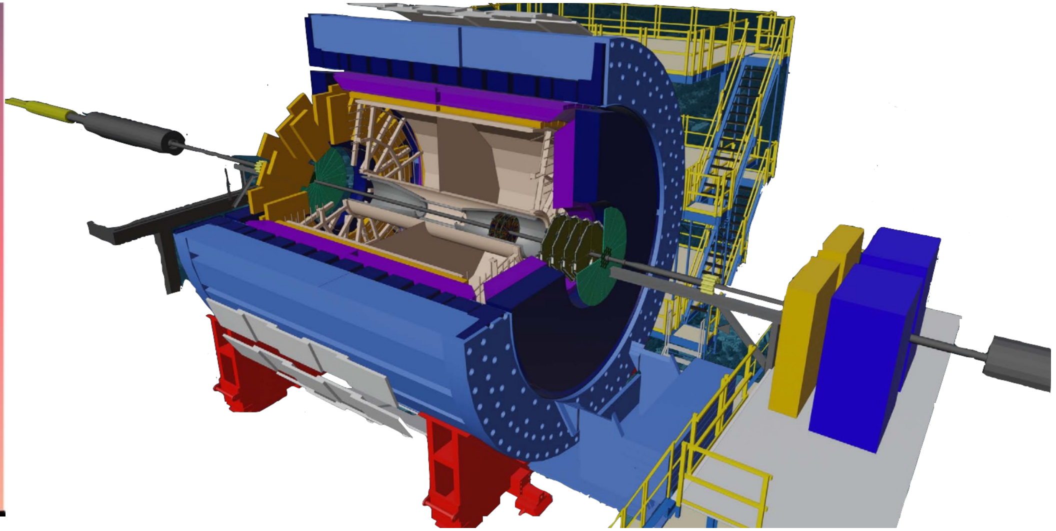
In part supported by

Overview of the STAR experiment



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CIPANP-2022

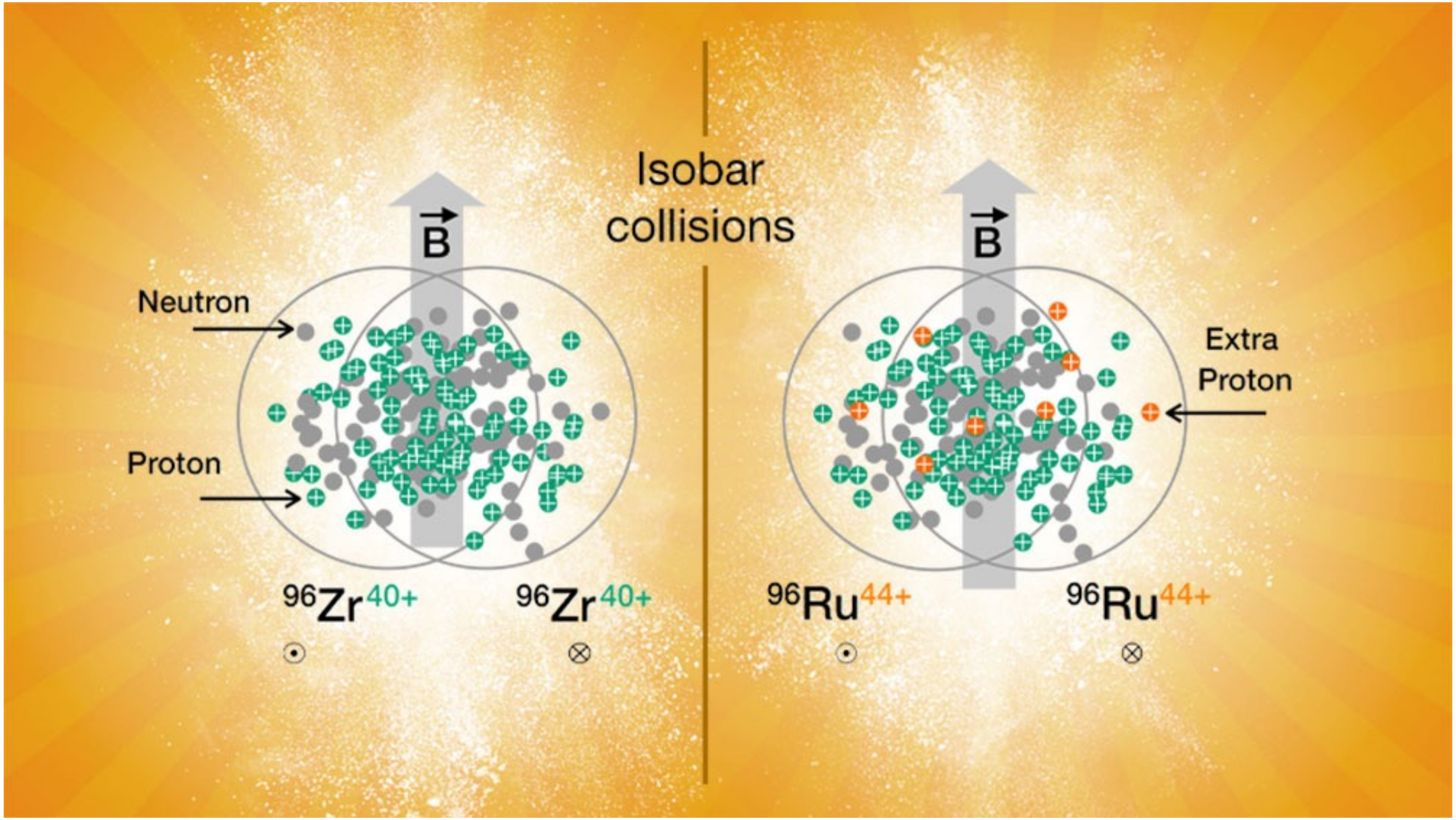
Outline

I. Isobar collisions and magnetic field effect
   a) Isobaric collision results

II. New insights into the collective effects
   a) Beam-energy scan
   b) Different collision systems

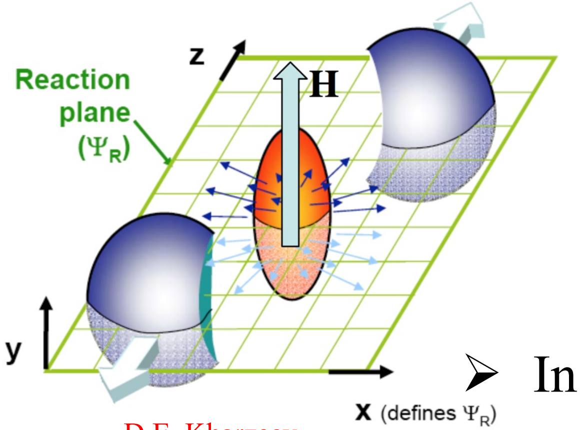
III. New insights into the nuclear shape and structure
   a) Deformation of the U nuclei
   b) Deformation study using the isobaric collisions

I) Isobar collisions and magnetic field effect



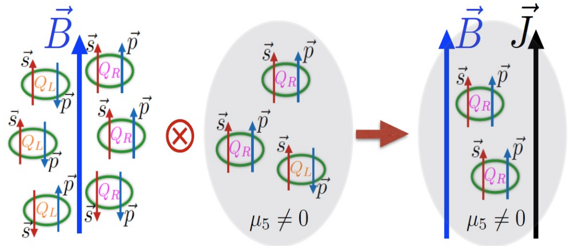
I) Isobar collisions and magnetic field effect

- Chiral Magnetic Effect (CME)



D.E. Kharzeev
Prog.Part.Nucl.Phys. 75 (2014) 133-151

D.E. Kharzeev et al.
Prog.Part.Nucl.Phys. 88 (2016) 1-28



Electric Current

Chiral Magnetic Conductivity

Chiral Chemical potential

$$\vec{J}_Q = \sigma_5 \vec{B}$$

$$\sigma_5 = C_A \mu_5$$

Kharzeev
hep-ph/0406125

$$C_A = Q^2 / (4\pi^2)$$

- In non-central collisions, a strong magnetic field is created $\perp$ to Ψ_{RP}

- The magnetic field acts on the chiral fermions with $\mu_5 \neq 0$ leading to an electric current along the magnetic field which results in a charge separation

CME-driven charge separation leads to a dipole term in the azimuthal distribution of the produced charged hadrons:

$$\frac{dN^{ch}}{d\phi} \propto 1 \pm 2\, a_1^{ch} \sin(\phi) + \cdots \qquad a_1^{ch} \propto \mu_5 \vec{B}$$

Can we identify & characterize this dipole moment?

The CME correlators have been used extensively for experimental measurements.

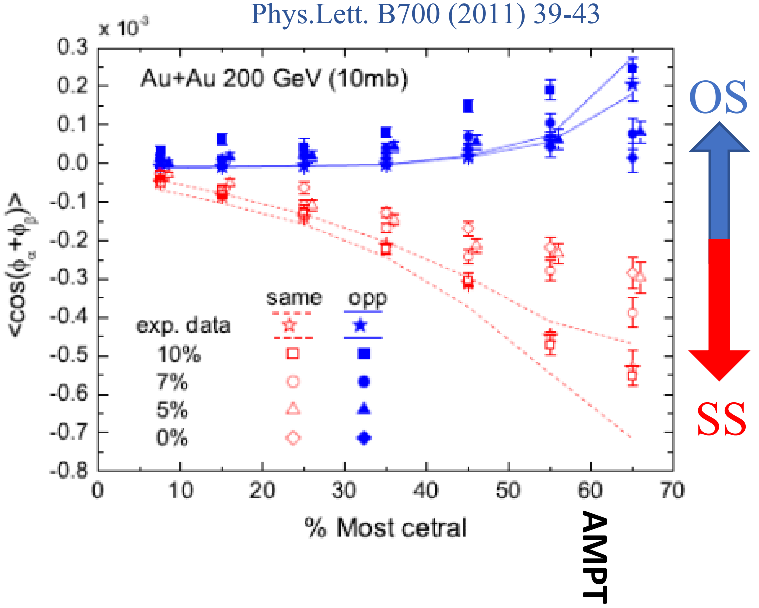
I) Isobar collisions and magnetic field effect

- Correlators to measure dipole charge separation

S. Voloshin, PRC 70 057901 (2004)

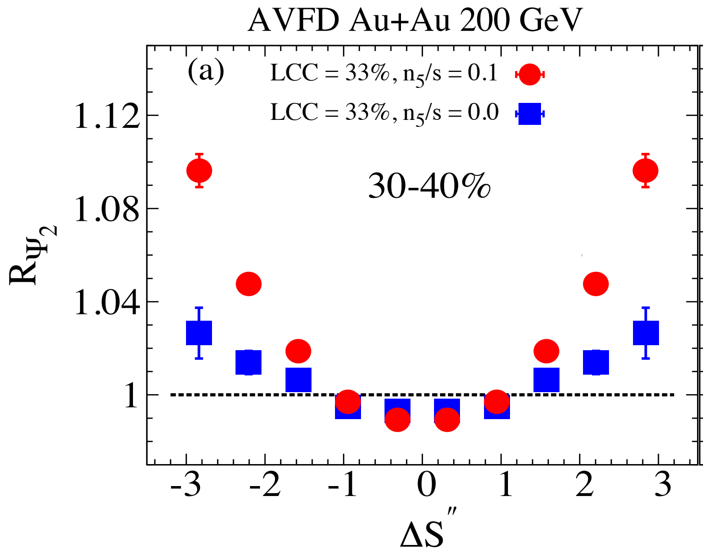
A well-known approach is to use the γ correlator to measure the dipole charge separation

Ma, Zhang
Phys.Lett. B700 (2011) 39-43



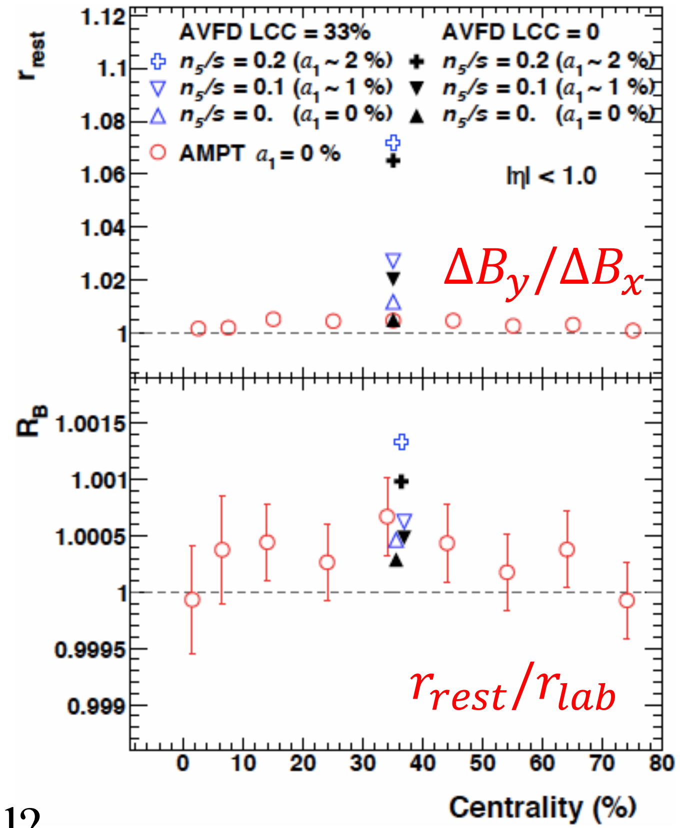
N. Magdy, et al, PRC 97 6, 061901 (2018)

The $R_{\Psi_m}(\Delta S)$ correlation function method is used to measure the dipole charge separation



A. Tang, Chinese Phys. C 44 054101 (2020)

The signed balance function method is recently used to measure the dipole charge separation



- The correlators' responses are similar for signal and background
- Background can account for a part, or all of the observed charge separation signal?

I) Isobar collisions and magnetic field effect

- Separating the signal from background is the main subject of the isobar collisions

N. Magdy, et al. PRC 98 (2018) 6, 061902

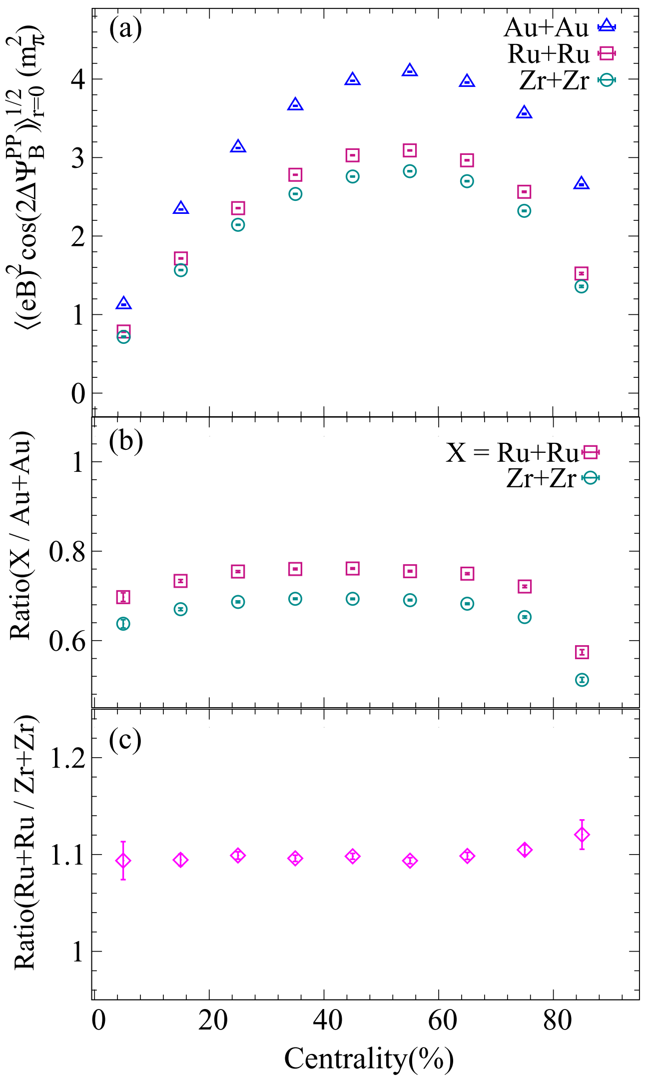
A. Tang, CPC 44 054101 (2020)

H-J. Xu, et al, CPC 42, 084103 (2018)

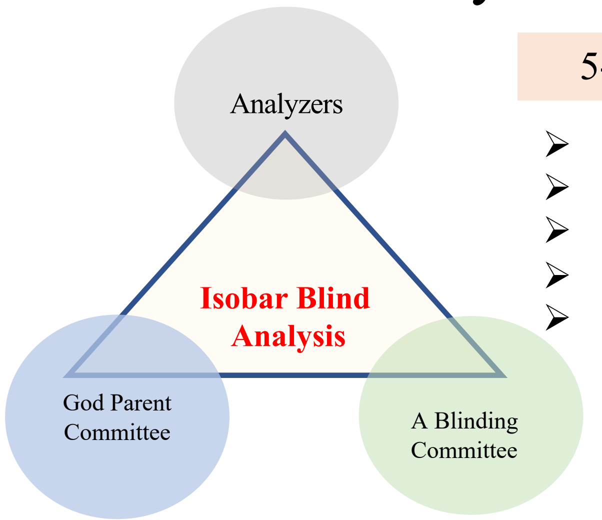
S. Voloshin, PRC 98, 054911 (2018)

J. Zhao , et al, EPJC 79 (2019) 168

Niseem Magdy, et al. PRC 98 (2018) 6, 061902



- Isobar Analysis: A large, collective effort



5-Isobar Blind Analyses

- $\Delta\gamma, \Delta\delta$ and κ
- $\Delta\gamma, \Delta\delta$ and $\Delta\gamma(\Delta\eta)$
- $\Delta\gamma$ in PP/SP and $\Delta\gamma(M_{inv})$
- $\Delta\gamma$ in PP/SP
- $R(\Delta S)$ Correlator.

Case for CME:

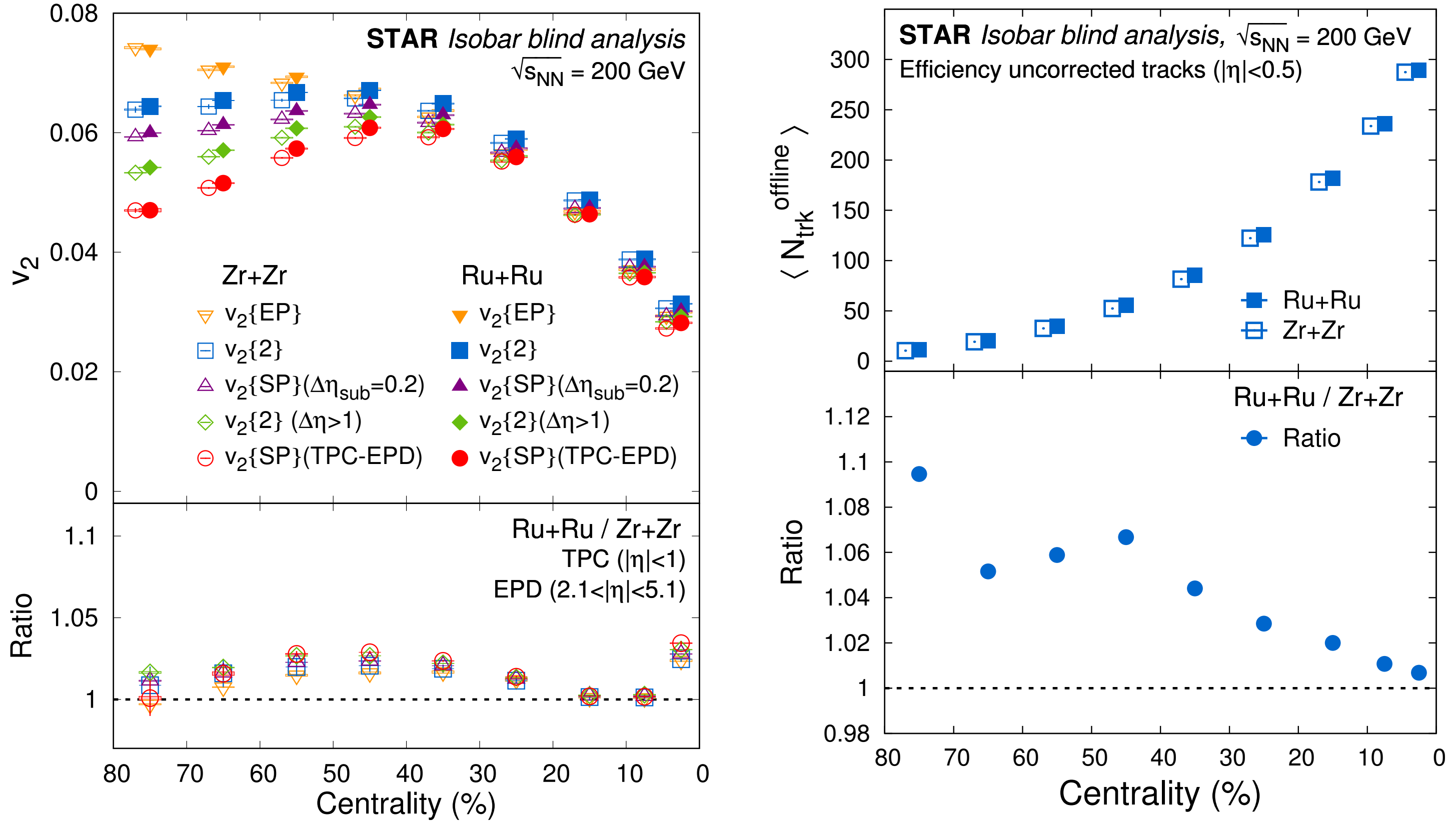
- $\Delta\gamma$ and its derivatives
  $\Delta\gamma/v_2$(Ru/Zr) > 1
  $\Delta\gamma_{112}/v_2$(Ru/Zr) $> \Delta\gamma_{123}/v_3$(Ru/Zr)
  κ(Ru/Zr) > 1
- $f_{CME}^{Ru} > f_{CME}^{Zr} > 0$
- $\sigma_{R\psi_2}^{-1}\left(\frac{Ru}{Zr}\right) > 1$

BNL, CCNU, Fudan, Huzhou, Purdue, SINAP, Stony Brook, Tsukuba, UCLA, UIC, and Wayne State

I) Isobar collisions and magnetic field effect

STAR Collaboration
PRC 105, 014901 (2022)

- Isobar Analysis: Expected CME background in isobar



- Observed differences in multiplicity and v_2 for the same centrality
  - ✓ Background differences between the two isobars are more complicated than previously thought
  - ✓ The predefined CME signature could be invalid

I) Isobar collisions and magnetic field effect

STAR Collaboration
PRC 105, 014901 (2022)

➢ Isobar Analysis: Results

Predefined CME signature:

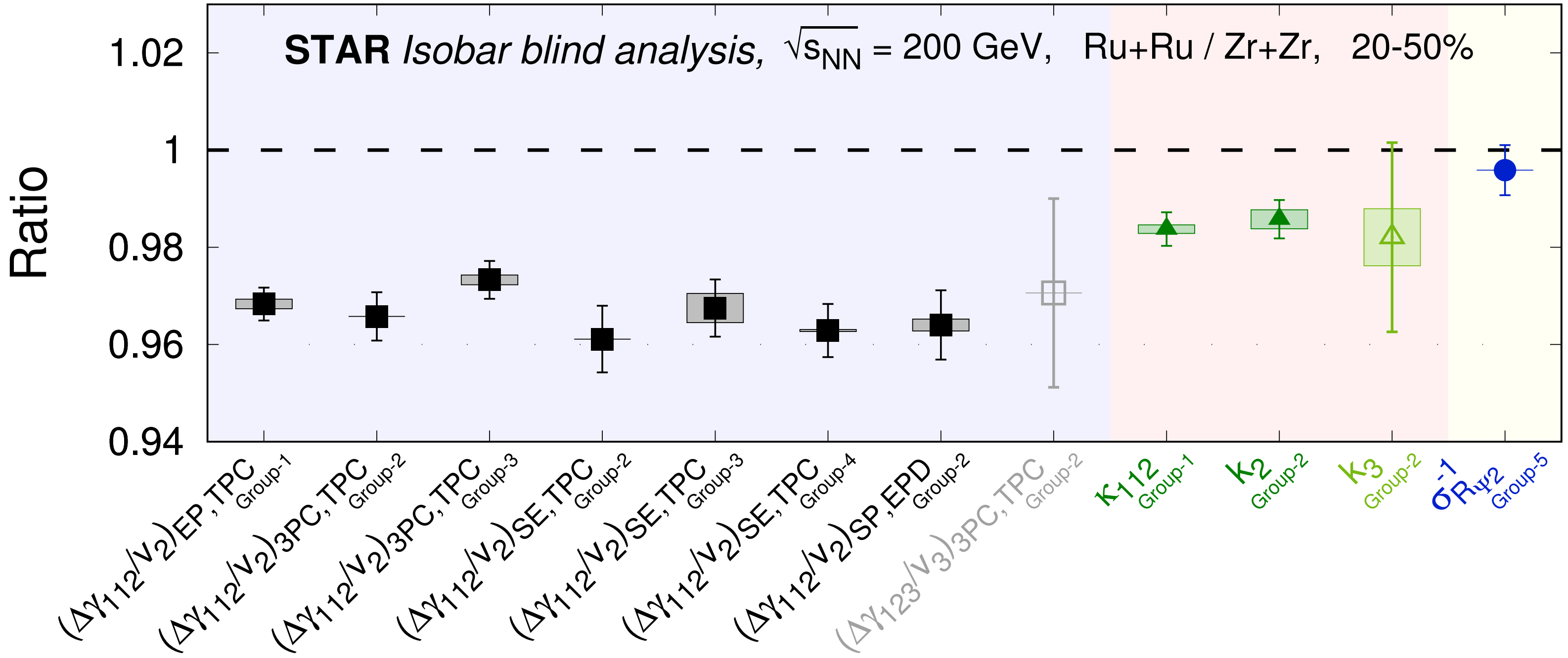
✓ $\Delta\gamma$ and its derivatives

$\Delta\gamma/v_2(\text{Ru/Zr}) > 1$

$\Delta\gamma_{112}/v_2(\text{Ru/Zr}) > \Delta\gamma_{123}/v_3(\text{Ru/Zr})$

$\kappa(\text{Ru/Zr}) > 1$

✓ $\sigma^{-1}_{R\psi_2}\left(\frac{Ru}{Zr}\right) > 1$

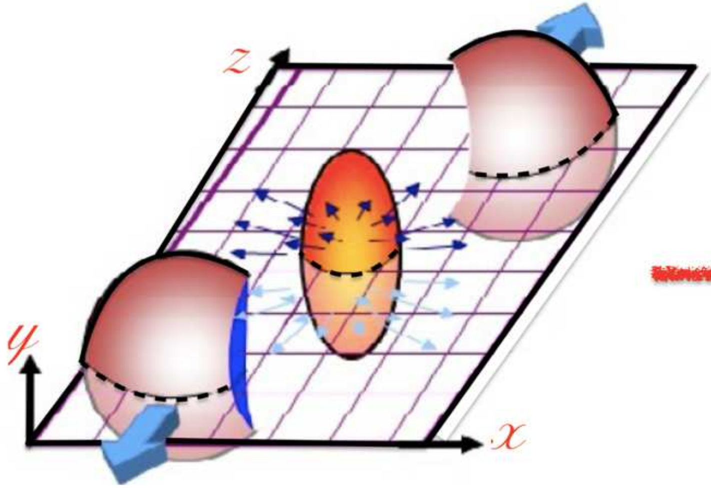


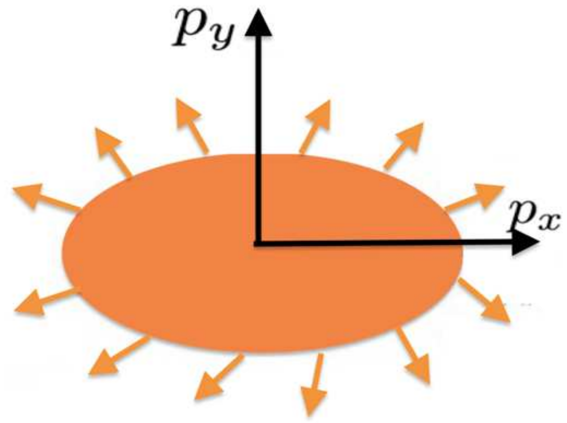
The predefined CME signature is not observed

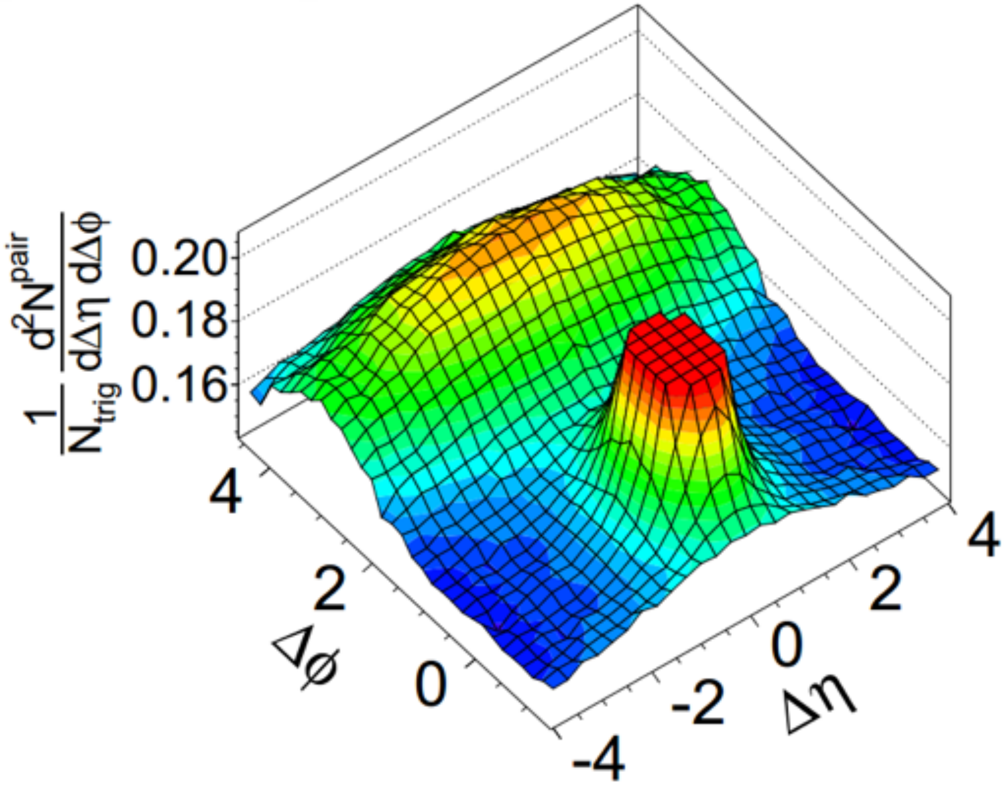
✓ Not an indication for the absence of the CME in the individual signal

- Ongoing work to characterize the effects of backgrounds

II) New insights into the collective effects



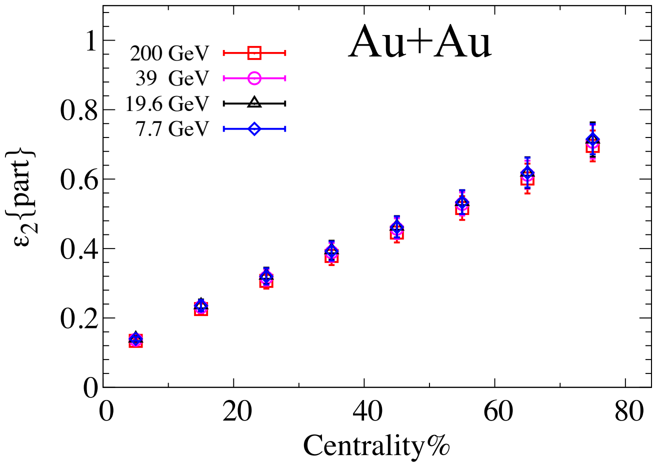




II) New insights into the collective effects

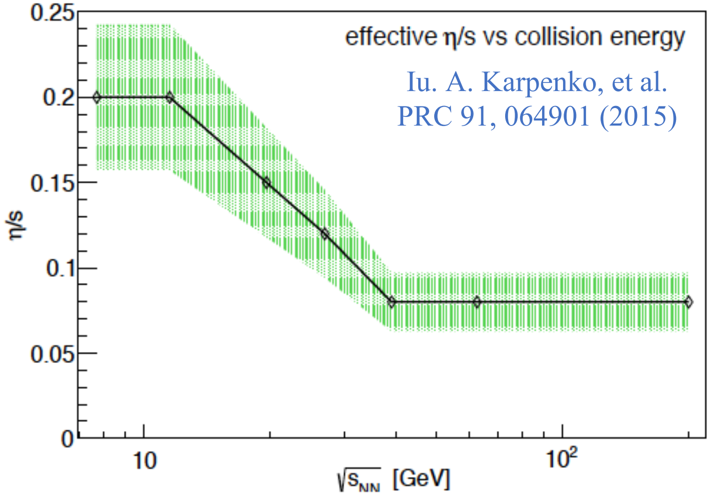
➢ Higher order flow harmonics are sensitive probes for $\frac{\eta}{s}(T)$ due to their enhanced viscous response

- Beam energy dependence for a given collision system:

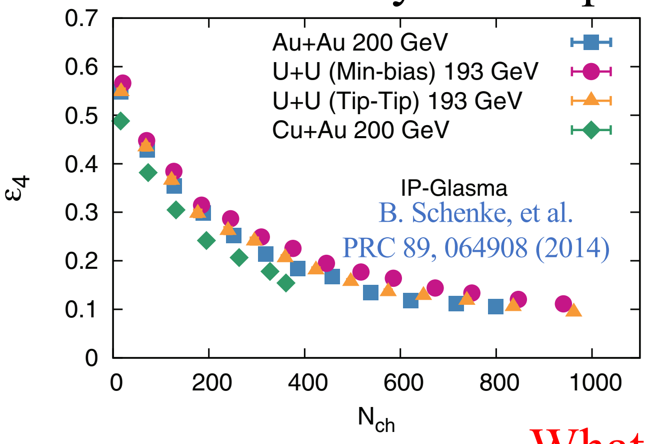


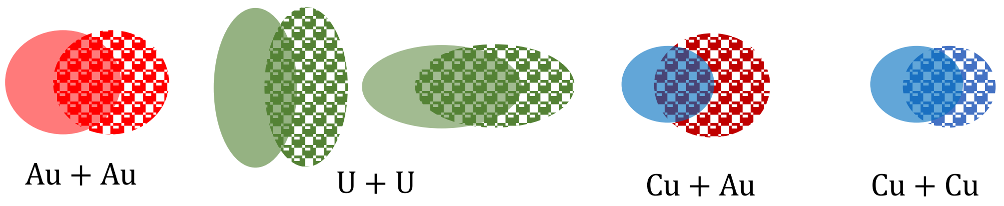
✓ Initial-state spatial anisotropy is approximately beam energy independent.

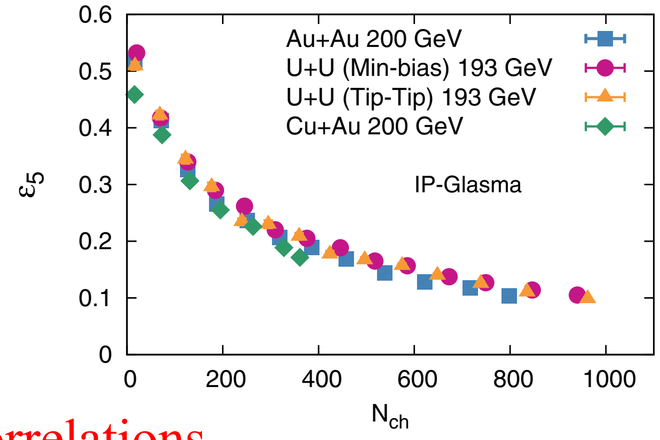
✓ Viscous attenuation ($\propto \frac{\eta}{s}(T)$) is beam energy dependent.



- Collision system dependence at a given beam energy:





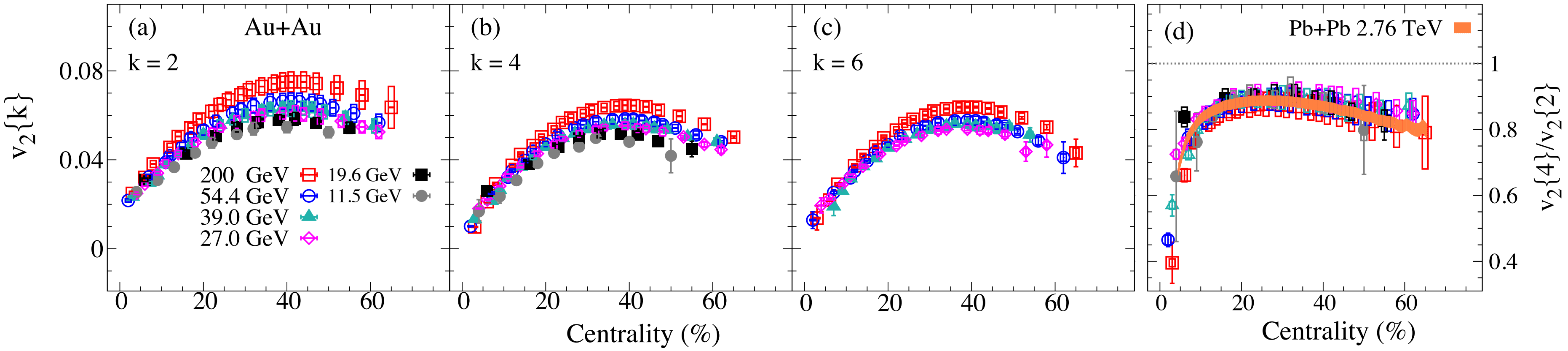


What are the respective roles of ϵ_n and its fluctuations and correlations, flow correlations and $\frac{\eta}{s}(T)$ as a function of beam energy?

II) New insights into the collective effects

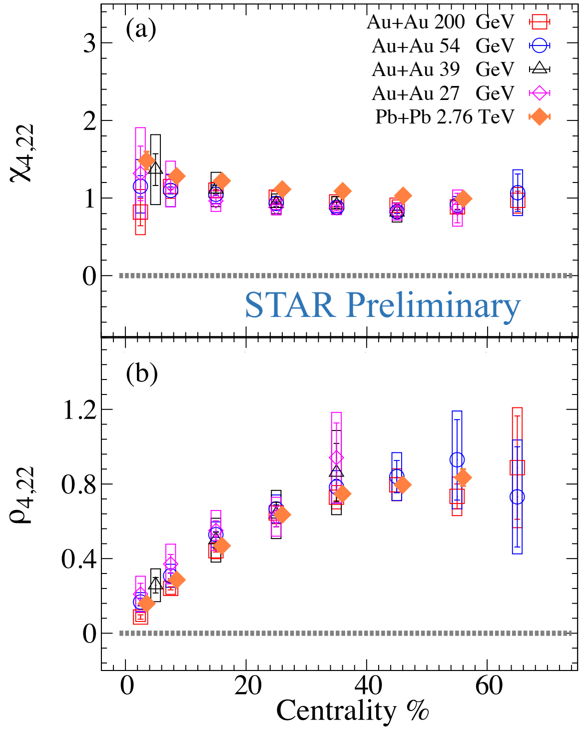
- ➢ Beam energy dependence for a given collision system:

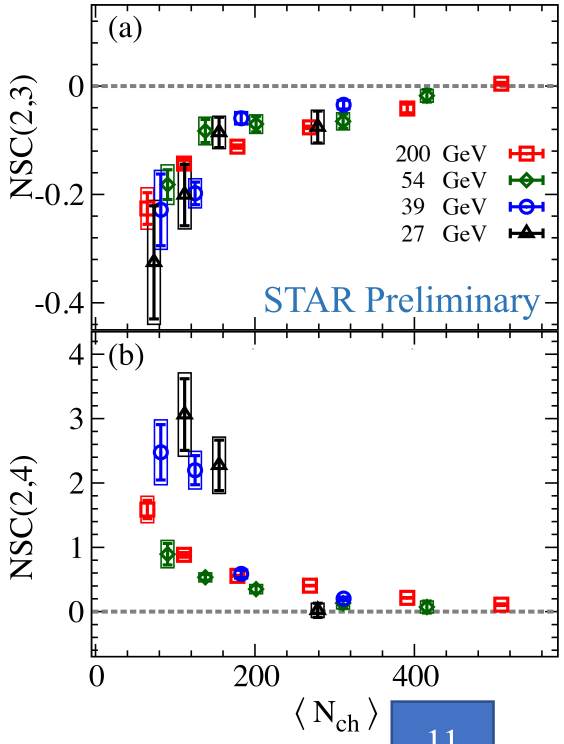
STAR Collaboration, arXiv:2201.10365



- ➢ The flow harmonics depend on beam energy.
  - ✓ Sensitive to the viscous effects (N_{ch}, $\langle p_T \rangle$, $\frac{\eta}{s}$, …)

- ➢ The dimensionless parameters show similar values and trends for different beam energies.
  - ✓ Sensitive to the ϵ_n and its fluctuations and correlations

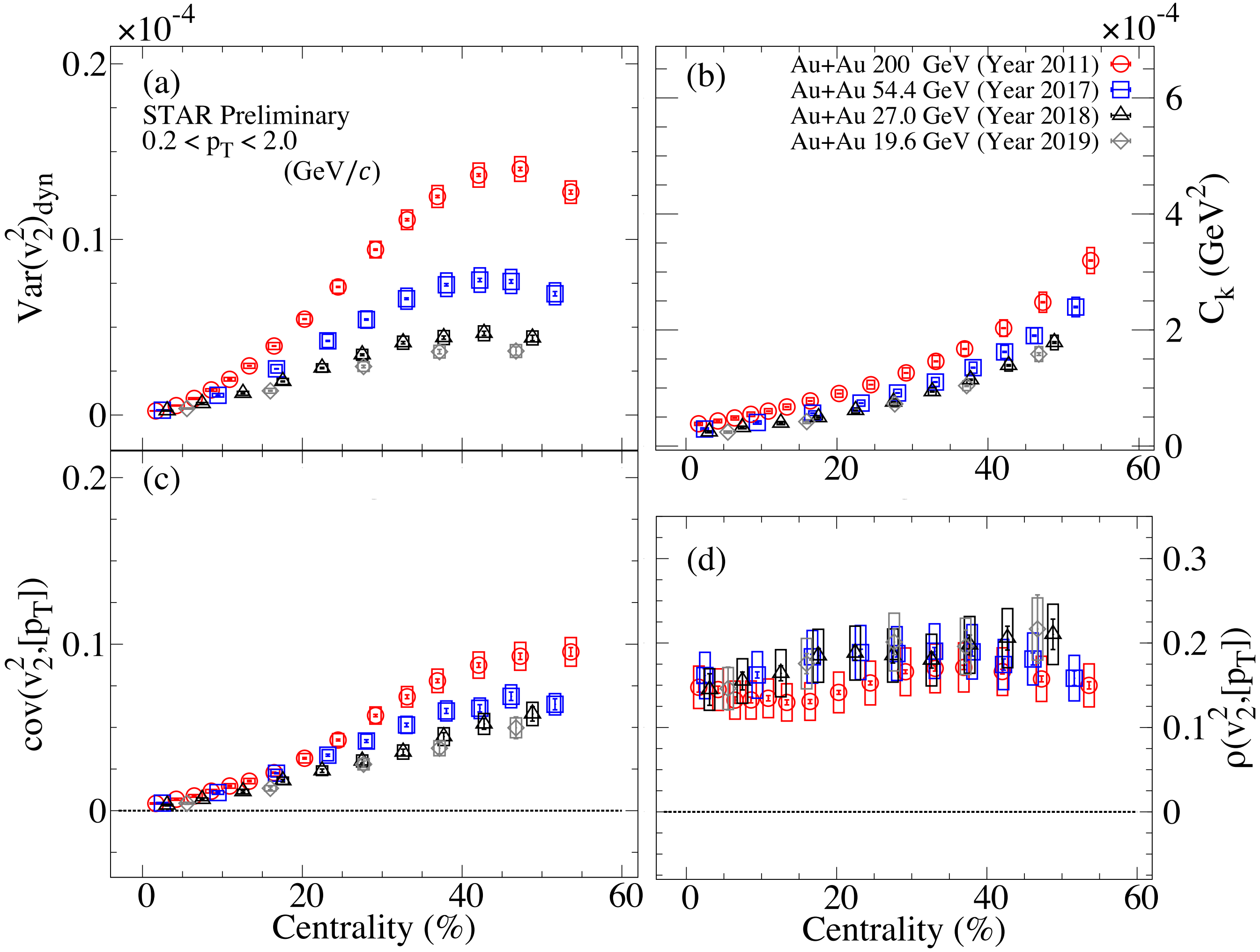




II) New insights into the collective effects

- Beam energy dependence for a given collision system:
- $v_2^2, [p_T]$ correlations

- $Var(v_2^2)_{dyn}$ decreases with beam-energy
- C_k decreases with beam-energy
- $cov(v_2^2, [p_T])$ decreases with beam-energy
  - ✓ Sensitive to the viscous effects (N_{ch}, $\langle p_T \rangle$, $\frac{\eta}{s}$, …)



- The Pearson correlation, $\rho(v_2^2, [p_T])$, shows no significant energy dependence within the systematic uncertainties
  - ✓ Sensitive to the ϵ_n and its fluctuations and correlations

II) New insights into the collective effects

- Beam energy dependence for a given collision system:

- $v_3^2, [p_T]$ correlations

- $Var(v_3^2)_{dyn}$ decreases with beam-energy
- C_k decreases with beam-energy
- $cov(v_3^2, [p_T])$ decreases with beam-energy
  - ✓ Sensitive to the viscous effects (N_{ch}, $\langle p_T \rangle$, $\frac{\eta}{s}$, …)

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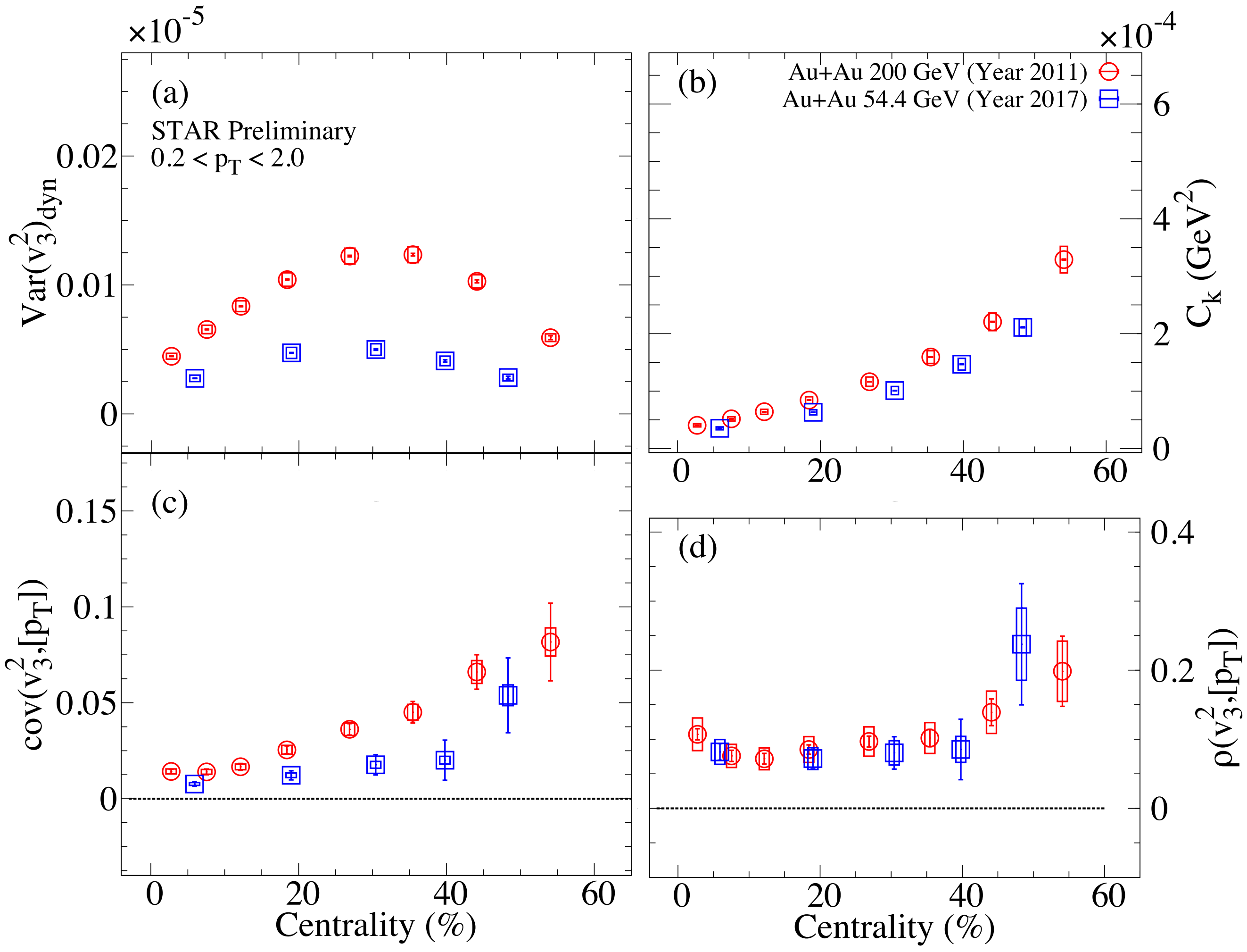
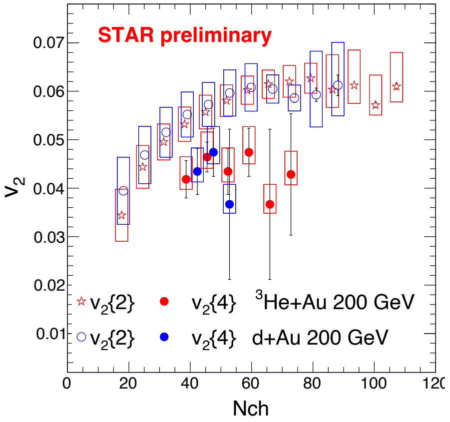


II) New insights into the collective effects

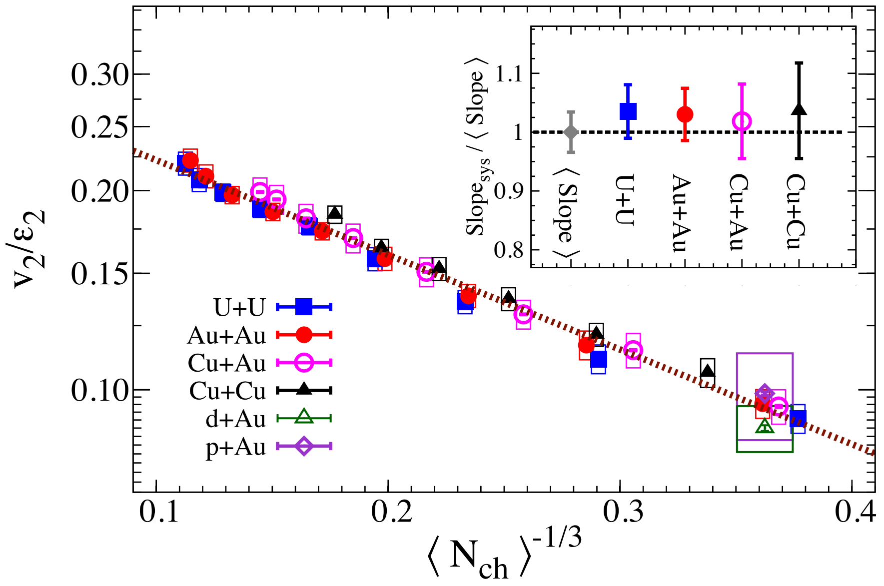
- Collision system dependence at a given beam energy:

$$\ln(v_n/\varepsilon_n) \propto -(\eta/s)\langle N_{Ch}\rangle^{-1/3}$$

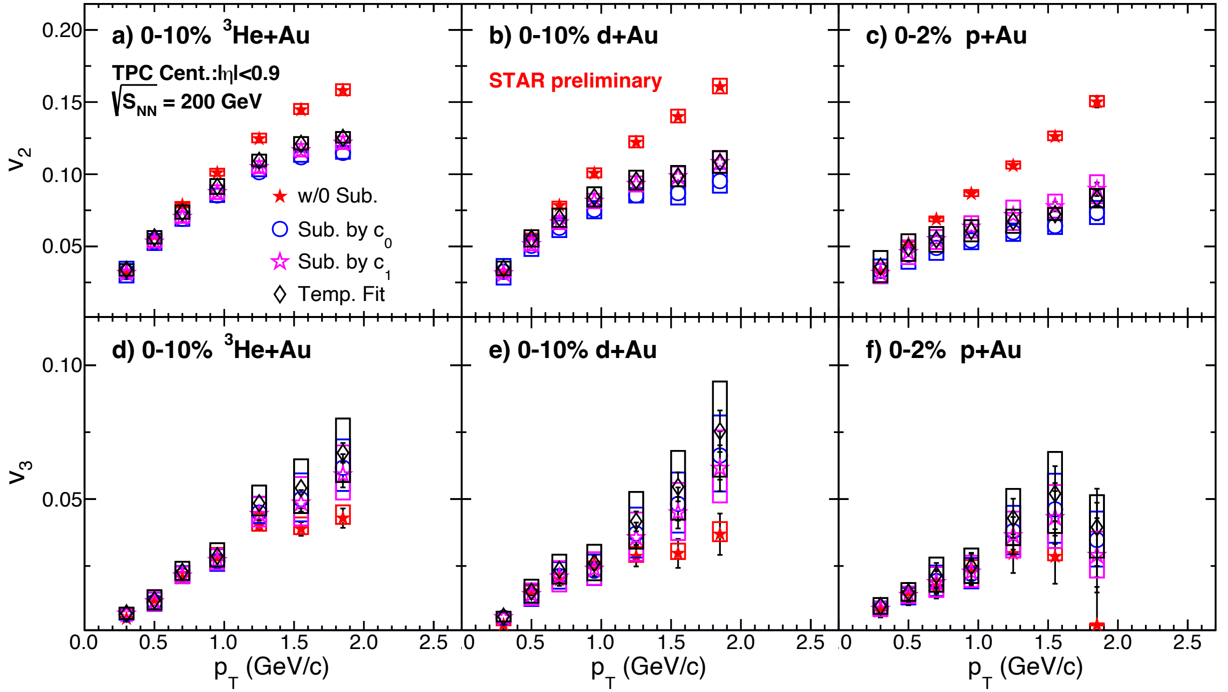
v_2 and $\ln\left(\frac{v_2}{\varepsilon_2}\right)$ vs. $\langle N_{Ch}\rangle^{-1/3}$ for different collision systems



STAR Collaboration, Phys.Rev.Lett. 122 (2019) 17, 172301



R. Lacey for the STAR Collaboration
Nuclear Physics A 00 (2020) 1–4



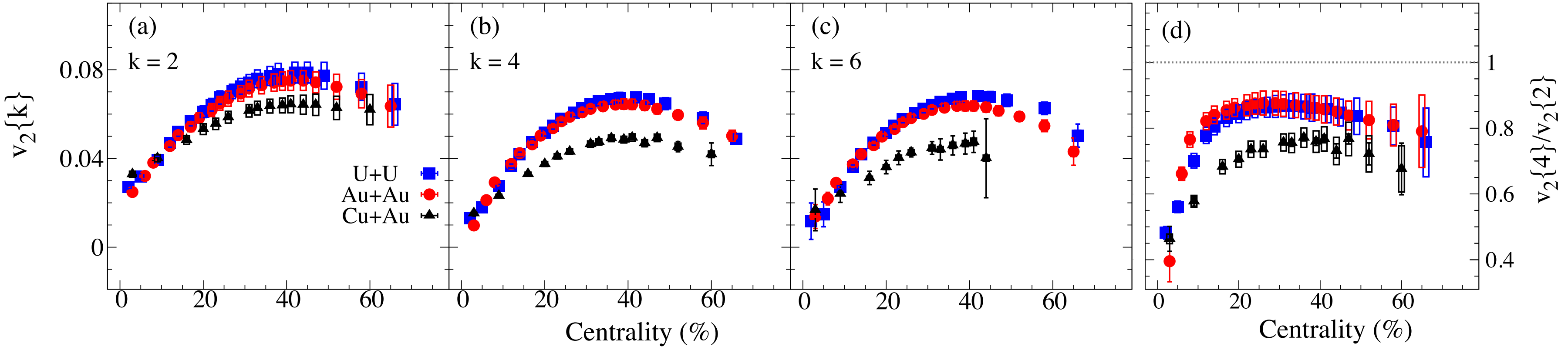
- $\frac{v_2}{\varepsilon_2}$ for all systems scales to a single curve.

- At similar N_{ch} different systems show similar values and trends

II) New insights into the collective effects

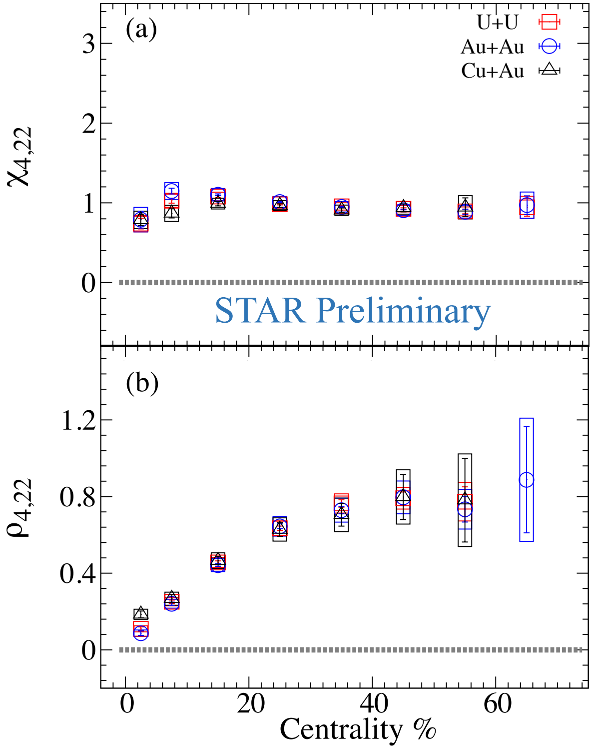
- Collision system dependence at a given beam energy:

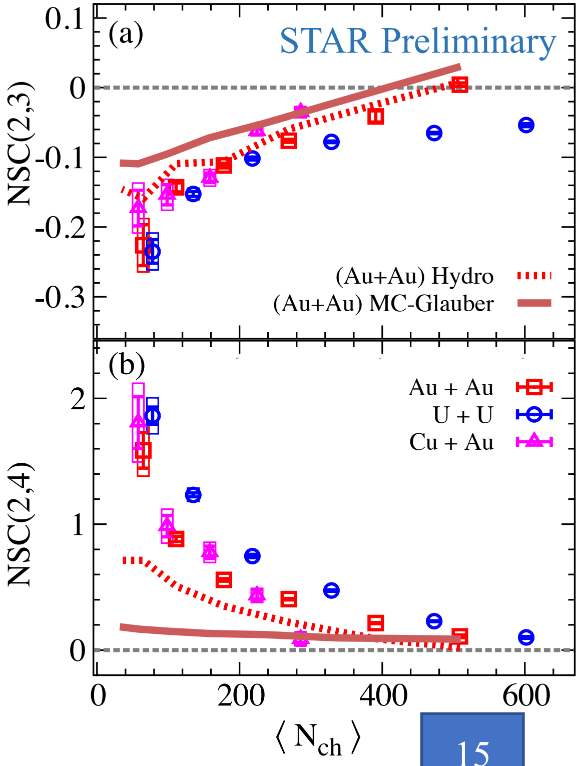
STAR Collaboration, arXiv:2201.10365



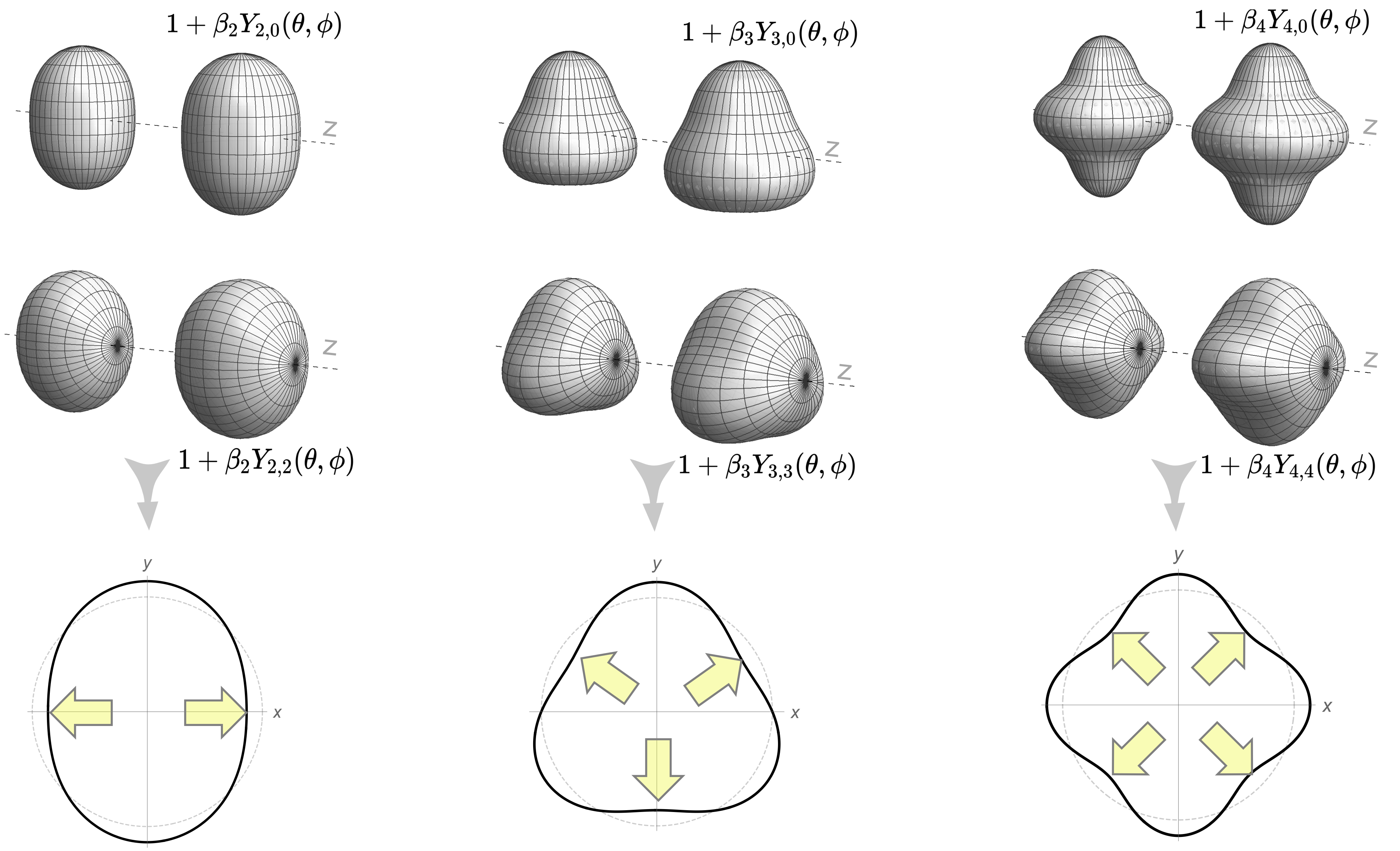
- The flow harmonics depend on beam energy.
  - ✓ Sensitive to the viscous effects (N_{ch}, $\langle p_T \rangle$, $\frac{\eta}{s}$, …)

- The dimensionless parameters show similar values and trends for different beam energies.
  - ✓ Sensitive to the ϵ_n and its fluctuations and correlations





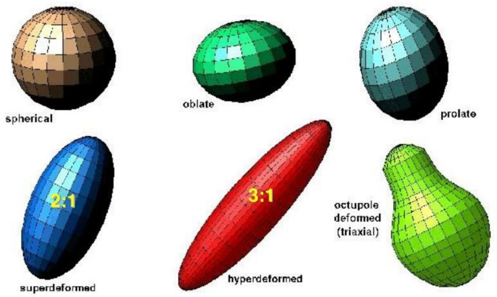
III) New insights into the nuclear shape and structure

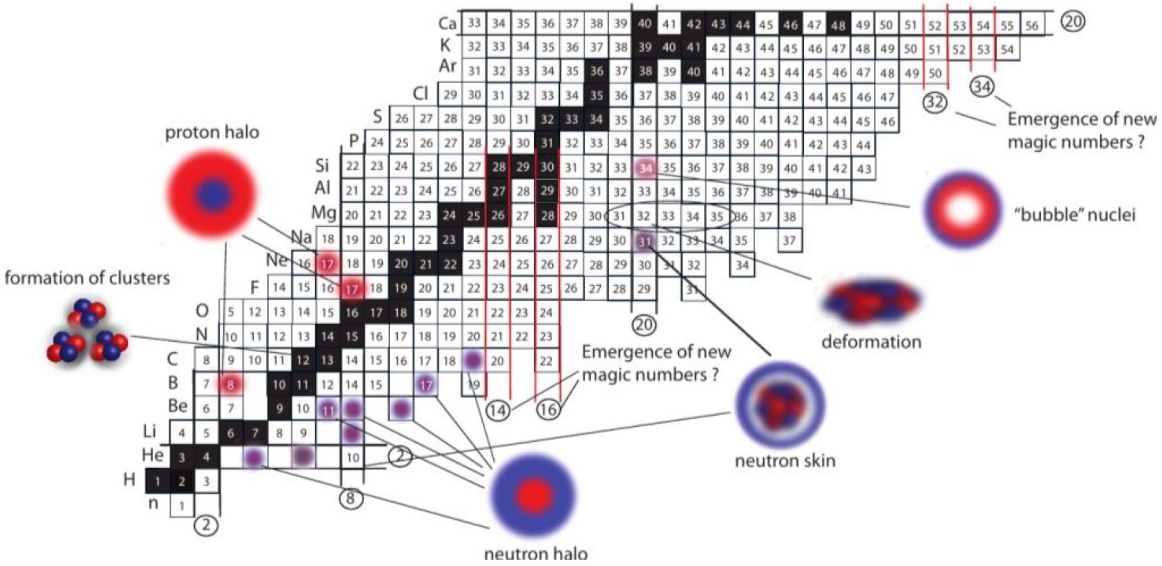


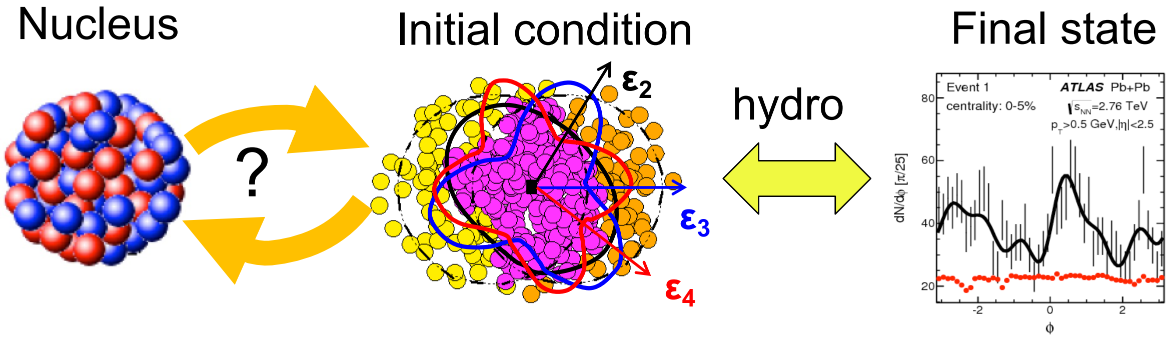
III) New insights into the nuclear shape and structure

➢ The rich structure of atomic nuclei

- Collective phenomena can reflect:
  - ✓ Clustering, halo, skin, bubble…
  - ✓ Quadrupole/octupole/hexdecopole deformations
  - ✓ Nontrivial evaluation with N and Z.







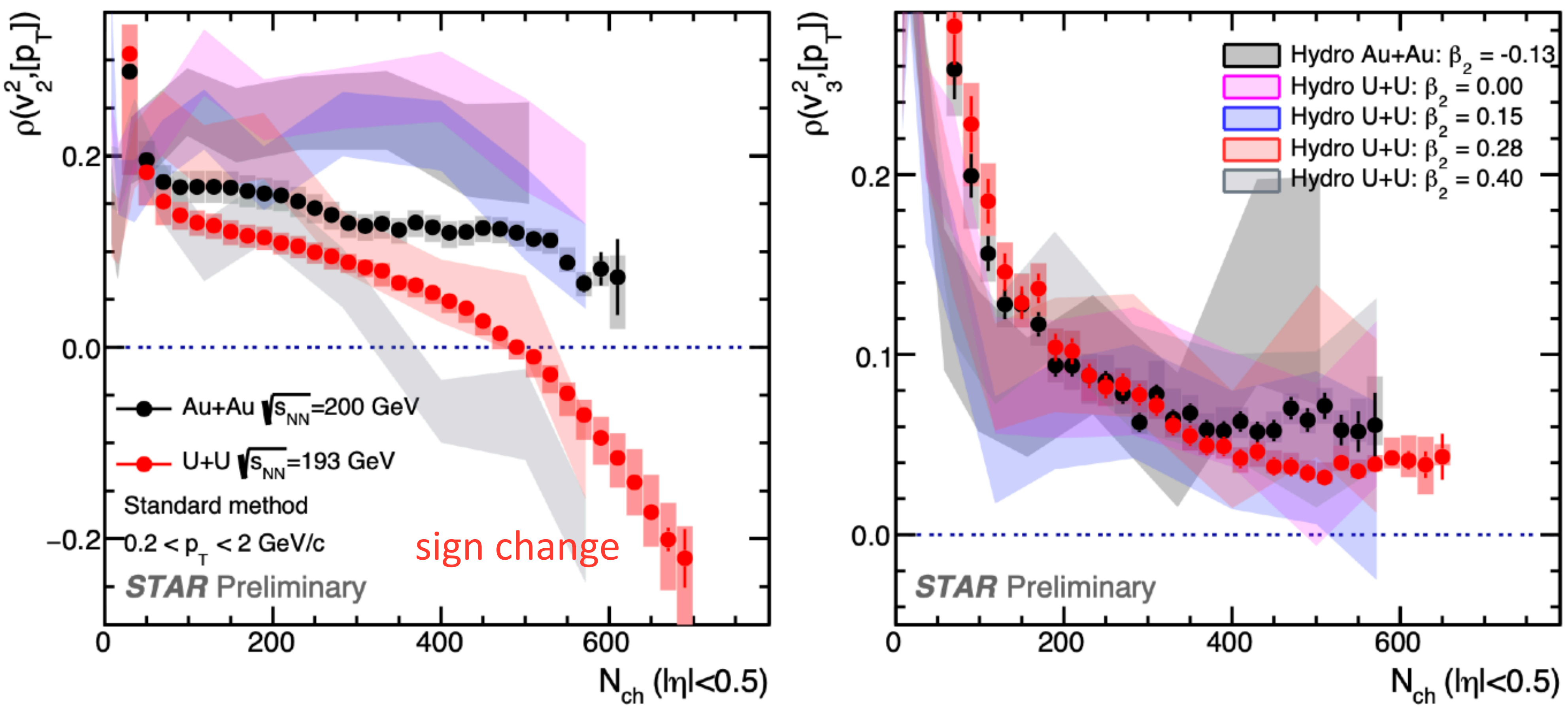
High energy:
Linear response in each event?

$$N_{ch} \propto N_{part} \qquad \frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n \quad n=2,3$$

III) New insights into the nuclear shape and structure

- Probing nuclear deformation in heavy-ion collisions

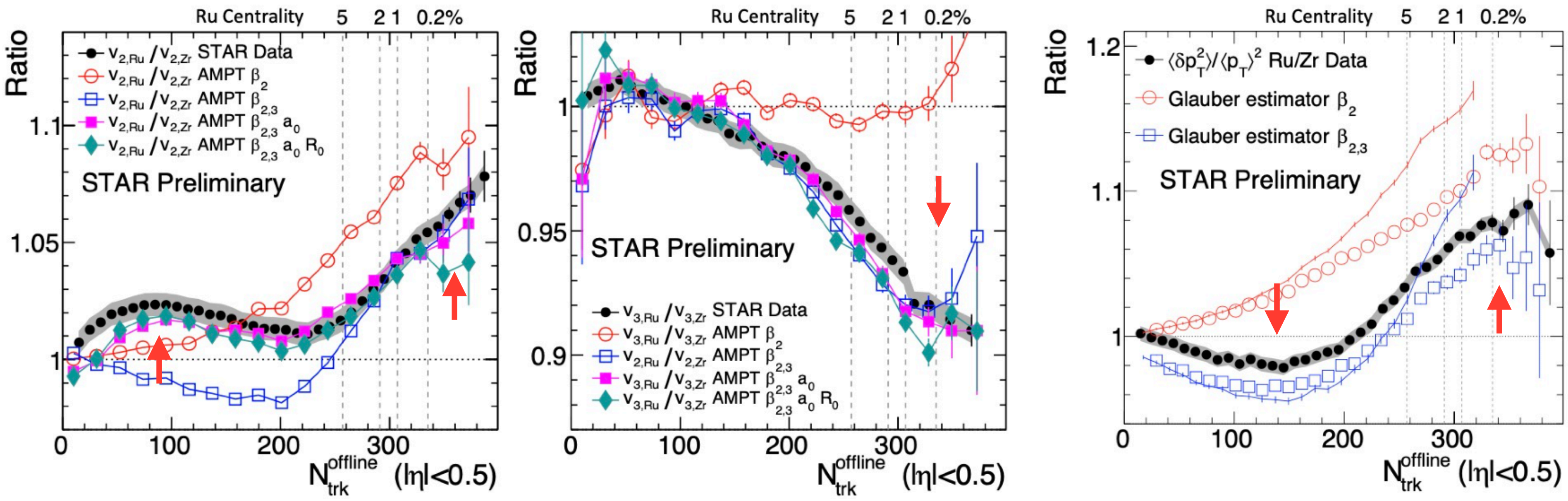
$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}((v_n^2)_{dyn}\langle \delta p_T \delta p_T \rangle}}$$



Sign change of $\rho(v_2, [p_T])$ confirms that U is prolate and $\beta_{2,U} = 0.28 \pm 0.03$ (IPGlasma + Hydro)

III) New insights into the nuclear shape and structure

- Probing nuclear deformation in heavy-ion collisions



- Mapping on same $N_{trk}^{offline}$ instead of centrality
- The ratios show non-monotonic trends
- The ratios well constrain the nuclear structure parameters

$\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$

$\beta_{3,\mathrm{Zr}} = 0.20 \pm 0.02$

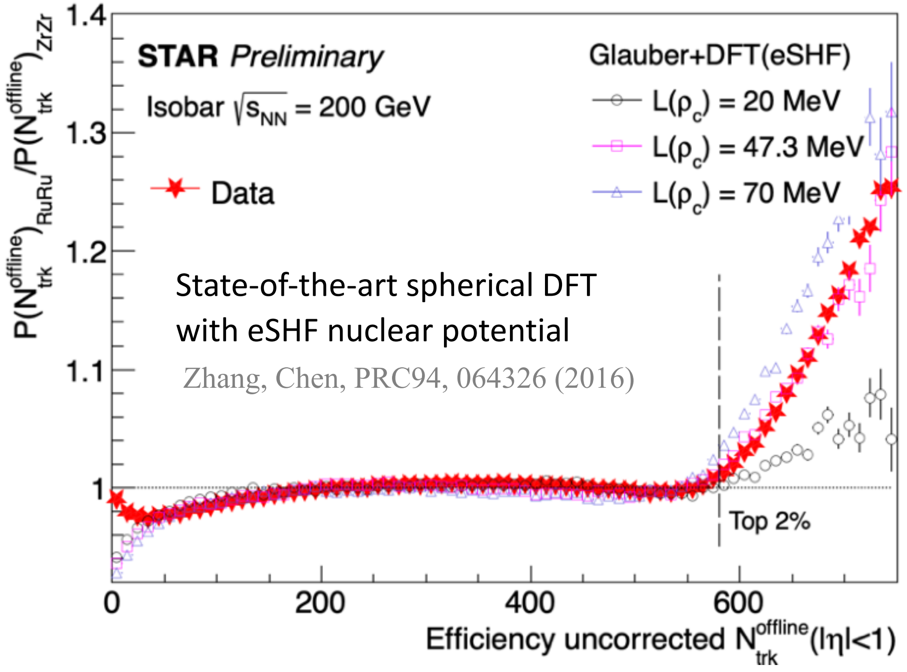
Estimate based on AMPT

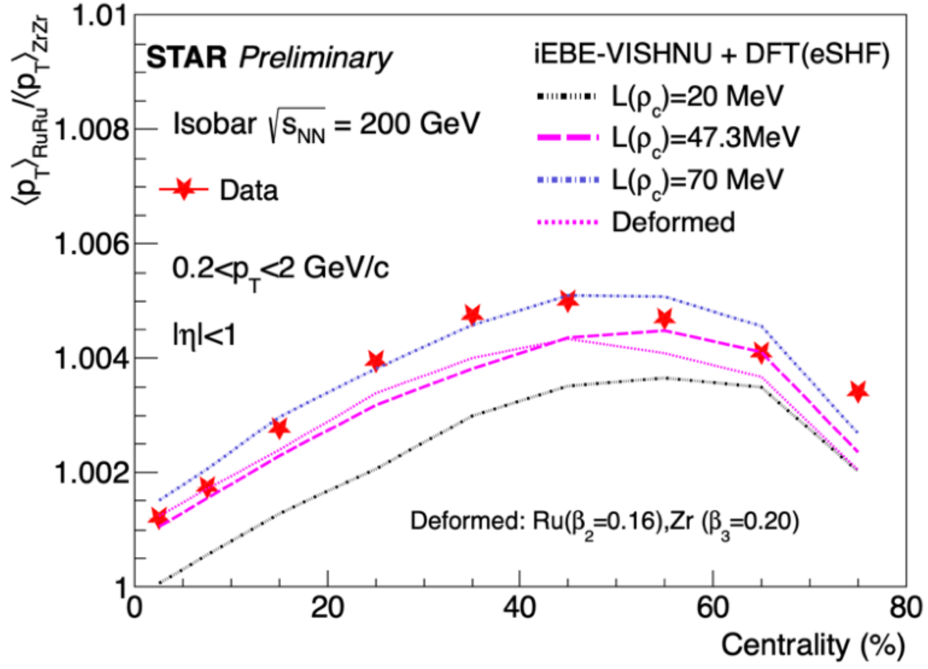
C. Zhang, J. Jia, PRL128, 022301 (2022)
J.Jia and C. Zhang, arXiv:2111.15559
B. Pritychenko, et.al. At.Data Nucl.Data Tables 107, 1 (2016)
T. Kebedi, et.al. At.Data Nucl.Data Tables 80, 35 (2002)

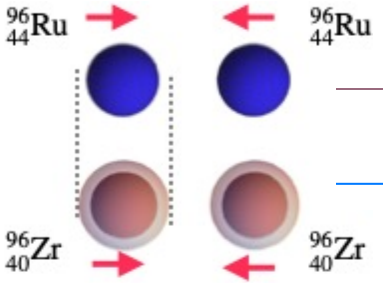
Species	β_2	β_3	a_0 (fm)	R_0 (fm)
Ru	0.162	0	0.46	5.09
Zr	0.06	0.20	0.52	5.02

III) New insights into the nuclear shape and structure

- Probing neutron skin thickness and symmetry energy in isobar collisions







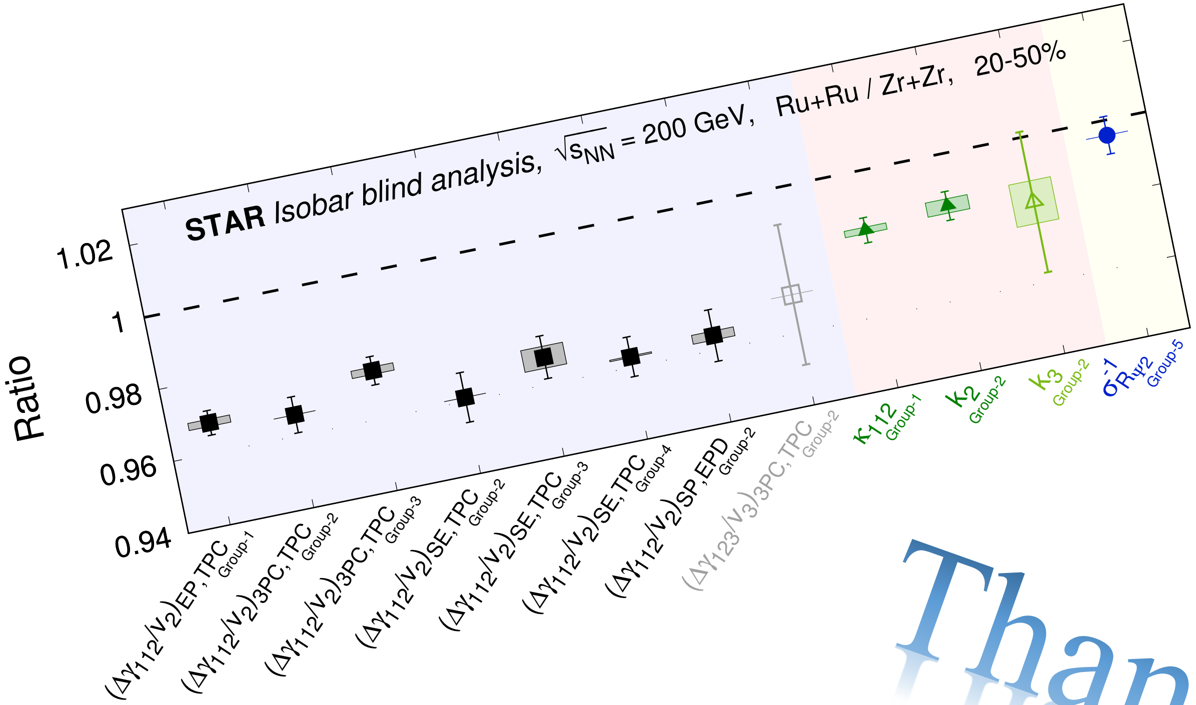
→ Smaller r, larger density → Larger N_{ch} and $\langle p_T\rangle$

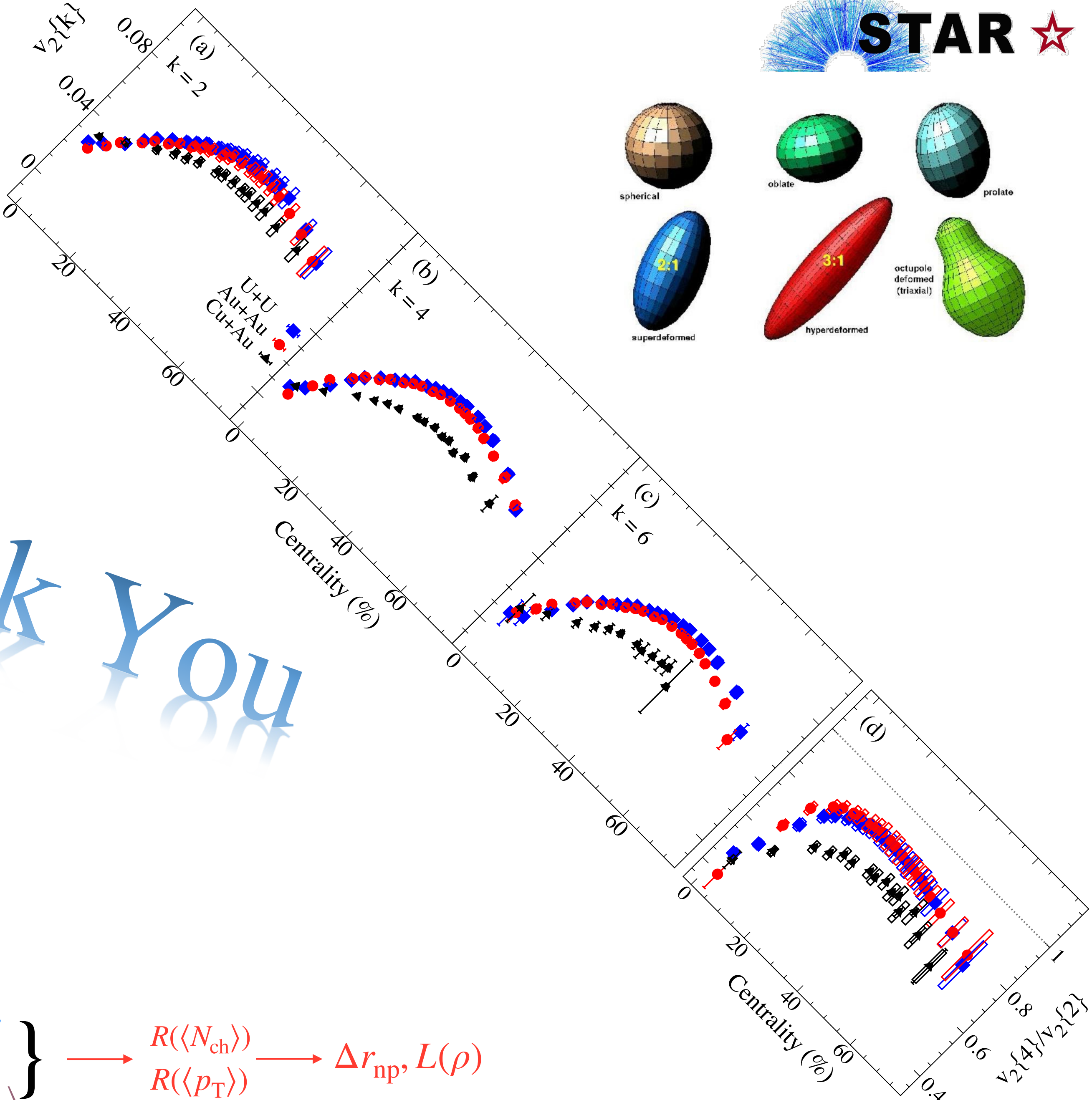
→ Larger r, smaller density → Smaller N_{ch} and $\langle p_T\rangle$

} → $R(\langle N_{ch}\rangle)$, $R(\langle p_T\rangle)$ → $\Delta r_{np}, L(\rho)$

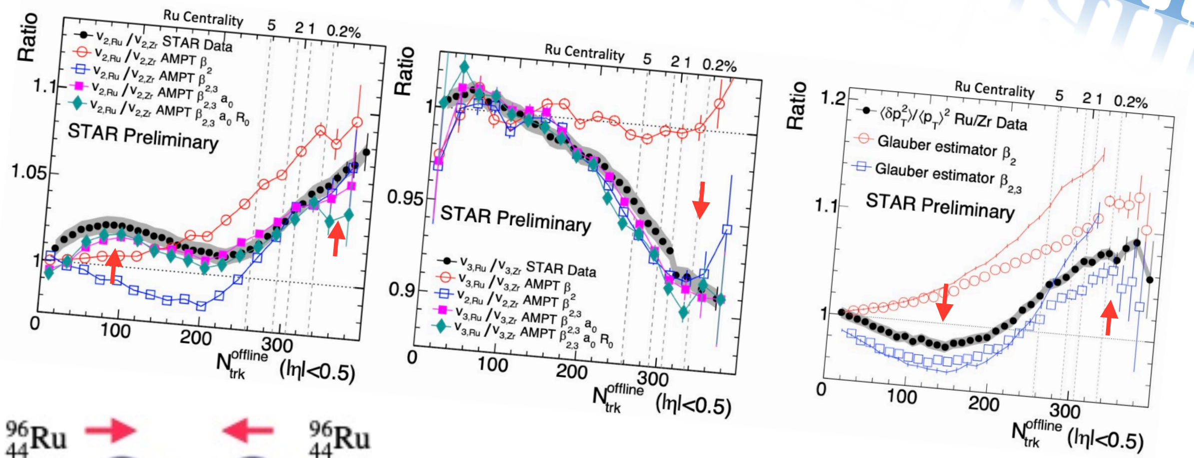
H. Li, HJX, et.al, PRL125, 222301 (2020)
HJX, et.al arXiv:2111.14812

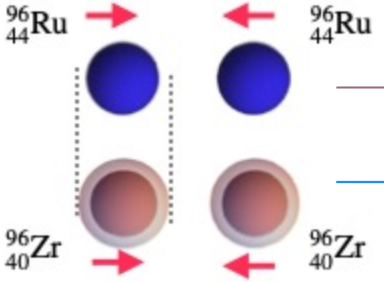
The multiplicity and $\langle p_T\rangle$ differences can probe neutron skin and symmetry energy





Thank You





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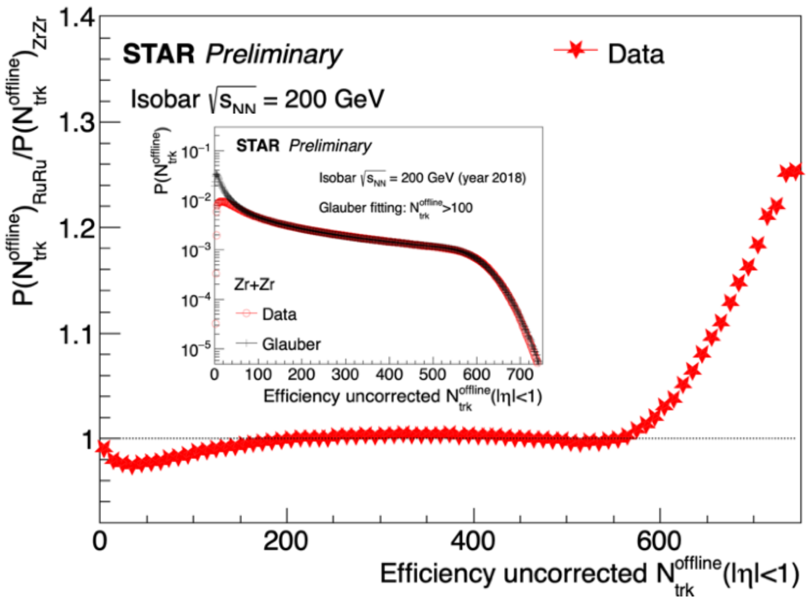
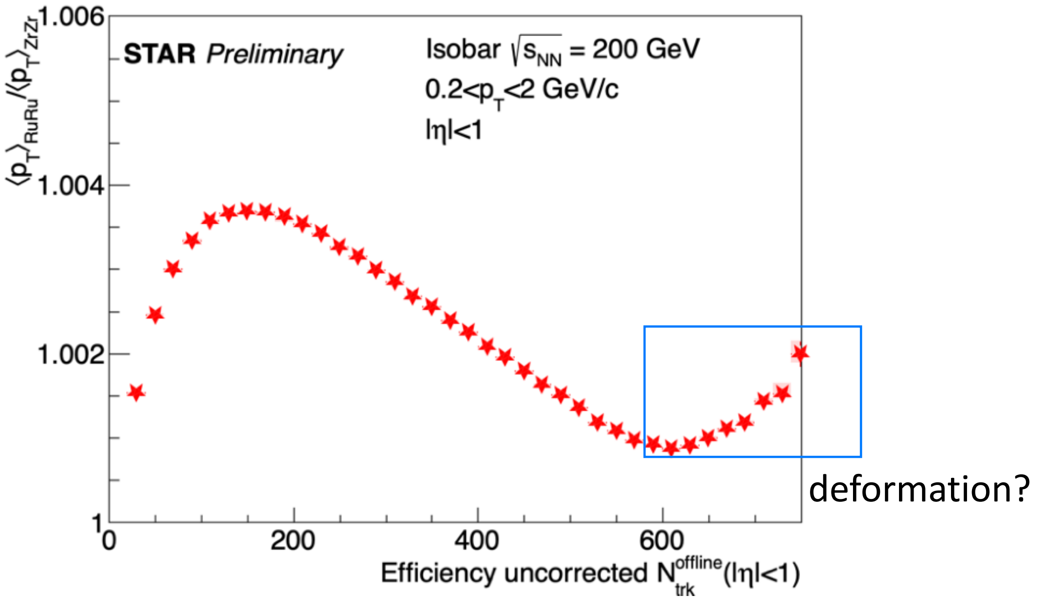
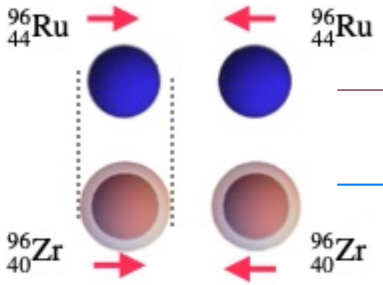
III) New insights into the nuclear shape and structure

- Probing neutron skin thickness and symmetry energy in isobar collisions







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H. Li, HJX, et.al, PRL125, 222301 (2020)
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