$ to initial condition KLN vs Glauber (almost like two isobars).



Two-pronged approach:

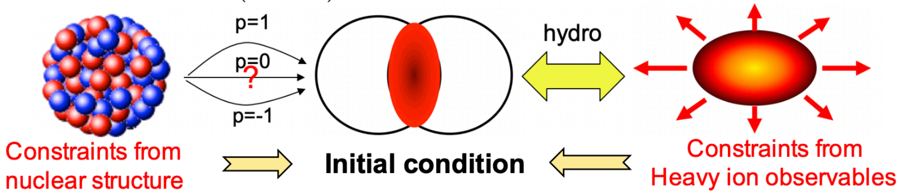
1) Vary the system size.
2) Vary the initial condition at same system size with different nuclear structure



Summary

- Constrain QGP initial condition with nuclear structure input and heavy ion observables
  ➔ Improve the extraction of QGP properties in the Bayesian approaches
- Understanding how initial condition responds to nuclear structure, in turn enables probing novel nuclear structure properties and compliments low-energy experiments.
- Collisions of carefully-selected isobar species across nuclear chart will allow us to map out initial condition from small to larger system

$$e(x,y) \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{q/p}$$



arXiv:2102.08158

PROGRAM

JANUARY 23 - FEBRUARY 24, 2023

Intersection of nuclear structure and high-energy nuclear collisions (23-1a)

INSTITUTE for NUCLEAR THEORY

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

250 stable isotopes, 141 isobar pairs or triplets

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		

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https://arxiv.org/abs/2209.11042

…the extraction of the properties of QGP…limited by our poor knowledge of the initial condition… in particular how it is shaped from the colliding nuclei. To attack this limitation, we propose collisions of selected species to assess how the initial condition changes under variations of the structure of the colliding ions. This knowledge, combined with event-by-event measures of particle correlations…, will probe the …structure of nuclei, and to confront and exploit the predictions of ab initio structure theories. The US nuclear community should capitalize on this interdisciplinary connection by pursuing collisions of well-motivated species at high-energy colliders.

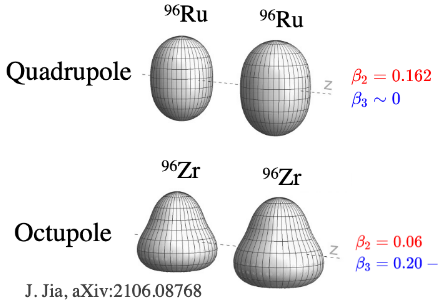
- **Impact on the hot QCD program.**

Our ability to constrain key properties of the QGP is hampered by our limited knowledge of the condition… Collisions of species… offer a new lever arm to understand this initial condition. In particular, in collisions of isobars, one can measure relative variations of observables that are sensitive only to the initial condition.. These variations .. probe the precise way the QGP is shaped from two colliding ions. … future collisions of isobars….will help to reduce the uncertainty in the determination of QGP properties from data.

- **Impact on the nuclear structure program.**

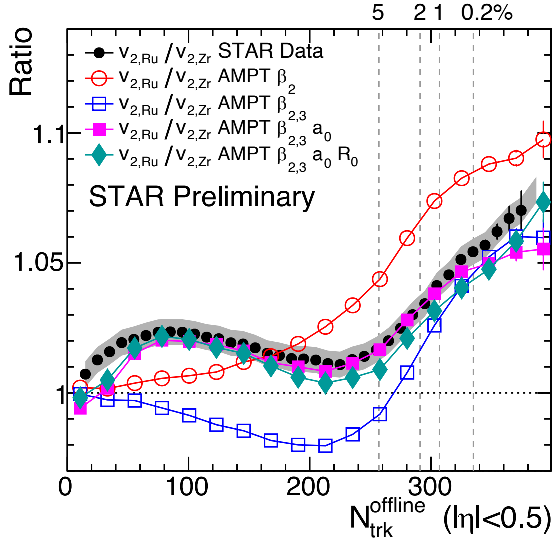
Explaining the emergence of nuclei.. is a major goal of the nuclear structure program, which can benefit from its synergy with the hot QCD program…. Event-by-event measures of particle angular correlations in HI collisions are sensitive to many-body correlations of nucleons, such as deformations, in the colliding nuclei... High-energy colliders are a new tool to gain deep insight into atomic nuclear systems and confront ab initio calculations of nuclear structure.

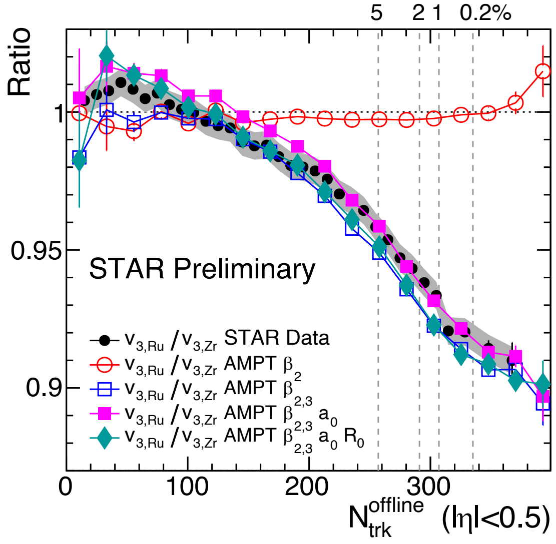
Nuclear structure via v_n-ratio



- β_{2Ru}~0.16 increase v_2, no influence on v_3 ratio
- β_{3Zr}~0.2 decrease v_2 in mid-central, decrease v_3 ratio
- Δa_0= -0.06fm increase v_2 mid-central, small influ. on v_3.
- Radius ΔR_0=0.07fm only slightly affects v_2 and v_3 ratio.

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

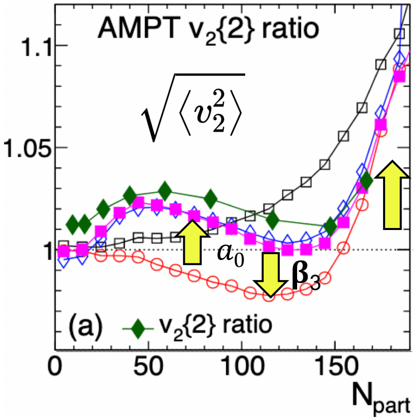




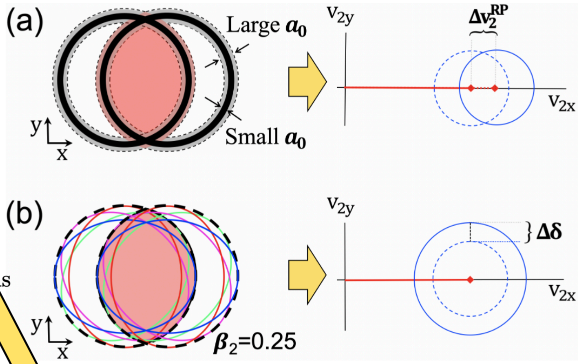
Simultaneously constrain these parameters using different N_{ch} regions

Separating shape and size effects

Nuclear skin contributes to $v_2^{rp} \sim v_2\{4\}$, deformation contribute to fluctuations



$$\langle v_2^2 \rangle = \underbrace{(v_2^{rp})^2}_{\text{mean}} + \underbrace{\delta^2}_{\text{fluctuations}}$$



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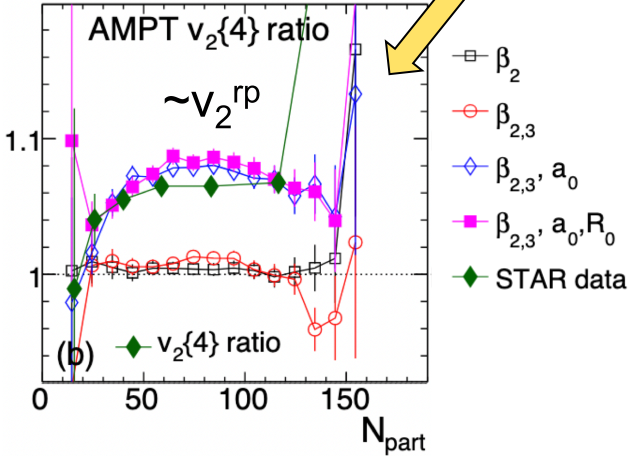
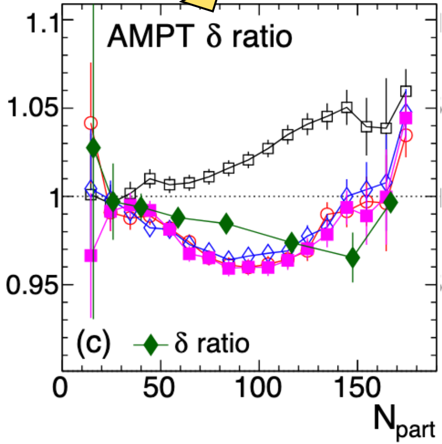
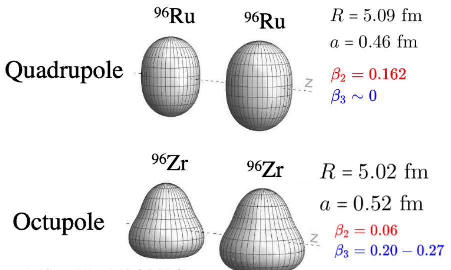




Nuclear structure via $p(N_{ch})$, <pT>-ratio

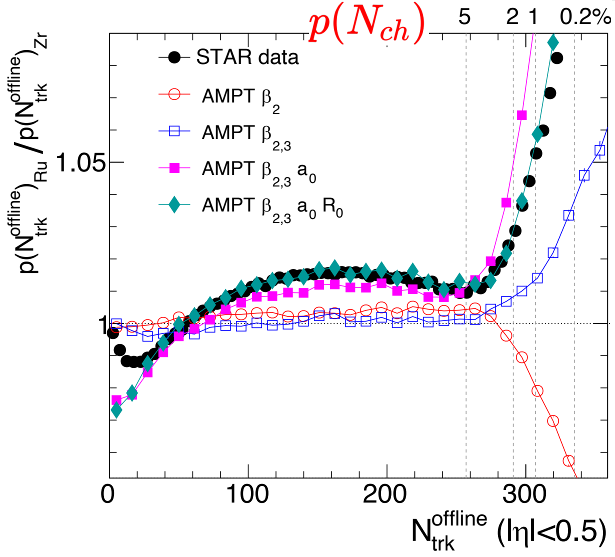
Earlier studies on this from H.Li, H.J Xu, PRL125, 222301 (2020) arXiv:2111.14812



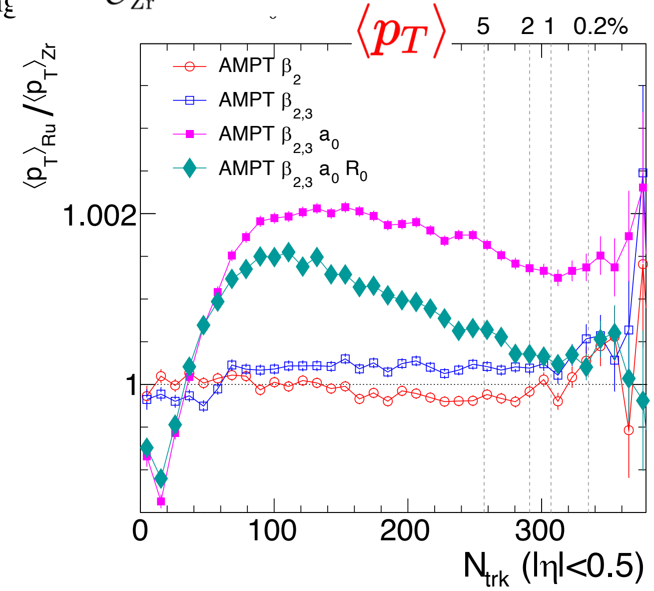
J. Jia, aXiv:2106.08768

- For Nch ratio:
  - β_{2Ru}~0.16 decrease ratio, increase after considering β_{3Zr}~0.2
  - The bump structure in non-central region from Δa_0 and ΔR_0
- For <pT>
  - Strong

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



Δa_0 and ΔR_0 influences add up



Δa_0 and ΔR_0 influences cancel

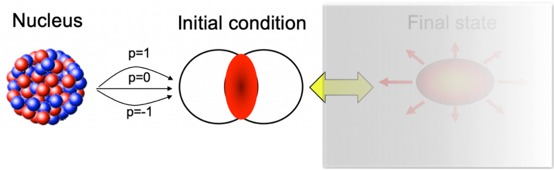
Isobar ratios not affected by final state

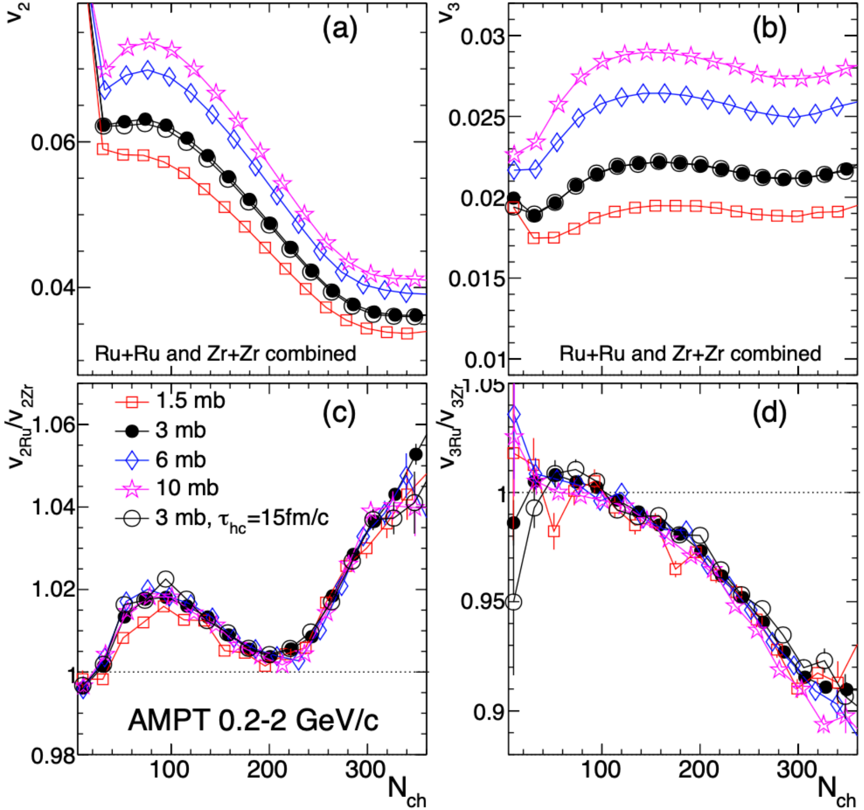
- Vary the shear viscosity via partonic cross-section
  - Flow signal c unchanged.

$$v_n = k_n \varepsilon_n$$

$$\frac{v_{n,\mathrm{Ru}}}{v_{n,\mathrm{Zr}}} \approx \frac{\varepsilon_{n,\mathrm{Ru}}}{\varepsilon_{n,\mathrm{Zr}}}$$

Robust probe of initial state!





Effect of viscosity on observables

Significant effects, but cancel in the ratio

Wilke van der Schee, CERN