Elliptic flow for multi-strange hadrons as penetrating probes at RHIC

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Outline

- Introductions
  - Elliptic flow
  - Why multi-strange hadrons ?
- Latest STAR results in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - Number of constituent quark (NCQ) scaling
  - Violation of mass ordering between ϕ meson and proton
- Hybrid hydrodynamical model calculations
- Summary

I would like to thank Shiori Takeuchi and Tetsufumi Hirano for allowing me to present their recent hydrodynamical model calculations

Azimuthal anisotropy

$$\frac{dN}{d\phi} \sim 1 + 2v_1 \cos(\phi - \Psi_1) + 2v_2 \cos(2[\phi - \Psi_2]) + 2v_3 \cos(3[\phi - \Psi_3]) + \cdots,$$

$$v_2 = \langle \cos(2[\phi - \Psi_2]) \rangle$$

- Azimuthal anisotropy
  - Fourier expansion of azimuthal distribution with respect to the reaction plane
  - Fluctuation of constituents (nucleons or partons) → participant plane
    - Reaction plane ≠ participant plane
- Elliptic flow - v_2
  - Final state momentum anisotropy, 2nd harmonic coefficient
  - not necessary to describe collective hydrodynamic flow
  - 2 particle correlation is the most popular method

v_2^r

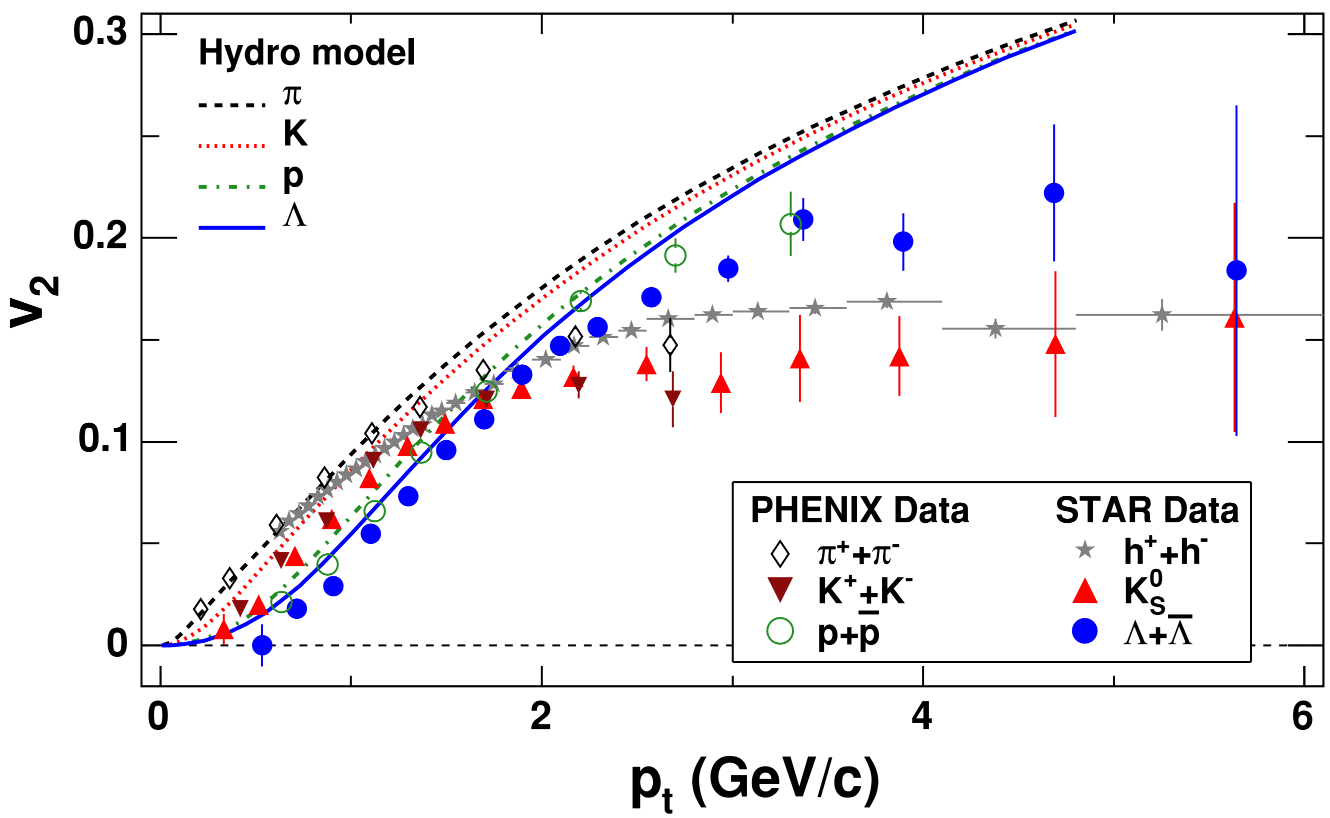
$$v_2^{\mathrm{obs}} = \langle \cos(2\phi - 2\phi_r) \rangle = v_2 \cdot \boxed{\langle \cos(2\phi_r - 2\Psi_2) \rangle}$$

$$v_2^{\mathrm{obs}} = \langle \cos(2\phi - 2\Phi_2) \rangle = v_2 \cdot \boxed{\langle \cos(2\Phi_2 - 2\Psi_2) \rangle}$$

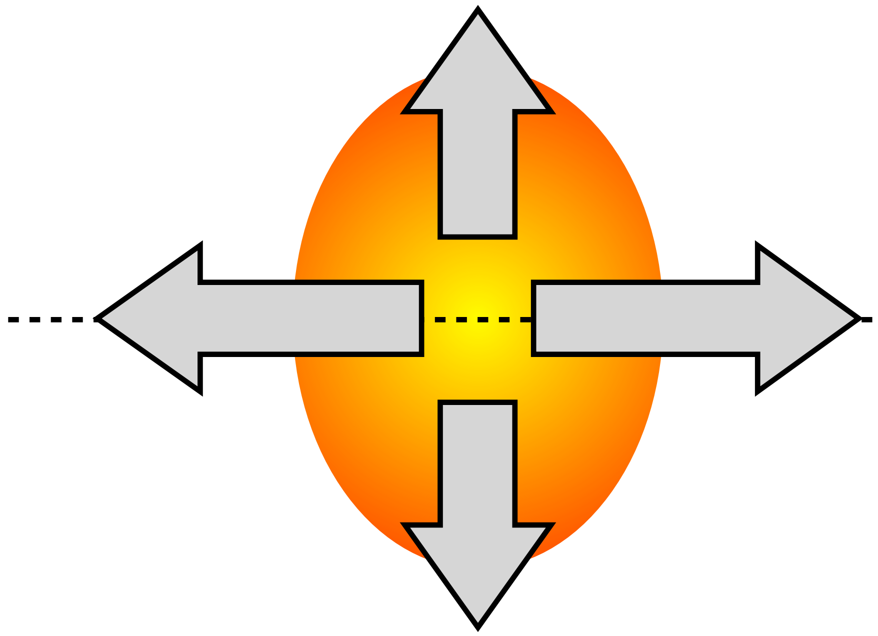
event plane resolution

Mass ordering of v_2 - radial flow

STAR: **Phys. Rev. C72**, 014904 (2005)



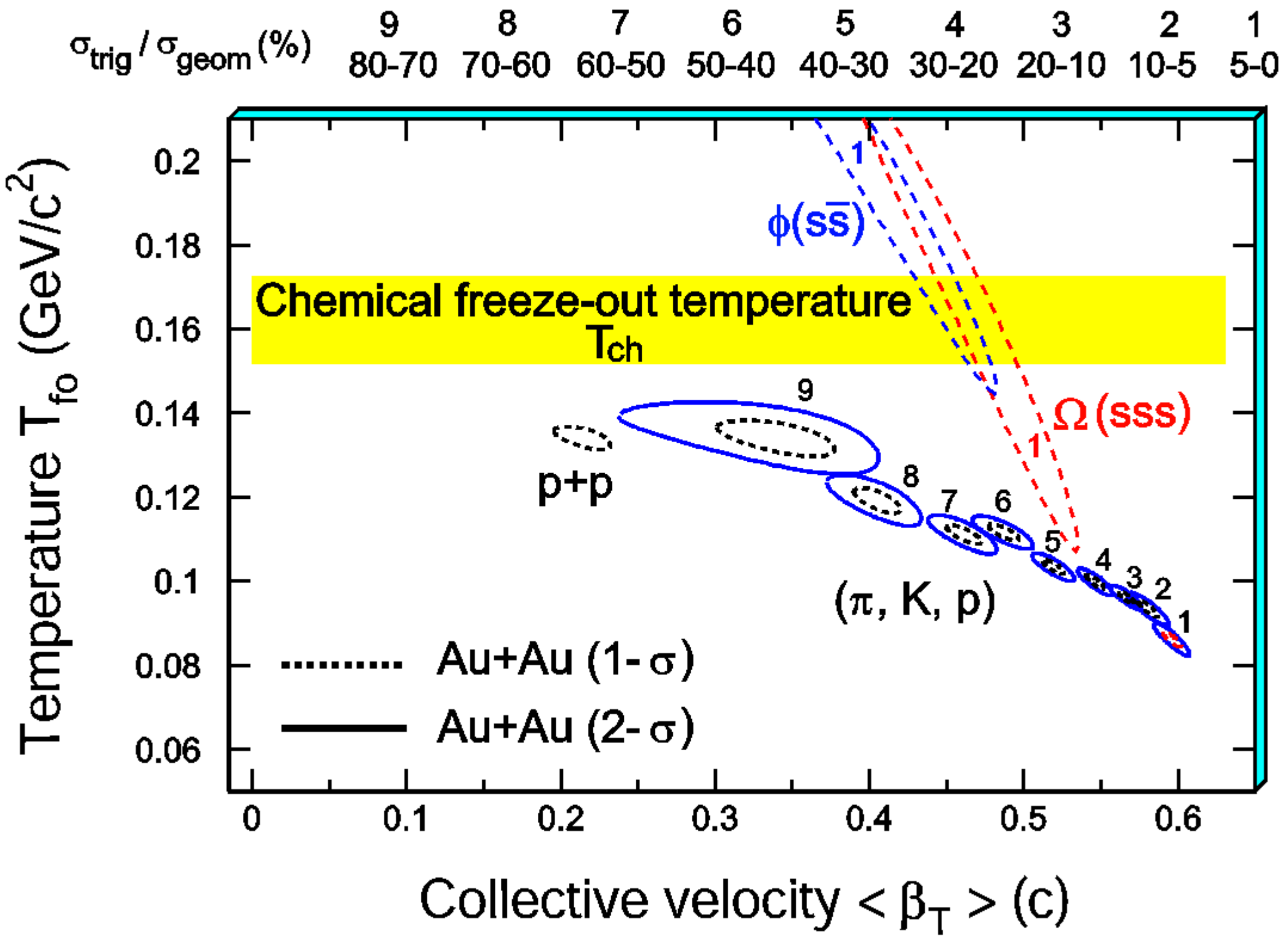
$$T_{\rm eff} = T_{\rm fo} + m_0 \langle \beta_T \rangle^2$$



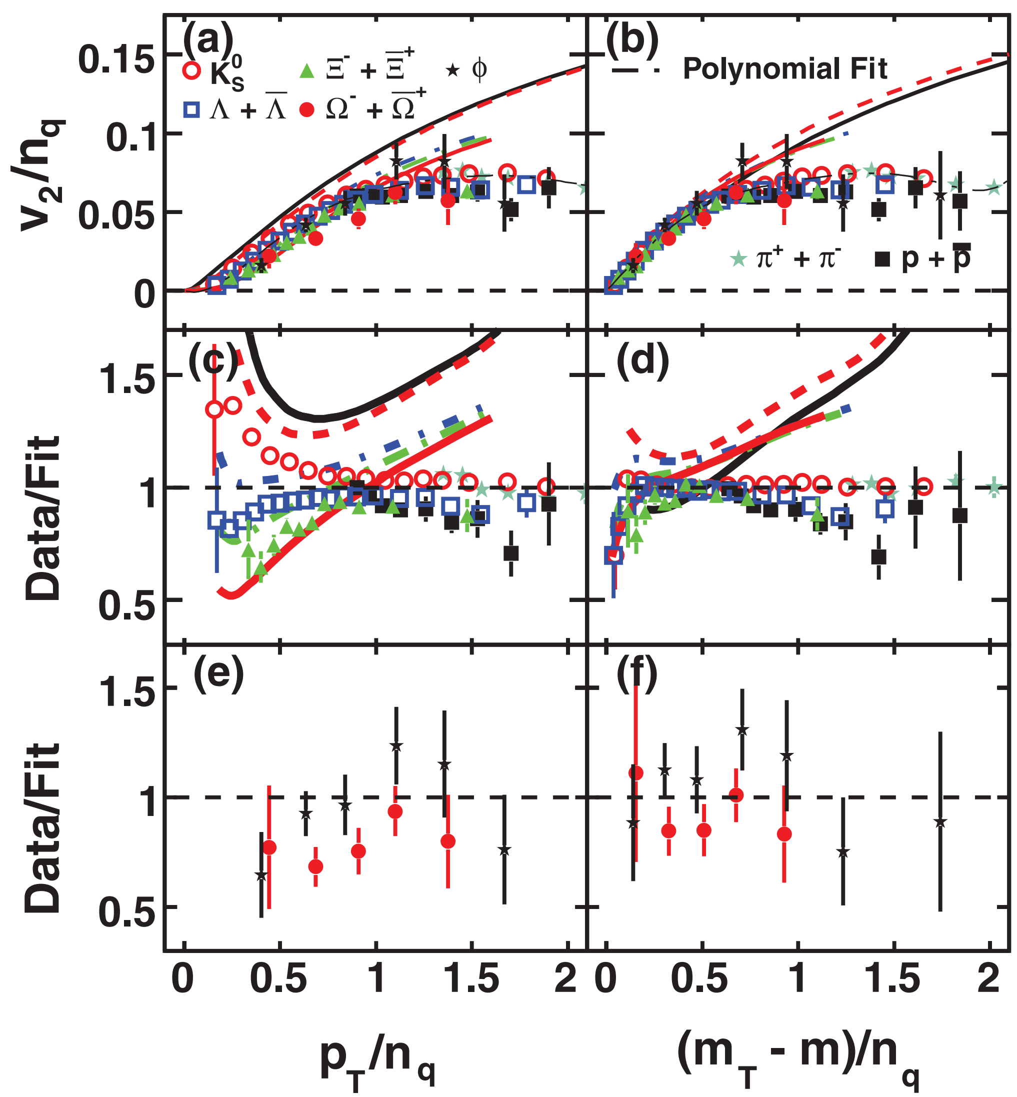
- Radial flow pushes heavier hadrons to higher p_T
  - Inverse slope ($T_{\rm eff}$) of p_T spectra depends on mass linearly
  - Due to the geometry deformation, hadrons around participant plane are pushed more than those around out-of-plane
  - v_2 decreases at low p_T, and the effect is stronger for heavier hadrons
  - ➡ Mass ordering of v_2

Why multi-strange hadrons ?

STAR White paper: **Nucl. Phys. A757** (2005) 102-183



STAR: **Phys. Rev. C77**, 054901 (2008)

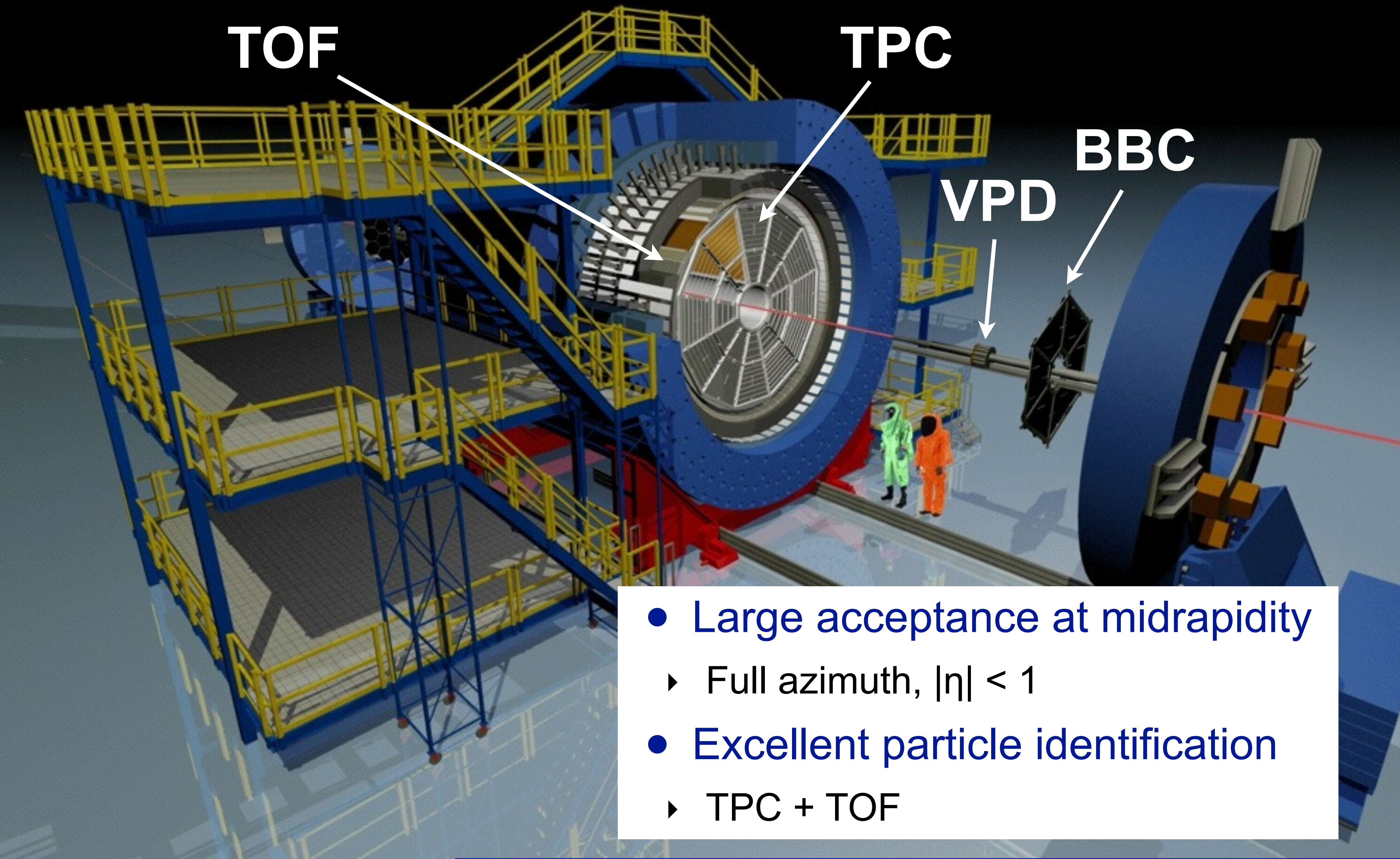


- Blast-wave model fit for p_T spectra support early freeze-out of multi-strange hadrons: $T_{fo} \sim T_{ch}$
  - probe to collectivity in early partonic stage of heavy ion collisions
- Statistics is limited in previous data to study the number of constituent quark (NCQ) scaling

Motivations

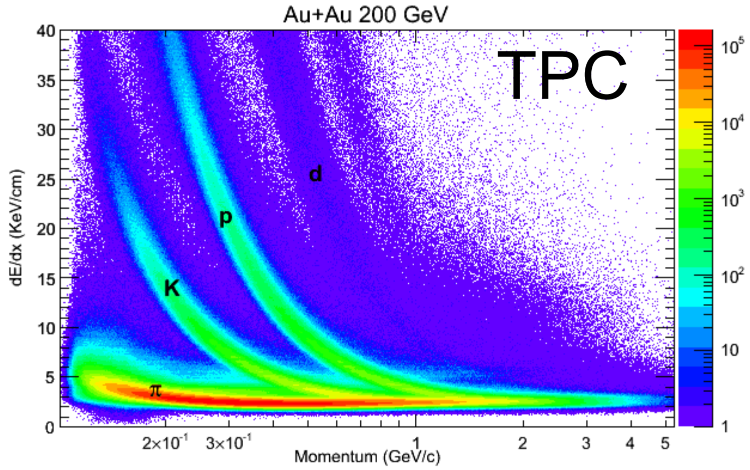
- v_2 for multi-strange hadrons is a good probe to partonic collectivity
  - Multi-strange hadrons freeze-out earlier than others
  - ➡ less hadronic rescattering (less radial flow effect)
  - ➡ penetrating probe to study partonic stage
  - Powerful tool to study NCQ scaling of v_2
  - We can also study the effect of hadronic rescattering on v_2 by comparing ϕ meson with proton
- Statistics is limited in previous data set
  - We have huge amount of data in year 2010 & 2011
  - In addition, particle identification will be improved with fully installed MRPC-TOF detector

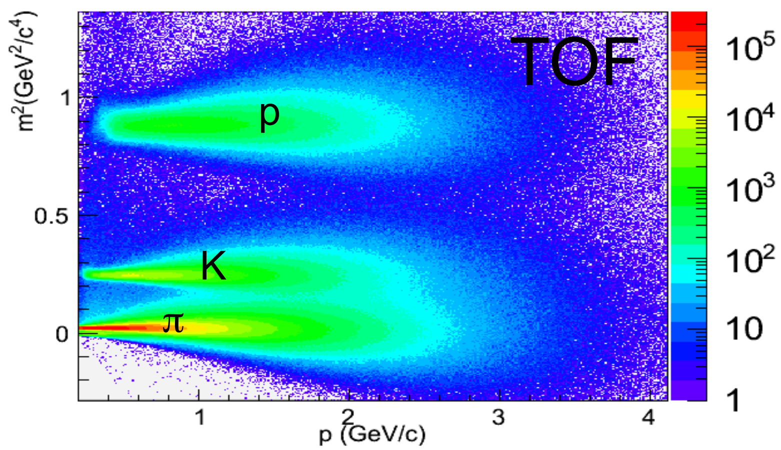
STAR experiment

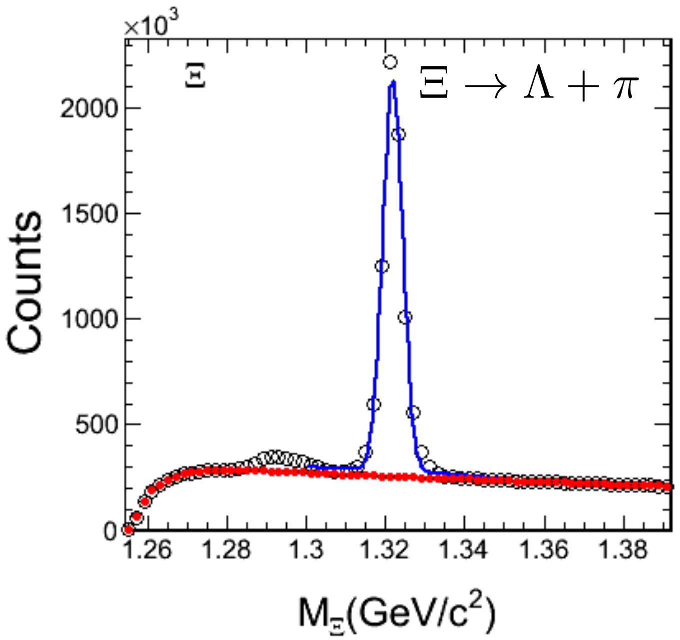


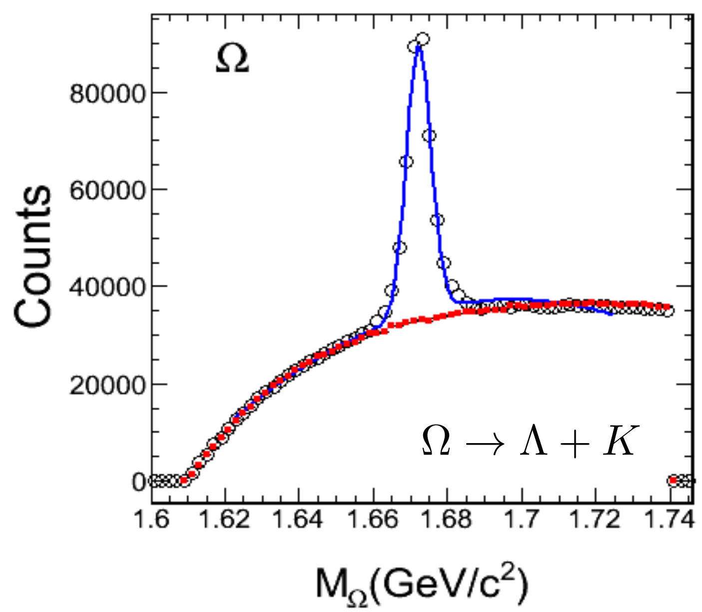
- Large acceptance at midrapidity
  - Full azimuth, $|\eta| < 1$
- Excellent particle identification
  - TPC + TOF

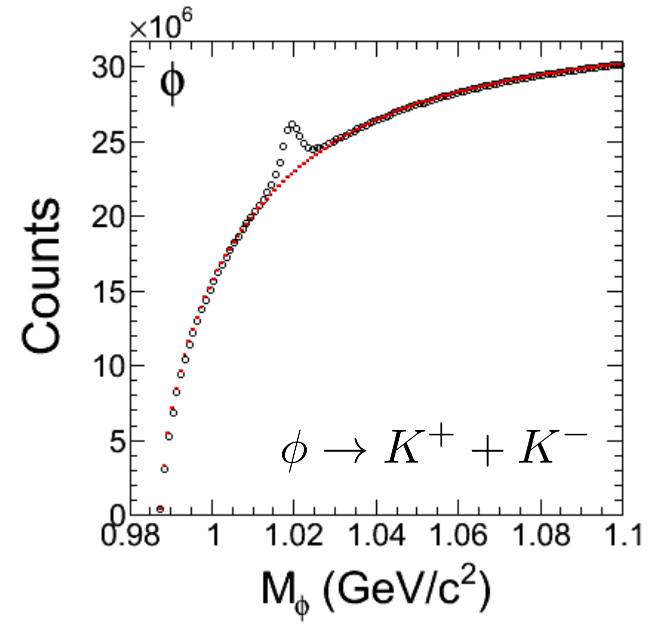
Particle identifications





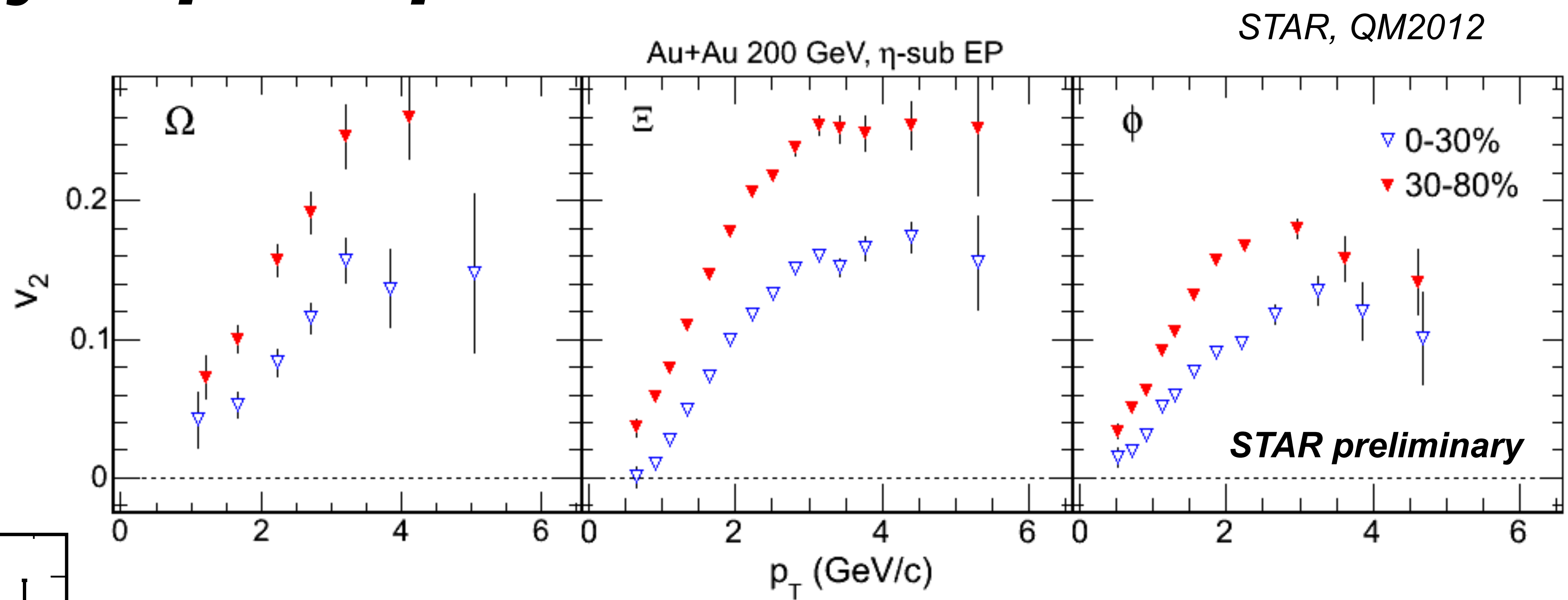


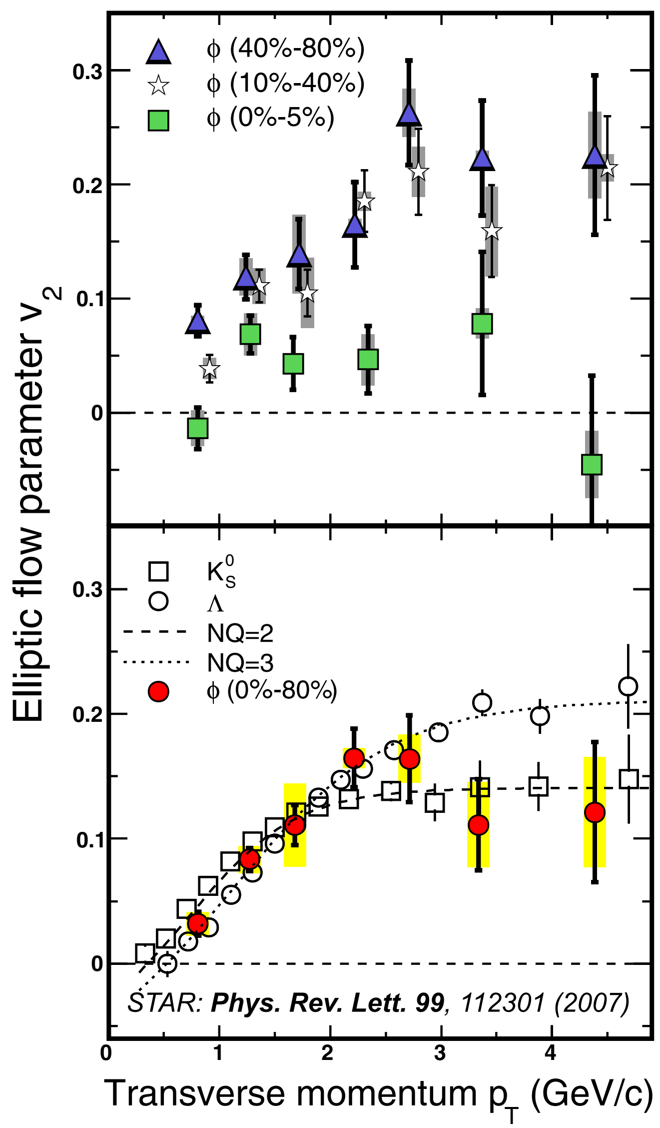




- Topological reconstruction of Ξ and Ω weak decay
  - reduce combinatorial backgrounds
- Calculate invariant mass
  - Combinatorial background is estimated by rotational background from the same event

Centrality & p_T dependence



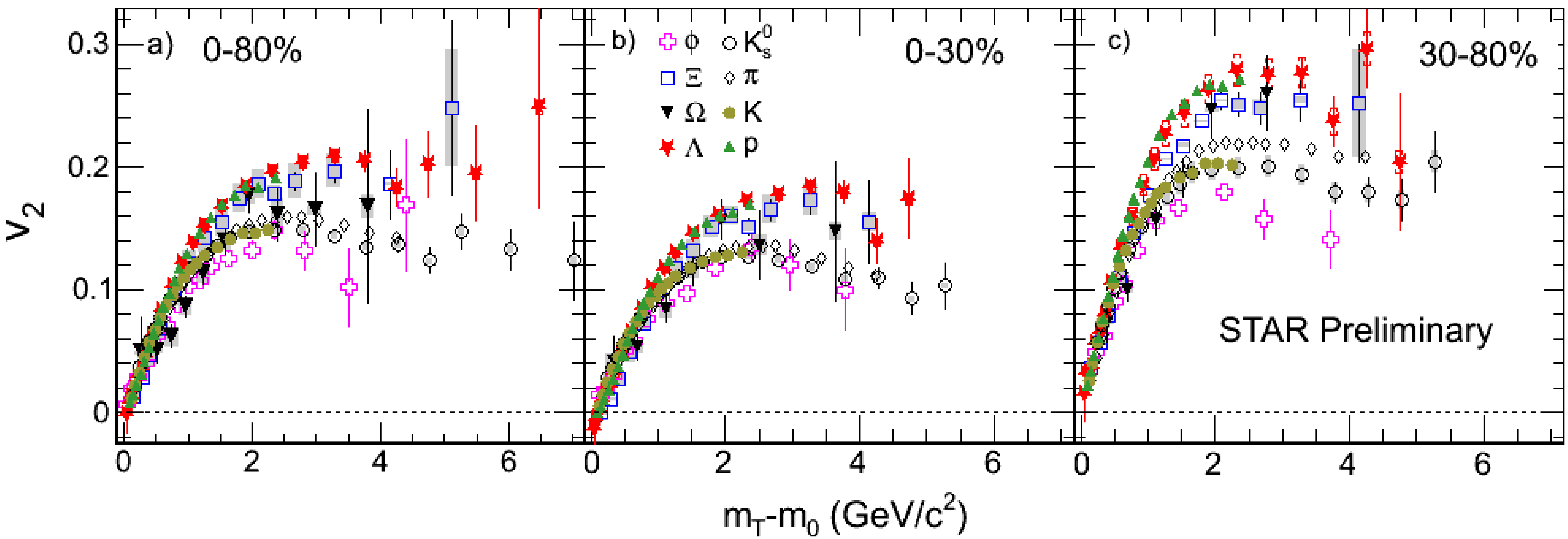


- Clear centrality dependence - initial geometry
- Similar p_T dependence with light hadrons

- Event plane method with $\Delta\eta$=0.1 gap
- Improve statistical error ϕ for meson
  - compare with left figure
- 2 centrality bins for Ω baryon

Transverse kinetic energy scaling

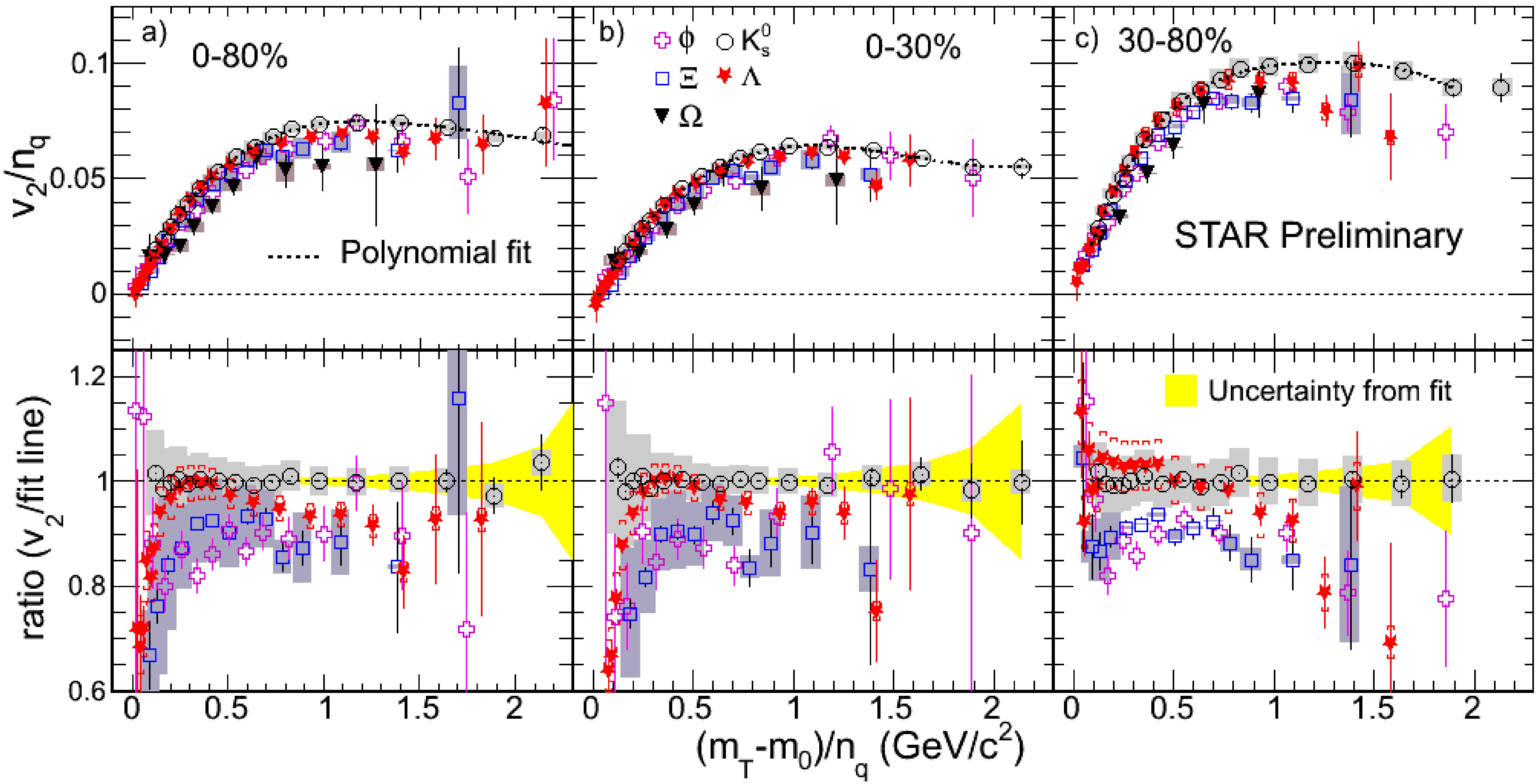
STAR, QM2012



- Mass ordering is almost vanished in terms of transverse kinetic energy $m_T - m_0$
- Clear baryon and meson splitting above 1-2 GeV/c^2
- Multi-strange hadrons seem to be smaller than other hadrons in 30-80%

NCQ scaling for multi-strange hadrons

STAR, QM2012



- Measure deviation relative to $K^0{}_s$
  - deviation at 30-80% is larger than 0-30% ?

Mass ordering violation, prediction

MASS ORDERING OF DIFFERENTIAL ELLIPTIC FLOW ... PHYSICAL REVIEW C **77**, 044909 (2008)

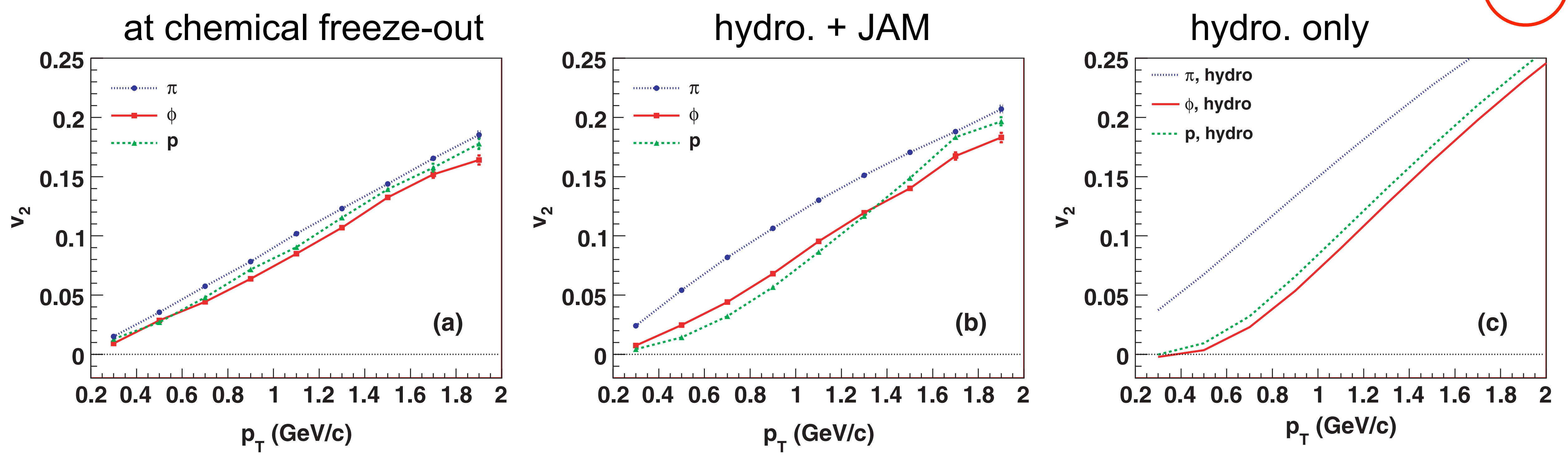
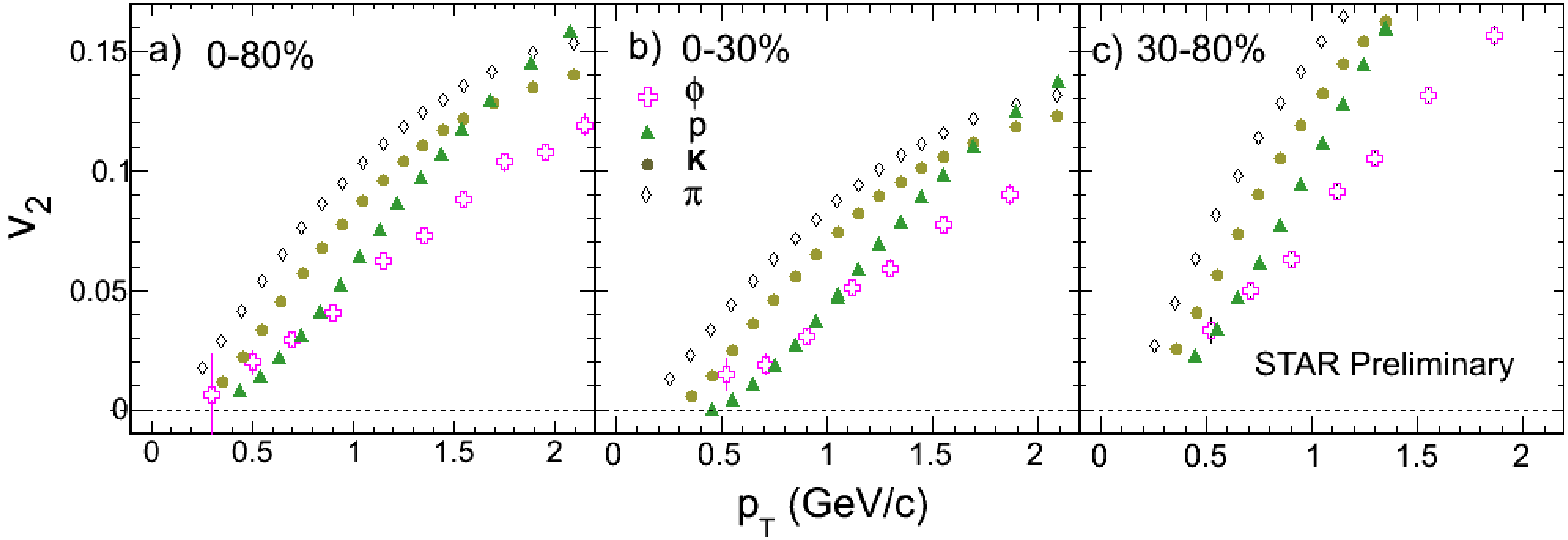


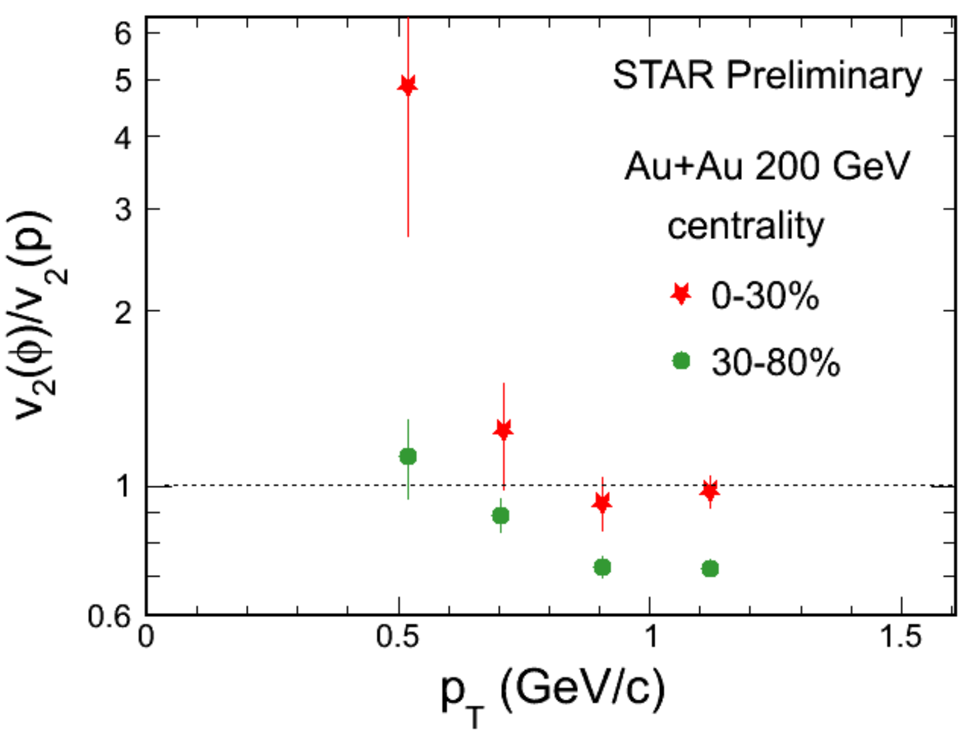
FIG. 9. (Color online) Transverse-momentum dependence of the elliptic flow parameters for pions (dotted blue), protons (dashed green), and ϕ mesons (solid red), for Au+Au collisions at $b = 7.2$ fm. (a) Before hadronic rescattering. (b) After hadronic rescattering. (c) Ideal hydrodynamics with $T_{\mathrm{th}} = 100$ MeV. The results for pions and protons are the same as shown in Fig. 5.

- Prediction: $v_2(\phi) > v_2(p)$ at low p_T
  - Due to less hadronic rescattering on ϕ meson
  - based on ideal hydrodynamical model + JAM hadronic cascade, single shot hydro (no initial fluctuations), ideal gas equation of state

v_2 at low p_T

STAR, QM2012





- $v_2(\phi) > v_2(p)$ in data at low p_T
  - The effect is stronger in central collisions
- Consistent with the scenario predicted in hydro. + hadron cascade model
- Systematic & quantitative comparison is necessary

Recent update of hydro. model

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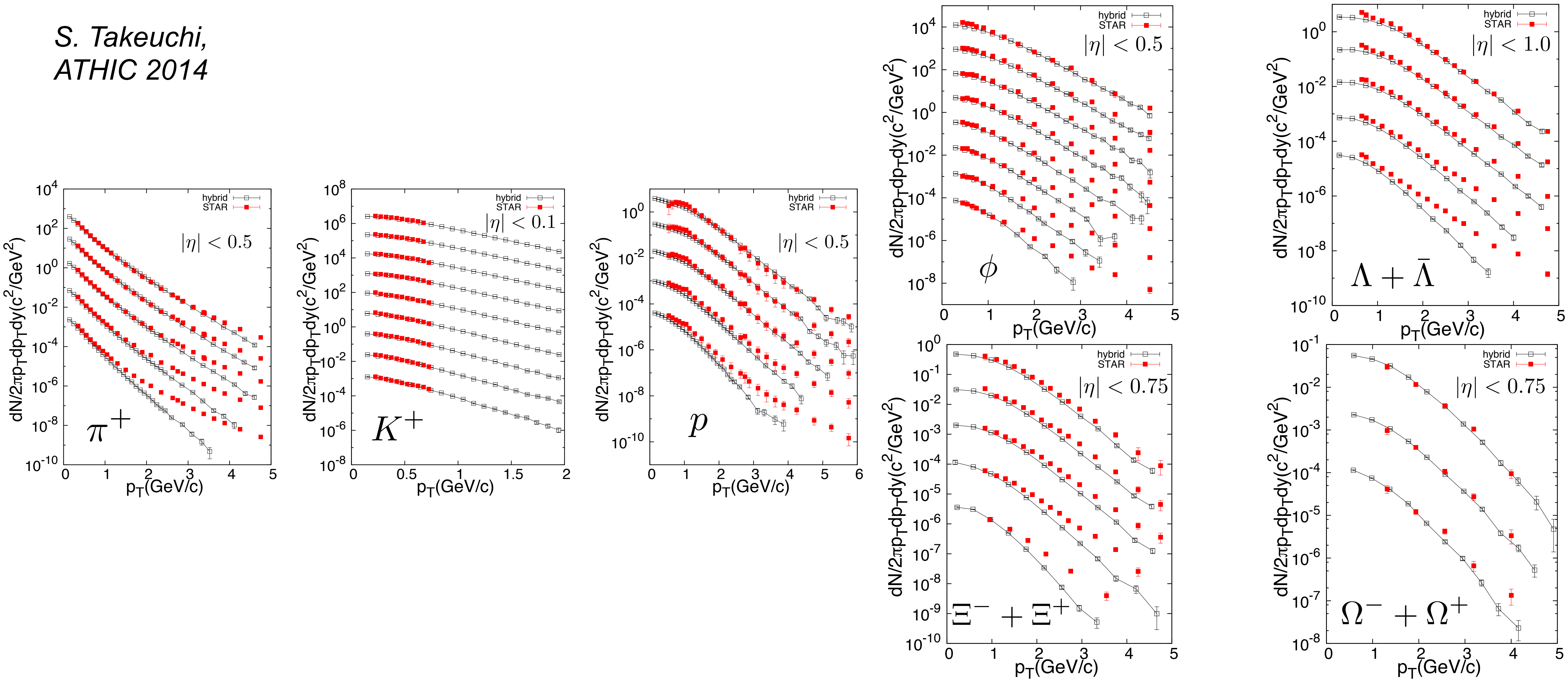

- Integrated dynamical model - hydro. + hadron cascade
  - Initial geometry fluctuation by MC Glauber model
  - Lattice equation of state
- Spectra are reproduced well at low p_T

$v_2(p_T)$

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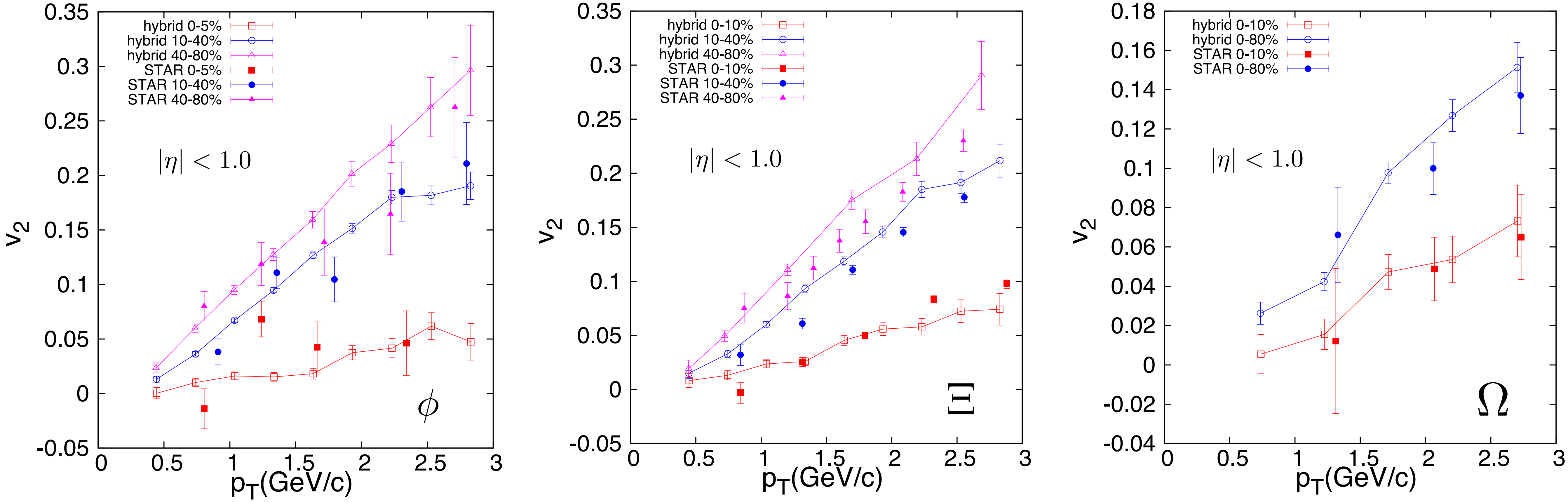

- Compared with previous published STAR data
- Reasonable agreement with the data
- Some deviations at peripheral collisions
  - due to the difference between event plane method (data) and reaction plane method (model)

Effect of hadronic rescattering

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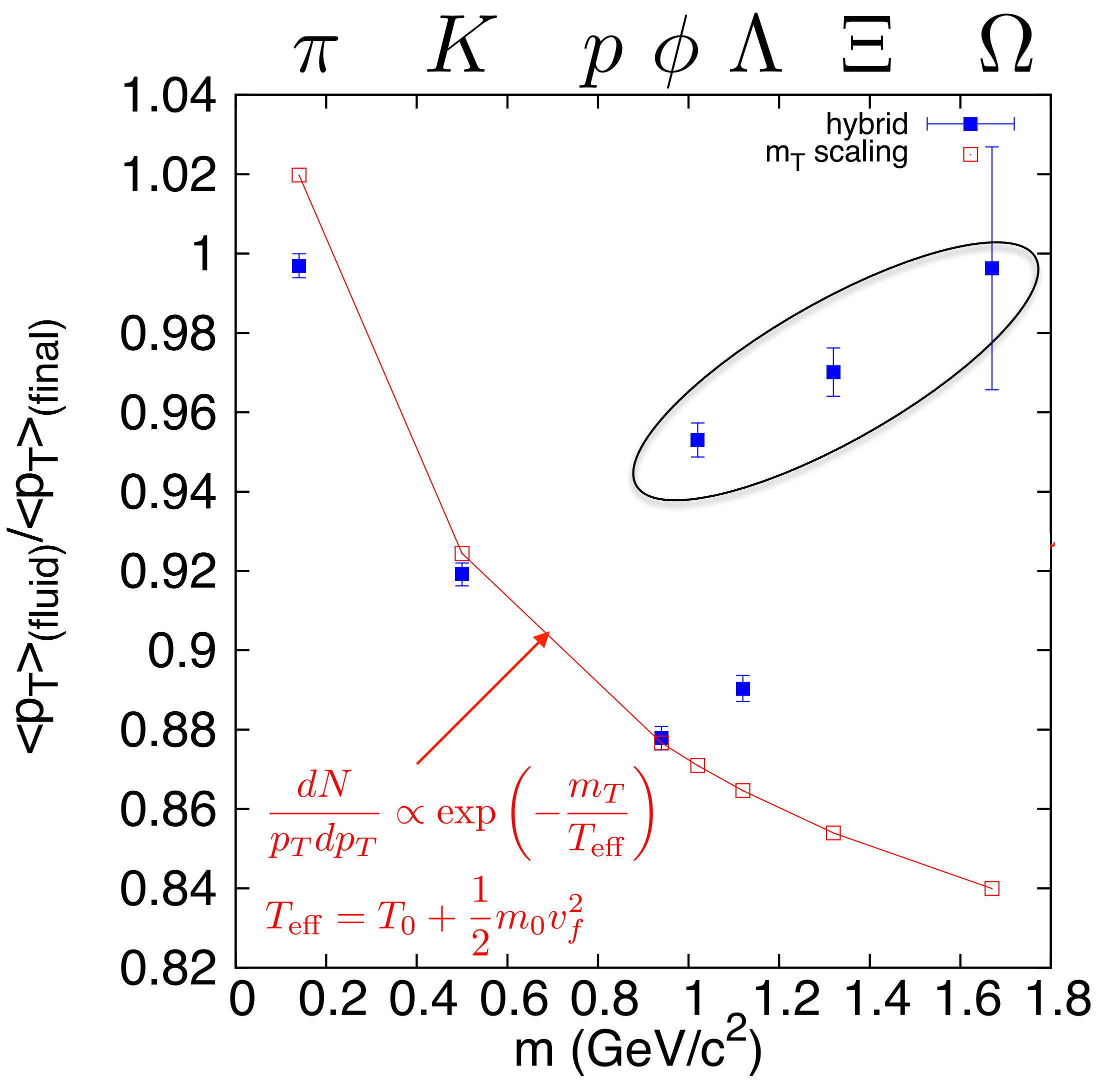

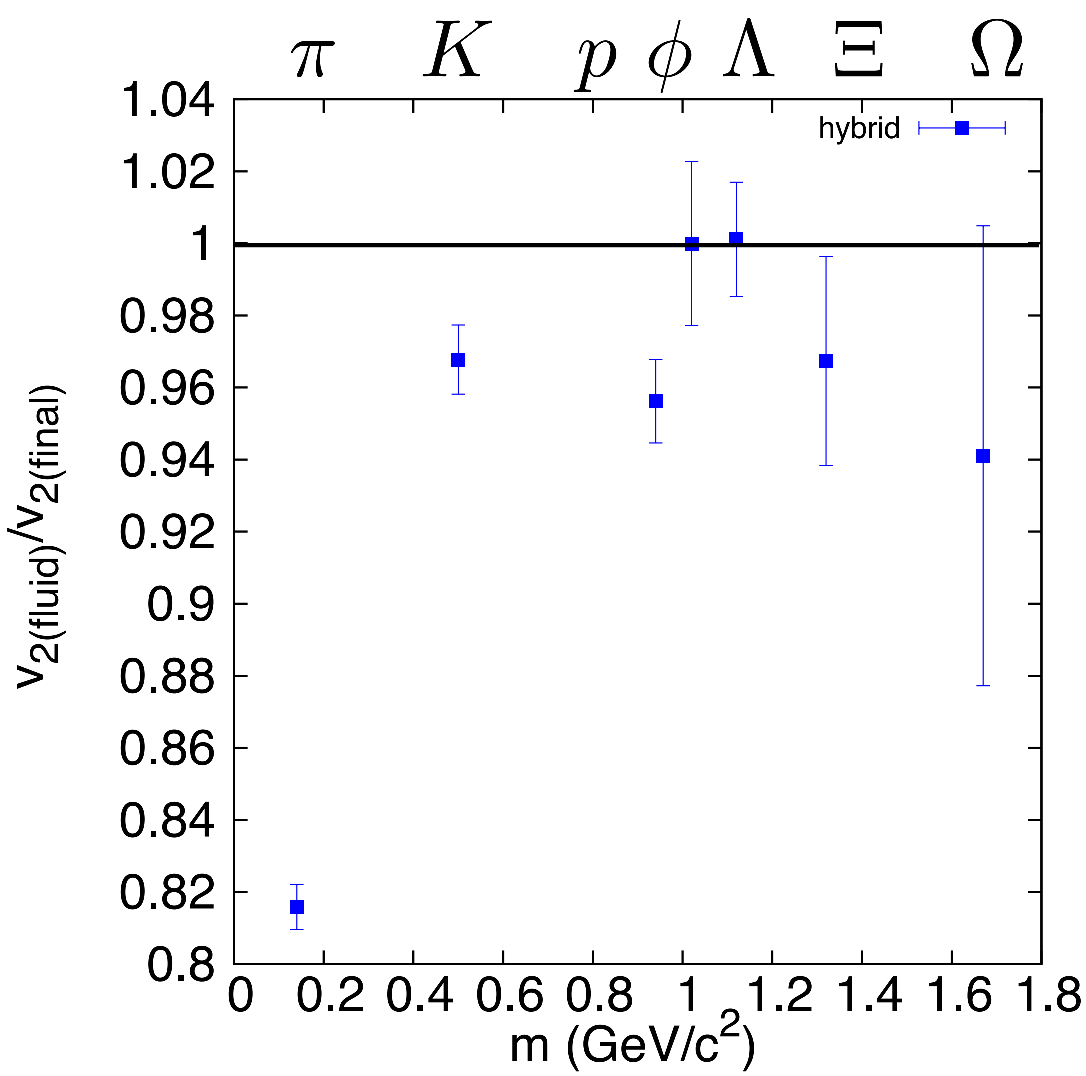

- Less rescattering effect on multi-strange hadrons
  - Mean p_T for multi-strange hadrons deviate from m_T scaling
  - v_2 almost unchanged between fluid and final stages

$v_2(\phi)$ vs $v_2(p)$

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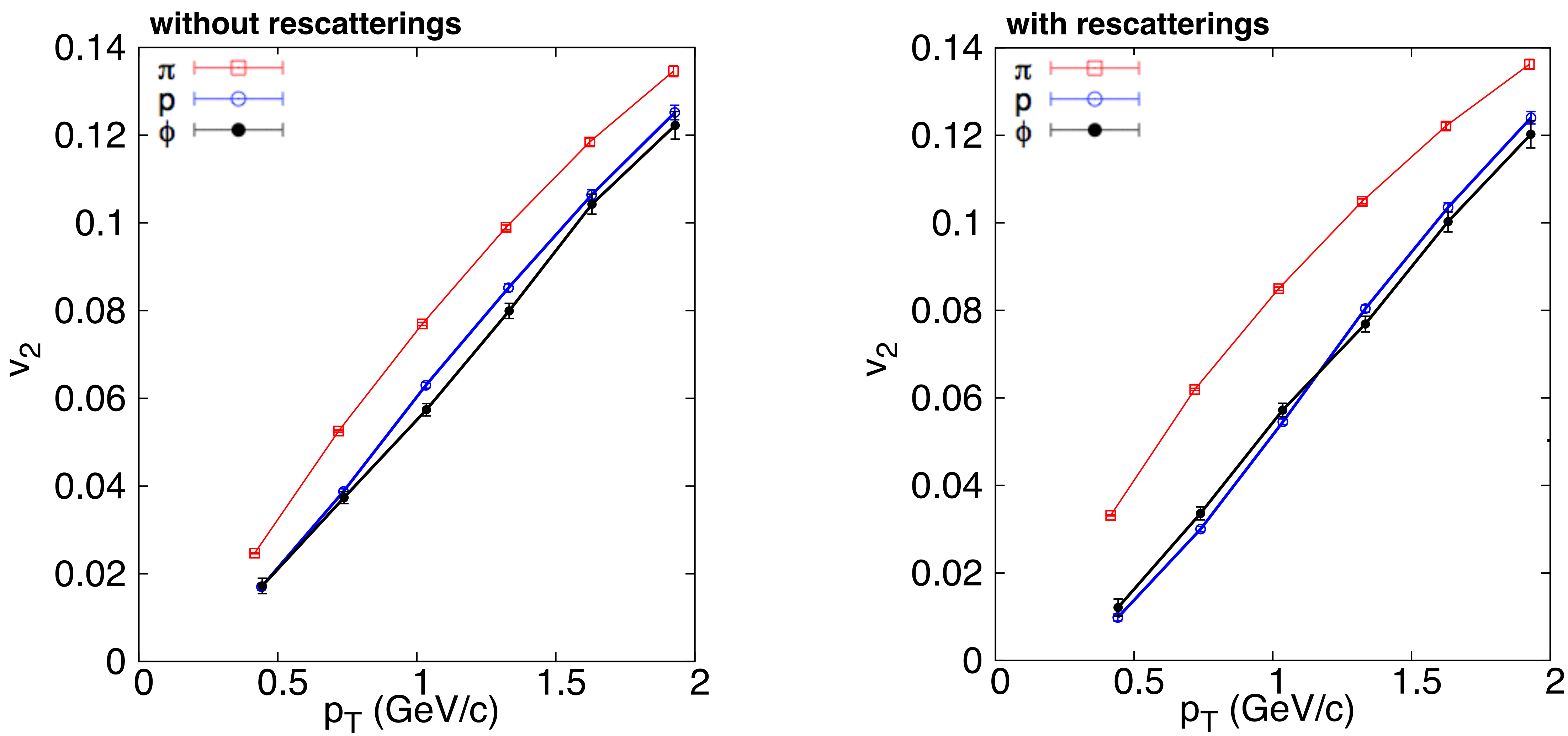

- Compare v_2 below ~1 GeV/c in p_T
  - $v_2(\pi) > v_2(p) \geq v_2(\phi)$ without rescattering
  - $v_2(\pi) > v_2(\phi) > v_2(p)$ with rescattering
- Confirmed violation of mass ordering
  - ~20% effect around 0.5 GeV/c in minimum bias events

Summary

- Multi-strange hadrons can be used as penetrating probes to understand medium properties in heavy ion collisions
- We have confirmed NCQ scaling for multi-strange hadrons with high precision data set
  - partonic collectivity for light quark sectors (*u*, *d*, *s*)
- Violation of mass ordering has been predicted, and observed by the comparison of ϕ meson and proton v_2
  - The effect is stronger in central collisions
- Recent hybrid hydrodynamical model provides realistic (initial state fluctuations + lattice EoS) calculation
  - which will allow us to make quantitative and systematic comparison with the data