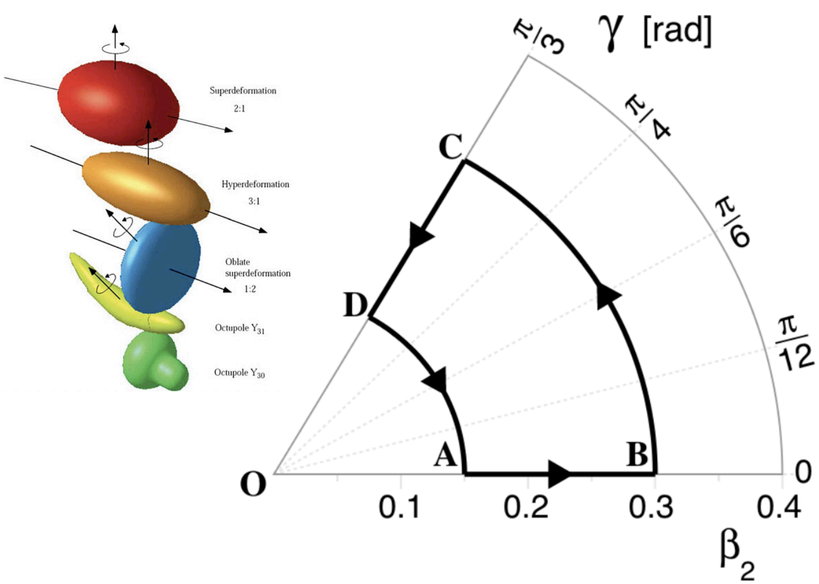
Stony Brook University | The State University of New York

Effects of nuclear structure in isobar collisions

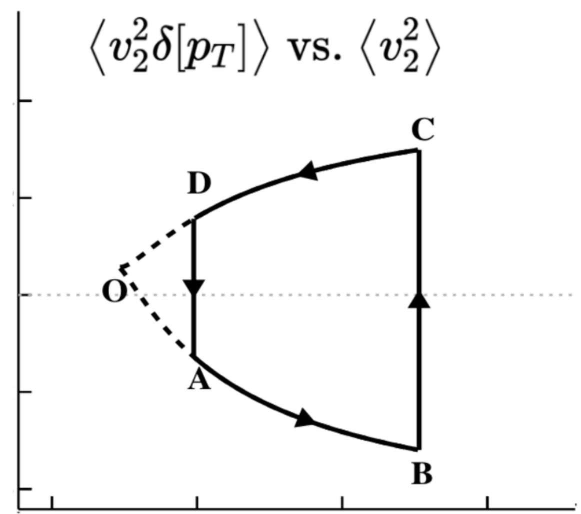
Jiangyong Jia

Nuclear structure



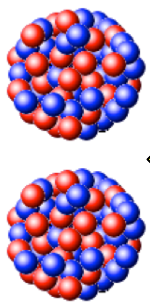
?

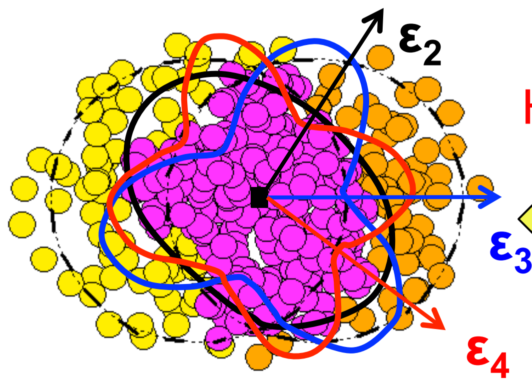
High-energy collisions

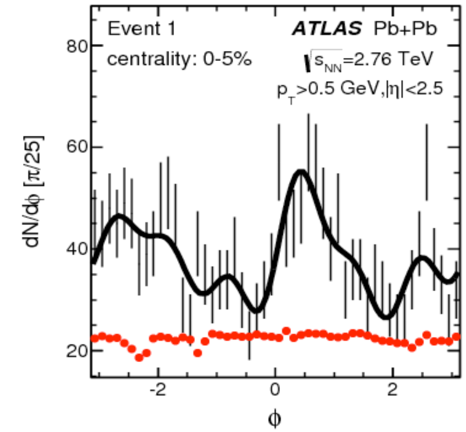


Hydrodynamic response to initial state

Nuclear Structure — Imaging? — **Initial State** — Hydro-response (Space-time dynamics) — **Final Particle flow**







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

- $\beta_2 \rightarrow$ Quadrupole deformation
- $\beta_3 \rightarrow$ Octupole deformation
- $a_0 \rightarrow$ Surface diffuseness
- $R_0 \rightarrow$ Nuclear size

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...

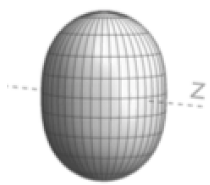
Shape of nuclei

Most ground state stable nuclei are deformed

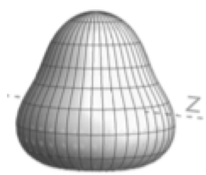
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

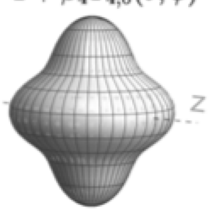
Quadrupole: $1+\beta_2 Y_{2,0}(\theta,\phi)$



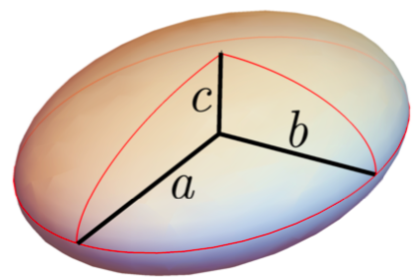
Octupole: $1+\beta_3 Y_{3,0}(\theta,\phi)$



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



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



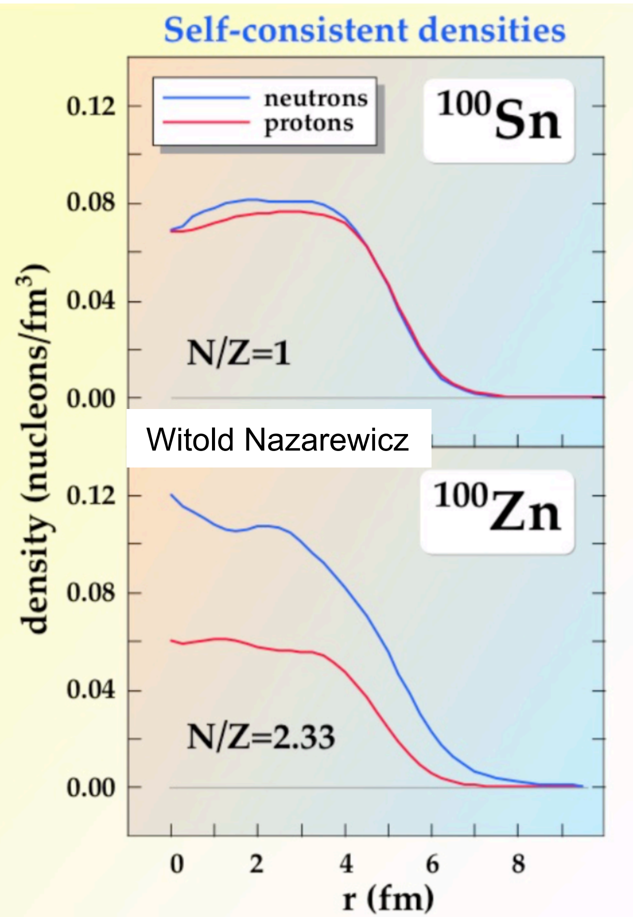
$0 \leq \gamma \leq \pi/3$

Prolate: a=b<c → β_2, $\gamma=0$

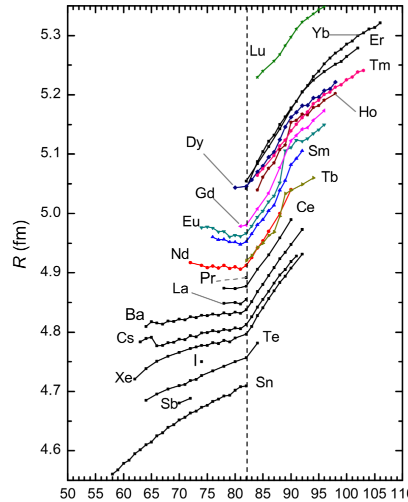
Oblate: a<b=c → β_2, $\gamma=\pi/3$ or $-\beta_2$, $\gamma=0$

Radial structure of nuclei

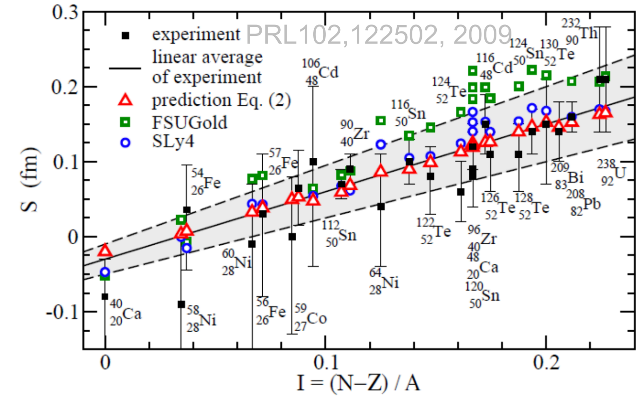
$$\rho = \frac{\rho_0}{1 + e^{(r - R_0(1+\sum_n \beta_n Y_n^0(\theta,\phi))/a_0}}$$



R_0

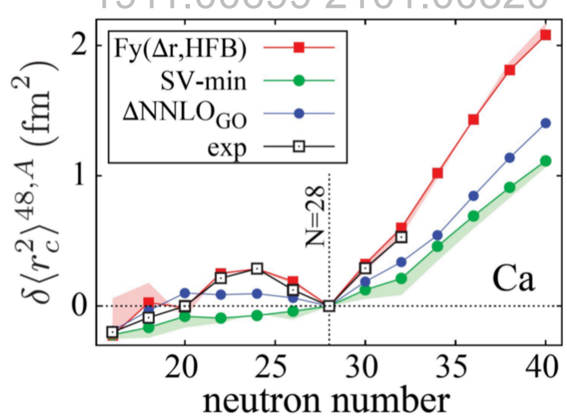


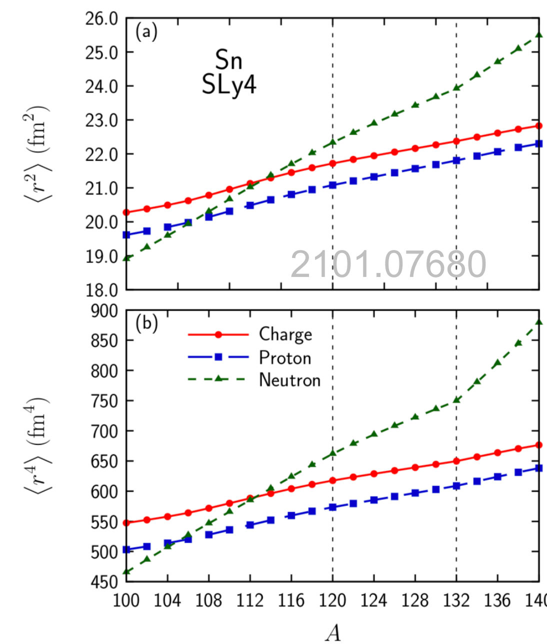
$\Delta r_{np}=R_n-R_p$.



Higher radial moments

1911.00699 2101.00320





Isobar collisions as precision tool

- Unique running mode of RHIC and STAR to minimize the detector systematics
  - 0.4% precision is achieved in ratio of many observables between two isobar systems→ precision imaging tool

A key question for any HI observable O

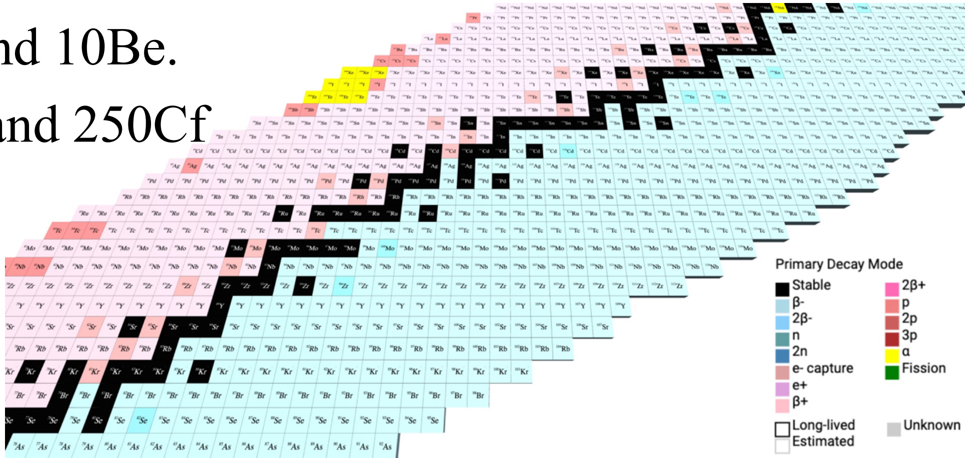
$$\frac{O_{\mathrm{X+X}}}{O_{\mathrm{Y+Y}}} \stackrel{?}{=} 1$$

$${}^{A}\mathrm{X} + {}^{A}\mathrm{X}\ vs\ {}^{A}\mathrm{Y} + {}^{A}\mathrm{Y}$$

Deviation from 1 must has its origin in the nuclear structure, which is reflected by the initial state and then survives the final state. A precision tool to study initial state and final state responses

- Many such pairs of isobars in the nuclear chart.
  - Small system isobar such as 10B and 10Be.
  - Large system isobar up to 250Cm and 250Cf

Can help many heavy ion physics questions



Parametric forms: nuclear shape

2109.00604

- ε_n has the form $\boldsymbol{\epsilon}_n = \boldsymbol{\epsilon}_{n;0} + \sum_{m=2}^{4} \boldsymbol{p}_{n;m}(\Omega_1, \Omega_2)\beta_m + \mathcal{O}(\beta^2)$

  $\underbrace{\boldsymbol{\epsilon}_{n;0}}_{\text{undeformed}}$, $\underbrace{\boldsymbol{p}_{n;m}(\Omega_1, \Omega_2)}_{\text{phase factor}}$

- $R_\perp^2 = \langle x^2 \rangle + \langle y^2 \rangle$ has the form $\delta d_\perp / d_\perp = \delta_d + \sum_{m=2}^{4} p_{0;m}(\Omega_1, \Omega_2)\beta_m + \mathcal{O}(\beta^2)$

  $d_\perp \equiv 1/R_\perp$

- Two particle correlation

$$\left\langle \varepsilon_n^2 \right\rangle \approx \left\langle \varepsilon_{n;0}^2 \right\rangle + \sum_{m,m'} \left\langle \boldsymbol{p}_{n;m} \boldsymbol{p}_{n;m'}^* \right\rangle \beta_m \beta_{m'} \qquad \left\langle \left(\frac{\delta d_\perp}{d_\perp} \right)^2 \right\rangle \approx \left\langle \delta_d^2 \right\rangle + \sum_{m,m'} \left\langle p_{0;m} p_{0;m'} \right\rangle \beta_m \beta_{m'}$$

- In reality for medium size nucleus and ignore β_4.

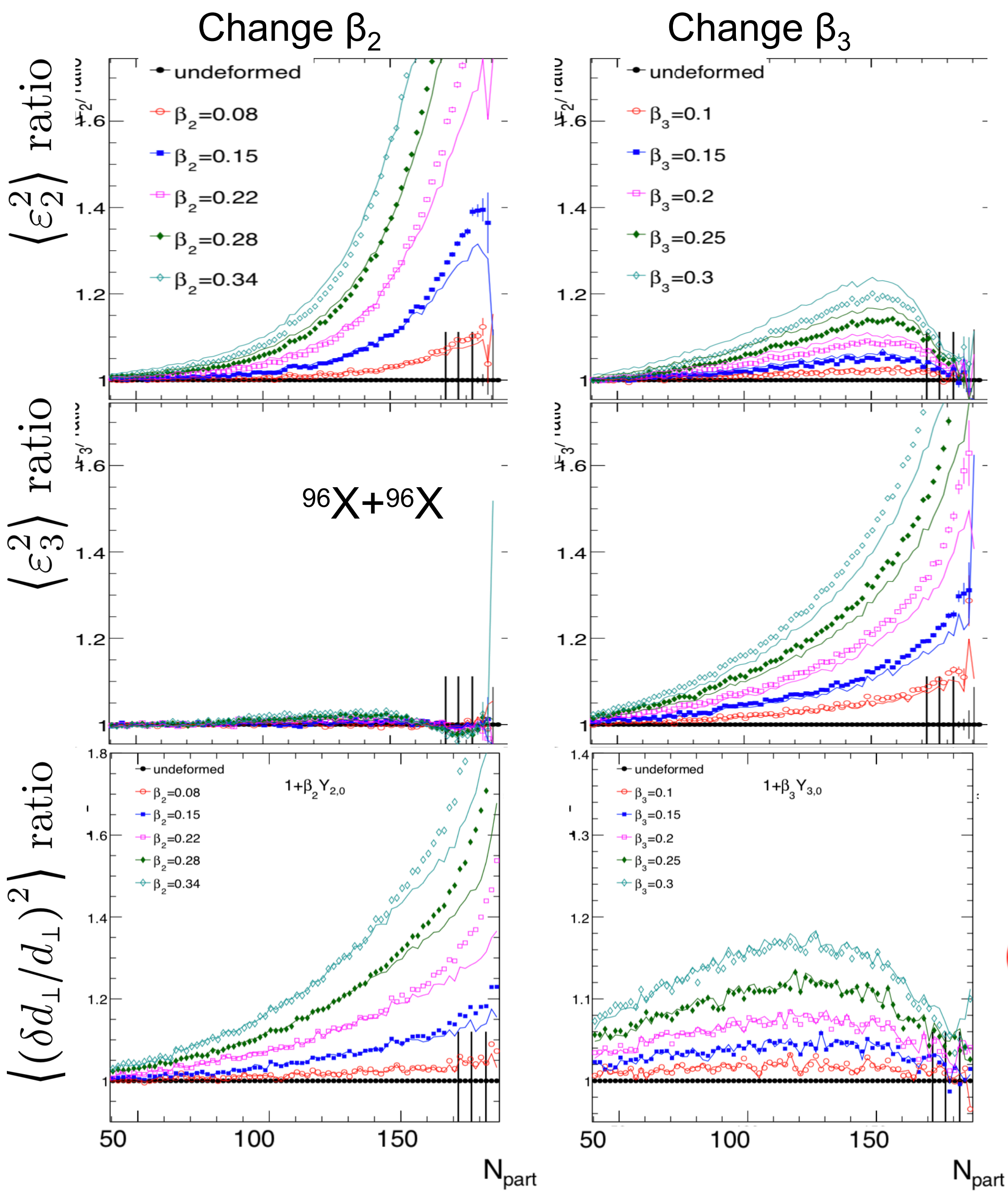
$$\left\langle \varepsilon_2^2 \right\rangle = a_2' + b_2' \beta_2^2 + b_{2,3}' \beta_3^2 \quad \left\langle \varepsilon_3^2 \right\rangle = a_3' + b_3' \beta_3^2$$

$$\left\langle (\delta d_\perp / d_\perp)^2 \right\rangle = a_0' + b_0' \beta_2^2 + b_{0,3}' \beta_3^2$$

- Again linear response to relate to final state: $v_n \propto \varepsilon_n \quad \frac{\delta [p_T]}{[p_T]} \propto \frac{\delta d_\perp}{d_\perp}$

Parametric dependence

See 2106.08768



medium size system:

$$\varepsilon_2^2 = a_2' + b_2'\beta_2^2 + b_{2,3}'\beta_3^2$$

$$\varepsilon_3^2 = a_3' + b_3'\beta_3^2$$

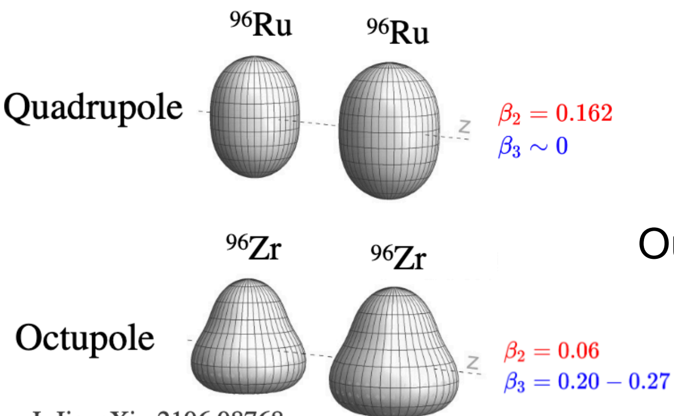
$$(\delta d_\perp/d_\perp)^2 = a_0' + b_0'\beta_2^2 + b_{0,3}'\beta_3^2$$

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

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

$$(\delta p_\mathrm{T}/p_\mathrm{T})^2 = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

Expectation of some ratios in isobar



J. Jia, aXiv:2106.08768

H. Xu, et.al. 2103.05595

^{96}Ru		^{96}Zr	
R	a	R	a
5.065	0.485	4.961	0.544

Our choice:

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02

$\Delta R = +0.07$ fm

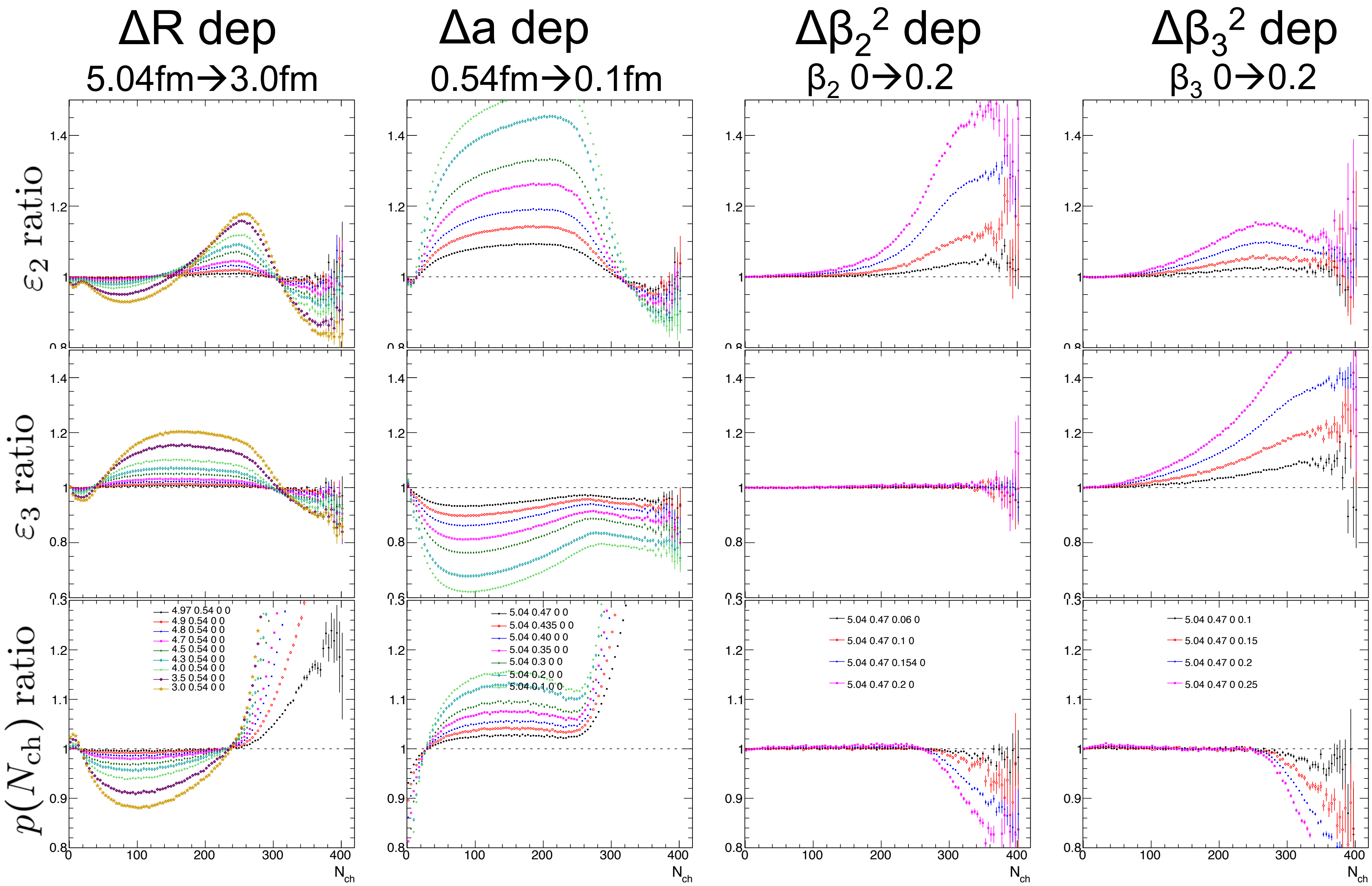
$\Delta a = -0.06$ fm

Heavy ion expectation: $$\frac{v^2_{n,\mathrm{Ru}}}{v^2_{n,\mathrm{Zr}}} \approx 1 + \frac{b_{n,2}}{a_n}(\beta^2_{2,\mathrm{Ru}} - \beta^2_{2,\mathrm{Zr}}) + \frac{b_{n,3}}{a_n}(\beta^2_{3,\mathrm{Ru}} - \beta^2_{3,\mathrm{Zr}})$$

In general: $$\frac{v_{n,\mathrm{Ru}}}{v_{n,\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta a + c_4\Delta R$$ $$c_1 = \frac{b_{n,2}}{2a_n} \quad c_2 = \frac{b_{n,3}}{2a_n}$$

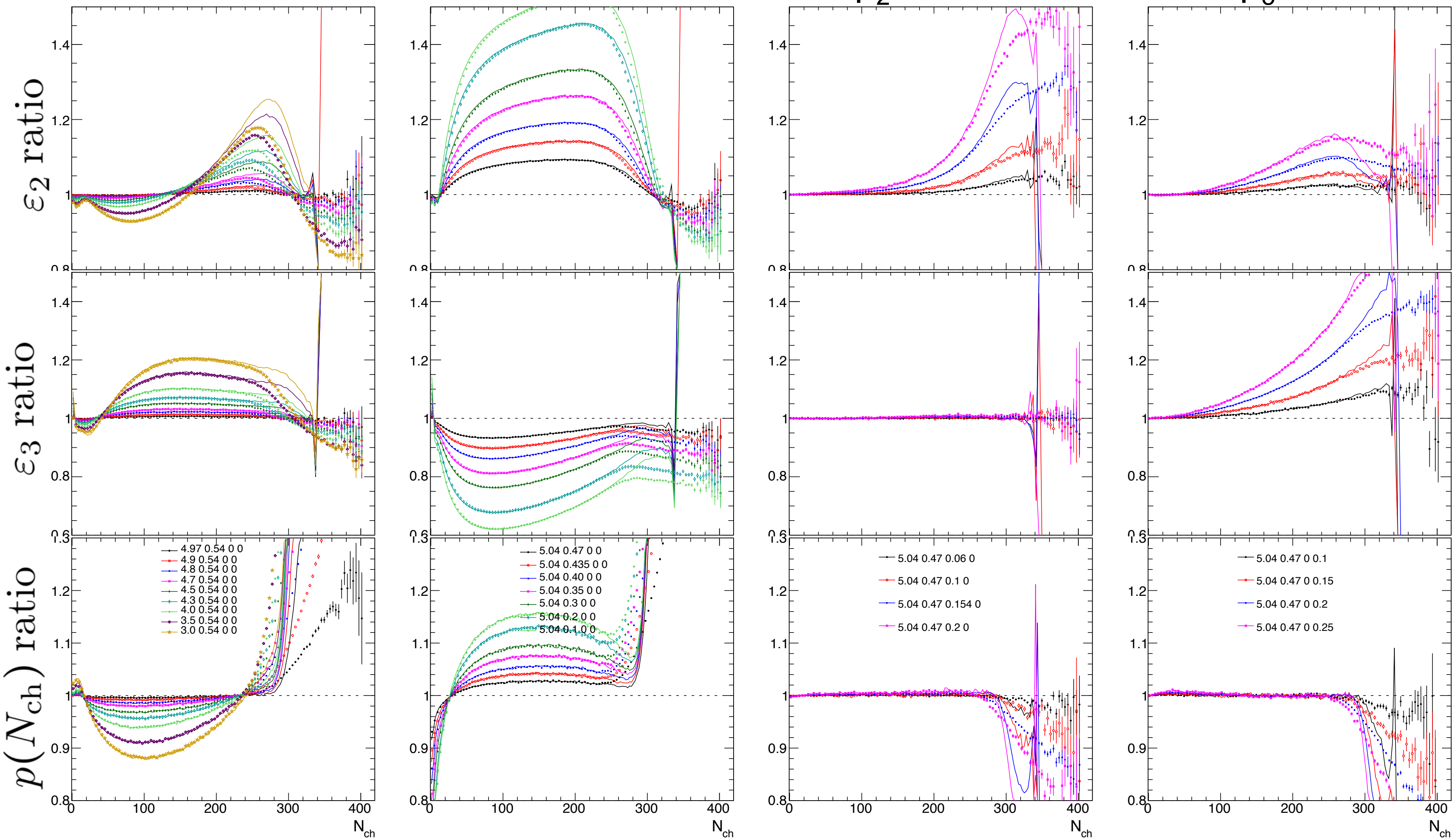
Similarly:
$$\frac{(\delta p_\mathrm{T}/p_\mathrm{T})^2_\mathrm{Ru}}{(\delta p_\mathrm{T}/p_\mathrm{T})^2_\mathrm{Zr}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta a + c_4\Delta R$$
$$\frac{p(N_\mathrm{ch})_\mathrm{Ru}}{p(N_\mathrm{ch})_\mathrm{Zr}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta a + c_4\Delta R$$

Glauber results: N_{ch} dep



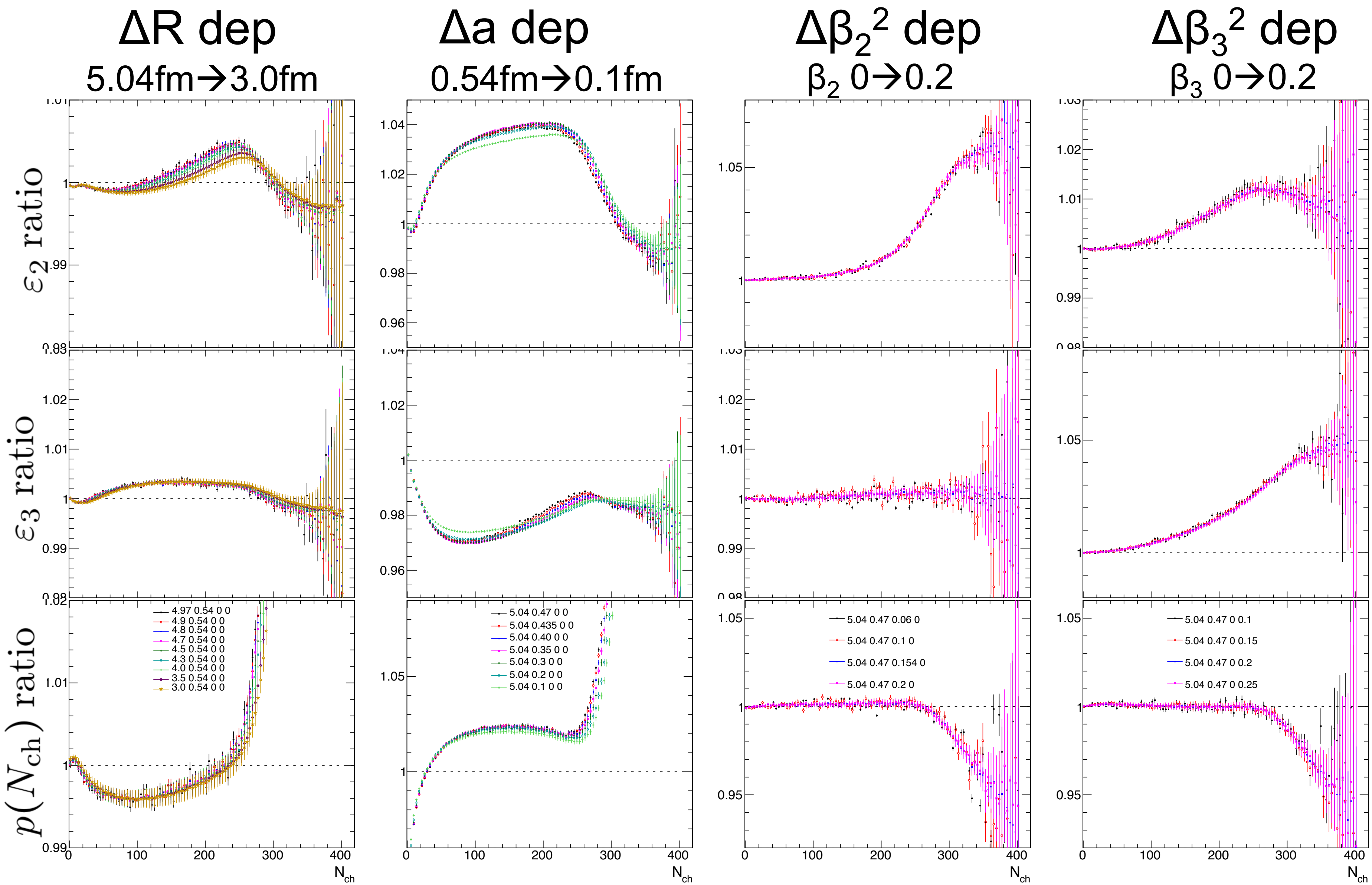
Glauber results: N_{ch} vs N_{qp} dep

ΔR dep	Δa dep	$\Delta\beta_2^2$ dep	$\Delta\beta_3^2$ dep
5.04fm→3.0fm	0.54fm→0.1fm	β_2 0→0.2	β_3 0→0.2



Particle production does not change shape in mid-central

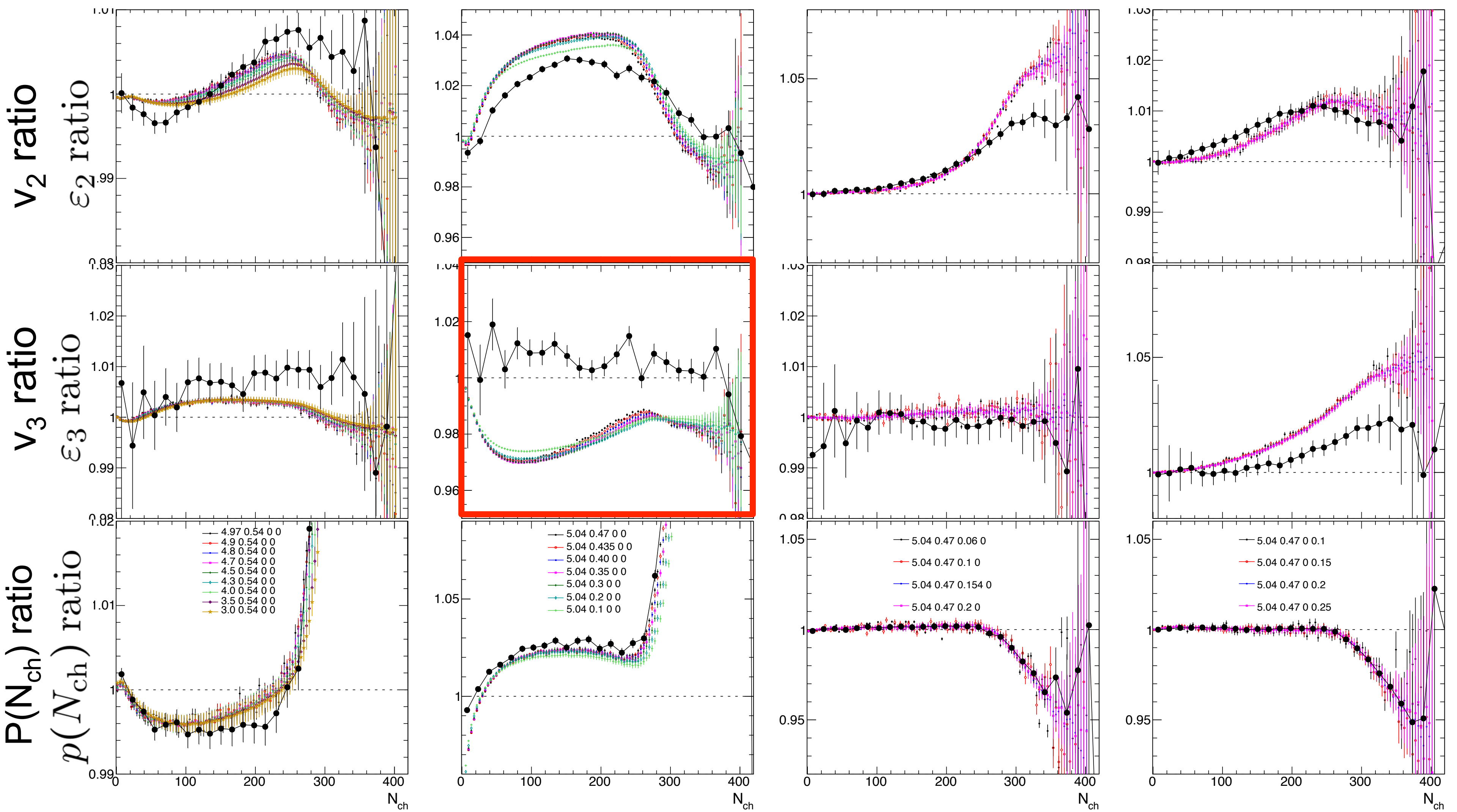
Glauber results scaled



Verifies the relation: $1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta a + c_4 \Delta R$

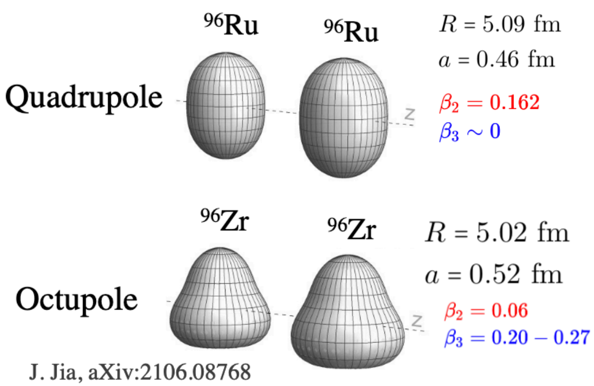
Compare with AMPT final state results

Final state ratio follow similar trends as data. Except one

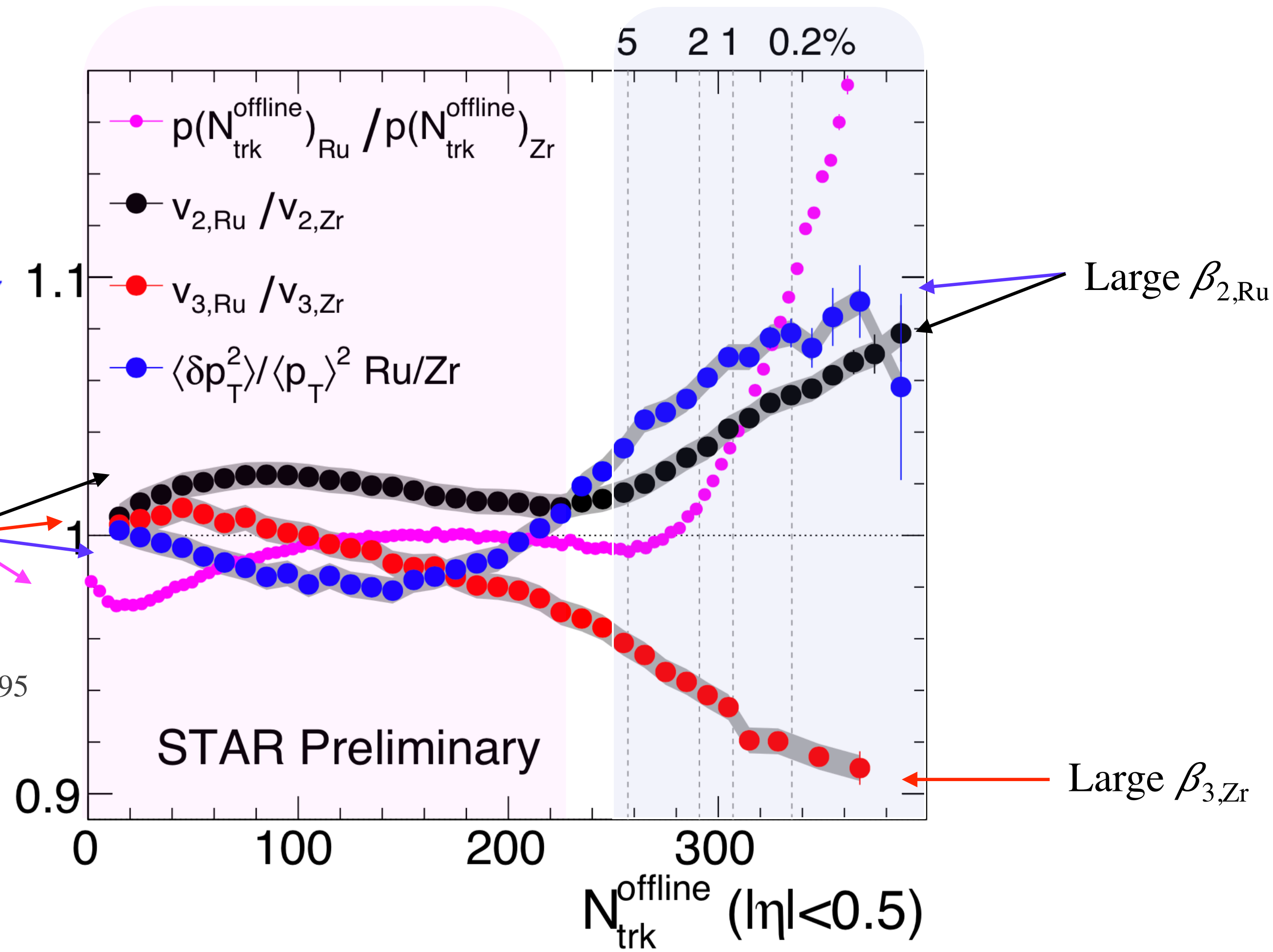


Note: Glauber model implemented in AMPT can be improved

Compare with isobar data



from Chunjian Zhang DNP STAR talk

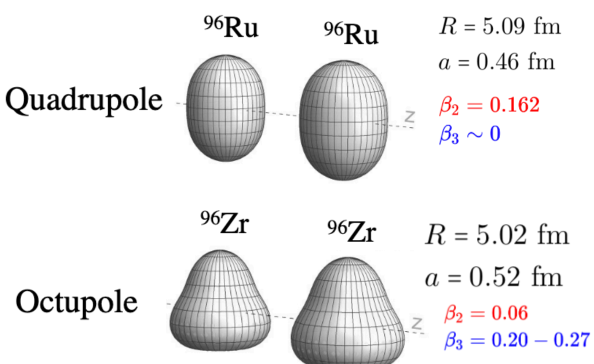


Nuclear deformation
+ Radial structures

STAR, arXiv:2109.00131
H. Xu et al., arXiv:1808.06711, 2103.05595
Q. Shou et al., arXiv:1409.8375
C. Zhang et al., arXiv:2109.01631
G. Giacalone et al., 2105.01638

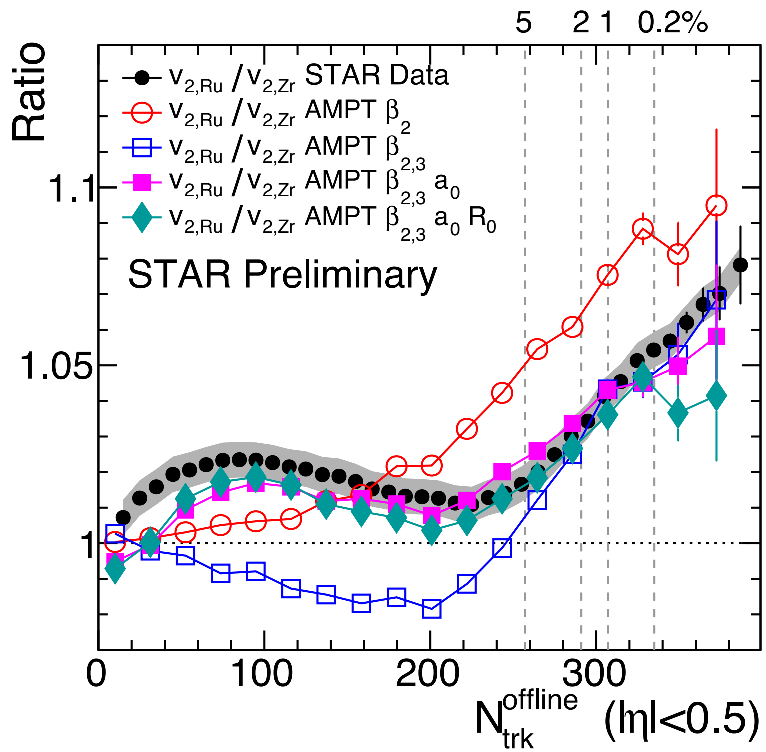
Use these ratios to probe shape and radial structure of nuclei.

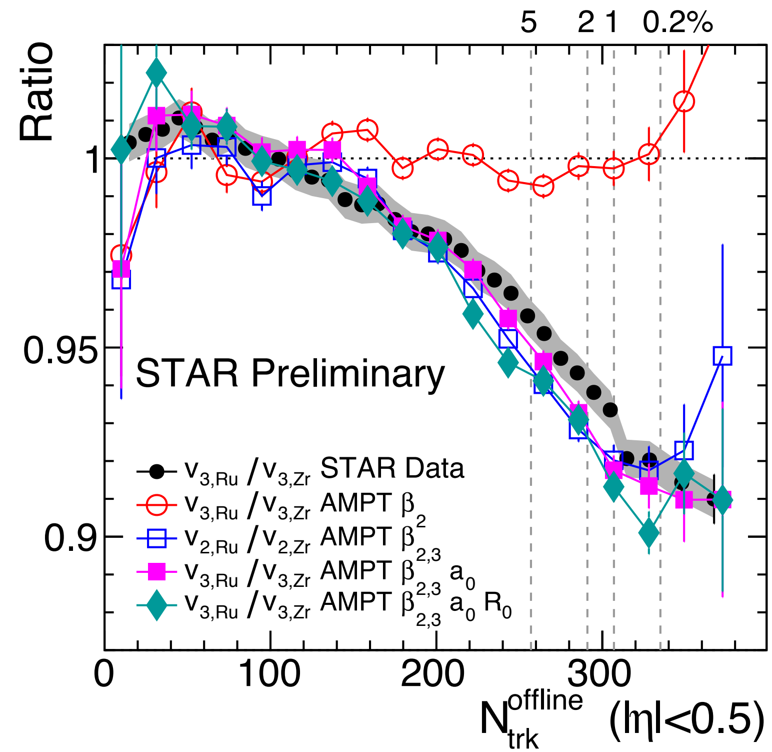
Nuclear structure via v_n-ratio



J. Jia, aXiv:2106.08768

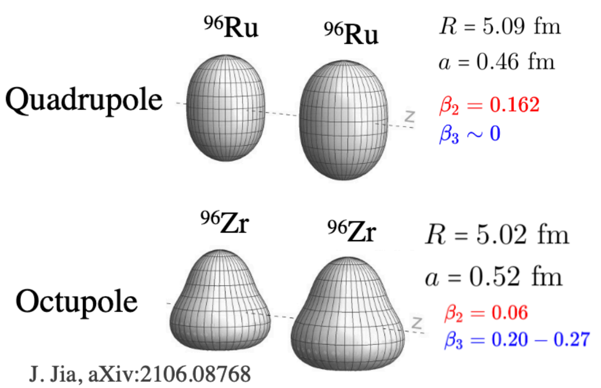
- β_{2Ru}~0.16 increase v_2, no influence on v_3 ratio
- β_{3Zr}~0.2 decrease v_2 in mid-central, decrease v_3 ratio
- diffu. Δa_0=-0.06fm increase v_2 mid-central, no influe. on v_3.
  - Similar study by Haojie et.al.
- Radius ΔR_0=0.07fm only slightly affects v_2 and v_3 ratio.





Simultaneously constrain these parameters using different N_{ch} regions

Nuclear structure via v_n-ratio



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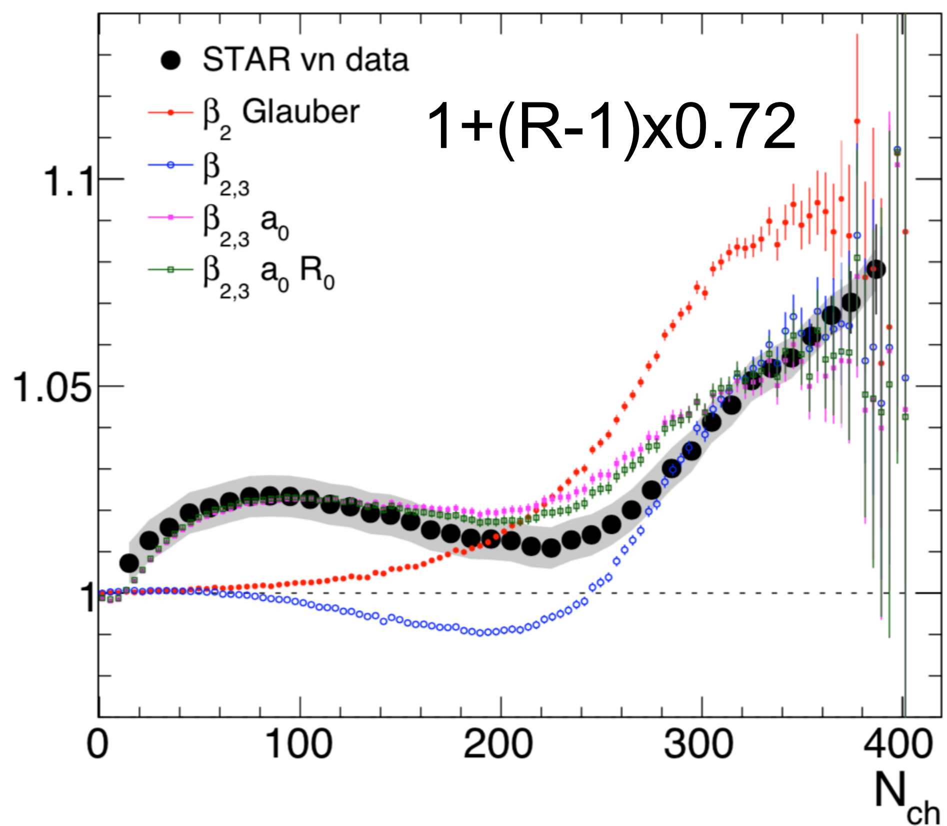
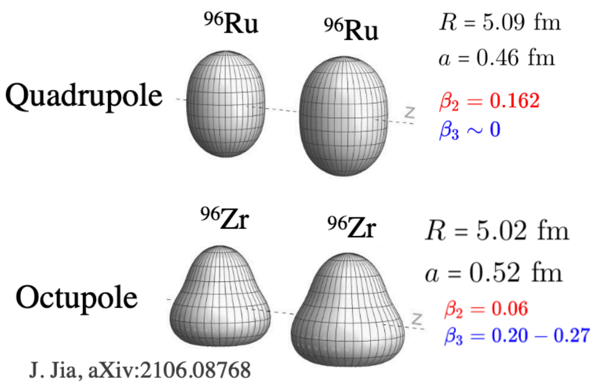
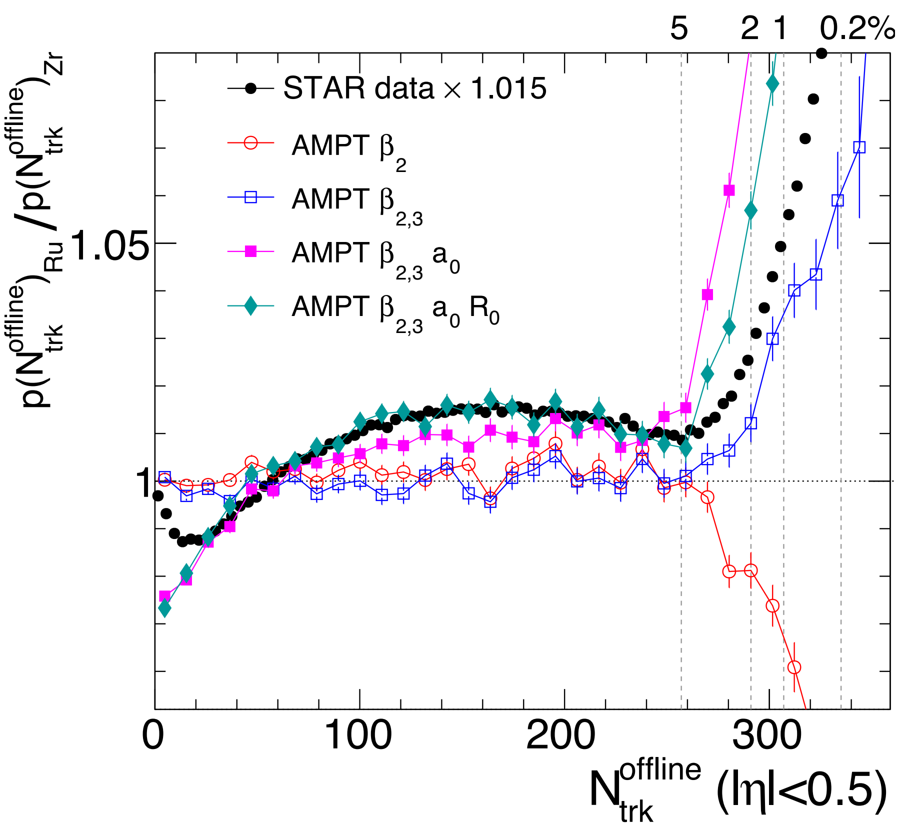
  - Similar study by Haojie et.al.
- Radius ΔR_0=0.07fm only slightly affects v_2 and v_3 ratio.
- Trends are reproduced by Glauber model with rescaling signal down by 0.72.



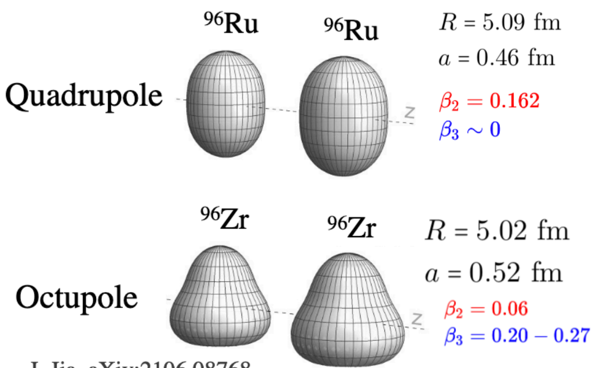
Nuclear structure via $p(N_{ch})$-ratio



- β_{2Ru}~0.16 decrease ratio, increase after considering β_{3Zr}~0.2
- The bump structure in non-central region mostly sensitive to differences in surface diffuseness Δa_0 and radius ΔR_0

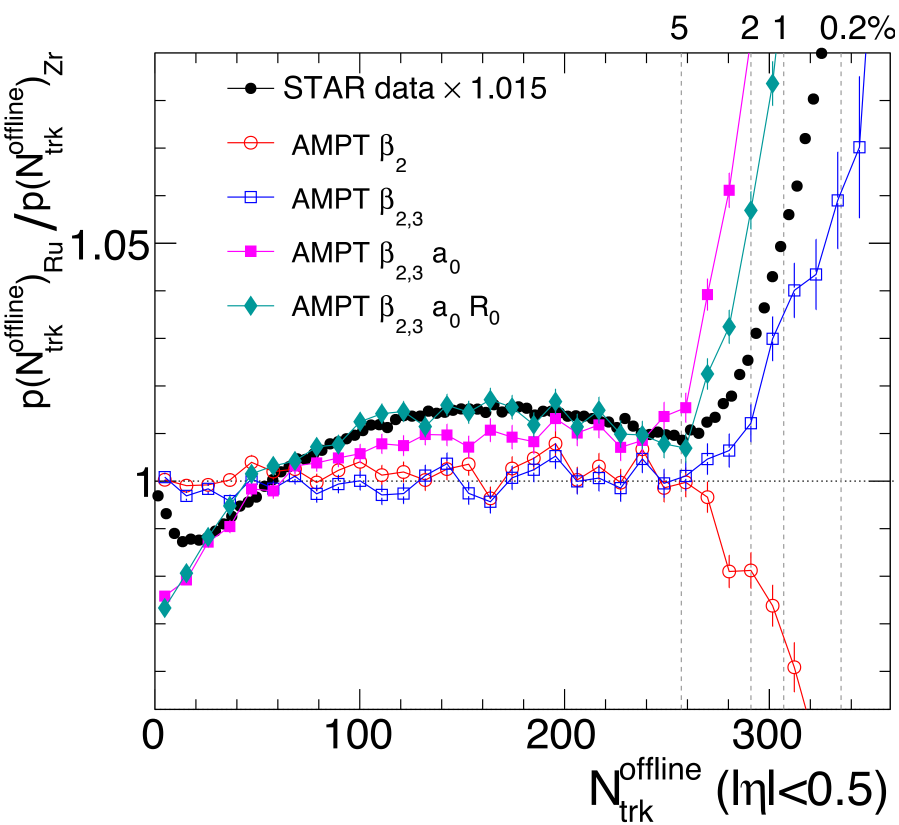


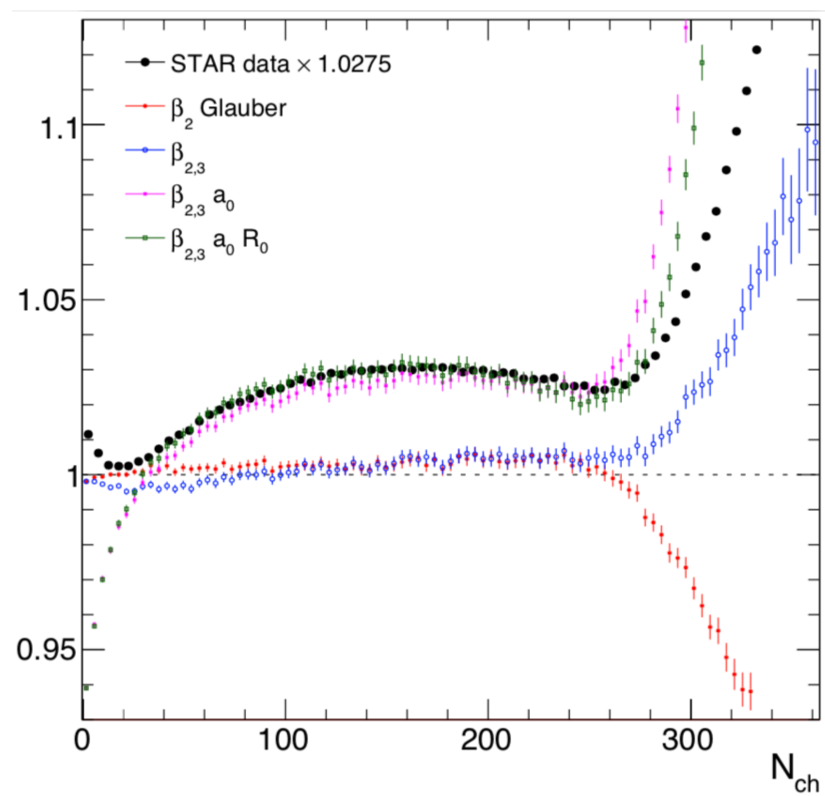
Nuclear structure via p(N_{ch})-ratio



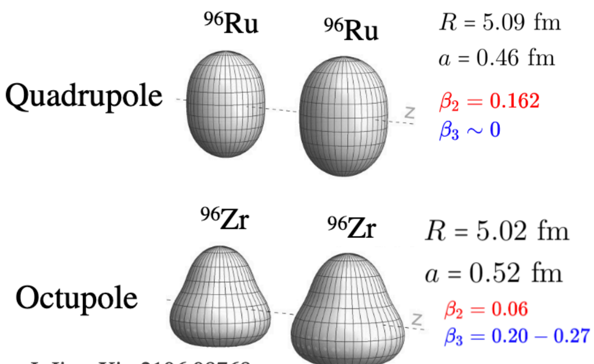
J. Jia, aXiv:2106.08768

- β_{2Ru}~0.16 decrease ratio, increase after considering β_{3Zr}~0.2
- The bump structure in non-central region mostly sensitive to differences in surface diffuseness Δa_0 and radius ΔR_0
- All these trends are quantitatively reproduced by Glauber
  - Note the normalization is sensitive to trigger efficiency!!
  - See related study by Haojie et.al.



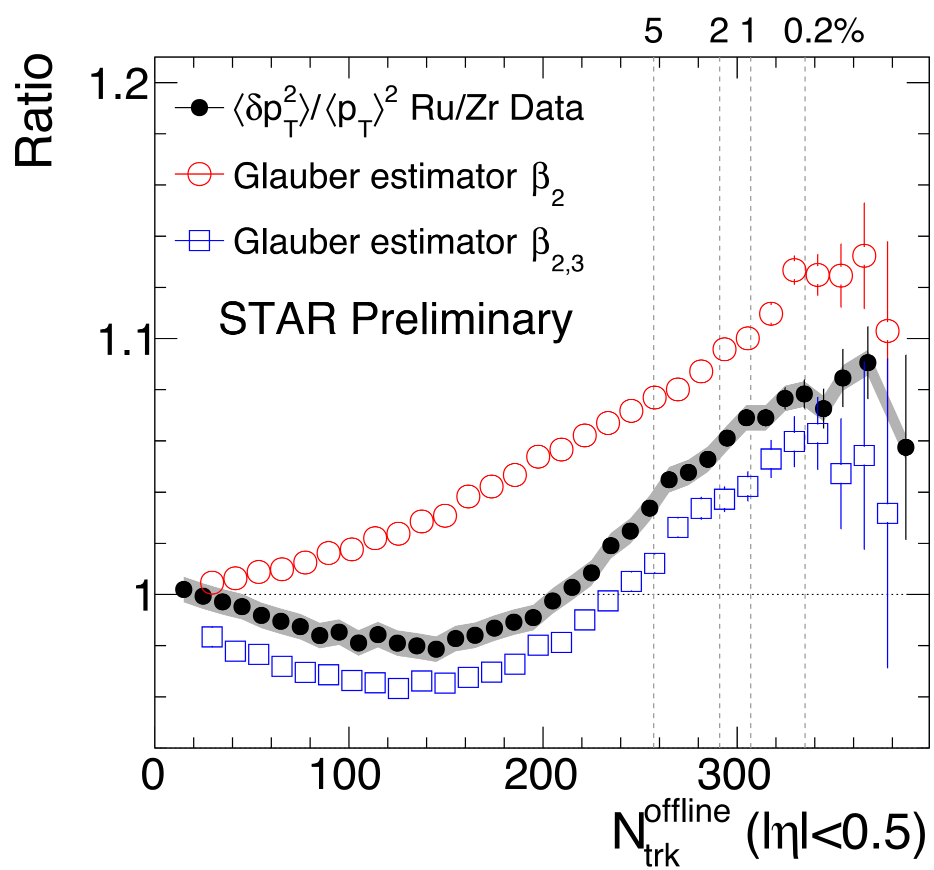


Nuclear structure via p_T fluctuations

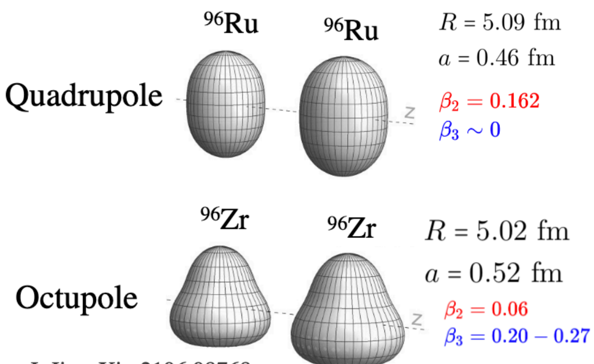


J. Jia, aXiv:2106.08768

- Glauber model is used by assuming $\frac{\delta[p_T]}{[p_T]} \propto \frac{\delta d_\perp}{d_\perp}$
- β_{2Ru}~0.16 increase ratio while β_{3Zr}~0.2 decrease it
- AMPT has wrong <pT> responses (see 2109.00604), but..

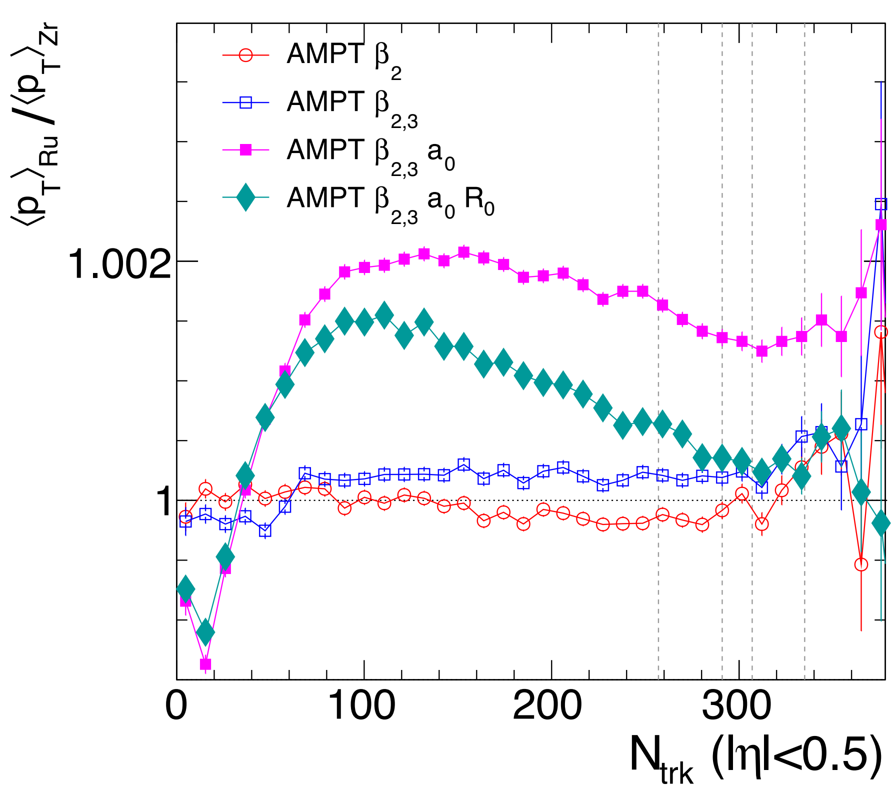


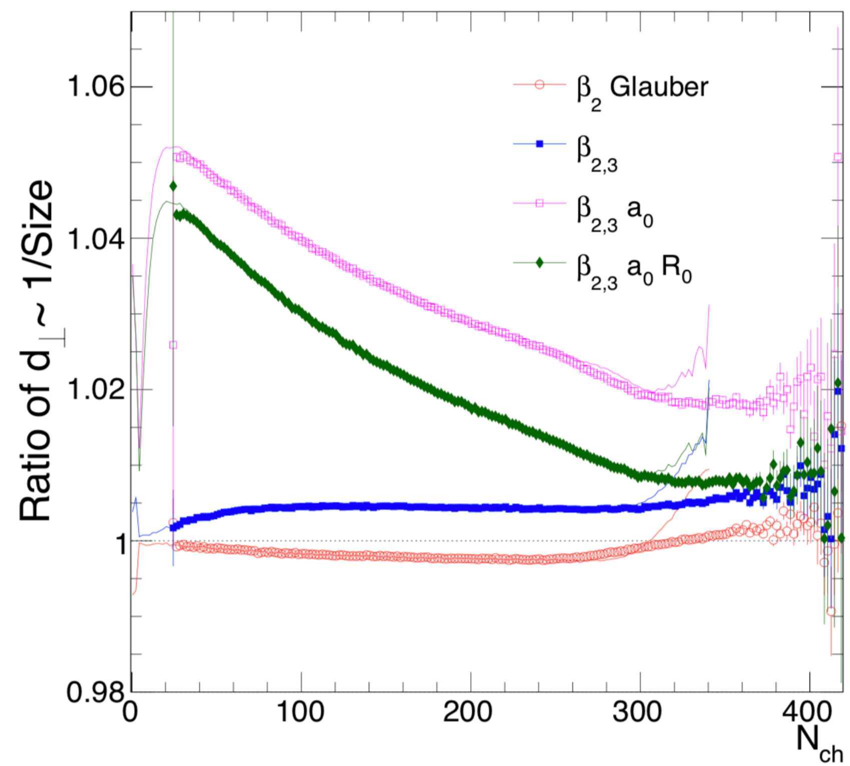
Nuclear structure via <p_T>



J. Jia, aXiv:2106.08768

- AMPT underestimate response by x3, so trust trends only
- $\beta_{2,}\beta_3$ small impact in noncentral, but some increase in UCC
- Enhancement dominated by surface diffuseness
- Radius difference leads to stronger N_{ch} dependence
- Glauber model also describe the trends..





Outlook

- Much more..
  - Three and four-particle observables provide more constraints and more information, e.g. triaxiality.
  - Nuclear PDF effect and its centrality dependences.
  - Transport of conserved charges and effects magnetic field..
- Great opportunity for possible system scans.
  - Larger systems have better statistical sensitivity e.g. 136Xe vs 136Ce
  - Small systems to disentangle geometry from initial momentum anisotropy
  - Profit from larger multiply/acceptance from LHC and also the question of energy dependence
- Model study to explore the connection to nuclear structure and potential for heavy ion physics.

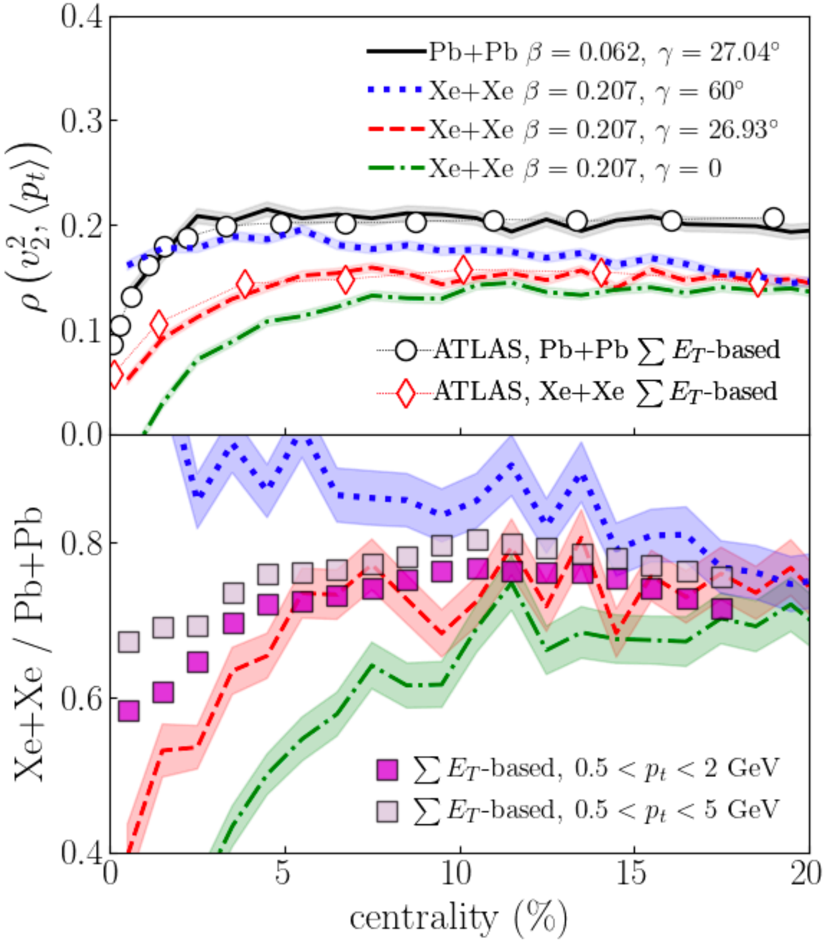
We're only limited by our imagination ⋯

RBRC Workshop **"Physics opportunities from the RHIC Isobar run"** **Jan 25-28, 2022**.

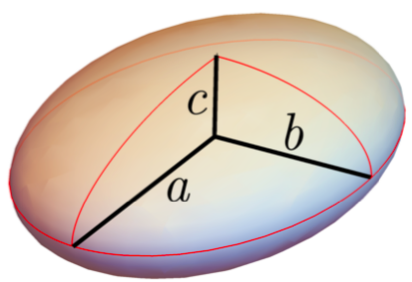
Organizers: Jiangyong Jia (Stony Brook), Chun Shen (RBRC/Wayne State), Derek Teaney (Stony Brook), and Zhangbu Xu (BNL)

v_2^2-p_T correlation at LHC

B Bally, M Bender, G Giacalone, V Somà 2108.09578



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



- Clear sensitivity to the triaxiality of 129Xe.