arXiv:2109.01631 arXiv:2105.05713
arXiv:2109.00604 arXiv:2105.01638
arXiv:2106.08768 arXiv:2102.08158

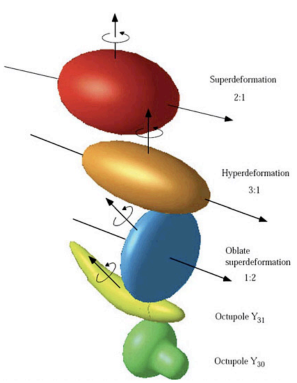
# New opportunities to probe nuclear deformation using high-energy heavy-ion collisions

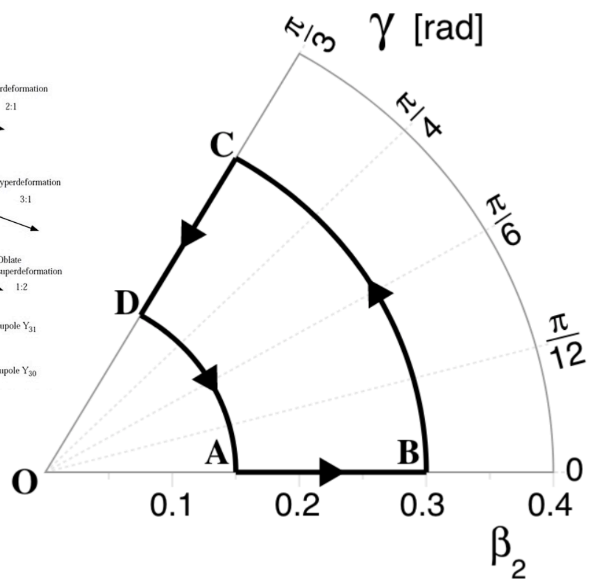
Jiangyong Jia

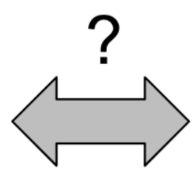
Collaborators: Giuliano Giacalone, Chunjian Zhang, Shengli Huang

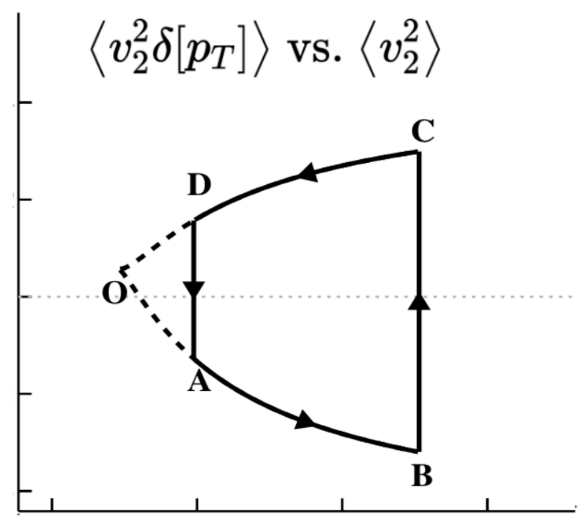
Nuclear structure

High-energy collisions



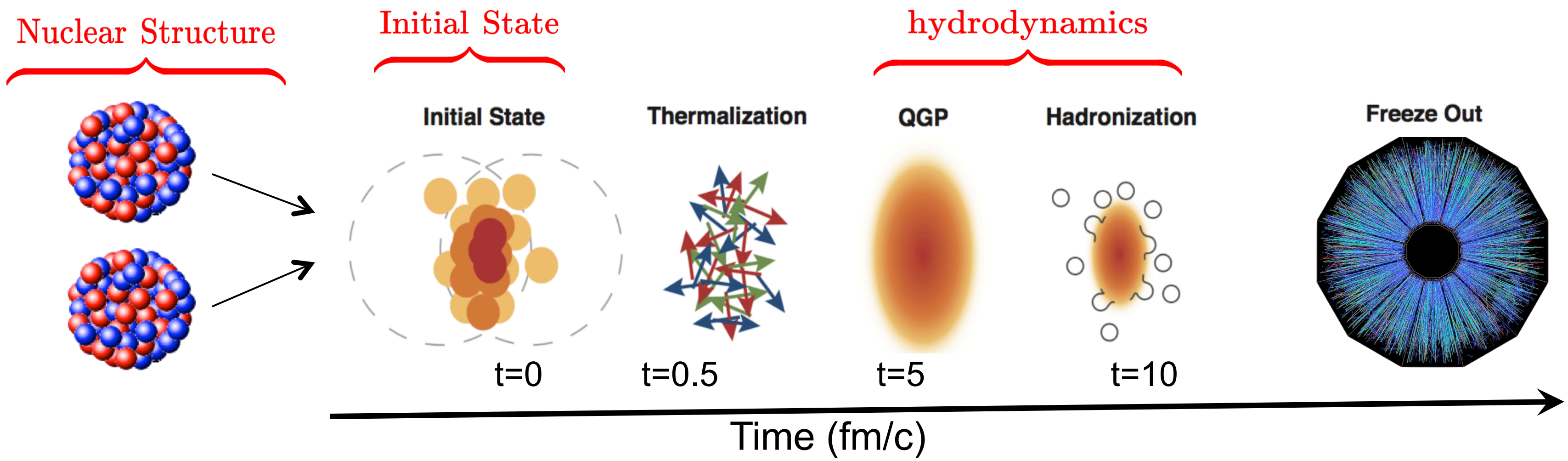



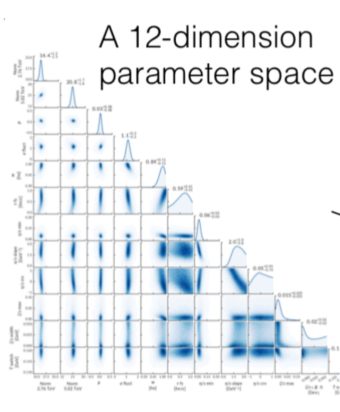



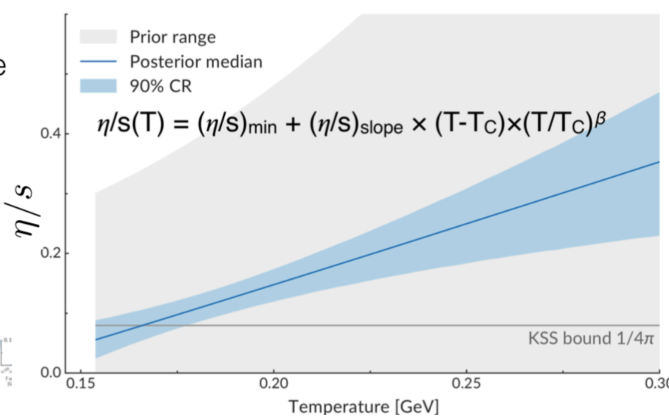
# Heavy ion collisions in the precision era

Space-time evolution of HI is a hydrodynamic response to the initial state geometry, controlled by the shape and radial profile of the colliding nuclei.




A precision tool for IS and FS demonstrated by multi-system Bayesian analysis



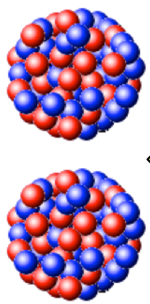

1605.03954,2010.15130,2011.01430

- Fit many observables with hydrodynamics
- Differential information in the parameter space
- Simultaneous constrain on the initial and final state

Precise enough to image nuclear structure? Impact on QGP properties?

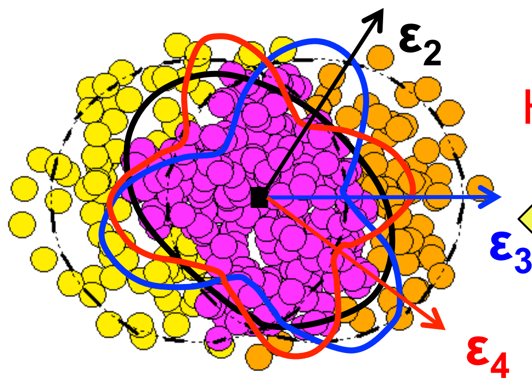
# Hydrodynamic response to initial state

Nuclear Structure



Imaging?

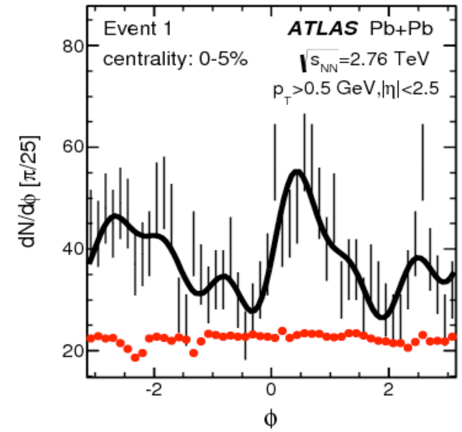
Initial State




Hydro-response

Space-time dynamics

Final Particle flow




$$\frac{\rho_0}{1+e^{(r-R_0(1+\sum_n \beta_n Y_n^0(\theta,\phi))/a_0}}$$

Initial Size    Initial Shape

$$R_\perp \propto \langle r_\perp^2 \rangle, \quad \mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$$

??

$$R_0 \quad a_0 \quad \beta_n$$

Radial Flow    Harmonic Flow

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

arXiv:1206.1905

High energy: approx. linear response in each event:

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

Previous works: PRC34.185, PRC61.021903, PRC61.034905, PRC.80.054903, nucl-th/0411054, 0712.0088, 1409.8375, 1507.03910, 1609.01949,1711.08499, 2007.00780.2103.05595. H. Stocker, W. Geiner, BA Li, E. Shuryak, PBM, U. Heinz, P. Philip, N.Xu, Q. Shou, P. Sorensen, F. Videbaek, A. Tang, P. Dasgupta, R. Chatterjee, D. Krivastava, F.Wang, H. Xu, Jaki. M. Luzum, P.Carzon...

## Influence of shape fluctuations in relativistic heavy ion collisions

A. Rosenhauer, H. Stöcker, J. A. Maruhn, and W. Greiner
Phys. Rev. C **34**, 185 – Published 1 July 1986

Article | References | No Citing Articles | PDF | Export Citation

## Uranium on uranium collisions at relativistic energies

Bao-An Li
Phys. Rev. C **61**, 021903(R) – Published 12 January 2000

Article | References | Citing Articles (25) | PDF | Export Citation

## High energy collisions of strongly deformed nuclei: An old idea with a new twist

E. V. Shuryak
Phys. Rev. C **61**, 034905 – Published 22 February 2000

Article | References | Citing Articles (26) | PDF | Export Citation

## Choice of colliding beams to study deformation effects in relativistic heavy ion collisions

S. Das Gupta and C. Gale
Phys. Rev. C **62**, 031901(R) – Published 23 August 2000

# Elliptic flow in central collisions of deformed nuclei

P. Filip

*Physics of Atomic Nuclei* **71**, 1609–1618 (2008) | Cite this article



# Anisotropic Flow and Jet Quenching in Ultrarelativistic $\mathrm{U}+\mathrm{U}$ Collisions

Ulrich Heinz and Anthony Kuhlman
Phys. Rev. Lett. **94**, 132301 – Published 6 April 2005



# Initial eccentricity in deformed $^{197}\mathrm{Au}+{}^{197}\mathrm{Au}$ and $^{238}\mathrm{U}+{}^{238}\mathrm{U}$ collisions at $\sqrt{s_{NN}}=200$ GeV at the BNL Relativistic Heavy Ion Collider

Peter Filip, Richard Lednicky, Hiroshi Masui, and Nu Xu
Phys. Rev. C **80**, 054903 – Published 5 November 2009



# Parameterization of deformed nuclei for Glauber modeling in relativistic heavy ion collisions

Q.Y. Shou [a, b], Y.G. Ma [a], P. Sorensen [c], A.H. Tang [c], F. Videbæk [c], H. Wang [c]

## Collision geometry and flow in uranium + uranium collisions

Andy Goldschmidt, Zhi Qiu, Chun Shen, and Ulrich Heinz
Phys. Rev. C **92**, 044903 – Published 7 October 2015

Article | References | Citing Articles (20) | PDF | HTML | Export Citation

## Spectra and elliptic flow of thermal photons from full-overlap U+U collisions at energies available at the BNL Relativistic Heavy Ion Collider

Pingal Dasgupta, Rupa Chatterjee, and Dinesh K. Srivastava
Phys. Rev. C **95**, 064907 – Published 15 June 2017

Article | References | Citing Articles (7) | PDF | HTML | Export Citation

## Hydrodynamic predictions for 5.44 TeV Xe+Xe collisions

Giuliano Giacalone, Jacquelyn Noronha-Hostler, Matthew Luzum, and Jean-Yves Ollitrault
Phys. Rev. C **97**, 034904 – Published 6 March 2018

Article | References | Citing Articles (50) | PDF | HTML | Export Citation

## Possible octupole deformation of $^{208}\mathbf{Pb}$ and the ultracentral $v_2$ to $v_3$ puzzle

P. Carzon, S. Rao, M. Luzum, M. Sievert, and J. Noronha-Hostler
Phys. Rev. C **102**, 054905 – Published 9 November 2020

Article | References | Citing Articles (1) | PDF | HTML | Export Citation

## Determine the neutron skin type by relativistic isobaric collisions

Hao-jie Xu [a], Hanlin Li [b], Xiaobao Wang [a], Caiwan Shen [a], Fuqiang Wang [a, c]

# Shape of nuclei

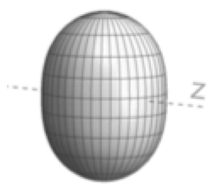
## Most ground state stable nuclei are deformed

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

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

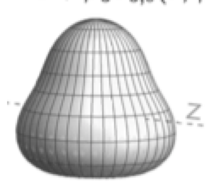
$1+\beta_2 Y_{2,0}(\theta,\phi)$

Quadrupole:



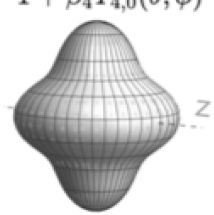

$1+\beta_3 Y_{3,0}(\theta,\phi)$

Octupole:

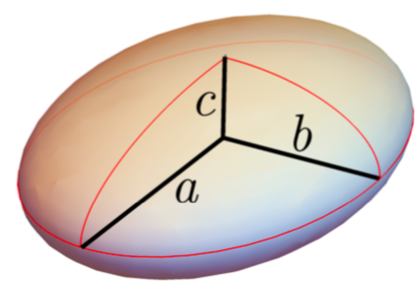



$1+\beta_4 Y_{4,0}(\theta,\phi)$

Hexadecapole:




Triaxial spheroid: $a \neq b \neq c$.




$0 \leq \gamma \leq \pi/3$

Prolate: a=b<c → $\beta_2$, $\gamma=0$

Oblate: a<b=c → $\beta_2$, $\gamma=\pi/3$ or $-\beta_2$, $\gamma=0$

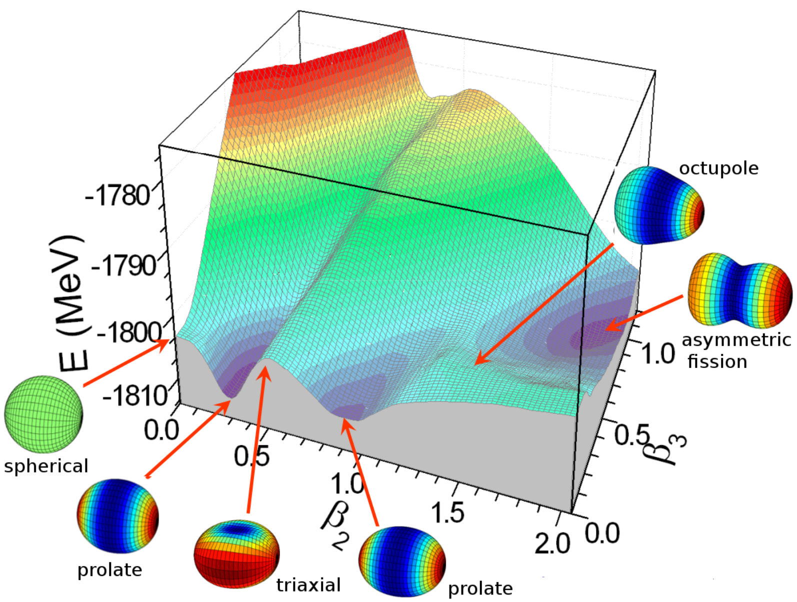
# Shape of nuclei

Most ground state stable nuclei are deformed

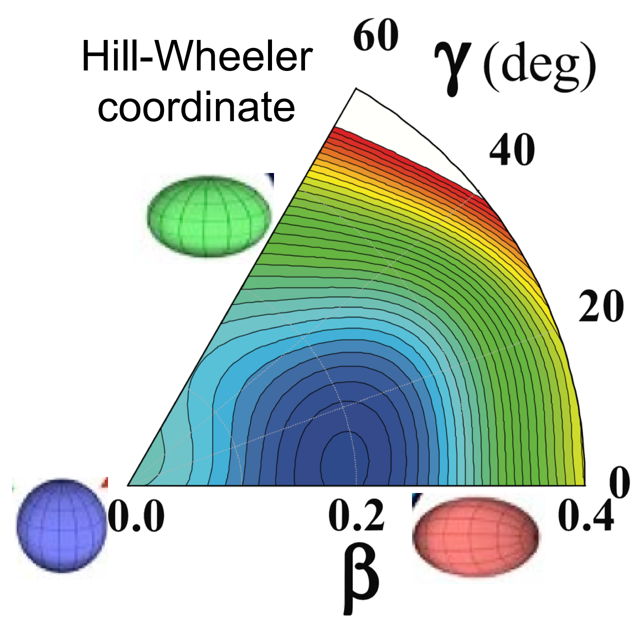
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

Shape determined by minimizing the potential energy surface

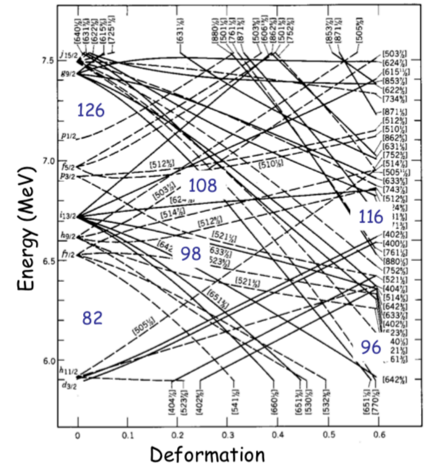



B.N. Lu, Meng Jie

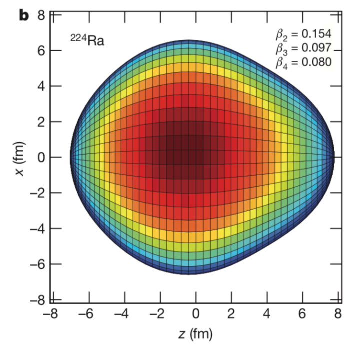



Main tool: transition rates B(En) among low lying states

# Some topics in nuclear shape studies

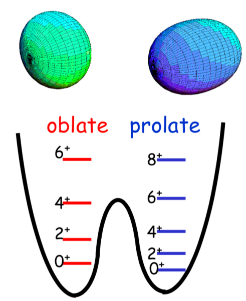


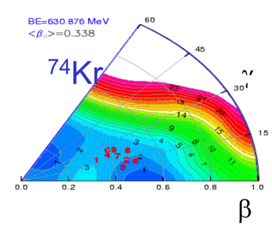

- Shape evolution: how the shape evolves along isotopic chain
  - Strong test on nuclear structure model




- Octuple (pear-shaped) deformation
  - Octupole correlation or static deformation
  - Strong test on EDM effects

- Trixaility : infers from γ-band, Chiral and Wobbling bands. Have large uncertainties.
  - shape coexistance



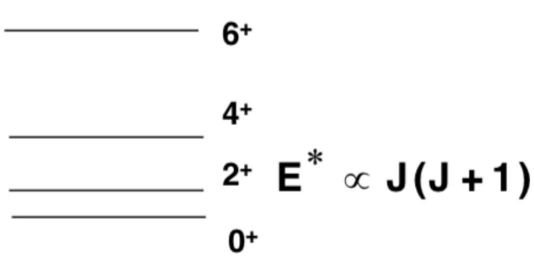



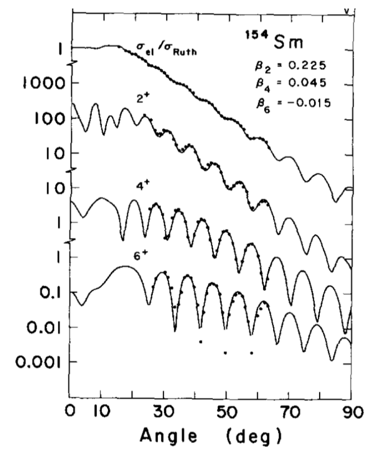

Use shape tomography in heavy-ion collision to help?

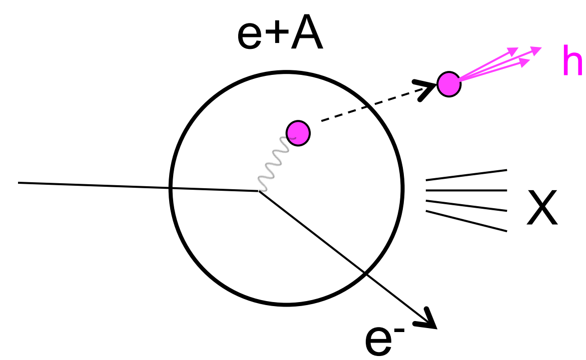
# Nuclear structure vs HI method

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

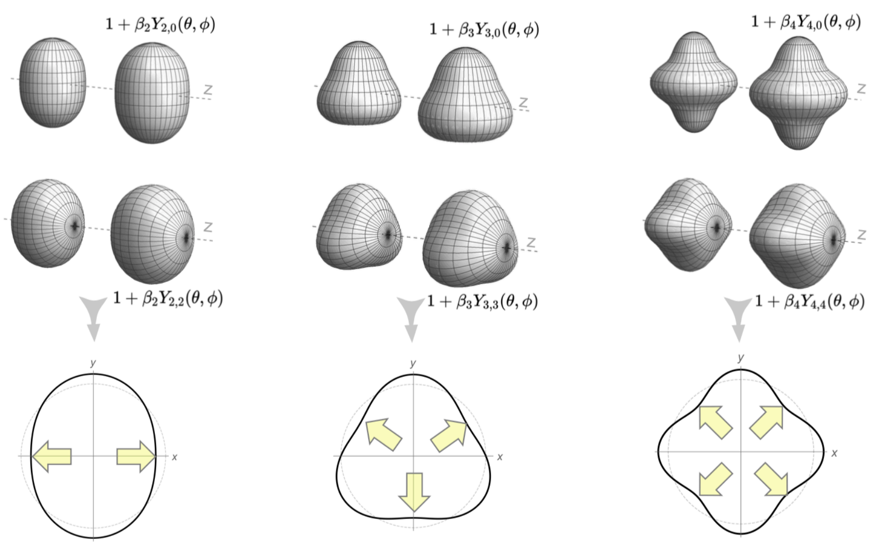
«rotational» spectrum



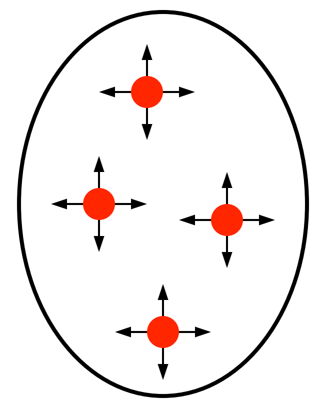




- Probe entire mass distribution: multi-point correlations




collective flow response to the shape



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

# Evidence of deformation in U+U vs Au+Au

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

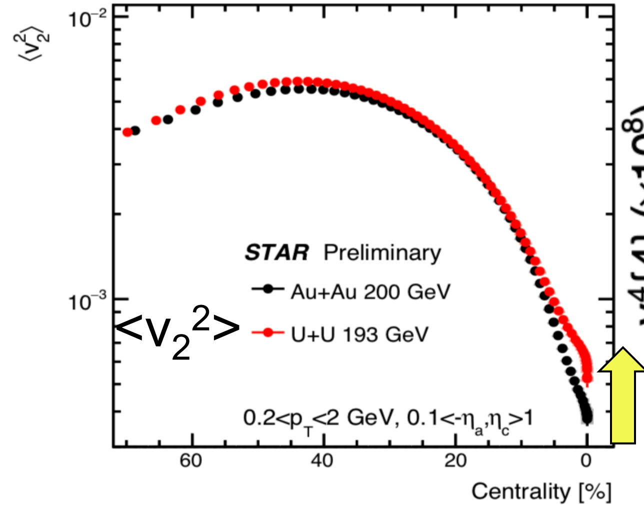
Large deformation in $^{238}$U relative to $^{197}$Au strongly influence flow signals

$\beta_{2U} \sim 0.28$

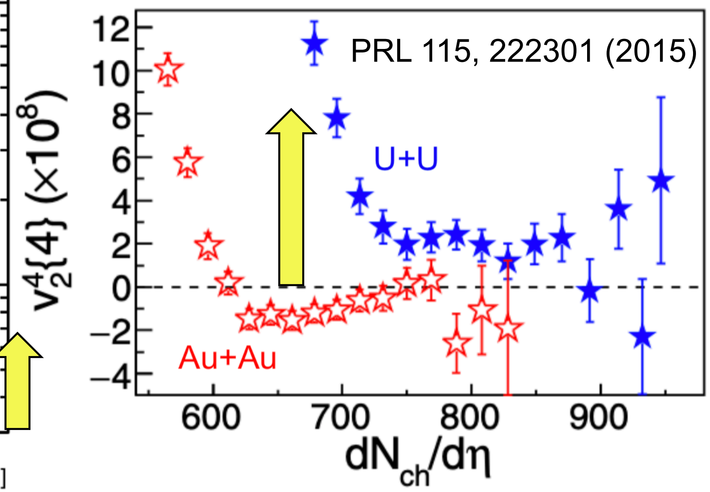
$\beta_{2Au} \sim$ small

How to turn these into a quantitative tool for nuclear structure ?

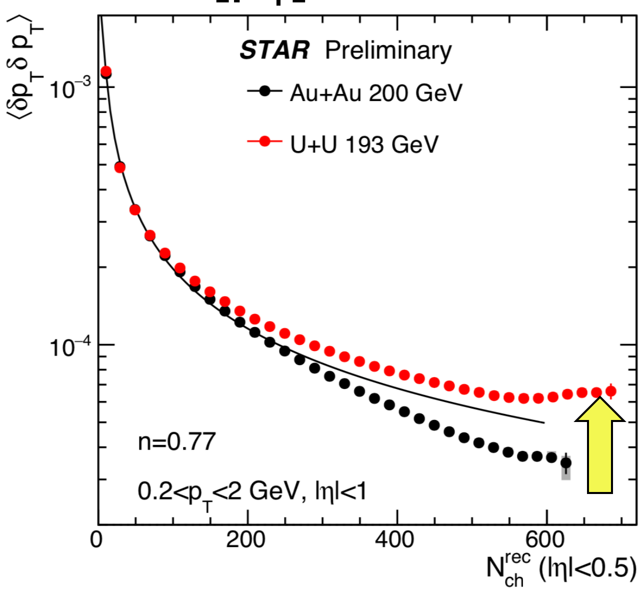
## $v_2$ variance



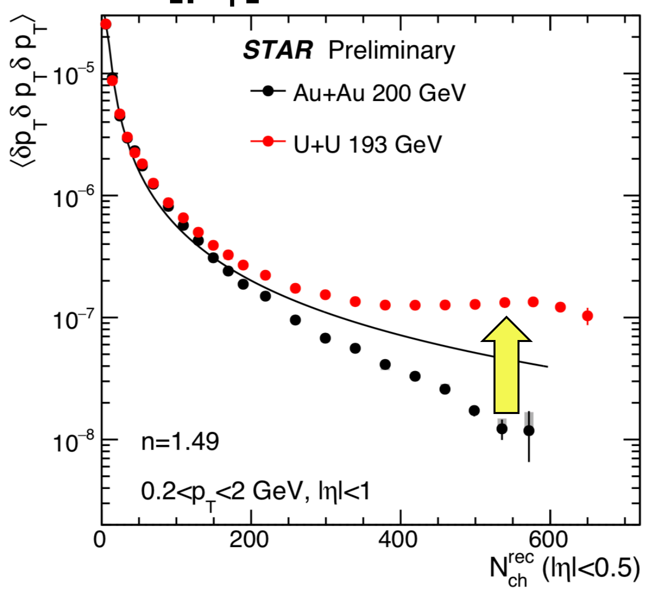

## $v_2$ kurtosis



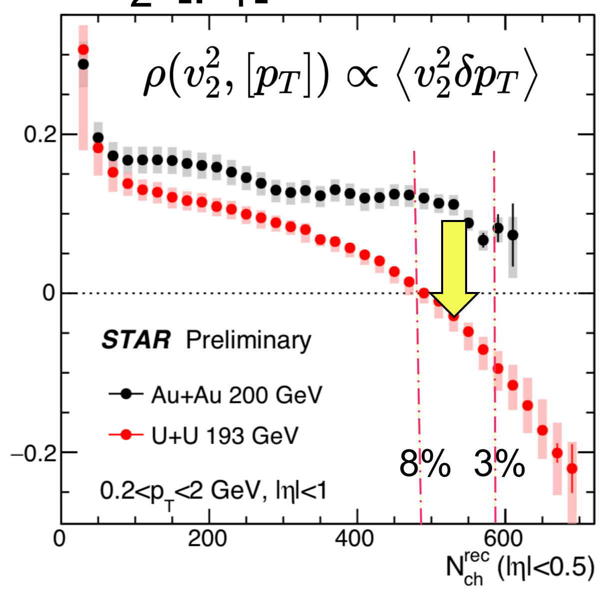

## $[p_T]$ variance




## $[p_T]$ skewness




## $v_2$-$[p_T]$ covariance

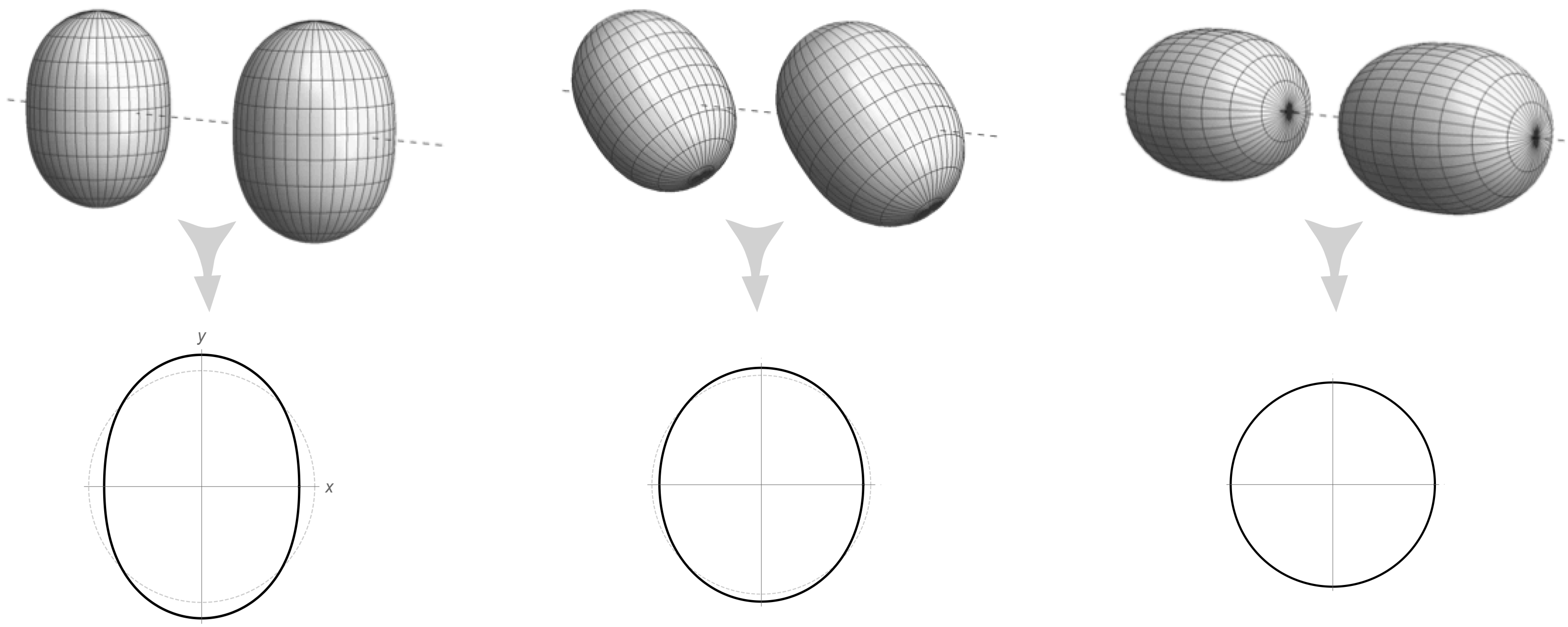


# Shape of the initial state in HI

Body-Body

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

Tip-Tip




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

shape of overlap = shape of nucleon dist. projected along Euler angle $\Omega = \varphi\theta\psi$

# Parametric form of the $\beta_2$ dependence

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

2109.00604

- $\varepsilon_2$ has the form

$$\epsilon_2 = \underbrace{\epsilon_0}_{\text{undeformed}} + \underbrace{p_2(\Omega_1, \Omega_2, \gamma)}_{\text{phase factor}}\beta_2 + \mathcal{O}(\beta_2^2)$$

γ only appear here, since when β=0, γ doesn't matter, must in the form of cos3γ, cos6γ, cos9γ…

- $R_\perp^2 = \langle x^2 \rangle + \langle y^2 \rangle$ has the form

$$d_\perp \equiv 1/R_\perp \qquad \delta d_\perp/d_\perp = \delta_d + p_0(\Omega_1, \Omega_2, \gamma)\beta_2 + \mathcal{O}(\beta_2^2)$$

- Measure deformation from cumuants of $p(\varepsilon_2)$ and $p(\delta d_\perp/d_\perp)$

- Again linear response to relate to final state:

$$v_n \propto \varepsilon_n \qquad \frac{\delta[p_T]}{[p_T]} \propto \frac{\delta d_\perp}{d_\perp}$$

# Influence to cumulants

## Single event

See 2109.00604

$$\frac{\delta d_\perp}{d_\perp} = \delta_d + p_0(\Omega_1, \Omega_2, \gamma)\beta_2 + \mathcal{O}(\beta_2^2)\ ,\ \boldsymbol{\epsilon}_2 = \boldsymbol{\epsilon}_0 + \boldsymbol{p}_2(\Omega_1, \Omega_2, \gamma)\beta_2 + \mathcal{O}(\beta_2^2)$$

fluctuation of $\delta_d$ $(\boldsymbol{\epsilon}_0)$ is uncorrelated with $p_0$ $(\boldsymbol{p}_2)$

## Variances

$$\left\langle (\delta d_\perp / d_\perp)^2 \right\rangle = \left\langle \delta_d^2 \right\rangle + \left\langle p_0(\Omega_1, \Omega_2, \gamma)^2 \right\rangle \beta_2^2\ ,\ \left\langle \varepsilon_2^2 \right\rangle = \left\langle \varepsilon_0^2 \right\rangle + \left\langle \boldsymbol{p}_2(\Omega_1, \Omega_2, \gamma)\boldsymbol{p}_2^*(\Omega_1, \Omega_2, \gamma) \right\rangle \beta_2^2$$

$$\propto \left\langle (\delta[p_{\mathrm{T}}]/[p_{\mathrm{T}}])^2 \right\rangle \qquad \propto \left\langle v_2^2 \right\rangle$$

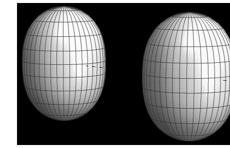
## Skewness

$$\left\langle (\delta d_\perp / d_\perp)^3 \right\rangle = \left\langle \delta_d^3 \right\rangle + \left\langle p_0^3 \right\rangle \beta_2^3 \qquad \left\langle \varepsilon_2^2 \delta d_\perp / d_\perp \right\rangle = \left\langle \varepsilon_0^2 \delta_d \right\rangle + \left\langle p_0 \boldsymbol{p}_2 \boldsymbol{p}_2^* \right\rangle \beta_2^3$$

$$\propto \left\langle (\delta[p_{\mathrm{T}}]/[p_{\mathrm{T}}])^3 \right\rangle \qquad \propto \left\langle v_2^2 \delta[p_{\mathrm{T}}]/[p_{\mathrm{T}}] \right\rangle$$

# Liquid drop model estimate for head-on collisions

Nucleus with a sharp surface: $\rho(r,\theta,\phi) = \begin{cases} 1 & r < R(\theta,\phi) \\ 0 & r > R(\theta,\phi) \end{cases}$



$$\frac{\delta d_\perp}{d_\perp} = \sqrt{\frac{5}{16\pi}}\beta_2\left(\cos\gamma D^2_{0,0} + \frac{\sin\gamma}{\sqrt{2}}\left[D^2_{0,2} + D^2_{0,-2}\right]\right) \;,\; \epsilon_2 = -\sqrt{\frac{15}{2\pi}}\beta_2\left(\cos\gamma D^2_{2,0} + \frac{\sin\gamma}{\sqrt{2}}\left[D^2_{2,2} + D^2_{2,-2}\right]\right)$$

$$\alpha_{2,0} \equiv \cos\gamma,\;\; \alpha_{2,\pm 2} \equiv \frac{\sin\gamma}{\sqrt{2}}$$

Variances

$$\left\langle \varepsilon_2^2 \right\rangle = \beta_2^2 \frac{15}{2\pi}\int\left(\sum_m \alpha_{2,m} D^2_{2,m}\right)\left(\sum_m \alpha_{2,m} D^2_{2,m}\right)^* \frac{d\Omega}{8\pi^2} = \frac{3}{2\pi}\beta_2^2$$

$$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle = \beta_2^2 \frac{5}{16\pi}\int\left(\sum_m \alpha_{2,m} D^2_{0,m}\right)^2 \frac{d\Omega}{8\pi^2} = \frac{1}{16\pi}\beta_2^2$$

do not depend on γ

Skewness

$$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle = \beta_2^3 \left(\frac{5}{16\pi}\right)^{3/2}\int\left(\sum_m \alpha_{2,m} D^2_{0,m}\right)^3 \frac{d\Omega}{8\pi^2} = \frac{\sqrt{5}}{224\pi^{3/2}}\cos(3\gamma)\beta_2^3$$

$$\left\langle \varepsilon_2^2 \frac{\delta d_\perp}{d_\perp}\right\rangle = \beta_2^3 \frac{15}{2\pi}\sqrt{\frac{5}{16\pi}}\int\left(\sum_m \alpha_{2,m} D^2_{2,m}\right)\left(\sum_m \alpha_{2,m} D^2_{2,m}\right)^*\left(\sum_m \alpha_{2,m} D^2_{0,m}\right) \frac{d\Omega}{8\pi^2} = -\frac{3\sqrt{5}}{28\pi^{3/2}}\cos(3\gamma)\beta_2^3$$

opposite sign

Expect a leading-order cos3γ dependence

# Monte Carlo Glauber model results



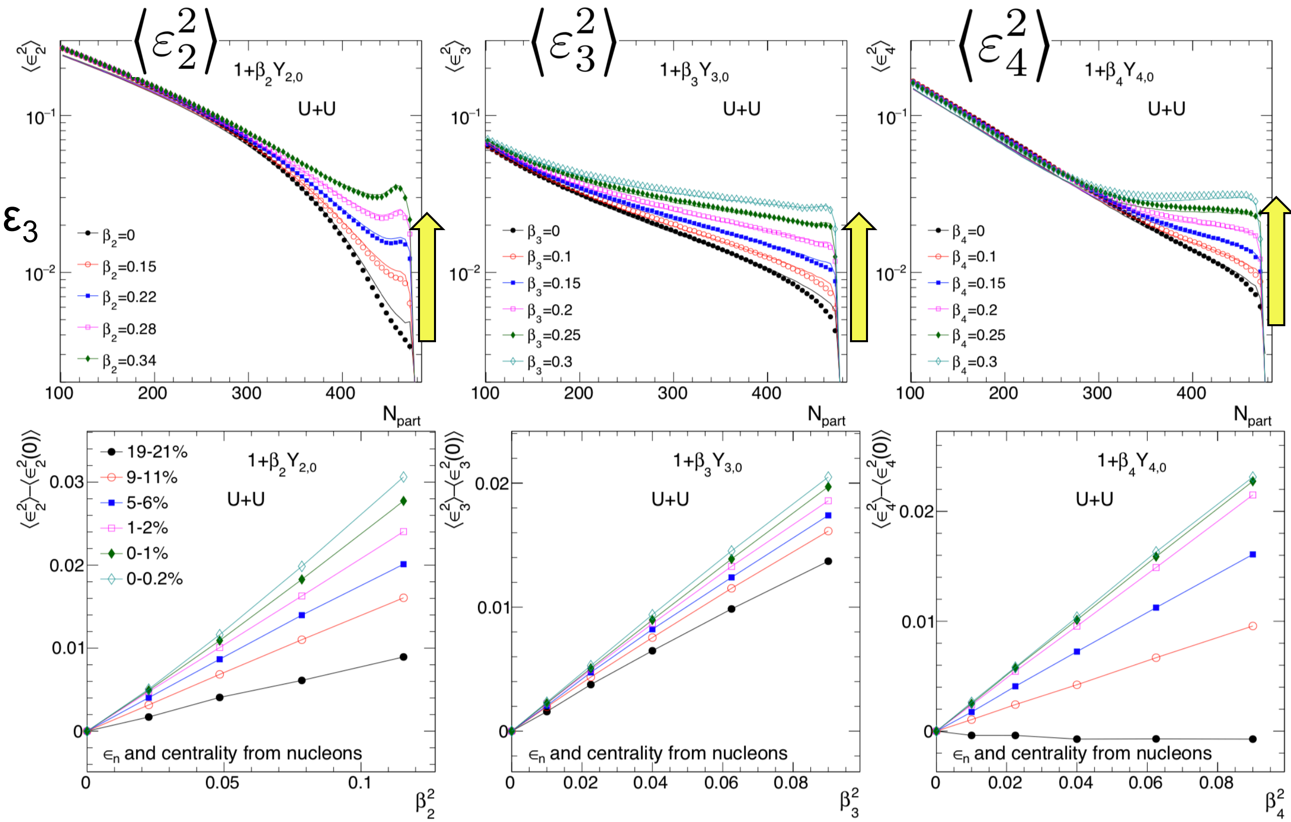
See 2106.08768

Clear enhancements in UCC

$\beta_3$ affects wide cent. range for $\varepsilon_3$

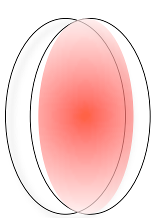
Dependence as expected

$$\left\langle \varepsilon_n^2 \right\rangle \approx a'_n + b'_n \beta_n^2$$

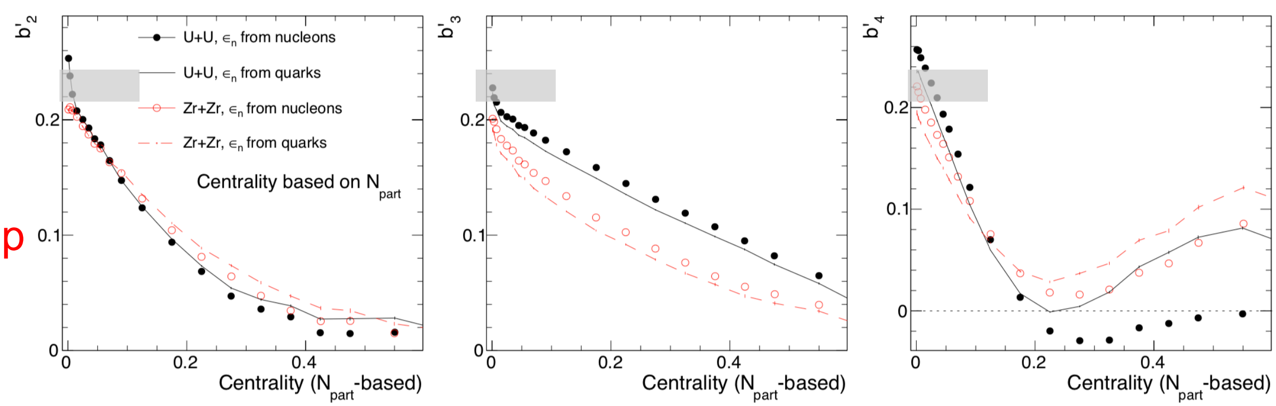



$b_n'$ coefficients are indep. of system size, same for nucleon Glauber and quark Glauber.

Influence of deformation is a Global geometry effects, not affected by nucleon fluct.s



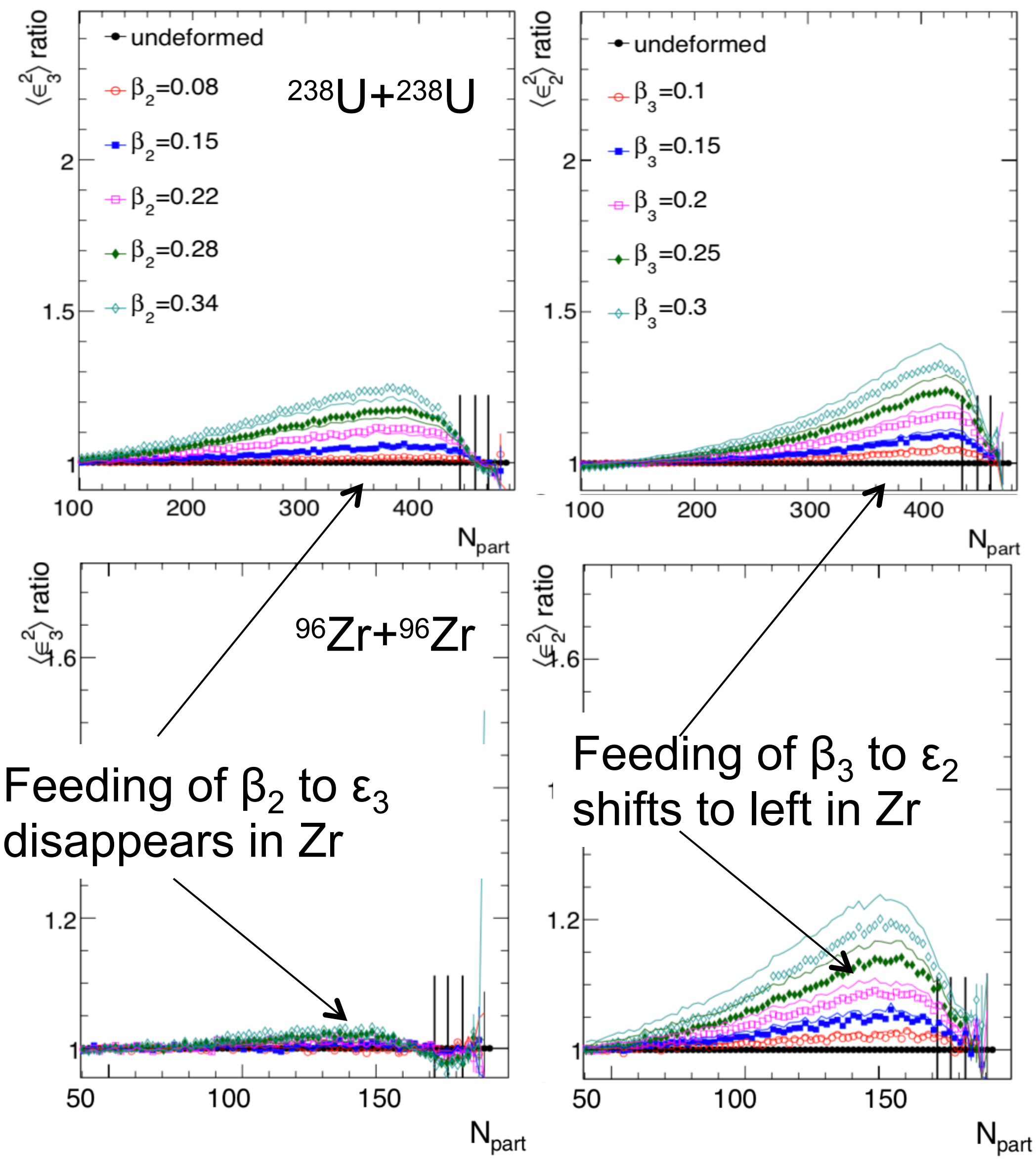
Agree with liquid drop model prediction in ultra-central region



# Does $\beta_n$ influence $\varepsilon_m$? m≠n

See 2106.08768

$$\left\langle \varepsilon_3^2 \right\rangle = a'_3 + b'_{3,2}\beta_2^2 \qquad \left\langle \varepsilon_2^2 \right\rangle = a'_2 + b'_{2,3}\beta_3^2$$




In medium size system:

$$\varepsilon_2^2 = a'_2 + b'_2\beta_2^2 + b'_{2,3}\beta_3^2$$

$$\varepsilon_3^2 = a'_3 + b'_3\beta_3^2$$

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2$$

$$v_3^2 = a_3 + b_3\beta_3^2$$

# Application: variances

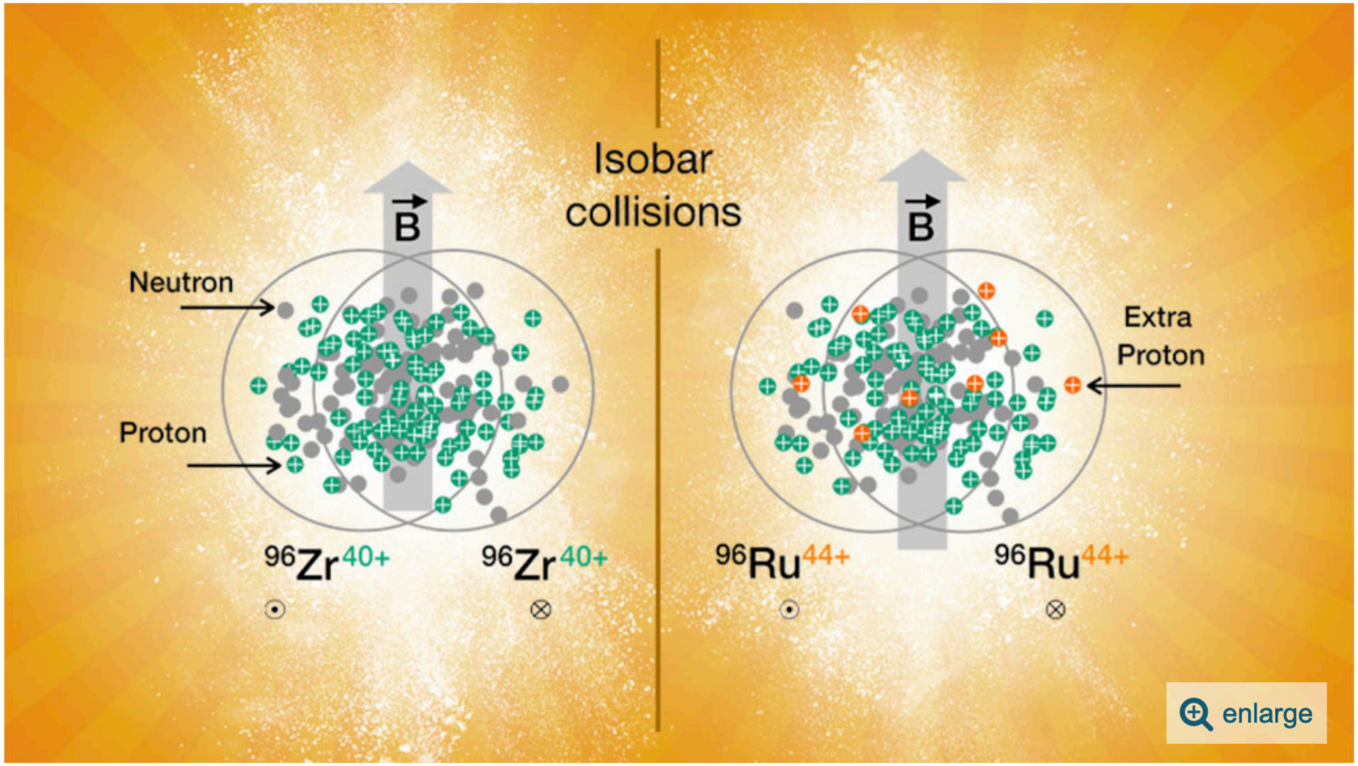
$$\langle \varepsilon_n^2 \rangle \quad \langle v_n^2 \rangle$$

# Results from Search for 'Chiral Magnetic Effect' at RHIC

## Collisions of 'isobars' test effect of magnetic field, searching for signs of a broken symmetry

August 31, 2021

arXiv:2109.00131




Physicists compared collisions of two different sets of isobars, which are ions that have the same overall mass but different numbers of protons—zirconium ($^{96}$Zr), with 40 protons, and ruthenium ($^{96}$Ru) with 44 protons. The higher proton number (and thus electric charge) in ruthenium should generate a stronger magnetic field during collisions than zirconium (indicated by size of gray arrows). Scientists expected the stronger magnetic field of ruthenium collisions to result in greater separation of charged particles emerging from those collisions than seen in zirconium collisions.

0.4% precision is achieved in ratio of many observables between two isobar systems→ isobar running mode is a precision imaging tool

# Nuclear deformation in isobar collision

- Isobar systems, i.e. 96Ru+96Ru and 96Zr+96Zr    arXiv:2102.08158

Collisions at $\sqrt{s_{NN}}$=200 GeV    Question: $\frac{v_{n,\mathrm{Ru+Ru}}}{v_{n,\mathrm{Zr+Zr}}} \stackrel{?}{=} 1$

- Nuclear structure data: $\beta_{2\mathrm{Ru}} >> \beta_{2\mathrm{Zr}}$    $\beta_{3\mathrm{Ru}} << \beta_{3\mathrm{Zr}}$

$\beta_2$ from ADNDT107,1(2016)

$\beta_3$ from ADNDT80,35(2002)

| | $\beta_2$ | $E_{2_1^+}$ (MeV) | $\beta_3$ | $E_{3_1^-}$ (MeV) |
|---|---|---|---|---|
| $^{96}$Ru | 0.154 | 0.83 | - | 3.08 |
| $^{96}$Zr | 0.062 | 1.75 | 0.202,0.235,0.27 | 1.90 |

$^{96}$Zr has very large octupole collectivity from $B(E3; 0_1^+ \rightarrow 3_1^-)$

- Heavy ion expectation: $v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2,\ \ v_3^2 = a_3 + b_3\beta_3^2$

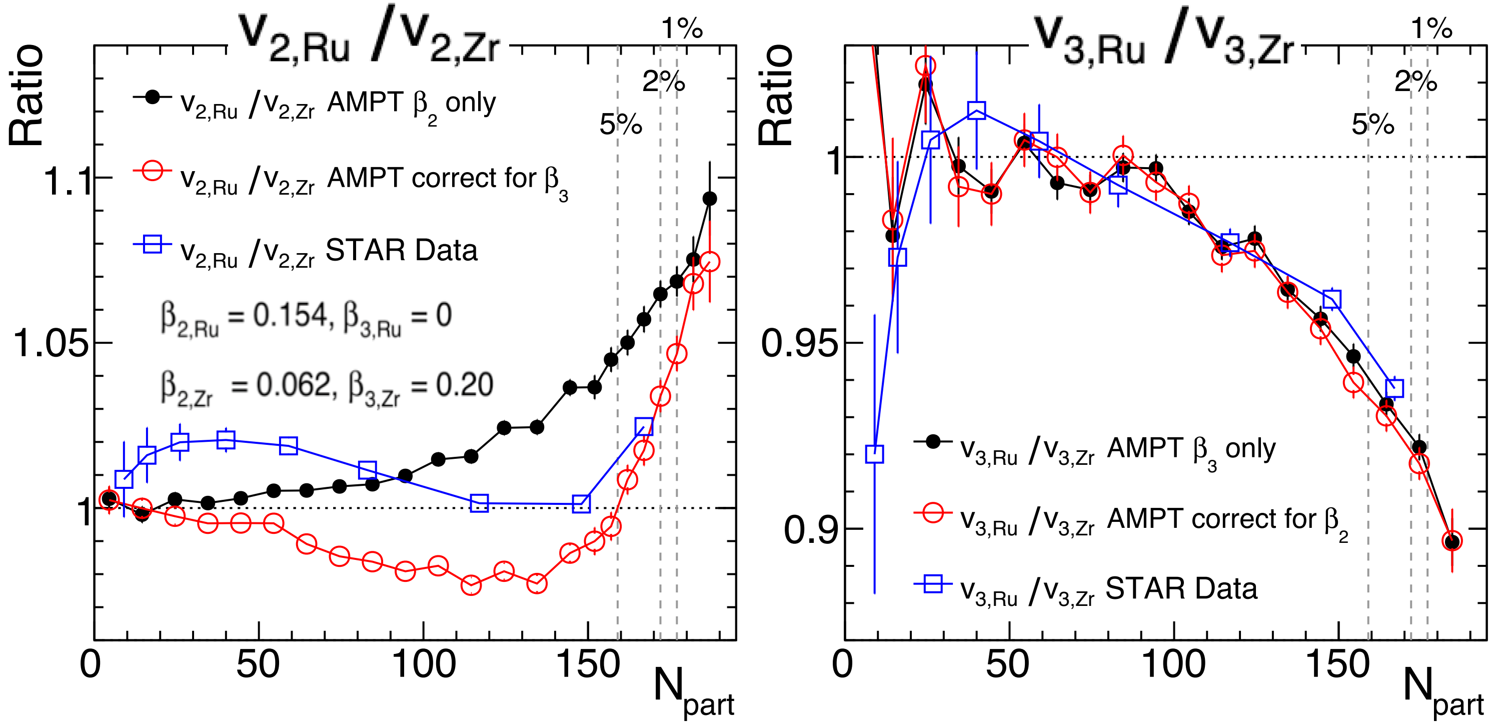
$$\frac{v^2_{2,\mathrm{Ru}}}{v^2_{2,\mathrm{Zr}}} \approx 1 + \frac{b_2}{a_2}(\beta^2_{2,\mathrm{Ru}} - \beta^2_{2,\mathrm{Zr}}) - \frac{b_{2,3}}{a_2}\beta^2_{3,\mathrm{Zr}}$$

$$\frac{v^2_{3,\mathrm{Ru}}}{v^2_{3,\mathrm{Zr}}} \approx 1 - \frac{b_3}{a_3}\beta^2_{3,\mathrm{Zr}}.$$

cancelation expected in non-central collisions

# Predicted ratio

arXiv:2109.01631




- $v_2$-ratio: Negative contribution from $\beta_{3zr}$ → sharper decrease in UCC
- $v_3$-ratio: strong decrease in UCC from $\beta_{3zr}$.

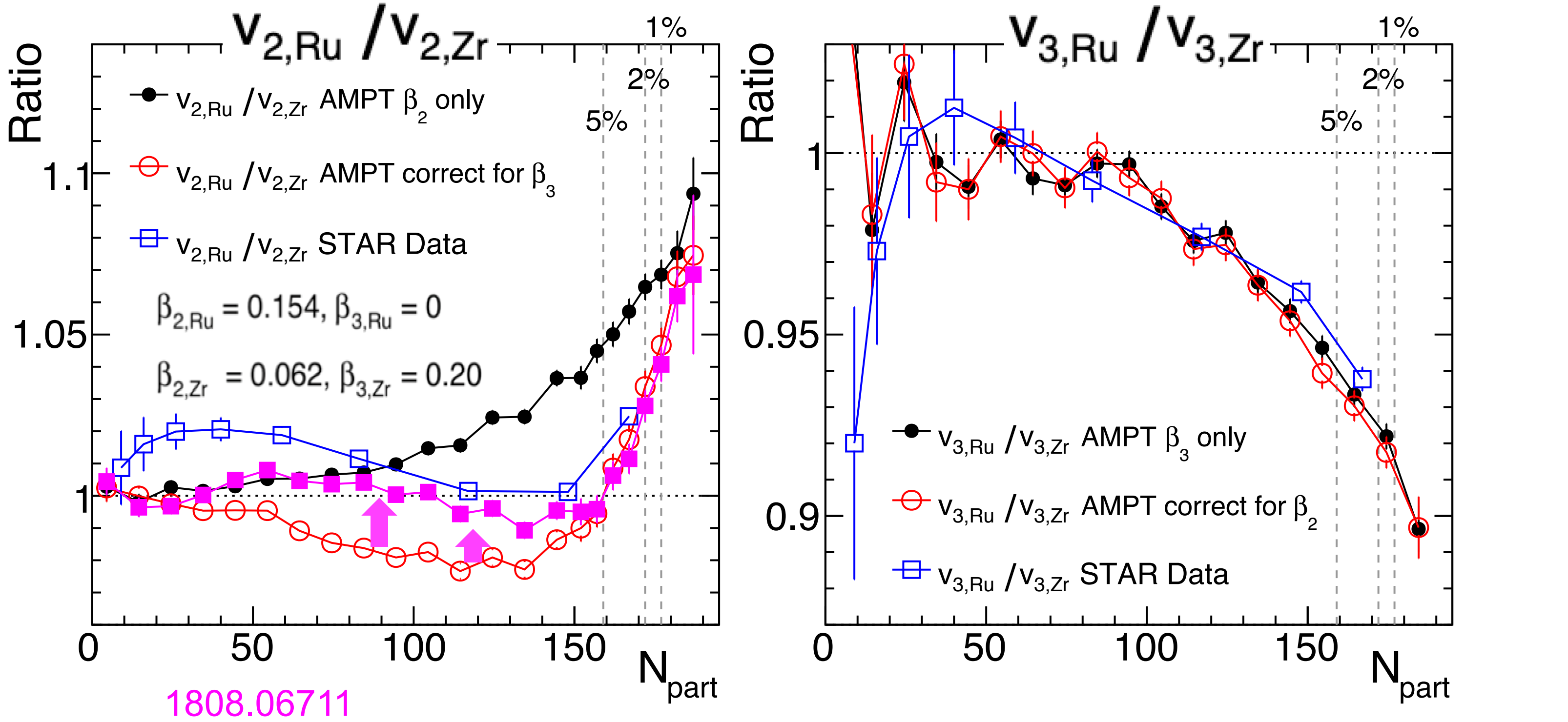
$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2) - \frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2$$

$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2} \approx 1 - \frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2.$$

cancelation expected in non-central collisions

# Predicted ratio

arXiv:2109.01631

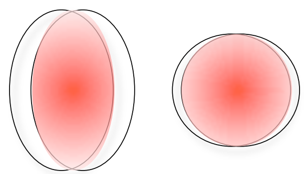



- $v_2$-ratio: Negative contribution from $\beta_{3zr}$ → sharper decrease in UCC
- $v_3$-ratio: strong decrease in UCC from $\beta_{3zr}$.
- Residual difference due to neutron skin of Zr?

Prefers $\beta_{3zr}$ ~ 0.2, lower end of NS measurements

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

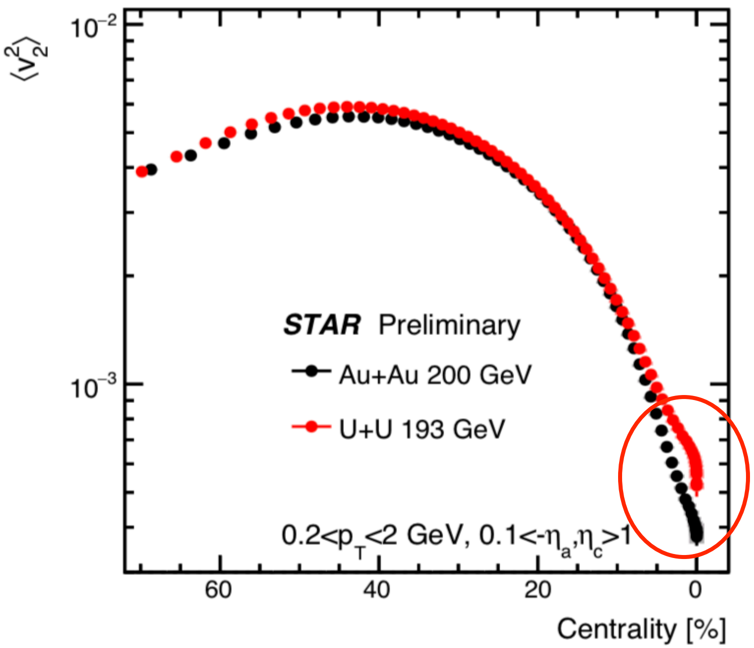
Collisions at $\sqrt{s_{NN}}$=193-200 GeV See:arXiv:2105.01638

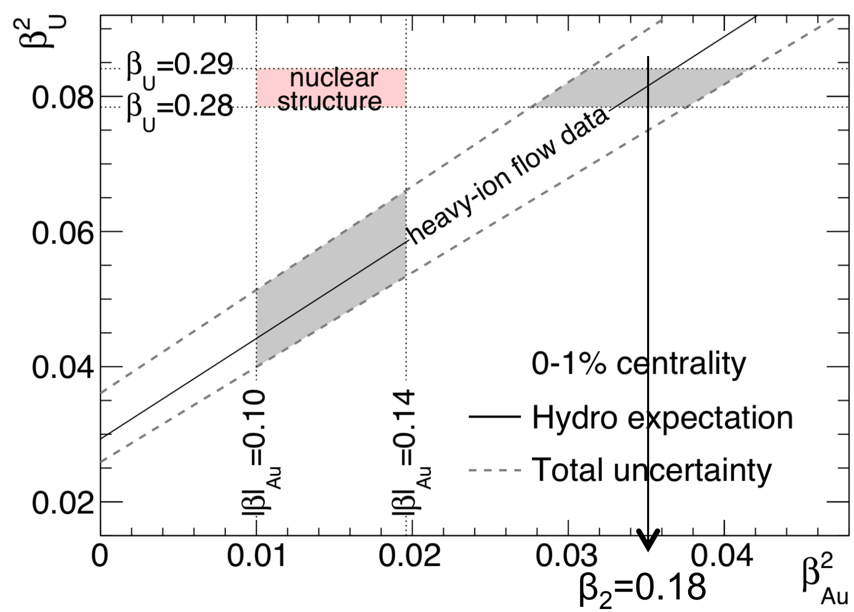



$$v^2_{2,\mathrm{Au}} = a_{\mathrm{Au}} + b\beta_2^2 \qquad v^2_{2,\mathrm{U}} = a_{\mathrm{U}} + b\beta_2^2$$

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 simple relation for $\beta_{2\mathrm{U}}$ and $\beta_{2\mathrm{Au}}$ : $\beta^2_{\mathrm{U}} = \frac{r_{v_2^2} r_a - 1}{b/a_{\mathrm{U}}} + r_{v_2^2}\beta^2_{\mathrm{Au}} \quad r_{v_2^2} = \frac{v^2_{2,\mathrm{U}}}{v^2_{2,\mathrm{Au}}}$




Suggests $|\beta_2|_{\mathrm{Au}}$~0.18+-0.02, larger than NS model of 0.13+-0.02
Note: 197Au is a odd-mass nuclei, $\beta_2$ not measured!

# How to do system (isobar) scan

arXiv:2106.08768

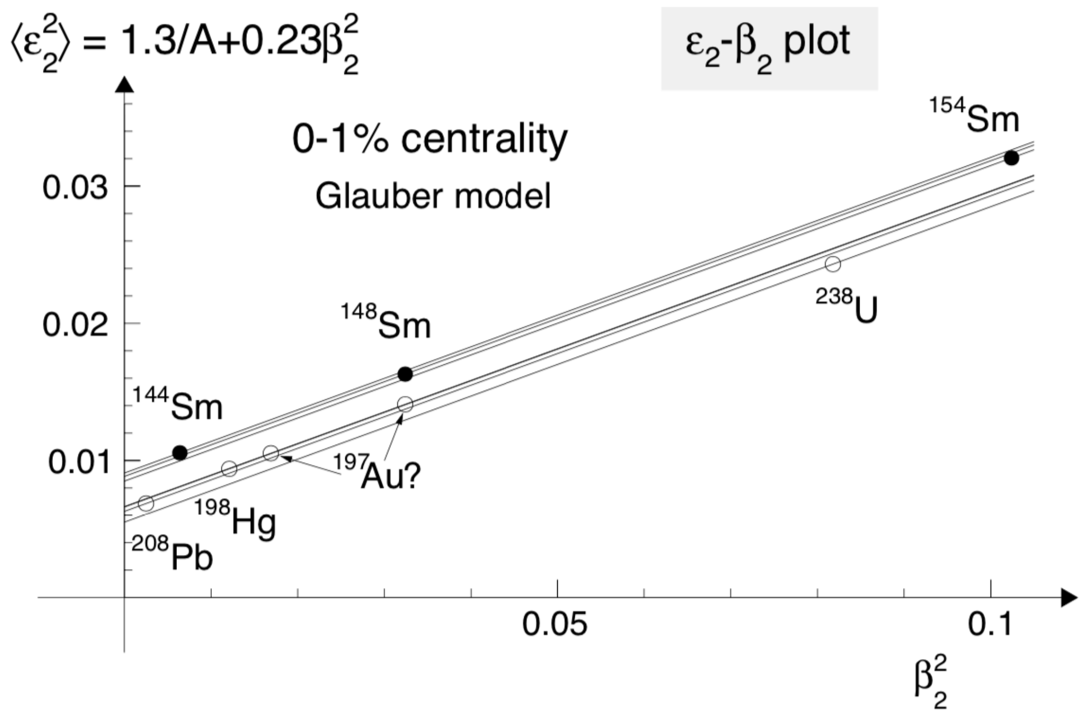
$$\left\langle \epsilon_2^2 \right\rangle = a' + b'\beta_2^2$$

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

In UCC 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.

Can fix the b and a with two isobar systems with known $\beta_2$, then make predictions for others.

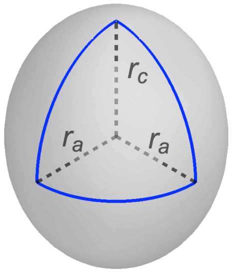
# Application: skewness

# Triaxiality γ:

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

## Prolate

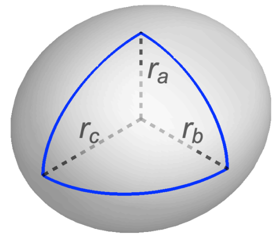
$\beta_2 = 0.25, \cos(3\gamma) = 1$




$r_a=r_b<r_c$

## Triaxial

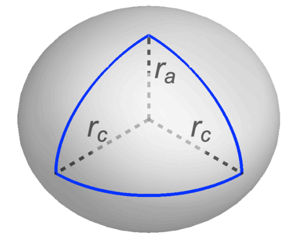
$\beta_2 = 0.25, \cos(3\gamma) = 0$



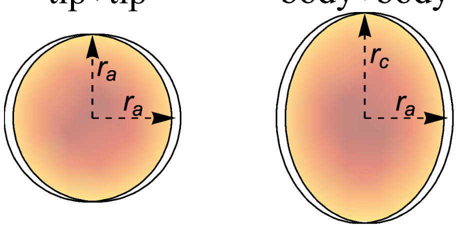

$2r_b=r_a+r_c$

## Oblate

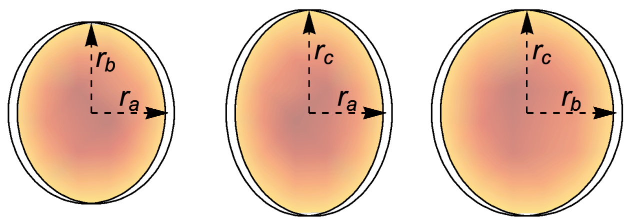
$\beta_2 = 0.25, \cos(3\gamma) = -1$



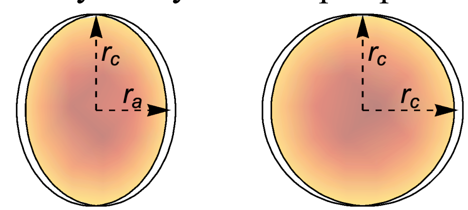

$r_a<r_b=r_c$




$\epsilon_2\downarrow, R_\perp\downarrow$ $\quad$ $\epsilon_2\uparrow, R_\perp\uparrow$




$\epsilon_2, R_\perp$ no linear correlation




$\epsilon_2\uparrow, R_\perp\downarrow$ $\quad$ $\epsilon_2\downarrow, R_\perp\uparrow$

$$\mathrm{cov}\left(\epsilon_2^2, R_\perp\right) > 0 \qquad \mathrm{cov}\left(\epsilon_2^2, R_\perp\right) = 0 \qquad \mathrm{cov}\left(\epsilon_2^2, R_\perp\right) < 0$$

$$\mathrm{cov}\left(\epsilon_2^2, d_\perp\right) < 0 \qquad \mathrm{cov}\left(\epsilon_2^2, d_\perp\right) = 0 \qquad \mathrm{cov}\left(\epsilon_2^2, d_\perp\right) > 0$$

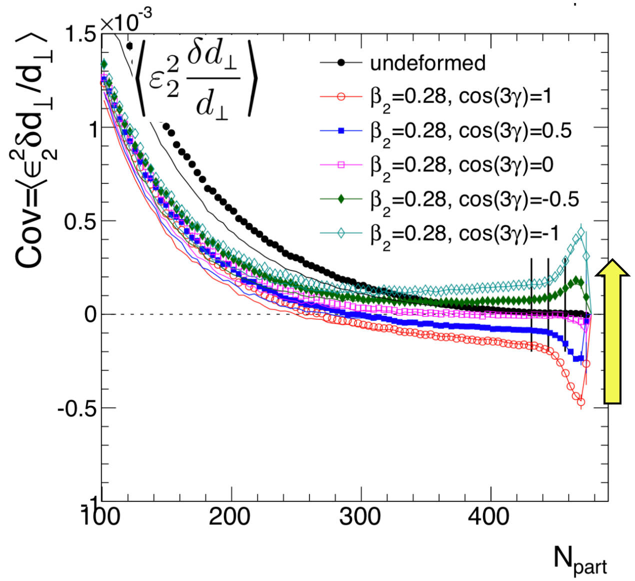
$$[p_T] \sim 1/R_\perp = d_\perp$$

# Influence of triaxiality on initial state

Skewness super sensitive to γ ☺

Described by

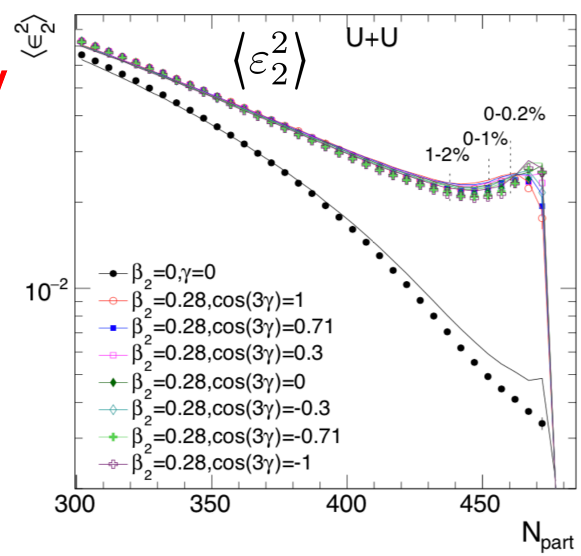
$$a' + (b' + c' \cos(3\gamma))\beta_2^3$$

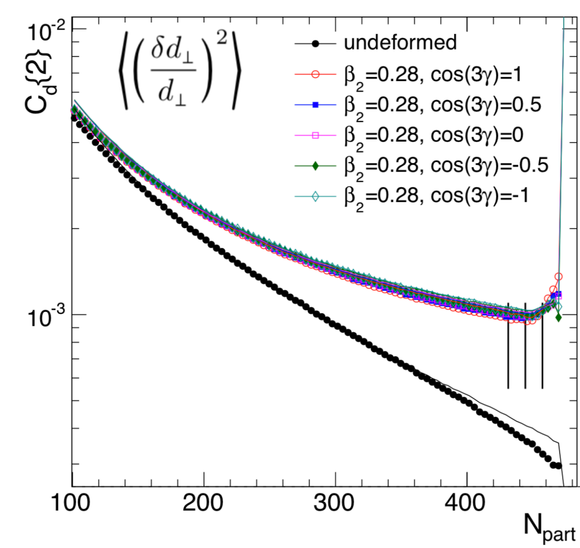



variances insensitive to γ

Only a function of $\beta_2$ in central

$$a' + b'\beta_2^2$$




Use variance to constrain $\beta_2$, use skewness to constrain γ

# ($\beta_2$,γ) diagram in heavy-ion collisions

The ($\beta_2$,γ) dependence in 0-1% U+U Glauber model can be approximated by:

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

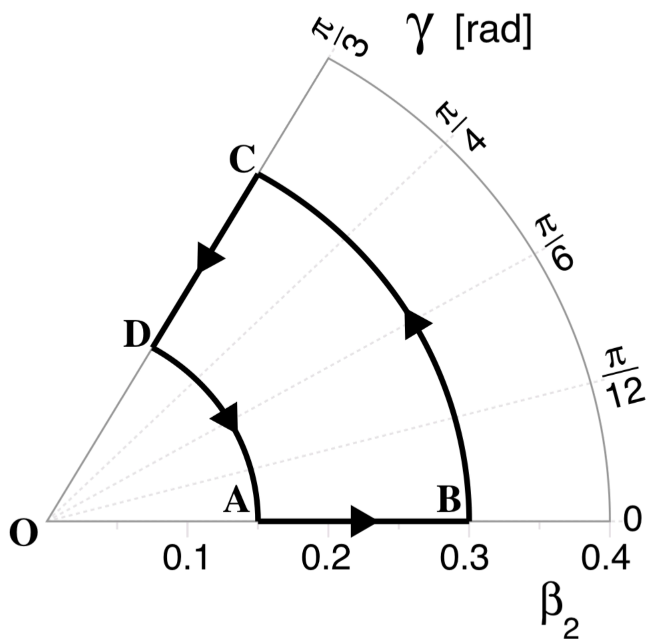
$$\langle (\delta d_\perp / d_\perp)^2 \rangle \approx [0.035 + \beta_2^2] \times 0.0093$$

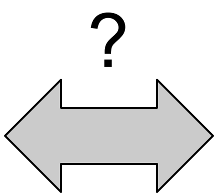
$$\langle \varepsilon_2^2 \delta d_\perp / d_\perp \rangle \approx [0.0005 - (0.07 + 1.36\cos(3\gamma))\beta_2^3] \times 10^{-2}$$

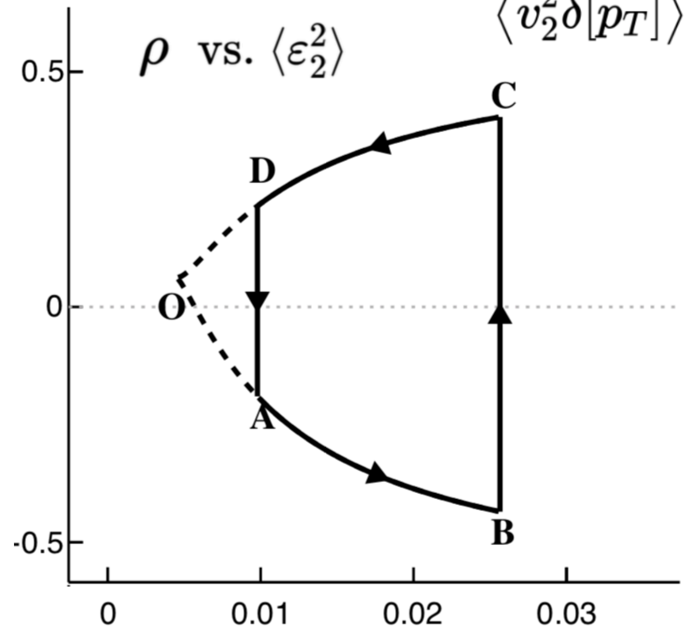
$$\rho = \frac{\langle \varepsilon_2^2 \delta d_\perp \rangle}{\langle \varepsilon_2^2 \rangle \sqrt{\langle (\delta d_\perp)^2 \rangle}}$$

Map from ($\beta_2$,γ) plane to HI observables

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

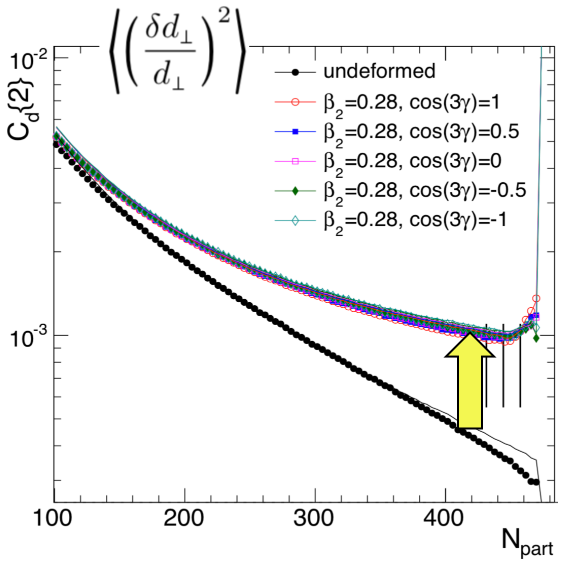


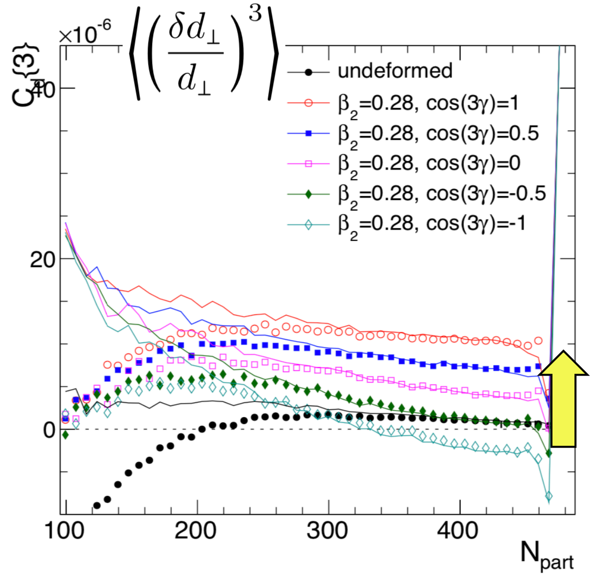



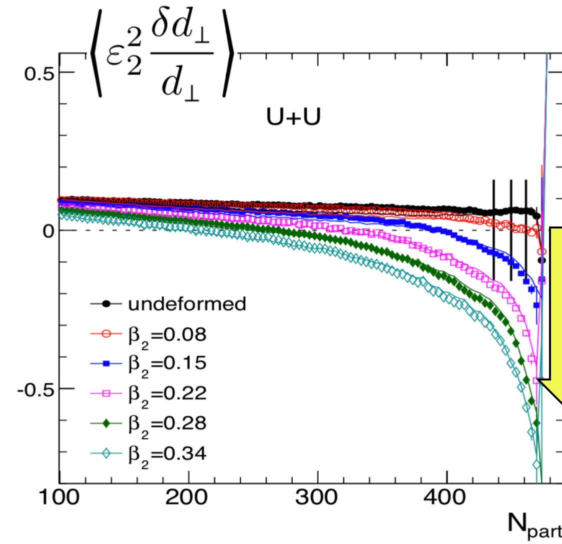




Collision system scan to map out this trajectory: calib. coefficients with species with known β,γ, then predict for species of interest.

# Contrast Glauber model with STAR data



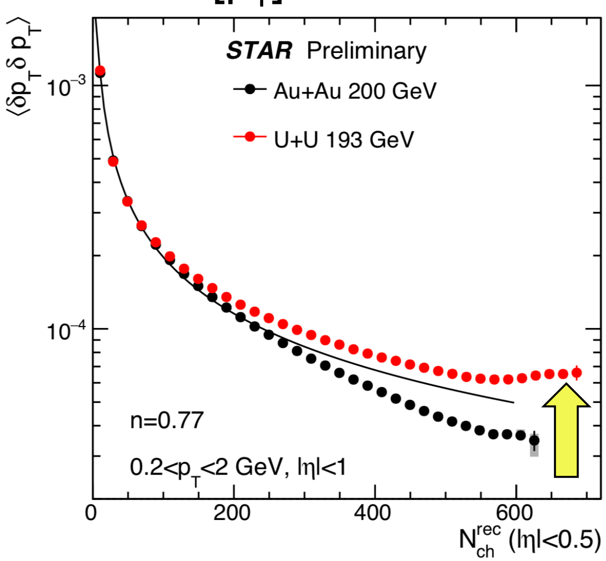



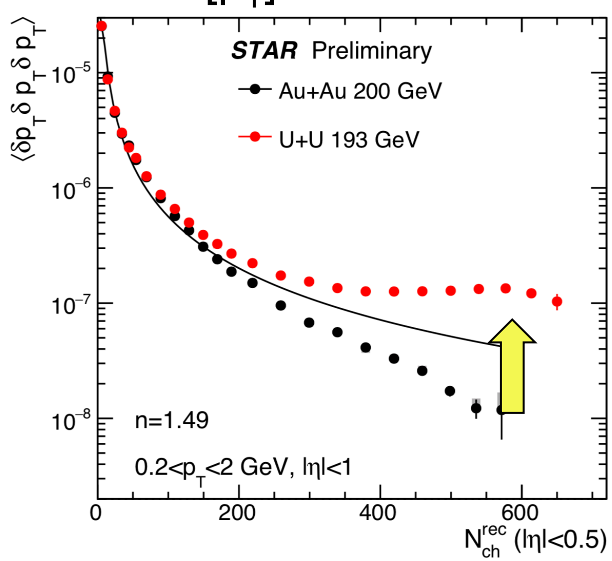



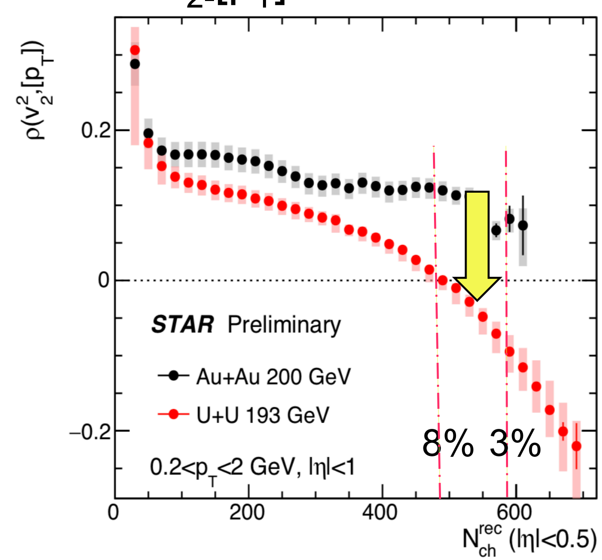

## $[p_T]$ variance

## $[p_T]$ skewness

## $v_2$-$[p_T]$ covariance



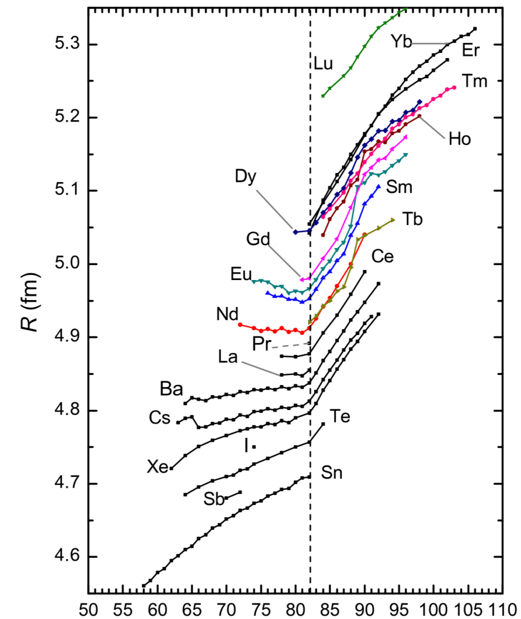




Require high-stat. hydro simulation to quantify the response!

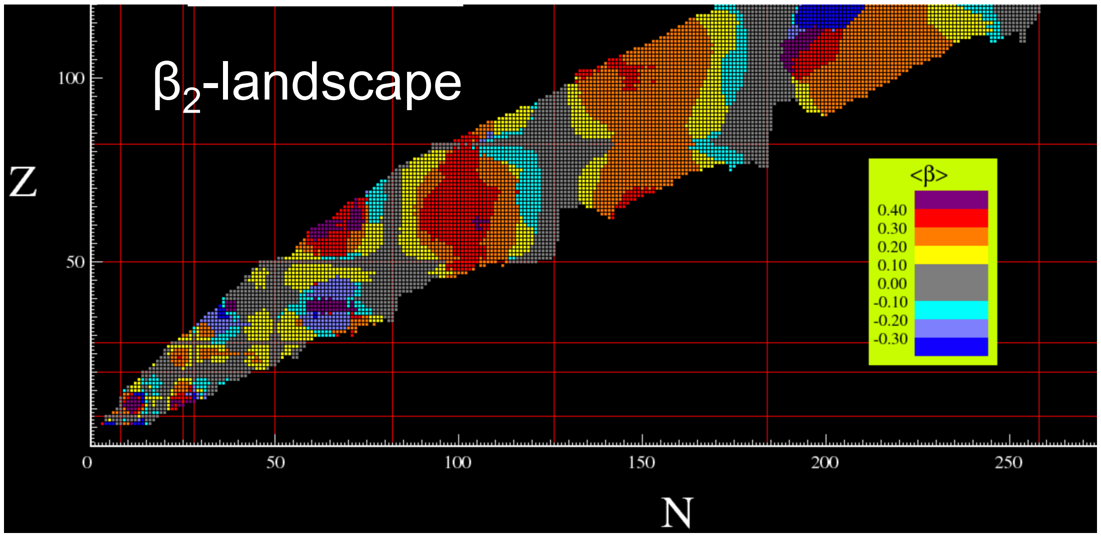
# shape/size landscapes from NS

Pretty much infinite possibilities.

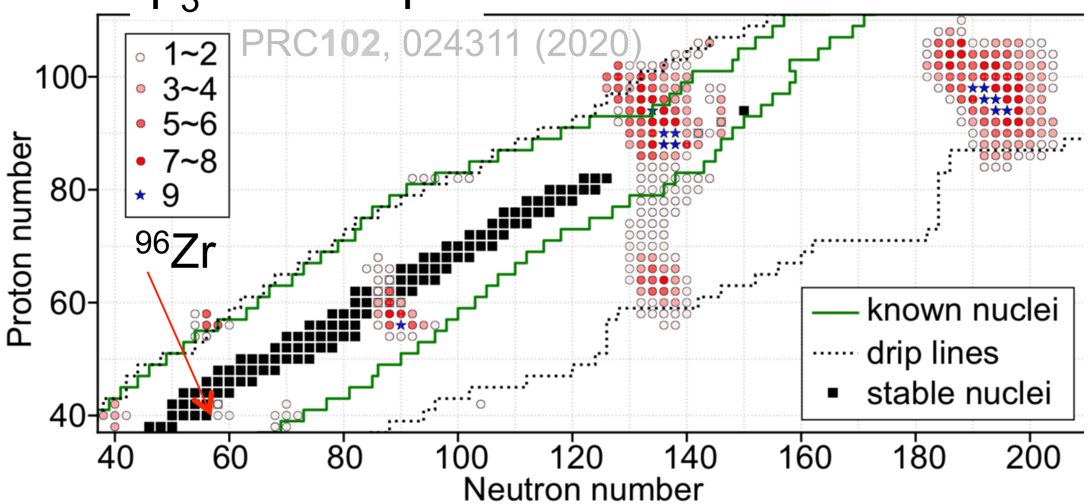
Radii-landscape



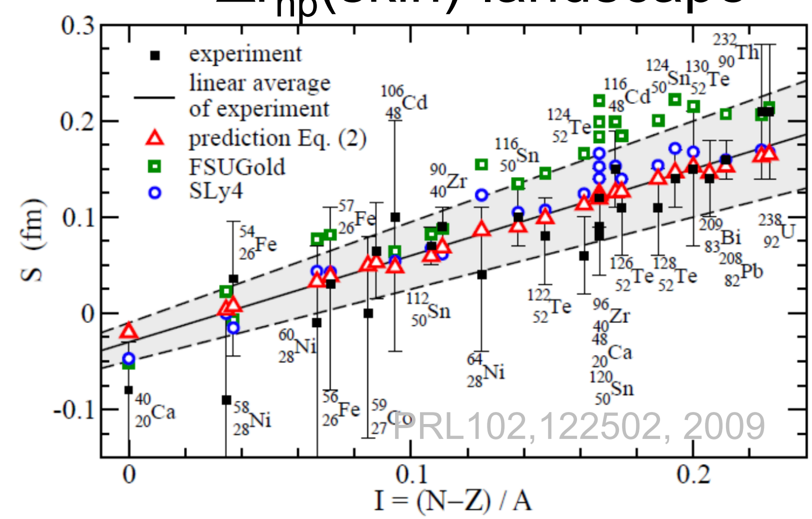

$\beta_2$-landscape




$\beta_3$-landscape




$\Delta r_{np}$(skin)-landscape



# sPHENIX BUR

Pretty much
Fixed in 2023-2025

| Year | Species | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $|z|$ <10 cm | Samp. Lum. $|z|$ <10 cm |
|---|---|---|---|---|---|---|
| 2023 | Au+Au | 200 | 24 (28) | 9 (13) | 3.7 (5.7) $nb^{-1}$ | 4.5 (6.9) $nb^{-1}$ |
| 2024 | $p^{\uparrow}p^{\uparrow}$ | 200 | 24 (28) | 12 (16) | 0.3 (0.4) $pb^{-1}$ [5 kHz]<br>4.5 (6.2) $pb^{-1}$ [10%-$str$] | 45 (62) $pb^{-1}$ |
| 2024 | $p^{\uparrow}$+Au | 200 | – | 5 | 0.003 $pb^{-1}$ [5 kHz]<br>0.01 $pb^{-1}$ [10%-$str$] | 0.11 $pb^{-1}$ |
| 2025 | Au+Au | 200 | 24 (28) | 20.5 (24.5) | 13 (15) $nb^{-1}$ | 21 (25) $nb^{-1}$ |

Potential BUR
2026–2027

| Year | Species | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $|z|$ <10 cm | Samp. Lum. $|z|$ <10 cm |
|---|---|---|---|---|---|---|
| 2026 | $p^{\uparrow}p^{\uparrow}$ | 200 | 28 | 15.5 | 1.0 $pb^{-1}$ [10 kHz]<br>80 $pb^{-1}$ [100%-$str$] | 80 $pb^{-1}$ |
| – | O+O | 200 | – | 2 | 18 $nb^{-1}$<br>37 $nb^{-1}$ [100%-$str$] | 37 $nb^{-1}$ |
| – | Ar+Ar | 200 | – | 2 | 6 $nb^{-1}$<br>12 $nb^{-1}$ [100%-$str$] | 12 $nb^{-1}$ |
| 2027 | Au+Au | 200 | 28 | 24.5 | 30 $nb^{-1}$ [100%-$str$/DeMux] | 30 $nb^{-1}$ |

# Proposal in STAR BUR

STAR Beam Use Request for RUN 2022-2025
https://drupal.star.bnl.gov/STAR/system/files/STAR_Beam_Use_Request_Runs22_25.pdf

- $\beta_n$ known mostly for even-even, but we collided several odd-mass ones ☹

A list of large systems from RHIC and LHC

| | $\beta_2$ | $\beta_3$ | $\beta_4$ | | $\beta_2$ | $\beta_3$ | $\beta_4$ |
|---|---|---|---|---|---|---|---|
| $^{238}$U | 0.286 [9] | 0.078 [10] | 0.094 [10] | $^{208}$Pb | 0.06 [9] | 0.04[11] | ? |
| $^{197}$Au | -(0.13-0.16) [12, 13] | ? | -0.03 [12] | $^{129}$Xe | 0.16 [12] | ? | ? |
| $^{96}$Ru | 0.16 [14] | ? | ? | $^{96}$Zr | 0.06 [14] | 0.20-0.27 | 0.06 [12] |

- Part1: calibrate systematics with two species around $^{197}$Au: $^{208}$Pb & $^{198}$Hg
  - $^{208}$Pb $\sqrt{s}$=0.2 vs $^{197}$Au $\sqrt{s}$=0.2 TeV: Quantify effects of Au deformation
    - $^{208}$Pb $\sqrt{s}$=0.2 RHIC vs 5 TeV @LHC: Precision on IS and pre-equlibrium dynamics
  - $^{198}$Hg $\sqrt{s}$=0.2 TeV: with known $\beta_2$ cross-check the consistency of $\beta_{2Au}$, $\gamma$ in $^{197}$Au.

5 days each opportunistically

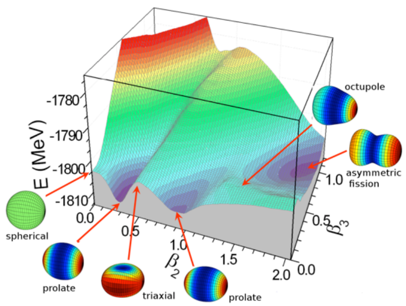
- Part2: explore more exotic regions for triaxial and octupole deformations
  - Scan a isotopic chain: $^{144}$Sm ($\beta_2$=0.08), $^{148}$Sm ($\beta_2$=0.14,triaxial), $^{154}$Sm ($\beta_2$=0.34)
    - These species are in region Z~56/N~88, where large octupole is expected/predicted.
  - Compare a pair with equal mass: $^{154}$Sm ($\beta_2$ = 0.34) and $^{154}$Gd ($\beta_2$ = 0.31)

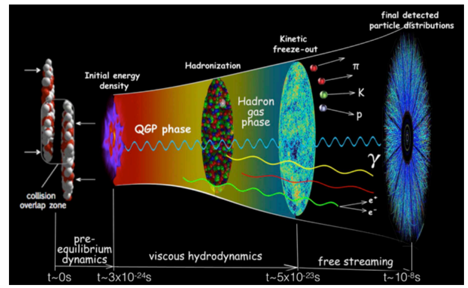
potentially for 2026

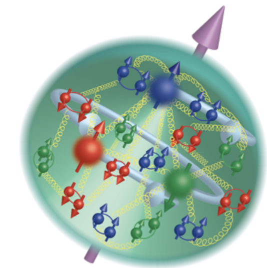
- Due to priority of sPHENIX, very limited possibility at RHIC. But maybe at LHC beyond 2030? and other heavy ion facilities?

# One concluding remark

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



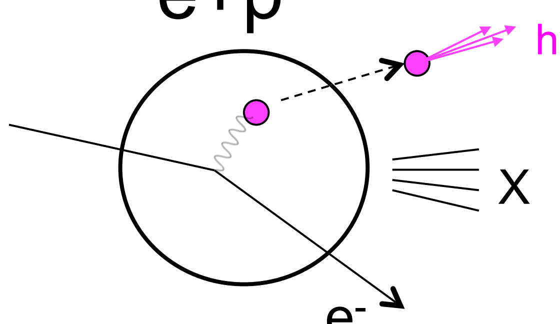



Nuclear structure | Heavy Ion physics | Partonic Structure

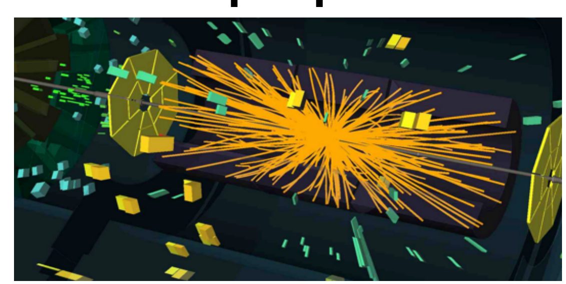
- Hydrodynamic flow is precise enough to provide feedback to NS and DIS in large A+A system.

- As tool & understanding of IS improve, possible even in p+A/pp?

e+p




p+p



HI-like event ~600 particles

# Open questions

- How are nuclear shape and radial profile inferred from hydrodynamic response related to properties measured in nuclear structure experiments?
- How does the uncertainty brought by nuclear structure impact the initial state of heavy-ion collisions and extraction of QGP transport properties?