WPCF 2022 – 15th Workshop on Particle Correlations and Femtoscopy

Measurement of nuclear deformation in relativistic heavy-ion collisions at STAR

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East Lansing, Michigan, July 20, 2022

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Supported in part by the U.S. DEPARTMENT OF ENERGY Office of Science

Stony Brook University

STAR

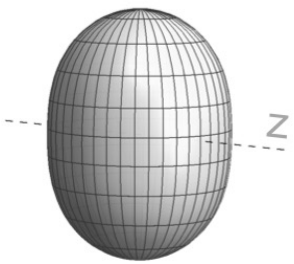
Nuclei shape, radial structure and nucleonic cluster

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

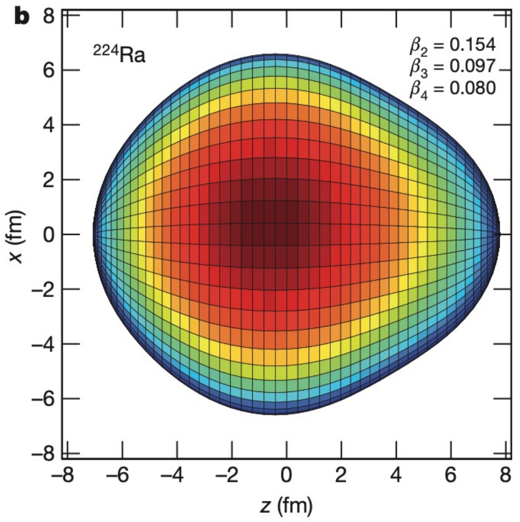
$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

Quadrupole

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

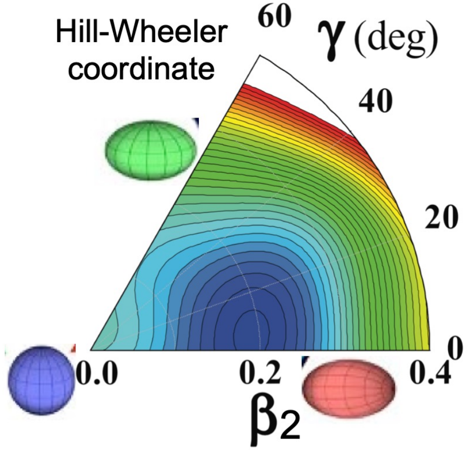


Octupole (pear-shaped) deformation



L. O. Gaffney et al., Nature497, 199(2013)

Hill-Wheeler coordinate



Triaxial spheroid

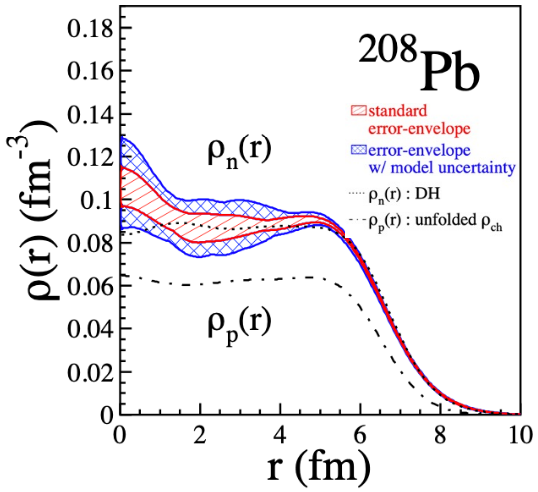
A. N. Andreyev et al., Nature405, 430(2000)

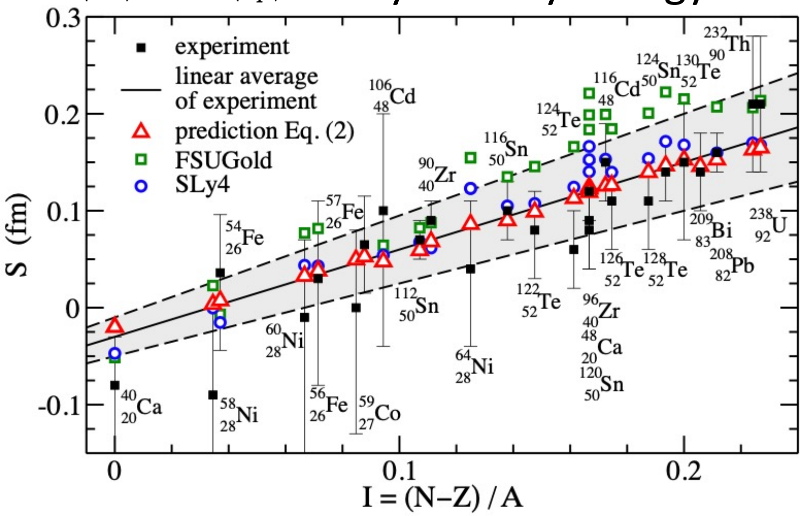
S. Cwiok et al., Nature433, 705(2005)

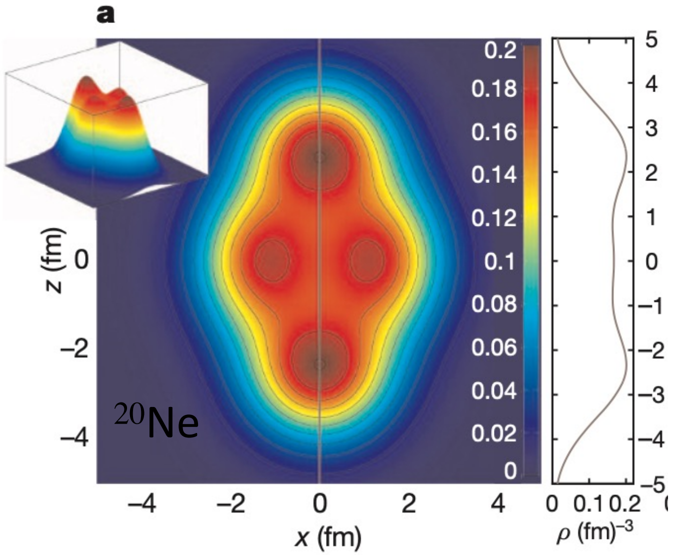
A. Trzcinska et al., PRL87, 082501(2001)

M. Centelles et al., PRL102, 122502(2009)

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





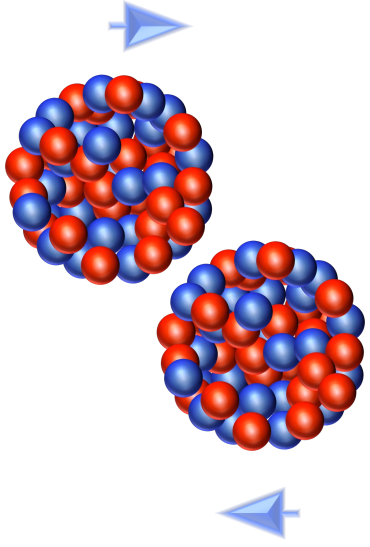


Nucleonic clustering in light nuclei

J.P. Ebran et al., Nature478, 341(2012)

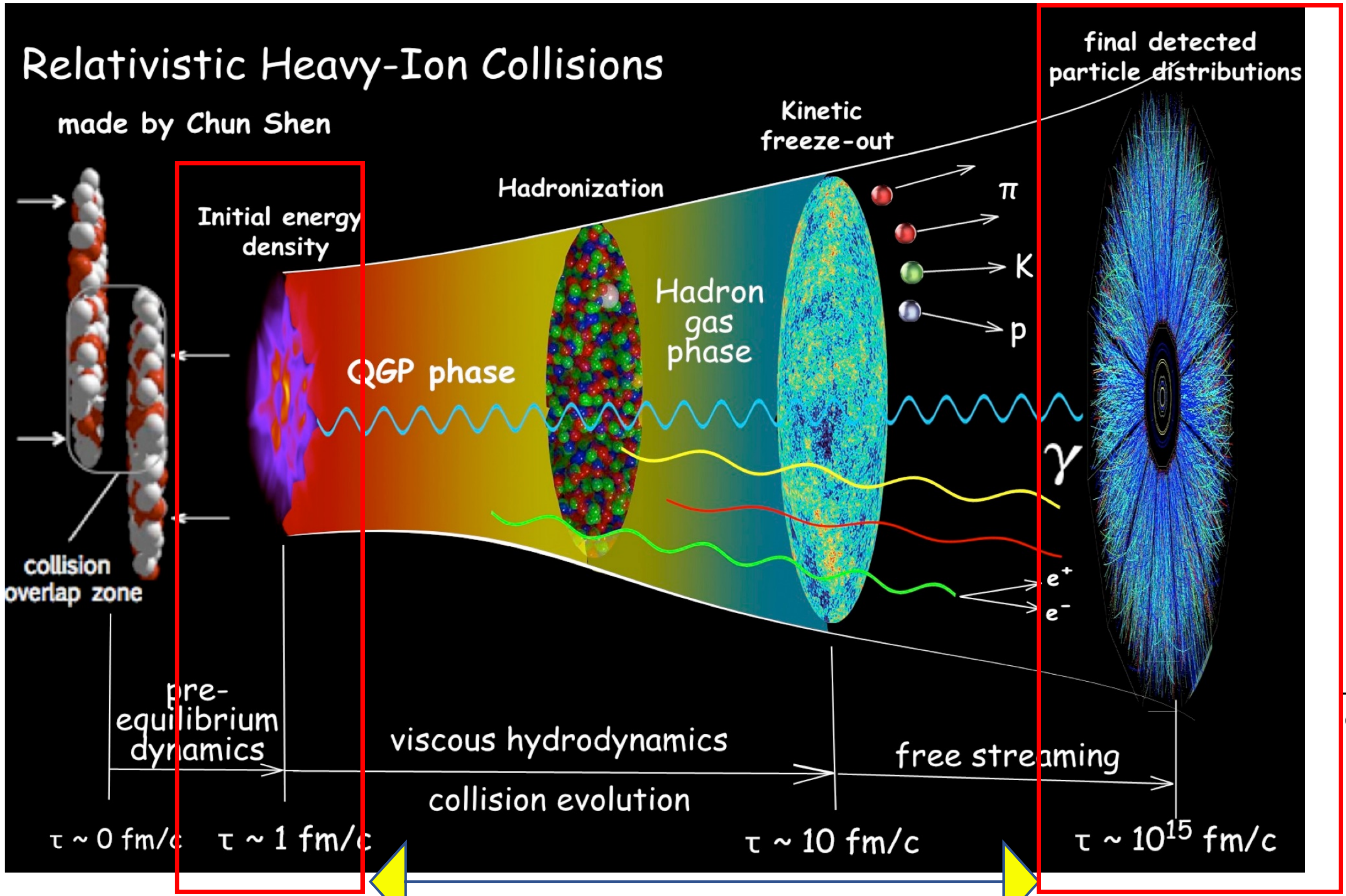
Relativistic heavy-ion collisions and nuclear structure

Nuclear Structure



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

- β_2 → Quadrupole deformation
- β_3 → Octupole deformation
- a_0 → Surface diffuseness
- R_0 → Nuclear size



Anisotropic flow

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

radial flow

?

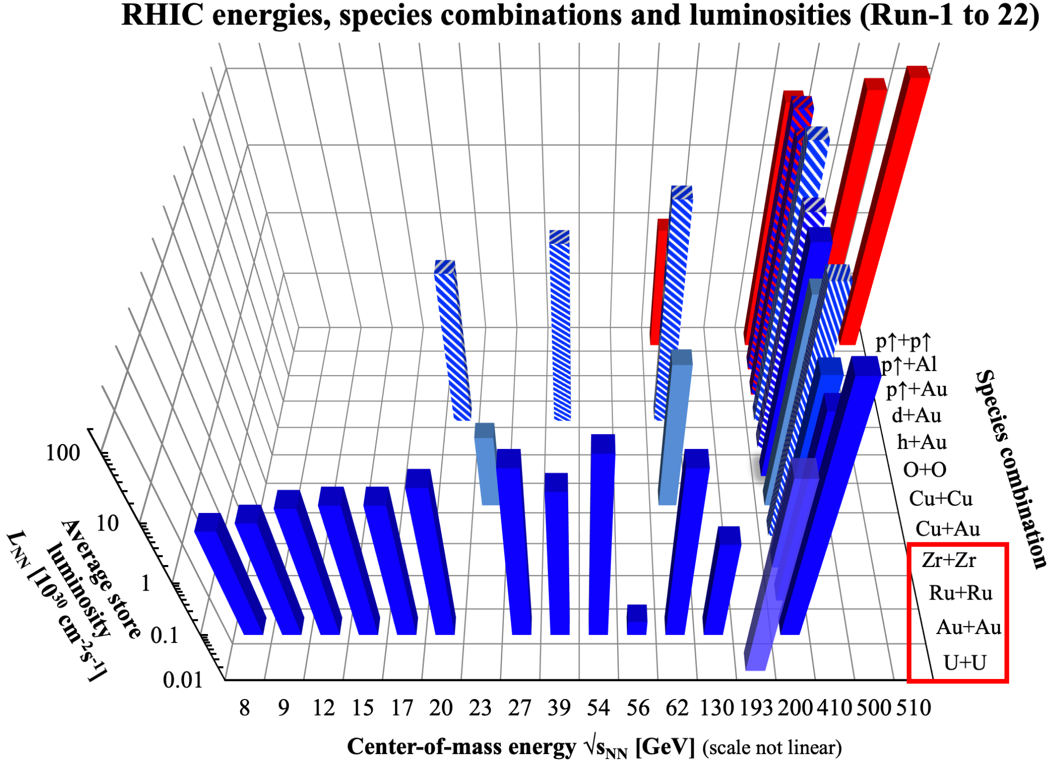
Initial Size: $R_\perp^2 \propto \langle r_\perp^2 \rangle$

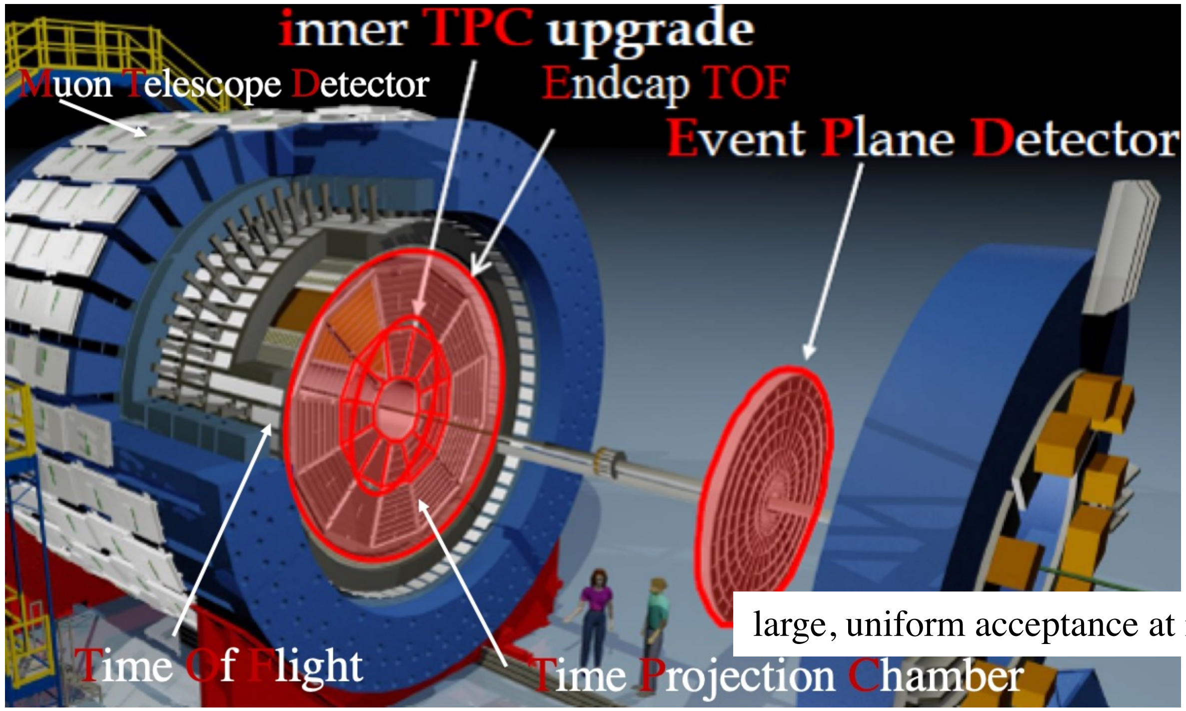
Initial Shape: $\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

R_0 a_0 β_n

High energy: approximate linear Response in each event $\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$ $V_n \propto \mathcal{E}_n$

Unique RHIC runs and the STAR detector





large, uniform acceptance at mid-rapidity

- Datasets: Au+Au@200 GeV, U+U@193 GeV; Ru+Ru@200 GeV, Zr+Zr@200 GeV
- Measurement based on TPC:

$$|\eta| < 1.0,\ 0.2 < p_T < 2\ \mathrm{GeV}/c$$

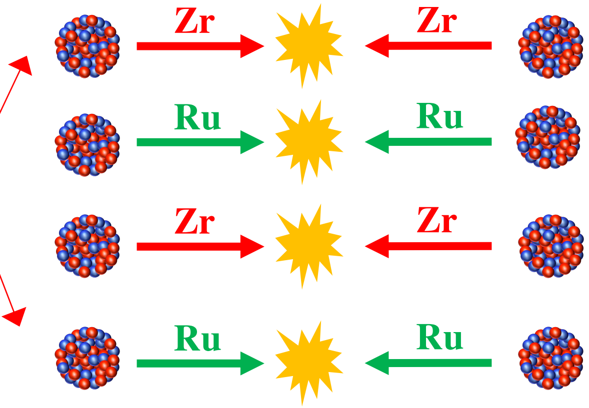
- Centrality based on N_{ch}^{rec} with $|\eta|$< 0.5

Special operation mode:

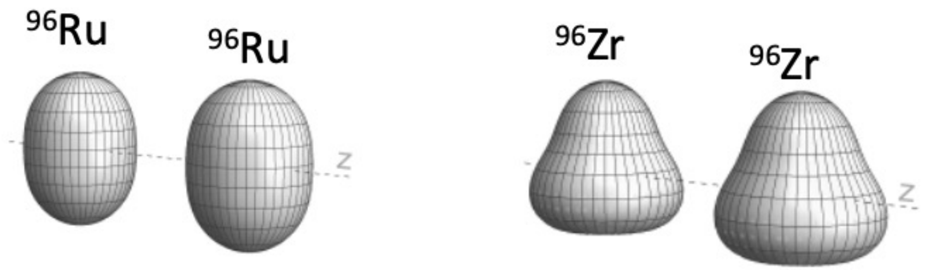
- Fill-by-fill switching between Ru+Ru and Zr+Zr
- Similar run conditions at STAR (minimize the systematics)

Ideal system to study nuclear structure:

$$\frac{v_{n,\mathrm{Ru+Ru}}}{v_{n,\mathrm{Zr+Zr}}} \stackrel{?}{=} 1$$



Anisotropic flow v_n



Nuclear parameters used in AMPT:

Species	β_2	β_3	a_0(fm)	R_0(fm)
Ru	0.162	0	0.46	5.09
Zr	0.06	0.20	0.52	5.02

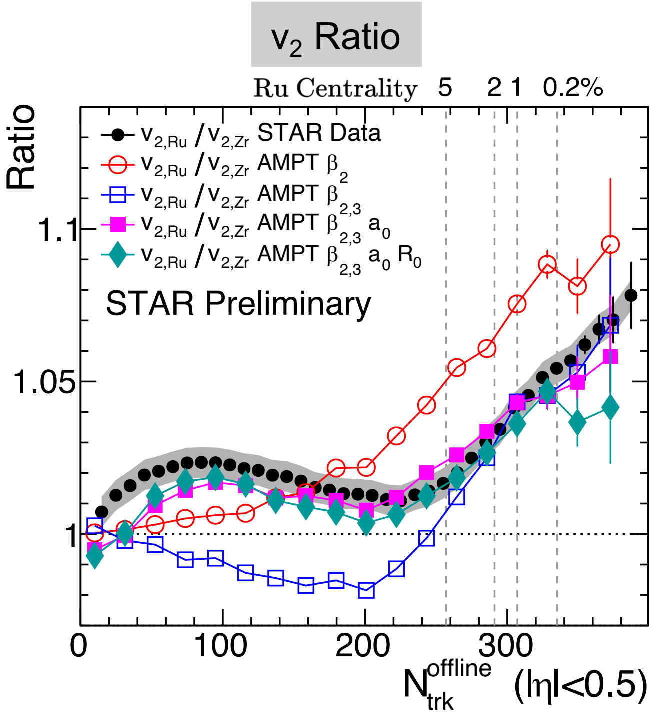
Heavy-ion expectation:

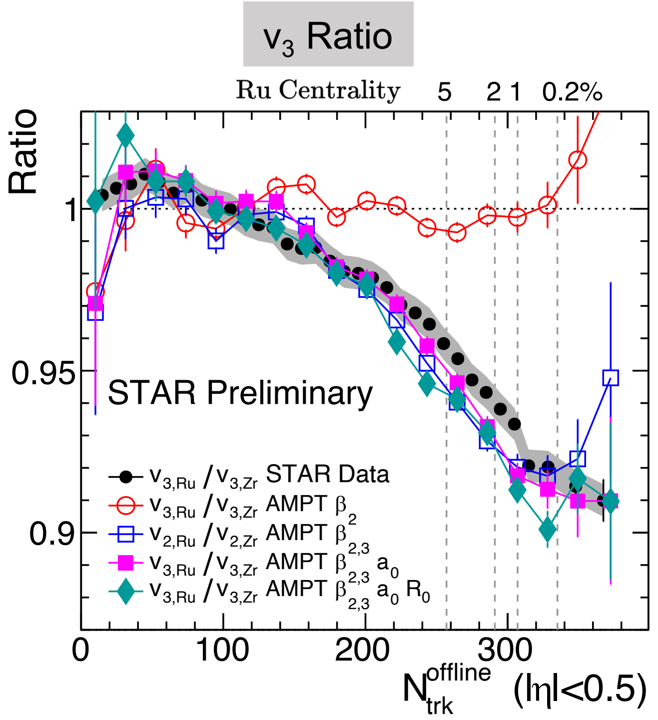
$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

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

Cancelation expected in non-central collisions

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





1) v_2 ratio: large $\beta_{2,\mathrm{Ru}}$, negative contribution from $\beta_{3,\mathrm{Zr}}$ ⇒ Sharper increase in central

2) v_3 ratio: strong decrease from $\beta_{3,\mathrm{Zr}}$ with negligible $\beta_{2,\mathrm{Ru}}$ distortion

3) Residual effect due to radial structure, e.g., neutron skin in Zr

4) No significant effect due to nuclear size

AMPT extractions:

$\beta_2^{\mathrm{Ru}} = 0.16 \pm 0.02 \quad \beta_3^{\mathrm{Zr}} = 0.20 \pm 0.02 \quad \Delta a_{0,\mathrm{Ru-Zr}} = -0.06$ fm

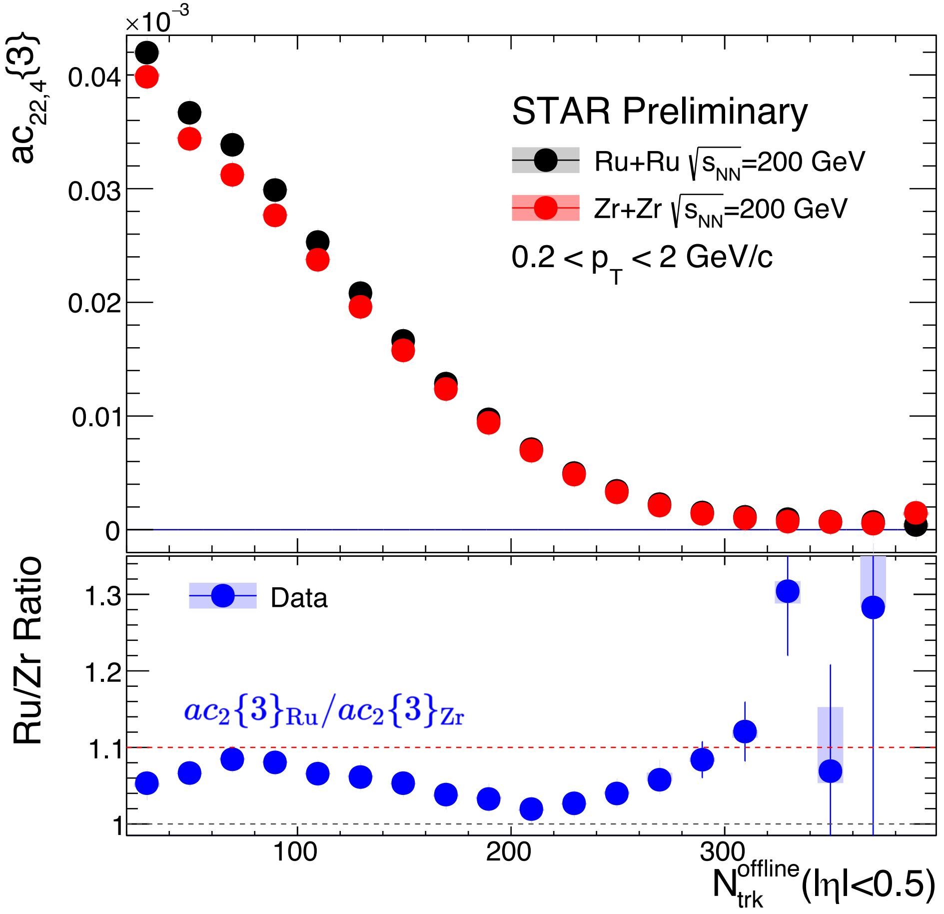
Direct indications and well constrains the nuclear deformation

C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, PRC105, 014905(2022); J. Jia and C. Zhang, arXiv: 2111.15559;
G. Nijs and W. Schee, arXiv:2112.13771 H.J. Xu et al., PLB819, 1136453(2021);F. Li, Y.G. Ma et al., arXiv:2201.10994;
X.L. Zhao and G.L Ma, arXiv:2203.15214; G. Giacalone, J. Jia and C. Zhang, PRL127, 242301(2021);

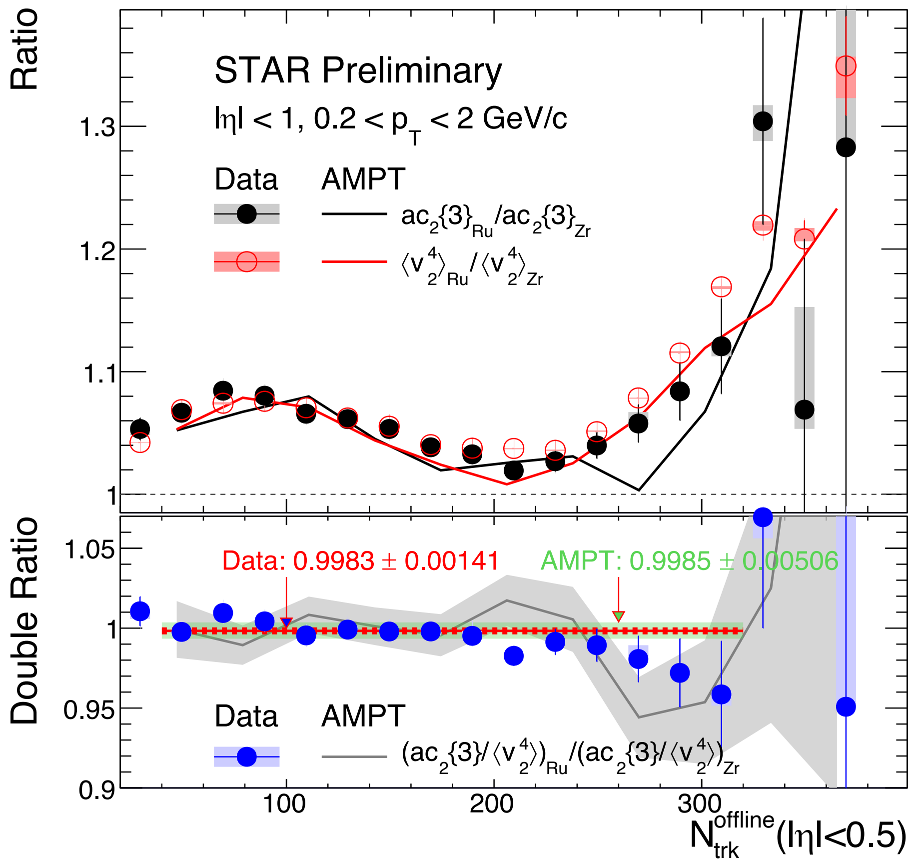
non-linear coupling coefficient

Asymmetric cumulant: $ac_2\{3\} = \langle V_2^2 V_4^* \rangle = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle$

Non-linear coupling coefficient: $\chi_{4,22} = \frac{\langle V_2^2 V_4^* \rangle}{\langle v_2^4 \rangle}$ $\quad V_4 = U_4 + \chi_{4,22} V_2^2$



Nonmonotonic trend: reflect nuclear structure



$$\frac{ac_2\{3\}_{\mathrm{Ru+Ru}}}{ac_2\{3\}_{\mathrm{Zr+Zr}}} \overset{?}{\approx} \frac{\langle v_2^4 \rangle_{\mathrm{Ru+Ru}}}{\langle v_2^4 \rangle_{\mathrm{Zr+Zr}}}$$

1) AMPT well reproduces data.

2) non-linear coefficients are expected to be identical in final state

(Fitting from 40 to 320)

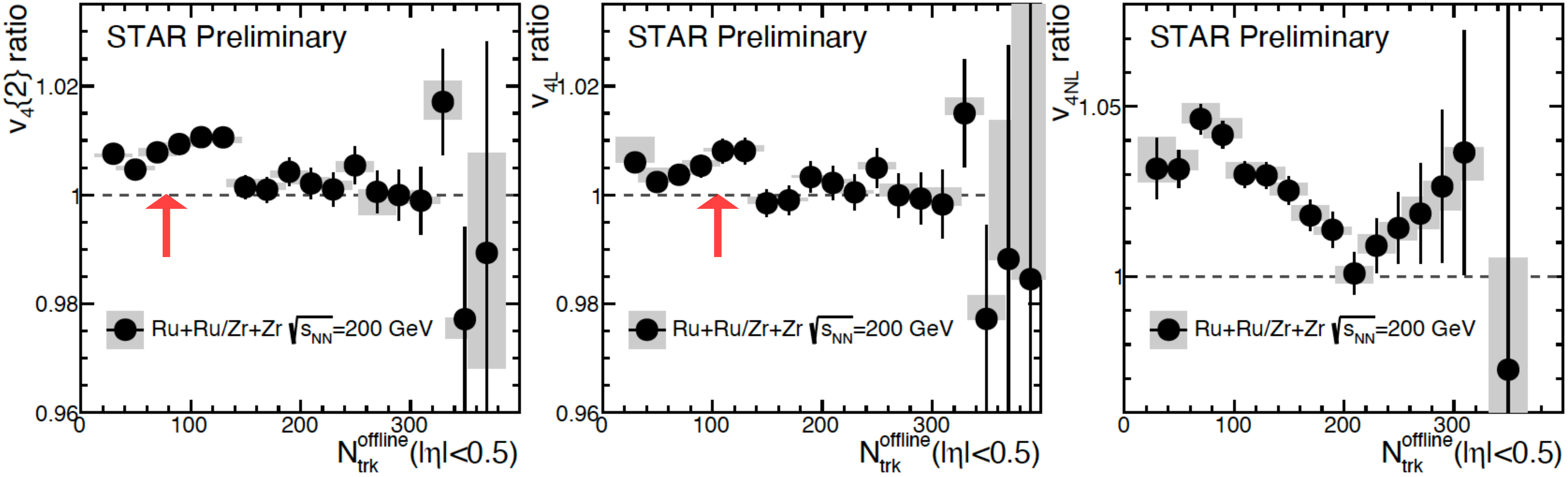
$$\mathrm{Data:}\ \frac{\chi_{4,22}^{\mathrm{Ru+Ru}}}{\chi_{4,22}^{\mathrm{Zr+Zr}}} = 0.9983 \pm 0.00141 \qquad \mathrm{AMPT:}\ \frac{\chi_{4,22}^{\mathrm{Ru+Ru}}}{\chi_{4,22}^{\mathrm{Zr+Zr}}} = 0.9985 \pm 0.00506$$

non-linear coupling are comparable between Ru and Zr

L. Yan and J. Ollitrault, PLB744,82(2015); G. Giacalone, L. Yan and J. Ollitrault, PRC97, 054905(2018);
S.J. Zhao, H.J. Xu, Y.X. Liu and H.C. Song, arXiv:2204.02387; J.Jia, G. Giuliano and C. Zhang, arXiv:2206.07184

Precision tests of the linear and nonlinear mode coupling

$$V_4 = V_{4\,\mathrm{L}} + \chi_4 (V_2)^2 \quad v_{4\,\mathrm{L}}^2 = v_4\{2\}^2 - v_{4,\mathrm{NL}}^2, \quad v_{4\mathrm{NL}}^2 \equiv \chi_4^2 \langle v_2^4 \rangle \quad \text{where} \quad \chi_4 = \frac{\langle V_2^2 V_4^* \rangle}{\langle v_2^4 \rangle}$$



J.Jia, G. Giuliano and C. Zhang, arXiv:2206.07184 , the AMPT study implies:

v_4 does not depend on β_2 and β_3, strongly impacted by a_0 and R_0

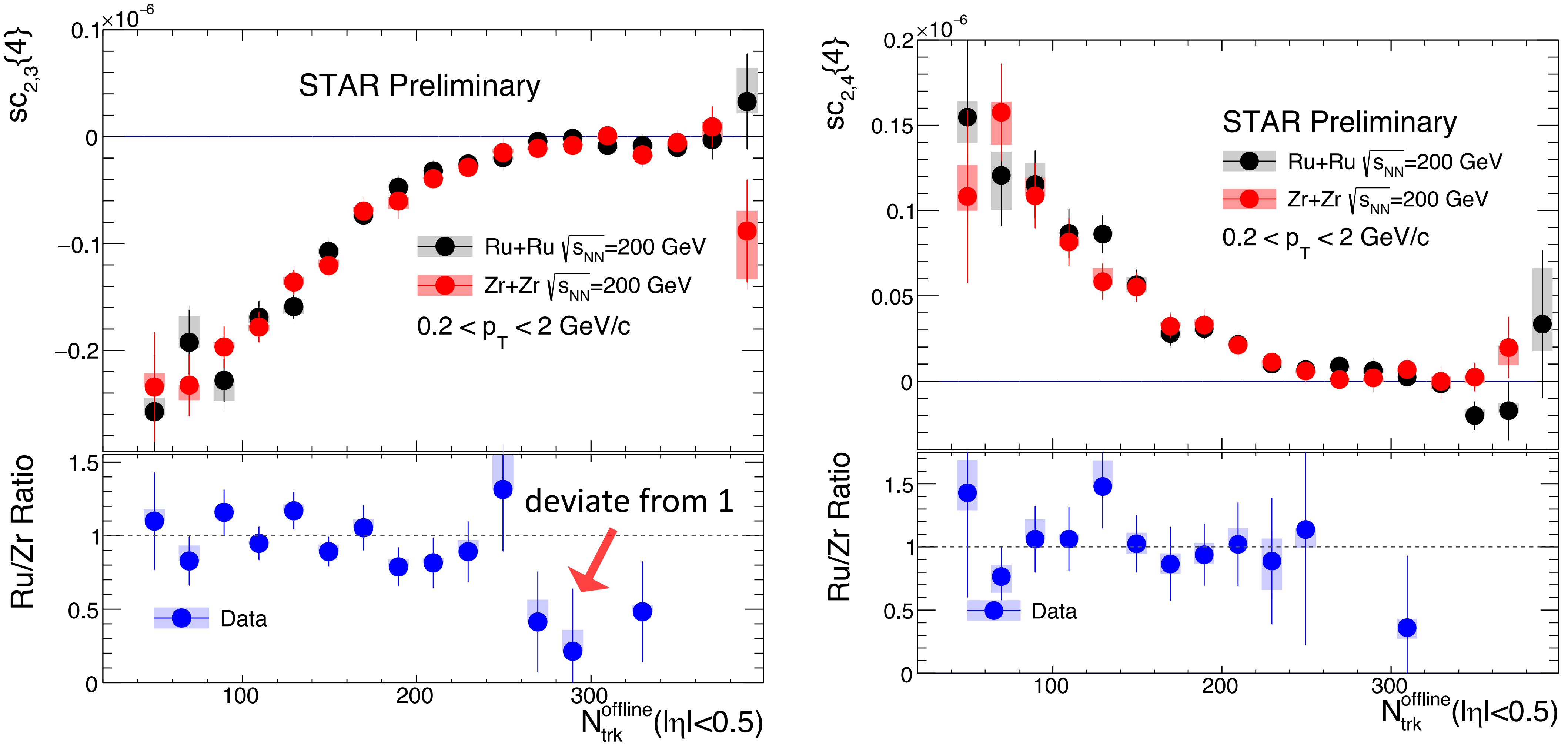
$v_{4\mathrm{NL}}^2 \sim \langle \epsilon_2^4 \rangle$, therefore affected by β_2, a_0 and R_0.

$v_{4\mathrm{L}} \sim \epsilon_4$, shows the above similar behaviors

Results are consistent with the expectations of hydrodynamic mode coupling of flow harmonics & effects of a_0 and R_0 in non-central collisions

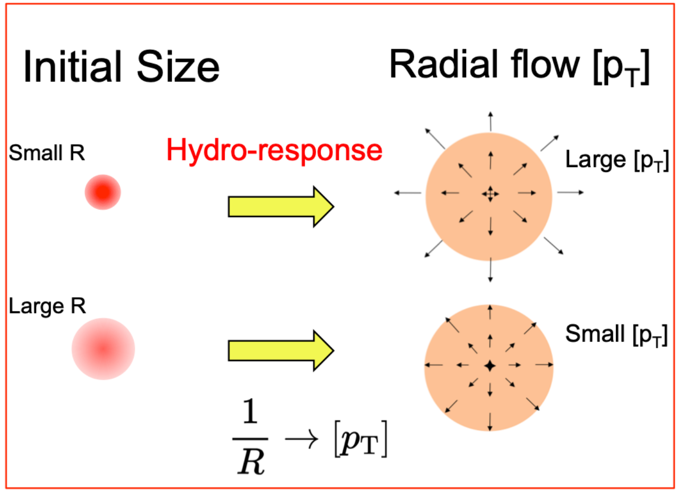
Symmetric cumulant

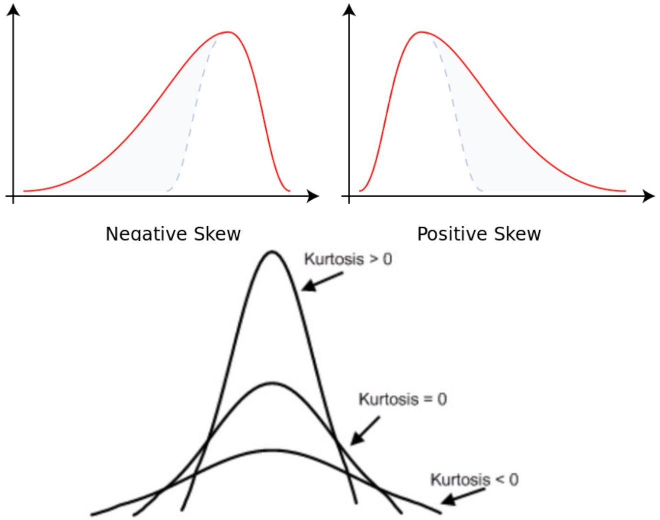
$$\mathrm{sc}_{n,m}\{4\} = \langle\langle\{4\}_{n,m}\rangle\rangle - \langle\langle\{2\}_n\rangle\rangle\langle\{2\}_m\rangle\rangle = \langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$$



$SC_{2,3}$ {4} shows hint of deviation from unity near central collisions as expected from nuclear structure effects.
---measurement uncertainties dominate"

Mean transverse momentum p_T fluctuations





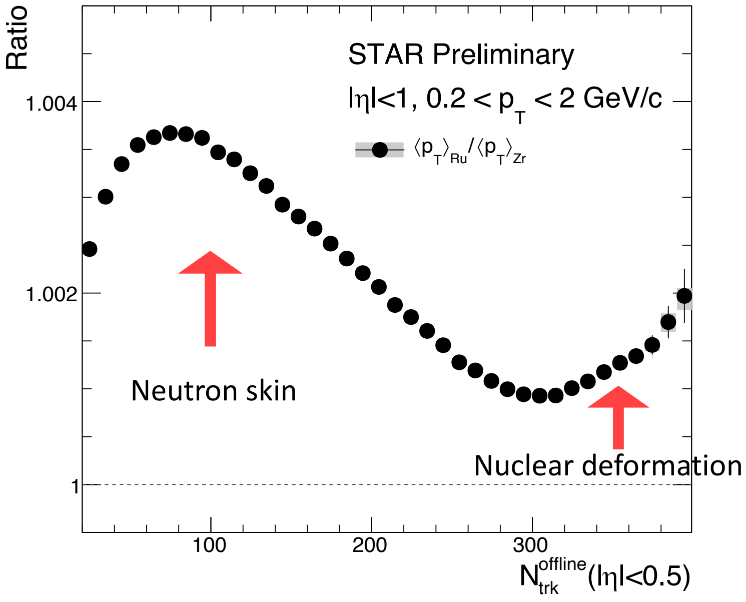
Mean $[p_T] \equiv \frac{\sum_i w_i p_{T,i}}{\sum_i w_i}, \langle\langle p_T \rangle\rangle \equiv \langle [p_T] \rangle_{evt}$

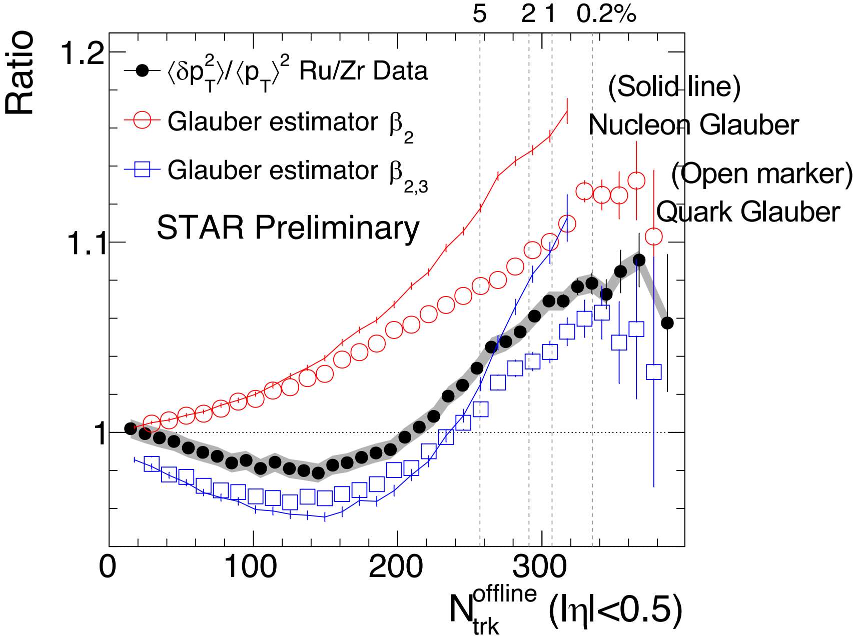
w_i is track weight

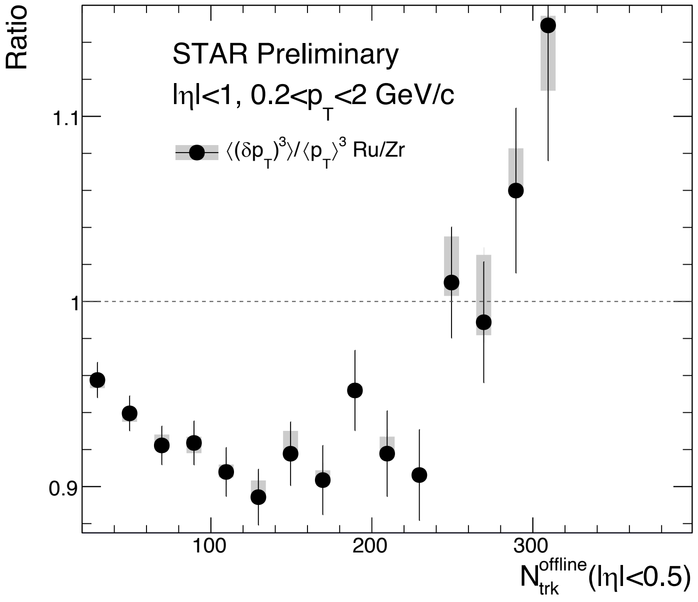
Variance $\left\langle (\delta p_T)^2 \right\rangle = \left\langle \frac{\sum_{i \neq j} w_i w_j (p_{T,i} - \langle\langle p_T \rangle\rangle)(p_{T,j} - \langle\langle p_T \rangle\rangle)}{\sum_{i \neq j} w_i w_j} \right\rangle_{evt}$

Skewness $\left\langle (\delta p_T)^3 \right\rangle = \left\langle \frac{\sum_{i \neq j \neq k} w_i w_j w_k (p_{T,i} - \langle\langle p_T \rangle\rangle)(p_{T,j} - \langle\langle p_T \rangle\rangle)(p_{T,k} - \langle\langle p_T \rangle\rangle)}{\sum_{i \neq j \neq k} w_i w_j w_k} \right\rangle$

kurtosis $\left\langle (\delta p_T)^4 \right\rangle_c = \left\langle (\delta p_T)^4 \right\rangle - 3\left\langle (\delta p_T)^2 \right\rangle$





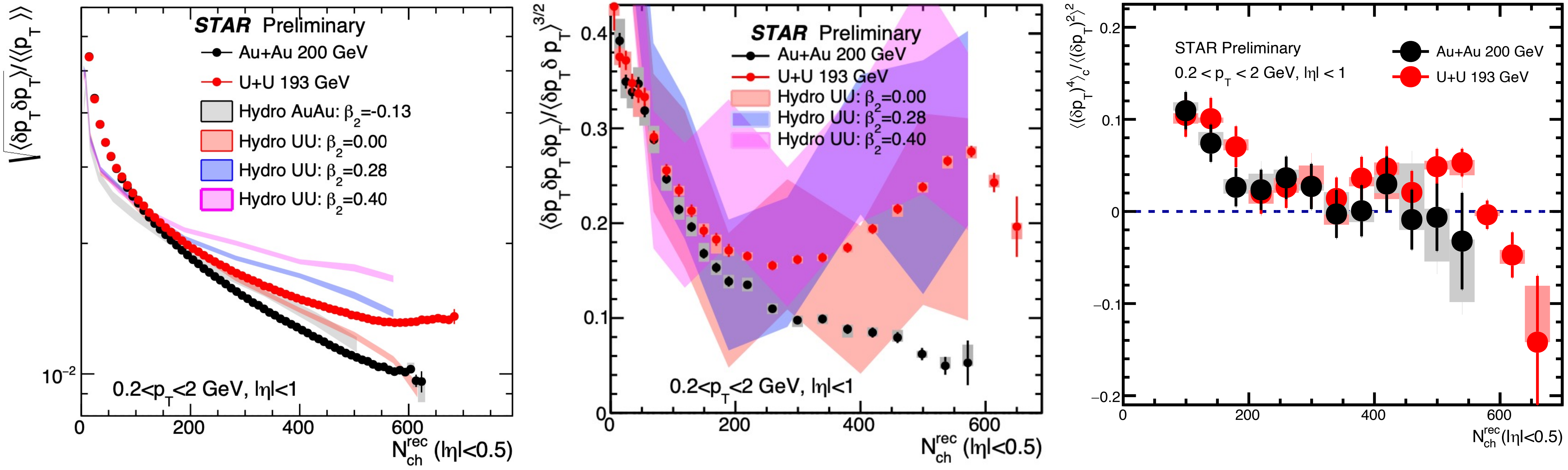


A complementary probe to decipher Ru and Zr structures.

G. Giacalone et al., PRC103, 024910(2021); J. Jia, PRC105, 044905(2022); S. Bhatta, C. Zhang and J.Jia, PRC105, 024904(2022); C. Zhang, S. Bhatta and J. Jia, 2206.01943

Mean transverse momentum p_T fluctuations

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke



Au+Au: follow power-law decrease, but with strong deviation in central normalized variance and normalized skewness

U+U: large enhancement in normalized variance and skewness and sign-change in normalized kurtosis

⟶ size fluctuations enhanced

Nuclear deformation role is confirmed by hydro calculations.

v_n –[p_T] correlations

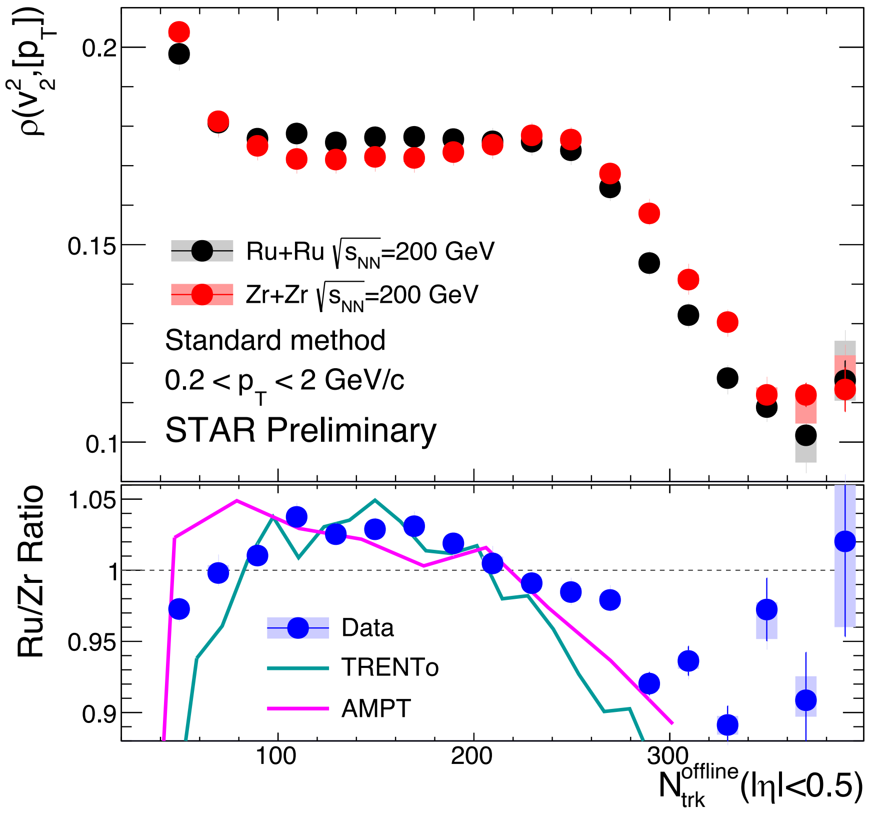
Pearson correlation coefficient:

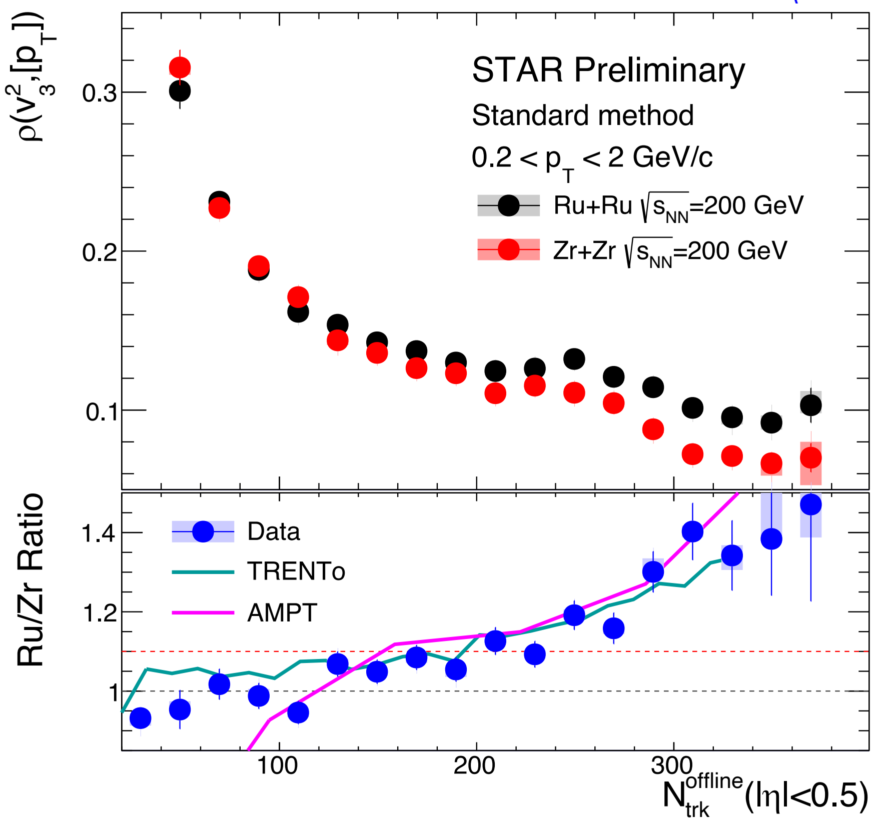
$$\mathrm{cov}(v_n^2,[p_\mathrm{T}]) \equiv \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j}(p_{\mathrm{T},k} - \langle\langle p_\mathrm{T}\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_\mathrm{evt}$$

$$\rho(v_n^2,[p_T]) = \frac{\mathrm{cov}(v_n^2,[p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_\mathrm{dyn}\langle\delta p_T \delta p_T\rangle}}$$

$$\mathrm{Var}\,(v_n^2)_\mathrm{dyn} = v_n\{2\}^4 - v_n\{4\}^4$$

$$\langle\delta p_\mathrm{T}\delta p_\mathrm{T}\rangle = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{\mathrm{T},i} - \langle\langle p_\mathrm{T}\rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_\mathrm{T}\rangle\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle_\mathrm{evt}$$





1) Ru/Zr ratio also reflects the possible nuclear structure.

2) Mostly dominated by the harmonic flow contributions.

3) TRENTo and AMPT can reproduce data

TRENTo assumption: $v_\mathrm{n} \propto \epsilon_\mathrm{n}$ $\quad [p_\mathrm{T}] \propto \frac{E}{S}$

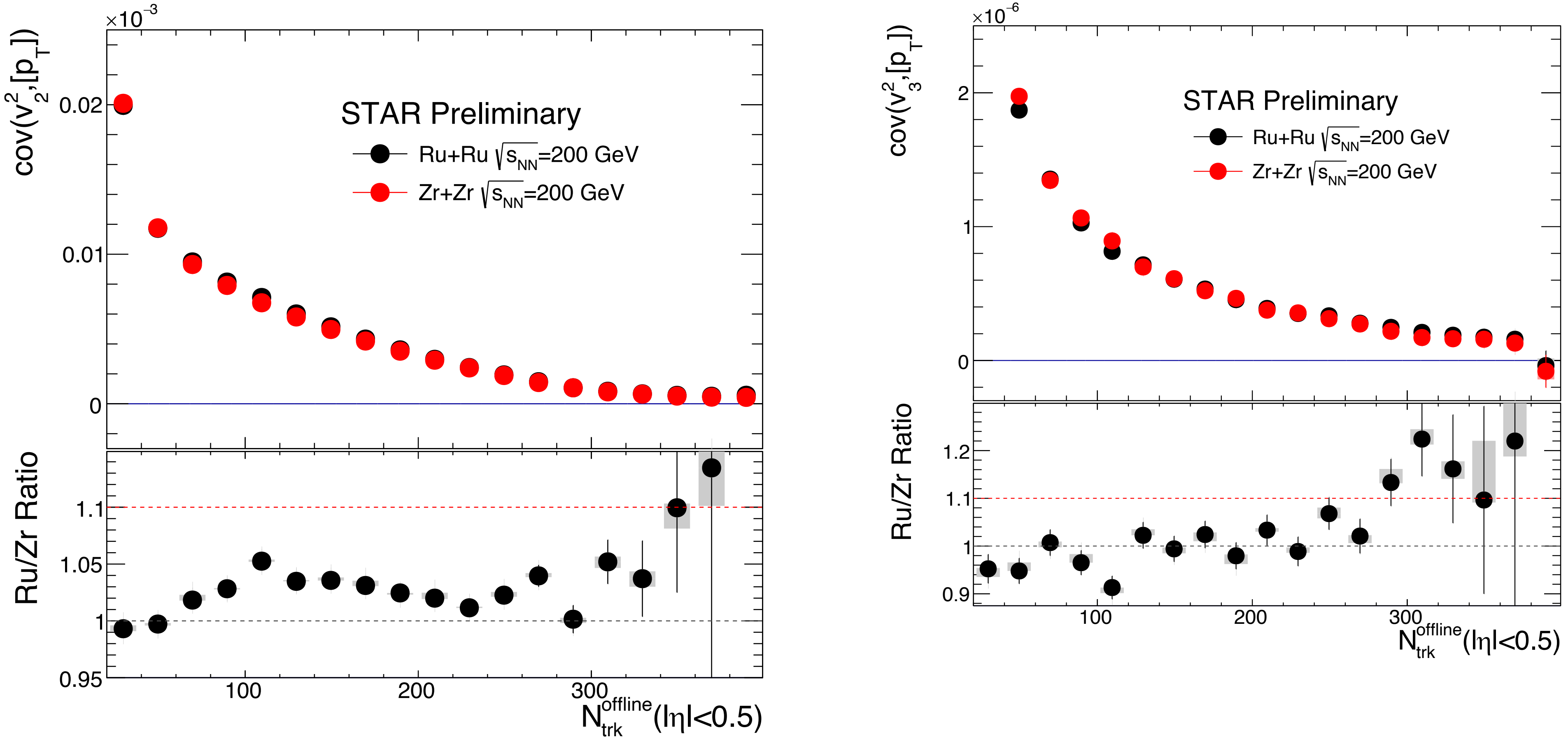
(TRENTo calc. from Giacalone)

P. Bozek, PRC93, 044908(2016); B. Schenke, C. Shen and P. Tribedy, PRC102, 044905(2020); G. Giacalone, PRL124, 202301(2020); J. Jia, S. Huang and C. Zhang PRC105, 014906(2022); C. Zhang, A. Behera, S. Bhatta and J.Jia, PLB822, 136702(2021)

v_n –[p_T] correlations

Pearson correlation coefficient:

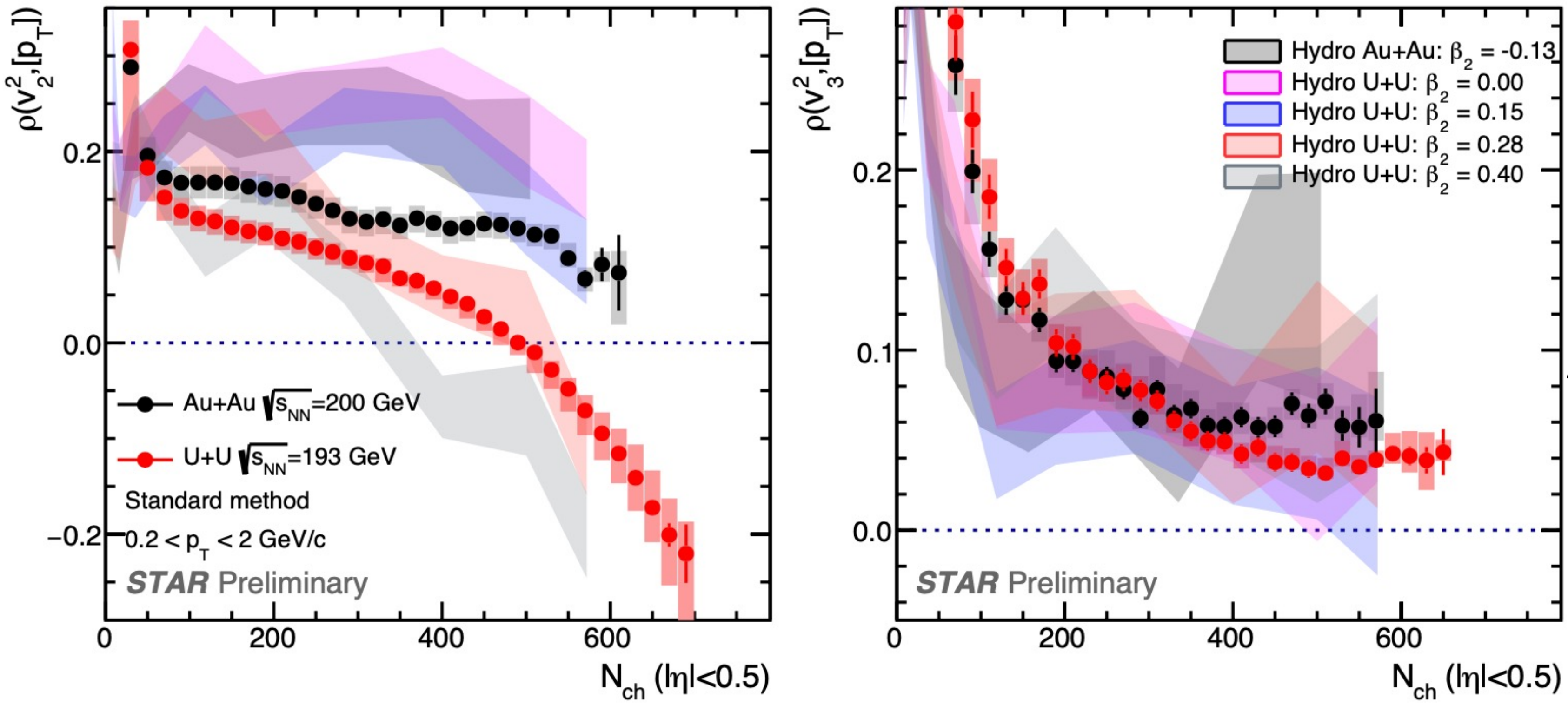
$$\mathrm{cov}\left(v_n^2, [p_\mathrm{T}]\right) \equiv \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j} (p_{\mathrm{T},k} - \langle\langle p_\mathrm{T}\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_{\mathrm{evt}}$$



Ru/Zr ratio also reflects the possible nuclear structure.

v_n –$[p_T]$ correlations in U+U and Au+Au

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (PRC102, 044905(2020))



$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}} \langle \delta p_T \delta p_T \rangle}}$$

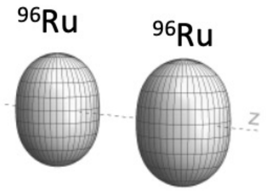
- Without deformation, CGC+hydro model shows positive $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ in central.
- With increasing β_2, model could describe the trend of $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$.
- Model shows that $\rho(\mathrm{v}_3^2, [\mathrm{p_T}])$ is insensitive to β_2.

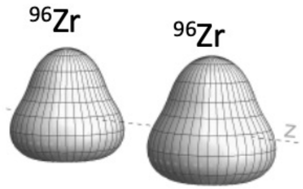
Sign-change of $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ confirms that ^{238}U is prolate and IP-Glasma+hydro constrains $\beta_{2,^{238}\mathrm{U}} = 0.28 \pm 0.03$

Conclusions and outlooks

- v_n ratios as a new probe to constrain nuclear structure parameters:

AMPT estimation: $\beta_2^{\mathrm{Ru}} = 0.16 \pm 0.02$ $\beta_3^{\mathrm{Zr}} = 0.20 \pm 0.02$ $\Delta a_{0,\mathrm{Ru-Zr}} = -0.06\ \mathrm{fm}$





- Experimental test on the non-linear coupling coefficient: identical for Ru+Ru and Zr+Zr in final state as expected

$$\mathrm{Data:}\ \frac{\chi_{4,22}^{\mathrm{Ru+Ru}}}{\chi_{4,22}^{\mathrm{Zr+Zr}}} = 0.9983 \pm 0.00141 \qquad \mathrm{AMPT:}\ \frac{\chi_{4,22}^{\mathrm{Ru+Ru}}}{\chi_{4,22}^{\mathrm{Zr+Zr}}} = 0.9985 \pm 0.00506$$

- Mean p_T fluctuations also as a complementary probe to decipher nuclear structure:

The nonmonotonic trend with N_{ch} in mean, enhancement in variance and skewness ratios, sign-change in kurtosis

- Pearson correlation coefficient also reflects possible nuclear structure dominated by flow in isobar.

TRENTo and AMPT reproduce data

IP-Glasma+hydro estimation: $\beta_{2,{}^{238}\mathrm{U}} = 0.28 \pm 0.03$

$^{238}\mathrm{U}$

Thank you for listening and thanks to the organizers.