# Probing the nuclear deformation with three-particle asymmetric cumulant in isobar collisions at RHIC

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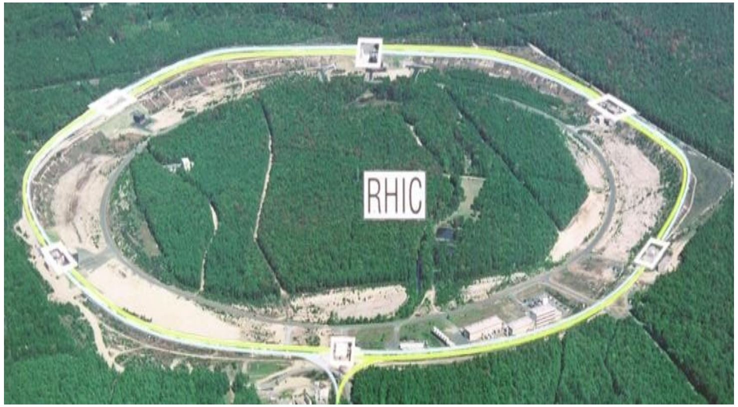
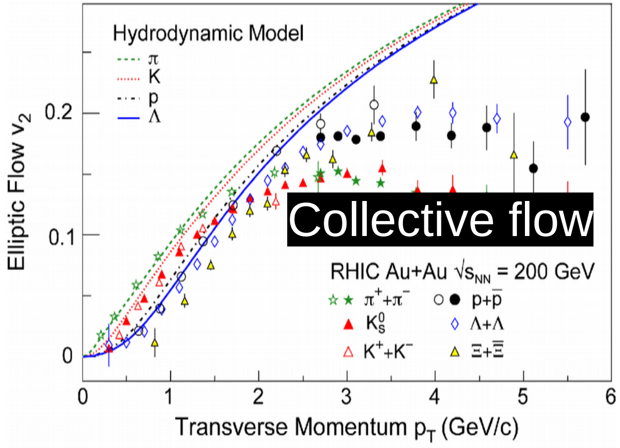
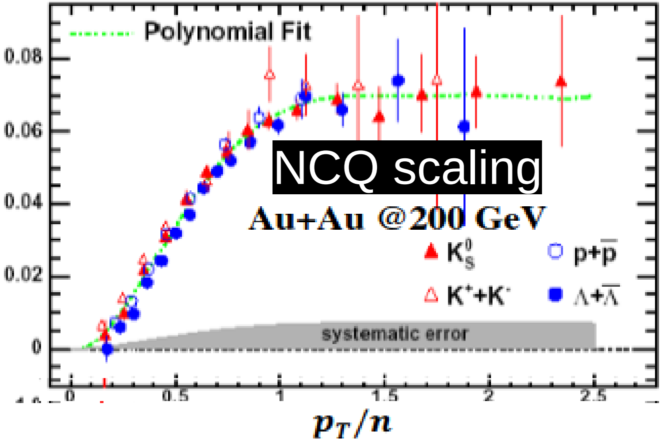
ArXiv: 2204.02387

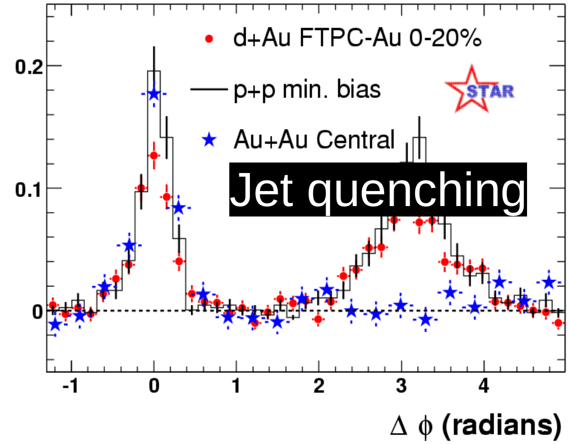
# QGP Signals in HIC

QGP has been formed at RHIC in heavy-ion collision.



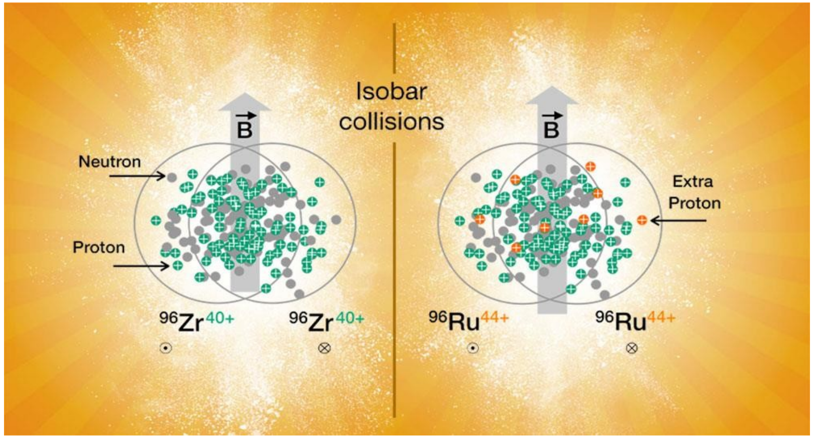




“The Frontiers of Nuclear Science, A Long Range Plan”, arXiv:0809.3137

# Isobar Collision: A Way to Search CME in HIC




$^{96}_{44}Ru + ^{96}_{44}Ru$

$^{96}_{40}Zr + ^{96}_{40}Zr$

Methodology:

Same background signal.

Different CME signal.

Take ratio to remove background effect.

CME signal:

Charge current

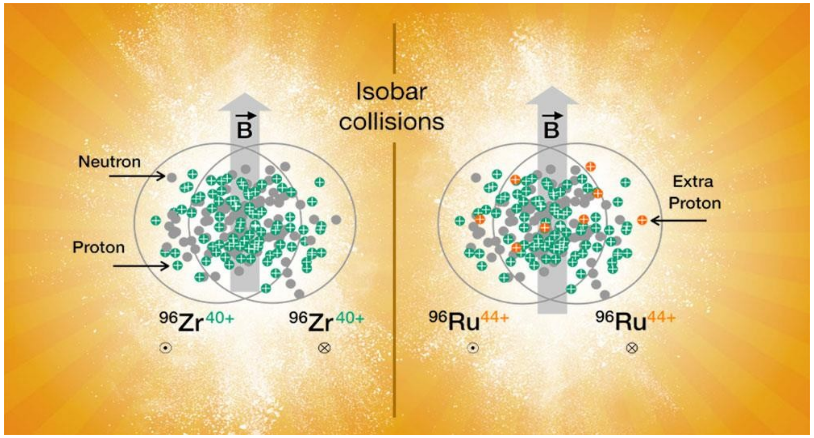
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

**Chiral Magnetic Effect (CME)**

Background signal:

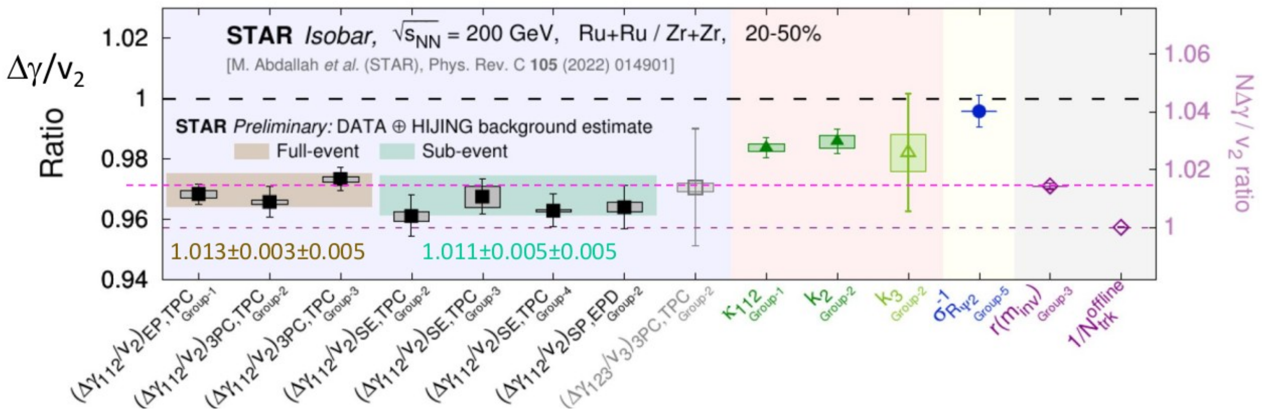
Expected to be similar at 20-50% centrality.

# Isobar Collision: A Way to Search CME in HIC

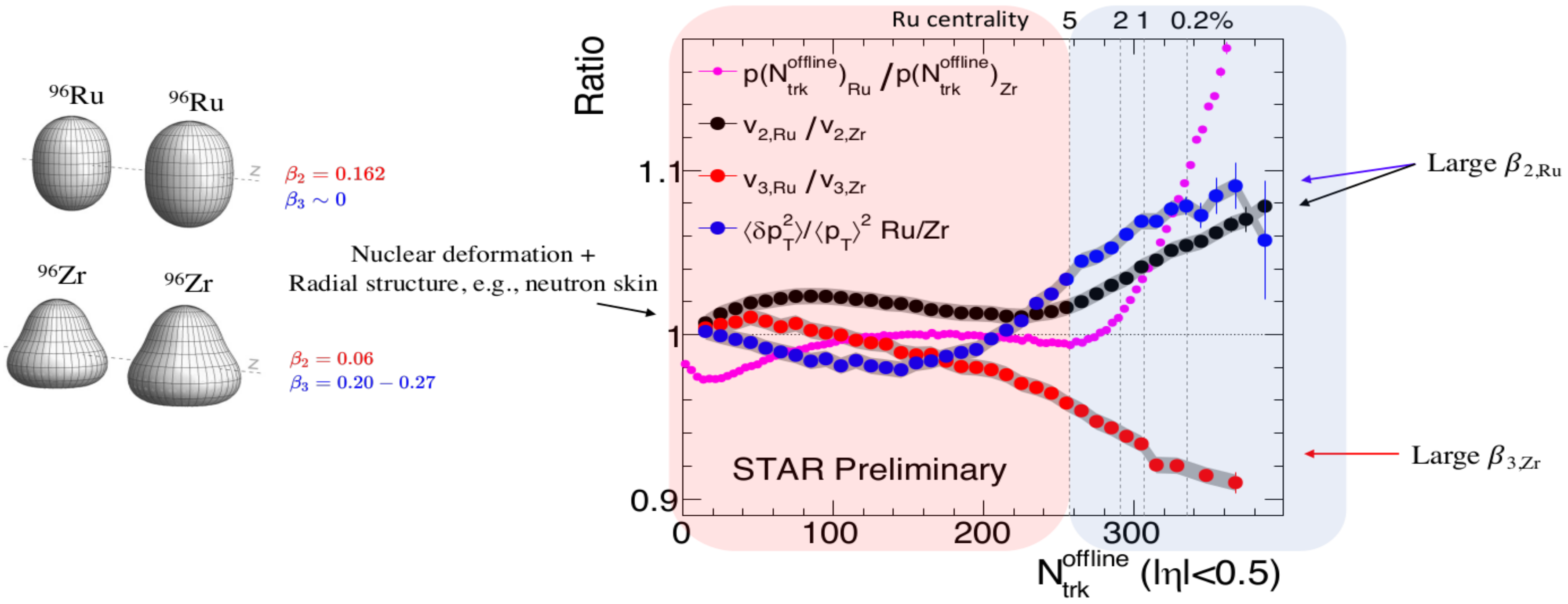



CME signal is not discovered due to large background effects from both multiplicity and flow.

More understanding of flow background to help CME searching.



# Isobar Collision: A Way to Probe Nuclear Structure

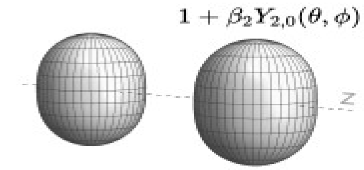



Ratio of bulk observables can image the shape of the nuclei.

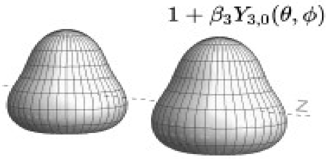
# Isobar Collision: A Way to Probe Nuclear Structure

Nuclear structure → Isobar collision → High energy Nuclear physics

High energy Nuclear physics → Isobar collision → Nuclear structure




× hydro evolution




× hydro evolution

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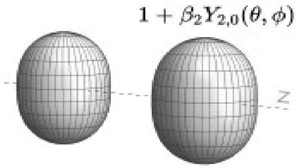


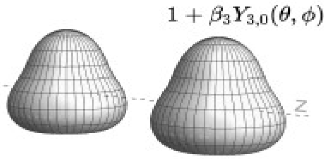


Ru / Zr
U / Au
Xe / Pb
……

**Constraint nuclear deformation in isobar collision.**

# Isobar Collision: A Way to Probe Nuclear Structure

Evidence of Quadrupole and Octupole Deformations in Zr96+Zr96 and Ru96+Ru96 Collisions at Ultrarelativistic Energies

Chunjian Zhang (SUNY, Stony Brook, Chem. Dept.), Jiangyong Jia (SUNY, Stony Brook, Chem. Dept. and Brookhaven)
Sep 3, 2021

Scaling approach to nuclear structure in high-energy heavy-ion collisions

Jiangyong Jia (SUNY, Stony Brook, Chem. Dept. and Brookhaven), Chun-Jian Zhang (SUNY, Stony Brook, Chem. Dept.)
Nov 30, 2021

Inferring nuclear structure from heavy isobar collisions using Trajectum

Govert Nijs (MIT, Cambridge, CTP), Wilke van der Schee (CERN)
Dec 27, 2021

Impact of nuclear structure on the CME background in $^{96}_{44}$Ru + $^{96}_{44}$Ru and $^{96}_{40}$Zr + $^{96}_{40}$Zr collisions at $\sqrt{s_{NN}}$ = 7.7 $\sim$ 200 GeV from a multiphase transport model

Fei Li (Fudan U., Shanghai), Yu-Gang Ma (Fudan U., Shanghai and NSFC, Beijing), Song Zhang (Fudan U., Shanghai and NSFC, Beijing), Guo-Liang Ma (Fudan U., Shanghai and NSFC, Beijing), Qi-Ye Shou (Fudan U., Shanghai and NSFC, Beijing)
Jan 26, 2022

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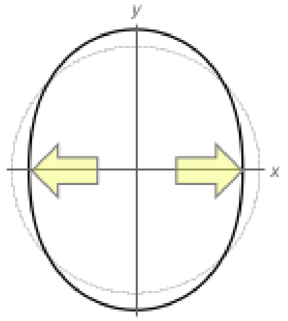
Current studies are mainly focus on the flows.
How about flow fluctuations and correlations?

# A systematic study of deformation:
# flow & flow fluctuation & flow correlation

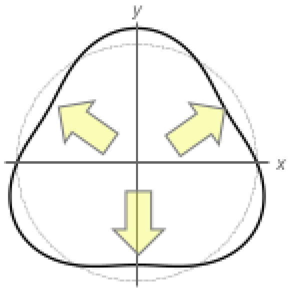
# Model setup

- Initial stage: TRENTo initial condition
- Pre-equilibrium dynamics: Free-streaming
- QGP evolution: VISH2+1
- Particalization: Cooper-Frye formula
- Hadronic scattering: UrQMD

| | $\beta_2$ | $\beta_3$ | $R_0$ | $a$ |
|---|---|---|---|---|
| Ru-para-I | 0.12 | 0.00 | 5.093 | 0.487 |
| Ru-para-II | 0.16 | 0.00 | 5.093 | 0.471 |
| Zr-para-I | 0.00 | 0.16 | 5.021 | 0.524 |
| Zr-para-II | 0.00 | 0.20 | 5.021 | 0.517 |

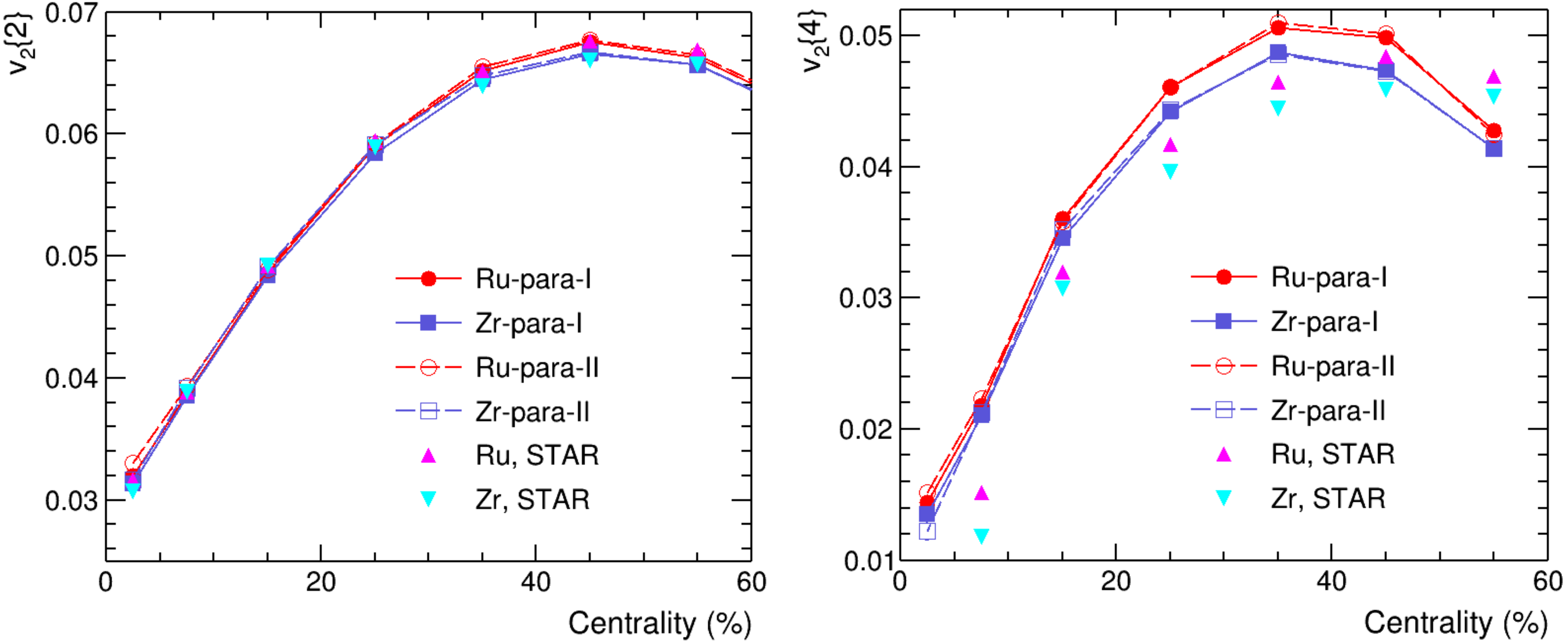



$1 + \beta_2 Y_{2,0}(\theta, \phi)$



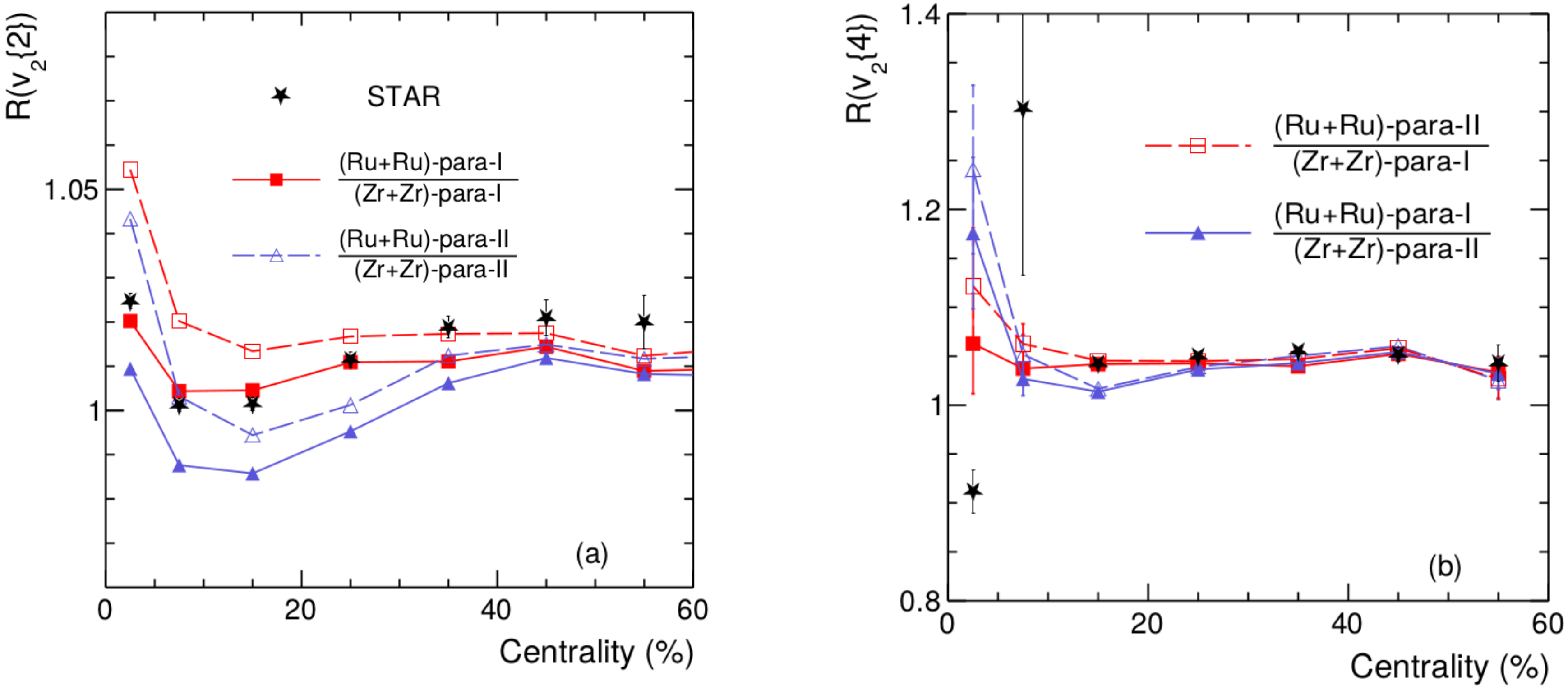

$1 + \beta_3 Y_{3,0}(\theta, \phi)$

# Separate description of $v_2\{2\}$ and $v_2\{4\}$




Quantitative description of $v_2\{2\}$, but overestimate for $v_2\{4\}$

# Flow and flow fluctuation

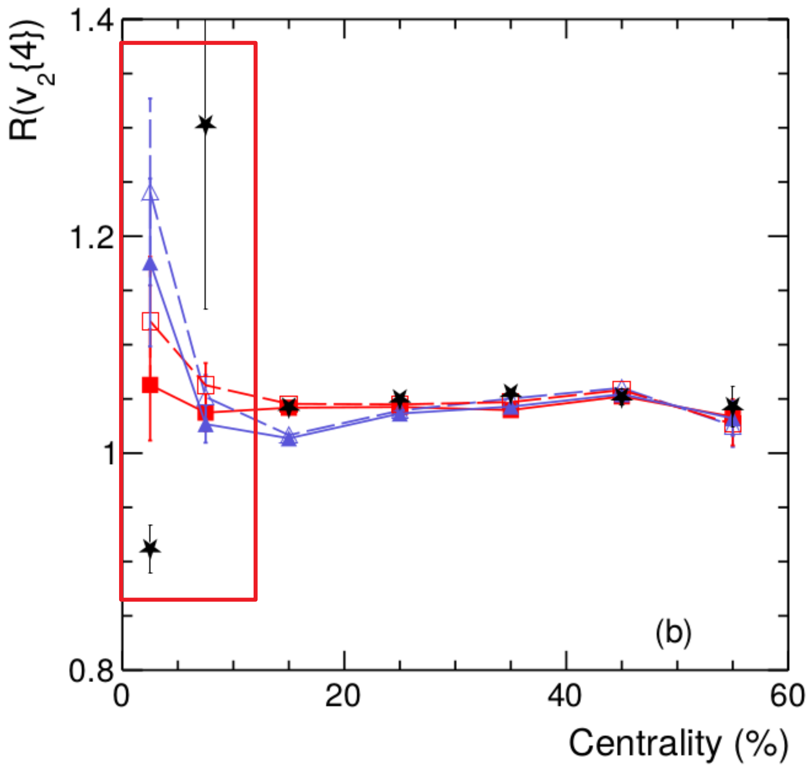



Roughly describe $v_2\{2\}$ ratio, but not for $v_2\{4\}$ ratio in central collisions.

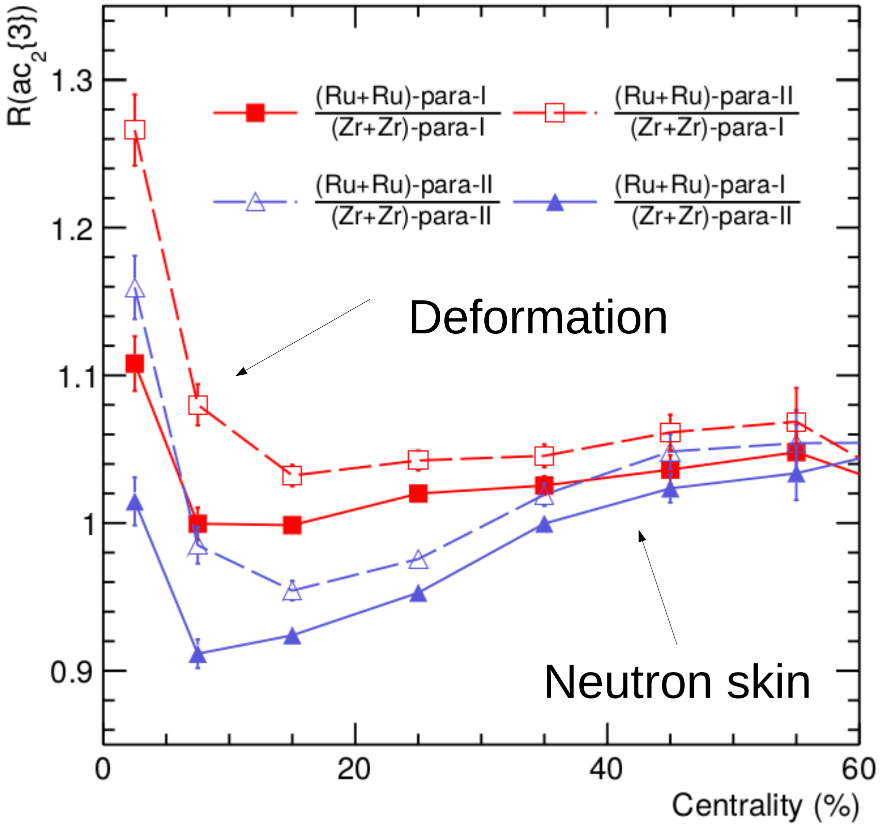
S. Zhao, H. Xu, Y. Liu, H. Song. arXiv: 2204.02387

# Flow and flow fluctuation

Careful treatments of both deformation and fluctuation are necessary to describe R($v_2${4}) in the most central collisions.



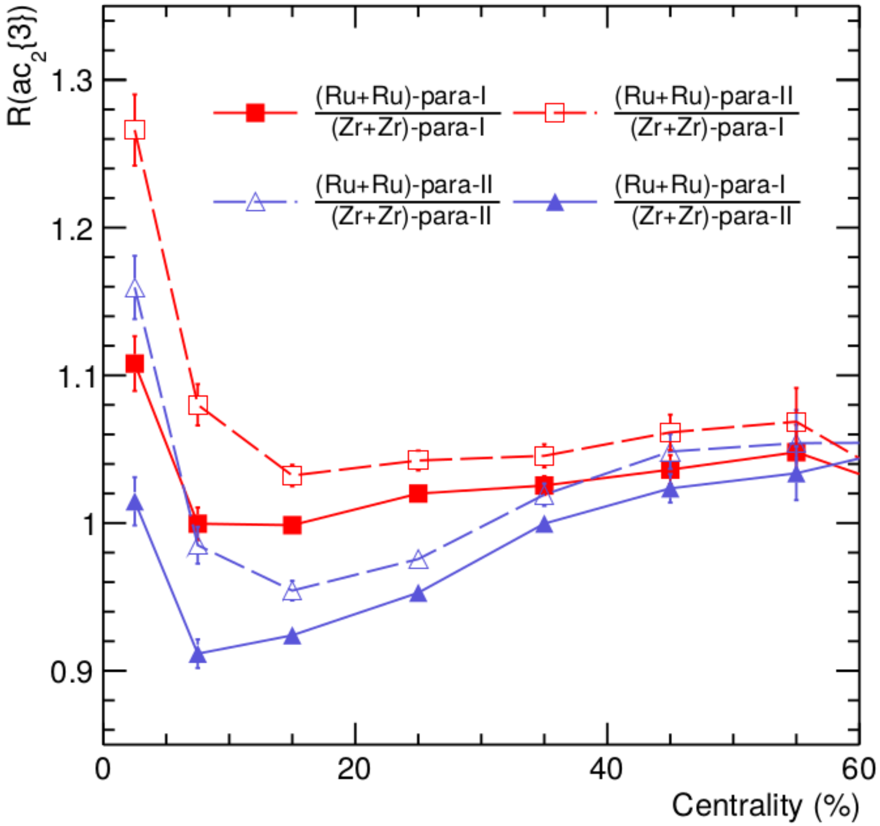
# Flow correlation: Three-particle asymmetric cumulant




$$
\begin{aligned}
ac_2\{3\} &\equiv \langle\langle 3\rangle_{2,2,-4}\rangle \\
&= \langle\langle e^{i(2\phi_1+2\phi_2-4\phi_3)}\rangle\rangle \\
&= \langle v_2^2 v_4 \cos[4(\Phi_2-\Phi_4)]\rangle
\end{aligned}
$$

A precise measurement of R($ac_2${3}) may help to better constraint the deformation of two nuclei.

# Flow correlation: Three-particle asymmetric cumulant



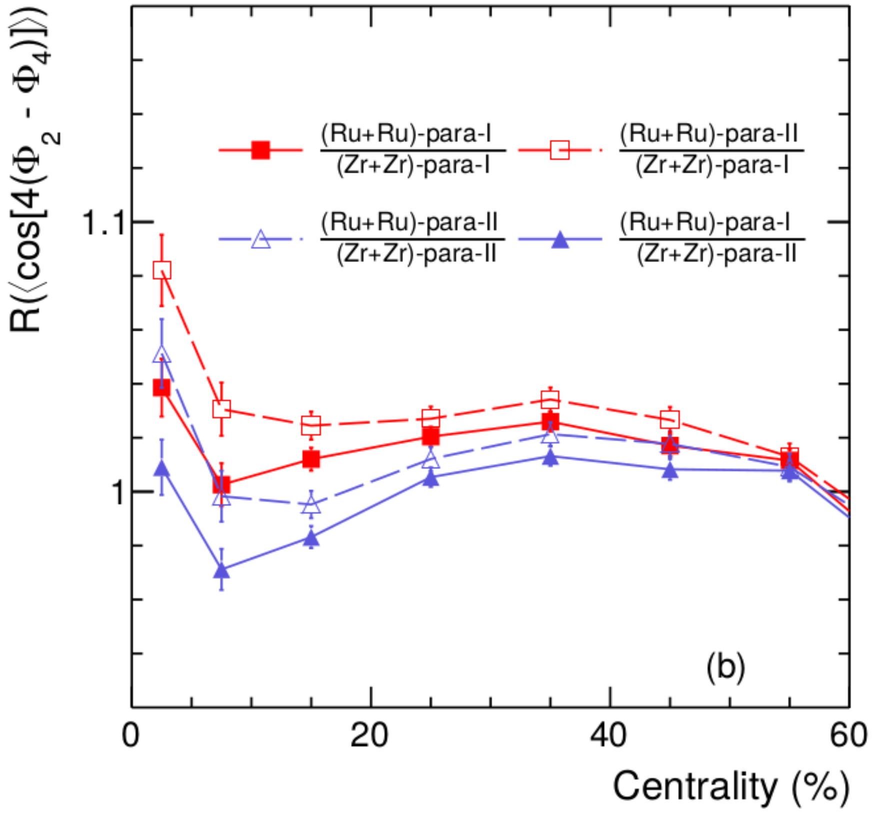

$$ac_2\{3\} \equiv \langle\langle 3\rangle_{2,2,-4}\rangle$$
$$= \langle\langle e^{i(2\phi_1+2\phi_2-4\phi_3)}\rangle\rangle$$
$$= \langle v_2^2 v_4 \cos[4(\Phi_2 - \Phi_4)]\rangle$$

Flow magnitude

Event-plane angle

Flow correlations may show more sensitivity of nuclear deformation.

# Nonlinear response

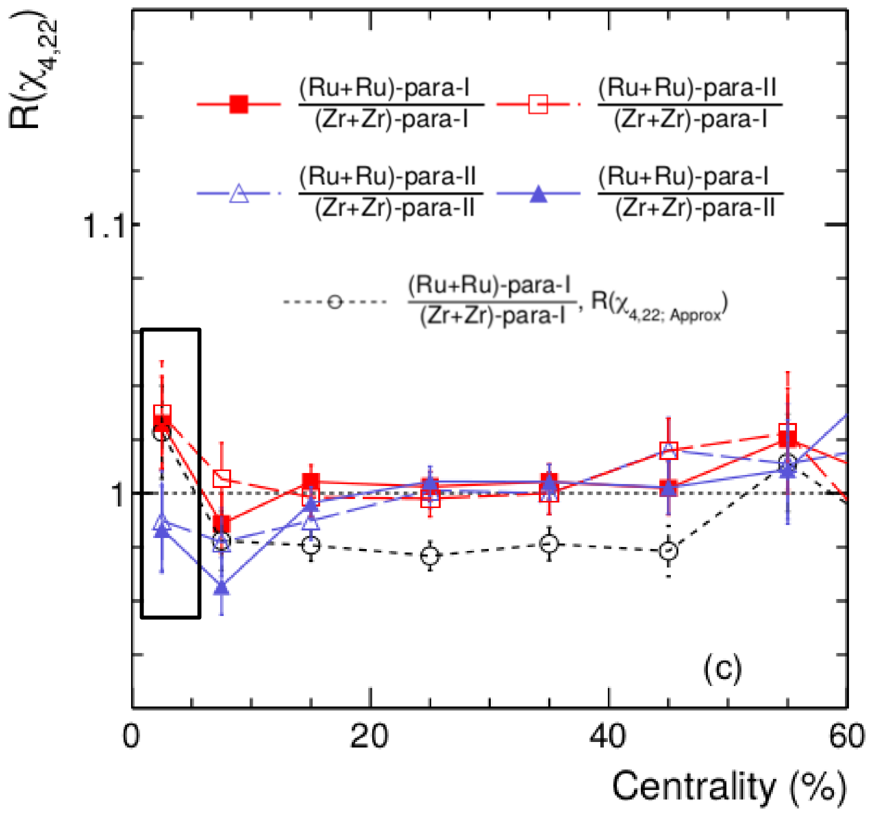



$$v_4^{\mathrm{Inclusive}} = v_4^{\mathrm{Linear}} + v_4^{\mathrm{NonLinear}}$$

$$\langle \cos[4(\Phi_2 - \Phi_4)] \rangle = \frac{v_4^{\mathrm{NonLinear}}}{v_4^{\mathrm{Inclusive}}}$$

Deformation would also affect the nonlinear response between $v_2$ and $v_4$.

# Nonlinear response




$$v_4^{\mathrm{Inclusive}} = v_4^{\mathrm{Linear}} + v_4^{\mathrm{NonLinear}}$$

$$\chi_{4,22} = \frac{v_4^{\mathrm{NonLinear}}}{\sqrt{\langle v_2^4 \rangle}}$$

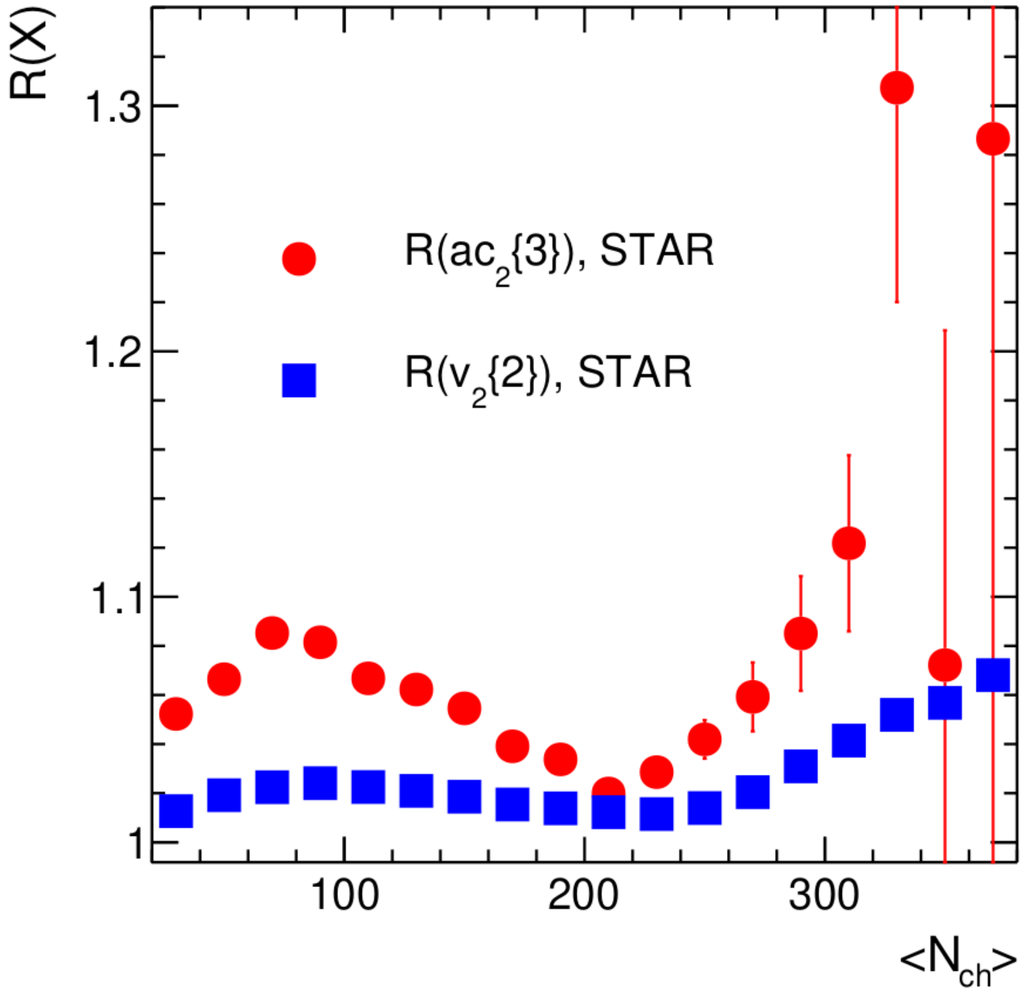
Nonlinear coefficient is insensitive to the deformation, except possible effects in the top 5% centrality.

# Summary

- Isobar collisions are good tools to study nuclear deformation.
- The behavior of R($v_2${4}) at top 5% centrality class should be treat carefully.
- $ac_2${3} would show more sensitivity to the nuclear deformation due to the contributions from flow magnitude and event-plane angle correlation.
- Nonlinear coefficient is nearly insensitive to the nuclear structure.
- A simultaneous study of harmonic flow, flow fluctuation and correlations may help to better constraint the deformation of Ru and Zr.

# Backup

# Backup



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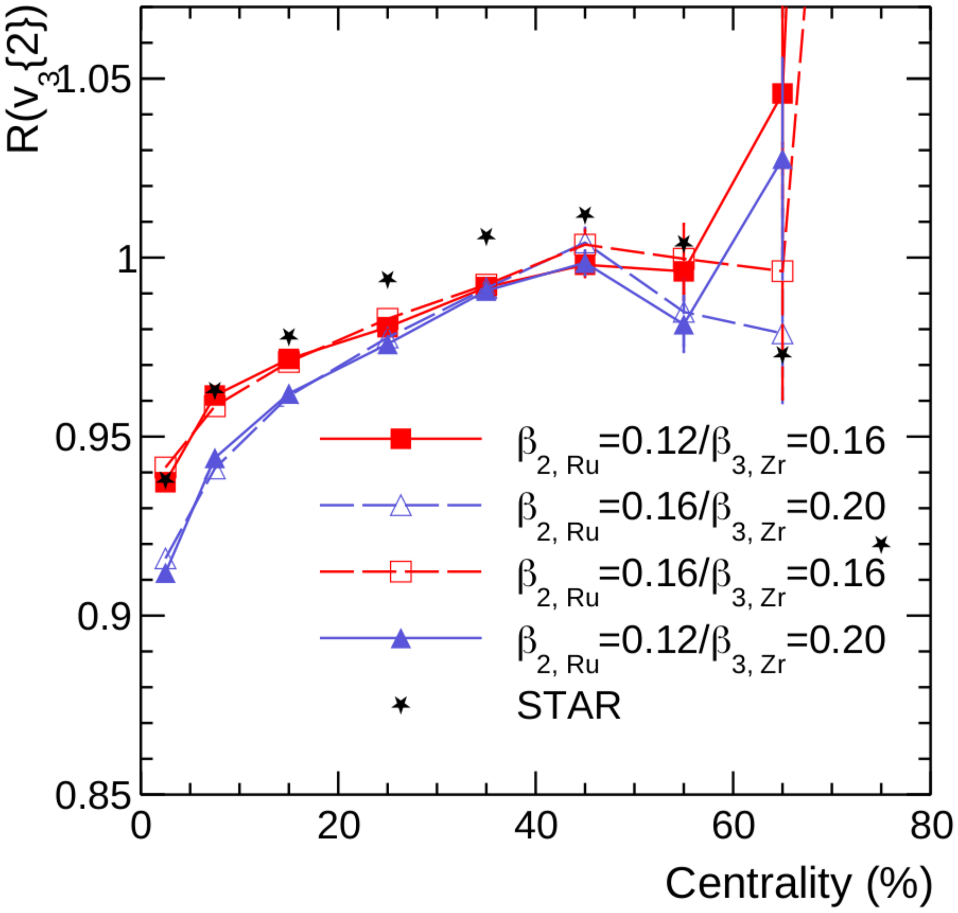
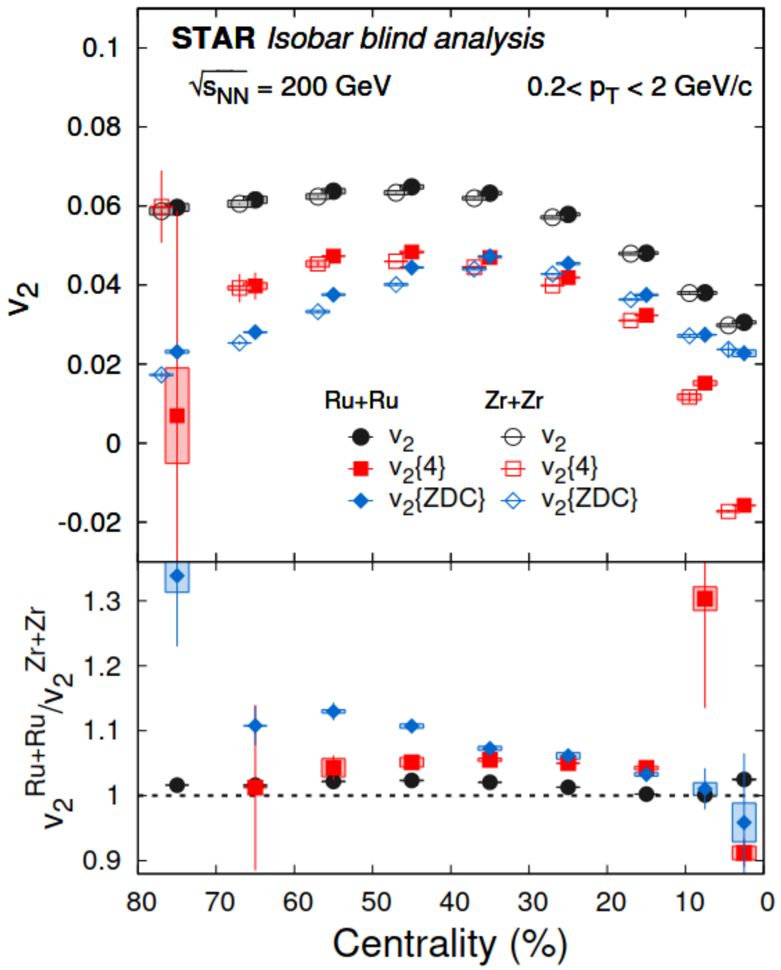

R(v3{2})
1.05
1
0.95
0.9
0.85
0
20
40
60
80
Centrality (%)
β2, Ru=0.12/β3, Zr=0.16
β2, Ru=0.16/β3, Zr=0.20
β2, Ru=0.16/β3, Zr=0.16
β2, Ru=0.12/β3, Zr=0.20
STAR

# Backup



STAR Isobar blind analysis
√sNN = 200 GeV
0.2< pT < 2 GeV/c
Ru+Ru
Zr+Zr
v2
v2{4}
v2{ZDC}
v2
v2{4}
v2{ZDC}
0.1
0.08
0.06
0.04
0.02
0
-0.02
1.3
1.2
1.1
1
0.9
v2Ru+Ru/v2Zr+Zr
80
70
60
50
40
30
20
10
0
Centrality (%)