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QM QUARK MATTER KRAKÓW 2022

Stony Brook University

STAR

Observation of nuclear deformation in isobar collisions

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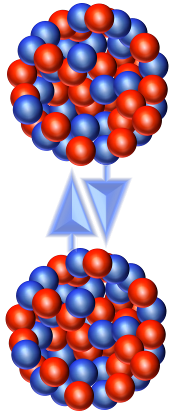
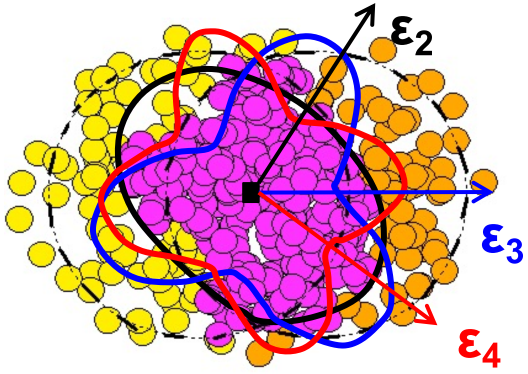
Nuclear Structure



Imaging?

Initial State



Hydrodynamic response

D. Teaney and L. Yan, PRC86, 044908(2012)

H.C. Song, S.A. Bass, U. Heinz, T. Hirano and C. Shen, PRL106, 192301(2011)

Final state particles

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

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

?

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

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

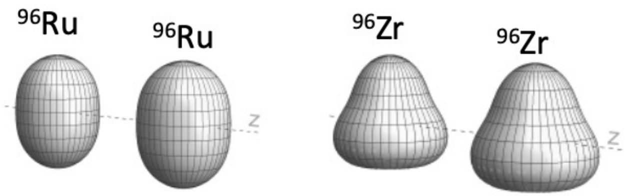
R_0 a_0 β_n

Radial Flow   Anisotropic Flow

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

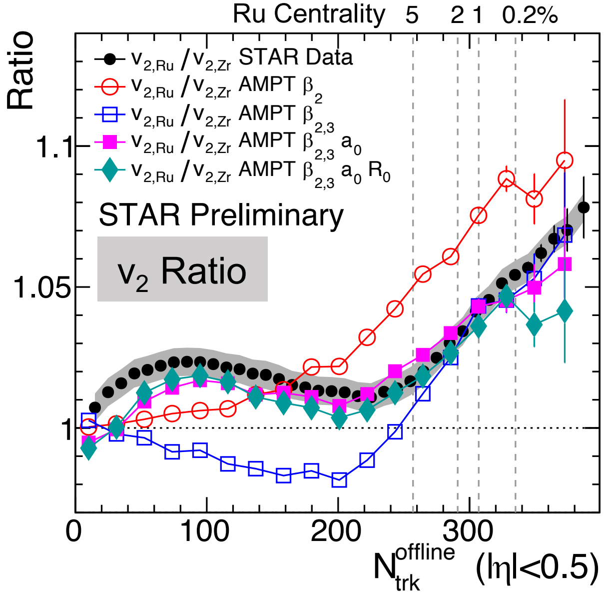
High energy: approximate linear Response in each event $\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$ $V_n \propto \mathcal{E}_n$

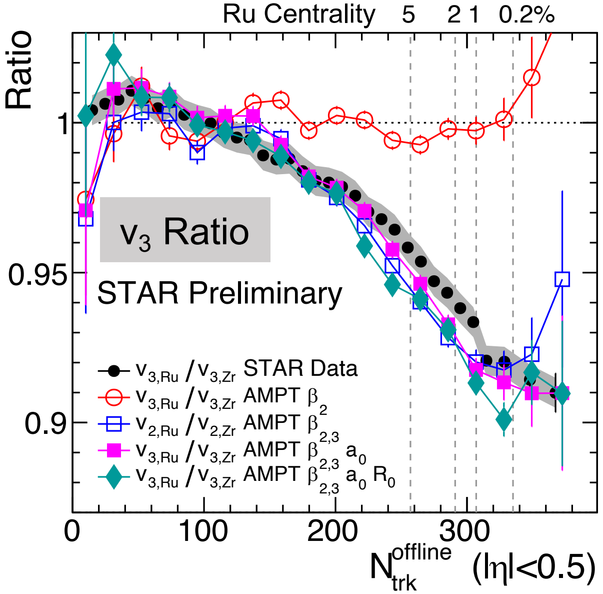
Harmonic flow and non-linear coupling coefficient



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

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

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

Cancelation expected in non-central collisions

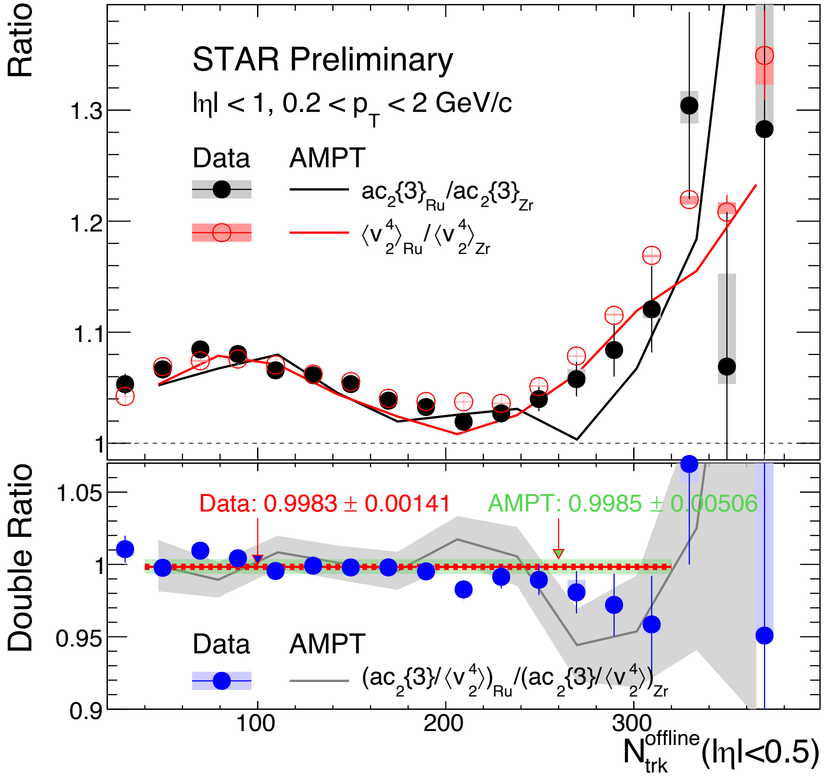
AMPT extractions:

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

Direct indication and well constrain the nuclear deformation

Asymmetric cumulant: $\mathrm{ac}_2\{3\} = \langle V_2^2 V_4^* \rangle = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle$

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



$$\frac{\mathrm{ac}_2\{3\}_{\mathrm{Ru+Ru}}}{\mathrm{ac}_2\{3\}_{\mathrm{Zr+Zr}}} \overset{?}{\approx} \frac{\langle v_2^4 \rangle_{\mathrm{Ru+Ru}}}{\langle v_2^4 \rangle_{\mathrm{Zr+Zr}}}$$

1) Nonmonotonic trend: reflect nuclear structure

2) AMPT well reproduce data.

3) non-linear coefficients are expected identical in final state

(Fitting from 40 to 320)

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

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
G. Giacalone, J. Jia and C. Zhang, PRL127, 242301(2021); H.J. Xu et al., PLB819, 1136453(2021); F. Li et al, arXiv:2201.10994; X.L. Zhao and G.L Ma, arXiv:2203.15214
L. Yan and J. Ollitrault, PLB744,82(2015); G. Giacalone, L. Yan and J. Ollitrault, PRC97, 054905(2018); H.C. Song, (RBRC Workshop)

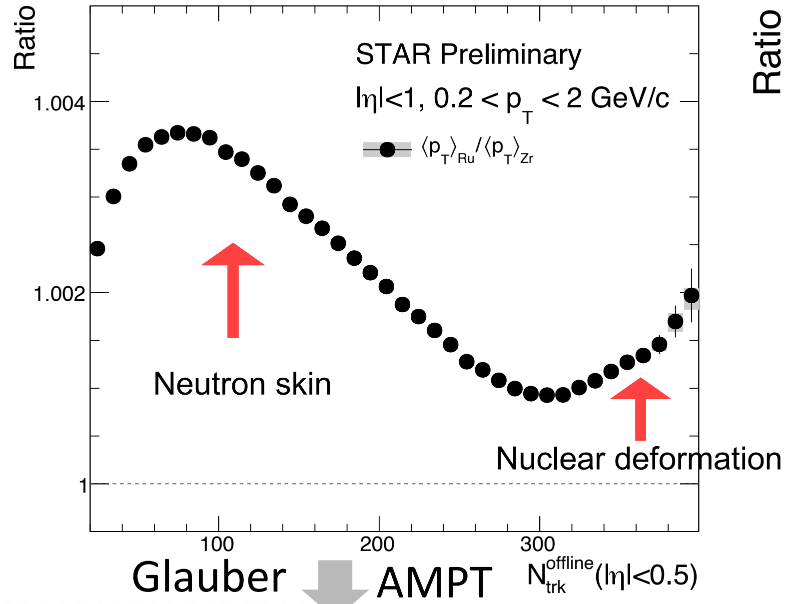
Neutron skin and nuclear deformation: Haojie Xu (STAR), Parallel Session T01

Mean transverse momentum fluctuations

Mean

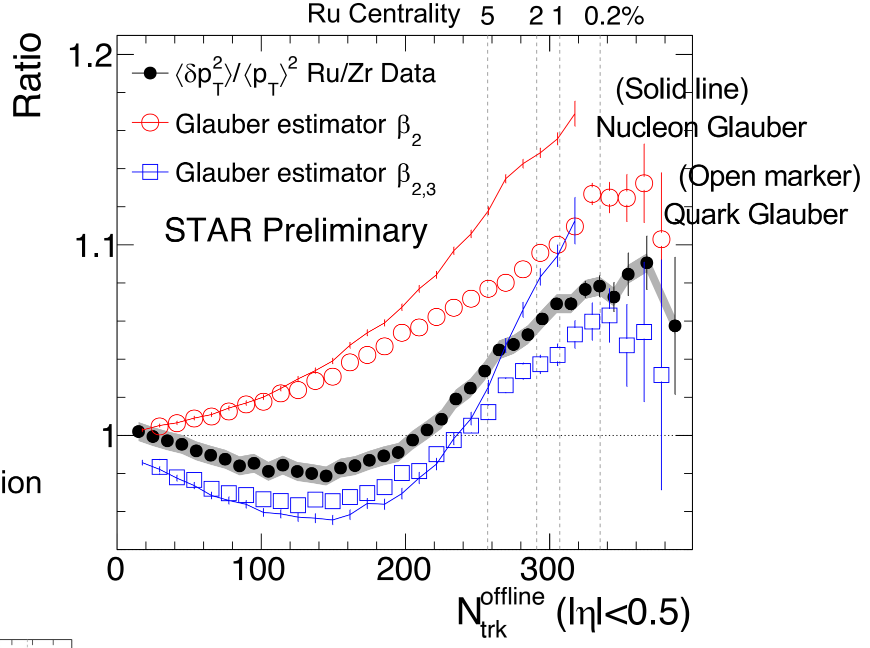
$$[p_{\mathrm{T}}] \equiv \frac{\sum_i w_i p_{\mathrm{T},i}}{\sum_i w_i}, \langle\langle p_{\mathrm{T}}\rangle\rangle \equiv \langle [p_{\mathrm{T}}]\rangle_{\mathrm{evt}}$$

w_i is track weight



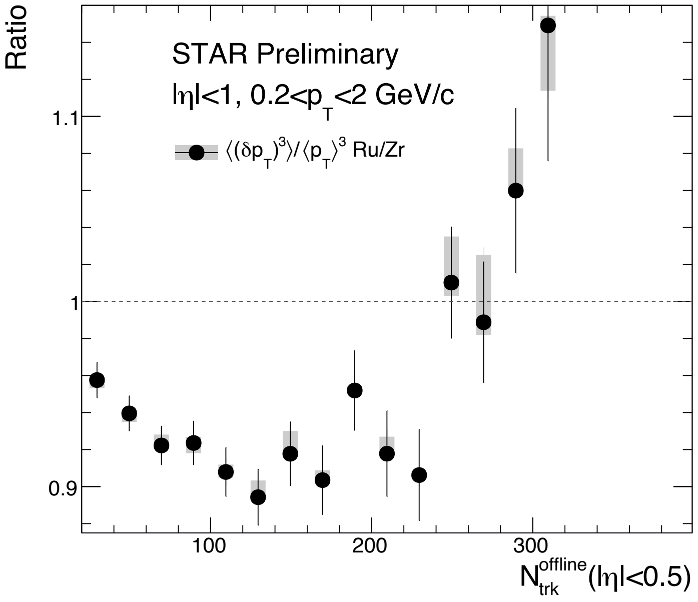
Variance

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

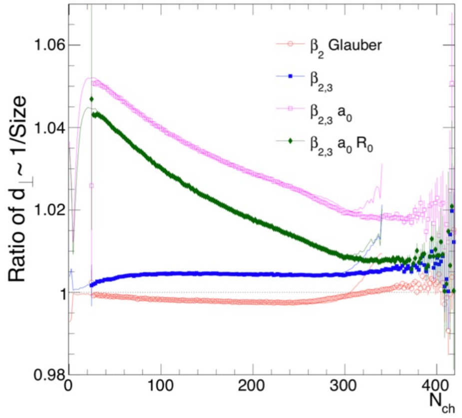


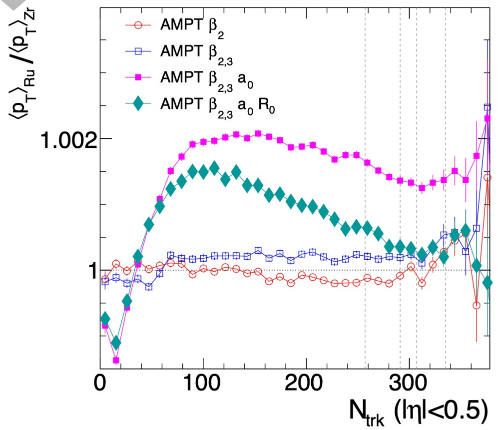
Skewness

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



Glauber → AMPT





1) Mean: nonmonotonic trend reflects neutron skin and nuclear deformation.

2) Variance and skewness:

Enhancement in mid-central due to $\beta_{2,\mathrm{Ru}}$ and large suppression due to $\beta_{3,\mathrm{Zr}}$.

A complementary probe to decipher the Ru and Zr structure.

G. Giacalone et al., PRC103, 024910(2021); J. Jia, arXiv:2109.00604; S. Bhatta, C. Zhang and J.Jia, PRC105, 024904(2022)

Pearson correlation coefficient

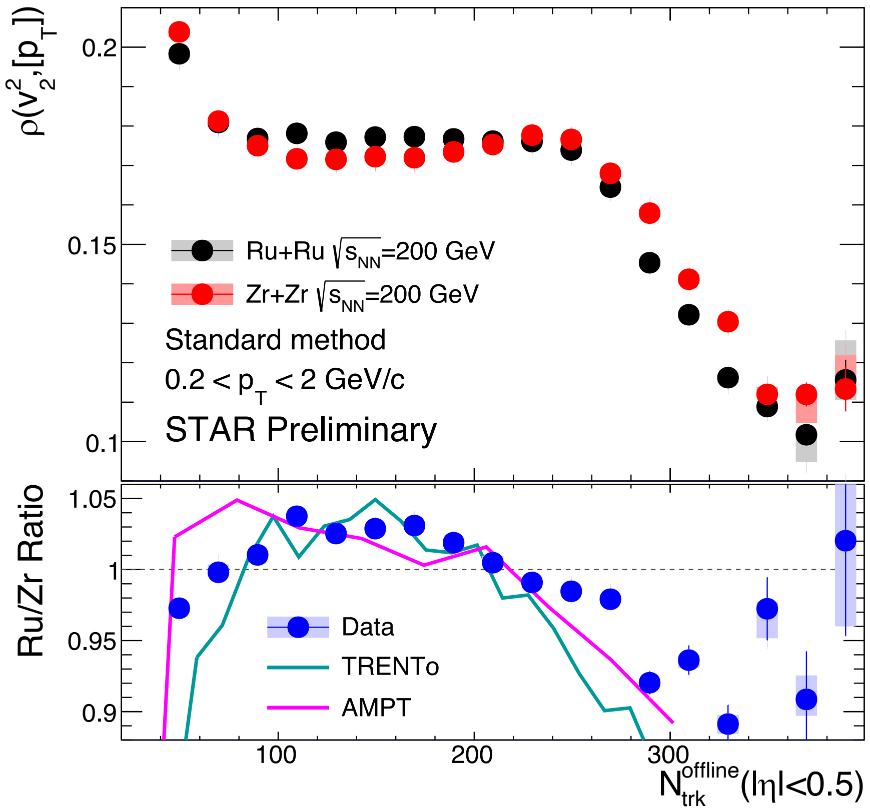
v_n-$[p_T]$ three particle correlator:

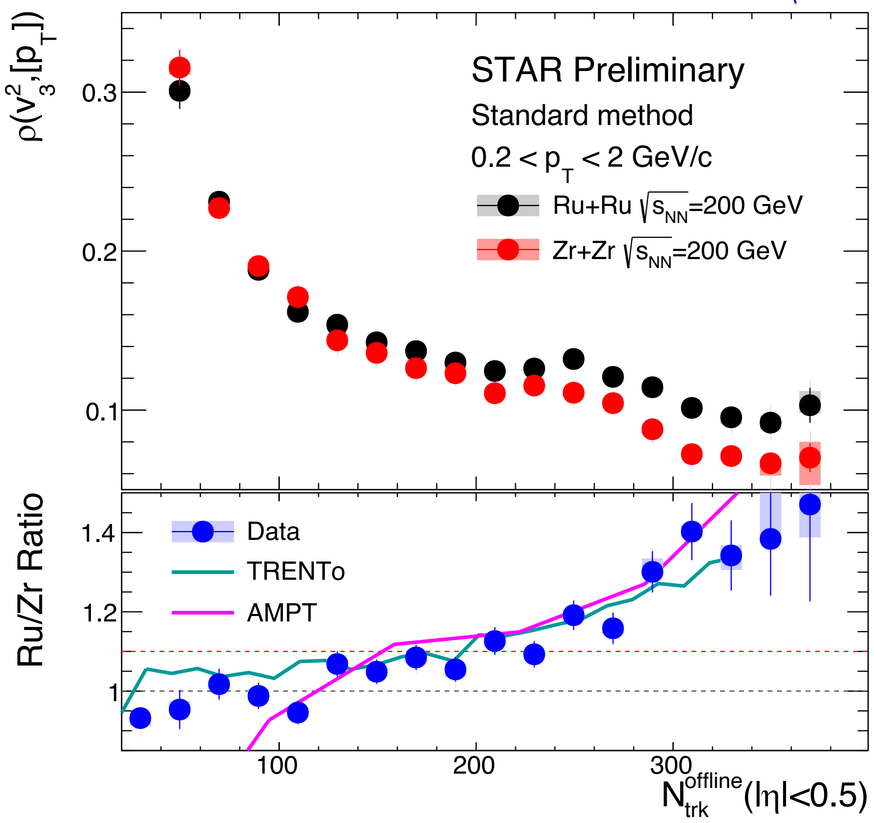
$$\mathrm{cov}(v_n^2,[p_\mathrm{T}]) \equiv \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j}(p_{\mathrm{T},k} - \langle\langle p_\mathrm{T}\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_\mathrm{evt}$$

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

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

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





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)

U+U and Au+Au nuclear deformation: Jiangyong Jia (STAR), Poster Session 2 T01

Conclusions and outlooks

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

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

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

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

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

Nonmonotonic trend in mean, variance and skewness ratios

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

TRENTo and AMPT reproduce data

Thank you @ QUARK MATTER KRAKÓW 2022