# Elliptic flow measurements of strange and multi-strange hadrons in isobar collisions at RHIC


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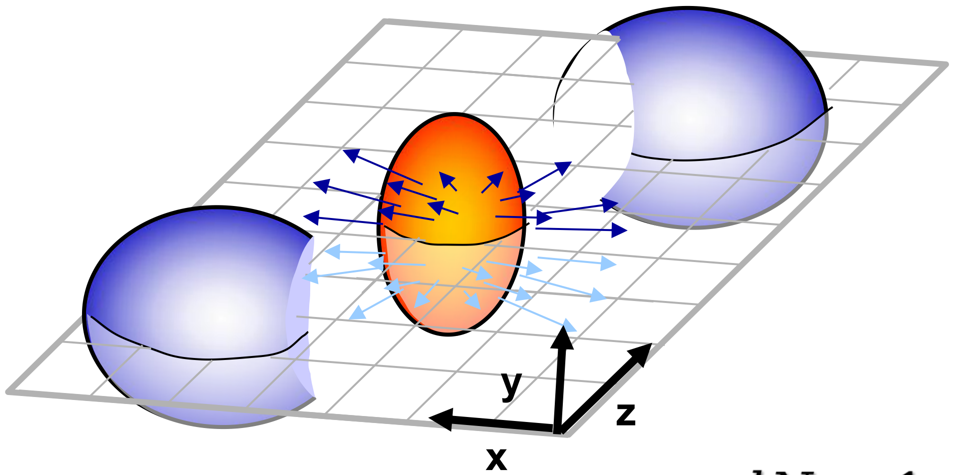
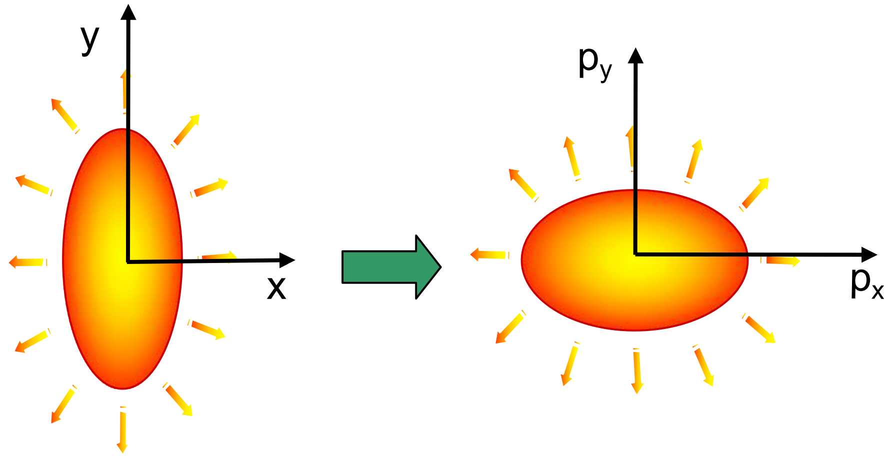
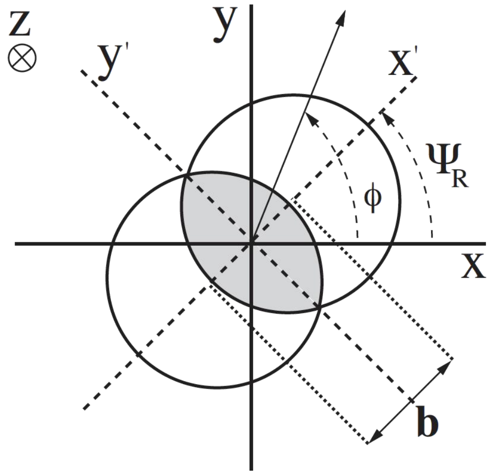
# Introduction: Elliptic flow




Reaction plane: xz plane




$$\frac{dN}{d\phi} \propto \frac{1}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_R)\right)\right]$$

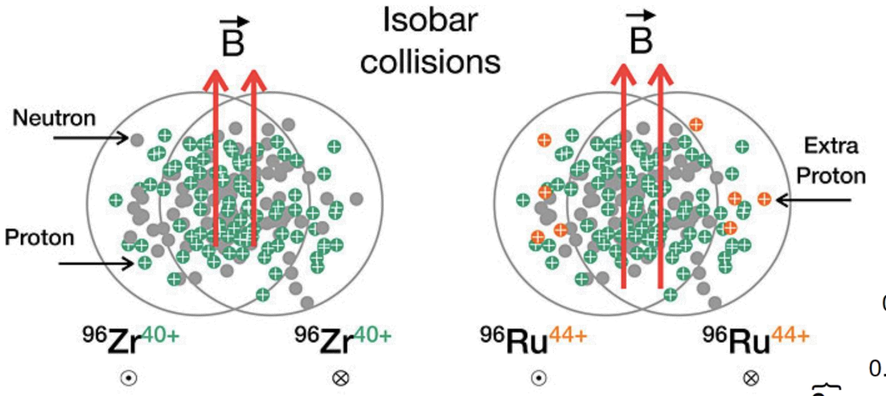
$$v_n = \langle \cos\left(n(\phi - \Psi_R)\right) \rangle$$

- Sensitive to early times in the evolution of the system
- Sensitive to the equation of state

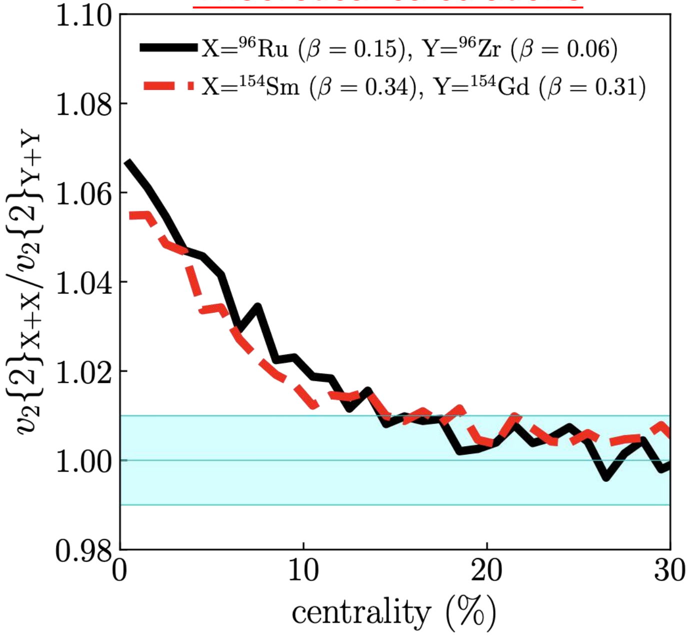
**Probe of the early (partonic) stage of the collision**

P. Klob, U. Heinz, Nucl. Phys. A715, (2003) 653c; A.M. Poskanzer & S.A. Voloshin, Phys. Rev. C 58 (1998) 1671

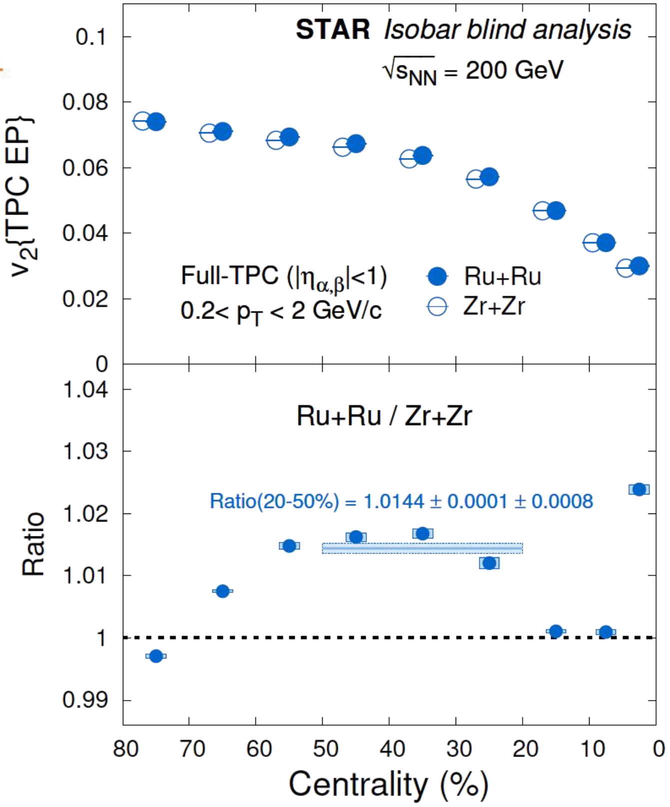
# Motivation




Theoretical calculations




Experimental measurements



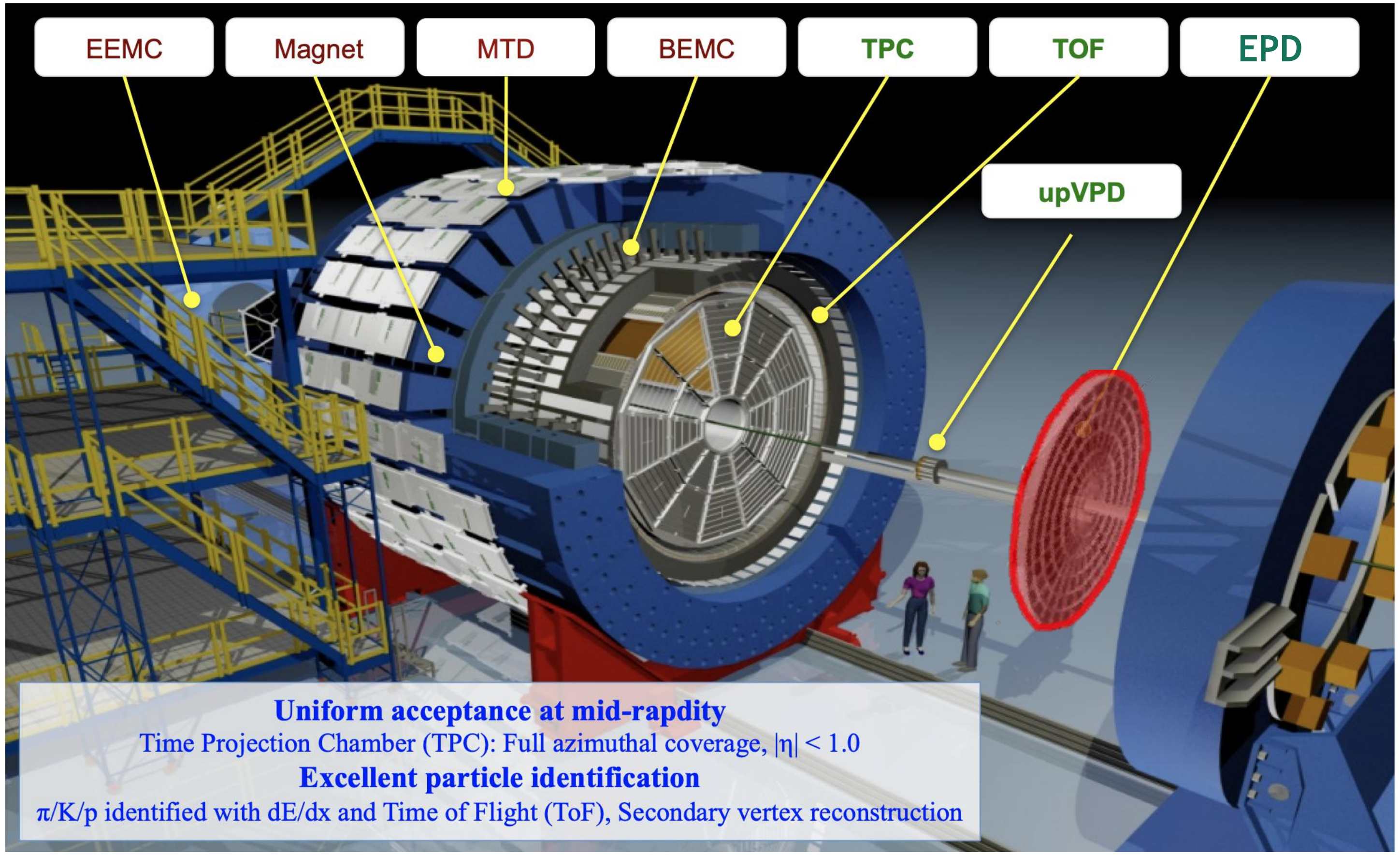

- Elliptic flow of (multi-)strange hadrons provide information on initial state anisotropies.
- Study of elliptic flow in isobar collisions may help in understanding the deformation of the colliding nuclei. for identified hadrons, one can check the ratio between the two isobar system:

$$\frac{(v_2)_{Ru+Ru}}{(v_2)_{Zr+Zr}} \stackrel{?}{=} 1$$

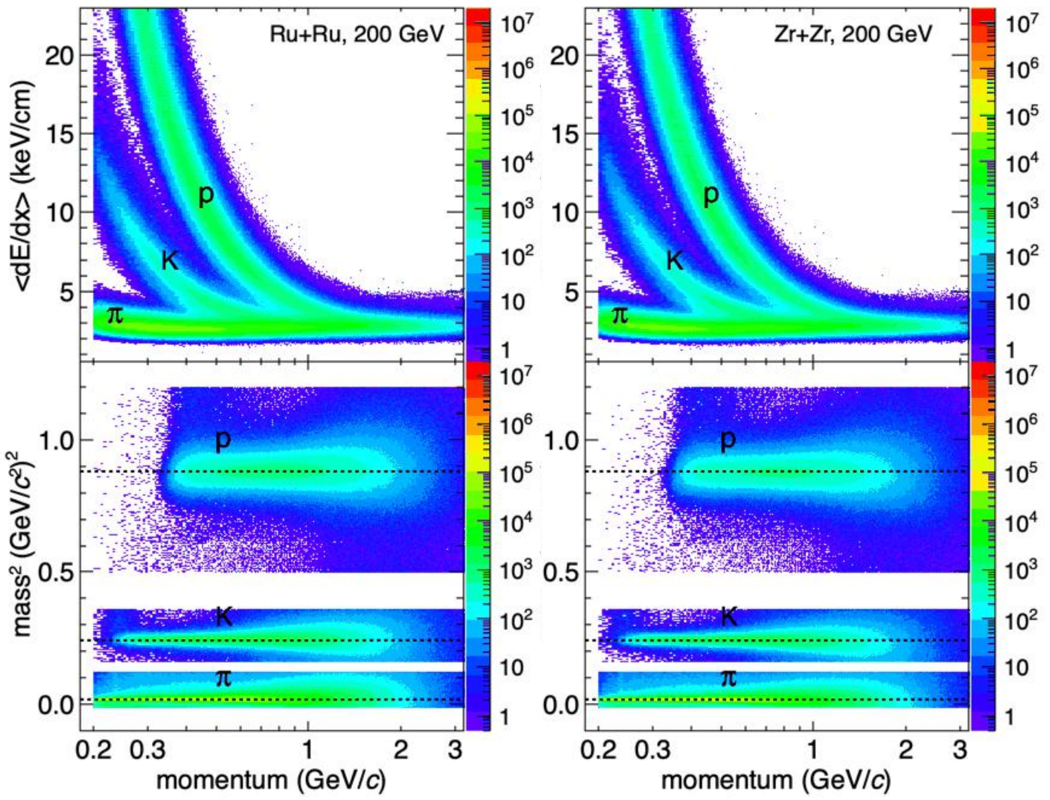
- Comaprison of elliptic flow among systems with different nuclear size can help in understanding system size dependence of the azimuthal anisotropy

G. Giacalone et al., Phys. Rev. C 104 (2021) L041903, M. S. Abdallah et al. (STAR), Phys. Rev. C 105 (2022) 14901

# STAR experiment




**Uniform acceptance at mid-rapdity**
Time Projection Chamber (TPC): Full azimuthal coverage, $|\eta| < 1.0$
**Excellent particle identification**
$\pi$/K/p identified with dE/dx and Time of Flight (ToF), Secondary vertex reconstruction




**Dataset:** Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV (2018)

Approximately 3.6 B events have been analysed

# Event plane method

- $2^{nd}$ harmonic event plane angle is defined as:

$$\Psi_n = \frac{1}{n} \tan^{-1}\left\{\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right\}; \quad \text{for } n = 2$$

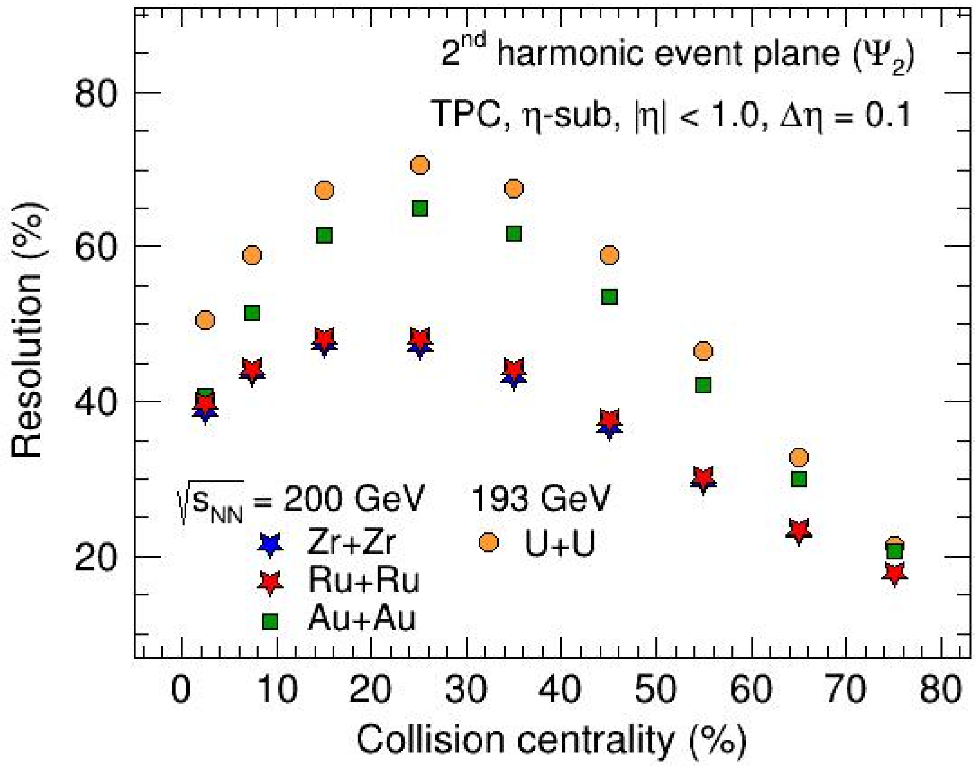
- Event plane angle calculated in two different η windows

  (a) $-1.0 < \eta < -0.05$ and (b) $0.05 < \eta < 1.0$

- The event plane angle resolution:

$$R = \sqrt{\cos 2\left(\Psi_2^a - \Psi_2^b\right)}$$

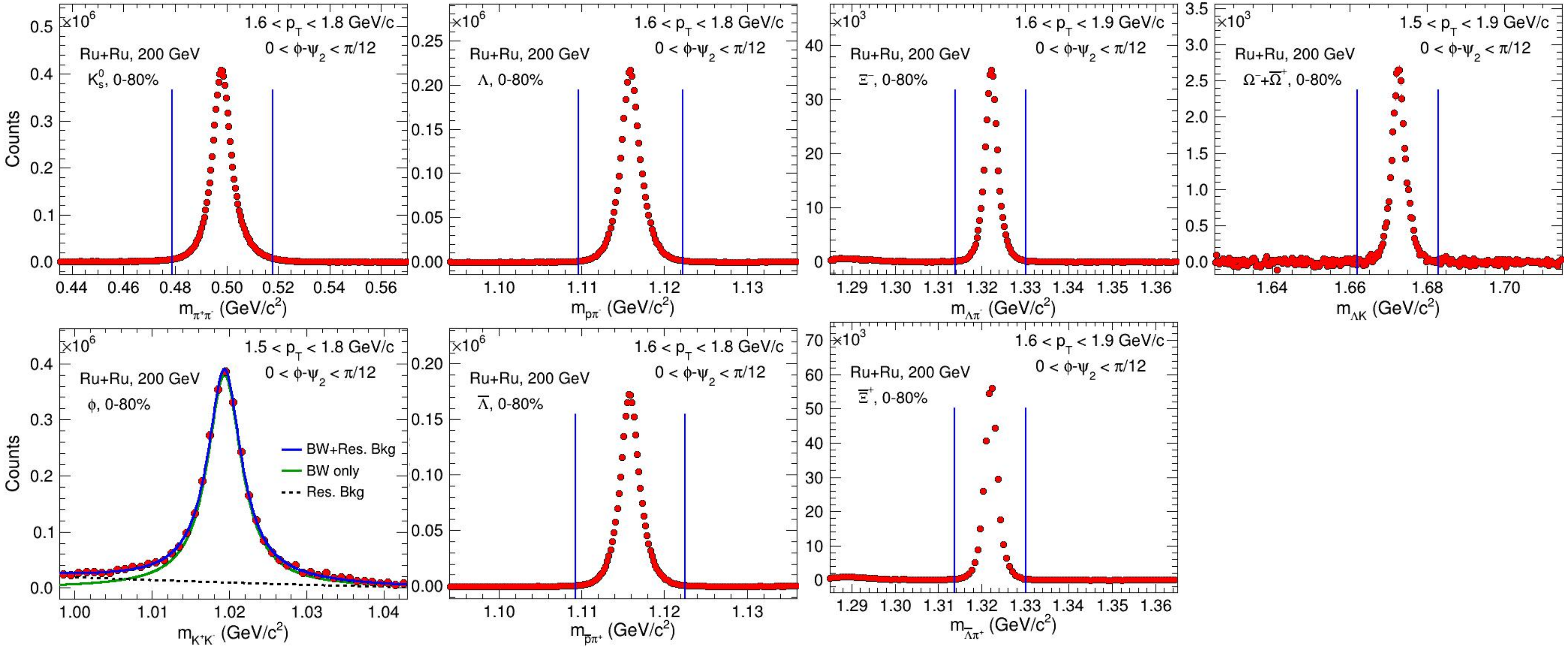
- Resolution correction applied to obtain the final $v_2$




A.M. Poskanzer & S.A. Voloshin, Phys. Rev. C 58 (1998) 1671

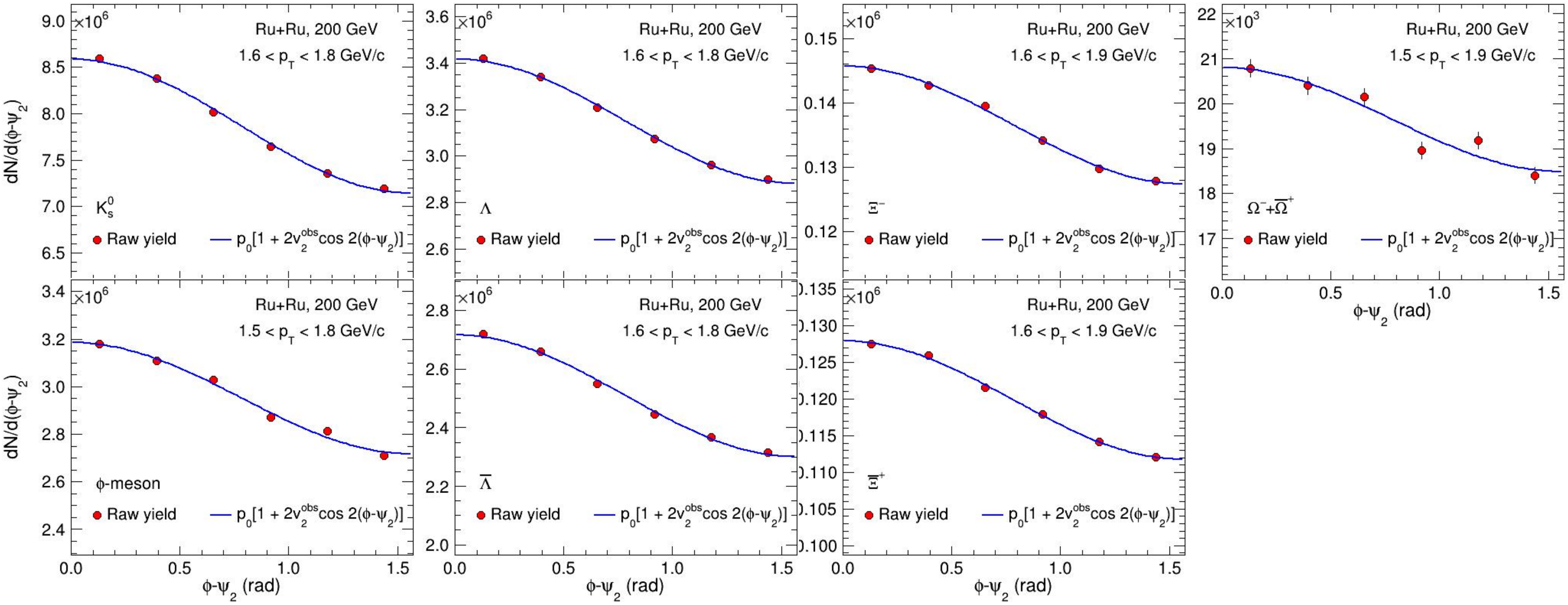
B. I. Abelev et al. (STAR), Phys. Rev. C 77 (2008) 054901;
M. S. Abdallah et al. (STAR) Phys. Rev. C 103 (2021) 064907

# Particle identification




- $K_s^0$, $\phi$, $\Lambda$, $\Xi$, and $\Omega$ have been reconstructed from their decay products using invariant mass technique.
- Background reconstruction using Event-mixing method for $\phi$-mesons, rotation method for $K_s^0$, $\Lambda$, $\Xi$, and $\Omega$.
- Signal extracted using bin counting within $\pm 3\sigma$ of the invariant mass peak for weak-decay particles and using Breit-Wigner fit for $\phi$-mesons.

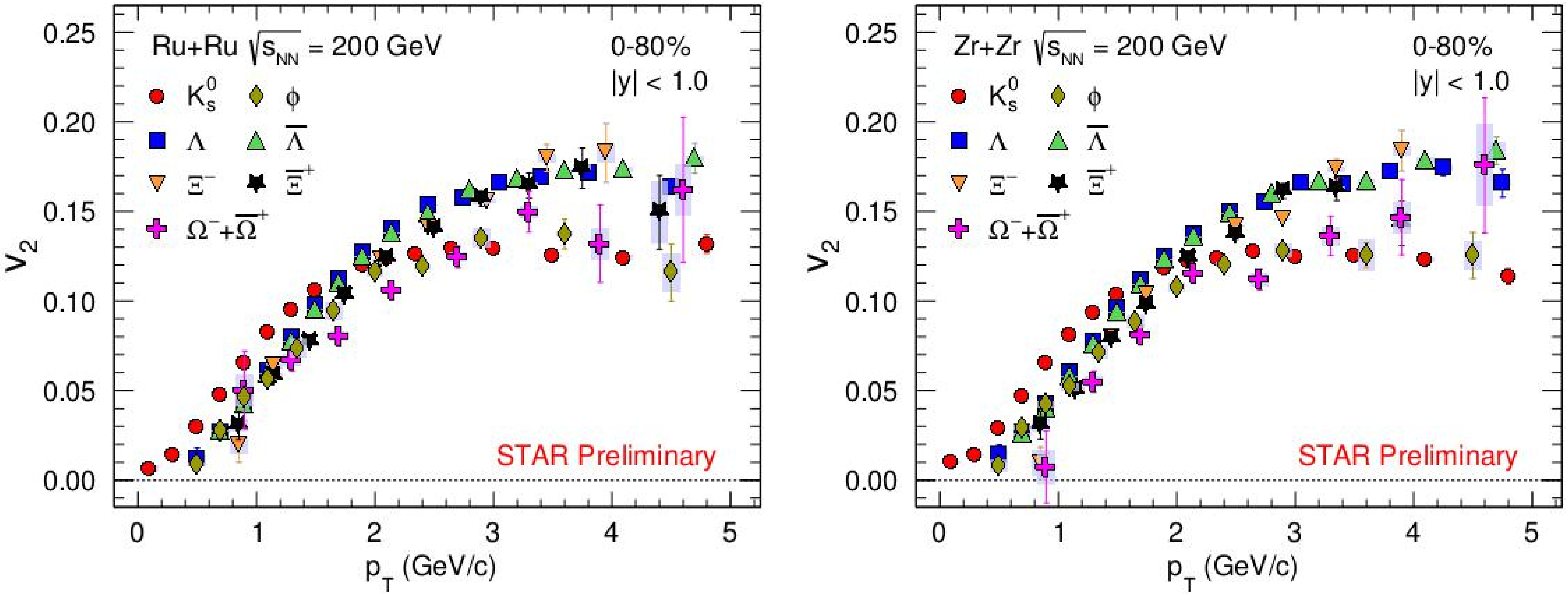
# Flow analysis method




Event plane method:

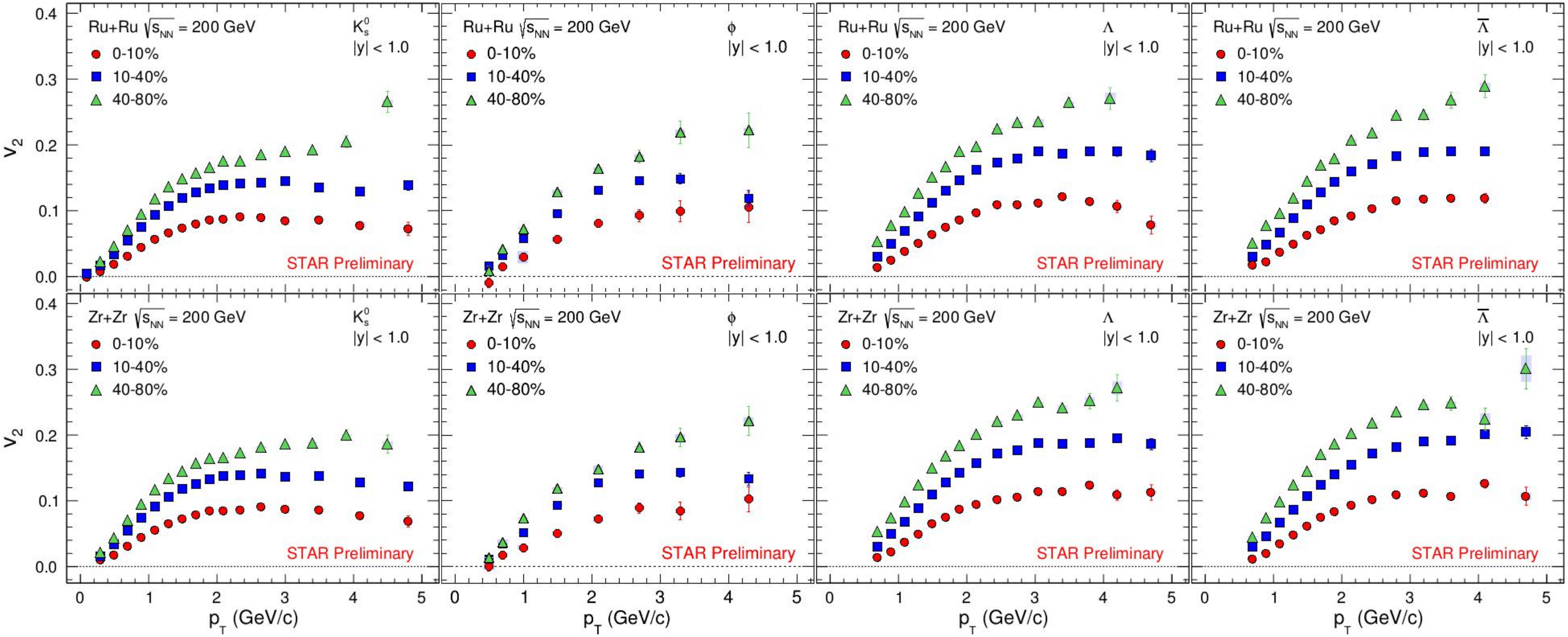
- Particle raw-yield as a function of $\phi$-$\Psi_2$ is fitted with a function for different $p_T$ ranges to extract observed $v_2$ coefficients.

# Results: Elliptic flow $v_2(p_T)$



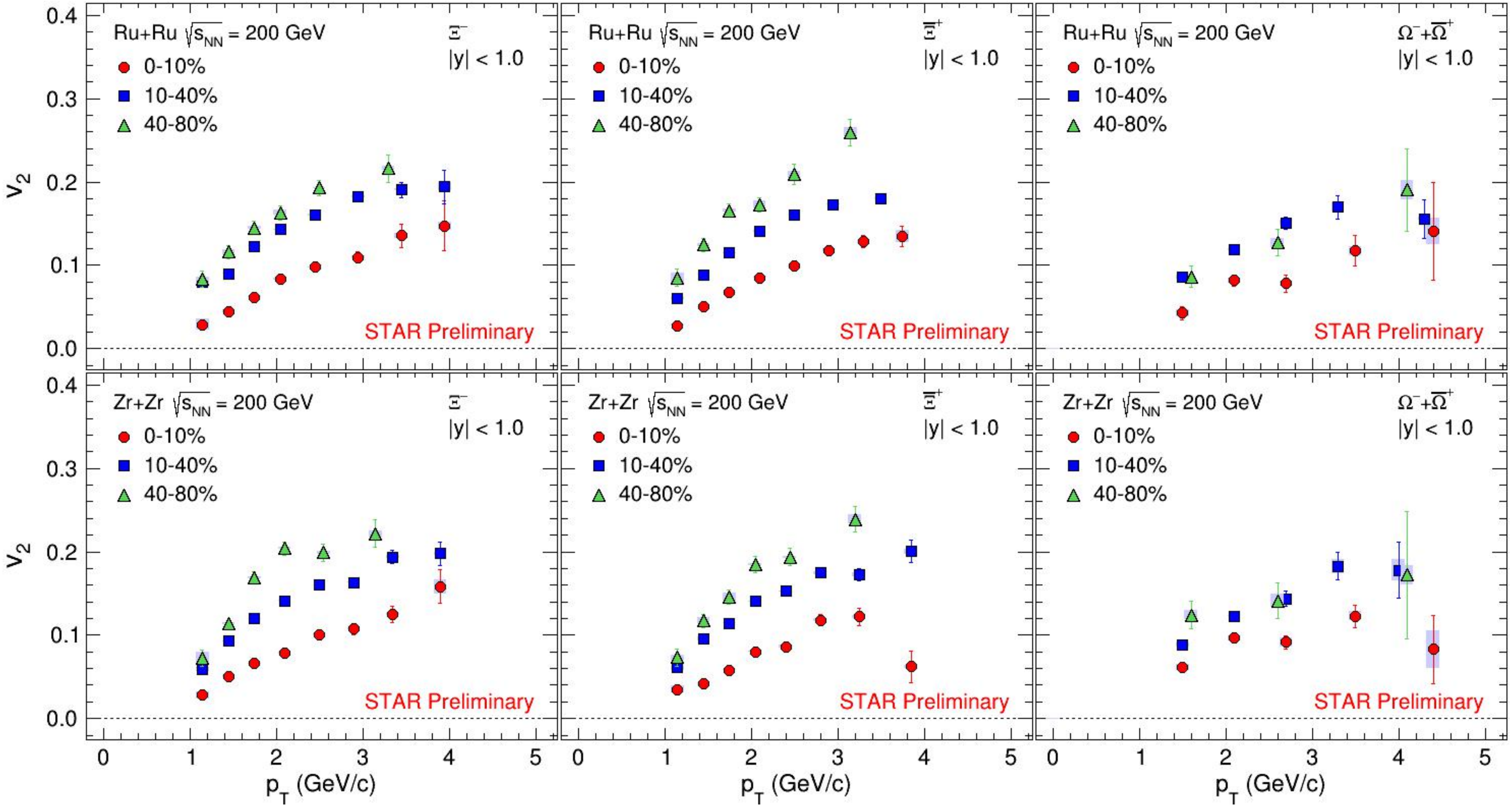

- Elliptic flow $v_2$ shows a particle mass ordering at low $p_T$ for minimum bias isobar collisions at $\sqrt{s_{NN}} = 200$ GeV.
- Splitting of flow coefficients between baryons and mesons at intermediate $p_T$ region ( > 2 GeV/c) is observed.
- A similar $p_T$ dependence is observed in both Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV.

# Centrality dependence of $v_2(p_T)$



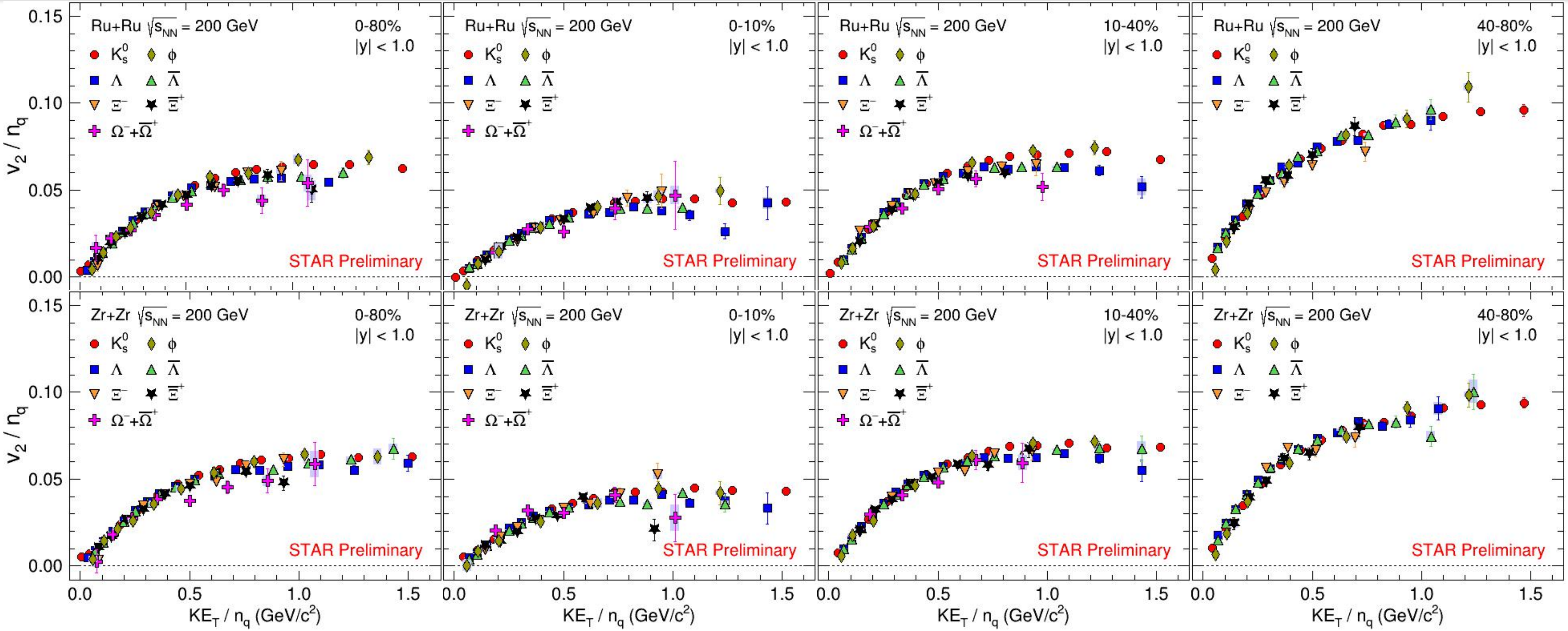

Elliptic flow $v_2(p_T)$ increases from central to peripheral collisions showing strong centrality dependence which indicate effect of initial eccentricity in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV.

# Centrality dependence of $v_2(p_T)$




Elliptic flow $v_2(p_T)$ increases from central to peripheral collisions showing strong centrality dependence which indicate effect of initial eccentricity in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV.

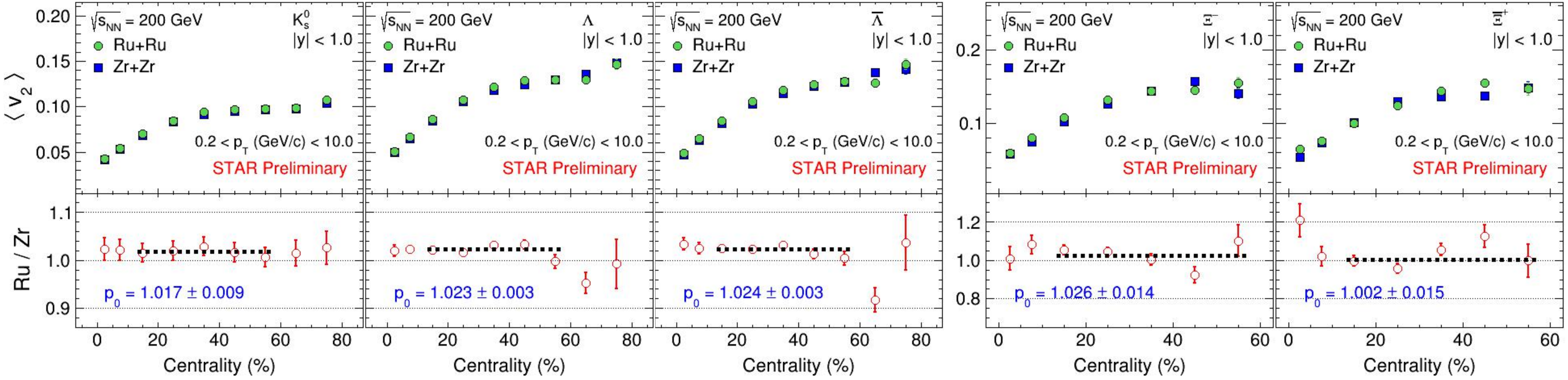
# Constituent quarks scaling




*$n_q$ = Number of constituent quarks (3 for baryons and 2 for mesons); Transverse kinetic energy ($KE_T$) = $m_T - m_0$*

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

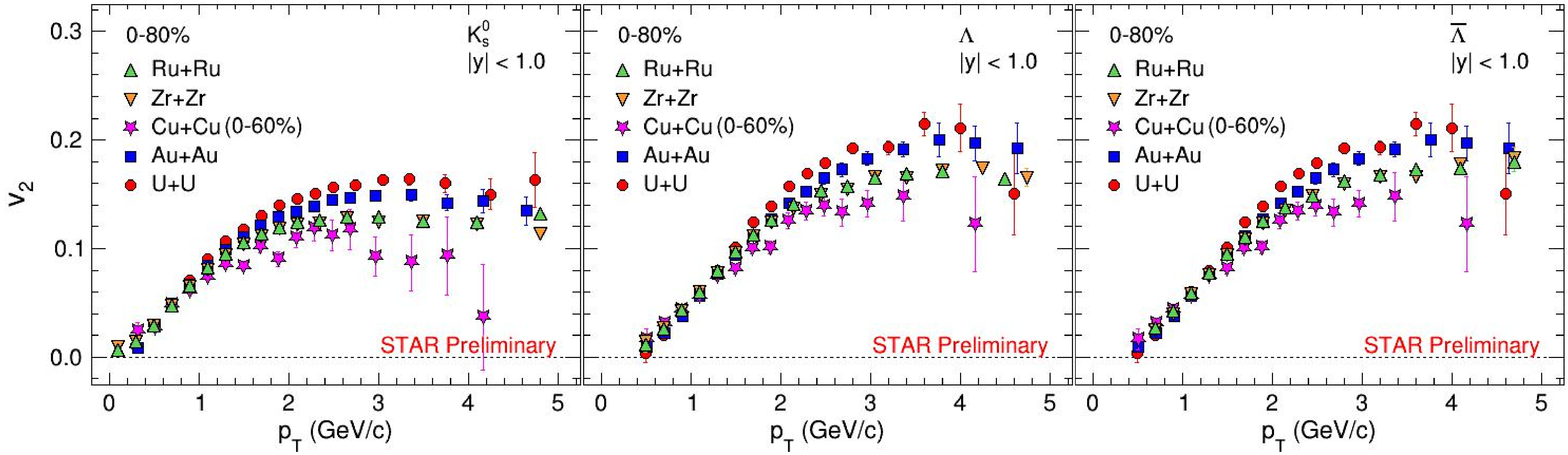
# Integrated $v_2$




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

Indication of larger nuclear deformity in Ru nuclei than in the Zr nuclei

# System size dependence (strange)



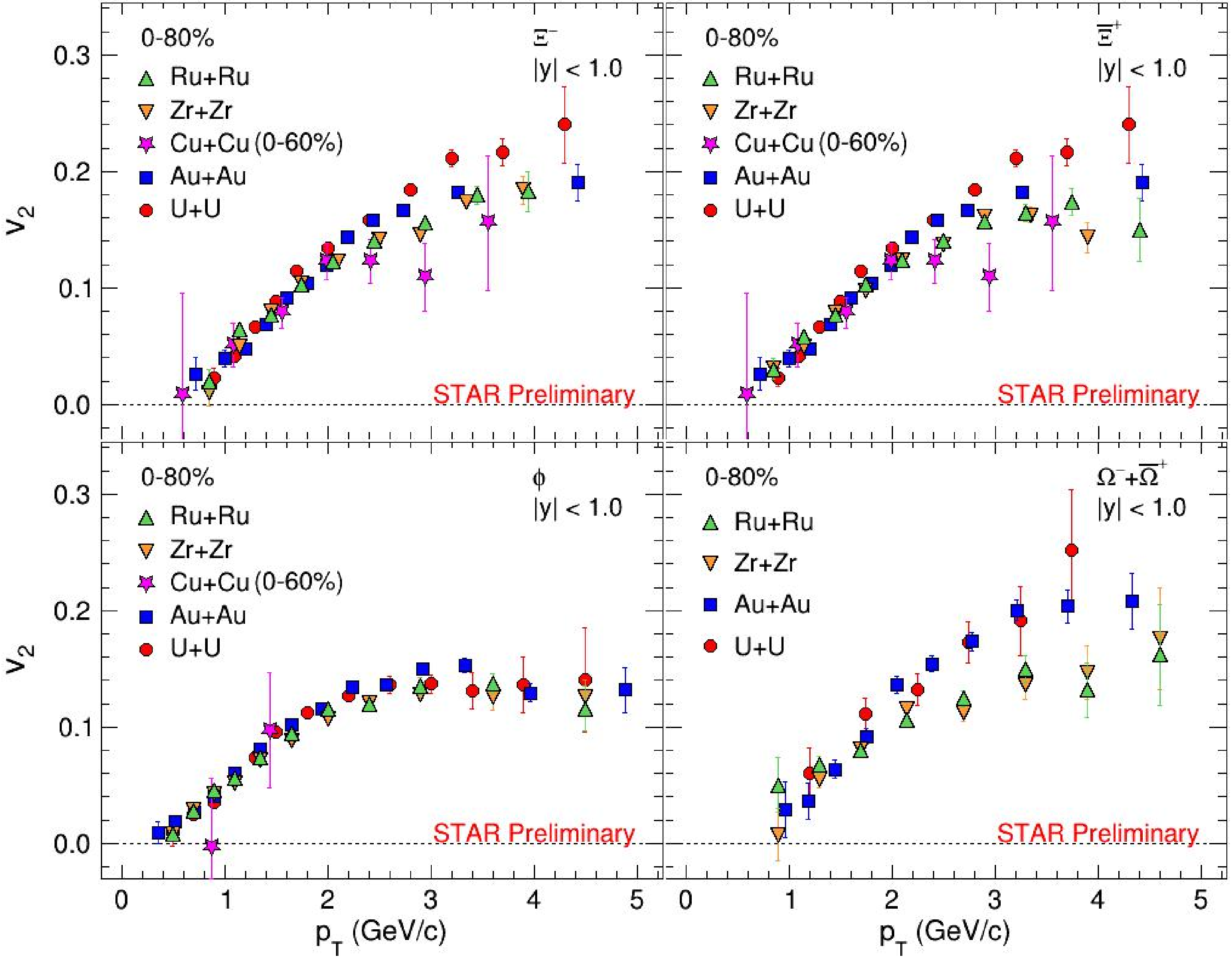

* *Error bars are combined statistical and systematic uncertainties*

- Elliptic flow $v_2(p_T)$ of strange hadrons at $p_T > 2$ GeV/c in isobar collisions is higher than the Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV and lower compared to U+U and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Elliptic flow at high $p_T$ increases with atomic mass number of nuclei indicating a nuclear size dependence

**B. I. Abelev et al. (STAR), Phys. Rev. C 77 (2008) 054901, Phys. Rev. C 81 (2010) 044902; M. S. Abdallah et al. (STAR) Phys. Rev. C 103 (2021) 064907**

# System size dependence (multi-strange)

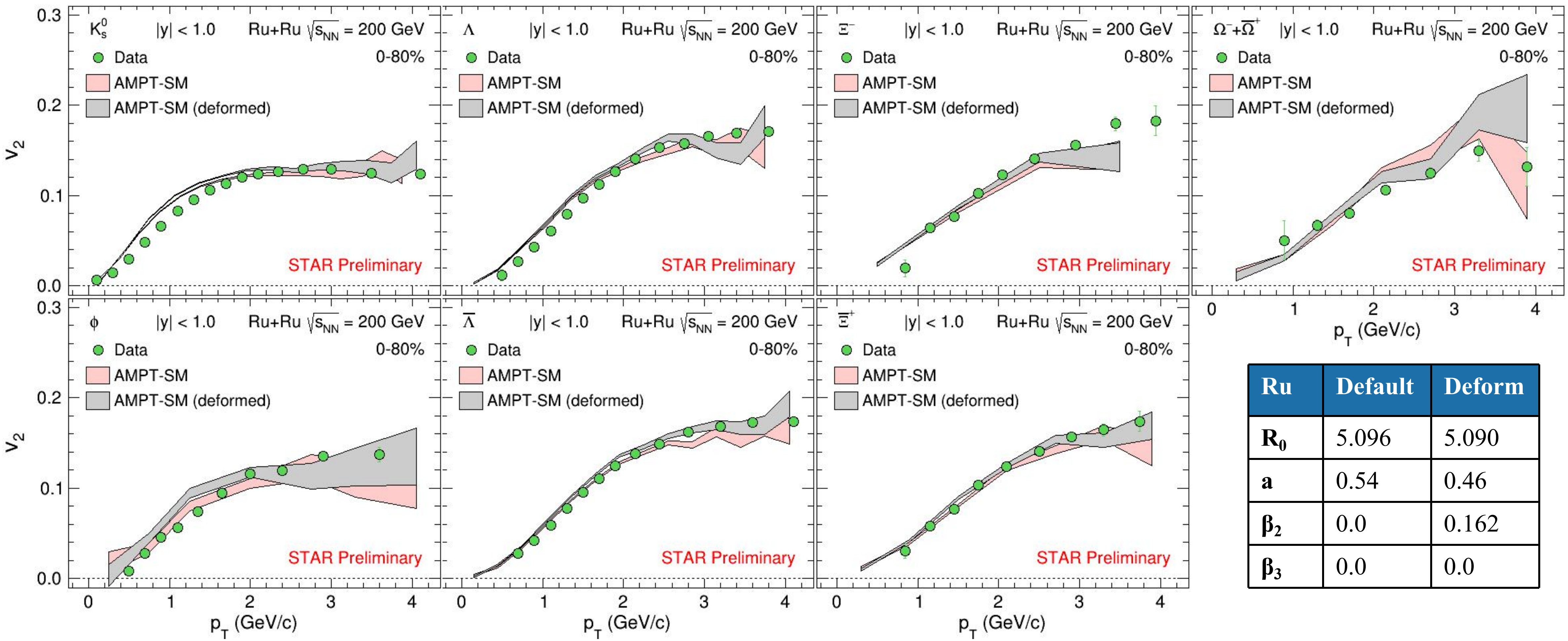



** Error bars are combined statistical and systematic uncertainties*

Elliptic flow of multi-strange hadrons in the measured $p_T$ range for isobar collisinos at $\sqrt{s_{NN}}$ = 200 GeV shows nuclear size dependence similar to the strange hadrons, while $\phi$-meson shows weak or no system size dependence.


**B. I. Abelev et al. (STAR), Phys. Rev. C 77 (2008) 054901**
**B. I. Abelev et al. (STAR), Phys. Rev. C 81 (2010) 044902**
**L. Adamczyk et al. (STAR), Phys. Rev. Lett. 116 (2016) 062301**
**M. S. Abdallah et al. (STAR) Phys. Rev. C 103 (2021) 064907**

# Model Comparison



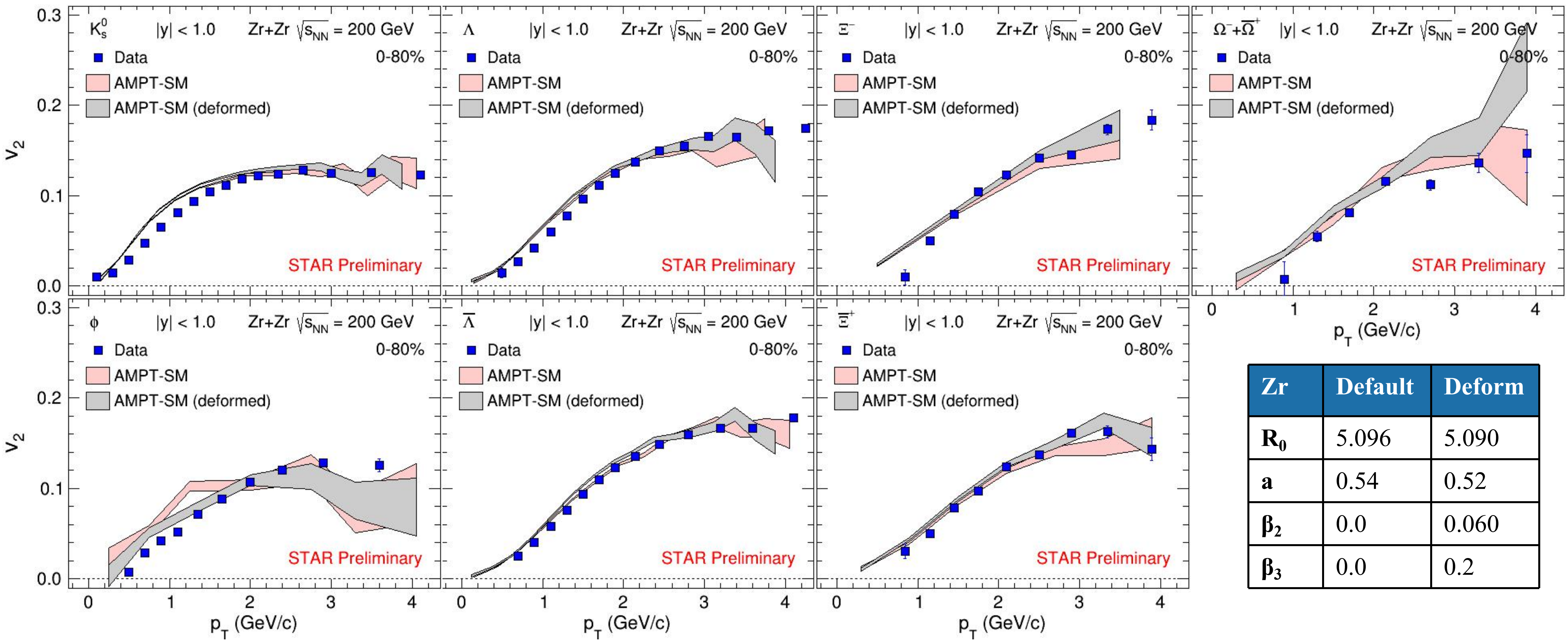

| Ru | Default | Deform |
|---|---|---|
| $R_0$ | 5.096 | 5.090 |
| a | 0.54 | 0.46 |
| $\beta_2$ | 0.0 | 0.162 |
| $\beta_3$ | 0.0 | 0.0 |

AMPT-SM model with and without nuclear deformation can describe the data 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 |
| $\beta_2$ | 0.0 | 0.060 |
| $\beta_3$ | 0.0 | 0.2 |

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



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# Summary

- Elliptic flow of strange ($K_s^0$, $\Lambda$, $\overline{\Lambda}$) and multi-strange ($\phi$, $\Xi$, $\Omega$) hadrons has been measured using event plane method in isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC.

**Partonic collectivity:**

- Strong centrality dependence and NCQ scaling of $v_2$ for (multi-)strange hadrons in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - ► Partonic collectivity in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC

**Nuclear size and deformation:**

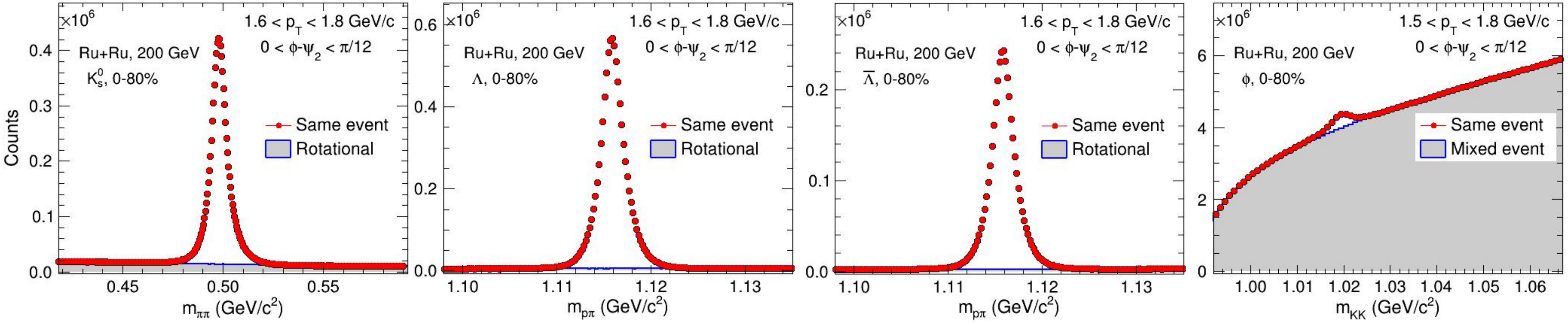
- Elliptic flow $\langle v_2 \rangle$ ratio between two isobars (Ru/Zr) shows a deviation of 2% from unity in mid-central collisions
  - ► Indicates higher deformation in Ru than in Zr nuclei
- $v_2(p_T)$ at higher $p_T$ (> 2 GeV/c) for strange hadrons increases with increasing system size
  - ► Indicates effect of nuclear size on elliptic flow at $\sqrt{s_{NN}}$ = 200 GeV

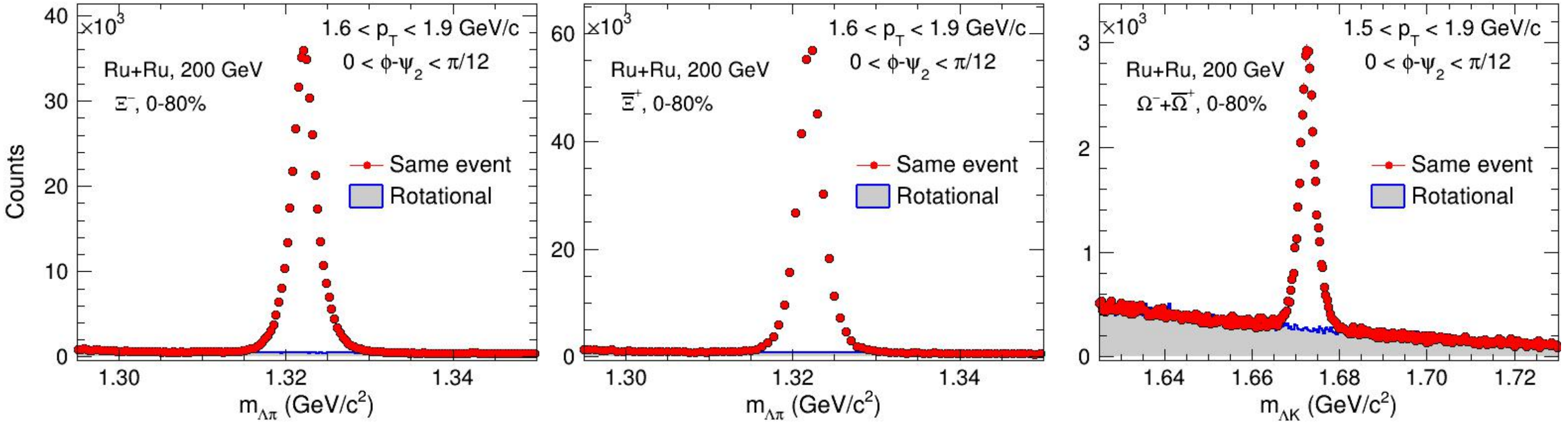
# Thank you for your attention!

# Backup

# Particle identification






| Particle |
| --- |
| $K_s^0 \rightarrow \pi^+ \pi^-$ |
| $\Lambda \rightarrow p\, \pi^-$ |
| $\overline{\Lambda} \rightarrow \overline{p}\, \pi^+$ |
| $\Xi^- \rightarrow \Lambda\, \pi^-$ |
| $\overline{\Xi}^+ \rightarrow \overline{\Lambda}\, \pi^+$ |
| $\Omega \rightarrow \Lambda\, K$ |
| $\phi \rightarrow K^+ K^-$ |

- $K_s^0$, $\phi$, Λ, Ξ, and Ω have been reconstructed from their decay products.
- Background reconstruction using various methods: Event-mixing method for $\phi$-mesons, rotation method for $K_s^0$, Λ, Ξ, and Ω.

# AMPT (SM) Model Parameters

**AMPT (String Melting) Model:**

- Parton-Parton interaction cross-section 3 mb is used.

Woods-saxon distribution: $\rho(r,\theta) = \rho_0 / \{1 + e^{[(r - R(\theta,\varphi))/a]}\}$

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

| Default | $R_0$ | a | $\beta_2$ | $\beta_3$ |
|---|---|---|---|---|
| Ru | 5.096 | 0.54 | 0.0 | 0.0 |
| Zr | 5.096 | 0.54 | 0.0 | 0.0 |
| **Deform** | **$R_0$** | **a** | **$\beta_2$** | **$\beta_3$** |
| Ru | 5.09 | 0.46 | 0.162 | 0.0 |
| Zr | 5.09 | 0.52 | 0.060 | 0.2 |