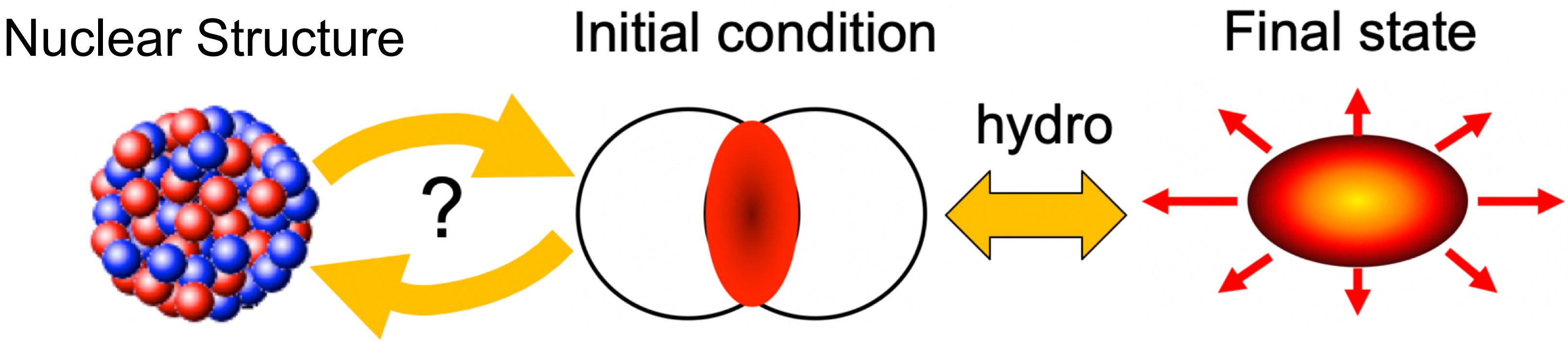
Stony Brook University | The State University of New York

Imaging heavy-ion initial condition & nuclear structure

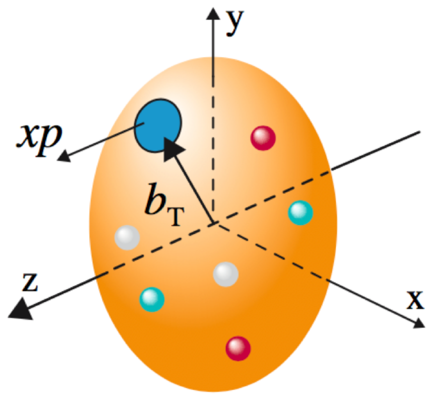
Jiangyong Jia

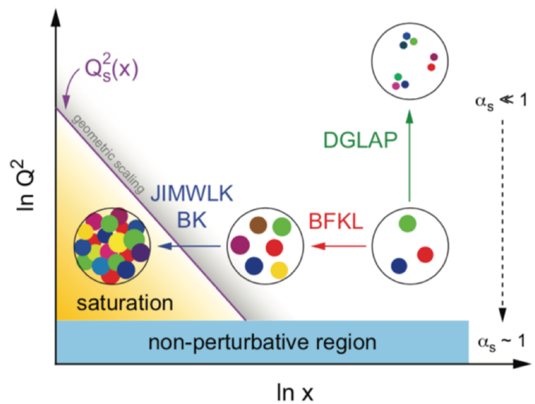


based partially on arXiv:2209.11042

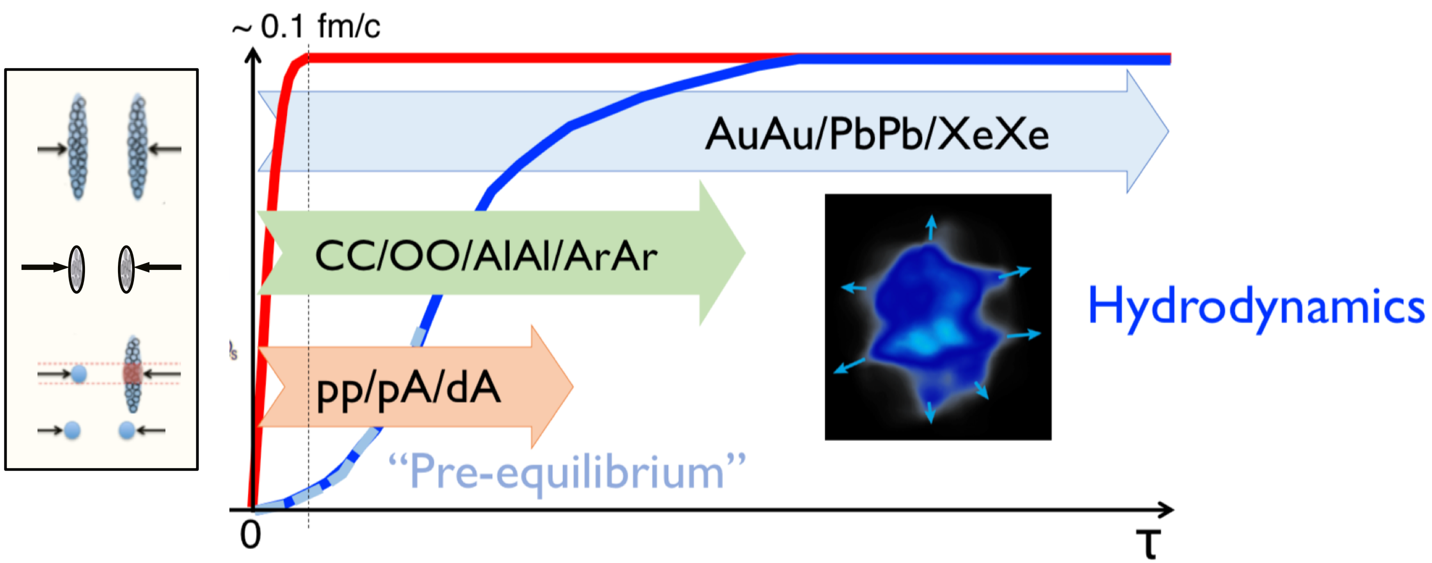
e+p/A vs nuclear collisions

- EIC: structures of nucleon and nuclear initial state





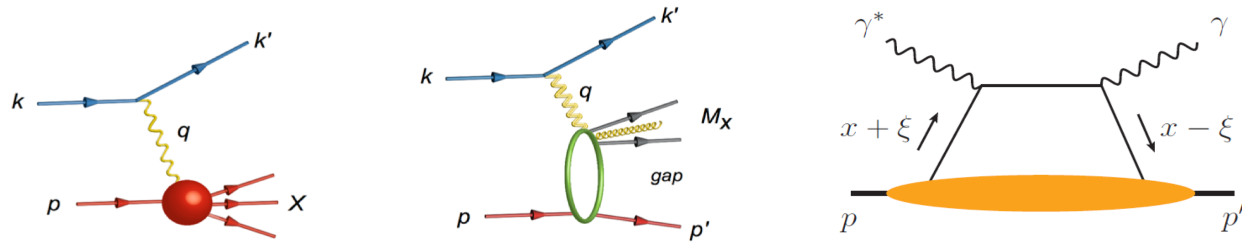
- Heavy-ion: Initial state and emergence of collectivity.



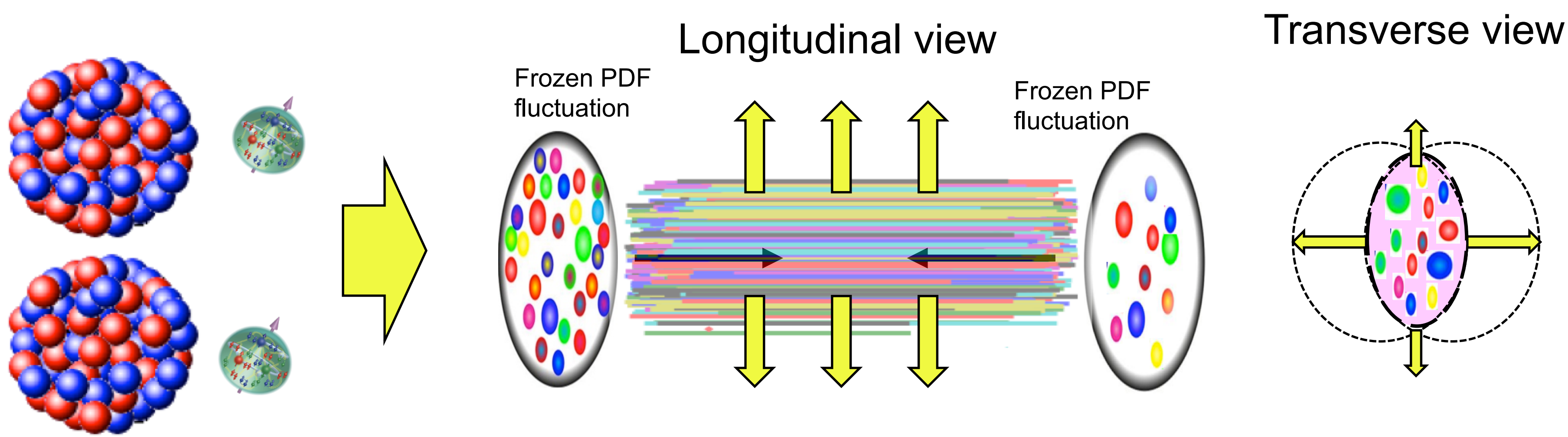
e+p/A vs nuclear collisions

- EIC: structures of initial state (one-body Wigner distribution)
  - Precise control on kinematics

Inclusive Semi-Inclusive Exclusive



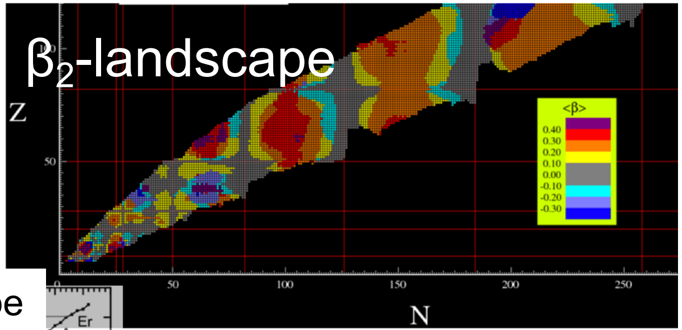
- Heavy-ion: Multi-Parton interactions (many-body distributions)

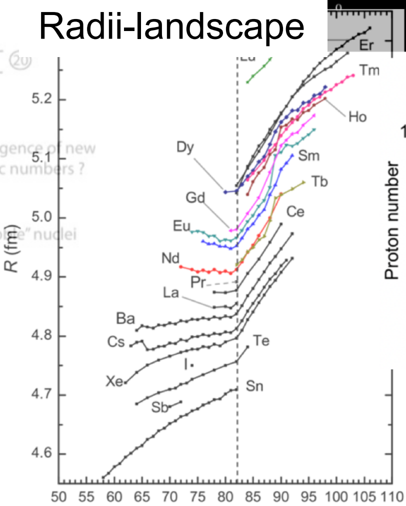


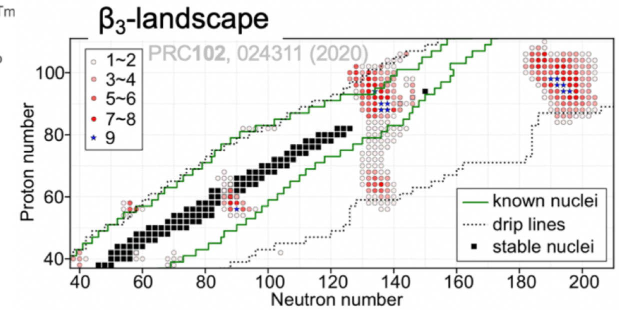
Probe distributions of nucleons and partons via collective response

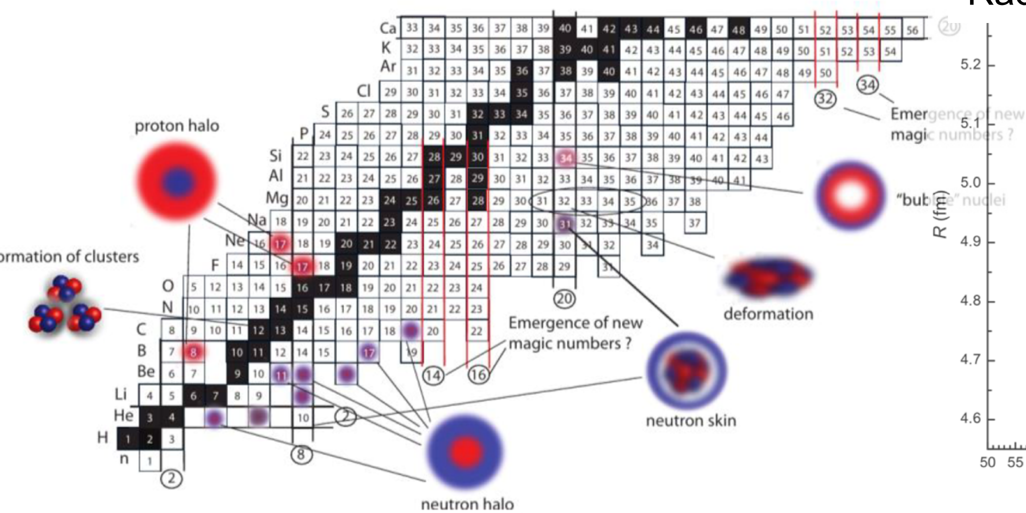
Rich structure of atomic nuclei

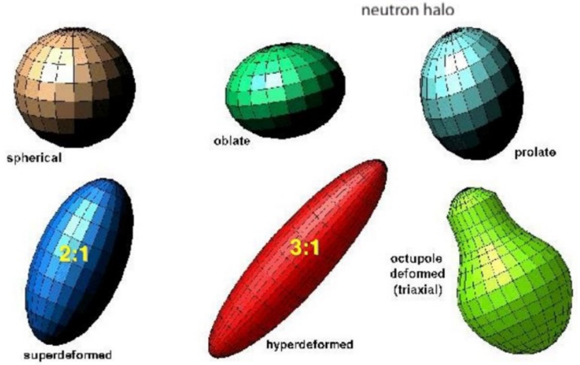
- Collective phenomena of many-body quantum system
  - clustering, halo, bubble, skin, deformations…
  - Momentum correlation e.g. SRC
  - Nontrivial evaluation with N and Z.











- Understanding via effective nuclear theories
  - Lattice, ab.initio (starting from NN interaction)
  - Shell models (configuration interaction)
  - DFT models (non-relativistic and covariant)

Collective structure for heavy ion collision

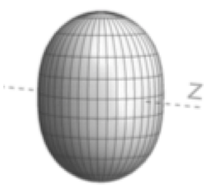
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

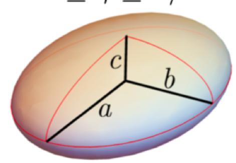
Quadrupole:

Triaxiality:

$1+\beta_2 Y_{2,0}(\theta,\phi)$

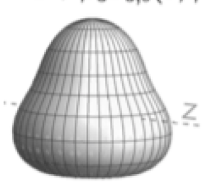


$0 \le \gamma \le \pi/3$



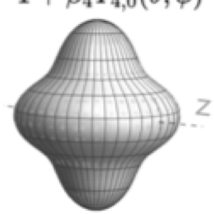
Octupole:

$1+\beta_3 Y_{3,0}(\theta,\phi)$



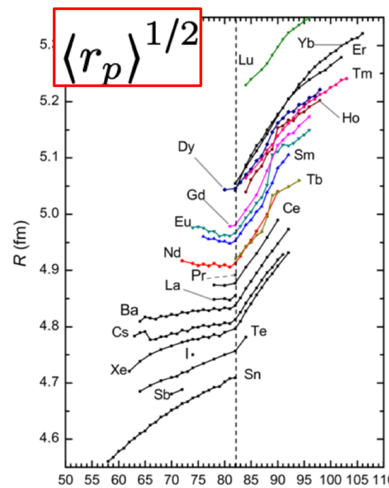
Hexadecapole:

$1+\beta_4 Y_{4,0}(\theta,\phi)$



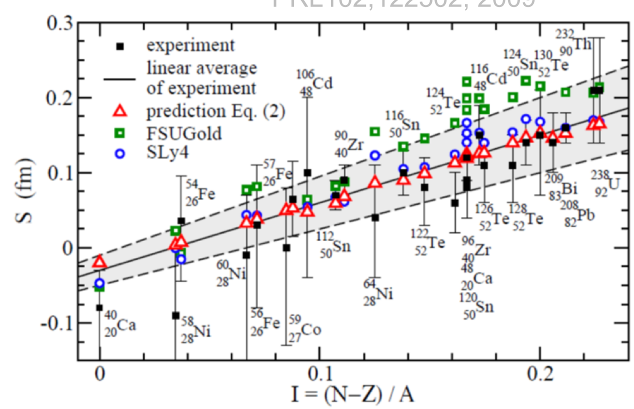
Radial distributions, R_0, a_0:

$\langle r_p \rangle^{1/2}$



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

PRL102,122502, 2009



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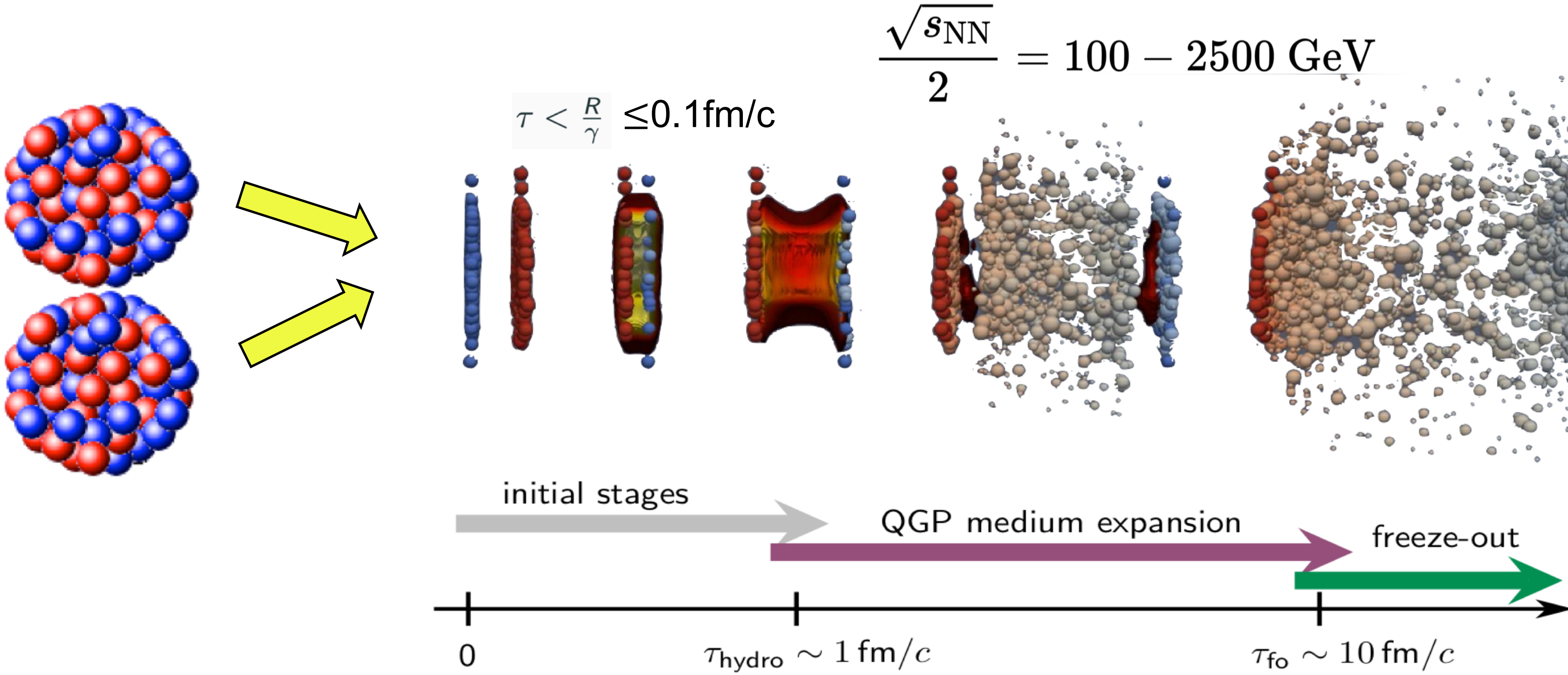
High-energy heavy ion collision



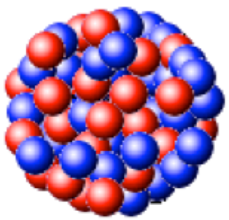
400 nucleons → 30000 hadrons

in 10^{-23} seconds

Key features facilitating the connection to nuclear structure 1) Extremely short passing time means that collision takes a snap-shot of the nuclear and nucleon wavefunction in the two nuclei. 2) Large particle production in overlap region means the produced QGP expands hydrodynamically in each event

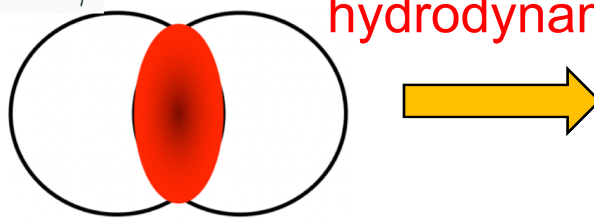
Connection to nuclear structure

Nuclear structure



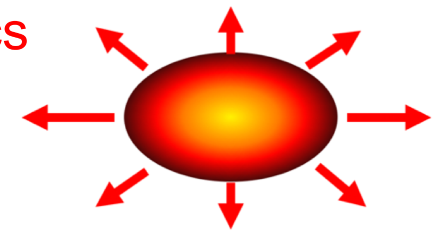
Initial condition

$\tau < \frac{R}{\gamma}$



hydrodynamics

Final state



Shape and radial dis.

$\beta_2 \rightarrow$ Quadrupole deformation

$\beta_3 \rightarrow$ Octupole deformation

$a_0 \rightarrow$ Surface diffuseness

$R_0 \rightarrow$ Nuclear size

Volume, size and shape

N_{part}

$R_\perp^2 \propto \langle r_\perp^2 \rangle,$

$\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

observables

Radial Flow   Harmonic Flow

$$\frac{d^2N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n \, e^{-in\phi}\right)$$

High energy: approx. linear response in each event:

$$N_{ch} \propto N_{part} \qquad \frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

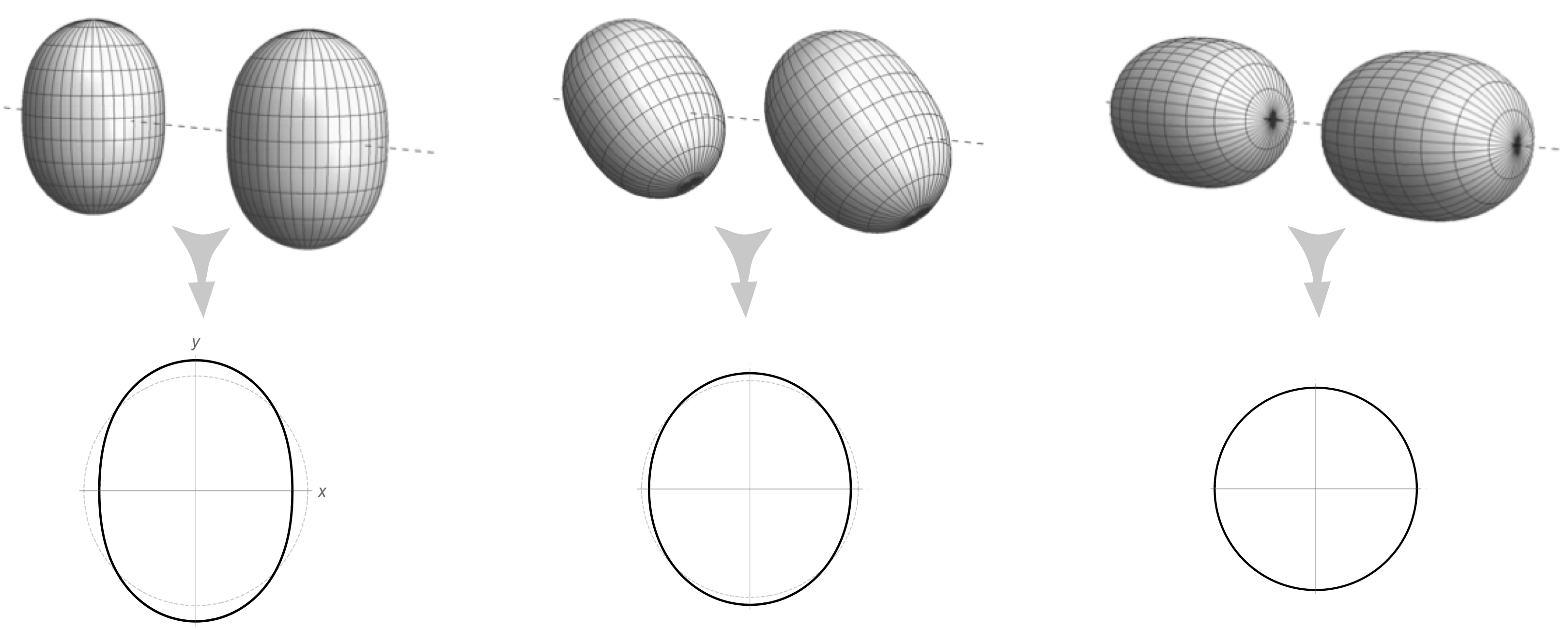
- Discuss how nuclear structure impacts the initial condition and observables
- Case study with isobar collision data.
- Discuss the prospect of nuclear structure imaging with system scan.

How nuclear shape influences HI initial condition

Body-Body

$$\mathcal{E}_2 = \epsilon_2 e^{i2\Phi} \propto \left\langle \boldsymbol{r}_\perp^2 e^{i2\phi} \right\rangle$$

Tip-Tip



$\varepsilon_2 \sim 0.95\beta_2$ $\varepsilon_2 \sim 0.48\beta_2$ $\varepsilon_2 \sim 0$

$$\boldsymbol{\epsilon}_2 = \underbrace{\boldsymbol{\epsilon}_0}_{\text{undeformed}} + \underbrace{\boldsymbol{p}(\Omega_1, \Omega_2)}_{\text{phase factor}} \beta_2 + \mathcal{O}\left(\beta_2^2\right) \Longrightarrow \left\langle \epsilon_2^2 \right\rangle \approx \left\langle \epsilon_0^2 \right\rangle + 0.2\beta_2^2$$

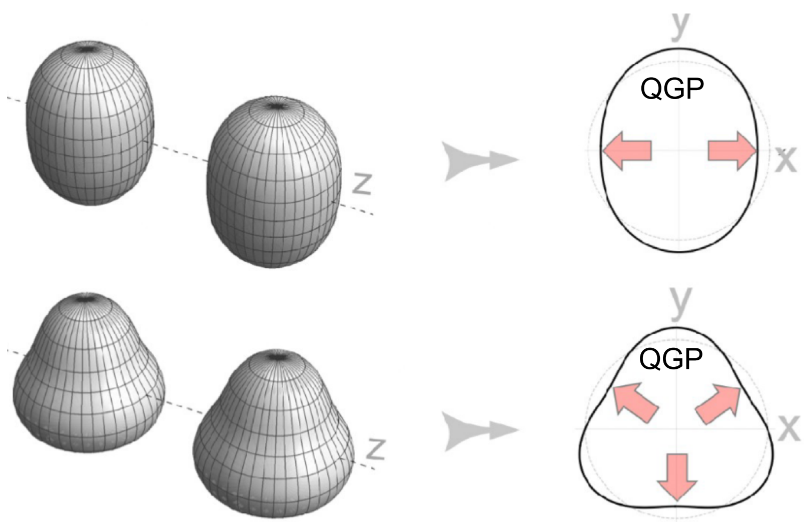
$$\left\langle v_n^2 \right\rangle \propto \left\langle \epsilon_n^2 \right\rangle$$

Shape depends on Euler angle Ω=φθψ

Expected structure dependencies

arXiv:2106.08768

$$\langle v_n^2 \rangle \propto \langle \epsilon_n^2 \rangle \qquad \mathcal{E}_n = \epsilon_n e^{in\Phi} \propto \langle \boldsymbol{r}^2 Y_{n,n} \rangle$$

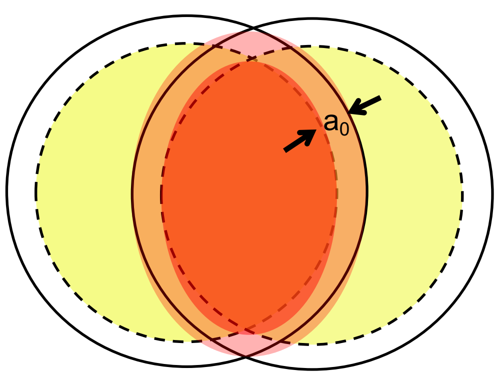


$$\langle v_2^2 \rangle \approx a_2 + b_2 \beta_2^2 + c_3 \beta_3^2$$

$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad R_\perp^2 \propto \langle \boldsymbol{r}^2 Y_{2,0} \rangle$$

$$\left\langle (\delta p_\mathrm{T} / p_\mathrm{T})^2 \right\rangle \approx a_0 + b_0 \beta_2^2 + c_0 \beta_3^2$$

$$\langle v_3^2 \rangle \approx a_3 + b_3 \beta_3^2$$



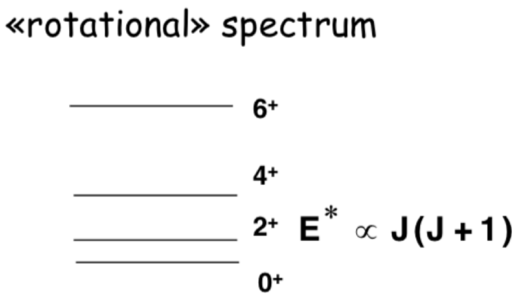
The shape and size the overlap, therefore v_2 and p_T, also depend on diffuseness a_0 and radius R_0

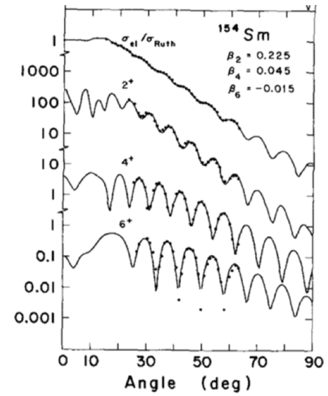
At fixed N_{part} $\quad a_0 \searrow \;\Rightarrow\; v_2 \nearrow \quad p_T \nearrow$

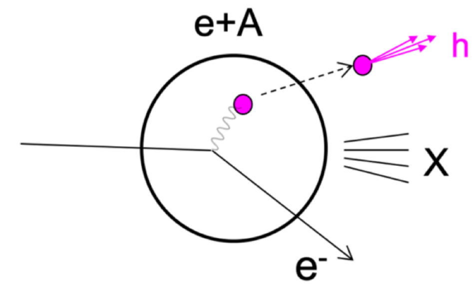
$R_0 \searrow \;\Rightarrow\; p_T \nearrow$

Low-energy vs high-energy method

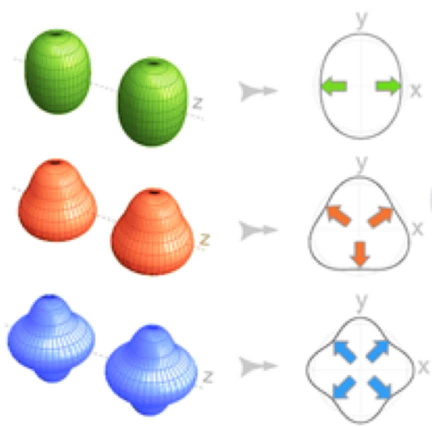
- Shape from B(En), radial profile from e+A or ion-A scattering



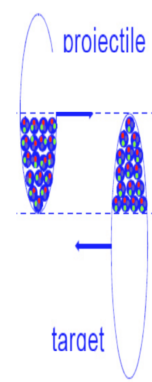


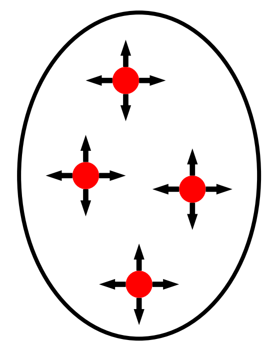


- Shape frozen in crossing time ($<10^{-24}$s), probe entire mass distribution via multi-point correlations.



Collective flow response to nuclear structure





$$S(\mathbf{s}_1, \mathbf{s}_2) \equiv \langle \delta\rho(\mathbf{s}_1)\delta\rho(\mathbf{s}_2)\rangle$$
$$= \langle \rho(\mathbf{s}_1)\rho(\mathbf{s}_2)\rangle - \langle \rho(\mathbf{s}_1)\rangle\langle \rho(\mathbf{s}_2)\rangle.$$

High-order fluctuations

- In principle, can measure any moments of p(1/R, ε_2, ε_3…)
  - Mean $\langle d_\perp \rangle$ → $\langle p_T \rangle$
  - Variances: $\langle \varepsilon_n^2 \rangle$, $\left\langle (\delta d_\perp/d_\perp)^2 \right\rangle$ $d_\perp \equiv 1/R_\perp$ → $\langle v_n^2 \rangle$, $\left\langle (\delta p_T/p_T)^2 \right\rangle$
  - Skewness $\langle \varepsilon_n^2 \delta d_\perp/d_\perp \rangle$, $\left\langle (\delta d_\perp/d_\perp)^3 \right\rangle$ → $\langle v_n^2 \delta p_T/p_T \rangle$, $\left\langle (\delta p_T/p_T)^3 \right\rangle$
  - Kurtosis $\langle \varepsilon_n^4 \rangle - 2\langle \varepsilon_n^2 \rangle^2$, $\left\langle (\delta d_\perp/d_\perp)^4 \right\rangle - 3\left\langle (\delta d_\perp/d_\perp)^2 \right\rangle^2$ → $\langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2$, $\left\langle (\delta p_T/p_T)^4 \right\rangle - 3\left\langle (\delta p_T/p_T)^2 \right\rangle^2$

    …

- All with rather simple connection to deformation, for example:
  - Variances

$$\langle \varepsilon_2^2 \rangle \sim a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2$$
$$\langle \varepsilon_3^2 \rangle \sim a_3 + b_3\beta_3^2$$
$$\langle \varepsilon_4^2 \rangle \sim a_4 + b_4\beta_4^2 + b_{4,2}\beta_2^2$$
$$\langle (\delta d_\perp/d_\perp)^2 \rangle \sim a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

  - Skewness

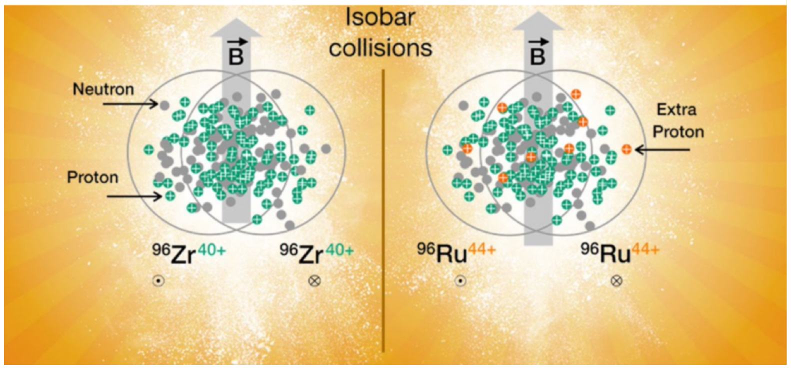
$$\left\langle \varepsilon_2^2 \delta d_\perp/d_\perp \right\rangle \sim a_1 - b_1\cos(3\gamma)\beta_2^3$$
$$\left\langle (\delta d_\perp/d_\perp)^3 \right\rangle \sim a_2 + b_2\cos(3\gamma)\beta_2^3$$

  - Kurtosis

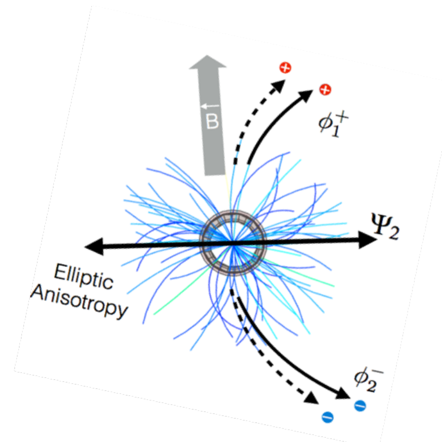
$$\left\langle \varepsilon_2^4 \right\rangle - 2\left\langle \varepsilon_2^2 \right\rangle^2 \sim a_3 - b_3\beta_2^4$$
$$\left\langle (\delta d_\perp/d_\perp)^4 \right\rangle - 3\left\langle (\delta d_\perp/d_\perp)^2 \right\rangle^2 \sim a_4 - b_4\beta_2^4$$

Isobar collisions at RHIC: a precision tool

	Z	N	mass
96Ru	44	52	95.907598(8)
96Zr	40	56	95.908273(3)



arXiv:2109.00131



Voloshin, hep-ph/0406311

- Designed to search for the chiral magnetic effect: strong P & CP violation of QCD in the presence of EM field. Turns out the CME signal is small, and isobar-differences are dominated by the nuclear structure differences.

- <0.4% precision is achieved in ratio of many observables between ^{96}Ru+ ^{96}Ru and ^{96}Zr+^{96}Zr systems→ a precision imaging tool

Isobar collisions at RHIC: a precision tool

- A key question for any HI observable O:

$$\boxed{\frac{O_{^{96}\mathrm{Ru}+^{96}\mathrm{Ru}}}{O_{^{96}\mathrm{Zr}+^{96}\mathrm{Zr}}} \stackrel{?}{=} 1}$$

Deviation from 1 must has origin in the nuclear structure, which impacts the initial state and then survives to the final state.

Isobar collisions at RHIC: a precision tool

- A key question for any HI observable O:

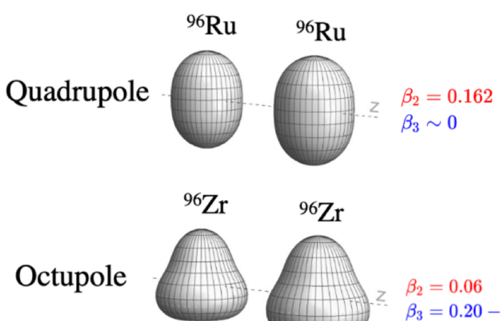
$$\boxed{\frac{O_{^{96}\mathrm{Ru}+^{96}\mathrm{Ru}}}{O_{^{96}\mathrm{Zr}+^{96}\mathrm{Zr}}} \stackrel{?}{=} 1}$$

Deviation from 1 must has origin in the nuclear structure, which impacts the initial state and then survives to the final state.

- Expectation

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

2109.00131



J. Jia, aXiv:2106.08768

$$\mathcal{O} \approx b_0 + b_1\beta_2^2 + b_2\beta_3^2 + b_3(R_0 - R_{0,\mathrm{ref}}) + b_4(a - a_{\mathrm{ref}})$$

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

Only probes isobar differences

Sly4

Species	β_2	β_3	a_0	R_0
Ru	0.162	0	0.46 fm	5.09 fm
Zr	0.06	0.20	0.52 fm	5.02 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

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

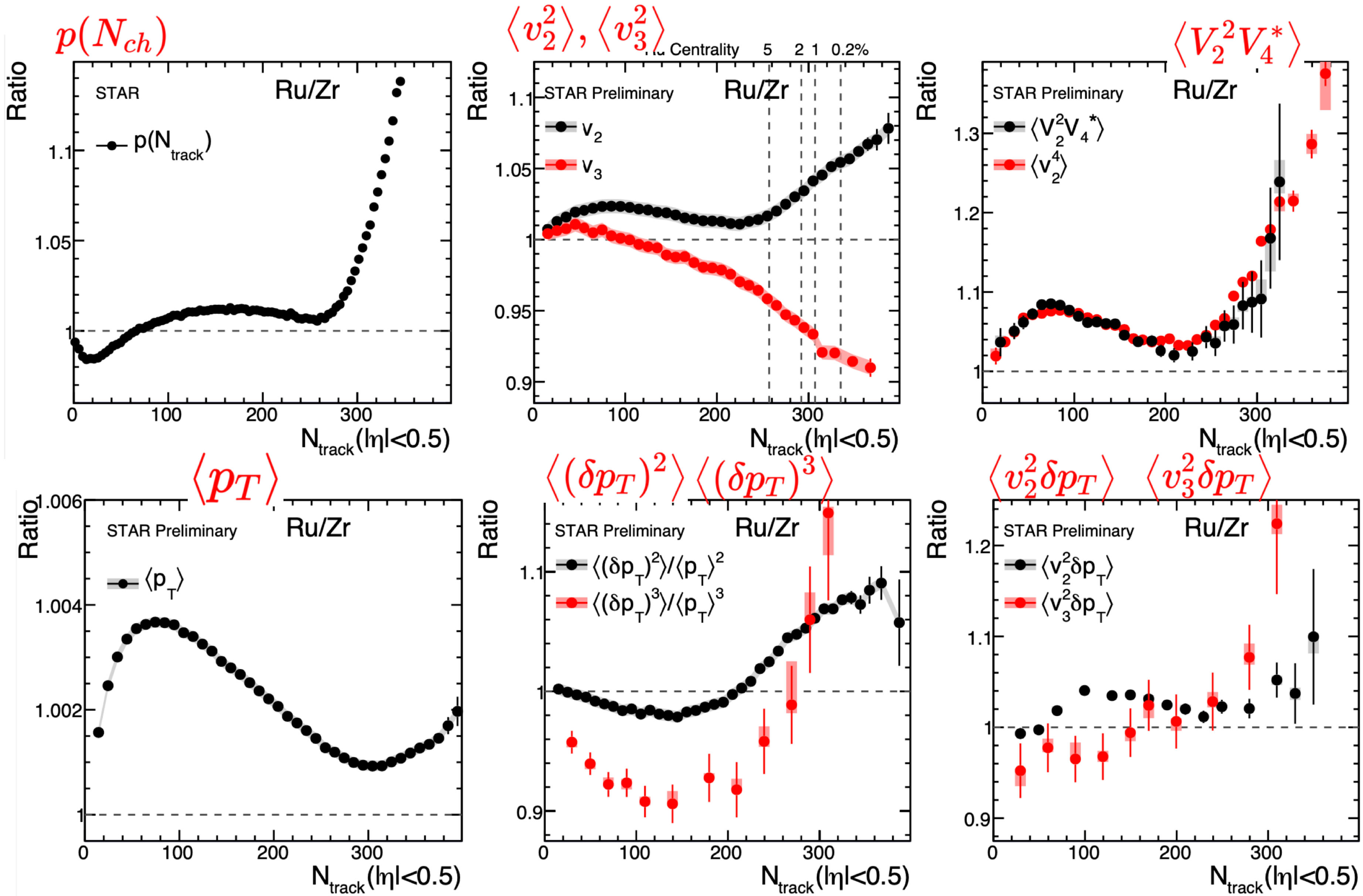
charge

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

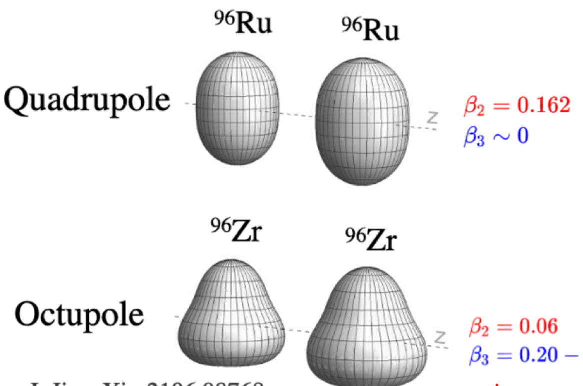
mass

Structure influences everywhere

$$\boxed{R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}}}$$



Nuclear structure via v_2-ratio and v_3-ratio



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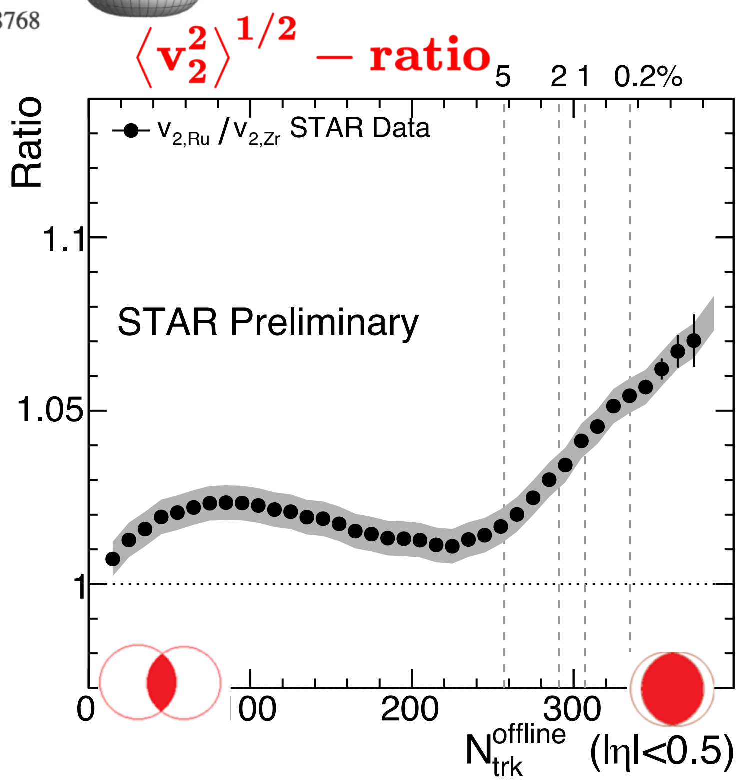
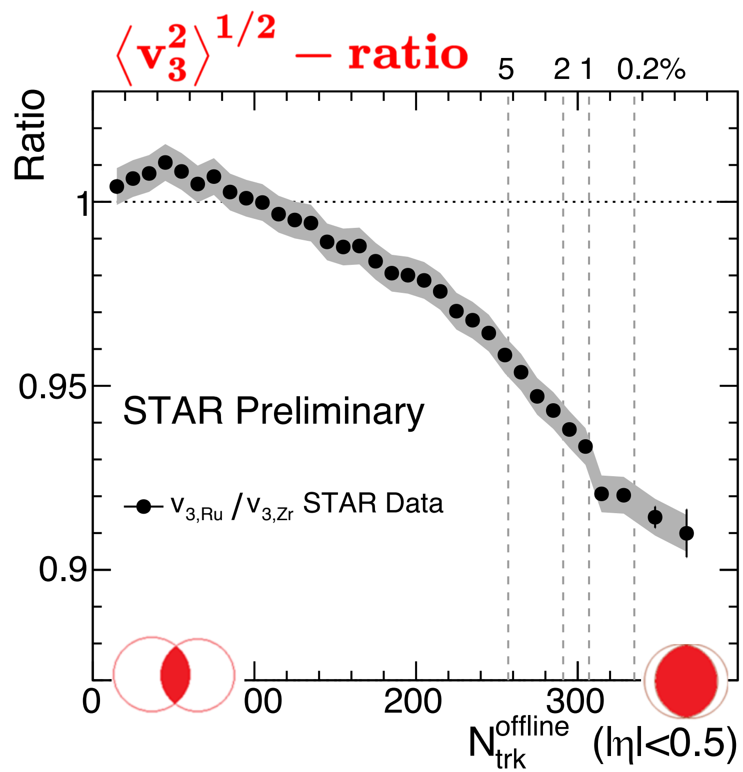
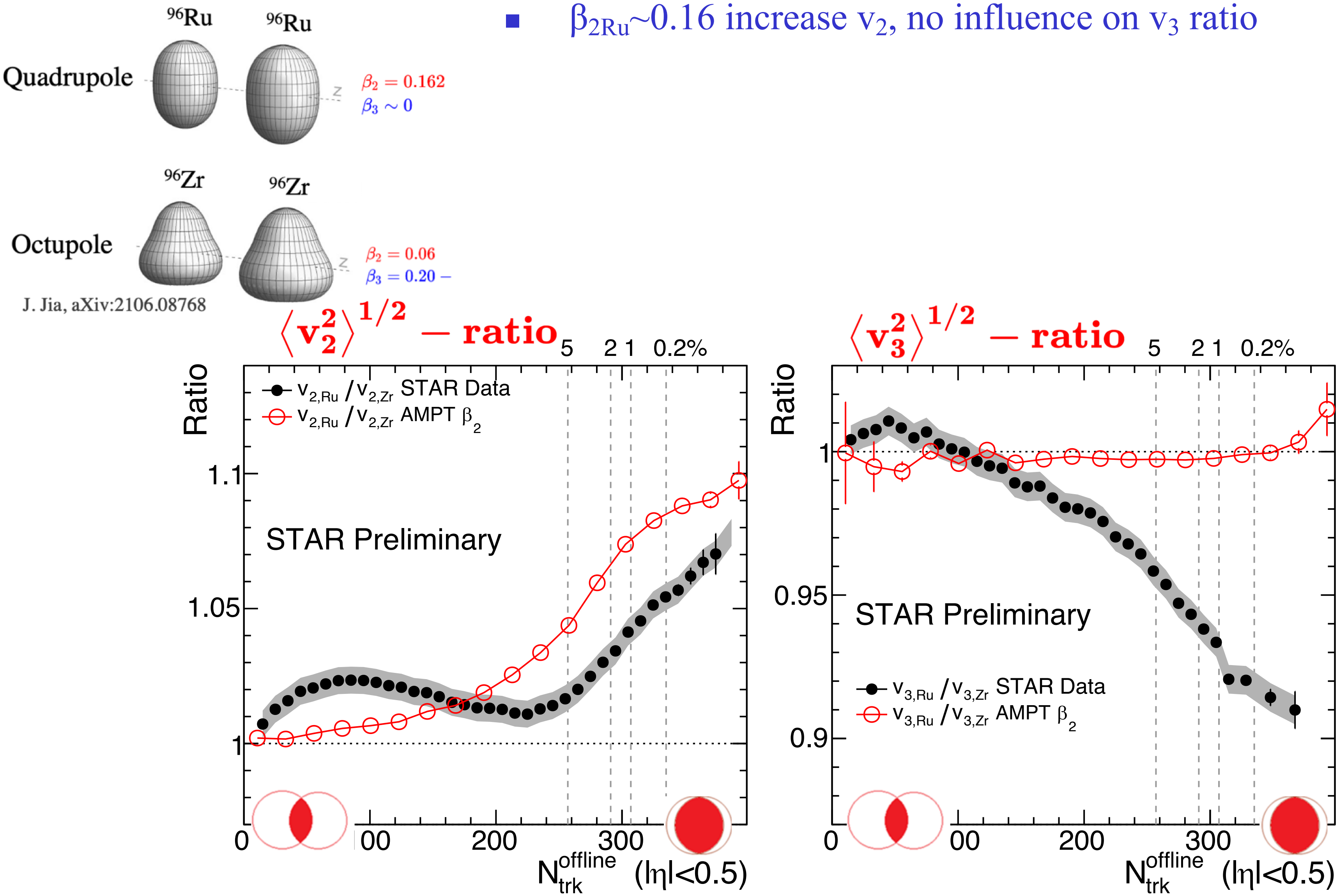




Compare to calculation from AMPT transport model

Nuclear structure via v_2-ratio and v_3-ratio

- β_{2Ru}~0.16 increase v_2, no influence on v_3 ratio



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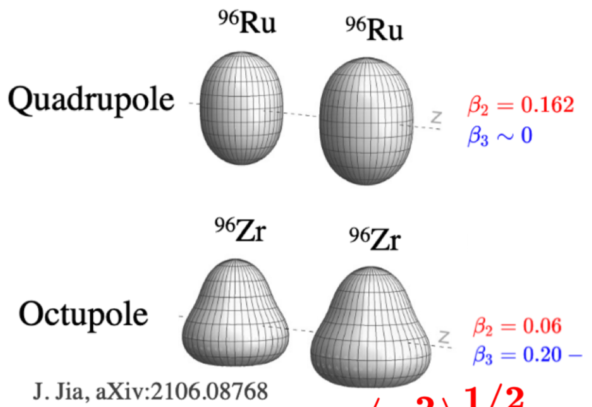
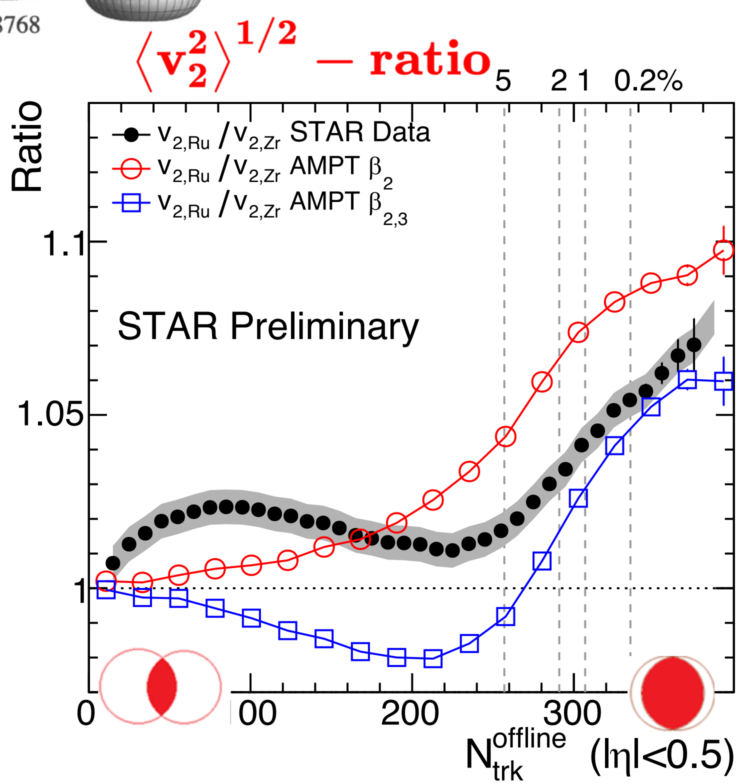
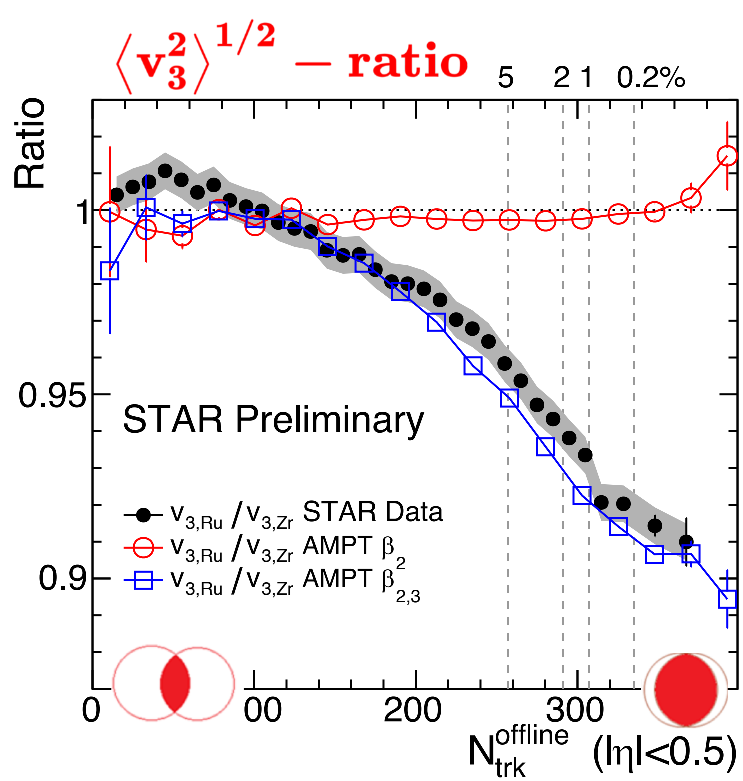


- β_{2Ru}~0.16 increase v_2, no influence on v_3 ratio
- β_{3Zr}~0.2 decrease v_2 in mid-central, decrease v_3 ratio





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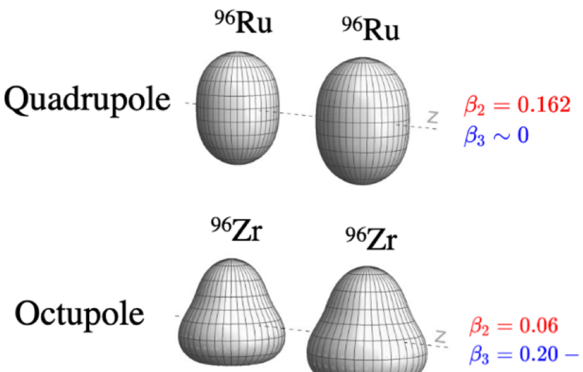
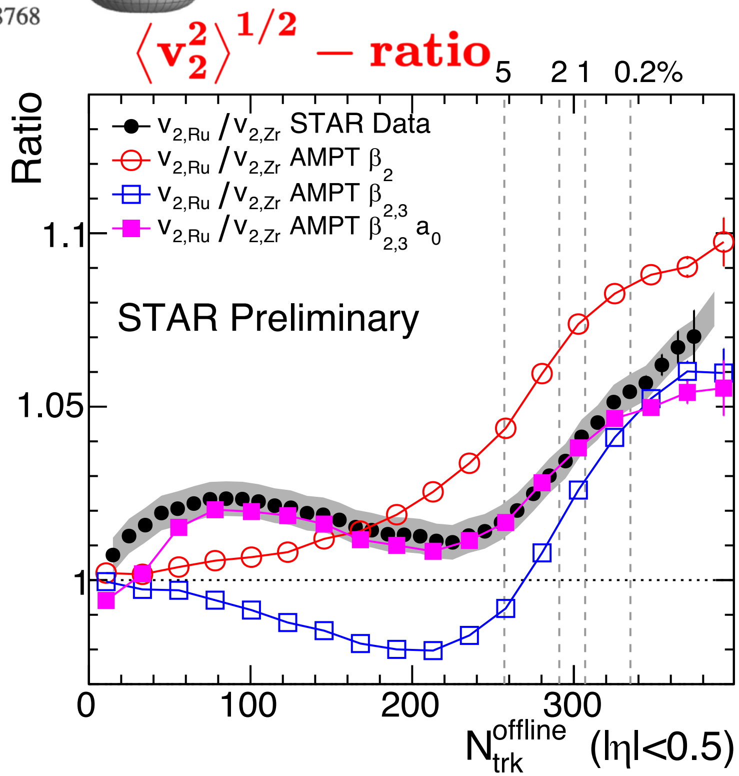
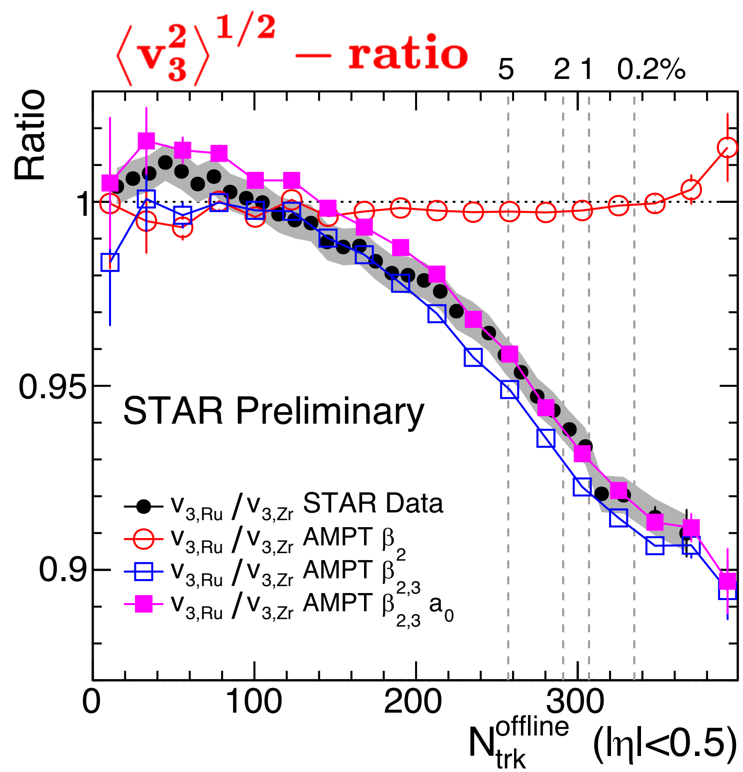


J. Jia, aXiv:2106.08768

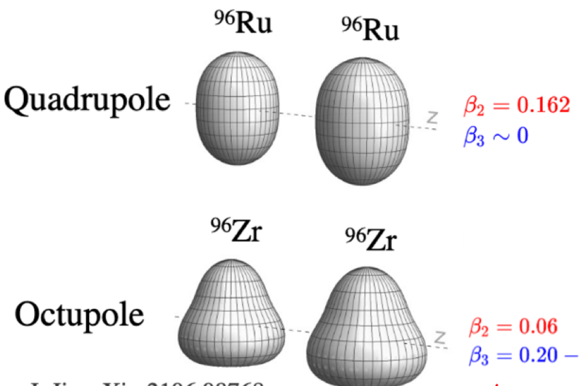
- β_{2Ru}~0.16 increase v_2, no influence on v_3 ratio
- β_{3Zr}~0.2 decrease v_2 in mid-central, decrease v_3 ratio
- Δa_0= -0.06fm increase v_2 mid-central, small influ. on v_3.





Compare to calculation from AMPT transport model

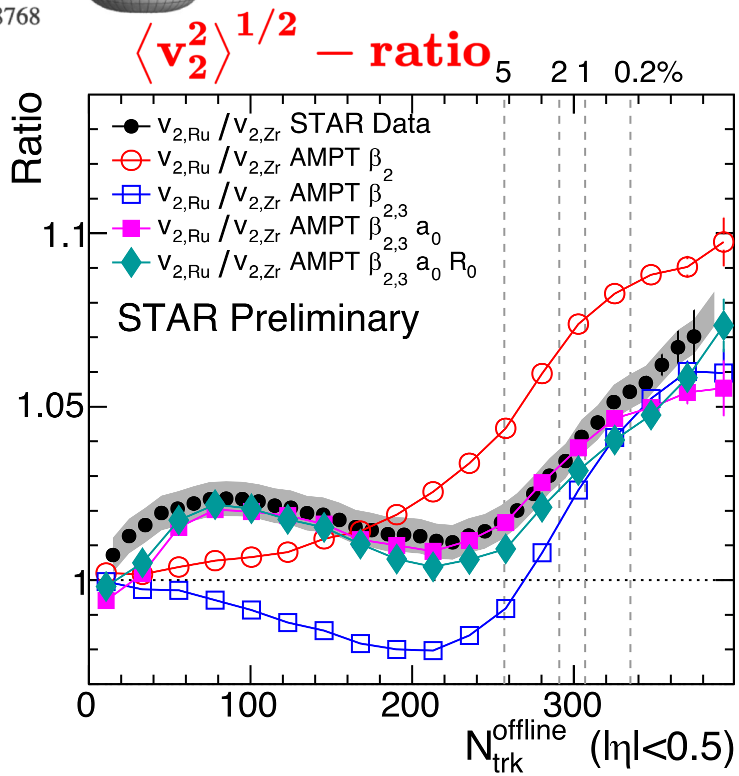
Nuclear structure via v_2-ratio and v_3-ratio

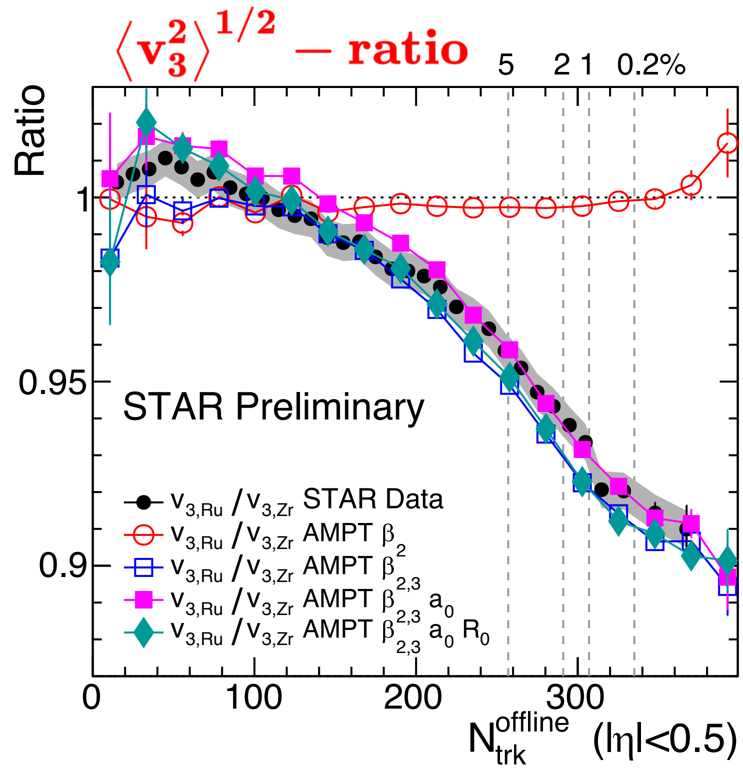


J. Jia, aXiv:2106.08768

- 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.

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

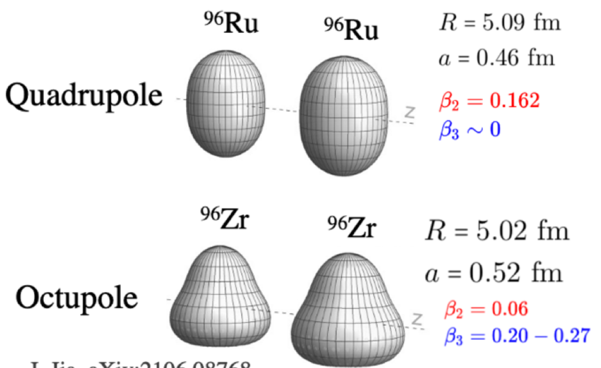




Simultaneously constrain these parameters using different N_{ch} regions

Nuclear structure via $p(N_{ch})$, $\langle p_T \rangle$-ratio

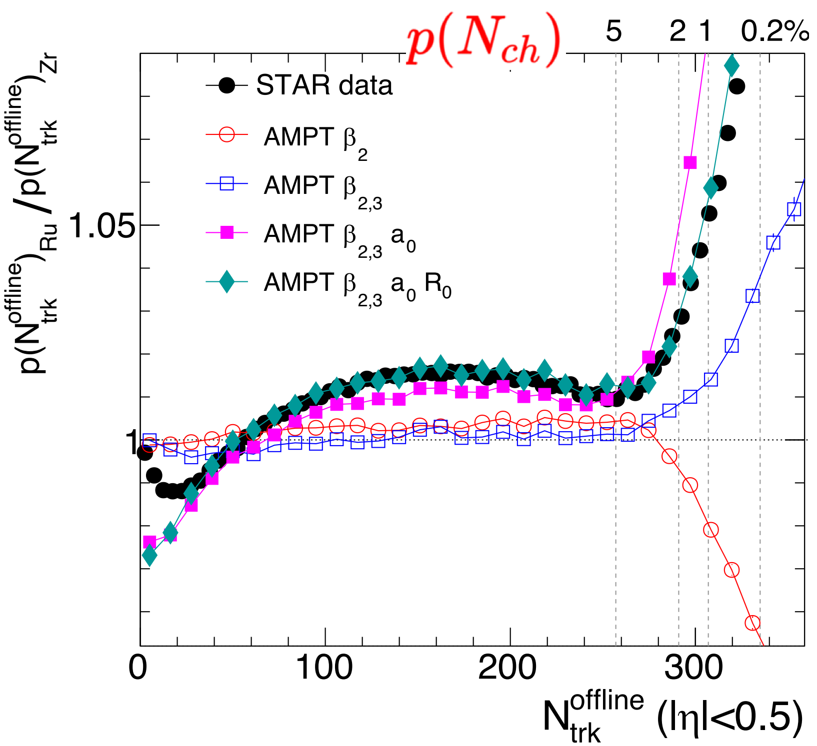
Earlier studies on this from H.Li, H.J Xu, PRL125, 222301 (2020) arXiv:2111.14812



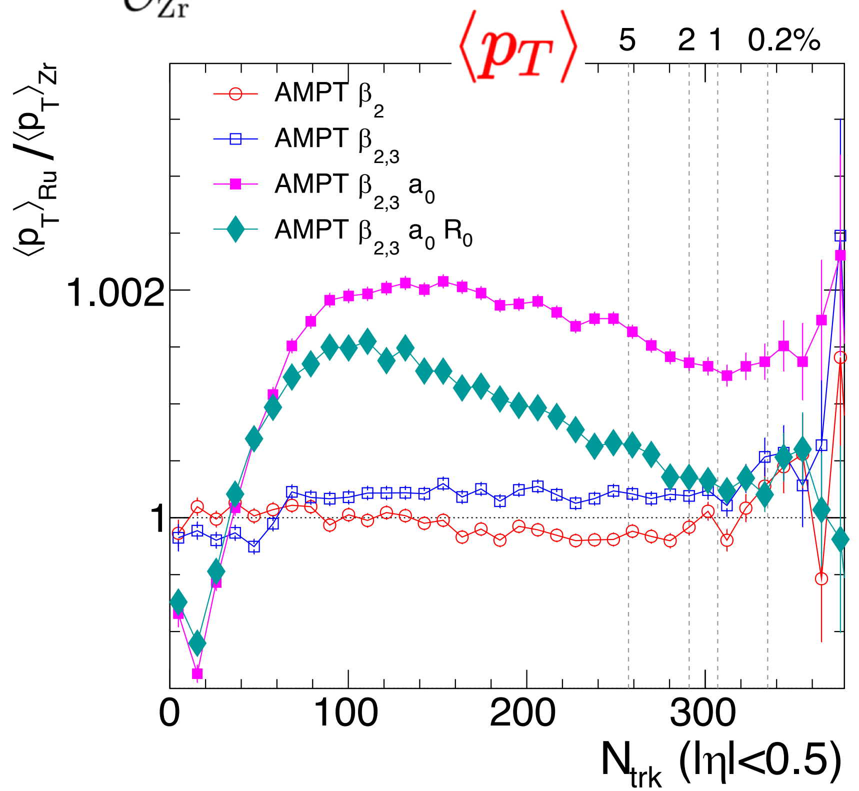
J. Jia, aXiv:2106.08768

- For N_{ch} 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 $\langle p_T \rangle$ ratio:
  - Strong influence from Δa_0 and ΔR_0

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

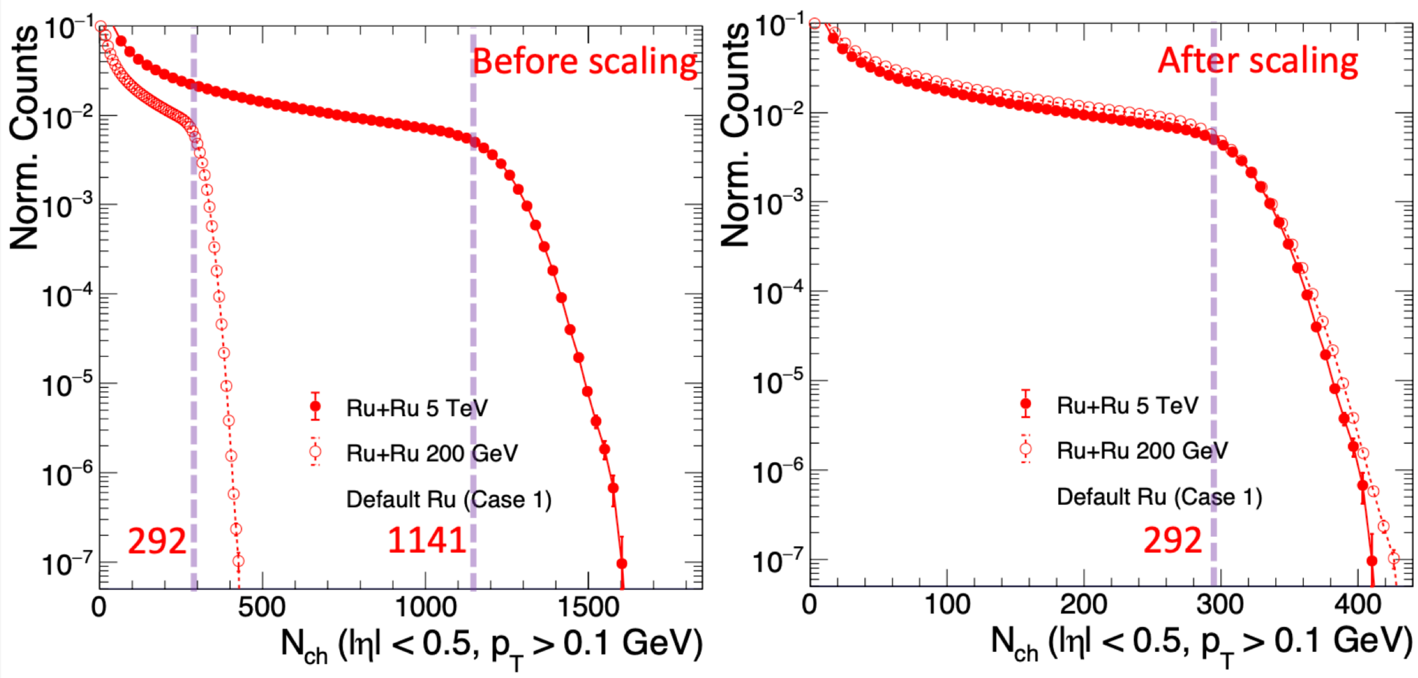


Δa_0 and ΔR_0 influences add up



Δa_0 and ΔR_0 influences partially cancel

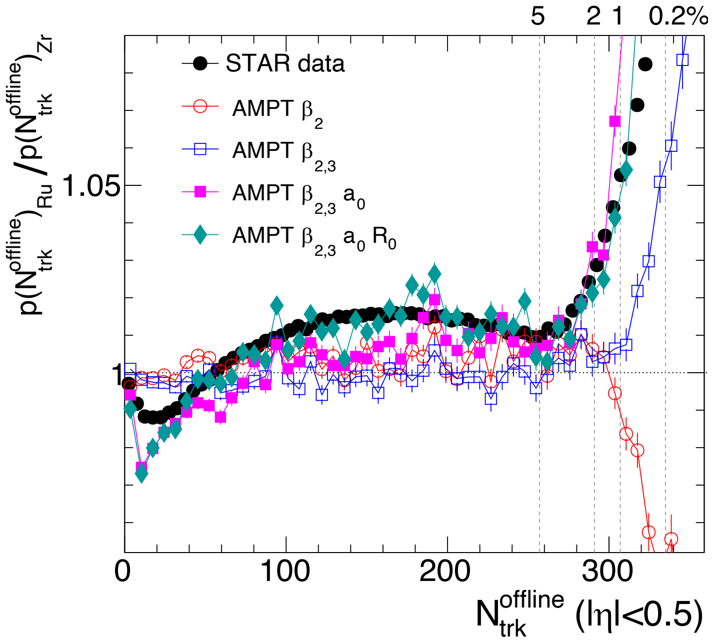
Energy dependence: RHIC vs LHC



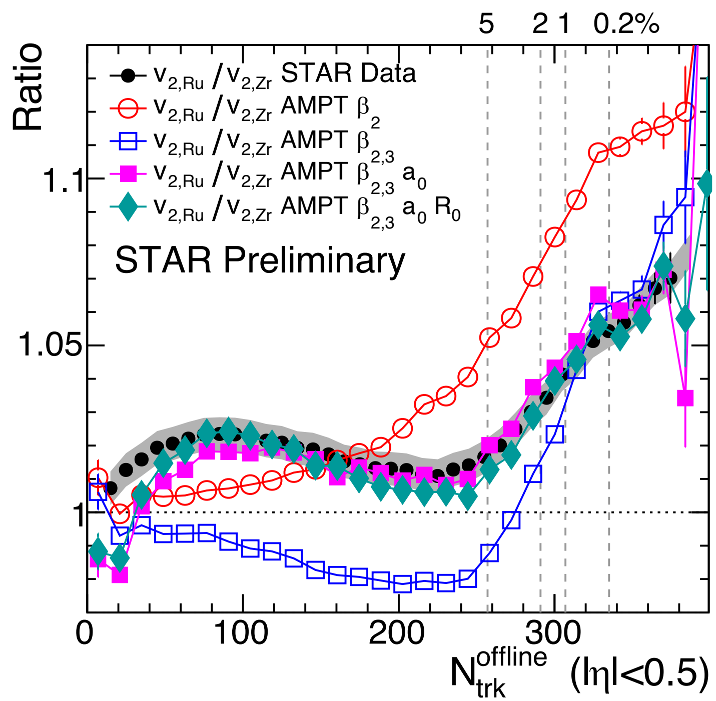
- x3 more particle density at $\sqrt{s_{NN}}$=5 TeV compare to 0.2 TeV
- But the shape after rescaling looks quite similar → collision geometry

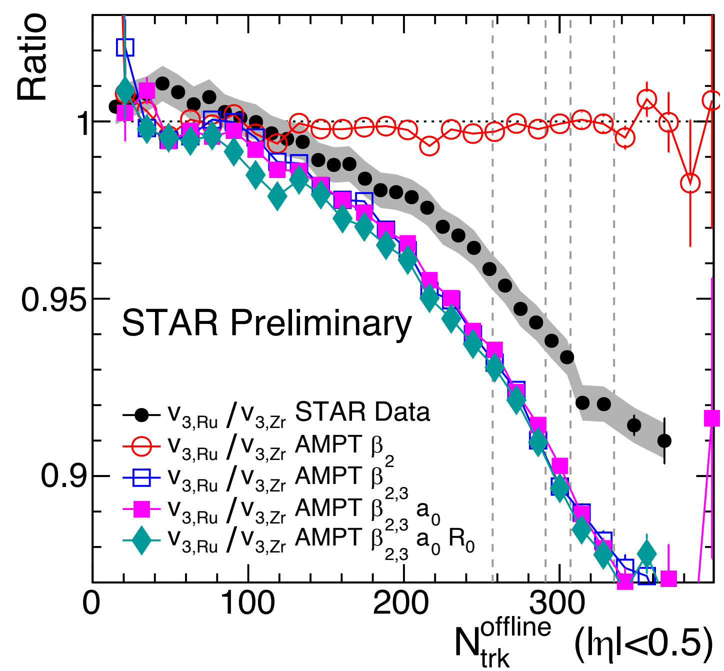
Results at LHC at 5 TeV

- The influence of nuclear shape and skin play similar role for $p(N_{ch})$ and v_2
- But stronger impact of $\boldsymbol{\beta}_3$ on v_3 😮
- Initial condition is $\sqrt{s}$ dependent: AMPT has nPDF and toy saturation effects implemented via p_0 and Lund parameters.



AMPT model





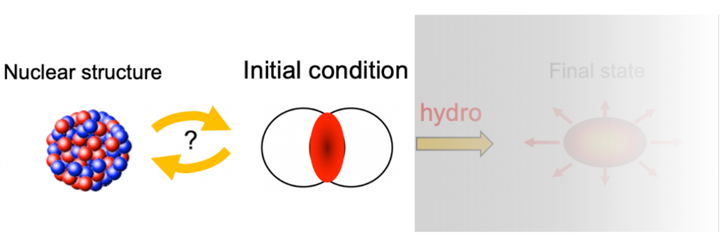
Isobar ratios not affected by final state

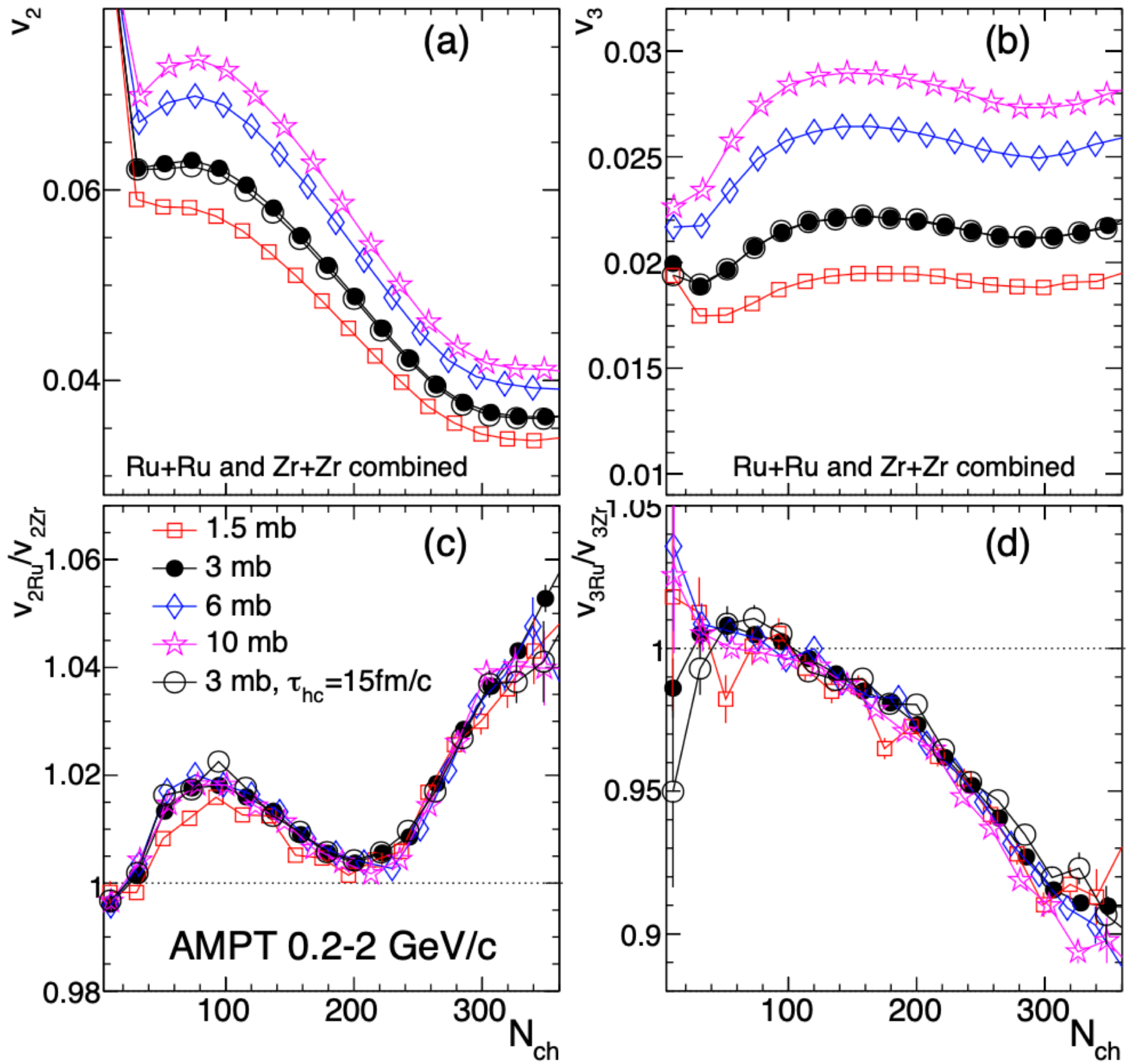
- Vary the shear viscosity via partonic cross-section
  - Flow signal change by 30-50%, the v_n ratio unchanged.

$$v_n = k_n \varepsilon_n$$

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

Robust probe of initial condition!





Isobar to constrain initial condition

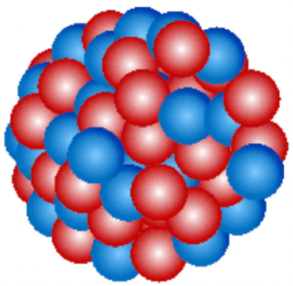
$$e(x,y) \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{q/p}$$

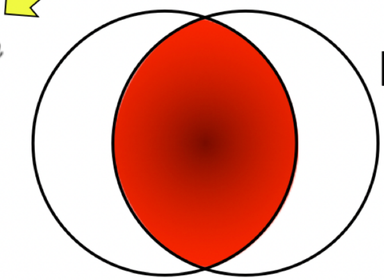
$$c_0\Delta\beta_2^2 + c_1\Delta\beta_3^2 + c_2\Delta R_0 + c_3\Delta a_0 \approx \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} - 1$$

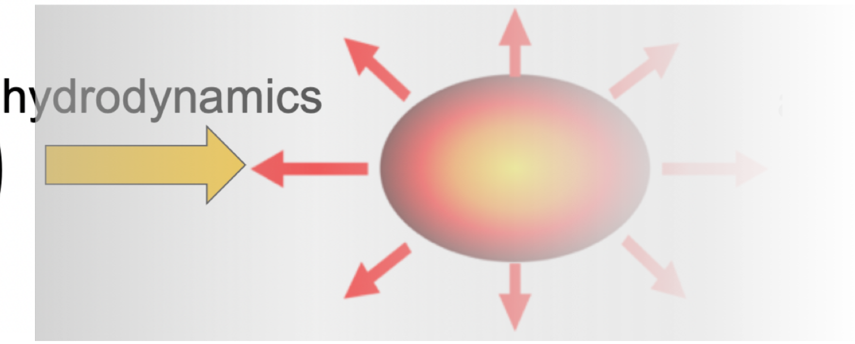
c_n relates nuclear structure and initial condition

$$T_A(x,y) = \int \rho(x,y,z)dz$$

$$p, q \Leftarrow c_n$$







Nuclear structure

Initial condition

Final state

- Different ways of depositing energy $T \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{q/p}$

$$e(x,y) \sim \begin{cases} T_A + T_B & N_{\mathrm{part}} - \text{scaling}, p = 1 \\ T_A T_B & N_{\mathrm{coll}} - \text{scaling}, p = 0, q = 2 \\ \sqrt{T_A T_B} & \text{Trento default}, p = 0 \\ \min\{T_A, T_B\} & \text{KLN model}, p \sim -2/3 \\ T_A + T_B + \alpha T_A T_B & \text{two-component model,} \\ & \text{similar to quark-glauber model} \end{cases}$$

Use nuclear structure as extra lever-arm for initial condition

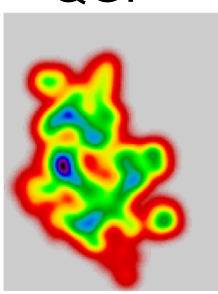
Exploiting the structure lever-arm

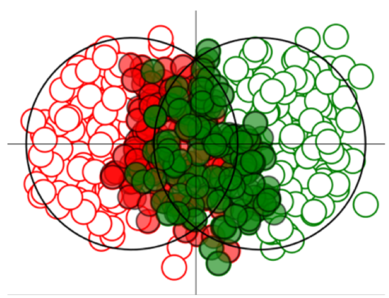
Flow observable = k $\otimes$ initial condition (structure)

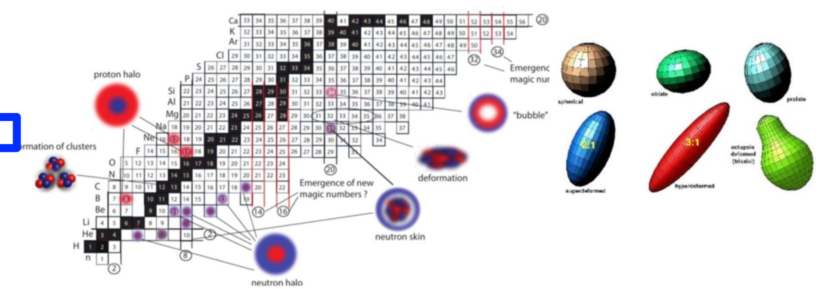
QGP response,
a smooth function of N+Z

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

QGP



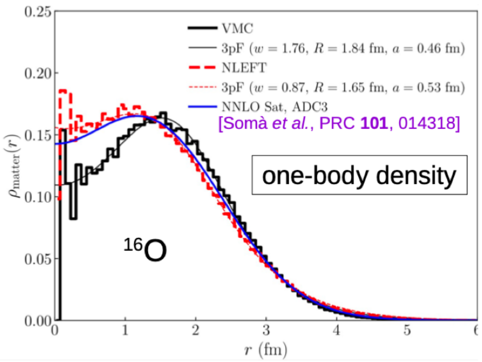


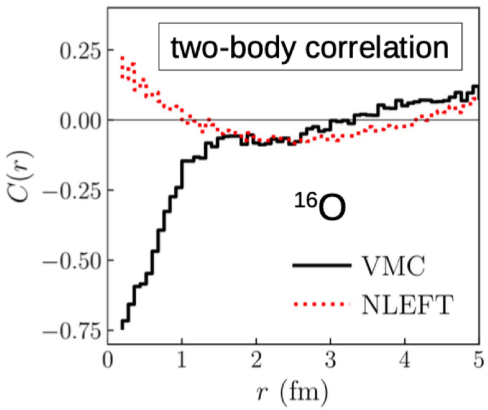


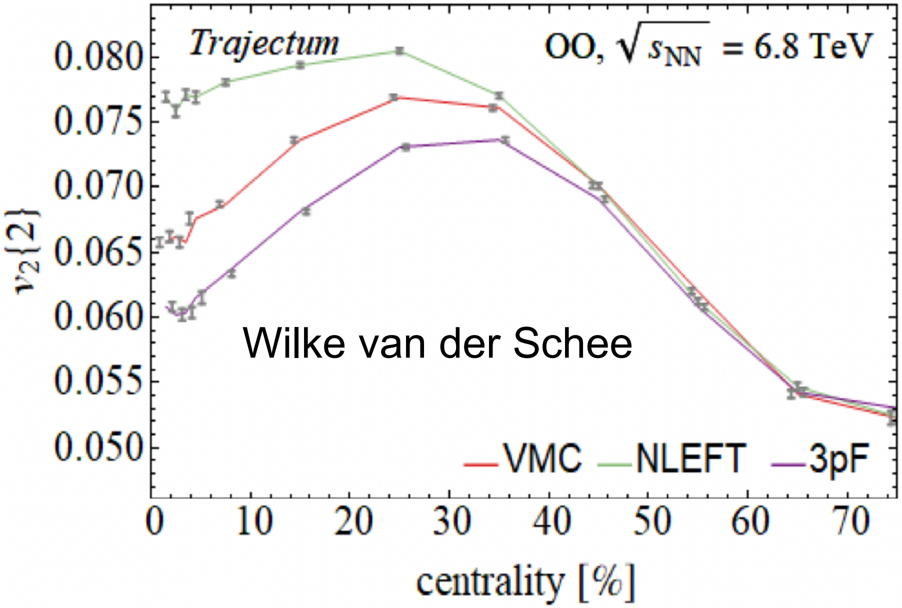
Example: Nuclear structure effects in light nuclei

Flow in $^{16}O+^{16}O$ could be sensitive to SRC, clustering, but difficult to isolate due to lack of baseline.

VMC: cluster Variational Monte Carlo
NLEFT: Nuclear Lattice Effective Field Theory







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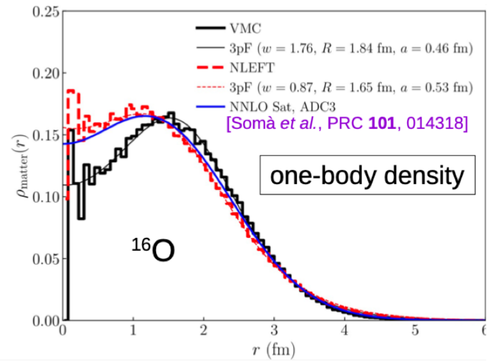
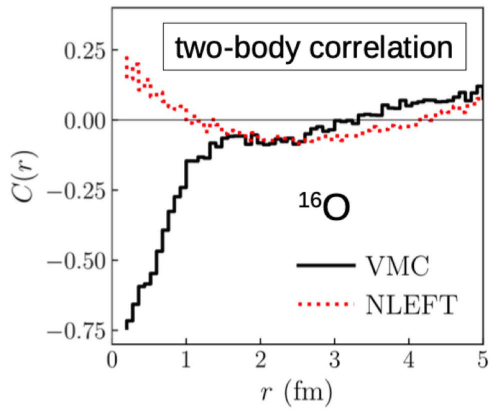
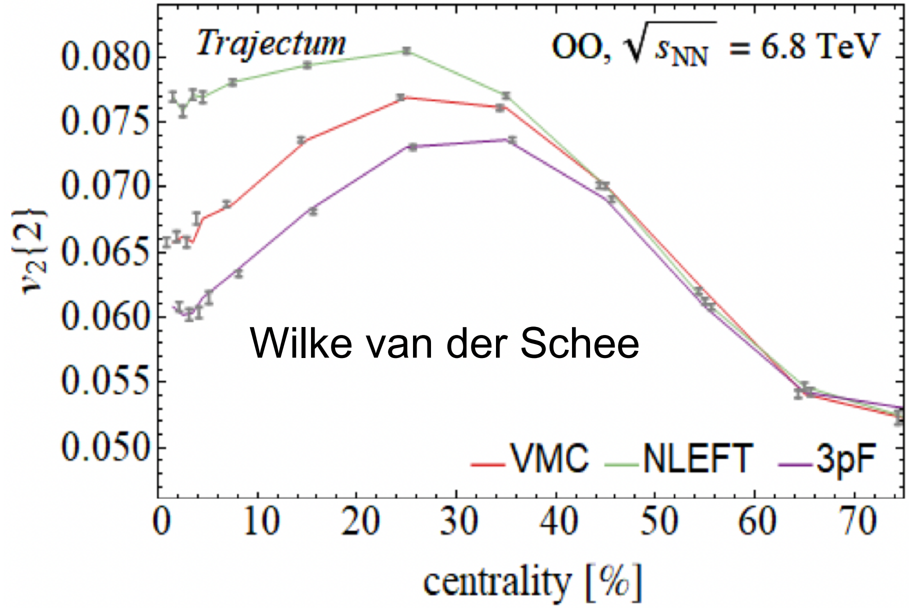
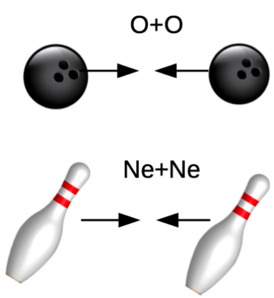
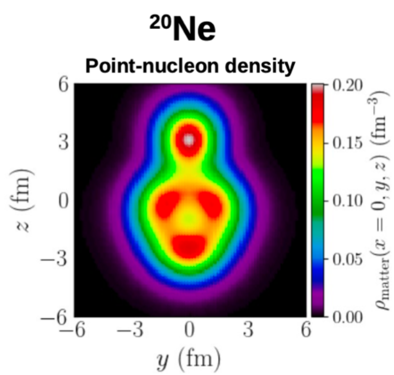
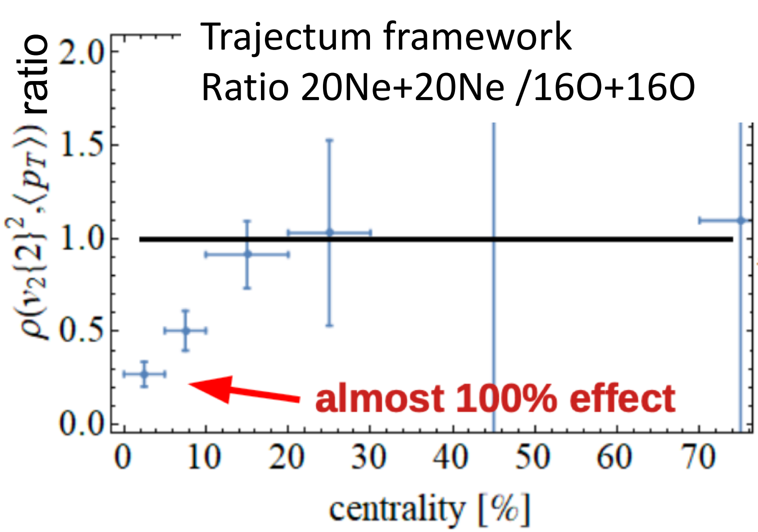








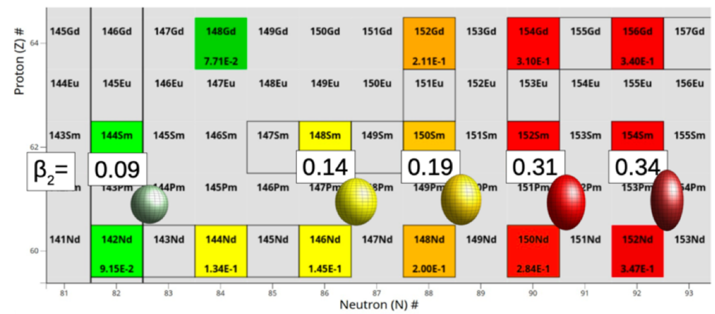




^{20}Ne with 5 alpha has the most extreme ground state shape: $\beta_2 \sim 0.7$, Use O+O and Ne+Ne to observe "strong" geometric effects at dN/dy~100.

Example: shape evolution of $^{144-154}$Sm isotopic chain

Transition from nearly-spherical to well-deformed nuclei when size increase by less than 7%. Using HI to access the multi-nucleon correlations leading to such shape evolution, as well as dynamical β_3 and β_4 shape fluctuations (in addition to initial condition)

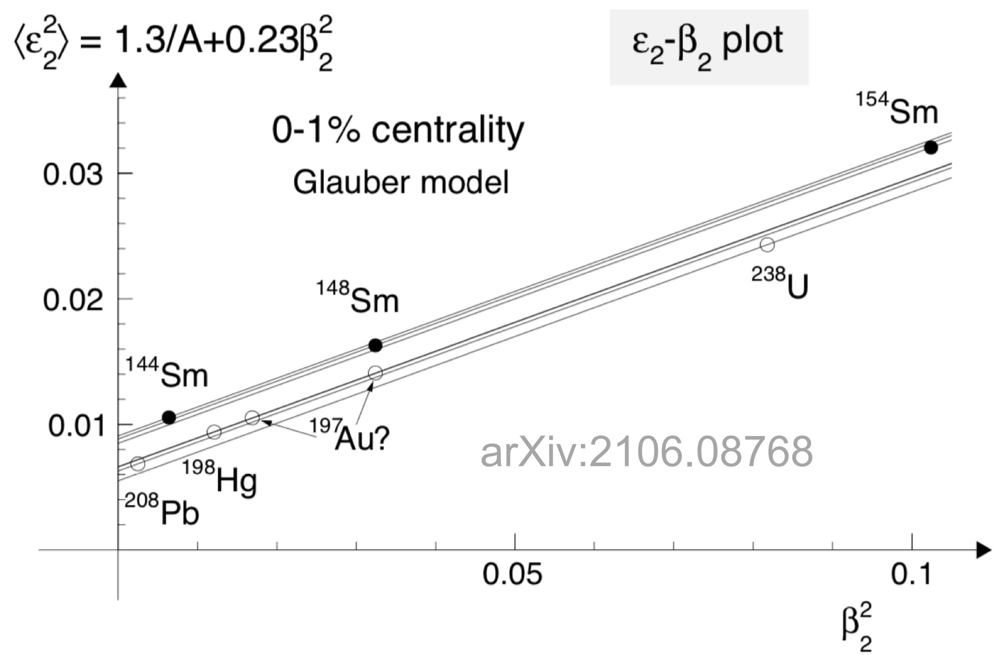


In central collisions

$$\left\langle \epsilon_2^2 \right\rangle = a' + b'\beta_2^2 \qquad a' = \langle \varepsilon_2^2 \rangle_{|\beta_2=0} \propto 1/A$$

$$\left\langle v_2^2 \right\rangle = a + b\beta_2^2 \qquad a = \langle v_2^2 \rangle_{|\beta_2=0} \propto 1/A$$

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 predict others.

Application in ^{197}Au+^{197}Au vs ^{238}U+^{238}U

arXiv:2105.01638

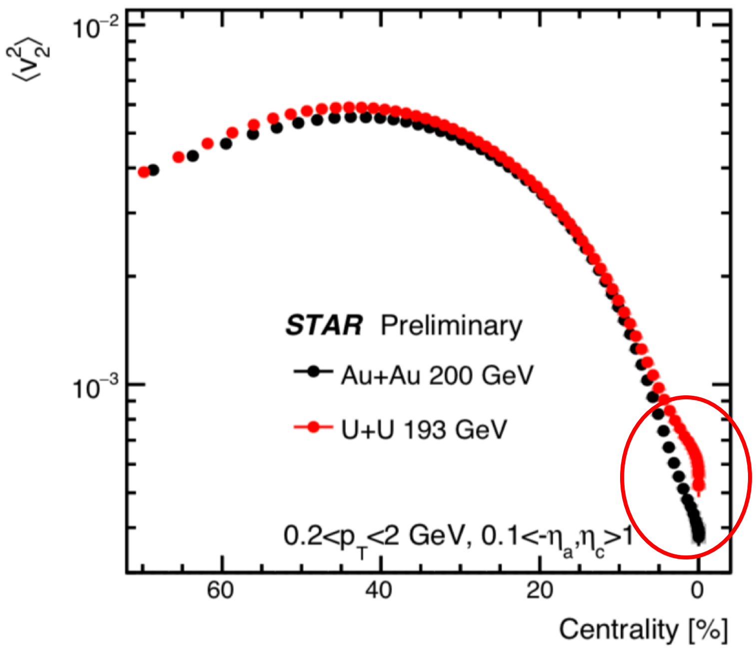
Ultra-central Collisions at $\sqrt{s_{NN}}$=193-200 GeV

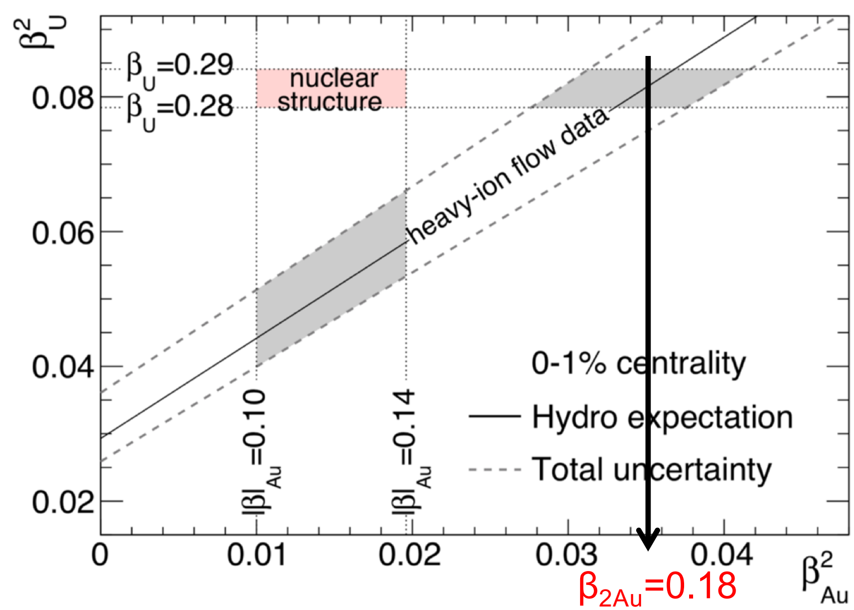
$$\begin{cases} v_{2,\mathrm{Au}}^2 = a_{\mathrm{Au}} + b\beta_{2,\mathrm{Au}}^2 \\ v_{2,\mathrm{U}}^2 = a_{\mathrm{U}} + b\beta_{2,\mathrm{U}}^2 \end{cases}$$

b~0.014

Need to correct for slightly different size: $a \propto 1/A\,,\quad r_a = \frac{a_{\mathrm{Au}}}{a_{\mathrm{U}}} = \frac{238}{197} = 1.21$

A linear relation for β_{2U} and β_{2Au} : $\beta_{\mathrm{U}}^2 = \frac{r_{v_2^2} r_a - 1}{b/a_{\mathrm{U}}} + r_{v_2^2}\beta_{\mathrm{Au}}^2 \quad r_{v_2^2} = \frac{v_{2,\mathrm{U}}^2}{v_{2,\mathrm{Au}}^2}$





Suggests $|\beta_2|_{Au}$~0.18+-0.02, larger than NS model of 0.13+-0.02

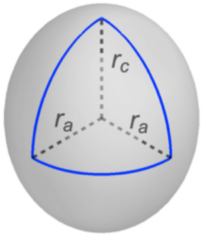
Example:Triaxility

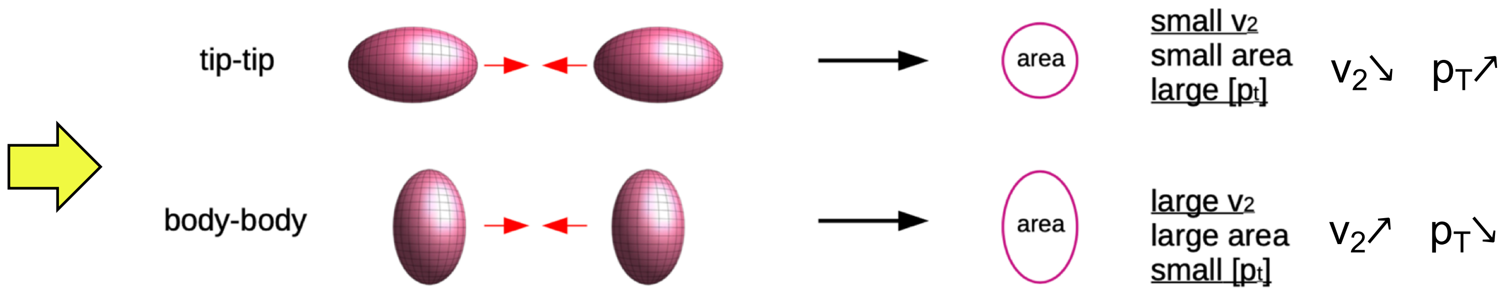
$$R(\theta,\phi) = R_0\Big(1 + \beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}]$$

1910.04673, 2004.14463

Prolate

$\beta_2 = 0.25, \cos(3\gamma) = 1$





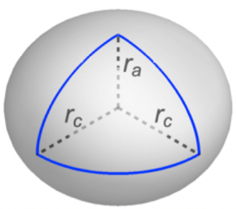
Need 3-point correlators to probe the 3 axes

$$\langle v_2^2\delta p_{\mathrm{T}}\rangle \sim -\beta_2^3\cos(3\gamma) \qquad \langle(\delta p_{\mathrm{T}})^3\rangle \sim \beta_2^3\cos(3\gamma)$$

2109.00604

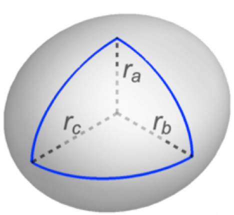
Triaxial

$\beta_2 = 0.25, \cos(3\gamma) = 0$



Oblate

$\beta_2 = 0.25, \cos(3\gamma) = -1$



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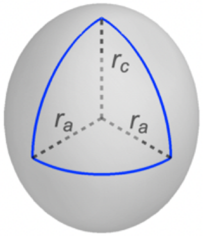

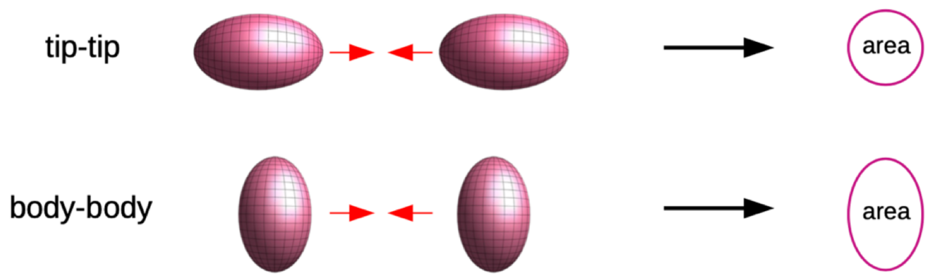

small v_2
small area
large [pt]

$v_2\searrow$ $p_T\nearrow$

large v_2
large area
small [pt]

$v_2\nearrow$ $p_T\searrow$

Need 3-point correlators to probe the 3 axes

$$\left\langle v_2^2 \delta p_{\mathrm{T}}\right\rangle \sim -\beta_2^3 \cos(3\gamma) \qquad \left\langle (\delta p_{\mathrm{T}})^3\right\rangle \sim \beta_2^3 \cos(3\gamma)$$

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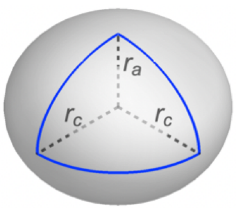

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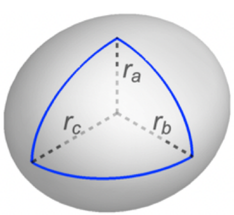
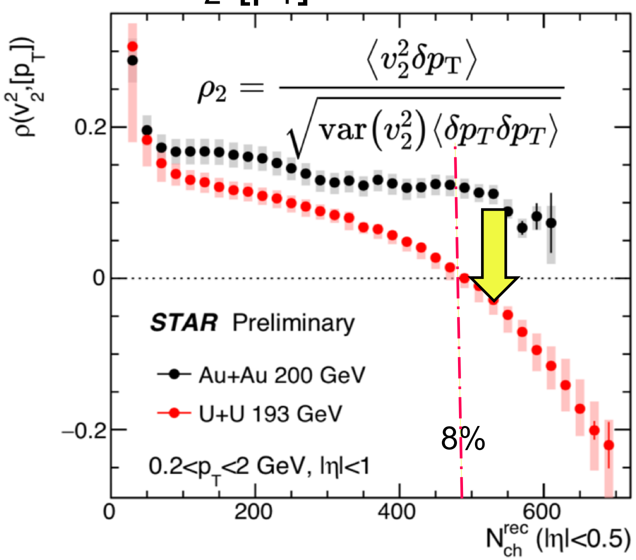
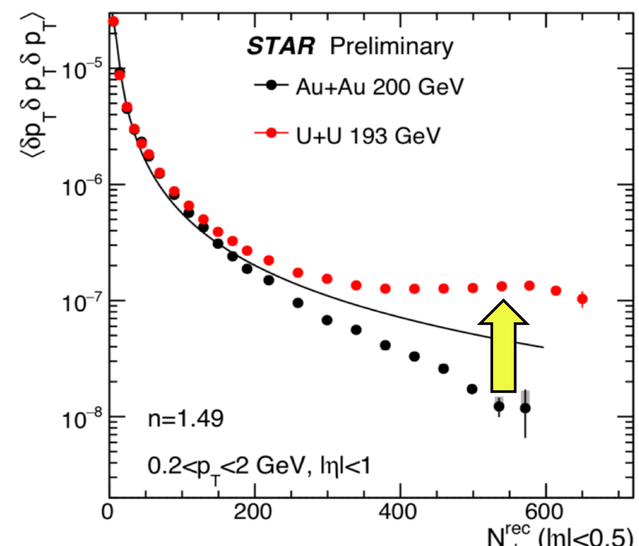


Compare U+U vs Au+Au: β_{2U} ~ 0.28, β_{2Au}~ 0.13:

v_2-[p_T] covariance



[p_T] skewness

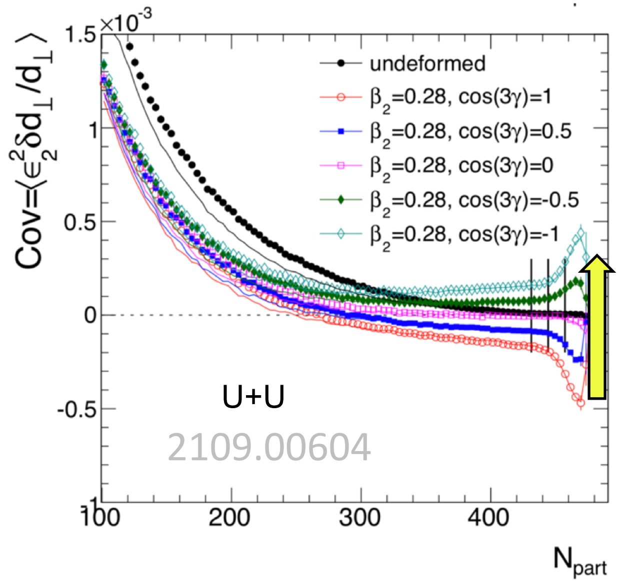


Influence of triaxiality: Glauber model

Skewness sensitive to γ

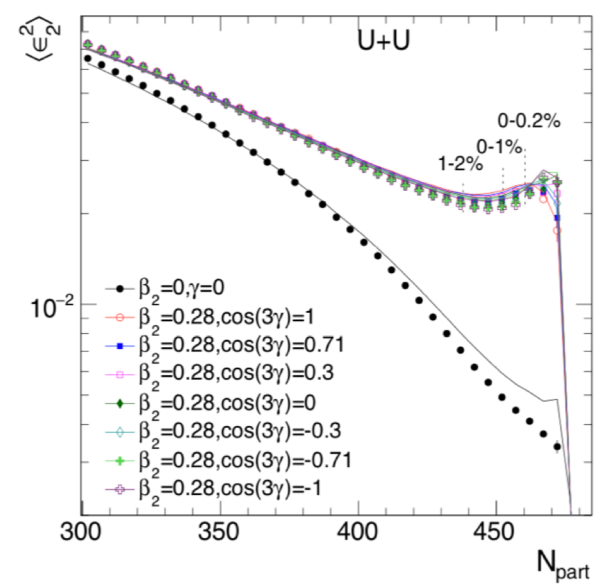
Described by

$$\left\langle \varepsilon_2^2 \frac{\delta d_\perp}{d_\perp} \right\rangle \propto \left\langle v_2^2 \delta p_{\mathrm{T}} \right\rangle \propto a + b\cos(3\gamma)\beta_2^3$$



variances insensitive to γ

$$\left\langle \varepsilon_2^2 \right\rangle \propto \left\langle v_2^2 \right\rangle \propto a + b\beta_2^2$$



Use variance to constrain β_2, use skewness to constrain γ

(β_2,γ) diagram in heavy-ion collisions

The (β_2,γ) dependence in 0-1% U+U Glauber model can be approximated by:

$$d_{\perp} \propto 1/R_{\perp}$$

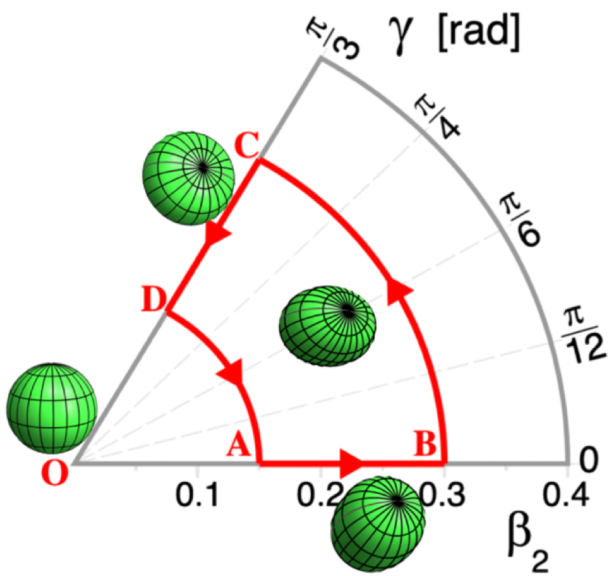
$$\langle \varepsilon_2^2 \rangle \approx [0.02 + \beta_2^2] \times 0.235$$

$$\langle (\delta d_{\perp}/d_{\perp})^2 \rangle \approx [0.035 + \beta_2^2] \times 0.0093$$

$$\langle \varepsilon_2^2 \delta d_{\perp}/d_{\perp} \rangle \approx [0.0005 - (0.07 + 1.36\cos(3\gamma))\beta_2^3] \times 10^{-2}$$

$$\rho = \frac{\langle \varepsilon_2^2 \delta d_{\perp} \rangle}{\langle \varepsilon_2^2 \rangle \sqrt{\langle (\delta d_{\perp})^2 \rangle}}$$

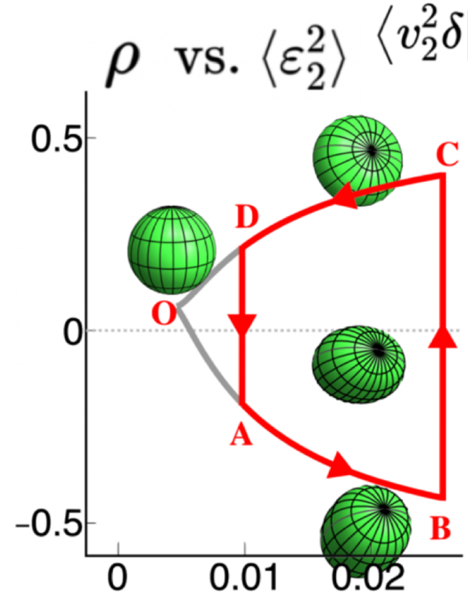
Map from (β_2,γ) plane to HI observables



?

How about

$\langle v_2^2 \delta[p_T] \rangle$ vs. $\langle v_2^2 \rangle$



Collision system scan to map out this trajectory: calibrate coefficients with species with known β,γ, then predict for species of interest.

Summary

- Constrain QGP initial condition with nuclear structure input, important for extraction of QGP properties
- Understanding how initial condition responds to nuclear structure, in turn enables imaging of nuclear structure properties.
- Collisions of carefully-selected isobar species (at LHC) will improve study of initial condition from small to large system

PROGRAM

JANUARY 23 - FEBRUARY 24, 2023

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

INSTITUTE for NUCLEAR THEORY

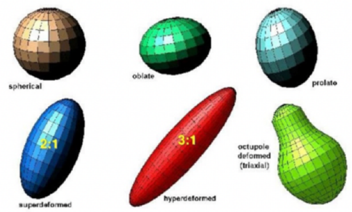
Organizers:
Giuliano Giacalone (Heidelberg)
Jiangyong Jia (Stony Brook & BNL)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Jaki Noronha-Hostler (Urbana-Champaign)
Fuqiang Wang (Purdue)

arXiv:2102.08158

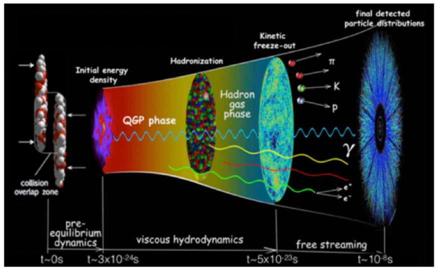
A	isobars	A	isobars	A	isobars
36	Ar, S	106	Pd, Cd	148	Nd, Sm
40	Ca, Ar	108	Pd, Cd	150	Nd, Sm
46	Ca, Ti	110	Pd, Cd	152	Sm, Gd
48	Ca, Ti	112	Cd, Sn	154	Sm, Gd
50	Ti, V, Cr	113	Cd, In	156	Gd, Dy
54	Cr, Fe	114	Cd, Sn	158	Gd, Dy
64	Ni, Zn	115	In, Sn	160	Gd, Dy
70	Zn, Ge	116	Cd, Sn	162	Dy, Er
74	Ge, Se	120	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		

Concluding remarks

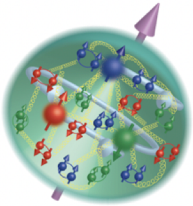
- HI relied on NS and DIS to provide inputs on initial state of A and p.



Nuclear structure



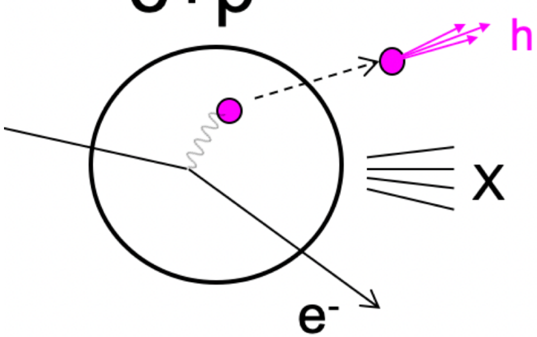
Heavy Ion physics



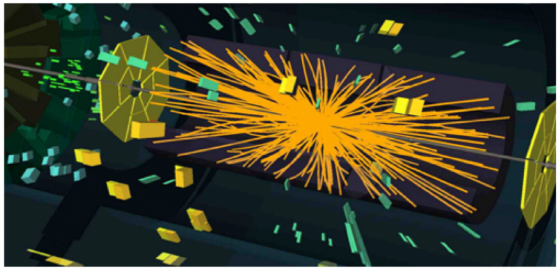
Partonic Structure

- HI physics now is precise enough to feedback to NS and DIS
  - Clearly possible in large A+A system. As understanding of early state improves, might be possible even in small system? Continued analysis & interpretation of HI data is important

e+p



p+p



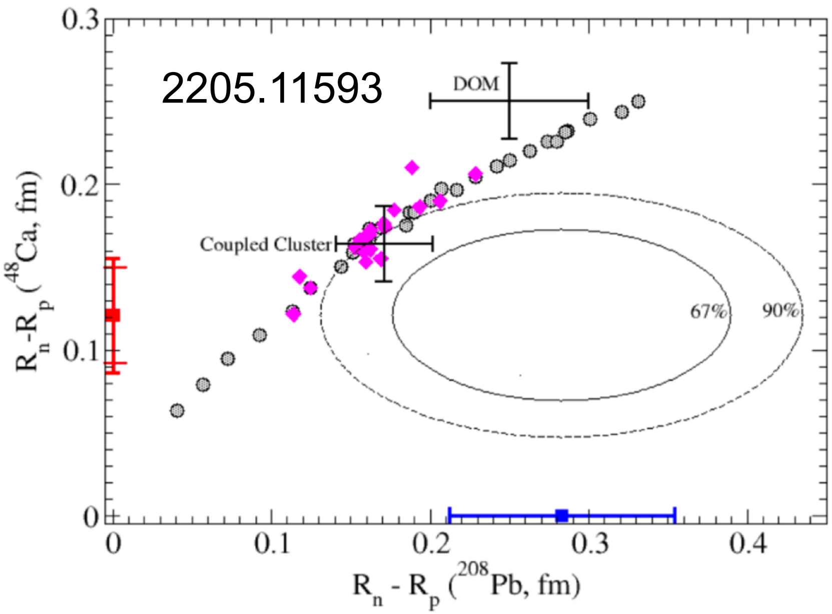
HI-like event ~600 particles

Neutron skin in high-energy collisions

The famous PREX and CREX has tension with theory and previous exp. Indicate a larger L value.

$$\Delta r_{\mathrm{np,Pb}} = 0.28 \pm 0.07\mathrm{fm}$$

$$\Delta r_{\mathrm{np,Ca}} = 0.14 \pm 0.03\mathrm{fm}$$



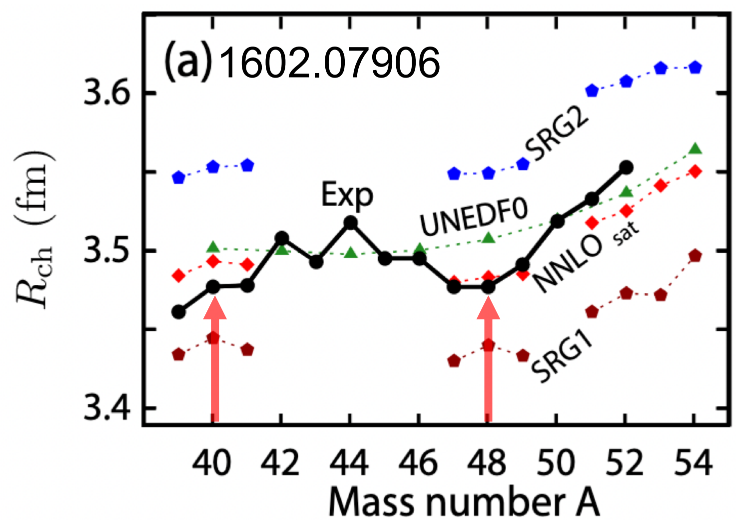
- Access the difference of neutron skin by comparing 40Ca+40Ca and 48Ca+48Ca

We know: $$\sqrt{\langle r_{\mathrm{p}}^2\rangle}(^{48}\mathrm{Ca}) = \sqrt{\langle r_{\mathrm{p}}^2\rangle}(^{40}\mathrm{Ca})$$
$$\sqrt{\langle r_{\mathrm{p}}^2\rangle}(^{40}\mathrm{Ca}) \approx \sqrt{\langle r_{\mathrm{n}}^2\rangle}(^{40}\mathrm{Ca})$$

Hence :

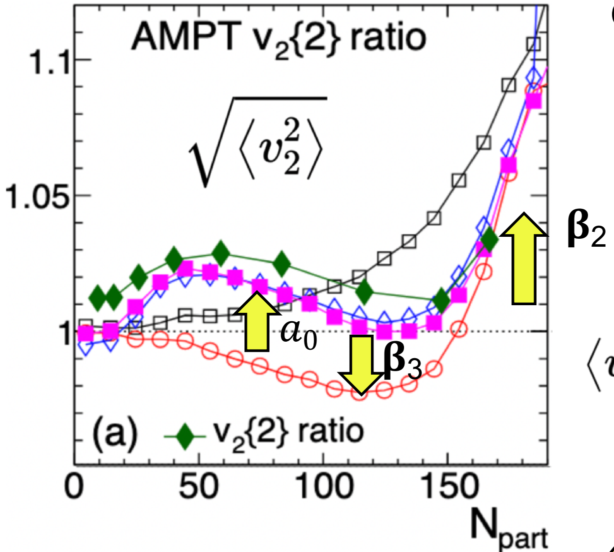
$$\Delta_{\mathrm{np}}(^{48}\mathrm{Ca}) - \Delta_{\mathrm{np}}(^{40}\mathrm{Ca}) \simeq \Delta_{\mathrm{np}}(^{48}\mathrm{Ca})$$

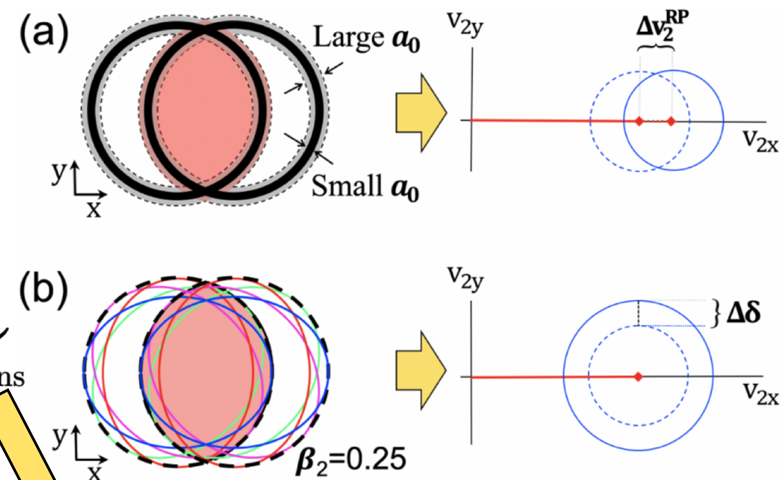
$$\propto \bar{R}_0 \Delta R_0 + 7/3\pi^2 \bar{a}\Delta a$$



Separating shape and size effects

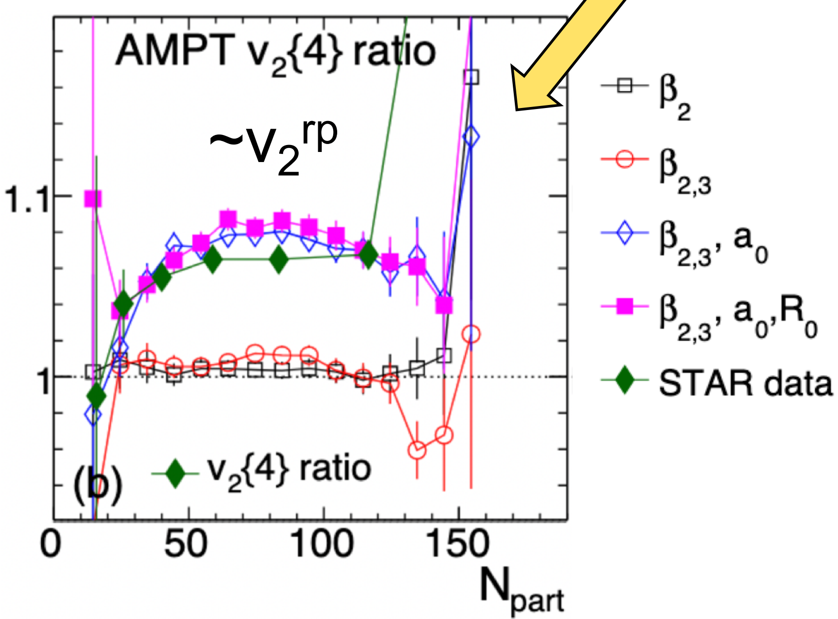
Nuclear skin contributes to $v_2^{rp} \sim v_2\{4\}$, deformation contribute to fluctuations

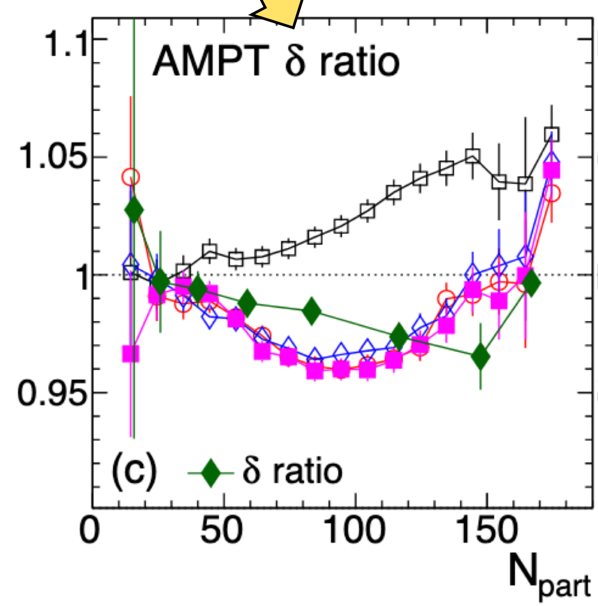




$$\langle v_2^2 \rangle = \underbrace{\left(v_2^{\mathrm{rp}}\right)^2}_{\text{mean}} + \underbrace{\delta^2}_{\text{fluctuations}}$$

2206.10449

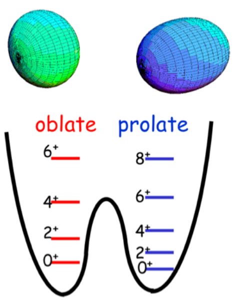


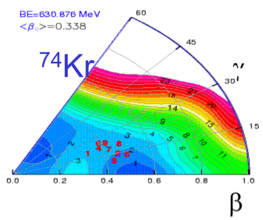


Shape fluctuations

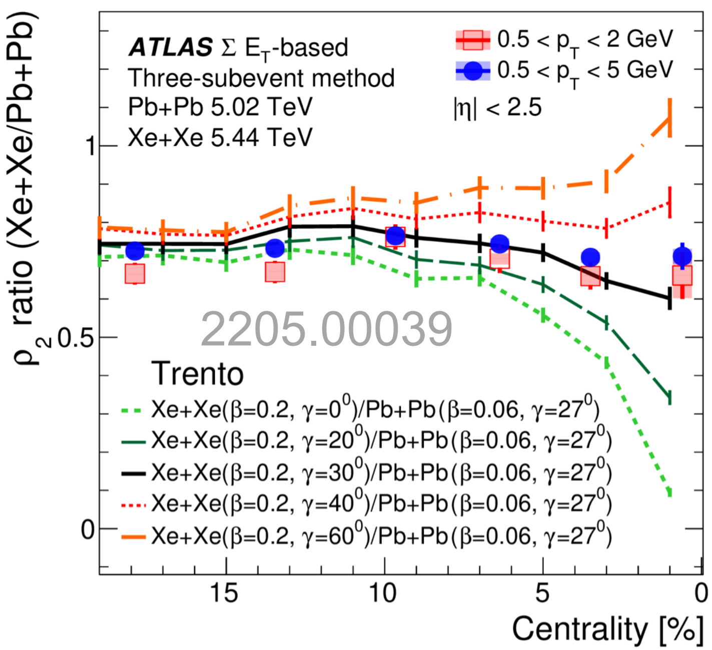
- Shape fluctuations and shape coexistence can be accessed via high-order correlations

Shape coexistence



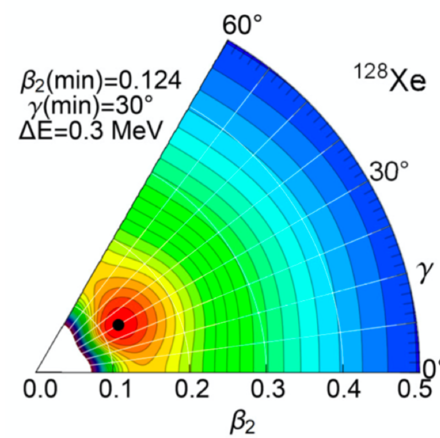


$$R = \frac{\left\langle v_2^2 \delta[p_T] \right\rangle_{^{129}Xe}}{\left\langle v_2^2 \delta[p_T] \right\rangle_{^{208}Pb}}$$



Bally et.al 2108.09578

Large shape fluct., esp along γ



PhysRevC.101.064318

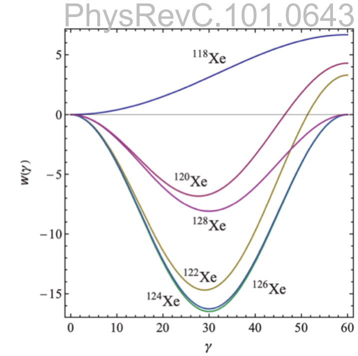
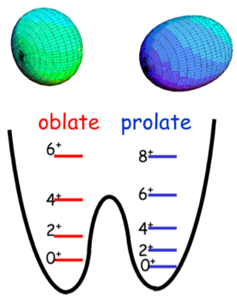


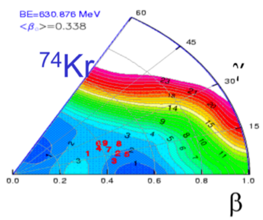
FIG. 3. The evolution of the γ potential defined by Eq. (7) with itted parameters c_1 and c_2, along the isotopic chain $^{118-128}$Xe.

Shape fluctuations

- Shape fluctuations and shape coexistence can be accessed via high-order correlations.

Shape coexistence





quadrupole operator $\hat{Q}$

$$\begin{cases} \langle\beta^2\rangle = \dfrac{16\pi^2}{9A^2R_0^4}\left\langle\hat{Q}^2\right\rangle & \text{2-p correlation} \\ \sigma^2(\langle\beta^2\rangle)/\langle\beta^2\rangle = \sigma^2\left(\langle\hat{Q}^2\rangle\right)/\langle\hat{Q}^2\rangle & \text{4-p correlation} \end{cases}$$

1906.07542

$$\begin{cases} \langle\cos 3\gamma\rangle = -\sqrt{\dfrac{7}{2}}\dfrac{\left\langle\hat{Q}^3\right\rangle}{\left\langle\hat{Q}^2\right\rangle^{3/2}} & \text{3-p correlation} \\ \dfrac{\sigma^2(\cos 3\gamma)}{(\cos 3\gamma)^2} = \dfrac{\sigma^2\langle\hat{Q}^3\rangle}{\langle\hat{Q}^3\rangle^2} + \dfrac{9}{4}\dfrac{\sigma^2\langle\hat{Q}^2\rangle}{\langle\hat{Q}^2\rangle^2} - 3\dfrac{\langle\hat{Q}^5\rangle - \langle\hat{Q}^3\rangle\langle\hat{Q}^2\rangle}{\langle\hat{Q}^3\rangle\langle\hat{Q}^2\rangle} & \text{6-p correlation} \end{cases}$$

Heavy ion observables:

$$\frac{\left\langle\varepsilon_2^2\right\rangle}{\frac{3}{4\pi}\beta_2^2} \Longleftrightarrow \frac{\left\langle\varepsilon_2^4\right\rangle - 2\left\langle\varepsilon_2^2\right\rangle^2}{-\frac{9}{56\pi^2}\beta_2^4}$$

$$\frac{\left\langle\varepsilon_2^2(\delta d_\perp/d_\perp)\right\rangle}{-\frac{3\sqrt{5}}{112\pi^{3/2}}\cos(3\gamma)\beta_2^3} \Longleftrightarrow \frac{\left(\left\langle\varepsilon_2^6\right\rangle - 9\left\langle\varepsilon_2^4\right\rangle\left\langle\varepsilon_2^2\right\rangle + 12\left\langle\varepsilon_2^2\right\rangle^3\right)/4}{\frac{27(373-25\cos(6\gamma))}{32\times 8008\pi^3}\beta_2^6}$$