Selected results from Isobar collisions at RHIC

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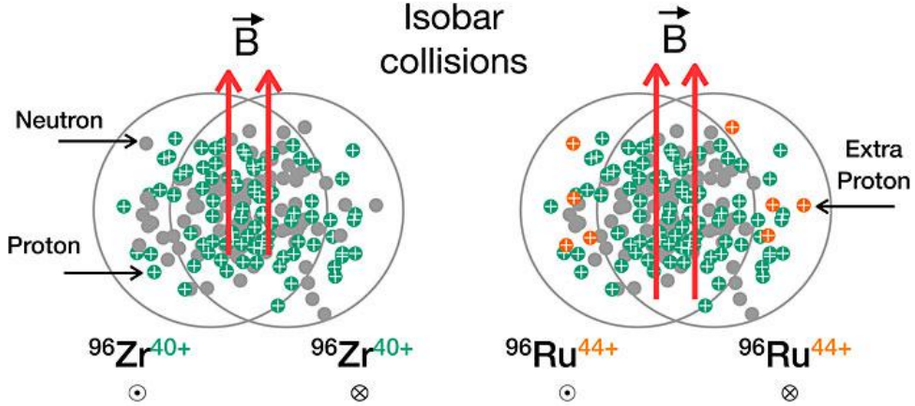
Motivation: Isobar collisions

Isobar Nuclei: $^{96}_{44}$Ru and $^{96}_{40}$Zr

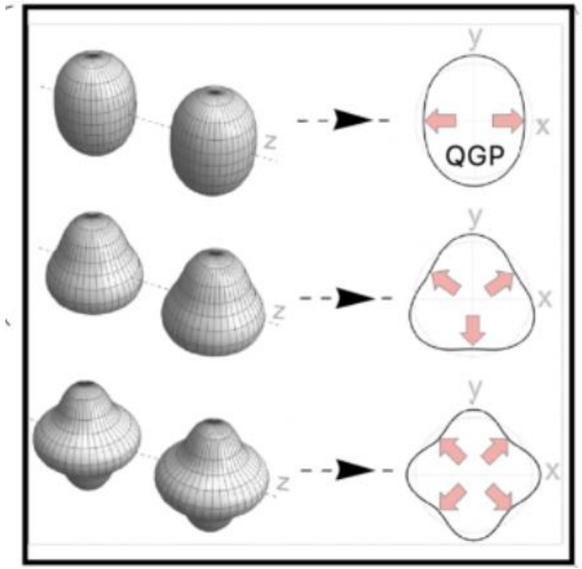
- Same mass number (A = 96) but different number of protons
- Size between large (U/Au) and small (Cu/O) systems
- Subtle difference in nuclear structure



Isobar collisions: Zr+Zr and Ru+Ru at RHIC

- Performed at RHIC-STAR experiment in year 2018
- Large statistics: 2B Zr & 1.8B Ru (MinBias) events collected
- Controlled run conditions, resulting in minimized systematics
- High precision & multi-differential studies on QGP properties

- Exploring differences in nuclear structures between Ru and Zr nuclei can reveal valuable insights. Potential impacts include:
  - Variations in charged particle multiplicity and p_T-spectra
  - Differences in collective flow
- These differences could arise from variations in the initial state and the final state

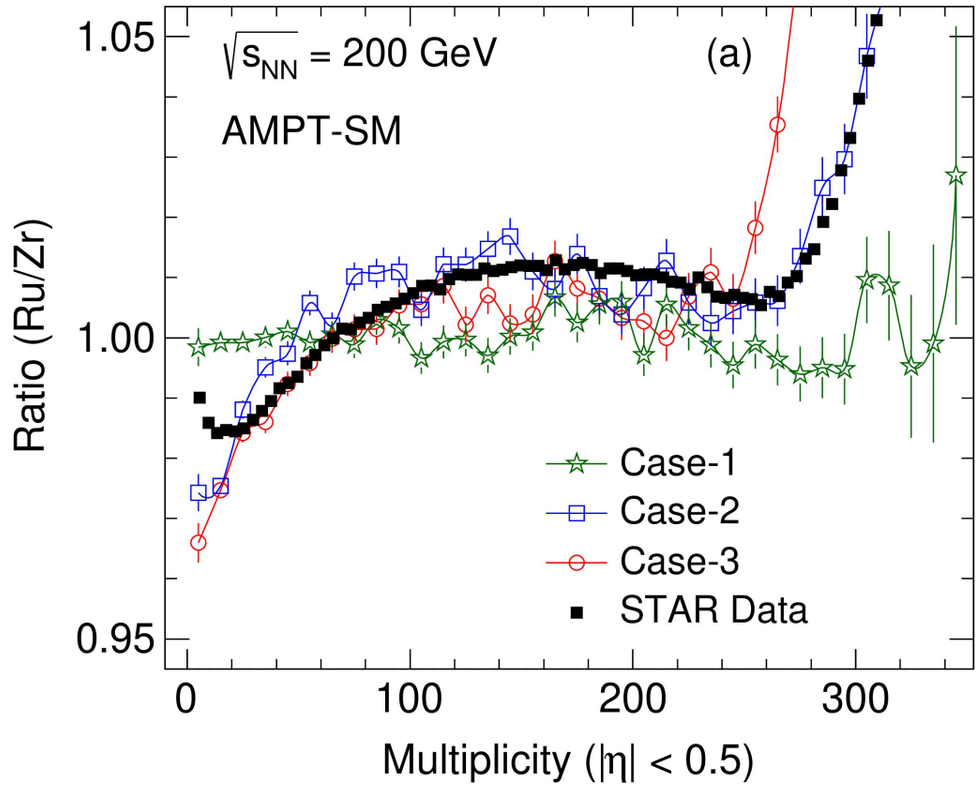


Charge Particle Multiplicity

Various deformation configurations of the Isobar Nuclei $^{96}_{44}$Ru and $^{96}_{40}$Zr in the AMPT model

	Ru			Zr		
Parameter	case 1	case 2	case 3	case 1	case 2	case 3
R_0	5.096	5.067	5.090	5.096	4.965	5.090
a	0.540	0.500	0.460	0.540	0.556	0.520
β_2	0	0	0.162	0	0	0.060
β_3	0	0	0	0	0	0.200

R_0: Radius parameter
β_2 : Quadruple deformity
β_3 : Octupole deformity
$Y_{l,m}(\theta,\varphi)$: Spherical harmonics



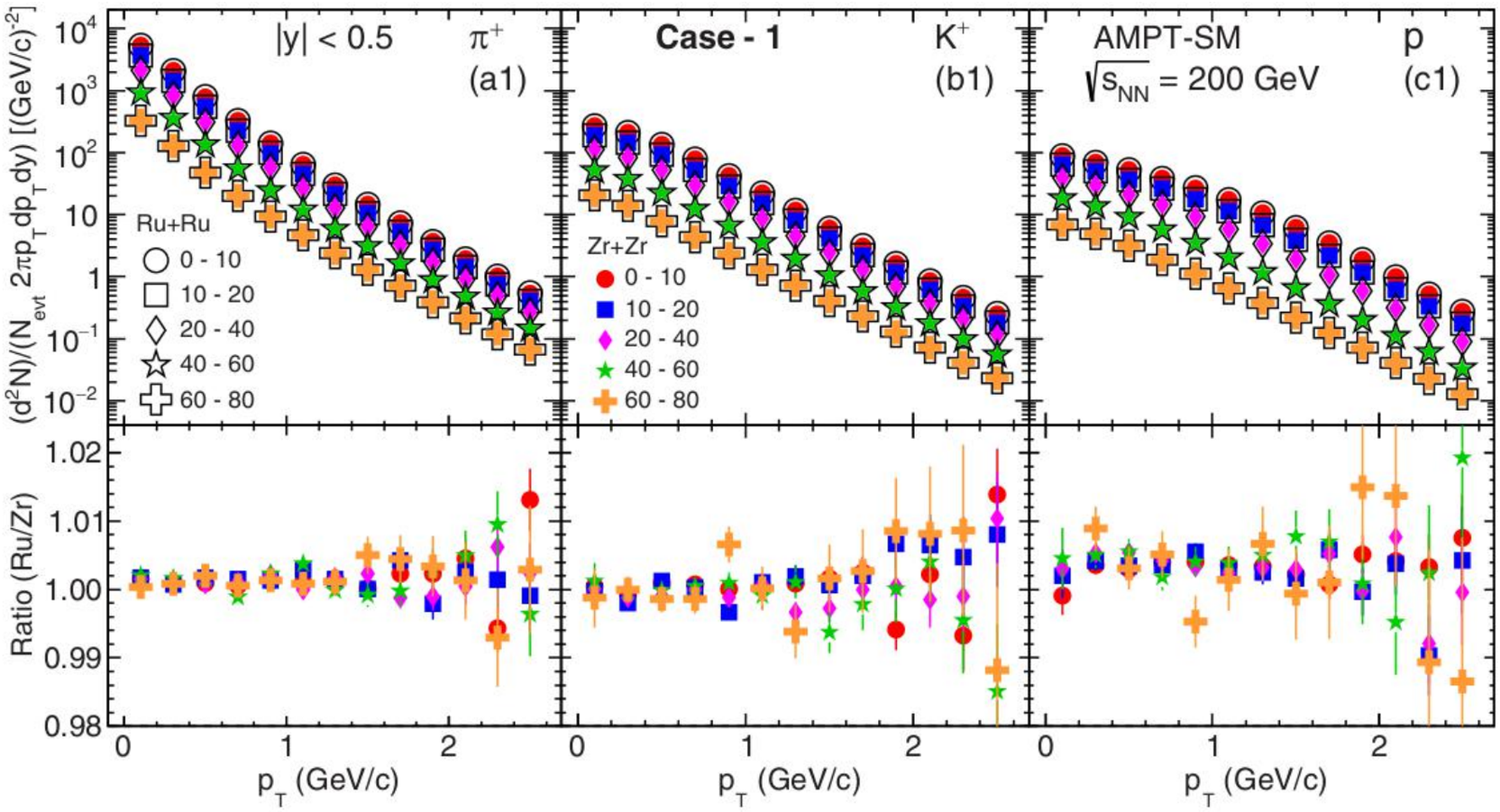
Charge particle multiplicity ratio:

In central collisions, case-2 of the AMPT model better describes the STAR experimental data, whereas in peripheral collisions, case-3 of the AMPT model describes the data better.

- Indicates influence of the nuclear size and thickness variation

AMPT: P. Sinha et al., Phys. Rev. C 108, 024911 (2023)
STAR: M. S. Abdallah et al., Phys. Rev. C 105, 014901 (2022)

Transverse Momentum Spectra



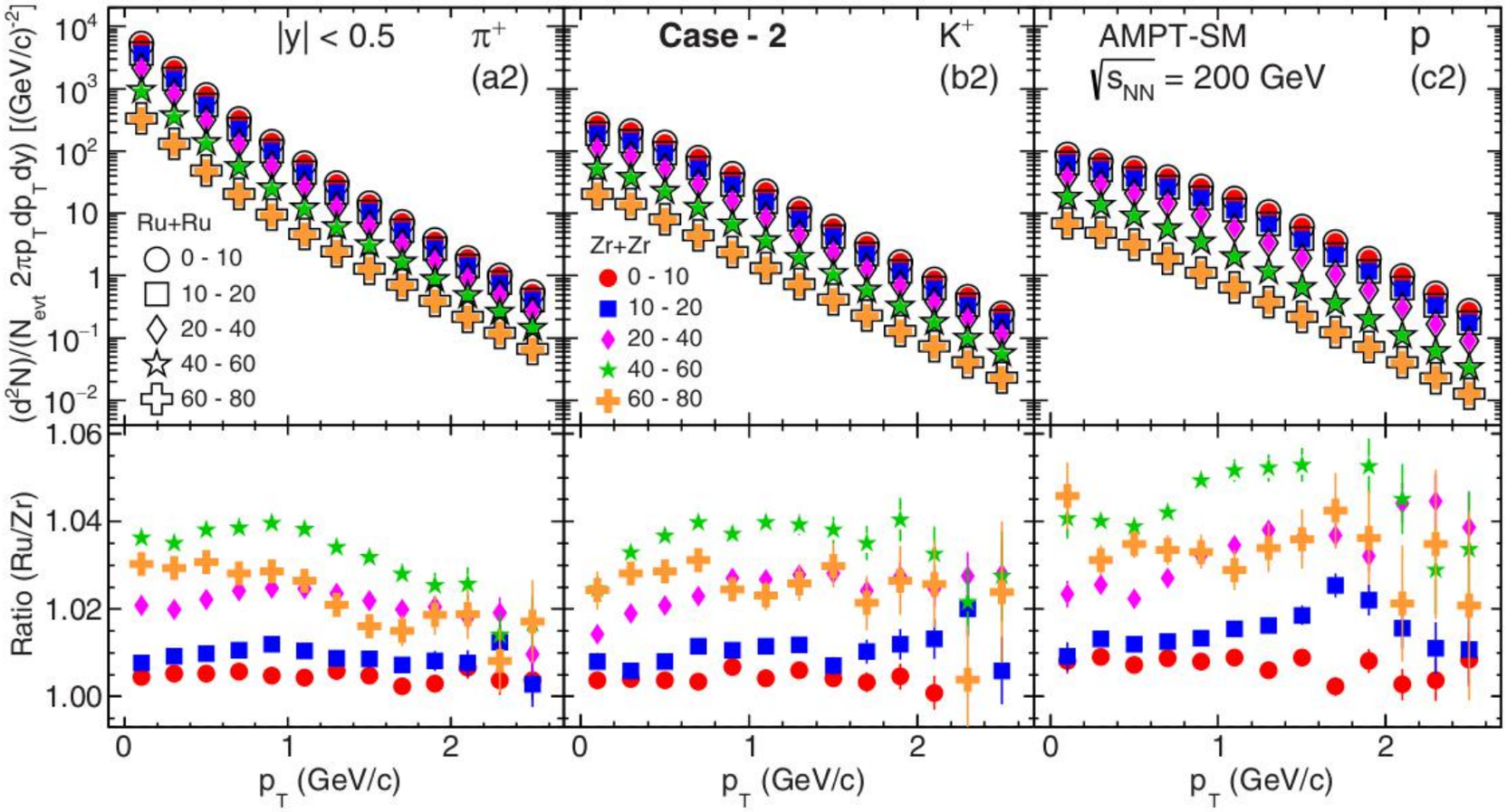
- Case 1: same nuclear size w/o deformation
- Case 2: different nuclear size w/o deformation
- Case 3: different nuclear size with deformation

Transverse momentum (p_T) spectra of identified hadrons (π, K, and p) at midrapidity ($|y| < 0.5$) in isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}} = 200$ GeV using the AMPT model.

➢ Case 1: No deviation observed from unity between the p_T spectra of identified hadrons in Ru+Ru and Zr+Zr collisions within statistical uncertainties.

P. Sinha et al., Phys. Rev. C 108, 024911 (2023)

Transverse Momentum Spectra



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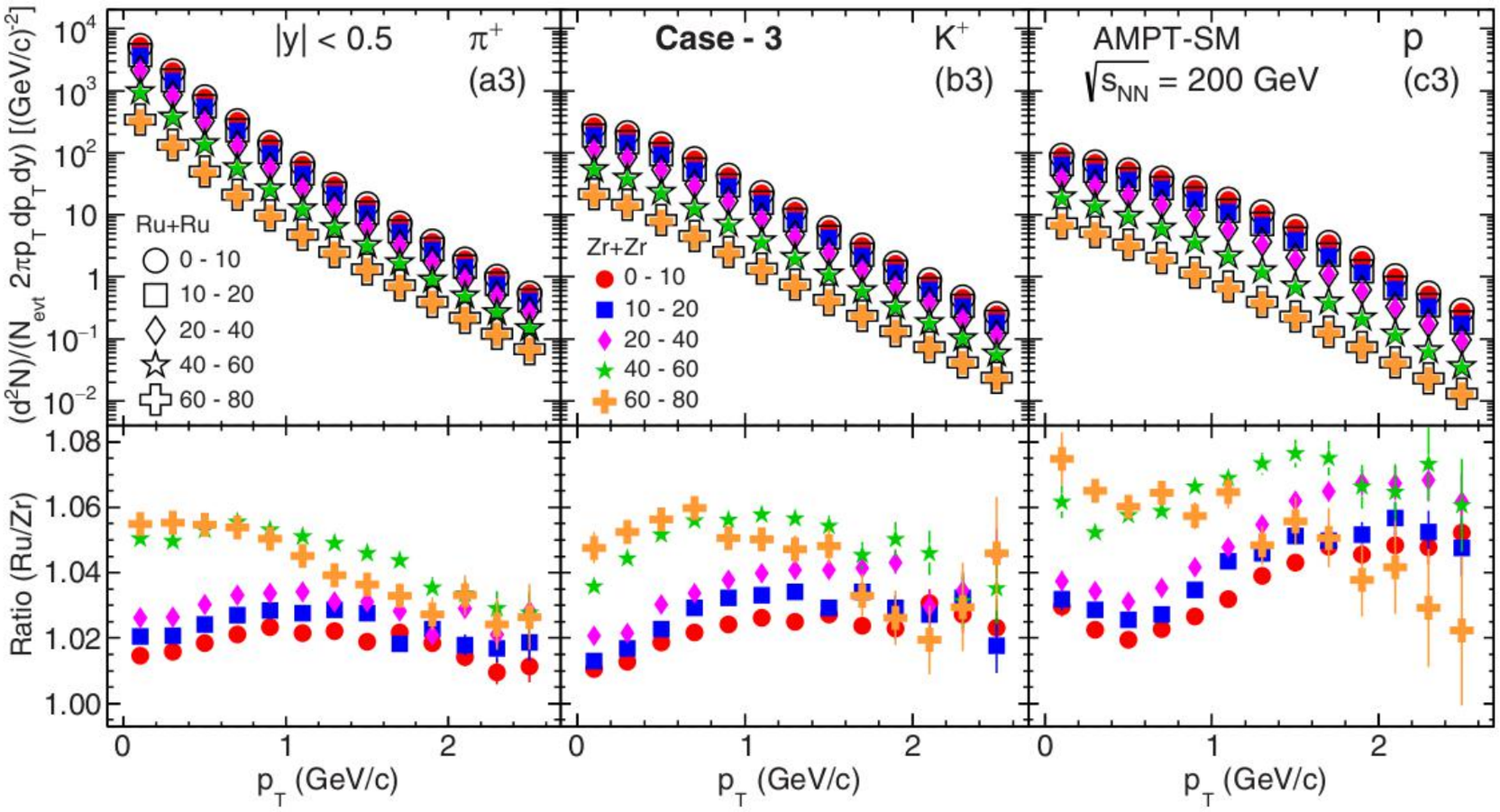
Transverse momentum (p_T) spectra of identified hadrons (π, K, and p) at midrapidity ($|y| < 0.5$) in isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}} = 200$ GeV using the AMPT model.

➢ Case 2: Deviation of 4% to 6% observed between the p_T spectra of identified hadrons in Ru+Ru and Zr+Zr collisions. Deviation increases from central to peripheral collisions.

P. Sinha et al., Phys. Rev. C 108, 024911 (2023)

Transverse Momentum Spectra



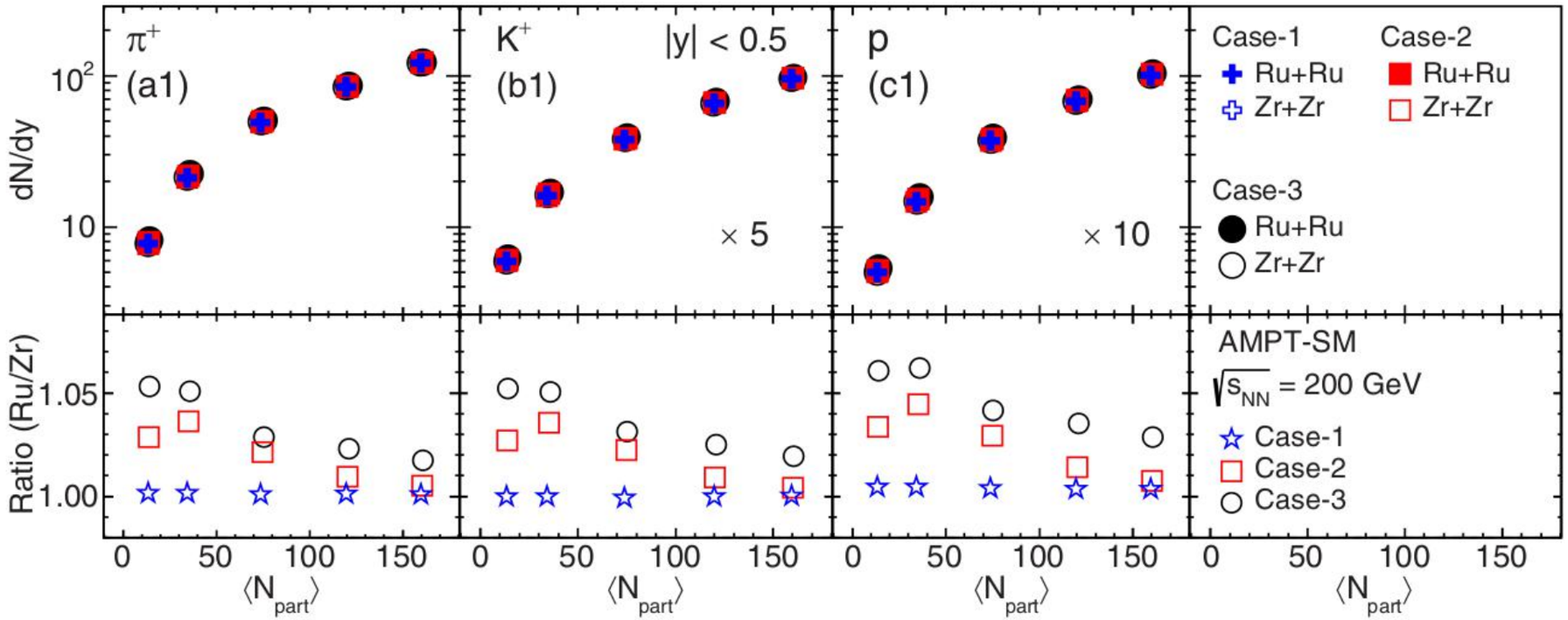
- Case 1: same nuclear size w/o deformation
- Case 2: different nuclear size w/o deformation
- Case 3: different nuclear size with deformation

Transverse momentum (p_T) spectra of identified hadrons (π, K, and p) at midrapidity ($|y| < 0.5$) in isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}} = 200$ GeV using the AMPT model.

➢ Case 3: Inclusion of deformation causes deviation to increase upto 6%-8% between the p_T spectra of identified hadrons in Ru+Ru and Zr+Zr collisions.

P. Sinha et al., Phys. Rev. C 108, 024911 (2023)

Particle Yield

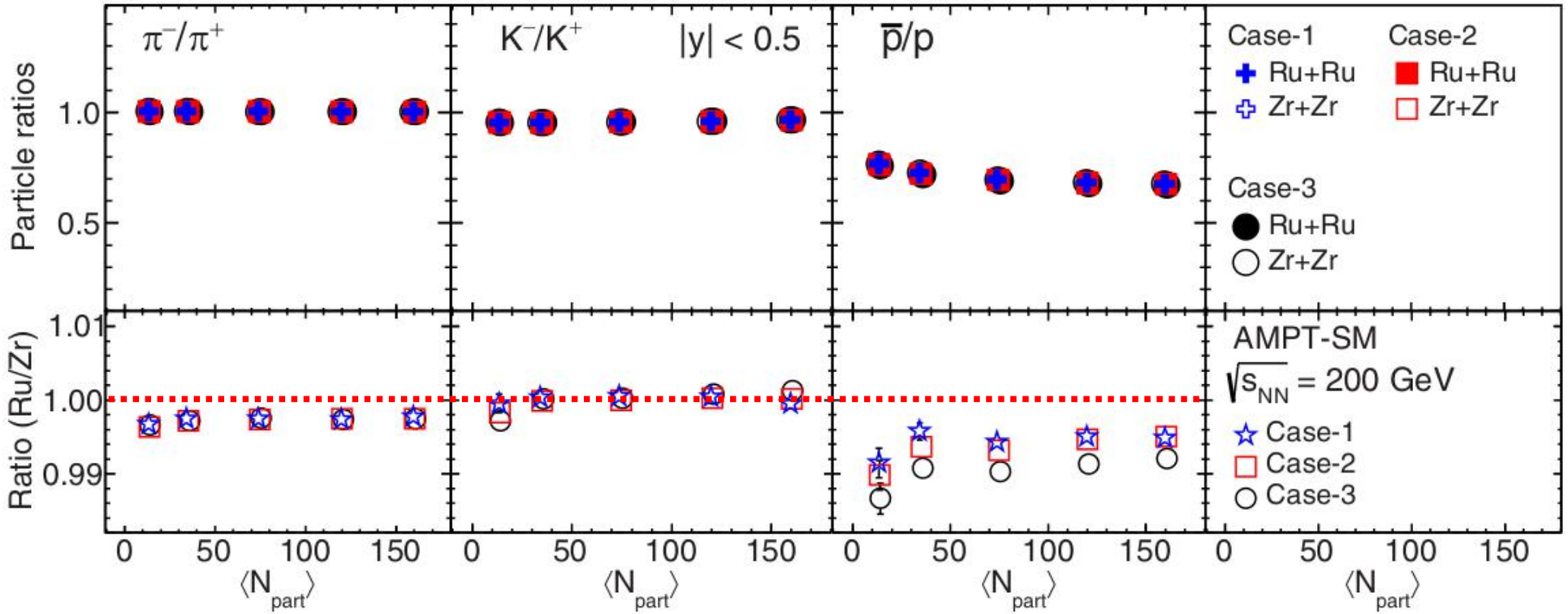


p_T-integrated yield (dN/dy) of identified hadrons (π, K, and p) at midrapidity (|y| < 0.5) in isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}}$ = 200 GeV using the AMPT model.

- Significant deviation (upto 6%) observed in the ratio of particle yields with the inclusion of different deformation and nuclear size in Ru+Ru and Zr+Zr collisions.
- Deviation increases towards peripheral collisions.

P. Sinha et al., Phys. Rev. C 108, 024911 (2023)

Particle Ratios



Ratio of π^-/π^+ between the two isobars is lower than unity

- Indicating effect of isospin

Ratio of p-bar/p is further lower than unity compared to π^-/π^+

- Indicating additional baryon stopping effect

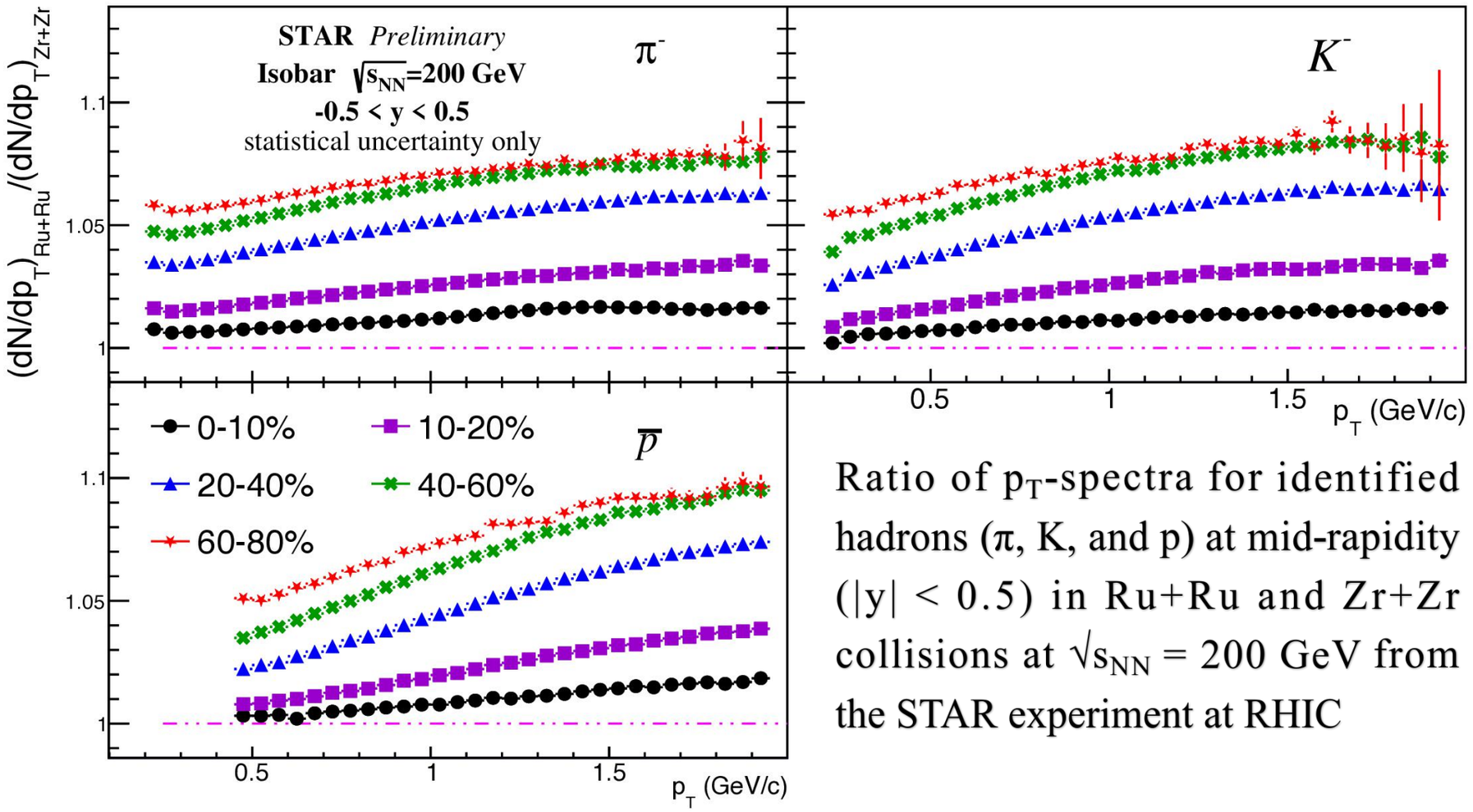
Ratio of K^-/K^+ is close to unity between the two isobars

- Indicating dominance of pair production mechanism

P. Sinha et al., Phys. Rev. C 108, 024911 (2023)

Particle Yield

STAR

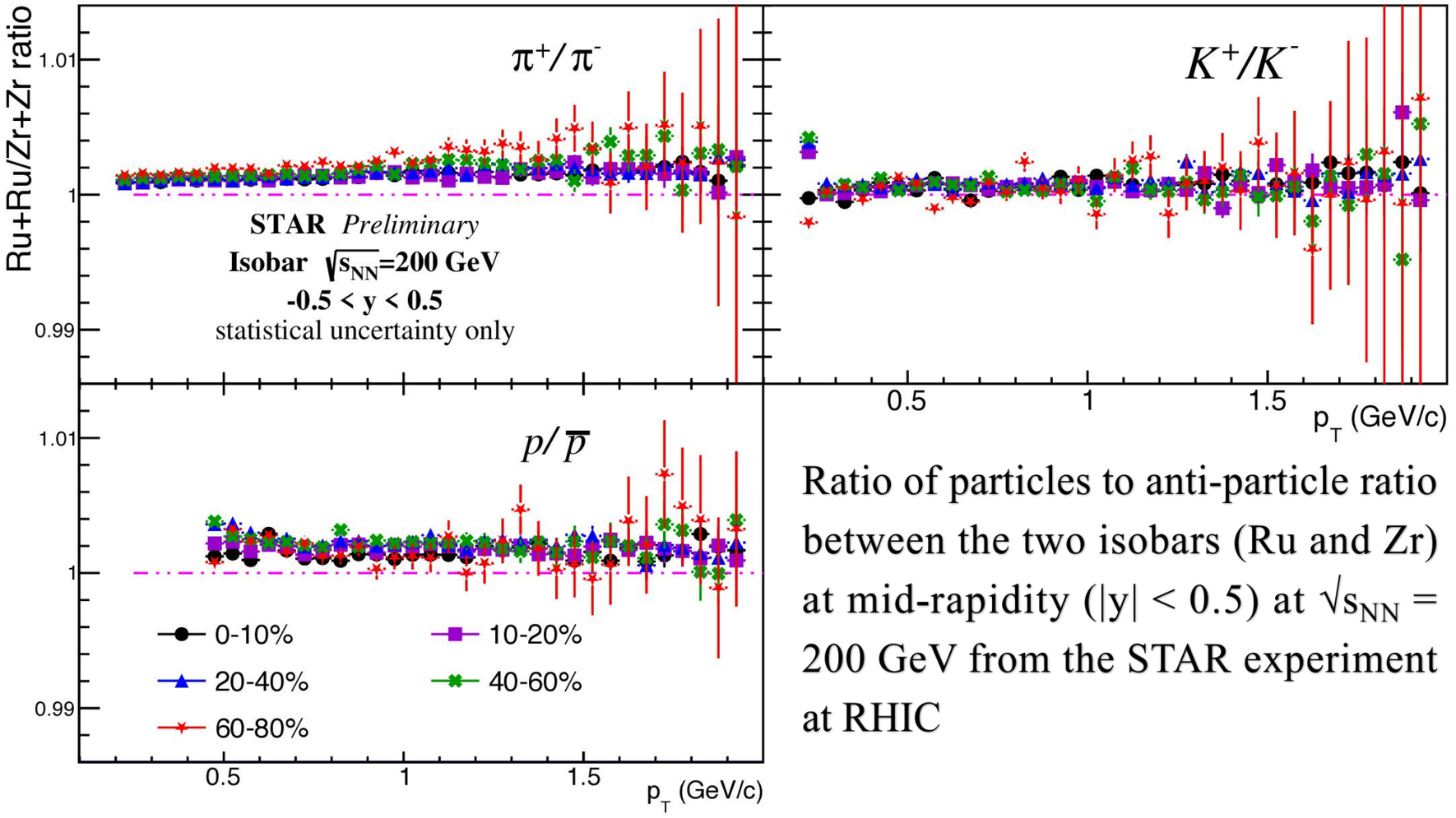


Ratio of p_T-spectra for identified hadrons (π, K, and p) at mid-rapidity ($|y| < 0.5$) in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV from the STAR experiment at RHIC

- A deviation of upto 8-10% between the p_T spectra of identified hadrons similar to the AMPT model is observed.
- Deviation increases from central to peripheral collisions.

Particle Ratios

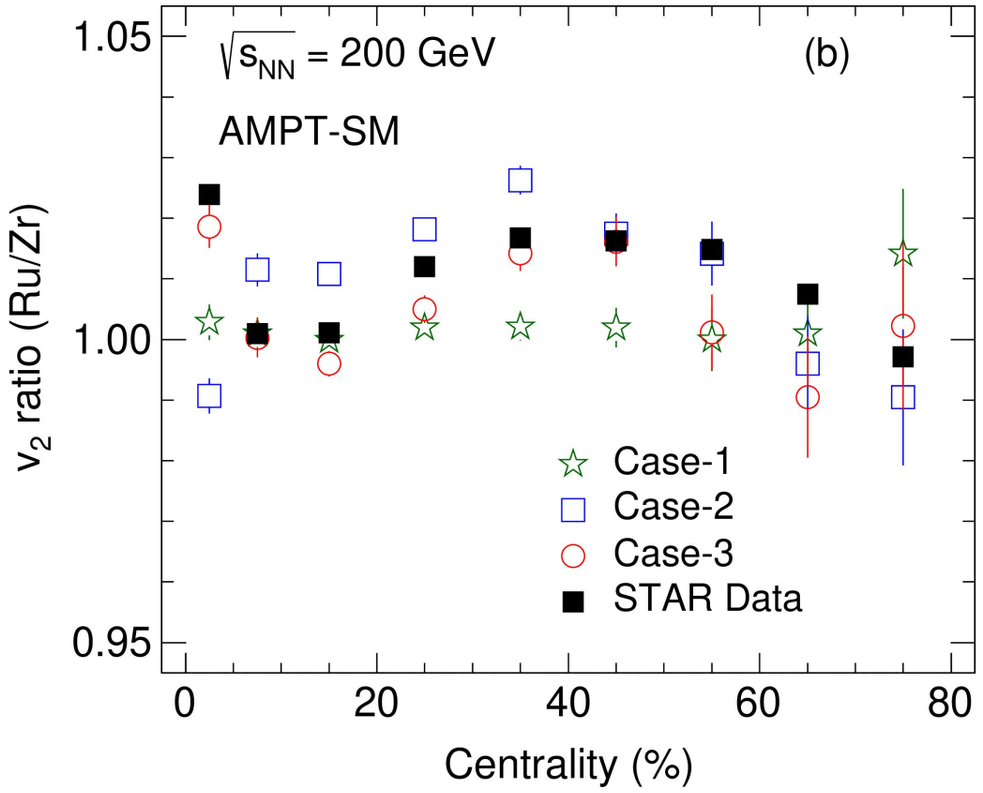
STAR

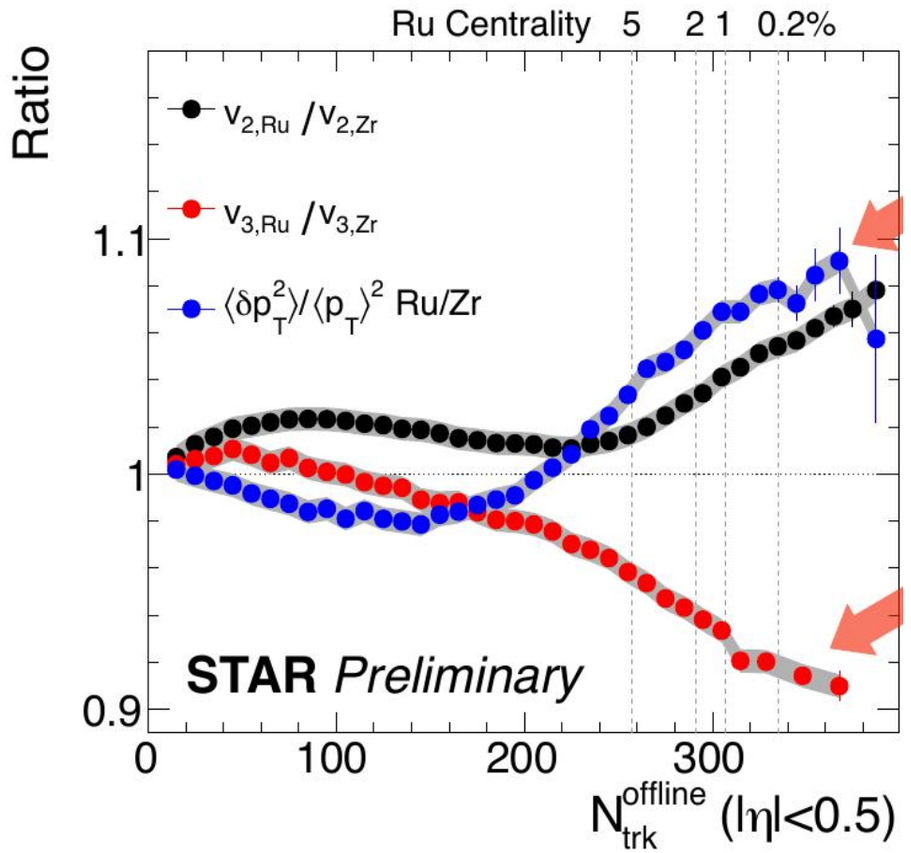


Ratio of particles to anti-particle ratio between the two isobars (Ru and Zr) at mid-rapidity ($|y| < 0.5$) at $\sqrt{s_{NN}}$ = 200 GeV from the STAR experiment at RHIC

- A deviation from unity of the ratio of particle to anti-particle between the two isobars similar to the case of AMPT model is observed.

Collective Flow

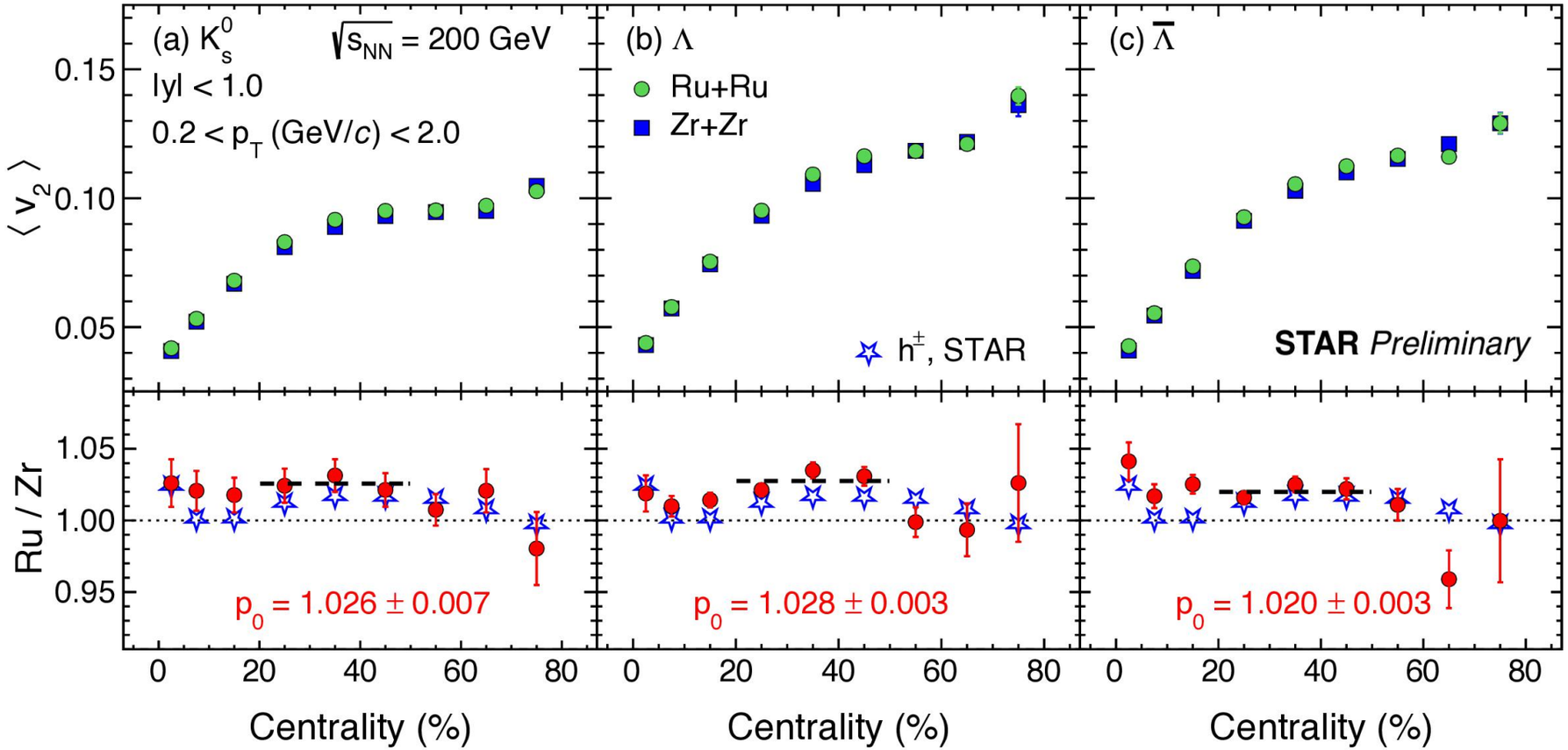




Ratio of integrated v_2 and v_3 between Ru+Ru and Zr+Zr collisions differs from unity

- Indication of larger quadruple deformity in Ru nuclei than in the Zr nuclei

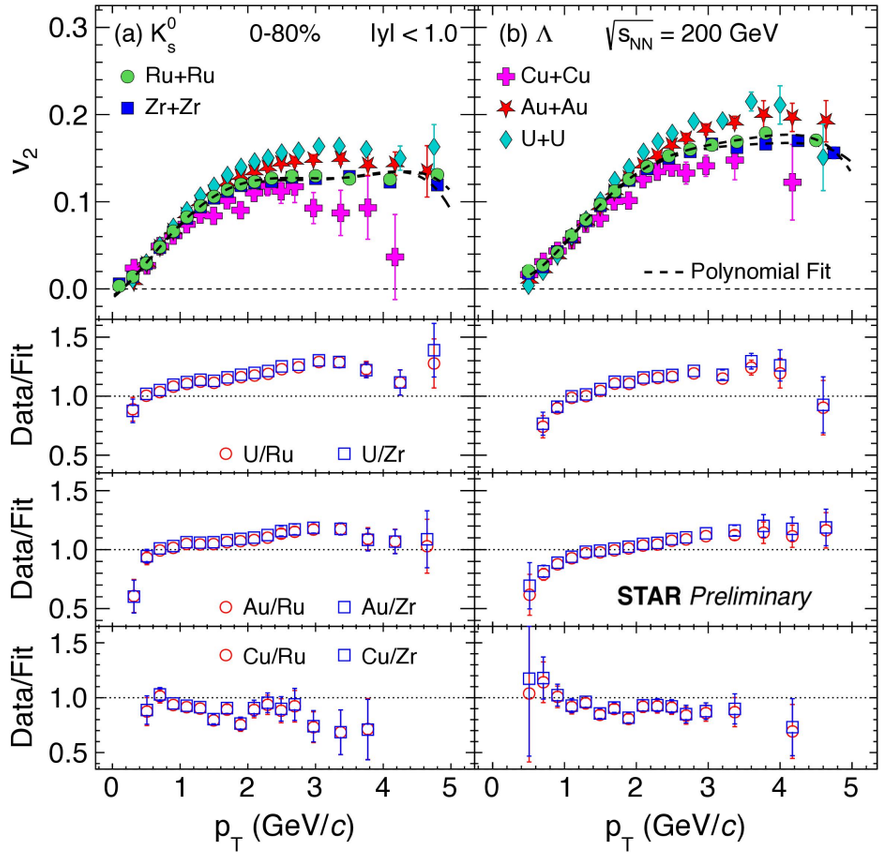
Nuclear size and deformation



Ratio of integrated v_2 between Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV for strange hadrons (K_s^0, Λ, and $\overline{\Lambda}$) show deviation from unity by 2% wtih >= 2σ significance in mid-central (10-60%) collisions.

- Indication of larger quadruple deformity in Ru nuclei than in the Zr nuclei

Nuclear size and deformation

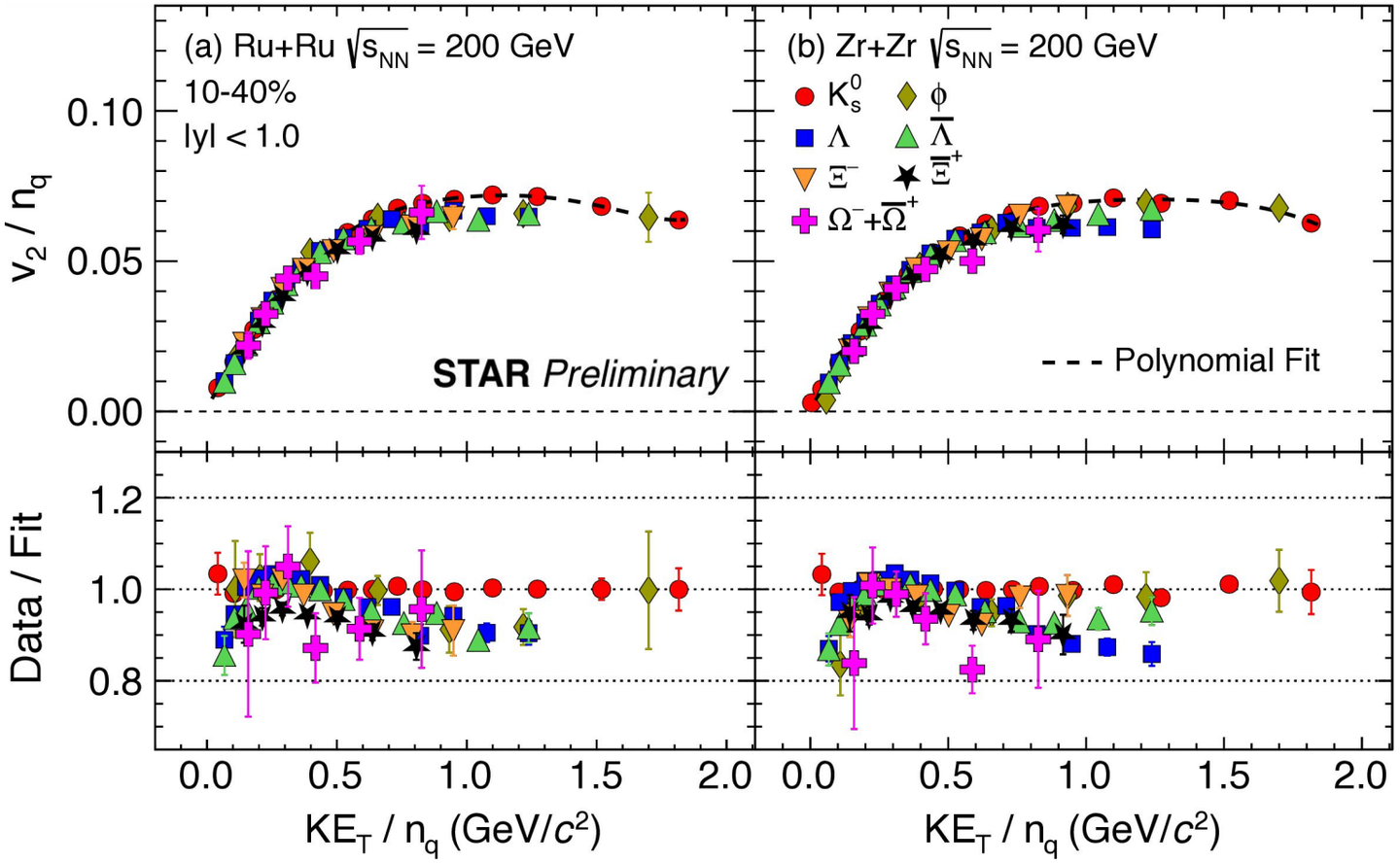


Elliptic flow at high p_T incresases with atomic mass number of nuclei

- Indicating a nuclear size dependence

[1] B. I. Abelev et al. (STAR Collaboration) Phys. Rev. C 77, 054901 (2008) [2] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 81, 044902 (2010)
[3] M. S. Abdallah et al. (STAR Collaboration) Phys. Rev. C 103, 064907 (2021)

NCQ scaling and collectivity



Elliptic flow (v_2) scaled by number of constituent quarks falling on a universal curve. The scaling hold good to ±10% within uncertainties in both Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV.

- Indicating partonic collectivity in smaller systems (Ru and Zr) as in the larger systems (Au or U).

Summary & Outlook

- **Influence of the nuclear size and structure**
  - Charge particle multiplicity, transverse momentum spectra, and elliptic flow of identified hadrons reveal differences in the nuclear structure of Ru and Zr nuclei. This information could be used to refine models that simulate collisions between nuclei of varying sizes and structures.
  - Ratio of v_2 and p_T correlation between differeent collision system provide access to nuclei deformation.

- **Collectivity in small system at 200 GeV**
  - Number of constituent quark scaling hold good to ±10% within uncertainties in both Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV, indicate partonic collectivity in such small systems.

- **System size dependence and its evolution**
  - Elliptic flow at high p_T incresases with atomic mass number of nuclei indicating nuclear size dependence.

More exciting results to come from the high statistics data of Isobar collisions at RHIC.....

Thank you for your attention!

Backup

Introduction: AMPT Model

- A multi-phase transport model (AMPT) string melting version 2.26t9 with a partonic cross-section of 3 mb.
- Nucleon distribution of nuclei in AMPT model is modeled using the Wood-Saxon function as:

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

R_0: Radius parameter
β_2 : Quadruple deformity
β_3 : Octupole deformity
$Y_{l,m}(\theta,\varphi)$: Spherical harmonics

- Nuclear deformation is characterized by modified radius parameter:

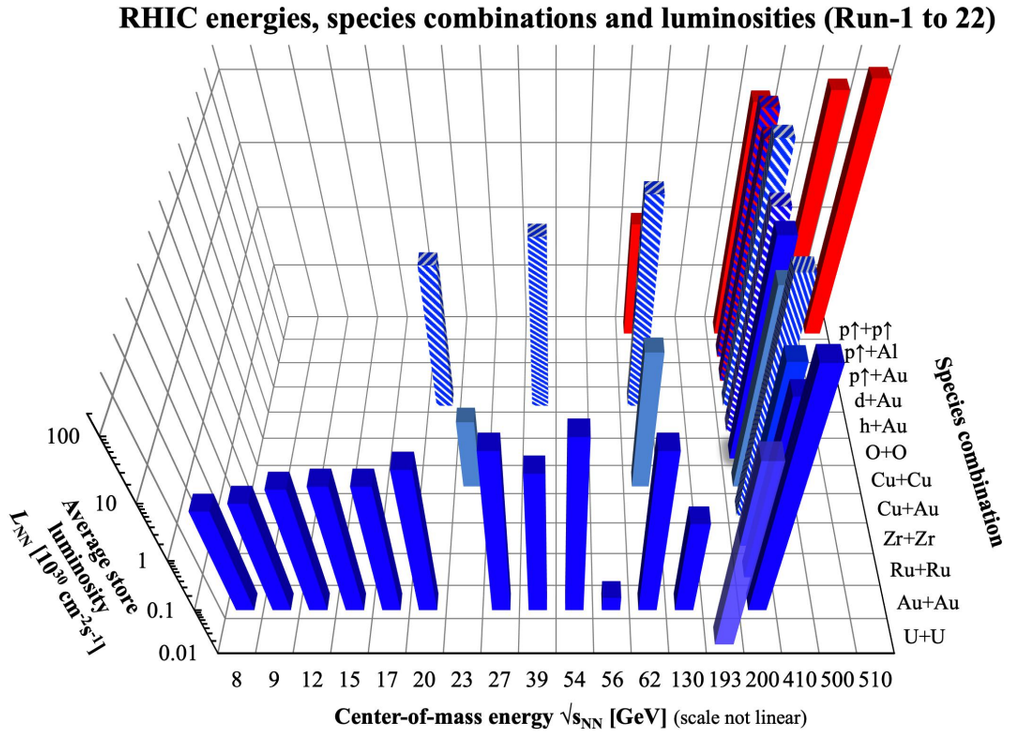
$$R(\theta,\phi) = R_0[1 + \beta_2 Y_{2,0}(\theta,\phi) + \beta_3 Y_{3,0}(\theta,\phi)]$$

- Various deformation configurations for the isobar nuclei ($^{96}_{44}$Ru and $^{96}_{40}$Zr) in the AMPT model:

	Ru			Zr		
Parameter	case 1	case 2	case 3	case 1	case 2	case 3
R_0	5.096	5.067	5.090	5.096	4.965	5.090
a	0.540	0.500	0.460	0.540	0.556	0.520
β_2	0	0	0.162	0	0	0.060
β_3	0	0	0	0	0	0.200

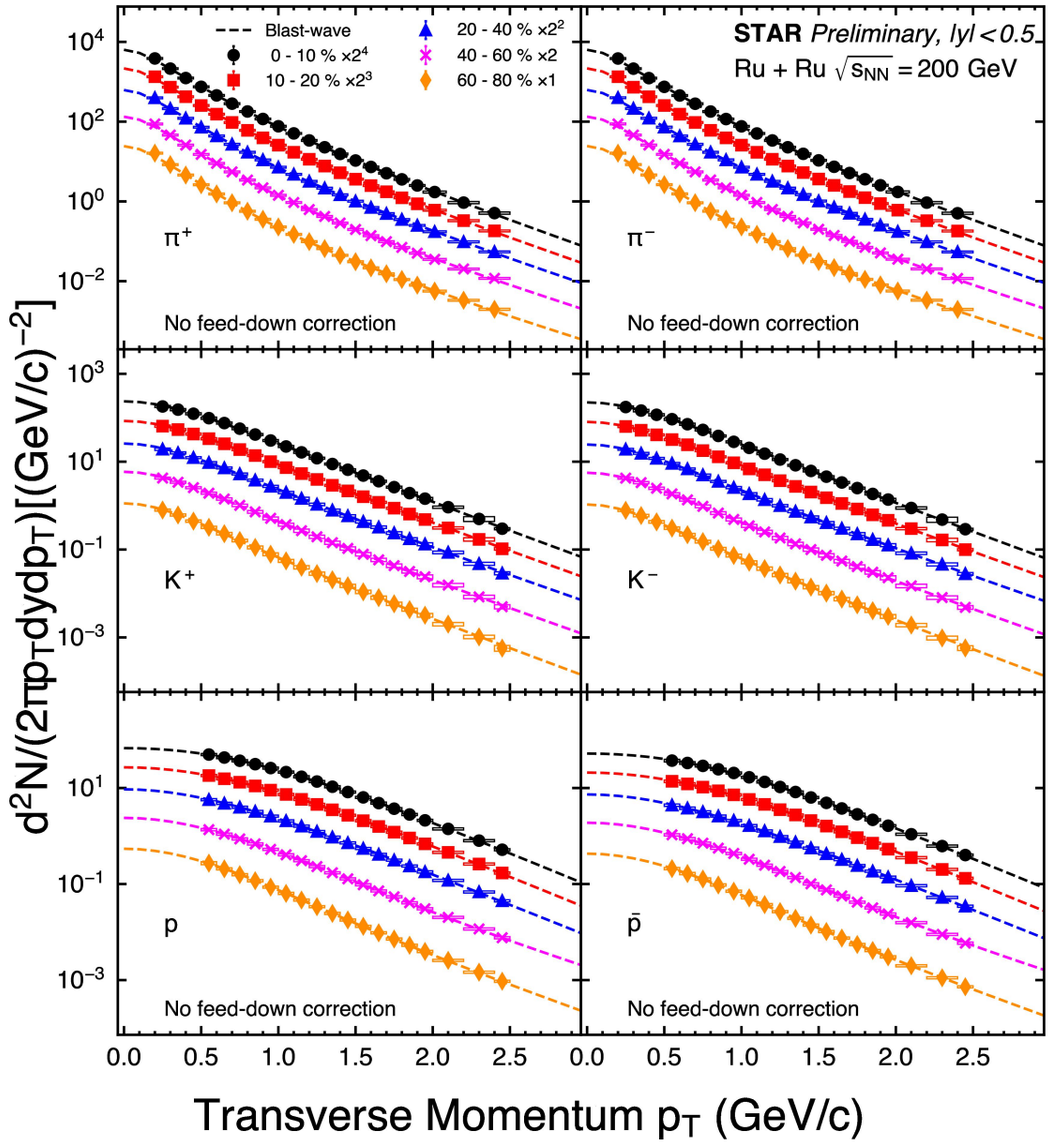
Beam energies and colliding systems at STAR

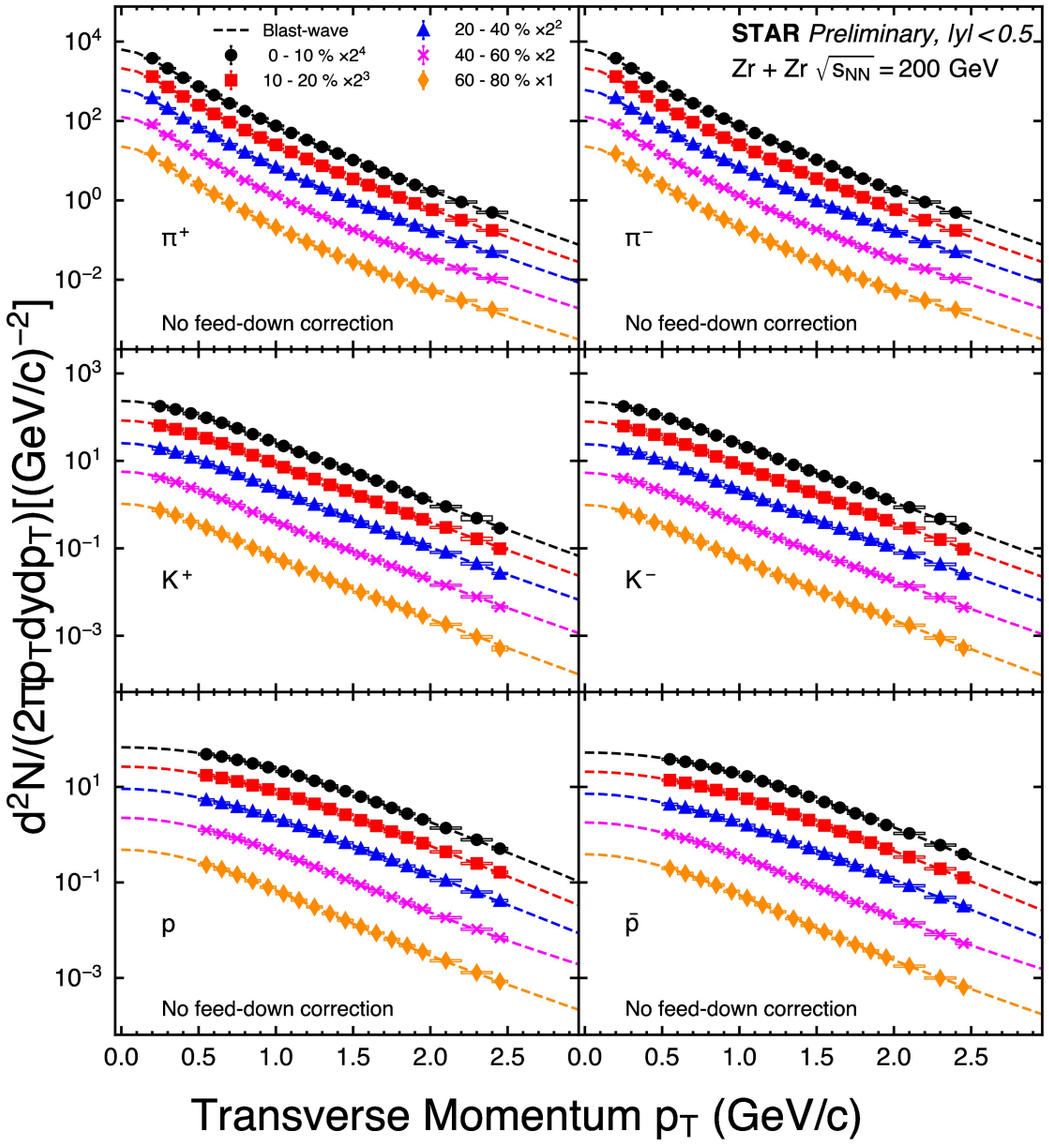
- Wide range of collision beam energies to explore QCD phase diagram
  - Beam Energy Scan Phase II (BES-II): $\sqrt{s_{NN}}$ = 7.7 – 54.4 GeV
  - Fixed Target (FXT): $\sqrt{s_{NN}}$ = 3.0 – 7.7 GeV
- Different collision species to study the QCD medium at top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV
  - U+U, Au+Au, Ru+Ru, Zr+Zr, Cu+Cu, O+O, Cu+Au, *He*^{3}+Au, *d*+Au, *p*+Au etc
- Increase in statistics over the years for precision measurement



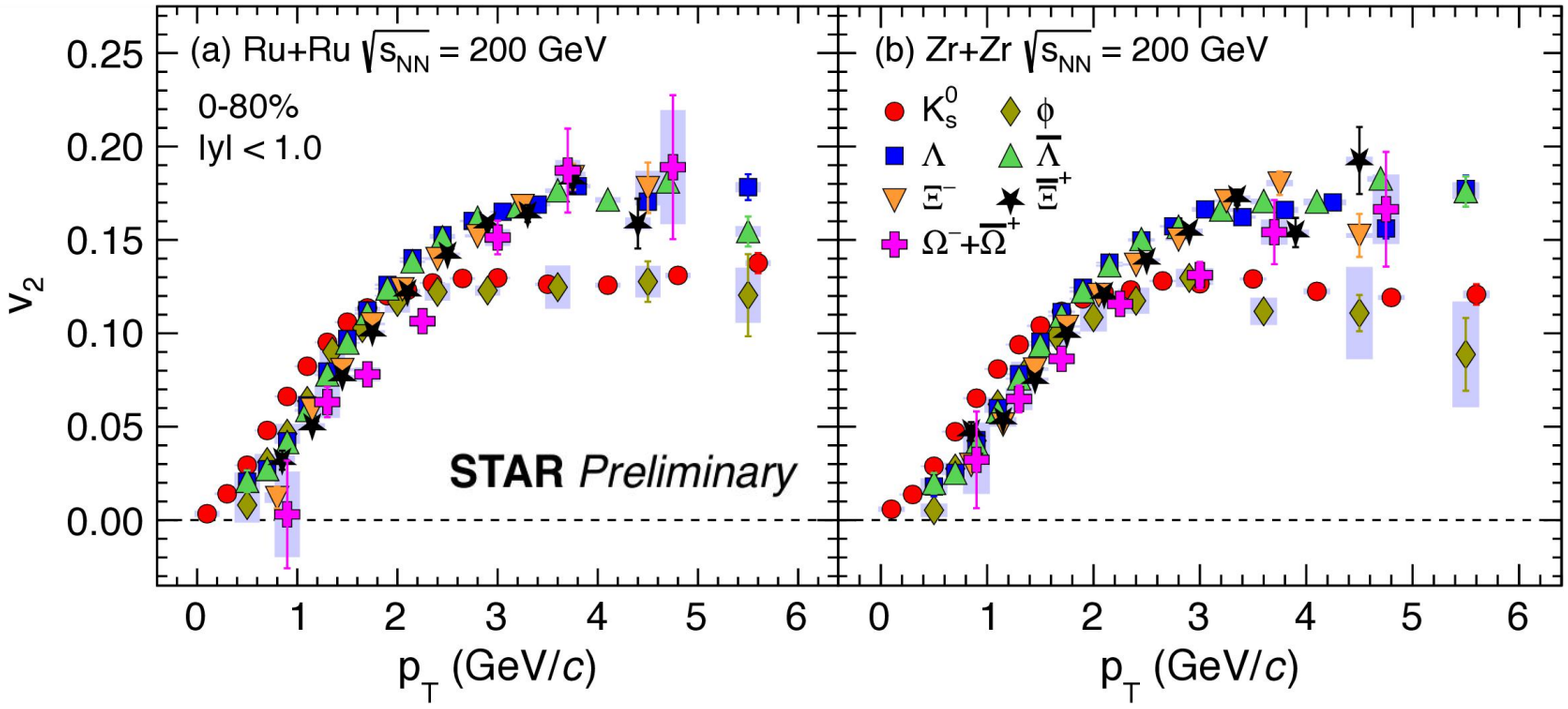
https://www.agsrhichome.bnl.gov/RHIC/Runs/

Transverse Momentum Spectra

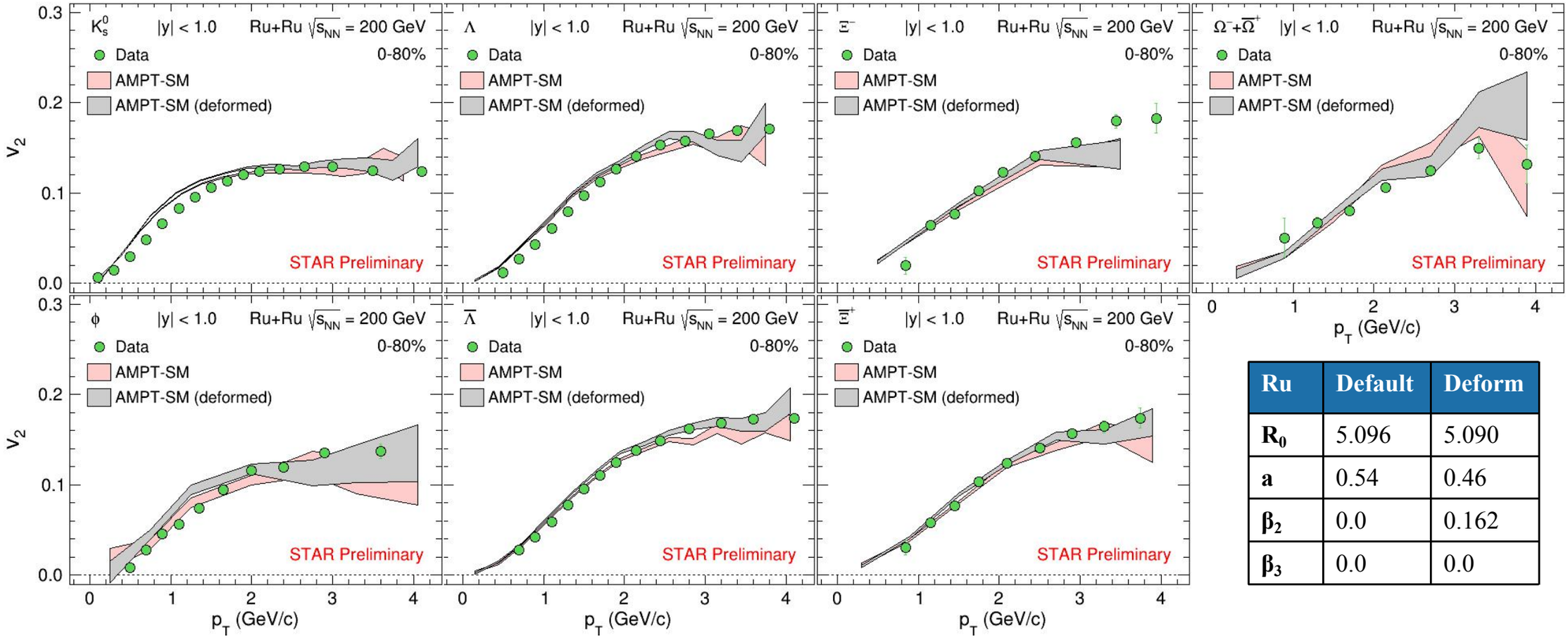




Elliptic Flow



Model Comparison

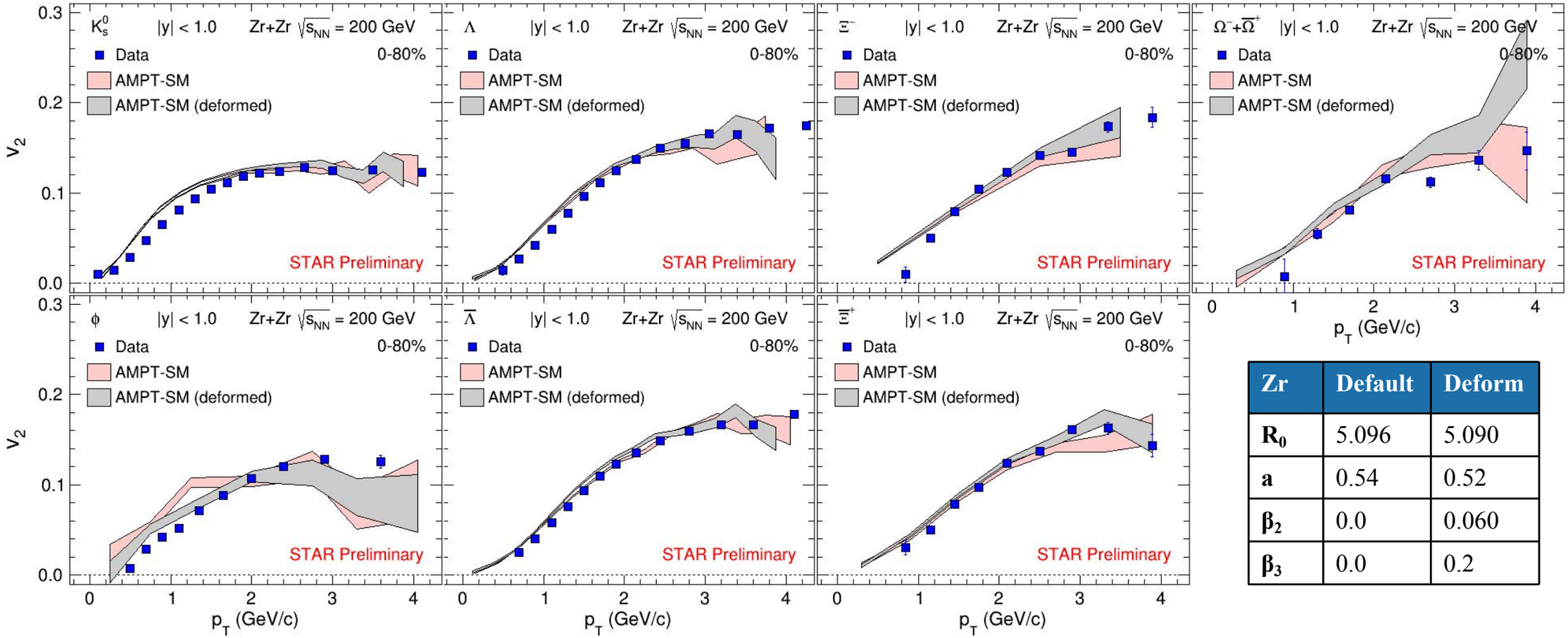


Ru	Default	Deform
R_0	5.096	5.090
a	0.54	0.46
β_2	0.0	0.162
β_3	0.0	0.0

AMPT-SM model with and without nuclear deformation describe the data well in the measured p_T range for minimum-bias isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV

B. Zhang et al., Phys. Rev. C 61, 067901 (2000)
Z.-W. Lin et al., Phys. Rev. C 64, 011902 (2001), Phys. Rev. C 72, 064901 (2005)

Model Comparison



Zr	Default	Deform
R_0	5.096	5.090
a	0.54	0.52
β_2	0.0	0.060
β_3	0.0	0.2

AMPT-SM model with and without nuclear deformation describe the data well in the measured p_T range for minimum-bias isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV

B. Zhang et al., Phys. Rev. C 61, 067901 (2000)
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