The non-linear response coefficient $\chi_{4,22}$ in Au+Au and U+U collisions

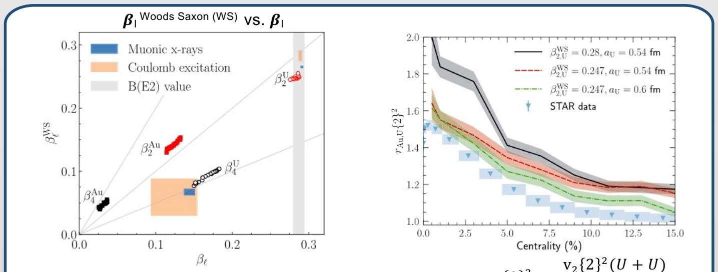
Jie Zhao(jie_zhao@fudan.edu.cn), Fudan University
for the STAR Collaboration

STAR 25 YEARS

Quark Matter 2025

Abstract

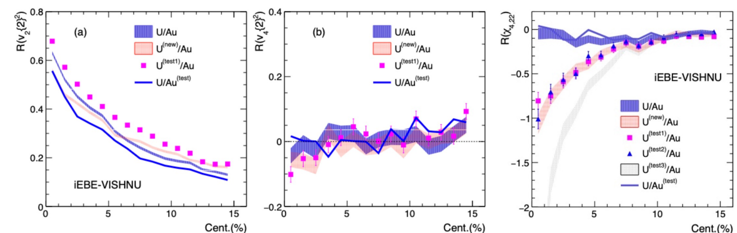
Relativistic heavy-ion collisions offer a unique opportunity to probe the deformation of colliding nuclei. The quadrupole deformation parameter β_2 has been extensively studied through the flow coefficient v_2 in such collisions, as well as through low-energy measurements of the electric quadrupole transition probabilities, $B(E_2)$. In contrast the hexadecapole deformation β_4 has often been neglected in modeling heavy-ion collisions, primarily due to large experimental and theoretical uncertainties. In this poster, we present measurements of the non-linear response coefficient between v_4 and v_2, $\chi_{4,22}$, in Au+Au and U+U collisions at 200 GeV and 193 GeV, respectively. A deviation from unity of the ratio of $\chi_{4,22}$ between U+U and Au+Au collisions would suggest sizeable hexadecapole deformation in Uranium-238. These results are compared with iEBE-VISHNU hydrodynamic and AMPT model studies, which incorporate the β_4 value of Uranium-238 from nuclear structure theory calculations.



$$r_{Au,U}\{2\}^2 = \frac{v_2\{2\}^2(U+U)}{v_2\{2\}^2(Au+Au)}$$

The "v_2 puzzle":

v_2 ratio can either explained by a large β_2 and/or large β_4. measurement of the β_4 of U are crucial to remove the ambiguity? [1,2]



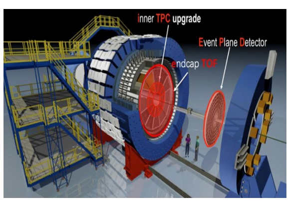
$$R(X) = 2\frac{X_{UU} - X_{AuAu}}{X_{UU} + X_{AuAu}}, \qquad v_4 = v_4^{(L)} + v_4^{(NL)} = v_4^{(L)} + \chi_{4,22} v_2^2$$

WS parameters for ^{238}U and ^{197}Au

	R_0 (fm)	a (fm)	β_2	β_4
U	6.87	0.556	0.286	0.000
$U^{(new)}$	6.90	0.538	0.259	0.100
$U^{(test1)}$	6.87	0.556	0.286	0.100
$U^{(test2)}$	6.87	0.556	0.232	0.100
$U^{(test3)}$	6.87	0.556	0.286	0.200
Au	6.38	0.535	−0.131	−0.031
$Au^{(test)}$	6.38	0.535	−0.160	−0.031

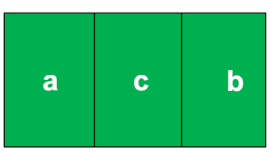
Hydrodynamic and AMPT studies show that due to the nonlinear response, v_4 is not a good probe to gauge the β_4, instead model studies show $\chi_{4,22}$ is an ideal probe to determine the β_4, which is insensitive to β_2 [3, 4]

Experimental analysis:



- **The STAR Detector**
  - ✓ 2π azimuthal coverage
  - ✓ Large acceptance

3 sub-event



-0.3 η 0.3

- **3 sub-event method**

$$v_n\{2\}^2 \equiv \langle\langle 2\rangle_{n,-n}\rangle = \langle\langle e^{i(n\phi_1^a - n\phi_2^b)}\rangle\rangle$$

$$ac_2\{3\} \equiv \langle\langle 3\rangle_{2,2,-4}\rangle = \langle\langle e^{i(2\phi_1^a + 2\phi_2^b - 4\phi_3^c)}\rangle\rangle$$

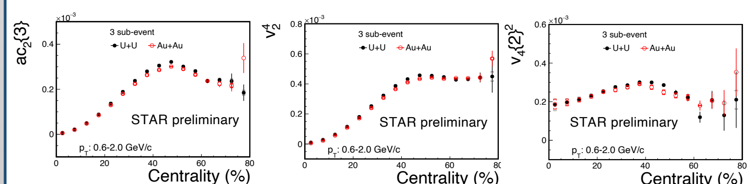
$$v_2^4 \equiv \langle\langle 4\rangle_{2,2,-2,-2}\rangle = \langle\langle e^{i(2\phi_1^c + 2\phi_2^c - 2\phi_3^a - 2\phi_4^b)}\rangle\rangle$$

$$\cos(4(\psi_2 - \psi_4)) = \frac{\langle Q_{2,a}^2 Q_{4,b}^*\rangle}{\sqrt{\langle Q_{4,a} Q_{4,b}^*\rangle}\sqrt{\langle Q_{2,a}^2 Q_{2,b}^{*2}\rangle}}$$

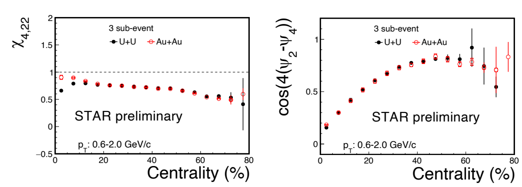
$$V_n = v_n \exp(in\Psi_n)$$

$$V_4 = V_{4L} + \chi_{422} V_2^2, \qquad \chi_{4,22} \equiv \frac{ac_2\{3\}}{\langle v_2^4\rangle}$$

Au+Au vs. U+U:

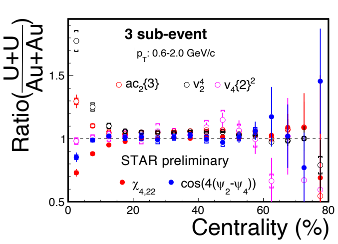


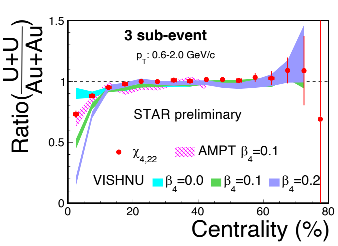
$ac_2\{3\}$, v_2^4, $v_4\{2\}^2$



$\chi_{4,22}$ and $\cos(4\psi_2 - 4\psi_4)$

Results:





- ❑ The centrality dependences of the ratios of the correlators between U+U and Au+Au collisions.
- ❑ $\chi_{4,22}$ ratio compared with model studies from iEVE-VISHNU hydrodynamic and AMPT, which included the β_4 of U.

Summary:

- Non-linear response coefficient $\chi_{4,22}$ in Au+Au and U+U collisions.
- The $\chi_{4,22}$ ratio between U+U and Au+Au deviation from unity in the central collisions.
- VISHNU with β_4=0.1 over predicts the deviation from1. Consistent with AMPT using β_4=0.1
- Indicate sizable hexadecapole deformation of Uranium-238 using the relativistic heavy-ion collisions.

Reference:

1) W. Ryssens, G. Giacalone, B. Schenke, C. Shen, PRL130, 212302(2023)
2) L. Adamczyk et al. (STAR), Phys. Rev. Lett. 115, 222301 (2015)
3) HJ. Xu, J. Zhao, FQ. Wang, PRL132, 262301 (2024)
4) ZN. Wang, JH. Chen, HJ. Xu, J. Zhao, PRC 110, 034907 (2024)

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

FUDAN UNIVERSITY 復旦大學

The STAR Collaboration