Azimuthal anisotropy measurments of strange and multi-strange hadrons in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV

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Outline:

- Introduction & Motivation
- STAR Experiment at RHIC
- Results
- Summary

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STAR

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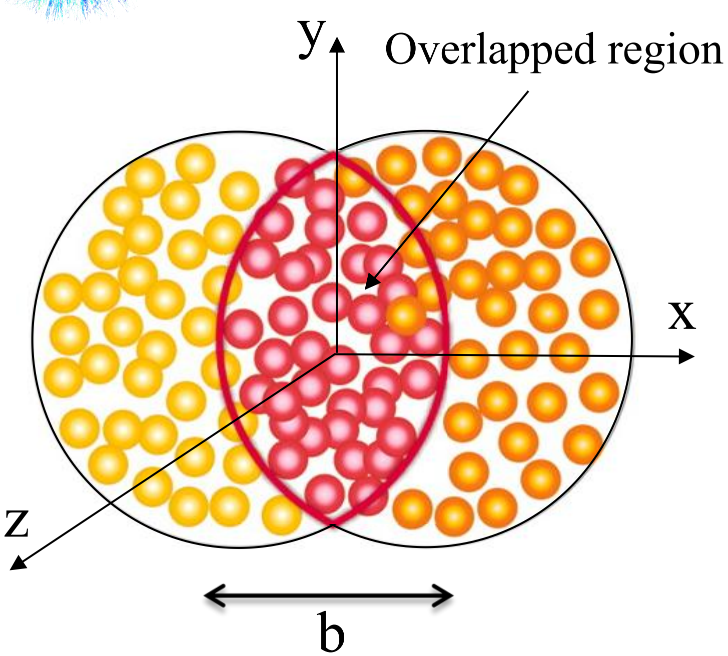
Azimuthal Anisotropy

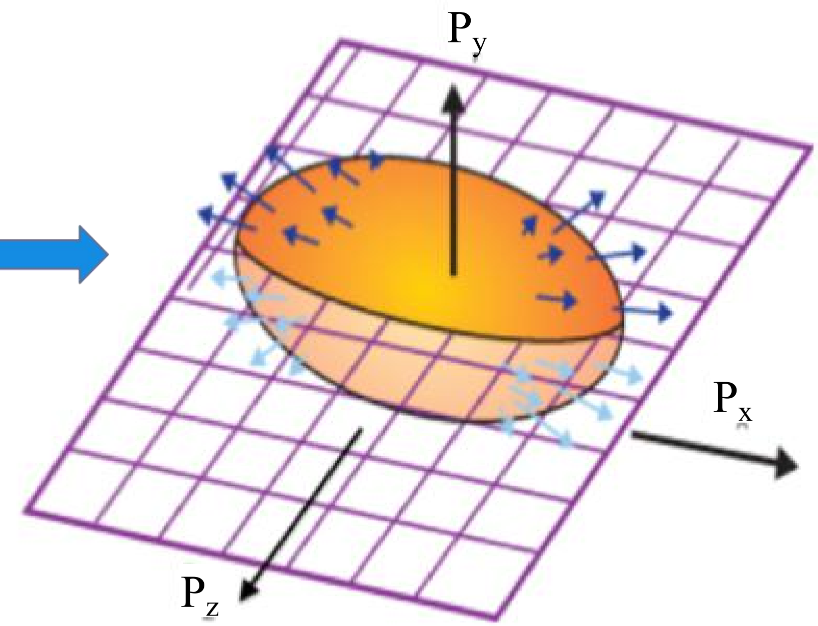


Interactions

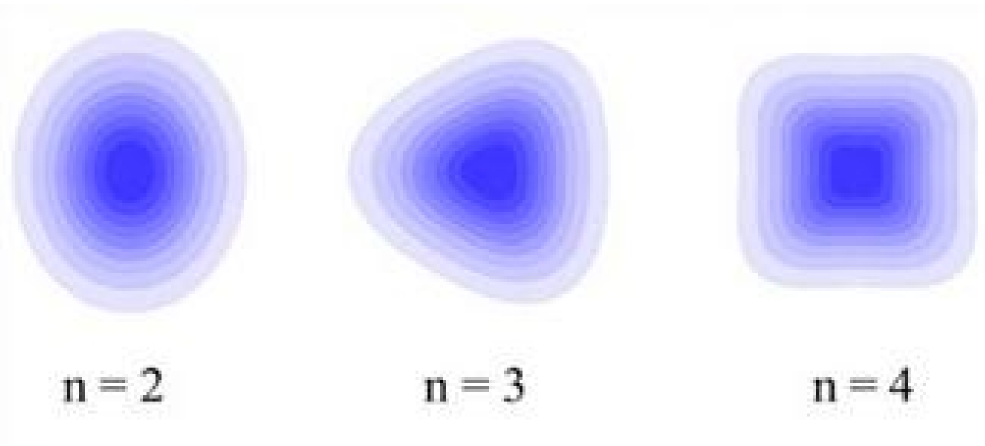
↓

Pressure(P)

$$y > x \rightarrow \frac{\partial P}{\partial x} > \frac{\partial P}{\partial y}$$



Different flow harmonics



Flow harmonics are sensitive to:

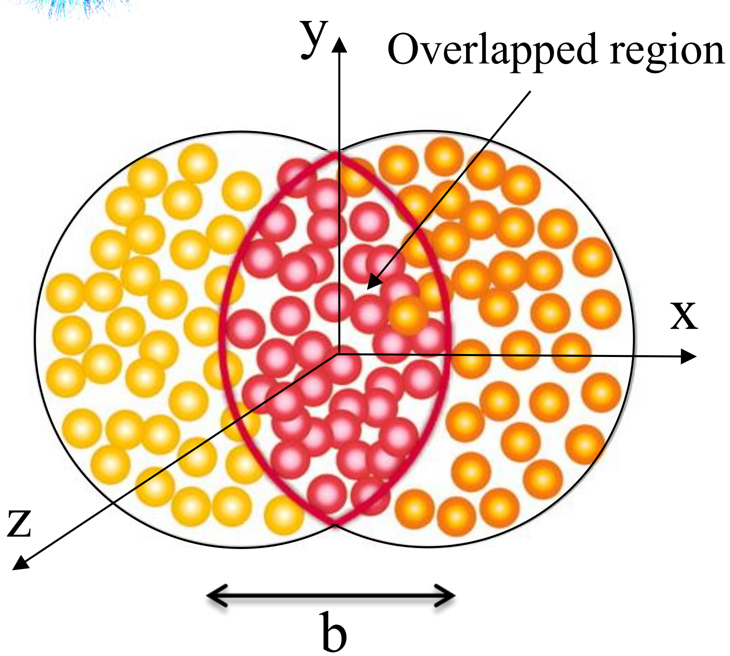
- Initial conditions
- Transport properties (η/s)

Flow harmonics can probe:

- hadronisation mechanism (e.g. quark coalescence)
- Effect of hadron rescattering

-- P. Klob, U. W. Heinz, Nucl. Phys. A715, (2003) 653c

Azimuthal Anisotropy



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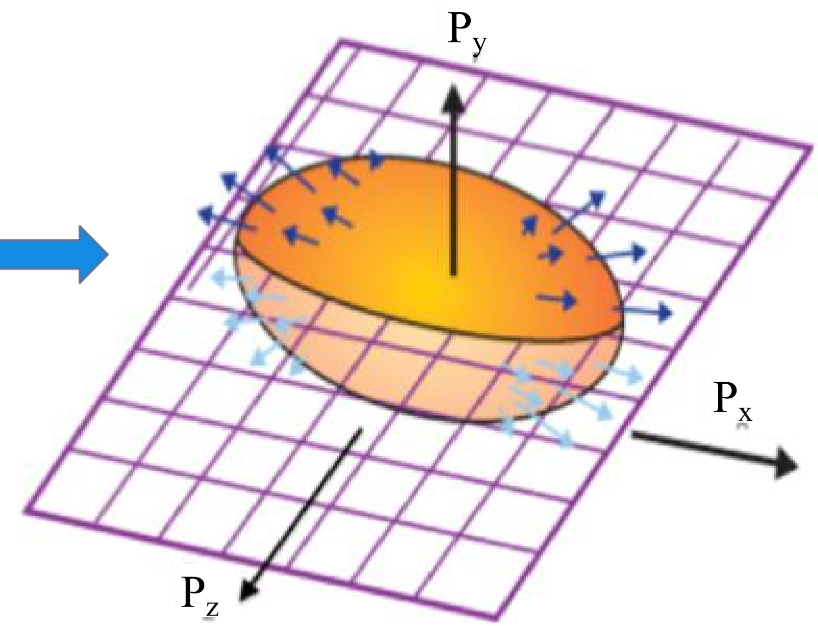
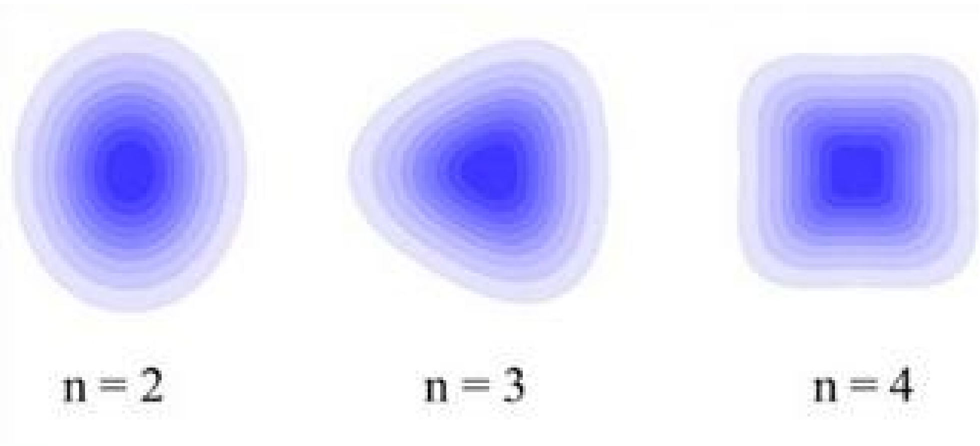


Different flow harmonics



Flow of (multi-) strange hadrons:

- (Multi-strange) hadrons freeze-out at higher temperature and their hadronic interaction cross-section with non-strange hadrons is expected to be small.
- Flow of (multi-) strange hadrons provides information on partonic collectivity of the initial stage.

-- P. Klob, U. W. Heinz, Nucl. Phys. A715, (2003) 653c

-- A. Shor, Phys. Rev. Lett. 54, 1122 (1985)

Flow Measurements

$$E\frac{d^3N}{dp^3} = E\frac{d^2N}{2\pi p_T dp_T d\eta}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos\{n(\phi - \Psi_n)\}\right]$$

ϕ = Azimuthal angle, Ψ_n = n^{th}-order event plane angle

Flow coefficients: $v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$

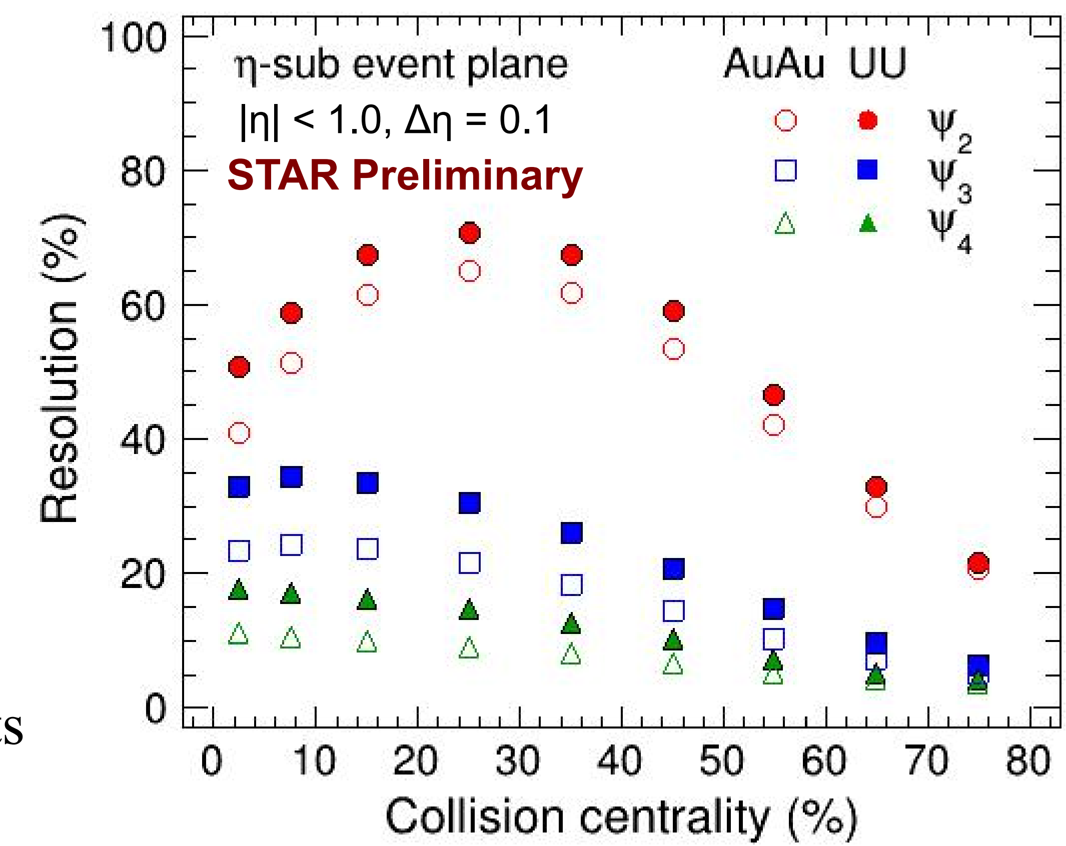
η-sub event plane method

$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\sum_{i=1}^{M} w_i \sin(n\phi_i)}{\sum_{i=1}^{M} w_i \cos(n\phi_i)}\right)$$

w_i are weights, which can be p_T or η of the particles.

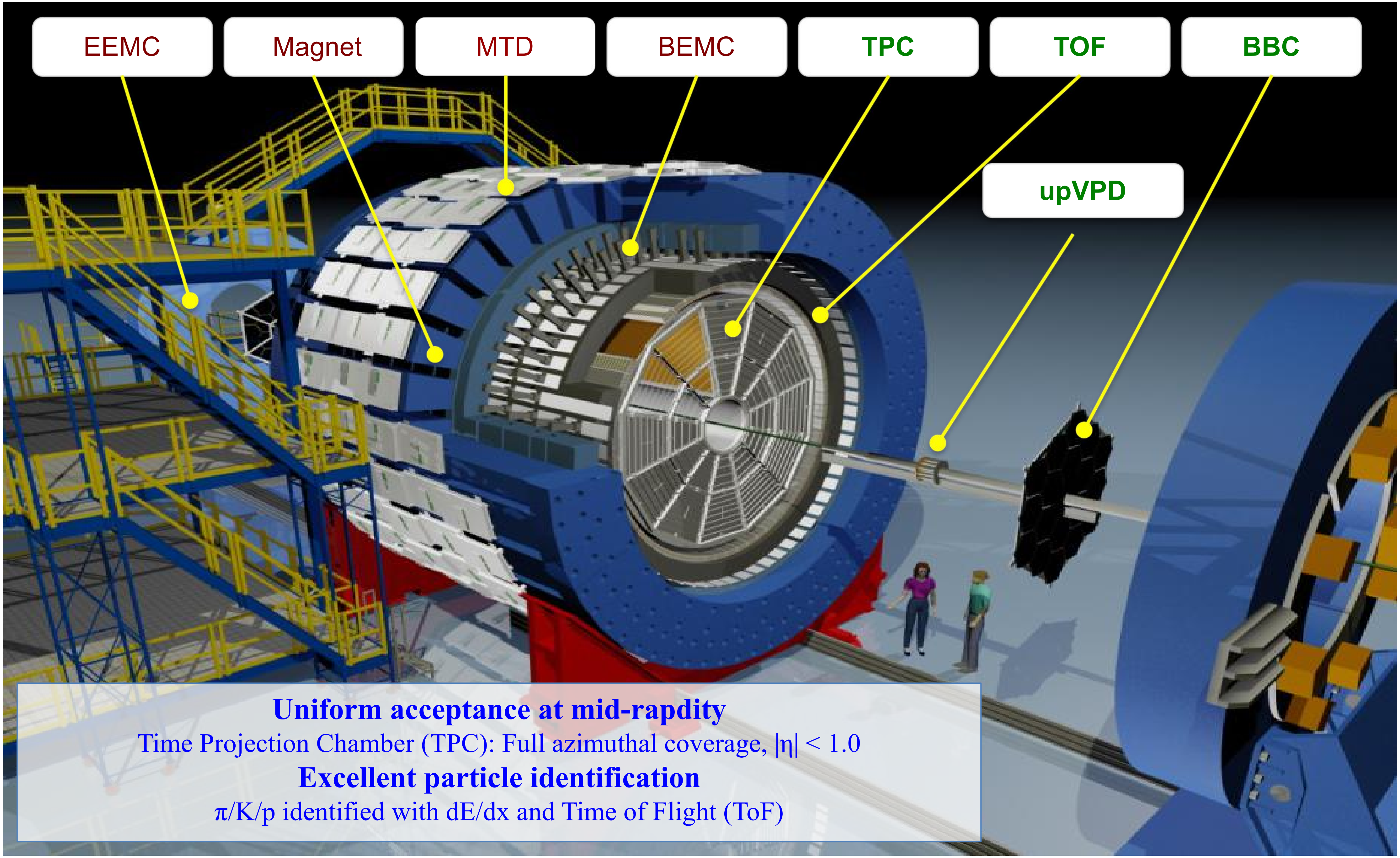
$$R = \sqrt{\langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle}$$

Event plane angle calculated in two sub-events A (0.05 < η < 1.0) and B (-1.0 < η < -0.05).



A.M. Poskanzer & S.A. Voloshin, Phys.Rev. C58 (1998)

STAR Experiment at RHIC



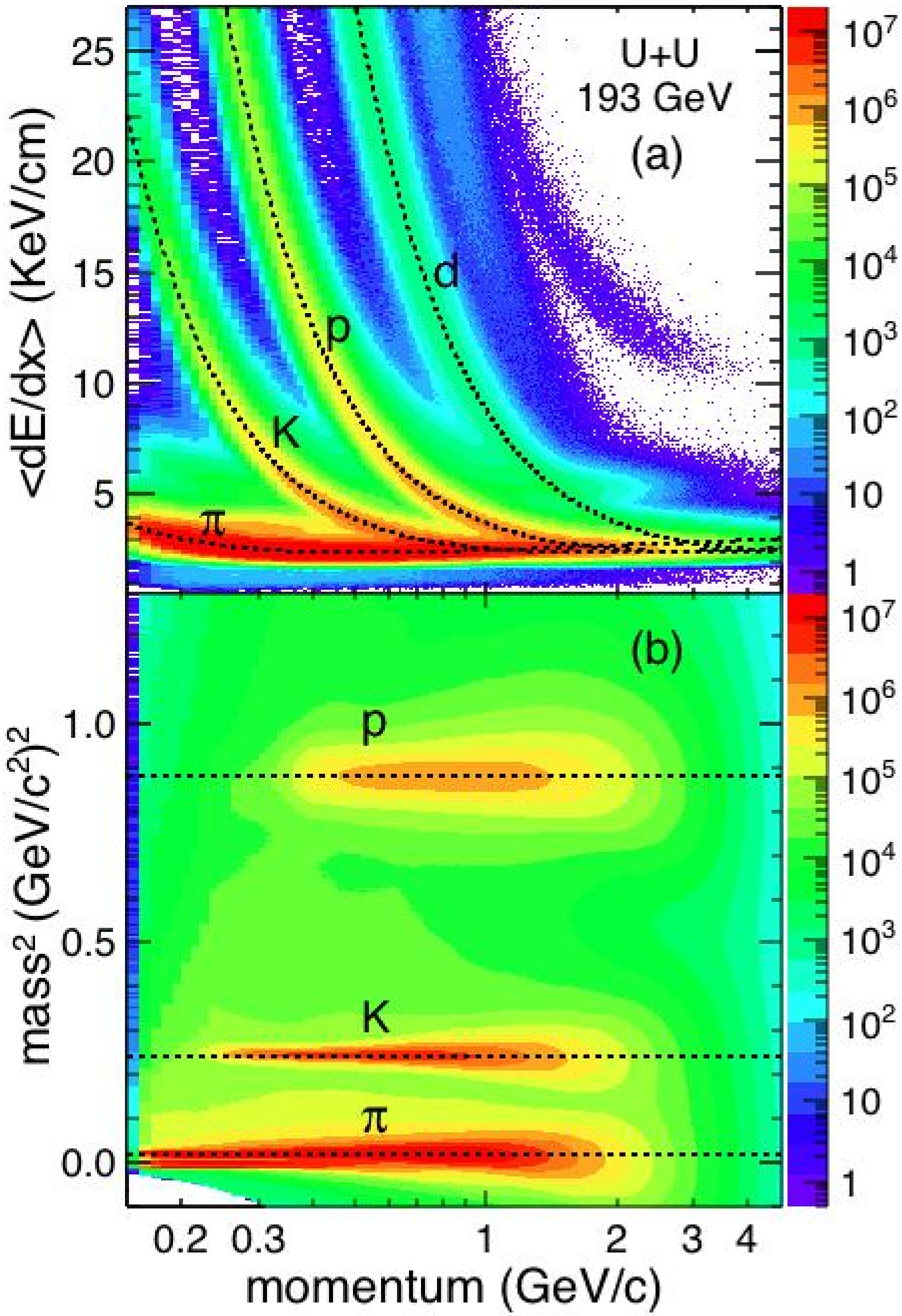
Uniform acceptance at mid-rapdity

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)

Particle Identification



Time Projection Chamber (TPC)

- dE/dx: specific energy loss
- dE/dx resolution (R_i) ≈ 7-8%

$$n\sigma_i = \frac{1}{R_i} log \frac{\langle dE/dx \rangle_{measured}}{\langle dE/dx \rangle_i^{Bichsel}}$$

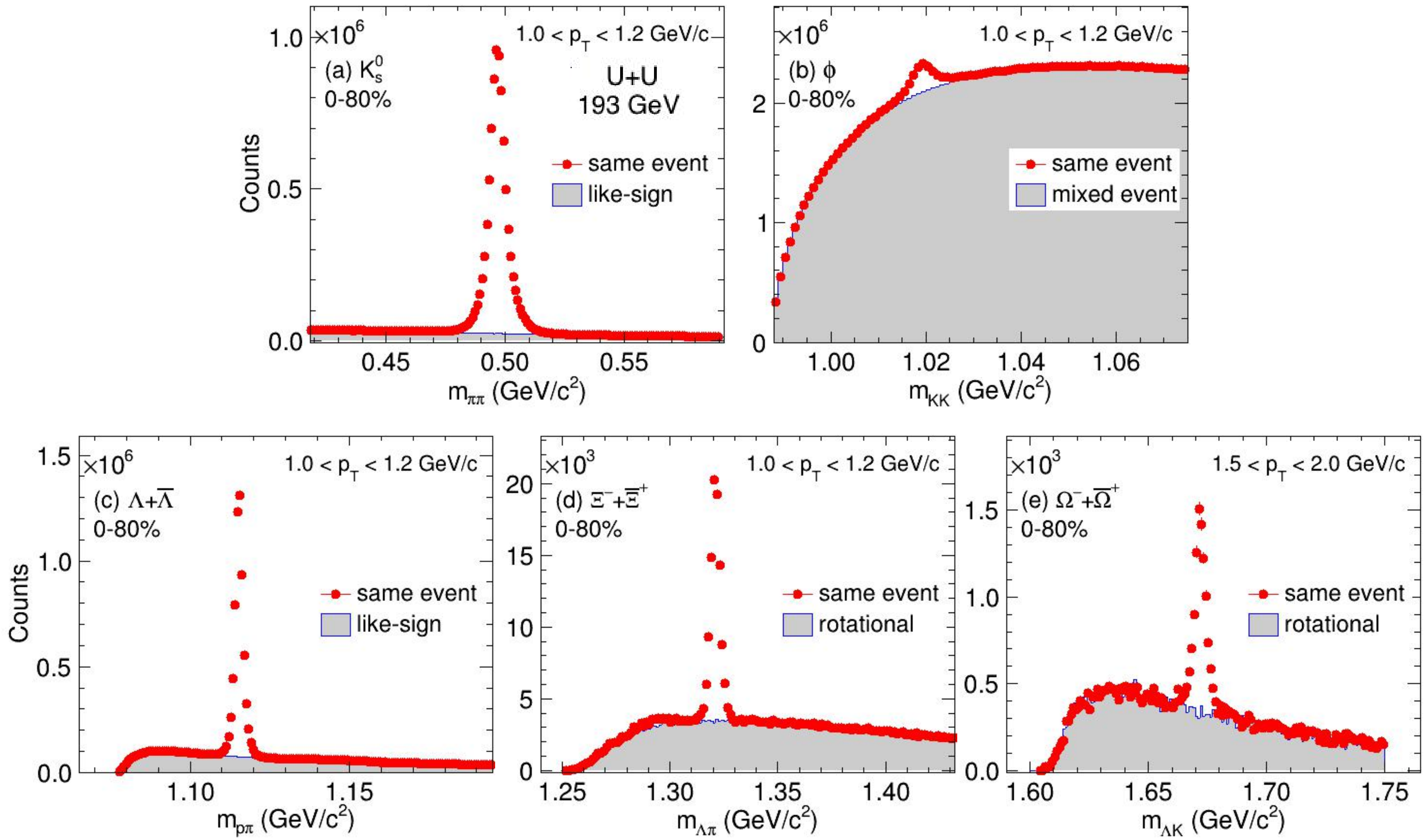
Time of Flight (TOF)

- β = Track length / arrival time
- Time of Flight resolution ≈ 100 ps

$$m^2 = p^2(1/\beta^2 - 1)$$

TPC: M. Anderson et al. Nucl. Instrum. Meth. A 499, 659 (2003); TOF: W. J. Llope et al. Nucl. Instrum. Meth. A 522, 252 (2004).

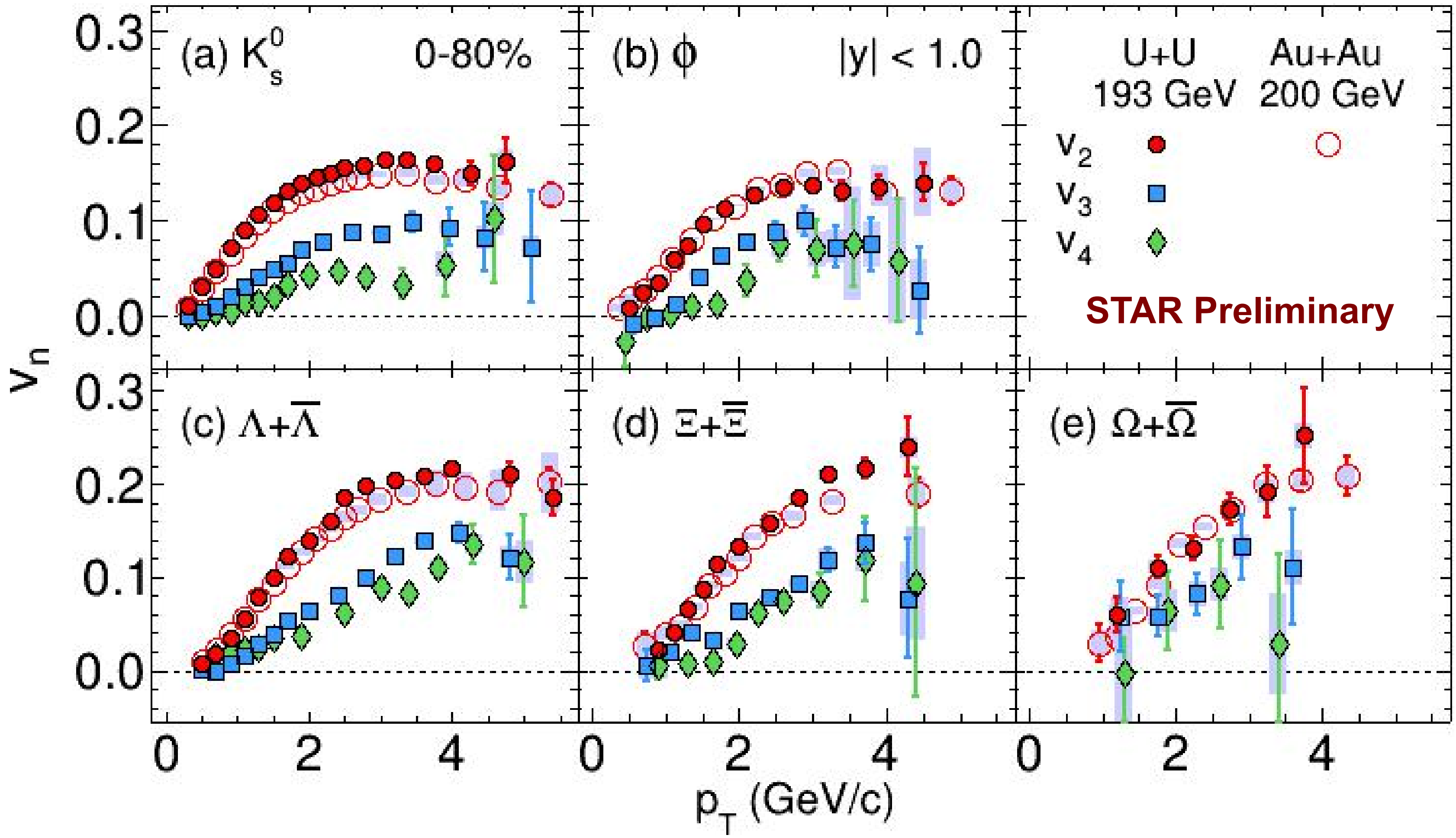
Particle Reconstruction



- Signal reconstruction using invariant mass technique: $\mathrm{M_{inv}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$
- Background reconstruction using various techniques: Event-mixing, like-sign and rotation.
- Weak decay particles are reconstructed using decay topoogy of their decay products.

Results

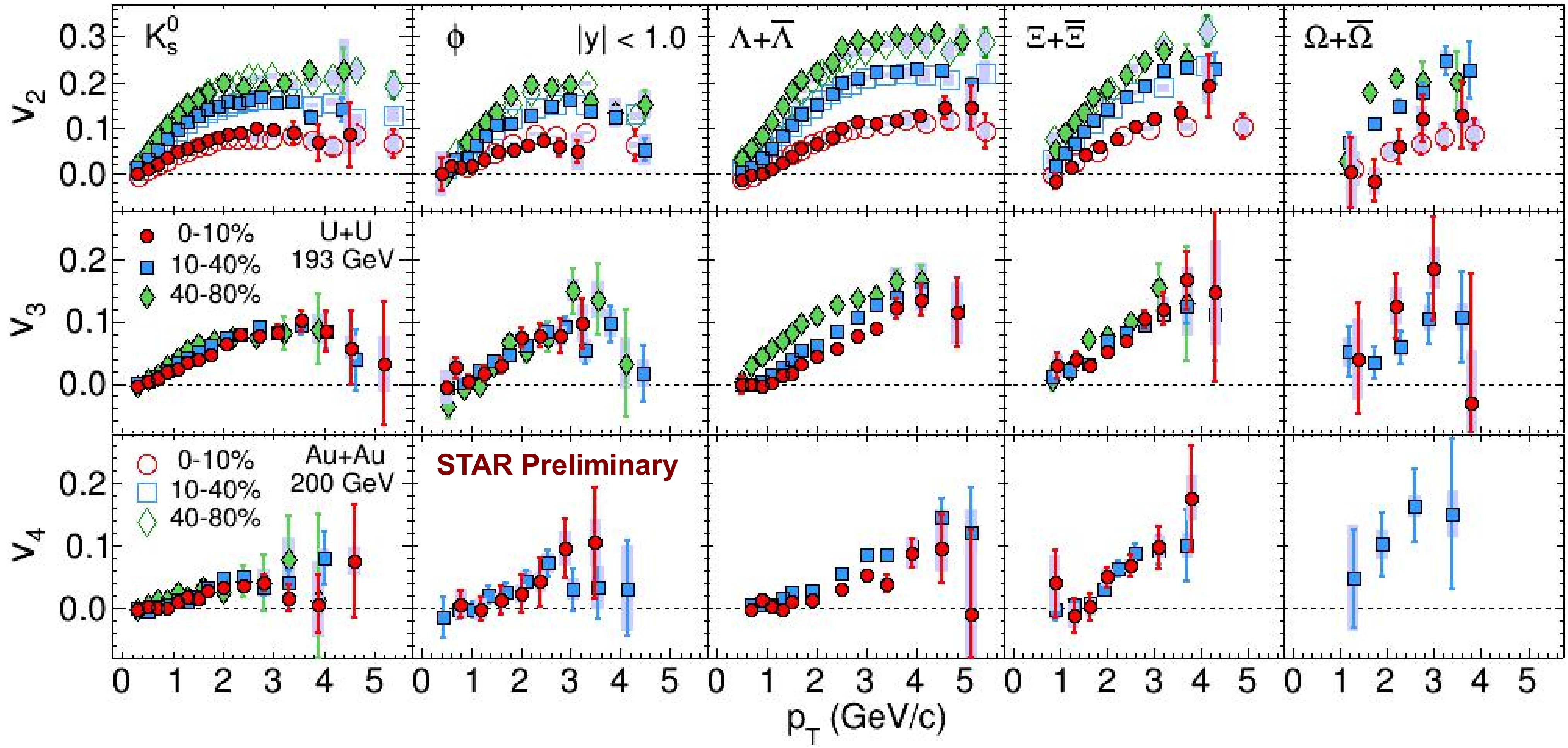
p_T evolution of flow harmonics: minimum bias (0-80%)



- For minimum bias (0-80%) U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV: $v_2 > v_3 > v_4$
- Similar order of elliptic flow v_2 between U+U and Au+Au collisions.
- Similar p_T dependence of v_2 in U+U and Au+Au collisions.

Au+Au 200 GeV: B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 77, 054901 (2008)

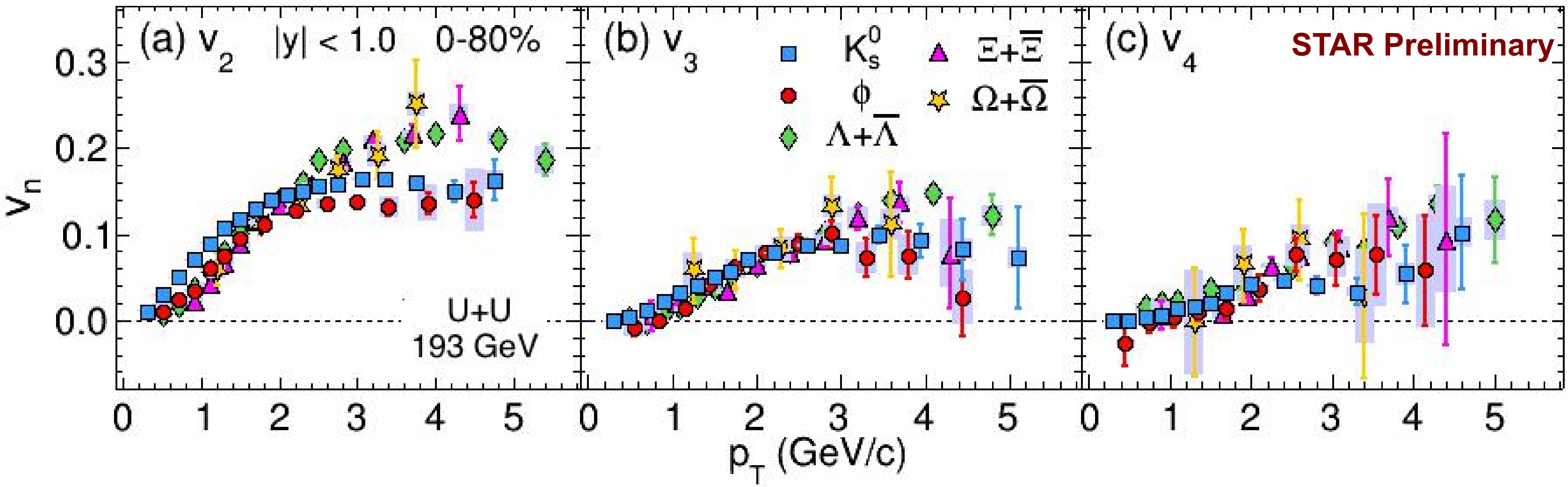
p_T evolution of flow harmonics: central (0-10%) vs. peripheral (40-80%) collisions



- Similary values of elliptic flow v_2 between U+U and Au+Au collisions for different centralities.
- Strong centrality dependence of v_2 in both U+U and Au+Au collisions.
- Higher order flow harmonics (v_3 and v_4) show a weak centrality dependence in U+U collisions.

Au+Au 200 GeV: B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 77, 054901 (2008)

Particle mass dependence of flow harmonics



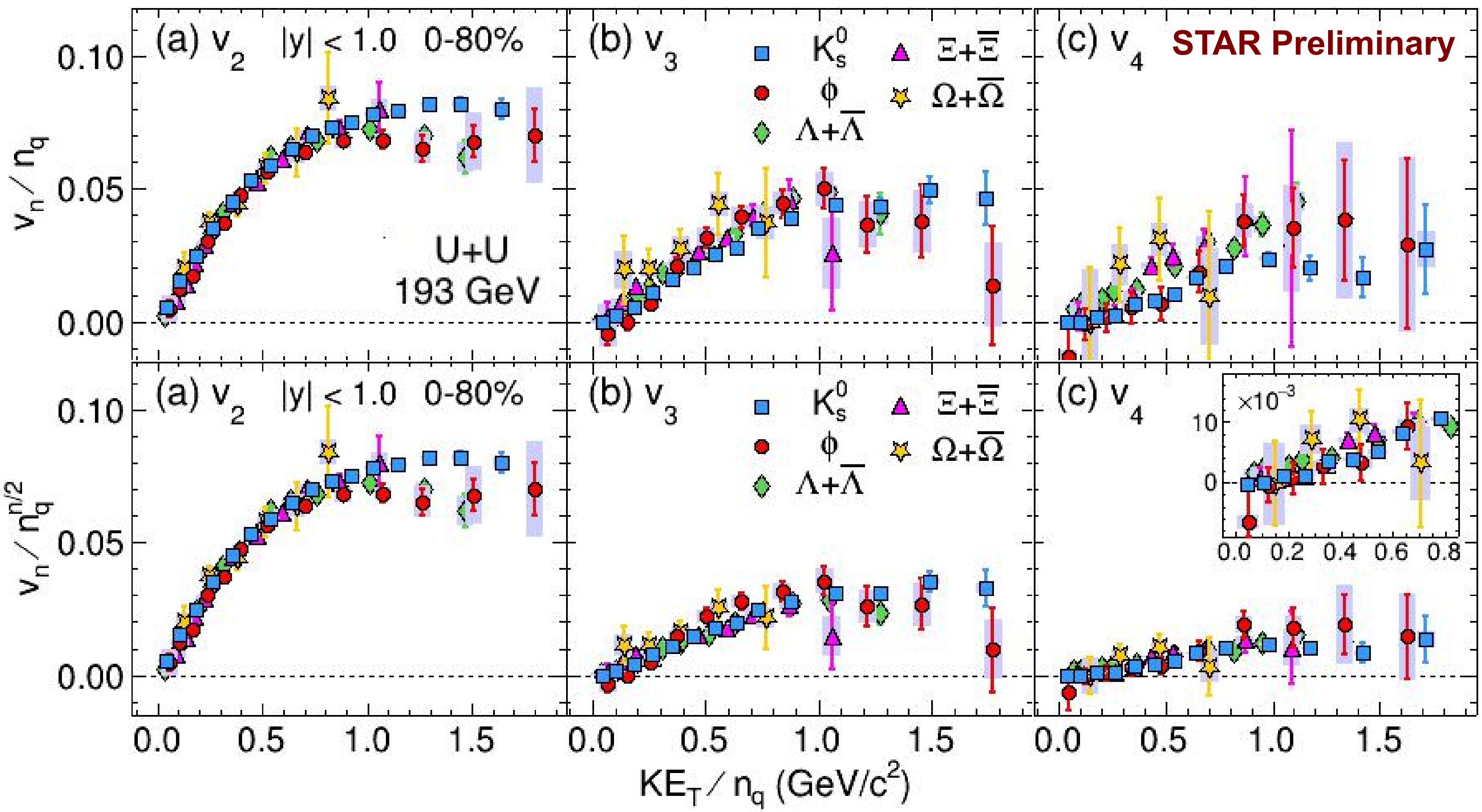
Elliptic flow (v_2):

- p_T < 2.5 GeV/c : Mass ordering of v_2 indicates effect of radial flow.
- p_T > 2.5 GeV/c : Baryon-Meson grouping of v_2 indicates parton coalescence mechanism.

Higher flow harmonics (v_3, v_4):

- p_T < 2-3 GeV/c : Mass ordering within statistical and systematic uncertainties.
- p_T > 3 GeV/c : Baryon-Meson grouping within statistical and systematic uncertainties.

NCQ scaling



Intermediate p_T (p_T > 2.5 GeV/c): v_n of baryons > v_n of mesons

NCQ scaling ➡ Quark coalescence as particle production mechanism.

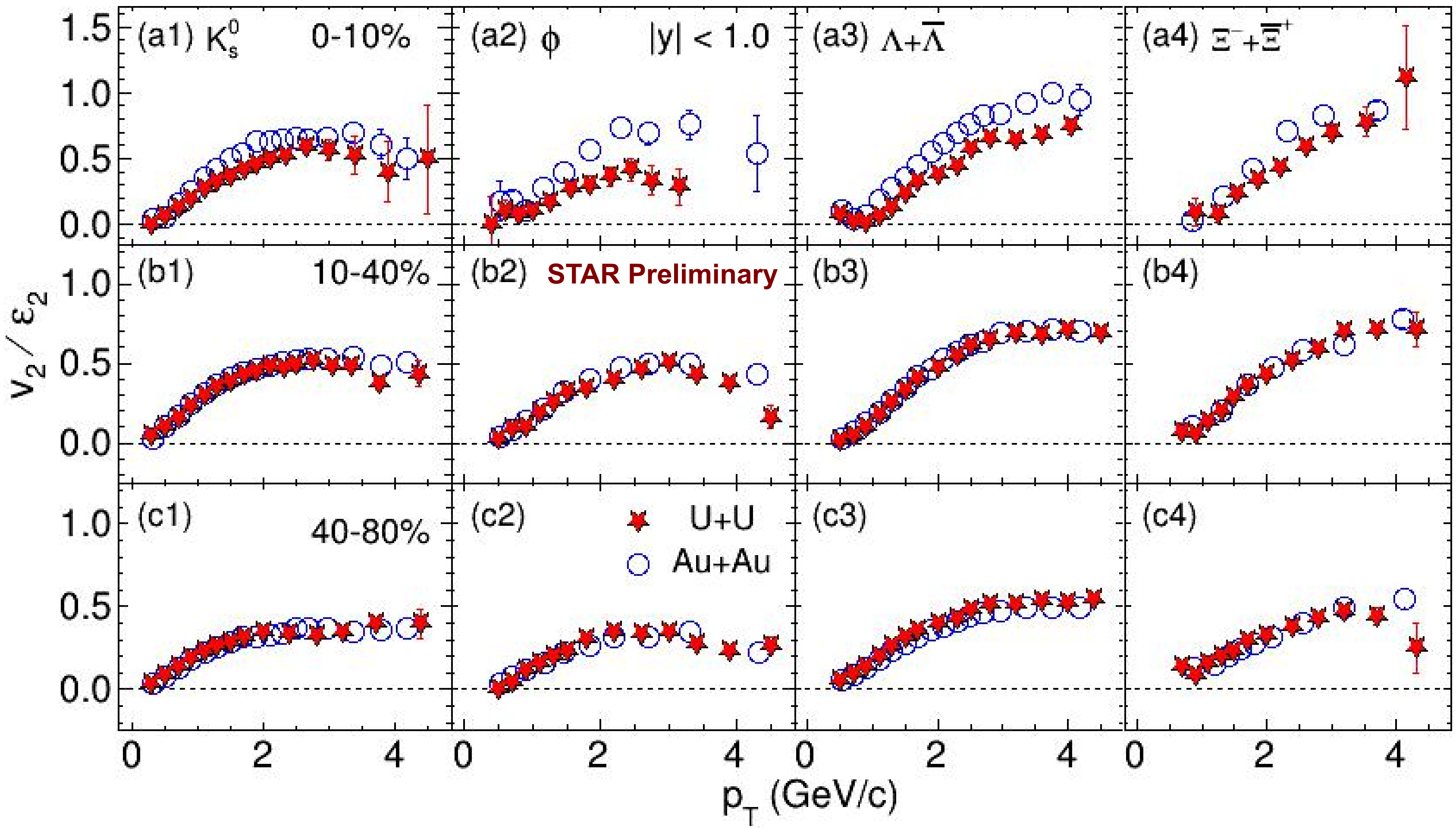
- **Elliptic flow:** v_2 / n_q follows a single curve for all particles studied. Athough there seems to be a deviaton from the NCQ scaling at KE_T/n_q > 1 GeV/c².
- **Higher flow harmonics:** Approximate scaling for v_3 and v_4
- Modified scaling works v_n / $n_q^{(n/2)}$ well for all flow harmonics.

n_q : Number of constituent quarks

$KE_T = m_T - m_0$ and

$m_T = \sqrt{(p_T^2 + m_0^2)}$

Eccentricity scaling: UU vs. AuAu



Most central collisions (0-10%):

- Higher values of v_2/ε_2 for Au+Au collisions compared to U+U collisions.

Mid-central (10-40%) and peripheral collisions (40-80%):

- Similar values of v_2/ε_2 in both U+U and Au+Au collisions.

Au+Au 200 GeV: B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 77, 054901 (2008)

Model Comparisons

Hydrodynamic Model

- Event-by-Event 3+1 dimensional hydrodynamic calculation.
- Lattice QCD equation of state.
- Ideal-hydrodynamic ($\eta/s = 0$).

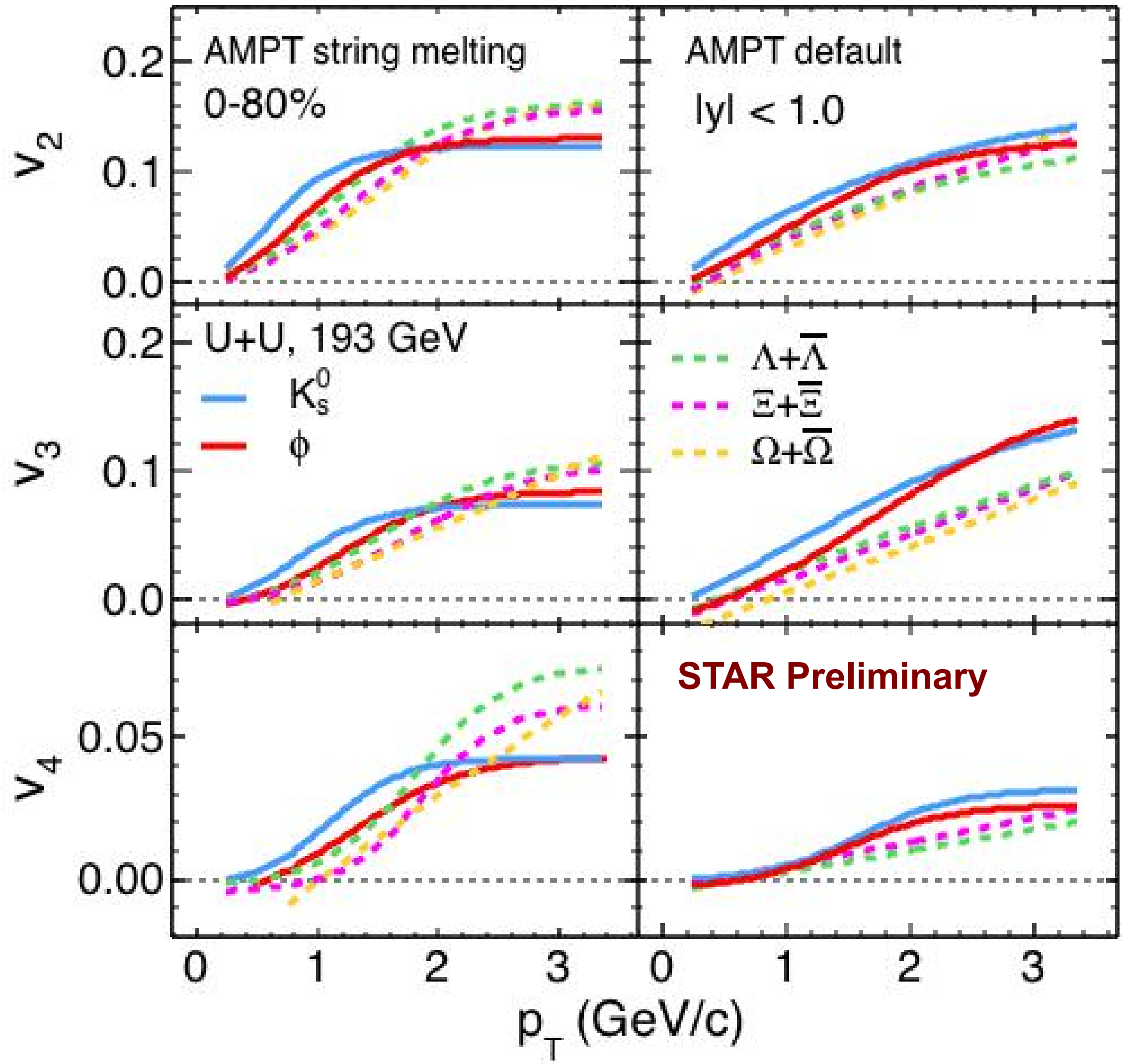
V. Roy, Private Communication (NISER, India)

Transport Model (AMPT)

- AMPT string melting:
  - quark coalescence with hadronic rescattering.
  - parton-parton cross section (3mb).
- AMPT default: No quark coalescence.

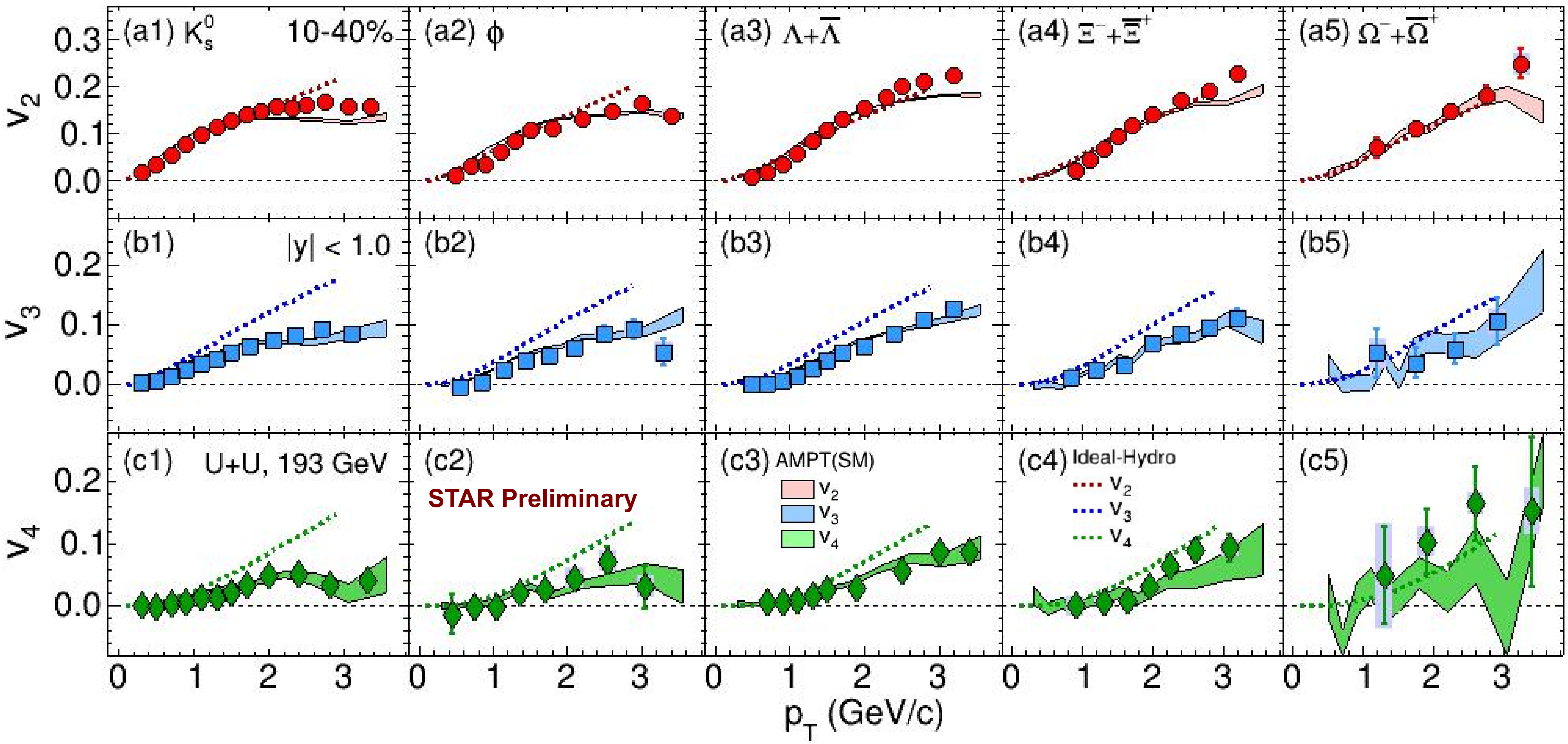
Z. W. Lin et. al. Phys. Rev. C 72, 064901 (2005), arXiv:nucl-th/0411110.

AMPT model: String Melting vs. Default



- Distinct mass ordering in low p_T region:
  - Effect of hadronic rescattering in development of radial flow.
- Baryon-meson grouping in intermediate p_T region:
  - Effect of quark coalescence.

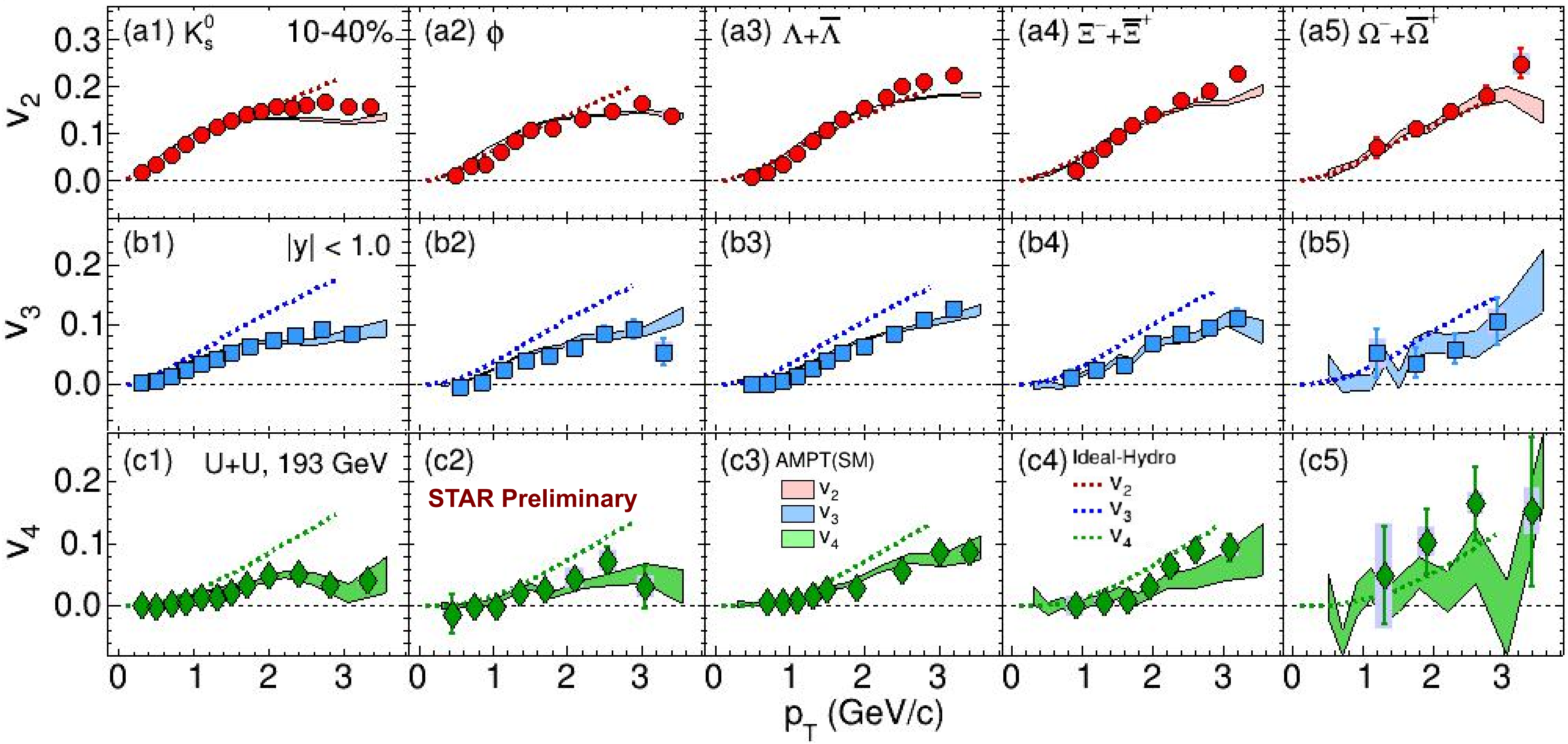
Hydrodynamic and AMPT model



AMPT (SM) model (3mb parton-parton cross-section):

- Reproduces both the mass ordering and baryon-meson grouping at low and intermediate p_T for all harmonics for U+U collisions at RHIC.

Hydrodynamic and AMPT model



Hydro model:

- Reproduces mass ordering of v_2, v_3 and v_4 for $p_T < 2$ GeV/c in U+U collisions.
- Over-estimate v_n mesurements which shows need of viscous corrections to the model.
- v_2 values are more closer compared to v_3 and v_4 which shows more sensitivity of higher order flow harmonics on η/s.

Summary

- Azimuthal anisotropy coefficients v_n (n = 2,3,4) for strange and multi-strange hadrons have been studied and compared between U+U and Au+Au collisions at $\sqrt{s_{NN}}$ = 193 GeV and 200 GeV at RHIC.

- Strong centrality dependence for elliptic flow (v_2) is observed in U+U collisions similar to Au+Au collisions. A weak centrality dependence is observed for higher order flow coefficients (v_3, v_4).

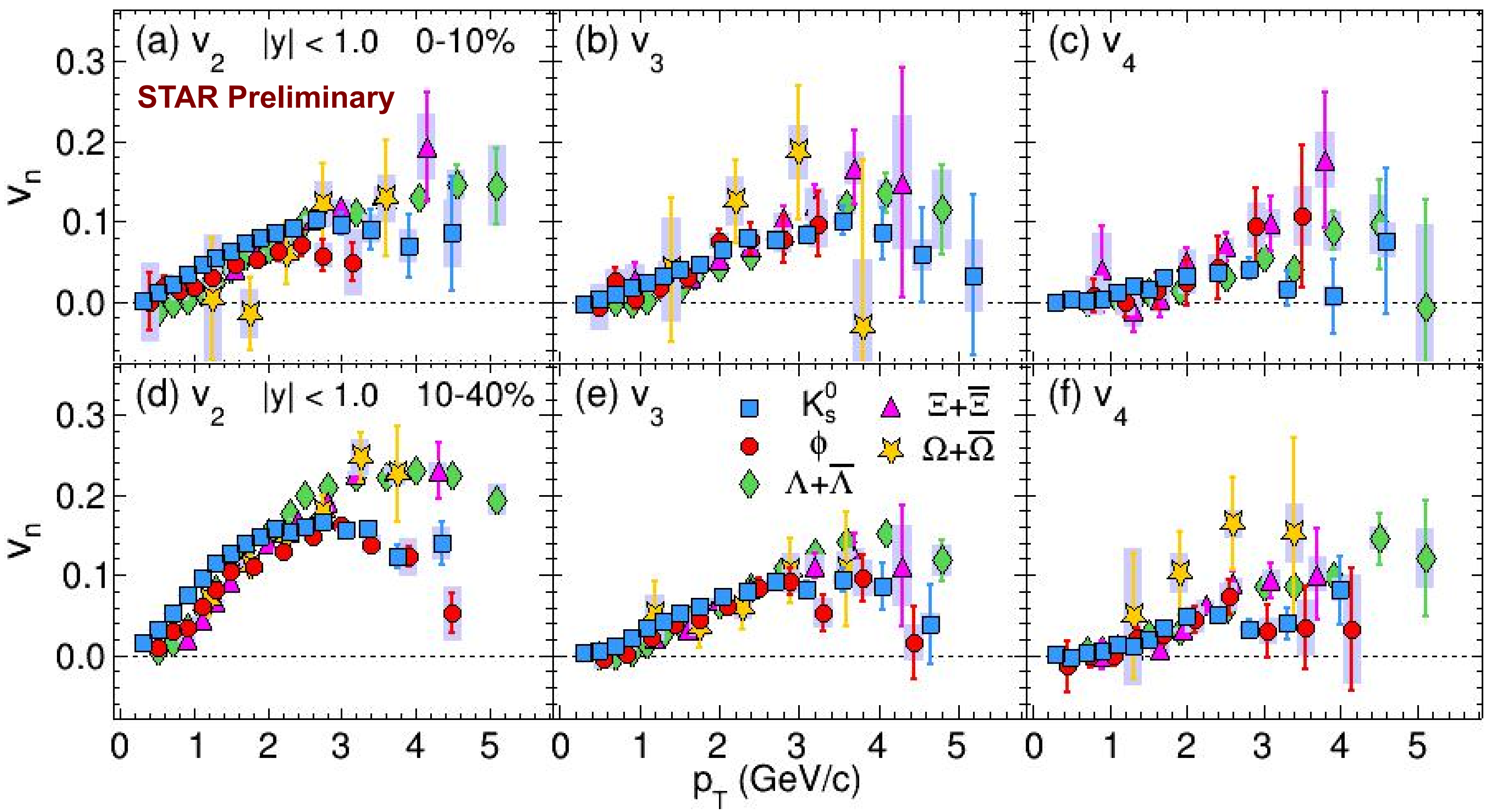
- Mass ordering of v_2, v_3 and v_4 at low p_T ($p_T < 2.5$ GeV/c) is observed in U+U collisions. AMPT model with string melting shows similar mass ordering of v_n and describe the data.

- Flow coefficients (v_n) divided by powers of number of constituent quarks follow a single curve within uncertainties in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV.

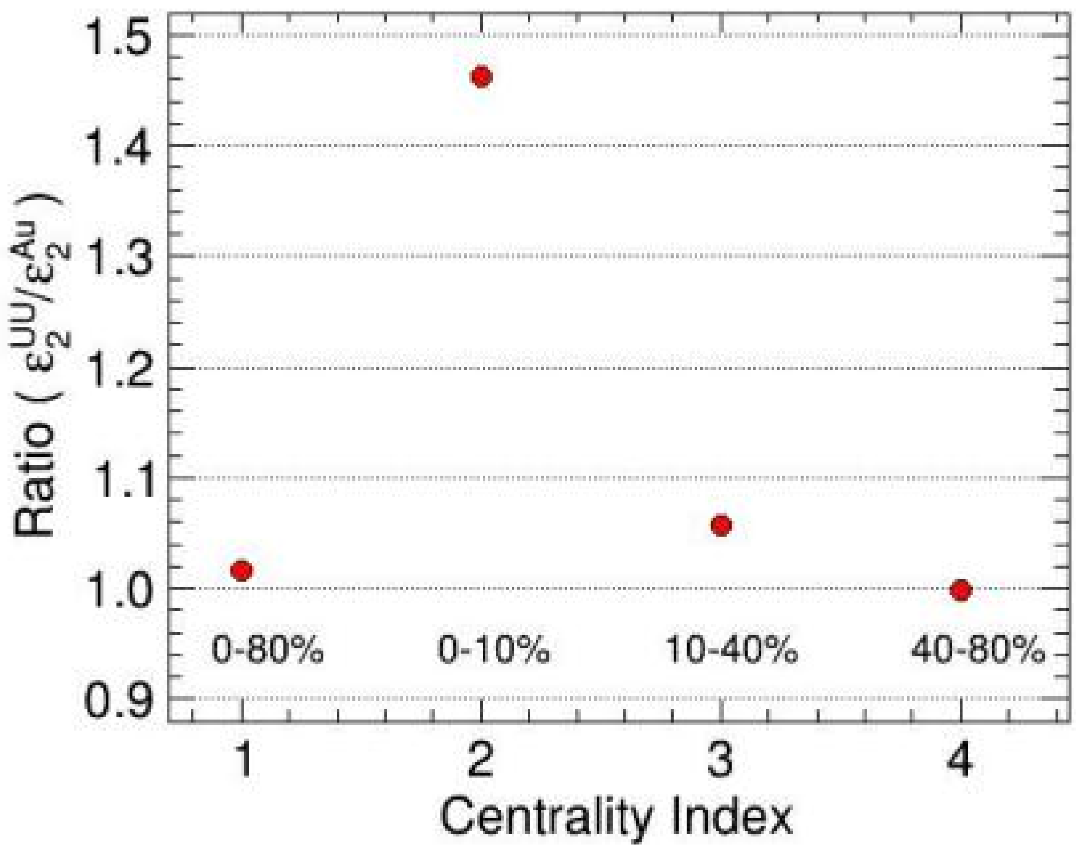
Thank you!

Backup

Particle mass dependence of flow harmonics: 0 - 10% and 10 - 40%



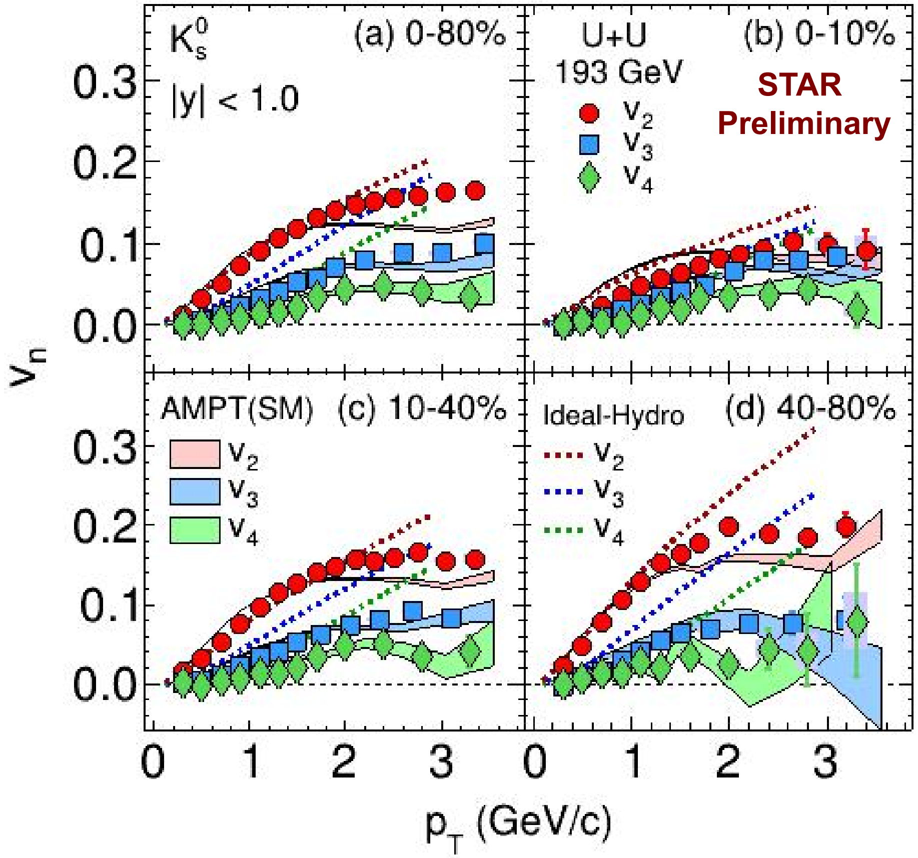
Eccentricity Ratio: UU and AuAu

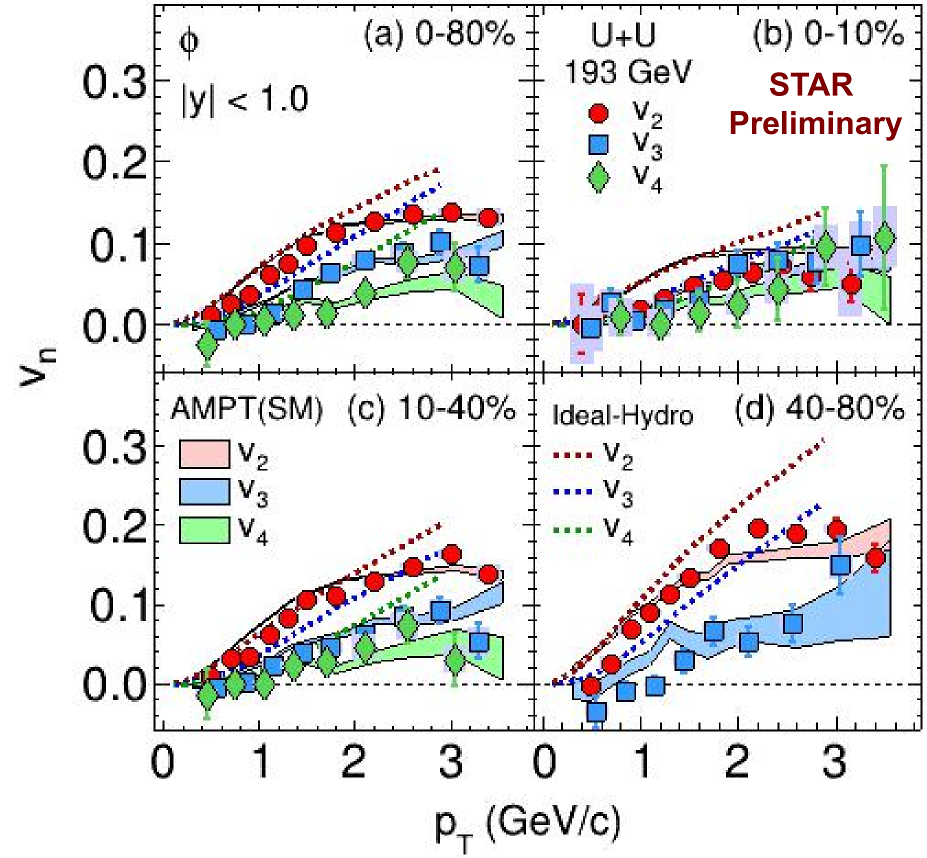


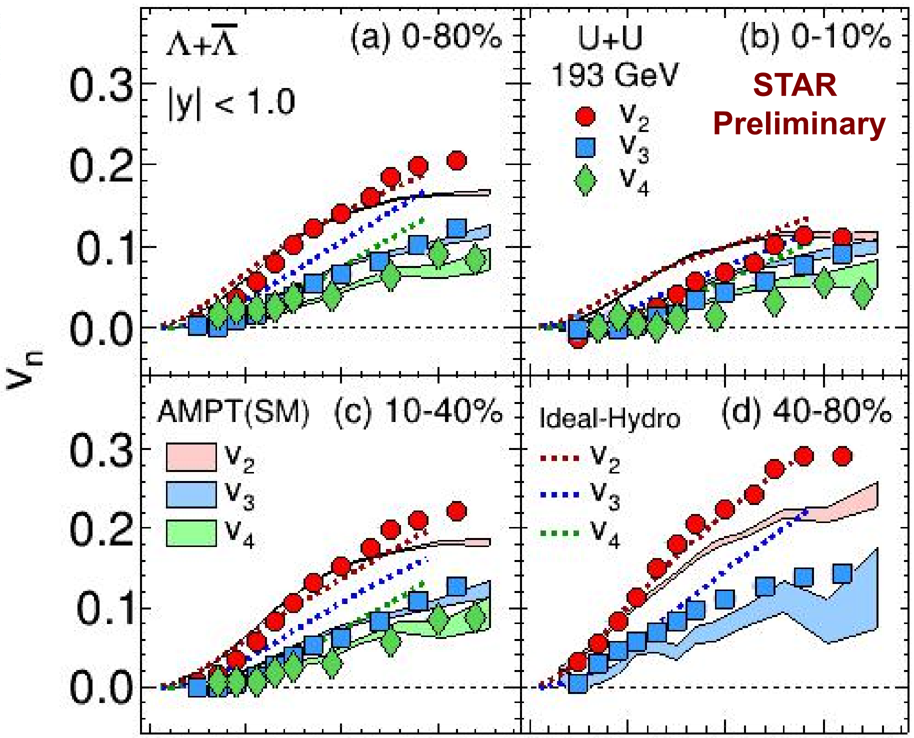
Glauber Eccentricity ε_2

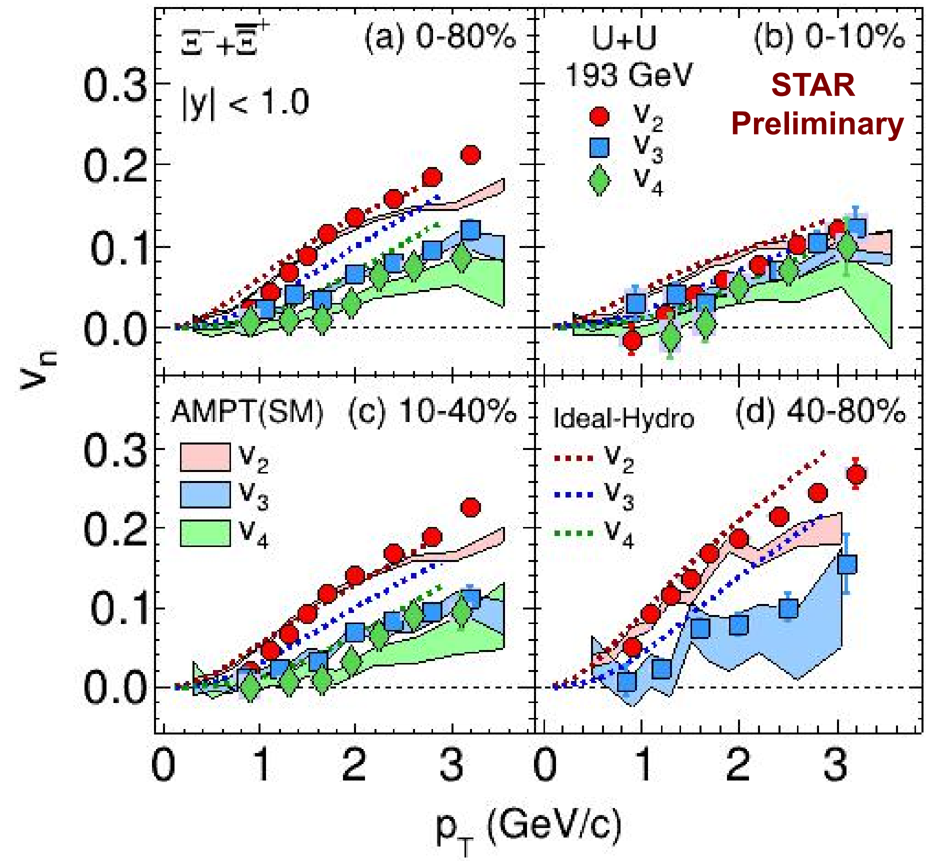
Centrality	UU	AuAu	Ratio (UU/Au)
0-80%	0.4497	0.4428	1.0156
0-10%	0.1725	0.1179	1.4631
10-40%	0.3237	0.3060	1.0578
40-80%	0.5668	0.5678	0.9982

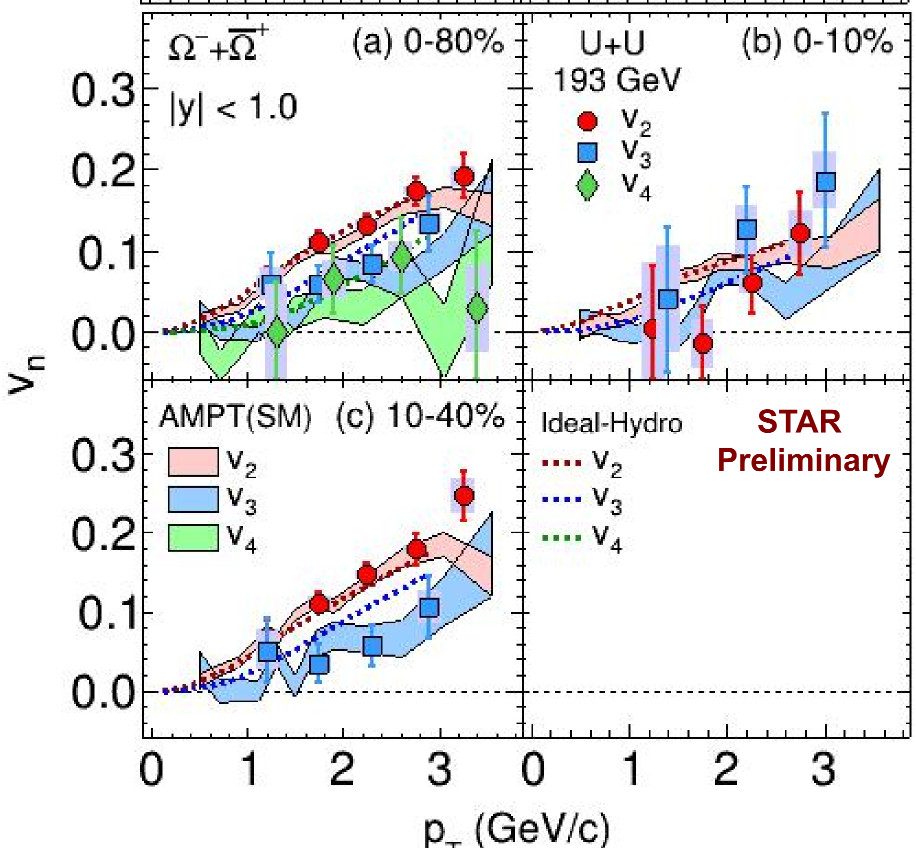
Model Comparisons






Λ+Λ̄
|y| < 1.0
(a) 0-80%
U+U
193 GeV
(b) 0-10%
STAR
Preliminary
v2
v3
v4
AMPT(SM)
(c) 10-40%
Ideal-Hydro
(d) 40-80%
0.0
0.1
0.2
0.3
vn


Ξ⁻+Ξ̄⁺
|y| < 1.0
(a) 0-80%
U+U
193 GeV
(b) 0-10%
STAR
Preliminary
v2
v3
v4
AMPT(SM)
(c) 10-40%
Ideal-Hydro
(d) 40-80%
0.0
0.1
0.2
0.3
vn
0
1
2
3
pT (GeV/c)


Ω⁻+Ω̄⁺
|y| < 1.0
(a) 0-80%
U+U
193 GeV
(b) 0-10%
v2
v3
v4
AMPT(SM)
(c) 10-40%
Ideal-Hydro
STAR
Preliminary
0.0
0.1
0.2
0.3
vn
0
1
2
3
pT (GeV/c)