Recent flow results at RHIC

Hiroshi Masui / University of Tsukuba

Flow and heavy flavour workshop in high energy heavy ion collisions: GRN workshop, Inchon, Feb./24-26, 2015

Outline

- Multi-strange hadrons
  - Mass ordering violation
- v_2 at RHIC Beam Energy Scan
  - Identified hadron v_2
  - Blast wave model fit to v_2
- Direct photon v_n & blast wave fit
- Summary

Reminder

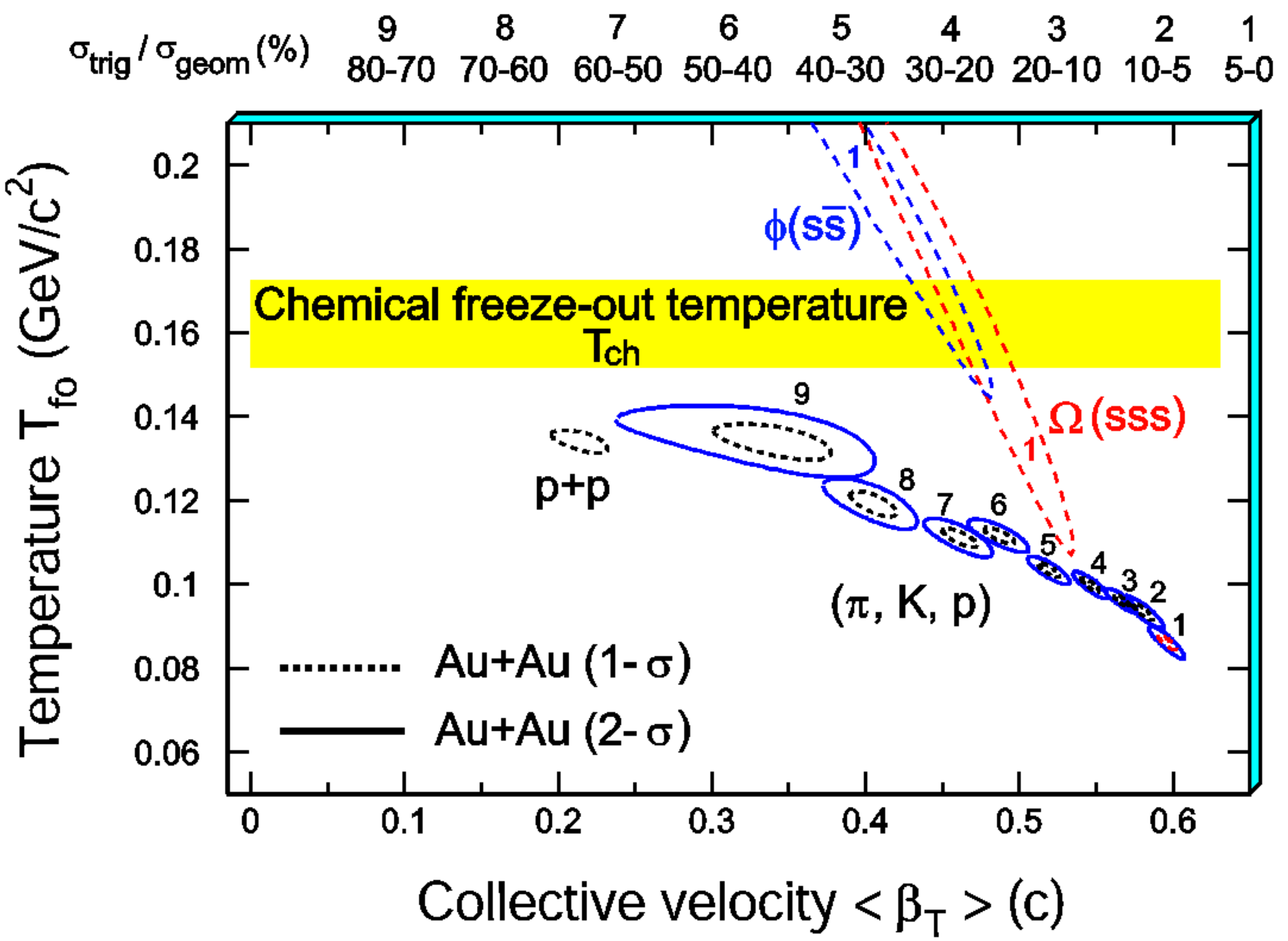
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n[\phi - \Psi_n]\right)$$

$$v_n = \langle \cos\left(n[\phi - \Psi_n]\right) \rangle$$

- $v_n \neq$ (hydrodynamical) flow
  - v_n is the azimuthal anisotropy of particles in momentum space
- Crucial to understand the non-flow background
  - momentum conservation (on v_1), resonance decay, jet, …
- Multi-particle correlation (cumulant), and/or large rapidity gap are typical methods to avoid non-flow
  - Most of non-flow is 2-particle correlation, short-range correlation in (pseudo)rapidity

Multi-strange hadrons

Multi-strange hadrons

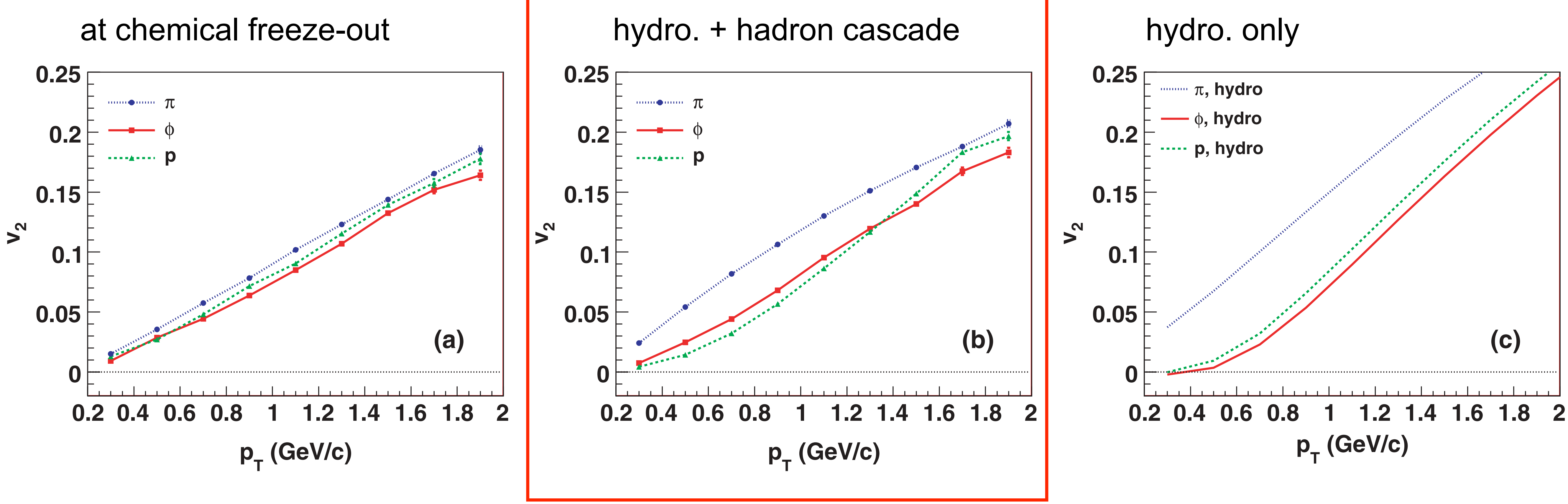


STAR White paper:
***Nucl. Phys. A757** (2005) 102-183*

- Multi-strange hadrons (ϕ, Ω) freeze-out early
- Ideal hydrodynamical model with hadron cascade shows mass ordering violation between p and ϕ
  - $v_2(p) < v_2(\phi)$ in low p_T
  - radial flow at late stage + less hadronic cross section for ϕ, Ω

Multi-strange hadrons

T. Hirano et al: **PRC77**, 044909 (2008)



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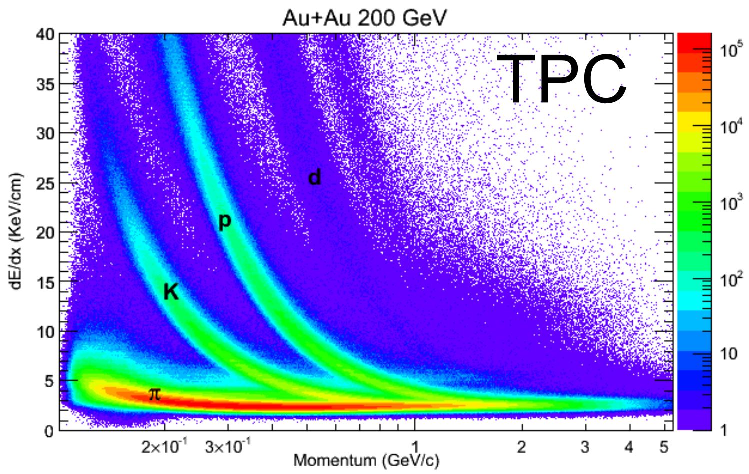
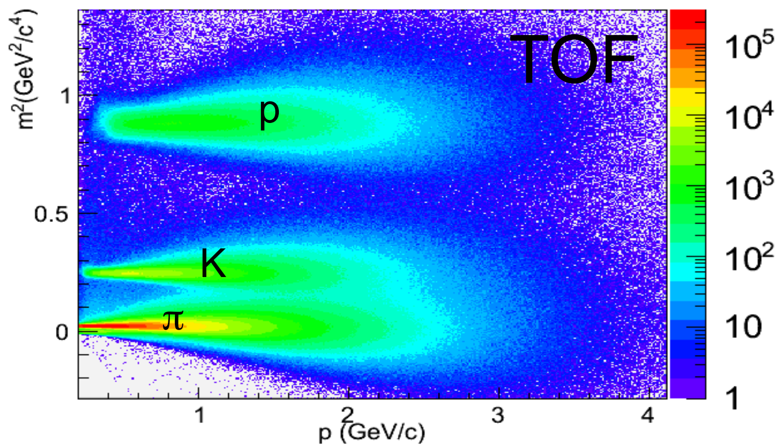
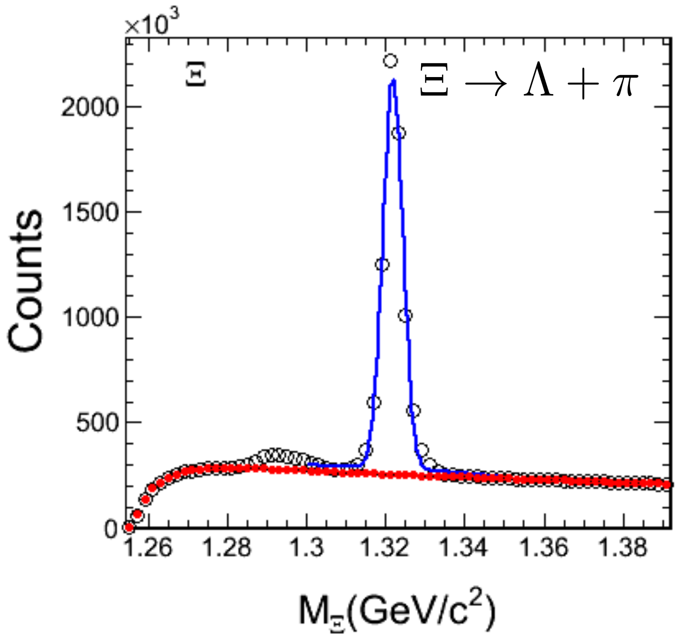
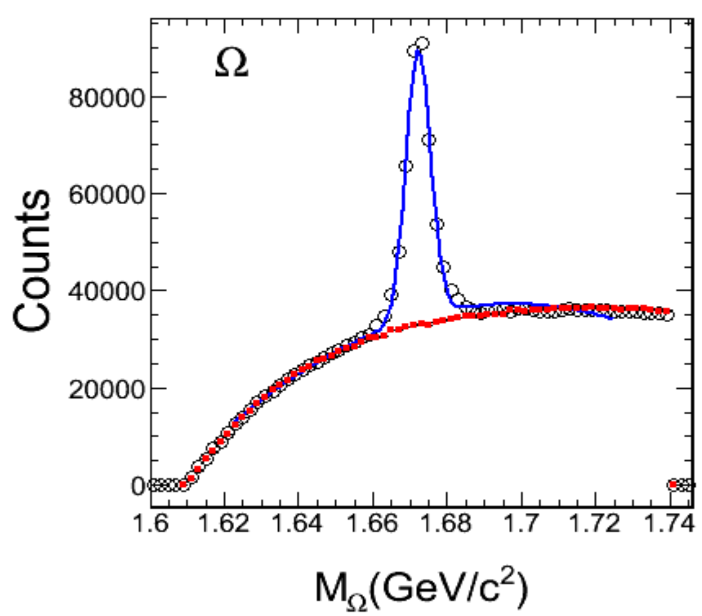
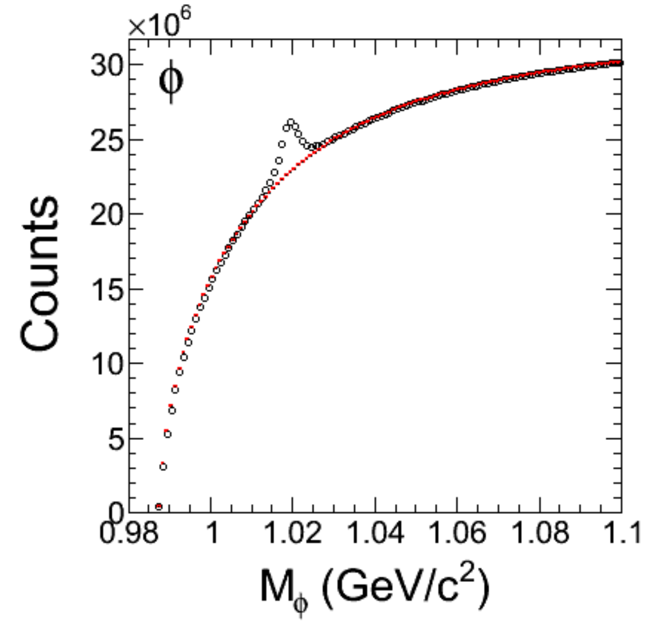
Particle identification







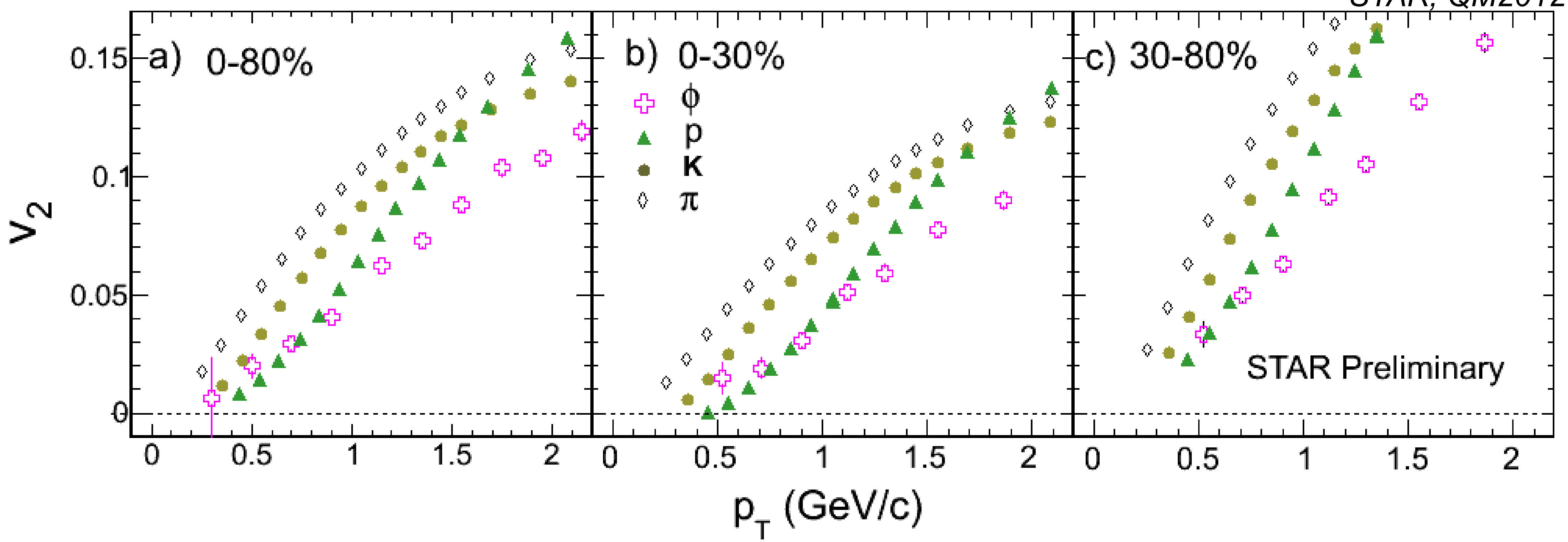


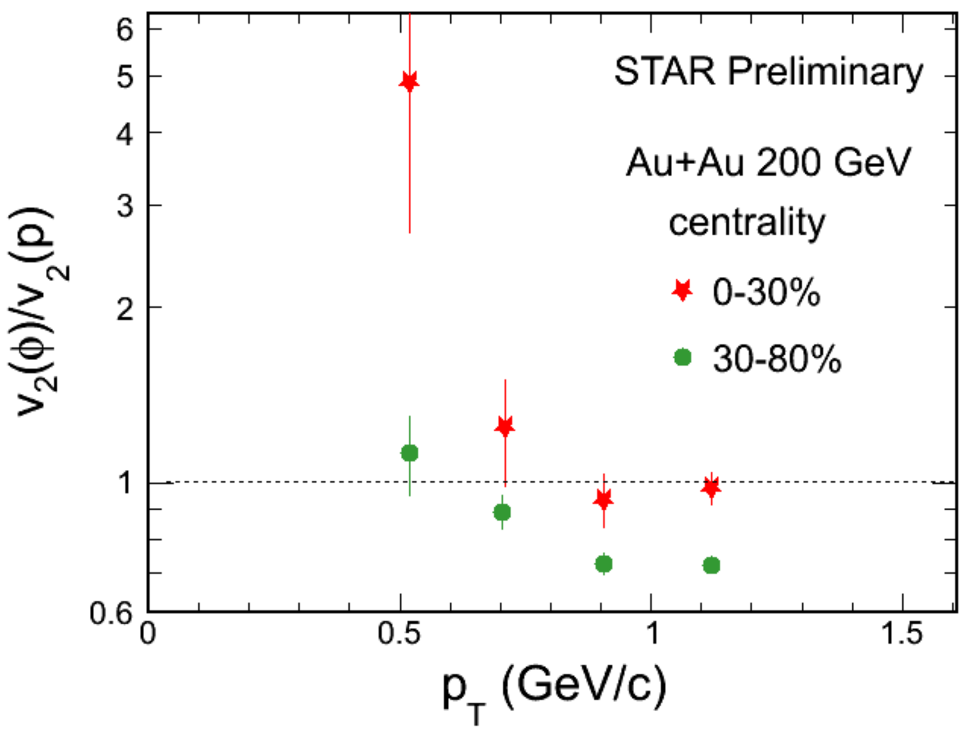


- Topological reconstruction of Ξ and Ω
- Combinatorial background is estimated by rotational background from the same event

Mass ordering of $v_2(p_T)$

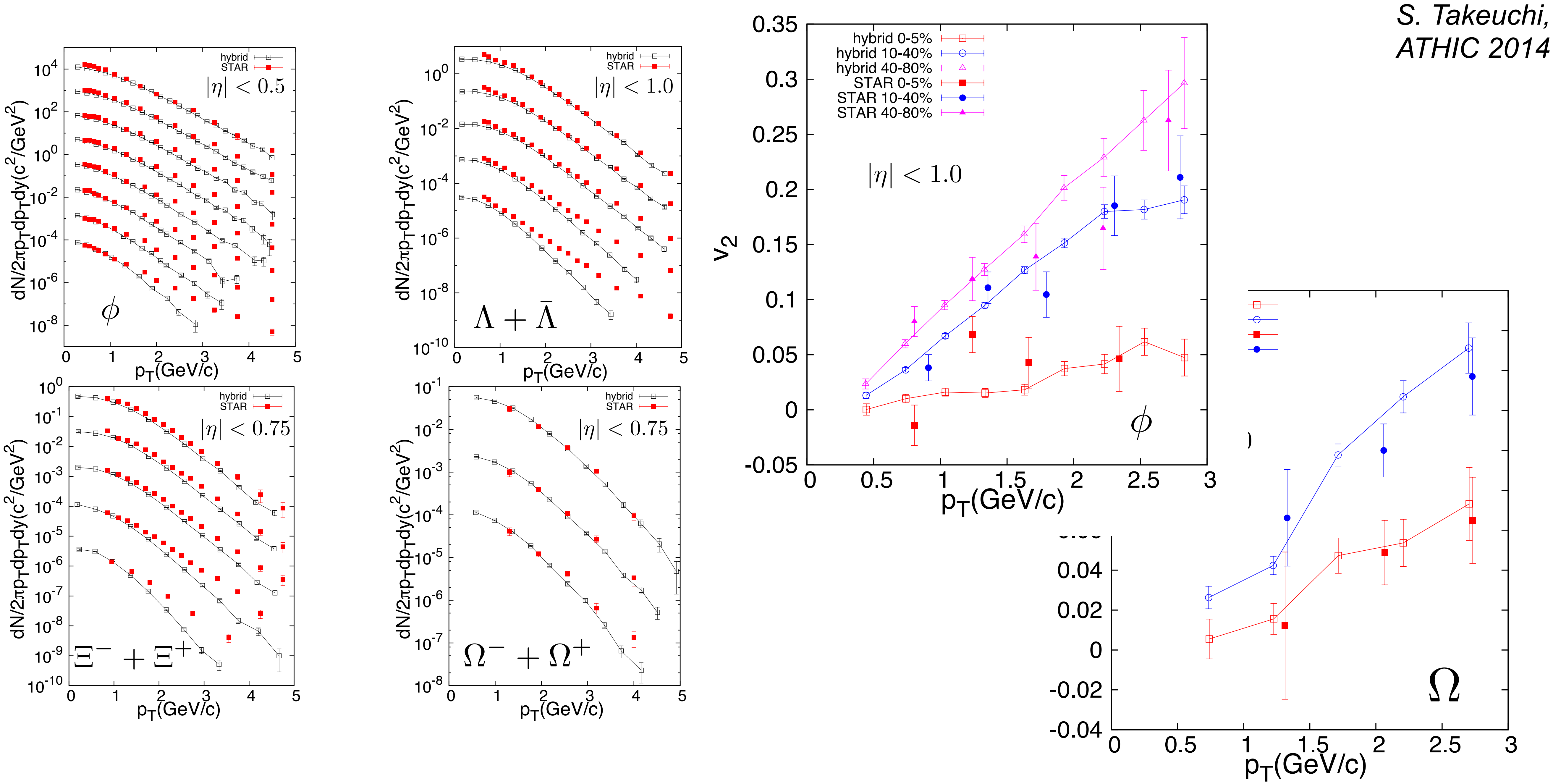
STAR, QM2012





- Event plane with gap $|\Delta\eta|$=0.1
- $v_2(\phi) > v_2(p)$ at low p_T
  - The effect is stronger in central
  - qualitatively consistent with the prediction from hydro. + hadron cascade model

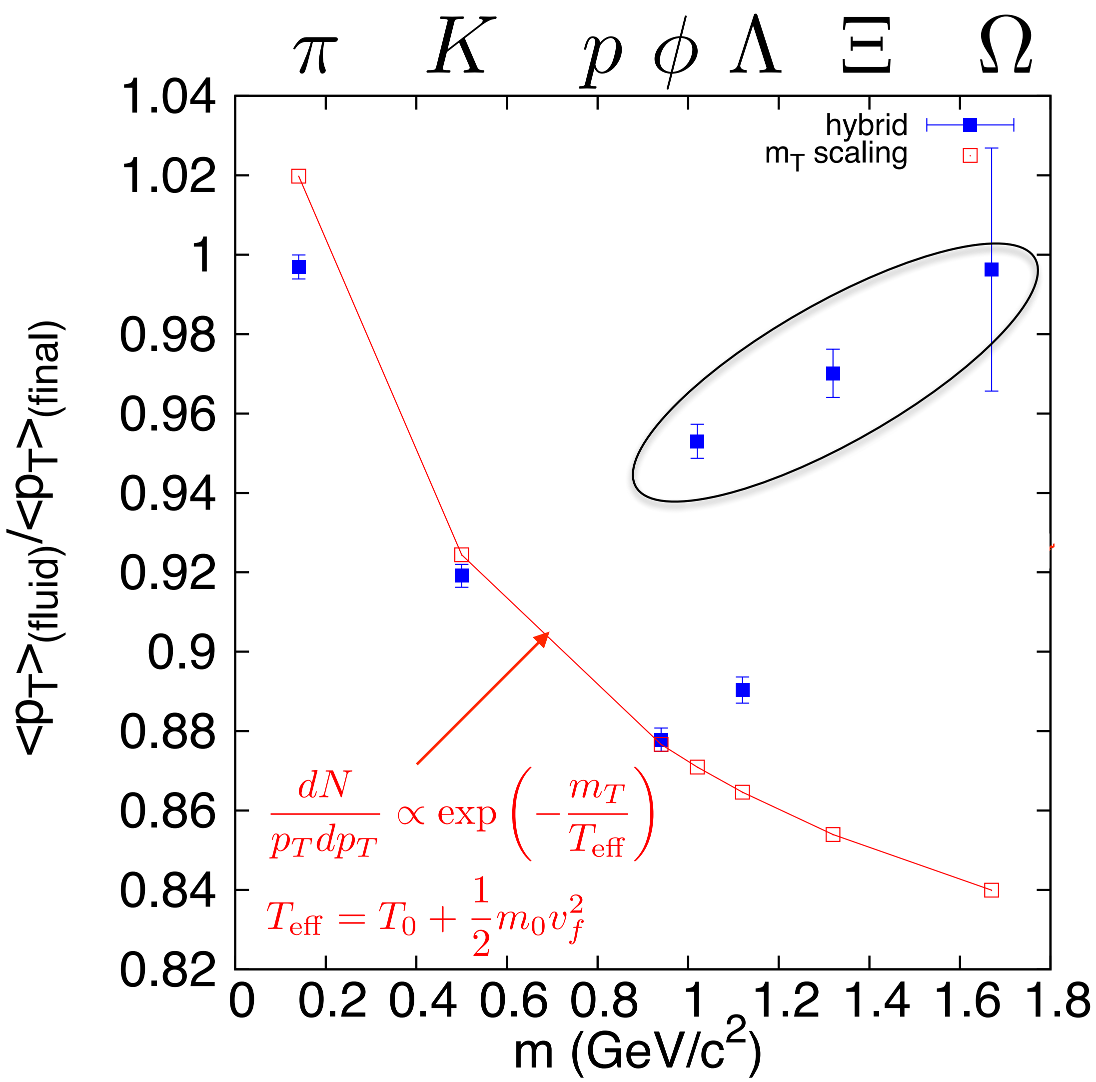
Recent update of hydro. model

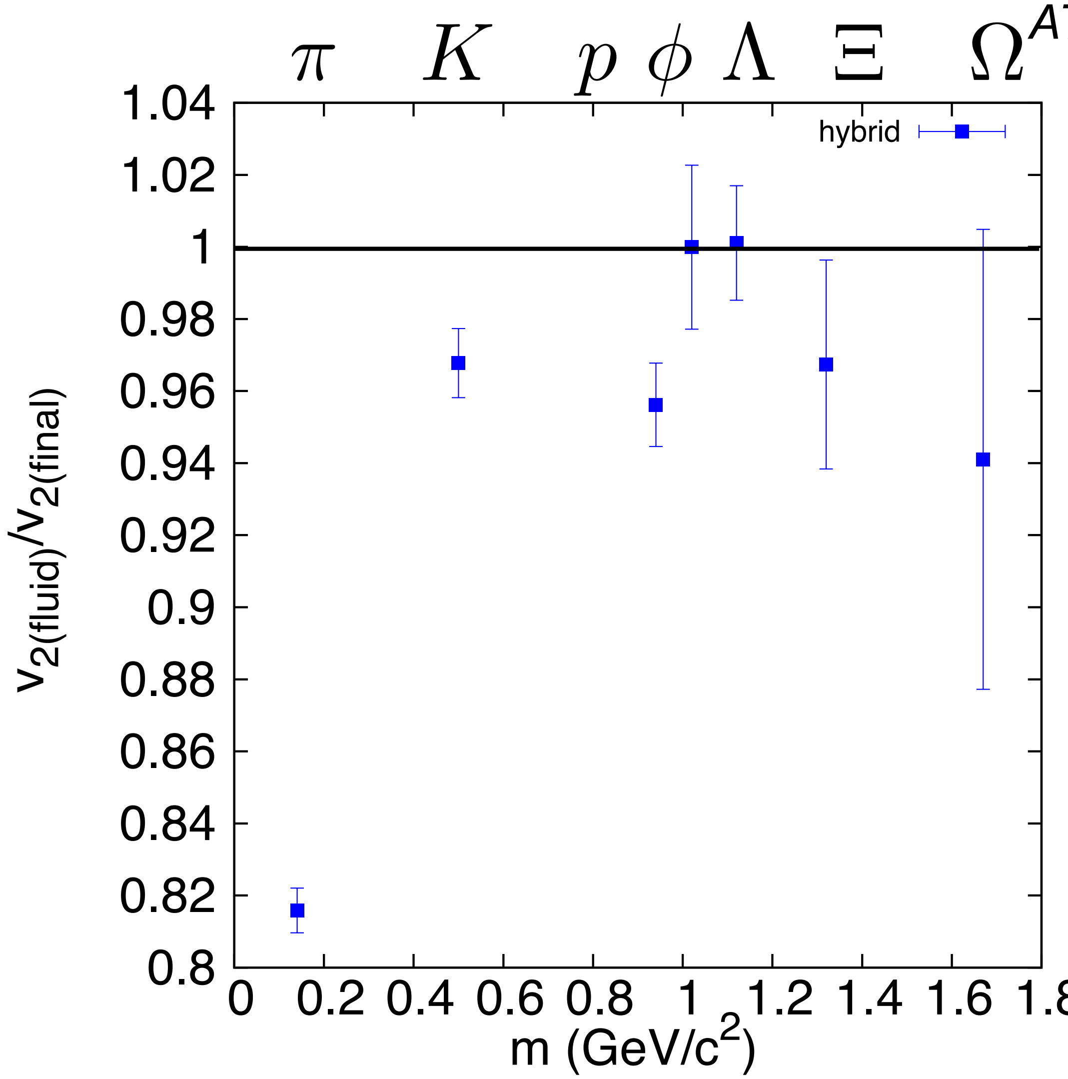


- Initial geometry fluctuation (MC Glauber), Lattice EoS
- Reasonable agreement with the data

Effect of hadronic rescattering

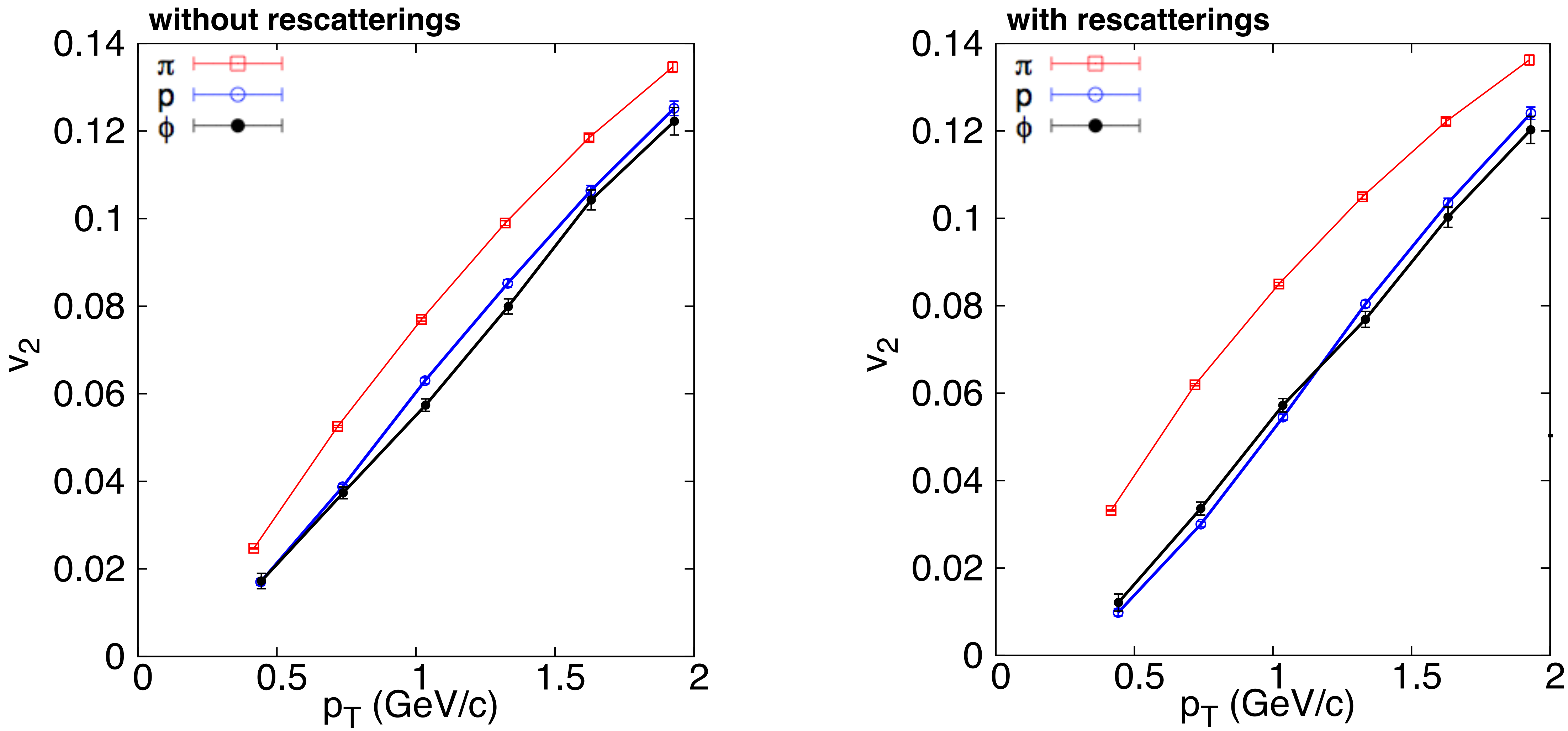
S. Takeuchi, ATHIC 2014





- 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 $v_2(p)$

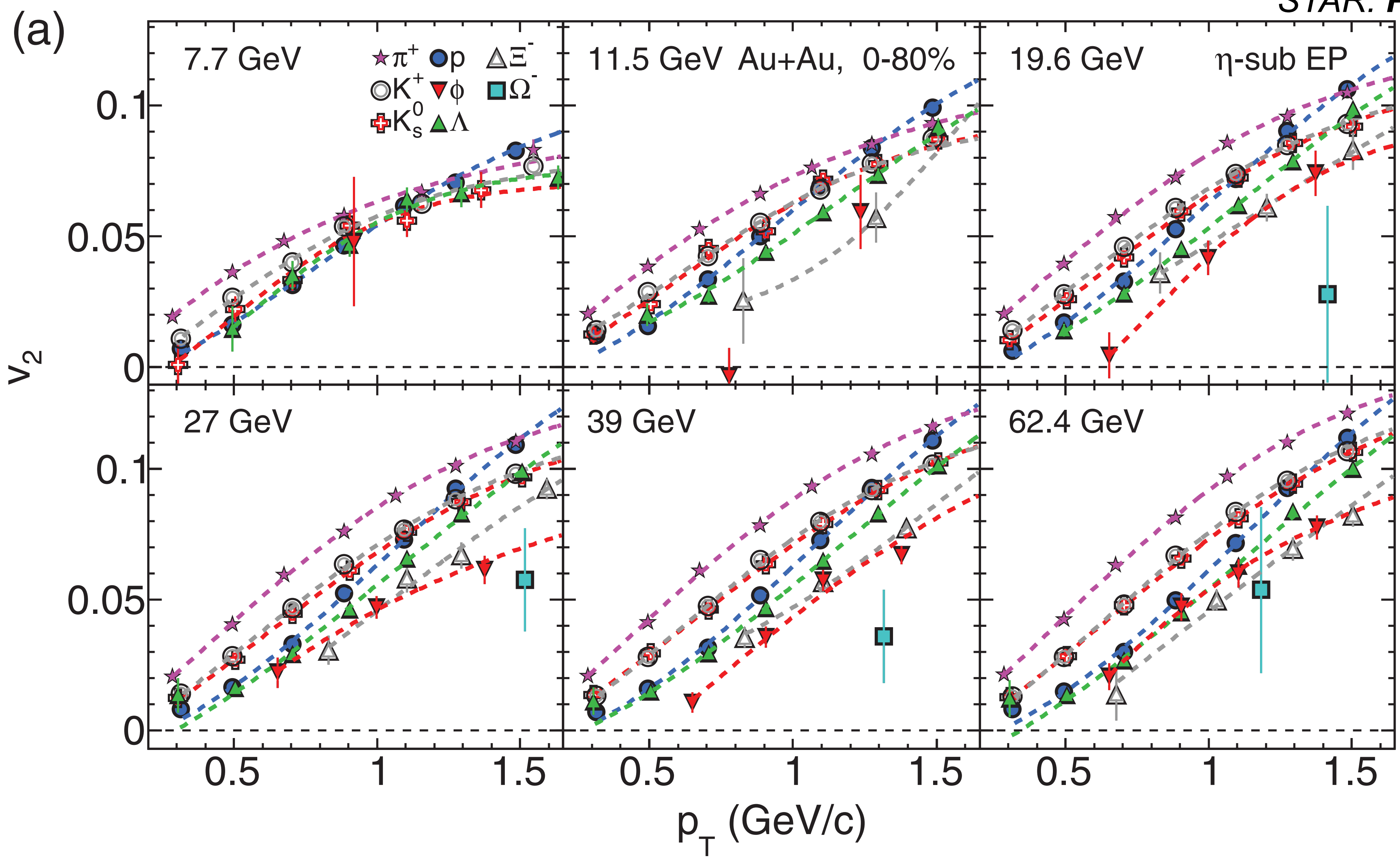


S. Takeuchi, ATHIC 2014

- 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

200 GeV is special ?

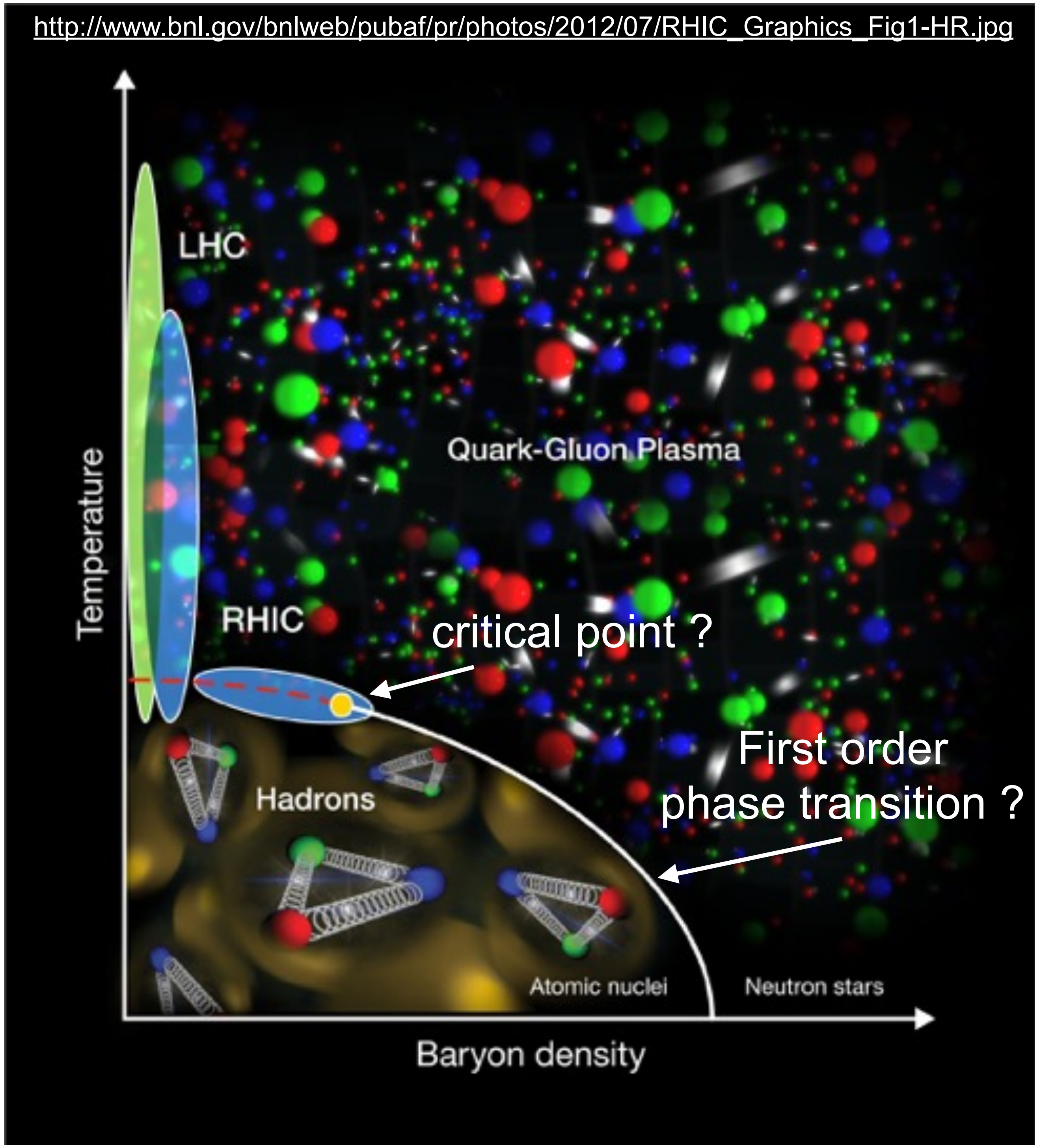
STAR: ***PRC88***, *014902 (2013)*



- $v_2(p) > v_2(\phi)$ in 7.7 - 62.4 GeV
  - Hadronic phase become dominant ?
  - Temperature dependent η/s ?

v_2 in RHIC Beam Energy Scan

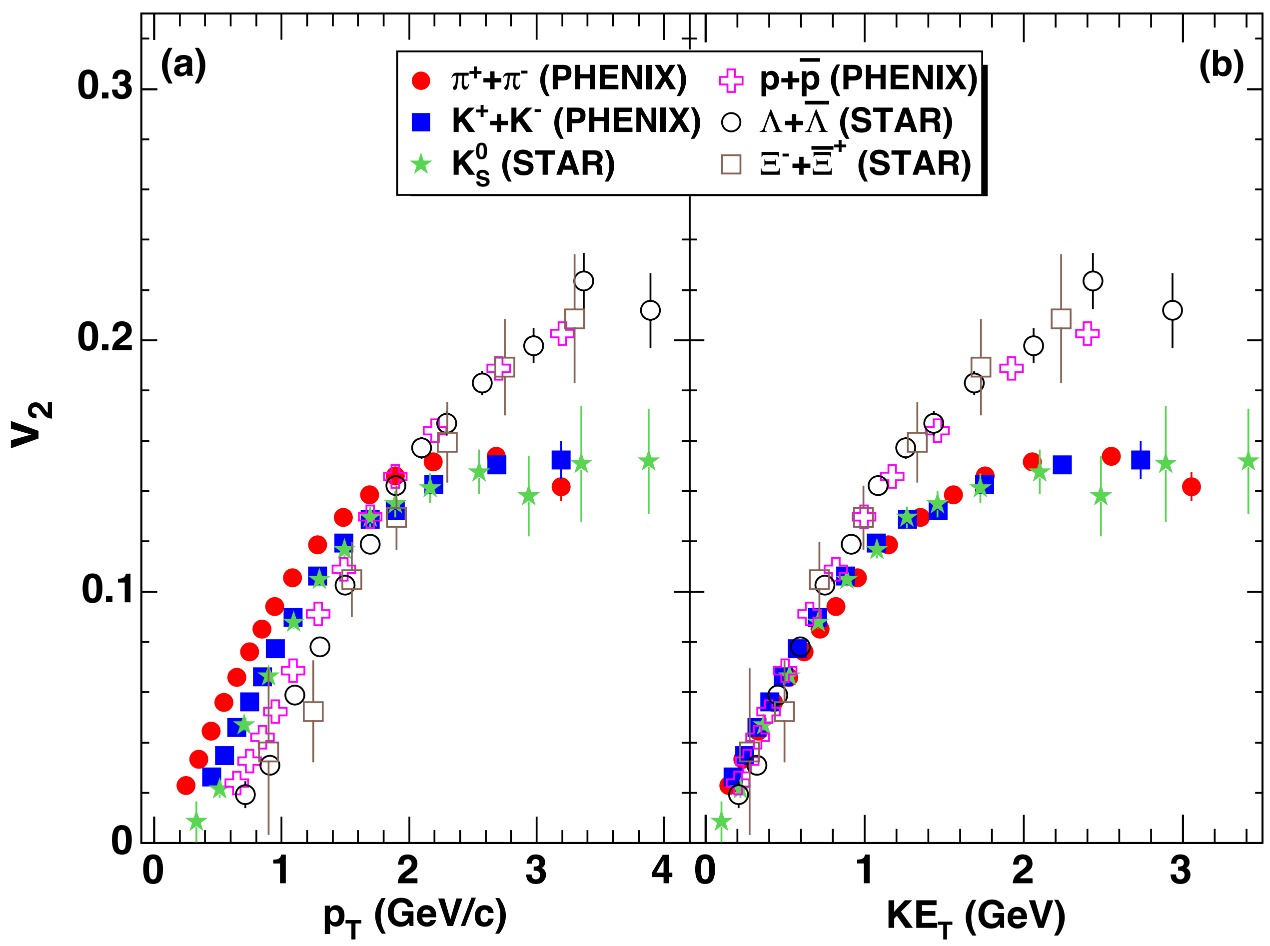
RHIC Beam Energy Scan

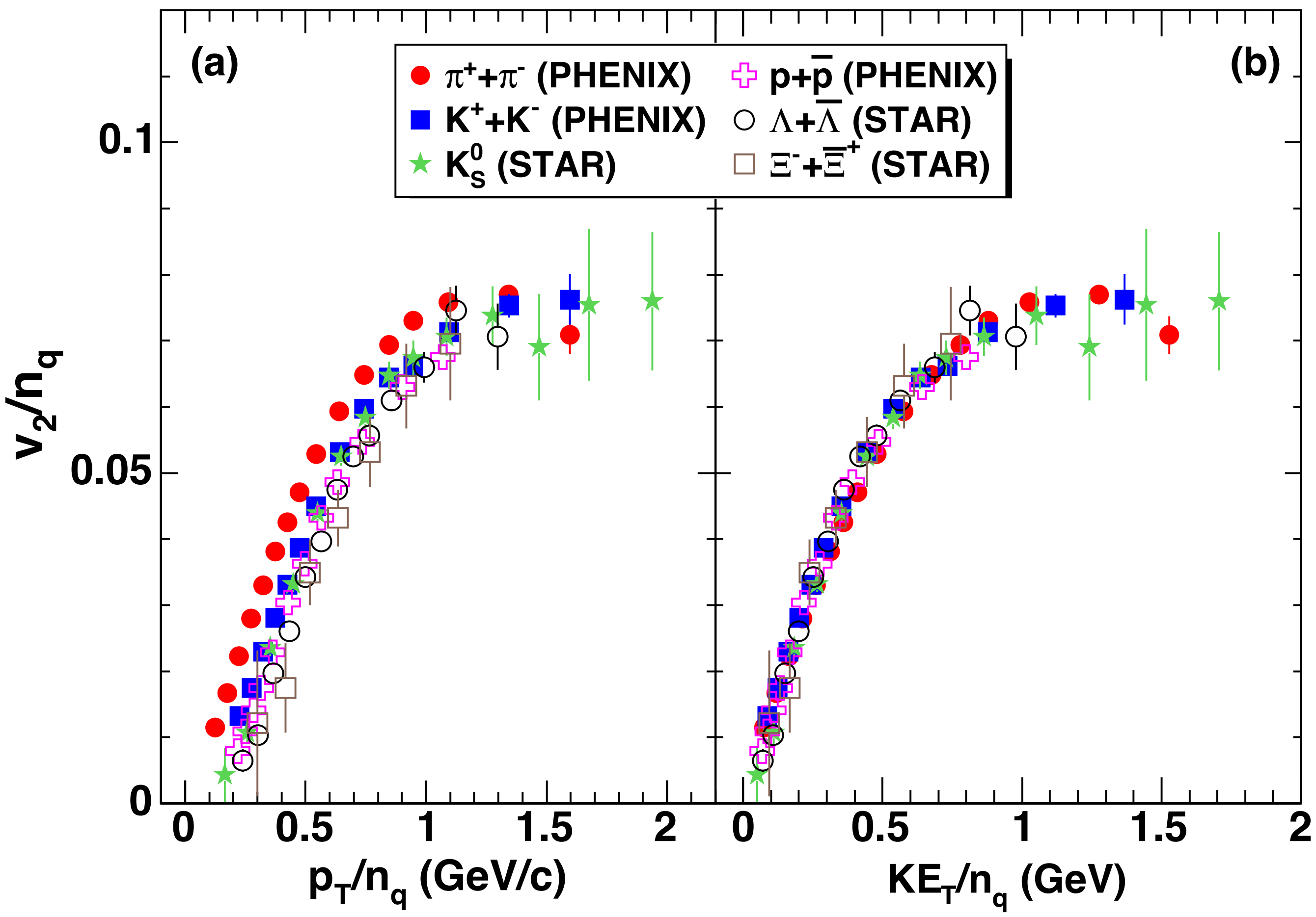


- Cross-over transition at μ_B=0
  - from 1st principle Lattice QCD calculations
- If phase transition is 1st order at high baryon density, the end point is QCD critical point
- Beam energy scan → reach high baryon density
- Goals of BES at RHIC:
  - Search for turn-off QGP signals
  - Search for signals of 1st order phase transition
  - Search for signals of QCD critical point

Number of Constituent Quark scaling

PHENIX: ***PRL98***, *162301 (2007)*

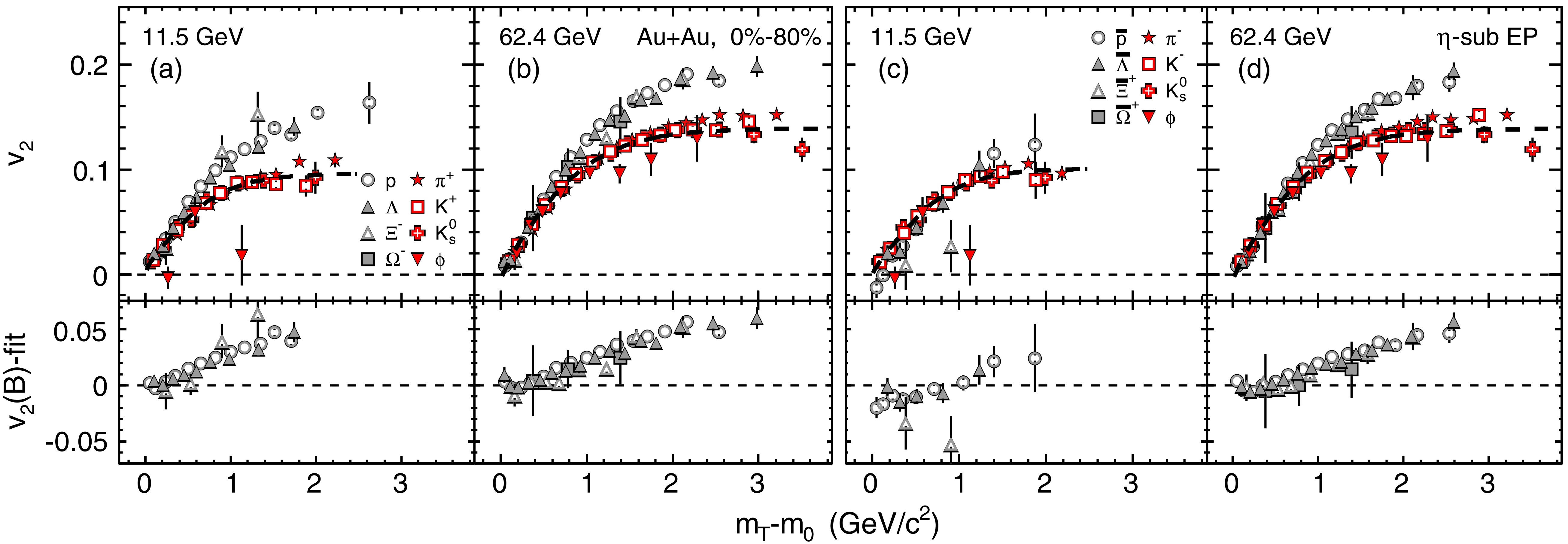




- Apparent scaling by $KE_T = m_T - m_0$
  - Meson and baryon branches
- NCQ scaling of v_2 → hadronization by parton coalescence
  - Originally predicted in intermediate p_T
  - Scaling works well down to low KE_T at RHIC

NCQ scaling of v_2

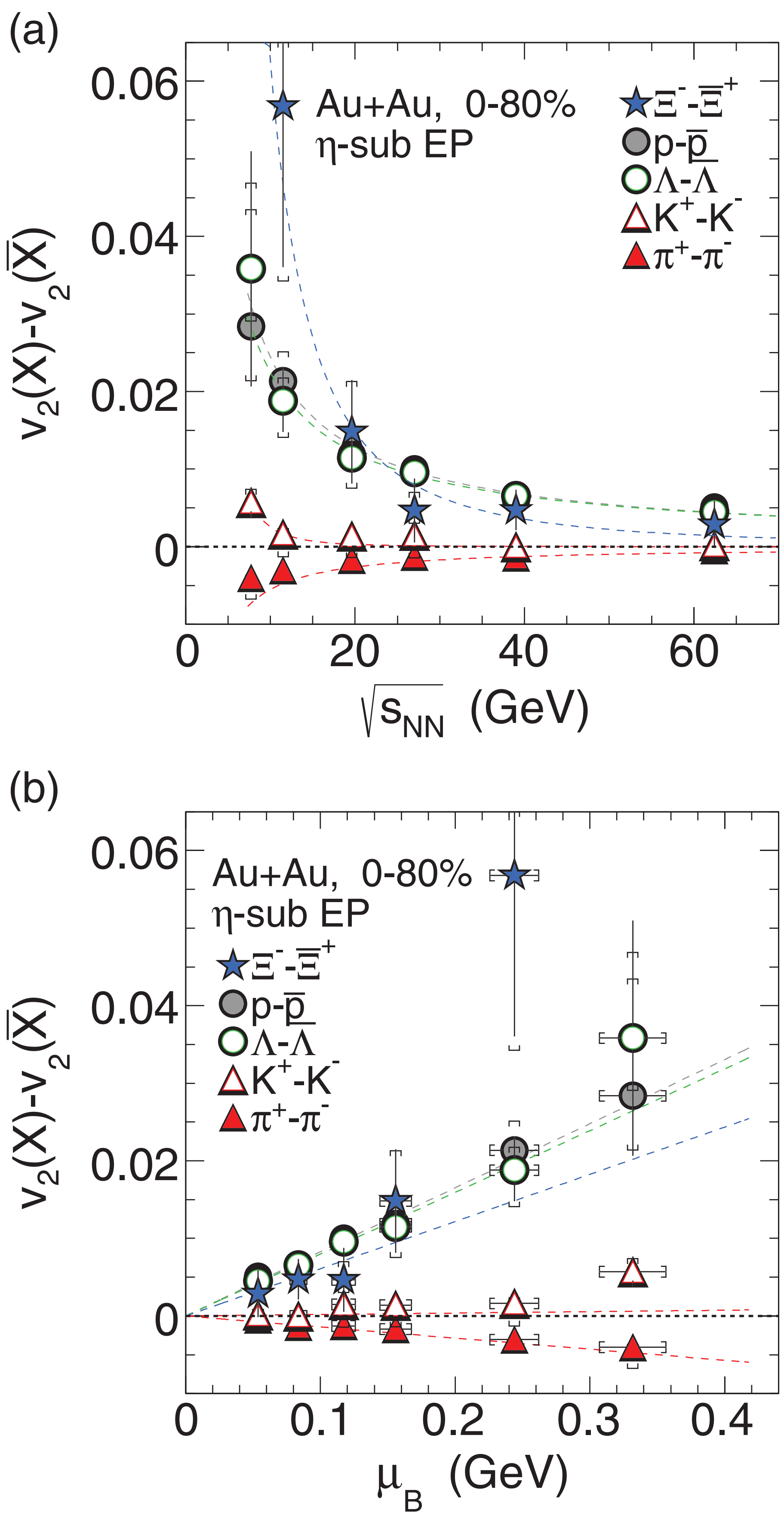
*STAR: **PRL110**, 142301 (2013)*



- Two branches, mesons & baryons in $v_2(m_T\text{-}m_0)$ at 62.4 GeV
- Antiparticles already scaled before dividing by n_q at 11.5 GeV
  - NCQ scaling doesn't hold for antiparticles
- ϕ meson could be deviated at 11.5 GeV (statistics is limited)

Particles vs antiparticles

STAR: ***PRC88***, *014902 (2013)*



- Quantify the difference of v_2 between particles and antiparticles
  - NCQ scaling does not hold between particles and antiparticles
  - Scaling seems to work separately

- Difference of v_2 increase with decreasing beam energy, in particular for baryons
- Difference of v_2 is linear as a function of μ_B
  - related to baryon stopping ?

Blast wave model

$$v_2(p_T) = \frac{\int_0^{2\pi} d\phi_s \cos(2\phi_s) I_2[\alpha_t(\phi_s)] K_1[\beta_t(\phi_s)][1 + 2s_2\cos(2\phi_s)]}{\int_0^{2\pi} d\phi_s I_0[\alpha_t(\phi_s)] K_1[\beta_t(\phi_s)][1 + 2s_2\cos(2\phi_s)]}$$

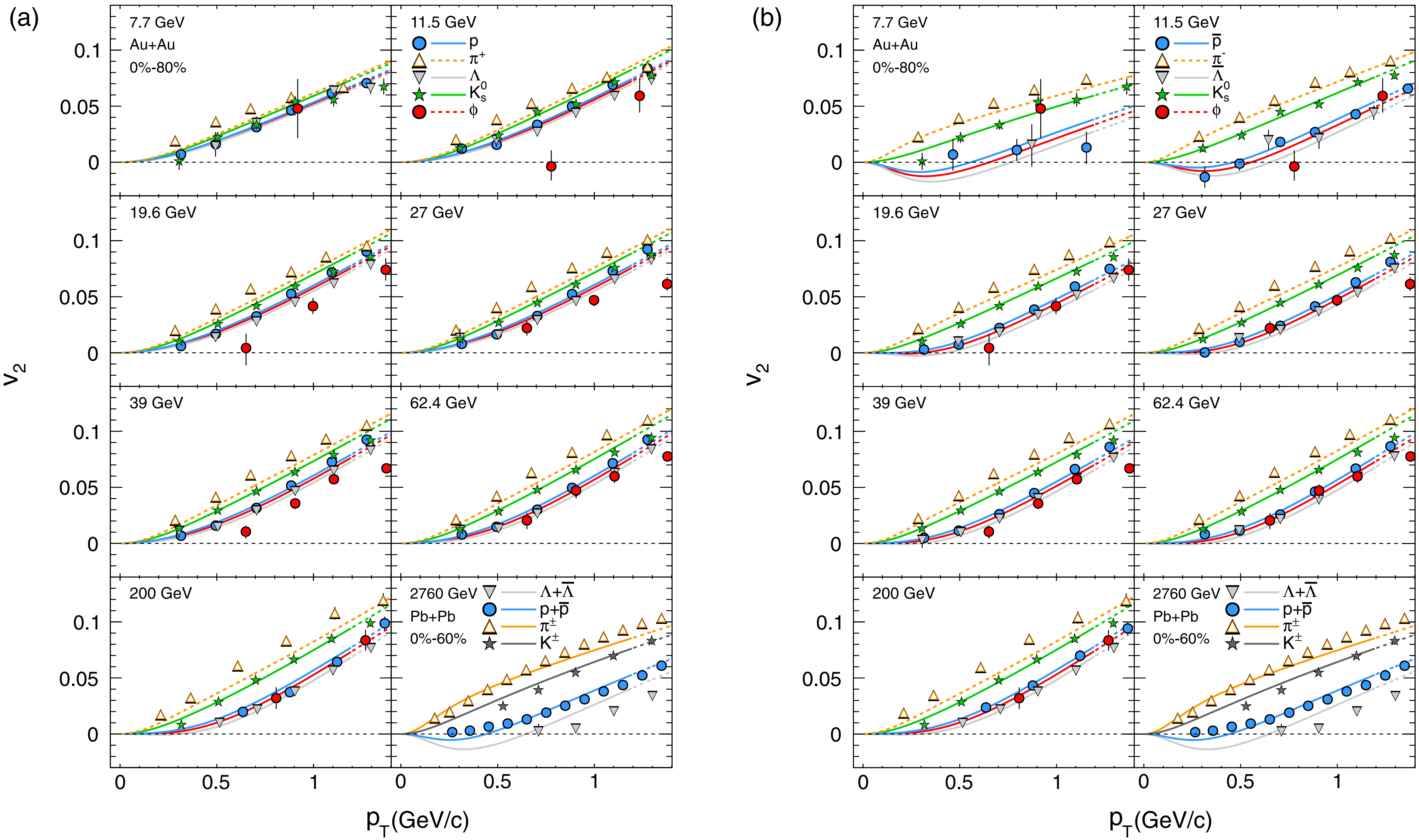
$$\alpha_t(\phi_s) = \frac{p_T}{T}\sinh\rho(\phi_s),\ \ \beta_t(\phi_s) = \frac{m_T}{T}\cosh\rho(\phi_s),$$

$$\rho(\phi_s) = \rho_0 + \rho_a\cos 2\phi_s,\ \ \beta = \tanh(\rho_0)$$

- Assumptions
  - boost invariant longitudinal expansion
  - system expands with common transverse velocity β
  - freeze-out at constant temperature T
- Mass dependence only appears in β_t via m_T
- Fit particles and antiparticles separately in p_T < 1.2 GeV/c
  - Simultaneous fit for measured particles (or antiparticles) with 3 parameters (s_2, ρ_0, ρ_a)
  - T is fixed to 120 MeV since published p_T spectra is not available

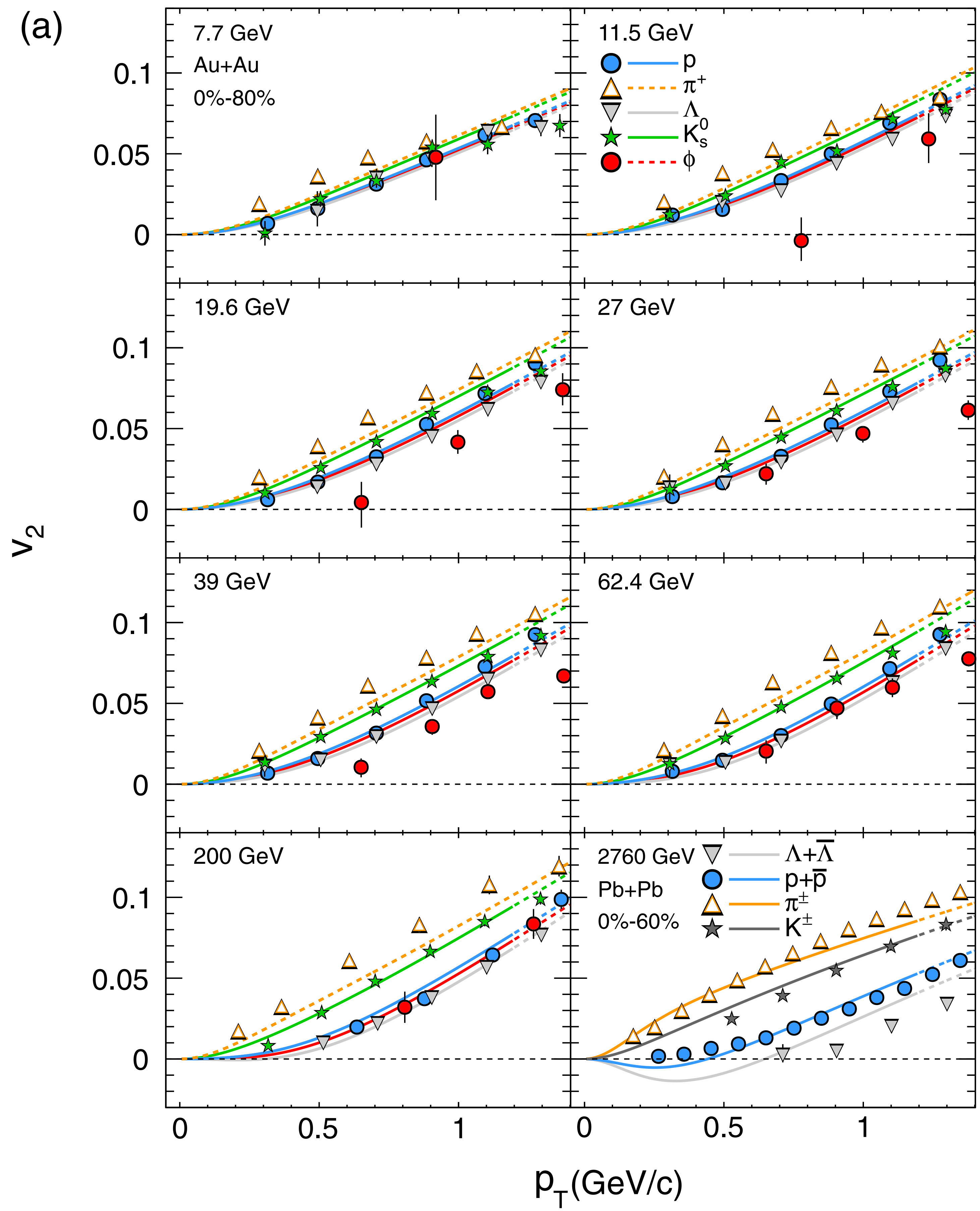
Blast wave fit to $v_2(p_T)$

X. Sun, H. Masui, A. M. Poskanzer, A. Schmah
***PRC91**, 024903 (2015)*



- Excluded pions from the fit for RHIC data (huge feed down)
- Clear mass ordering in blast wave fit

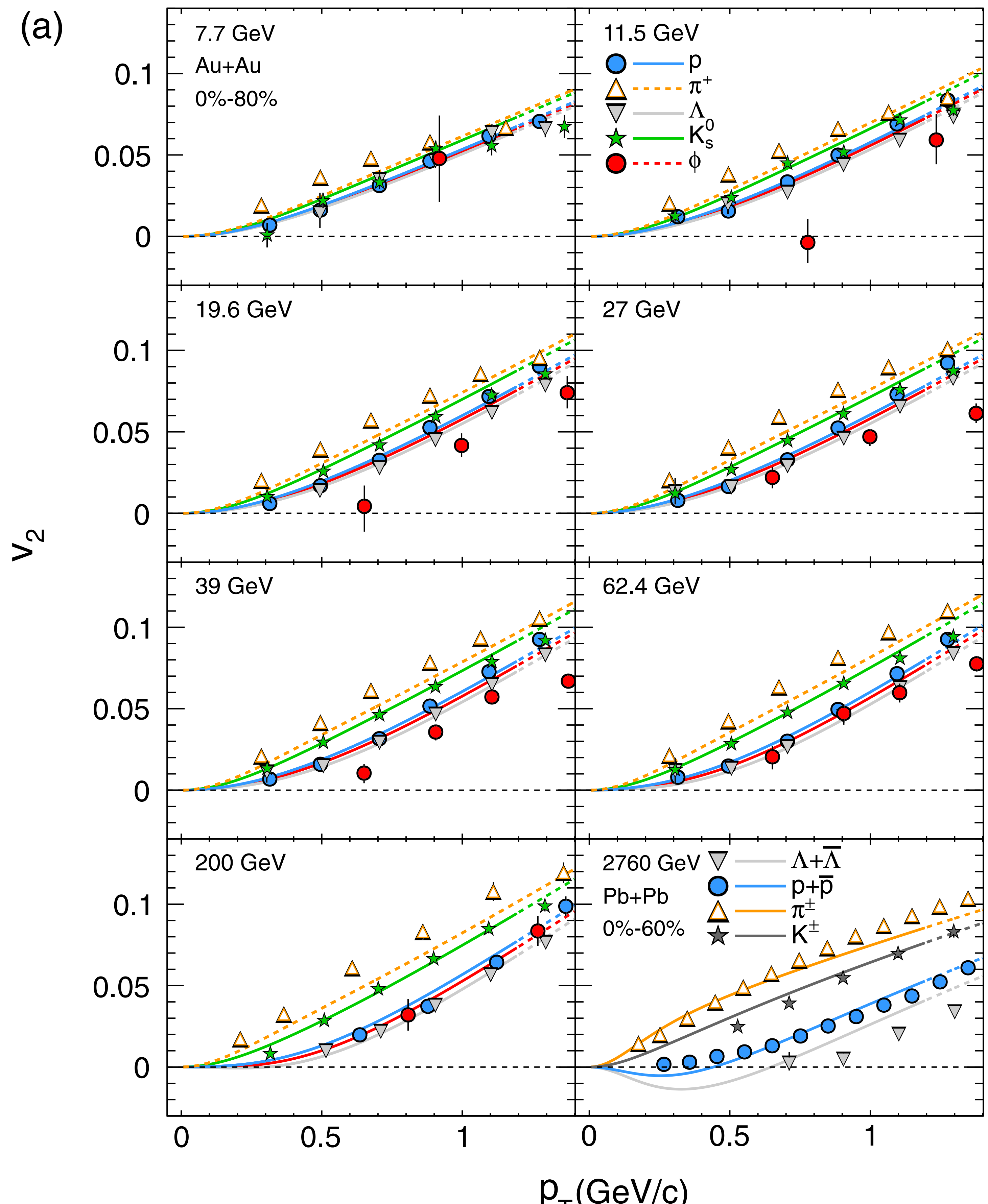
Why does blast wave work ?



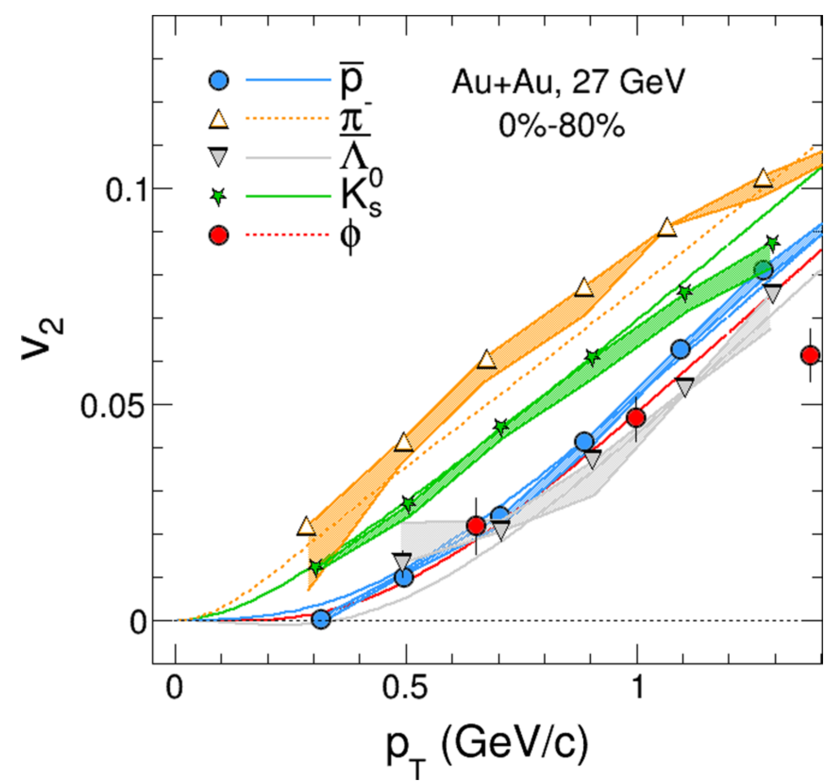
$$\beta_t(\phi_s) = \frac{m_T}{T}\cosh\rho(\phi_s)$$

- For the same β
  - heavier particles have larger p_T
    - $K_1(\beta_t) \sim \exp(-\beta_t)$
  - For a given p_T, v_2 is more out-of-plane extended for heavier particles
    - because particles around in-plane pushes to higher p_T
  - lighter particles have larger v_2

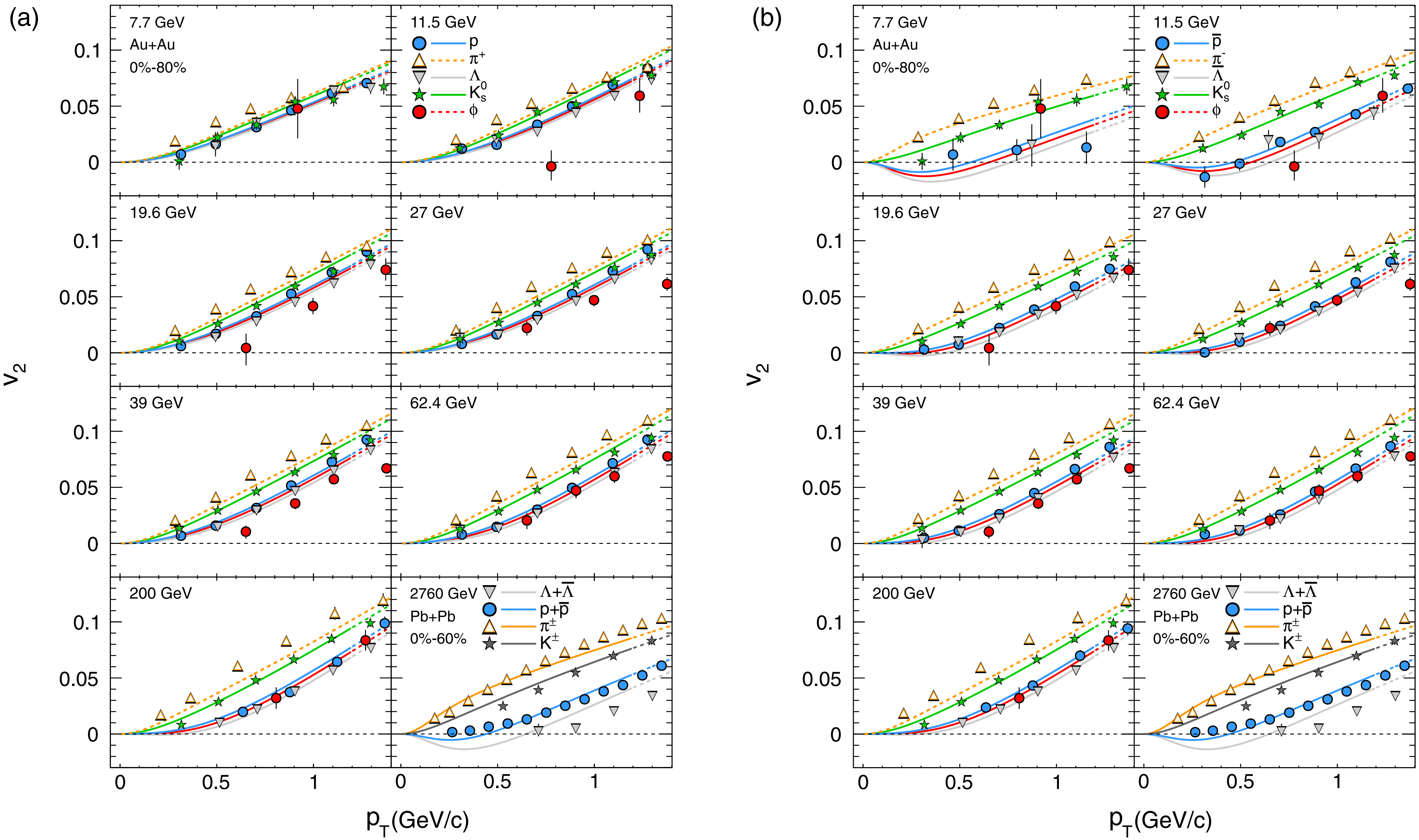
Feed down on pions ?



- pions
  - data > blast wave in 7.7-200 GeV
- feed down ?
  - Use MC simulation to evaluate feed down
    - due to lack of spectra, resonance measurements



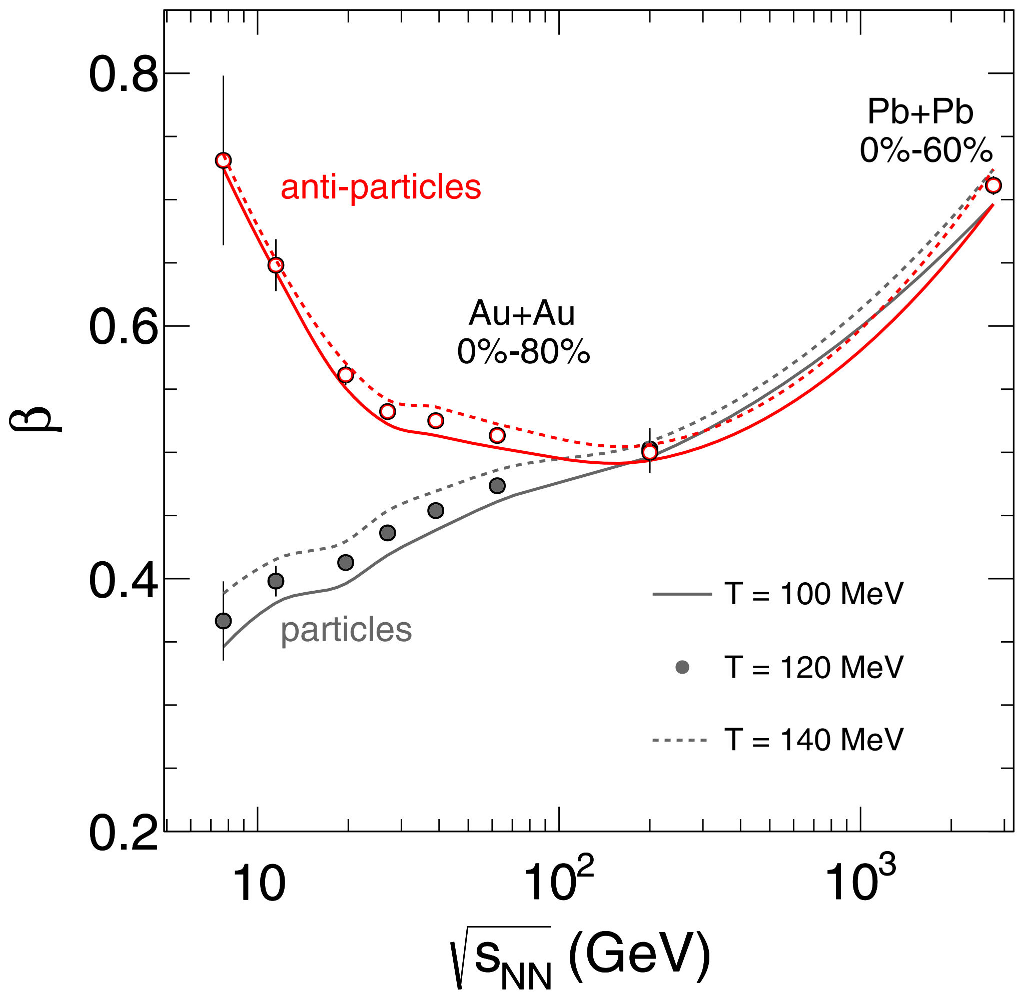
Large radial flow for antiparticles

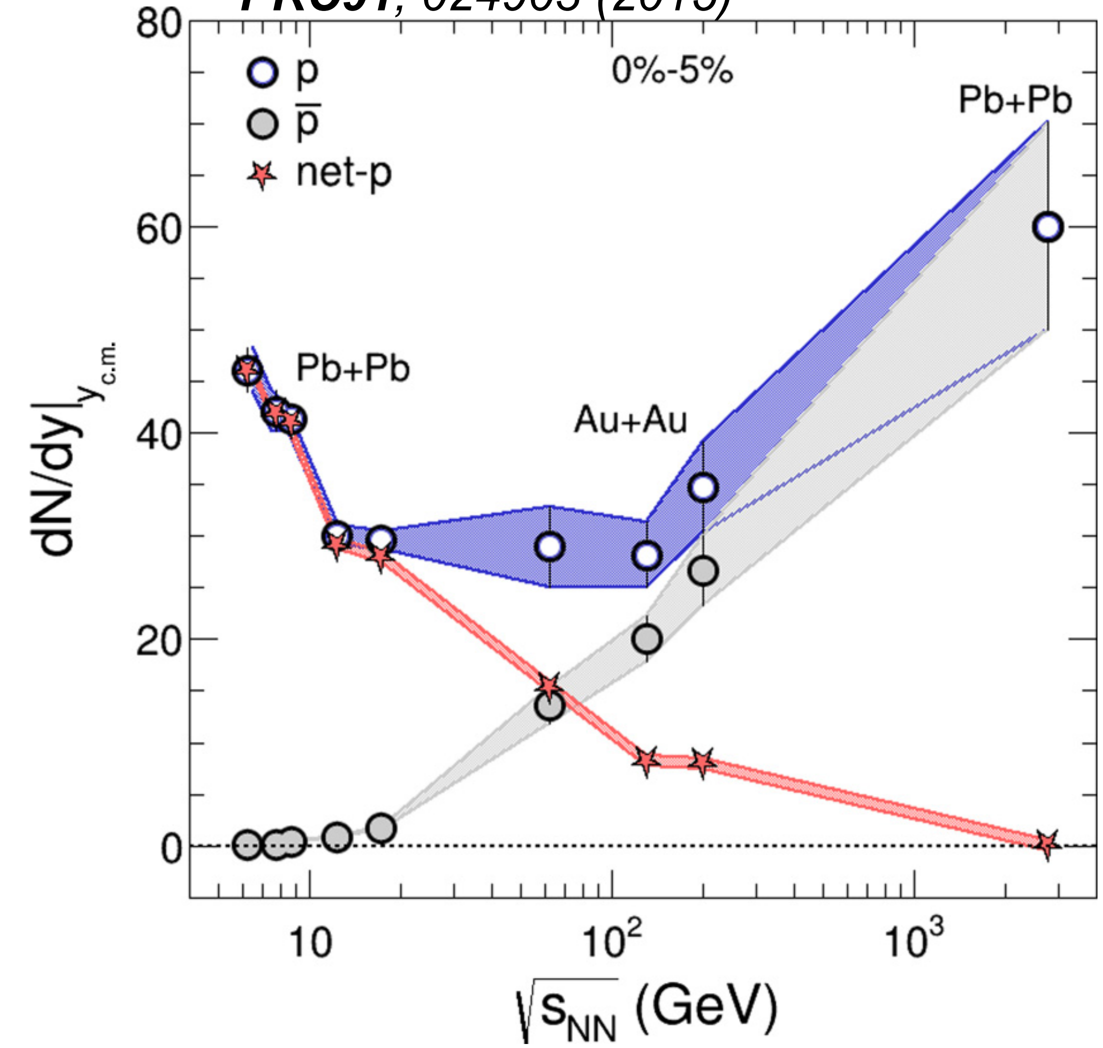


- Large spread of v_2 for antiparticles at lower energies
- Fit is better for antiparticles in terms of χ^2

Transverse velocity

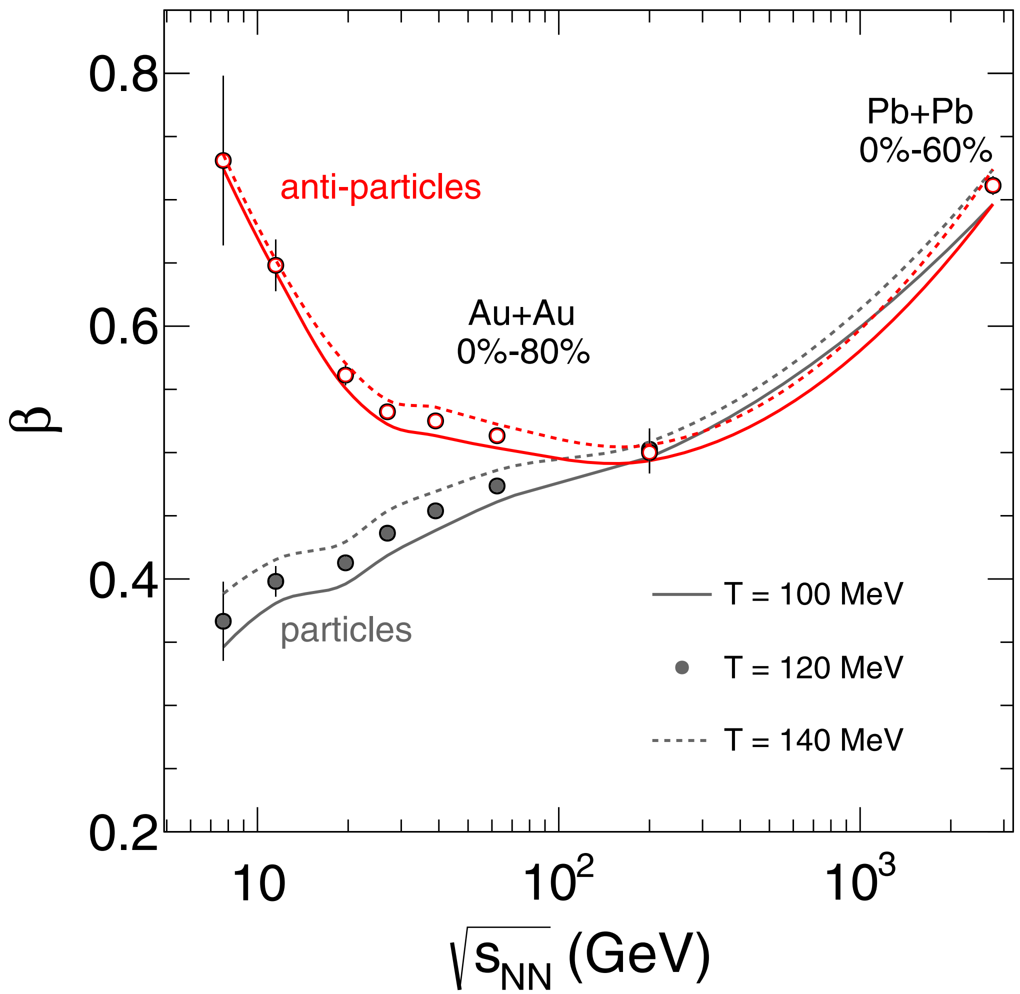
X. Sun, H. Masui, A. M. Poskanzer, A. Schmah
***PRC91**, 024903 (2015)*

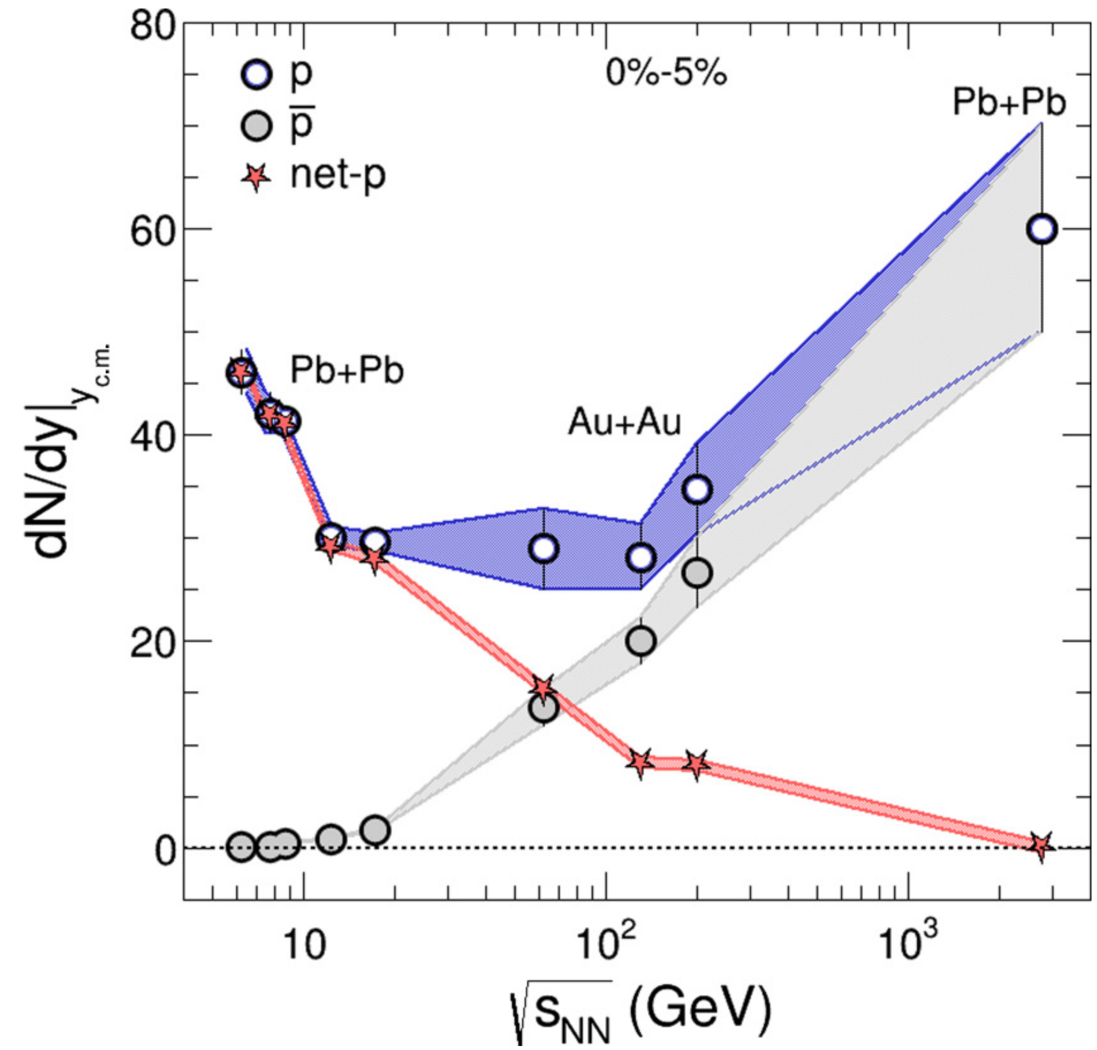




- Different β for particles and antiparticles at lower energies
- Possible scenarios
  - Antiparticles produced early → large β since radial flow is cumulative
- Fraction of net-protons (stopped protons) increase, already significant at 62.4 GeV → baryon stopping ?

Transverse velocity



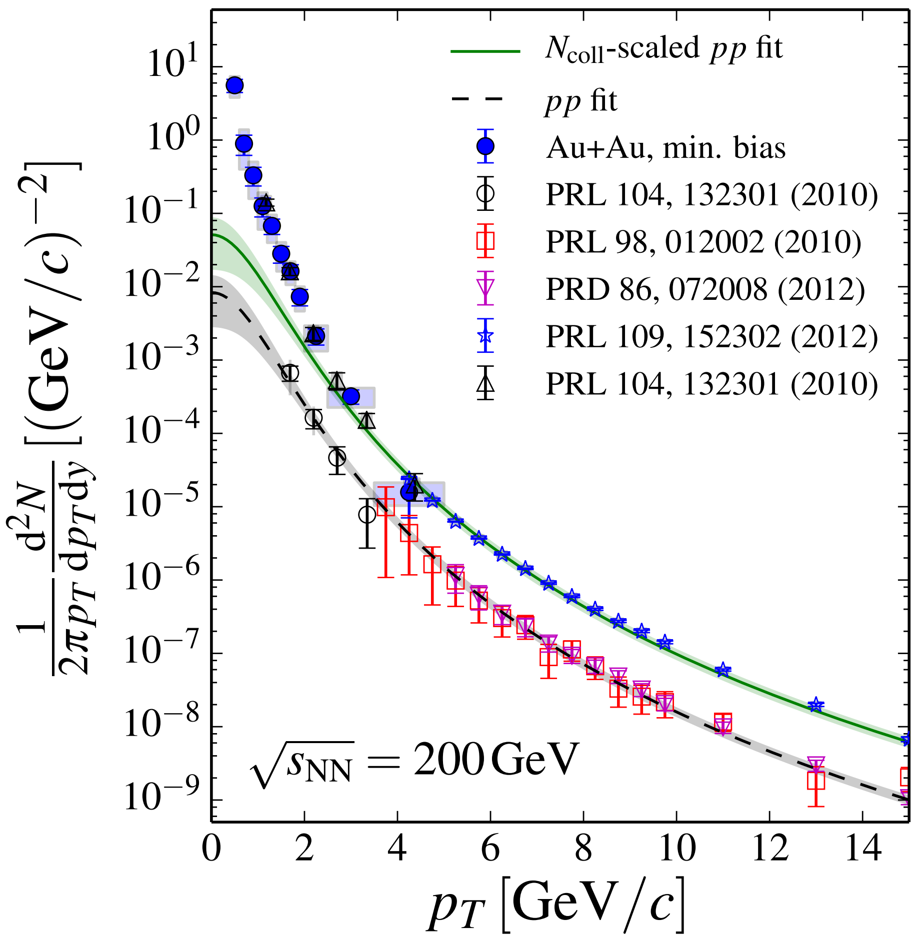


- Baryon stopping ?
  - v_2 could be different for produced and transported quarks → particles are contaminated by transported *u* & *d* quarks
  - Surface emission of antiprotons due to the absorption → effect is larger for lower energies (larger μ_B), smaller at higher energies

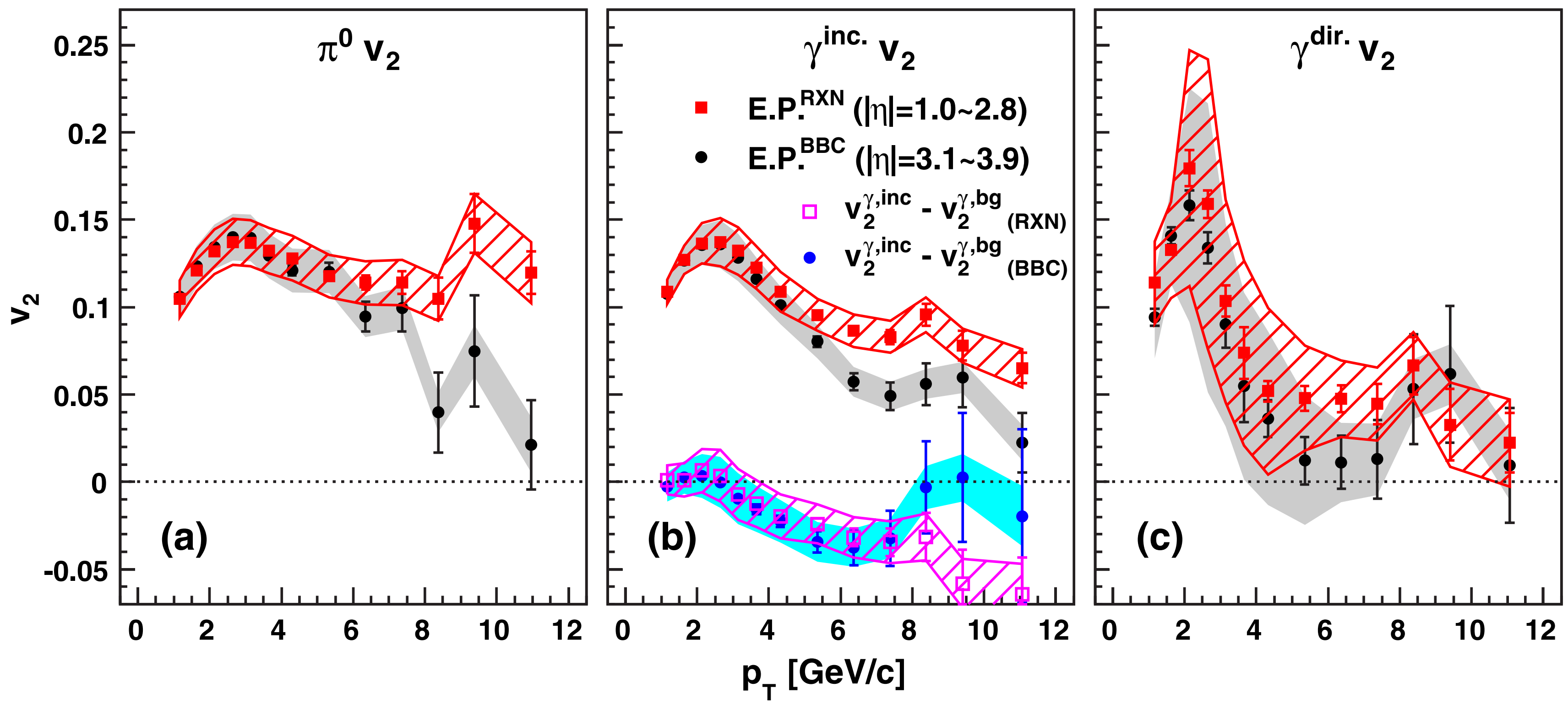
Direct photon v_n

Direct photon puzzle

PHENIX: arXiv:1405.3940v1

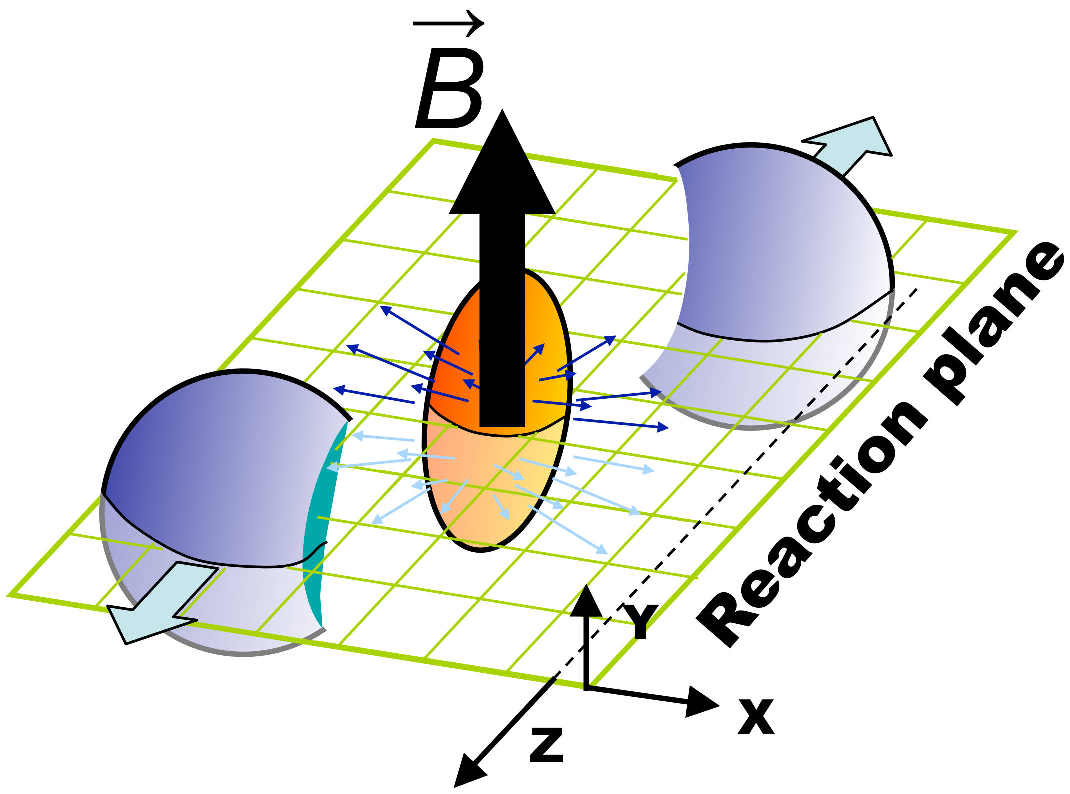


*PHENIX: **PRL109**, 122302 (2012)*



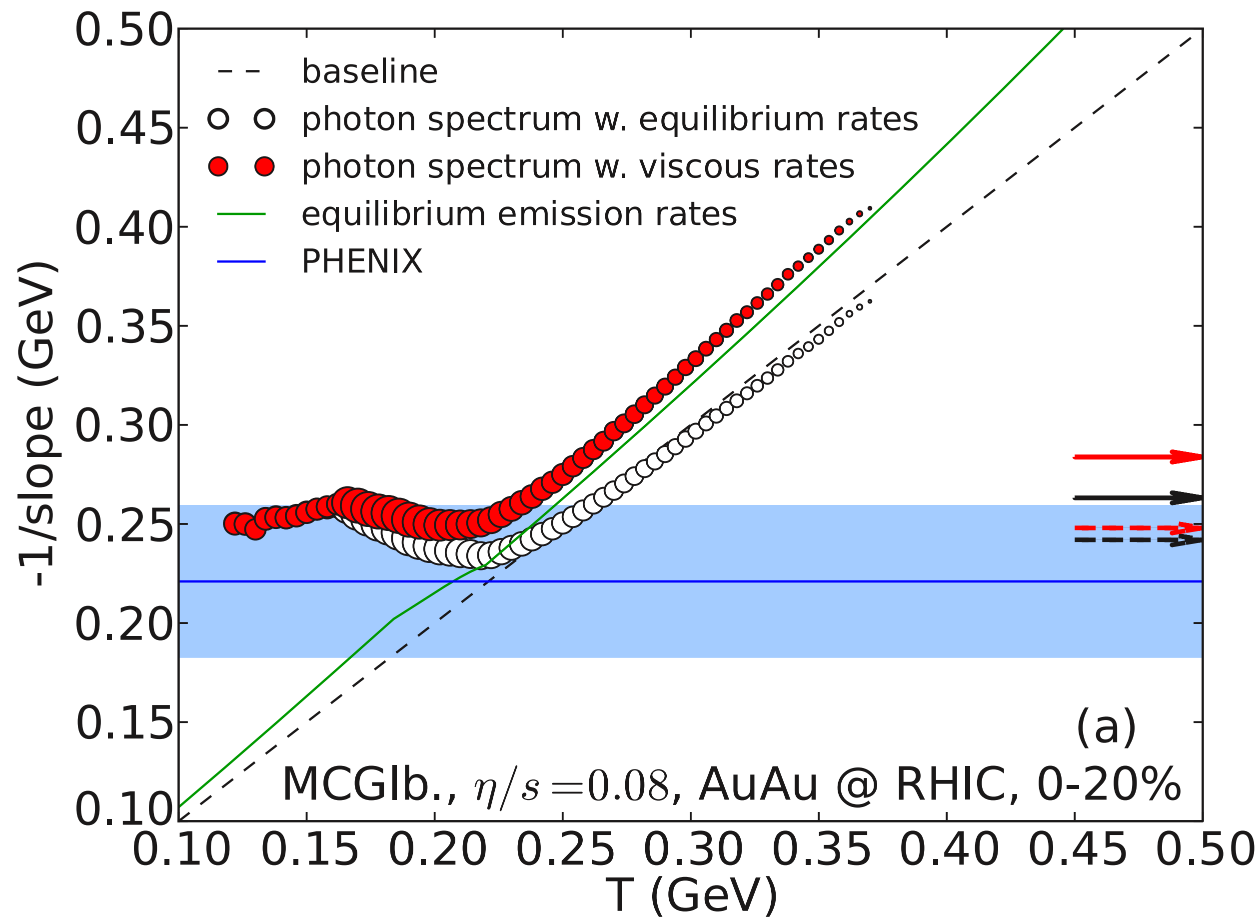
- Enhancement of direct photon p_T spectra relative to p+p
  - Inverse slope T~240 MeV (0-20%) for the excess of p_T spectra
- Large v_2 for direct photon at low p_T
  - comparable to the v_2 for π^0
- Is direct photon emitted early (p_T spectra) or late (v_2) ?

Several scenarios



*G. Basar et al, **PRL109**, 202303 (2012), …*

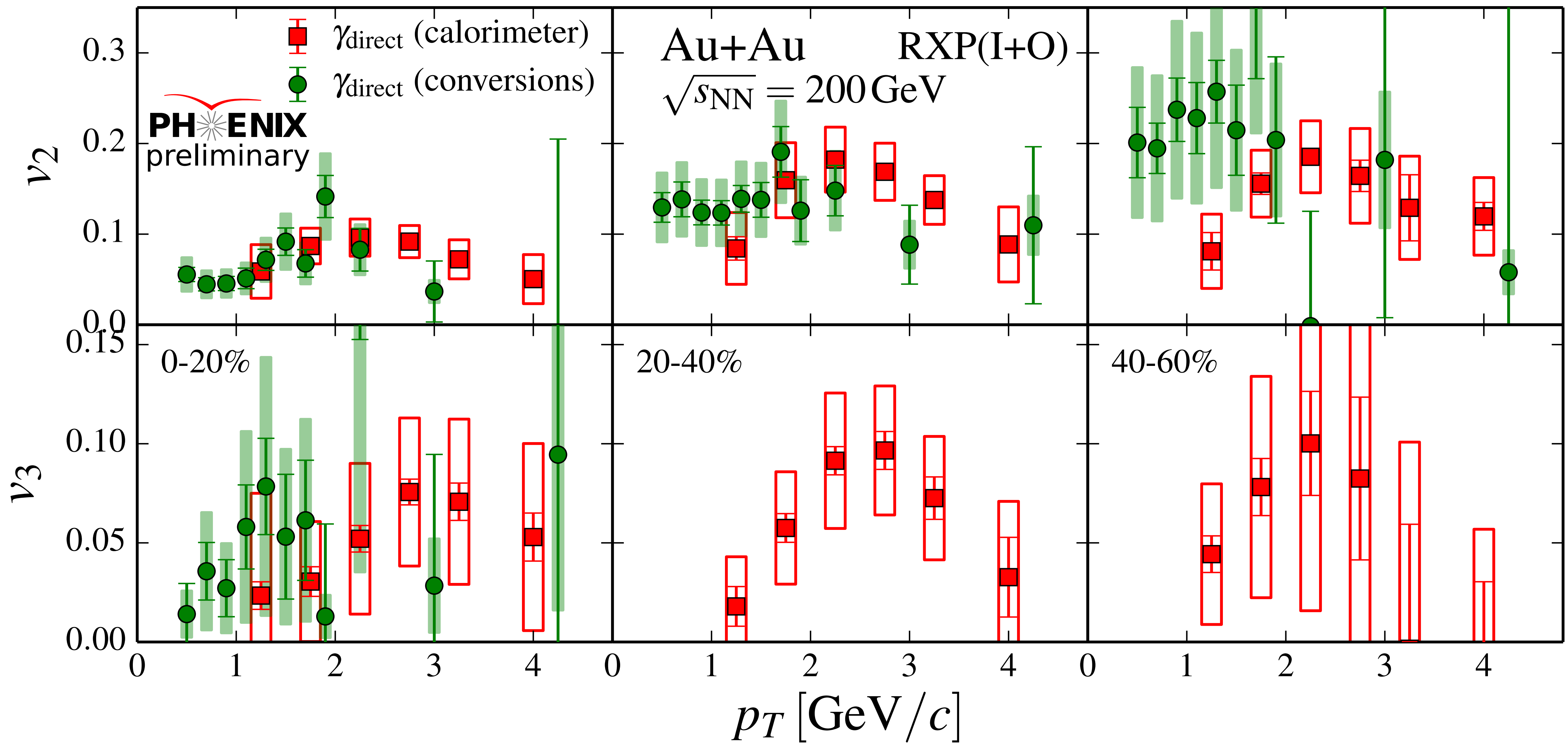
*C. Shen et al, **PRC89**, 044910 (2014)*



- Strong magnetic field → $v_2 > 0$, $v_3 \sim 0$
- Radial flow effect → $v_2 > 0$, $v_3 > 0$
- Measurements of v_3 provide additional constraints on direct photon production mechanism

Direct photon v_3

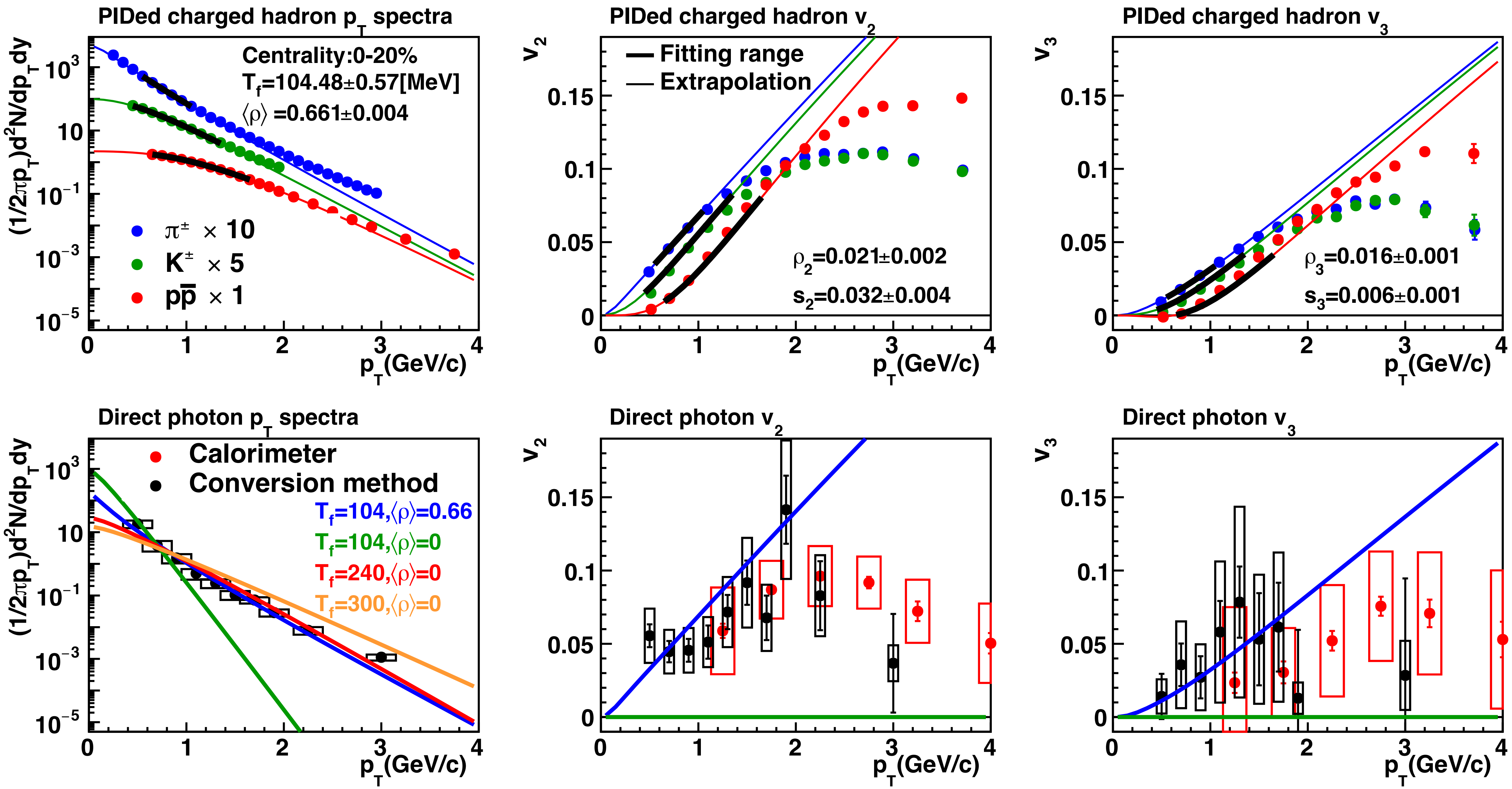
PHENIX: QM2014



- Non-zero, positive v_3
- No strong centrality dependence, similar with hadron v_3
- Strong magnetic field scenario cannot explain the data

Blast-wave fit

Sanshiro Mizuno, D-thesis



- Blast wave fit to direct photon p_T spectra & v_n
  - p_T spectra can be fitted with the same T for hadrons
  - Reasonable description for v_2 & v_3

Summary

- Multi-strange hadron v_2 at 200 GeV shows mass ordering violation
  - need quantitative comparison with the latest hydrodynamical models

- v_2 at RHIC BES (particles vs antiparticles)
  - NCQ scaling break down between particles and antiparticles
  - can be understood as different radial flow velocity (if mass ordering of v_2 is only due to radial flow)
  - Need more statistics, better model calculations

- Finite direct photon v_n at RHIC
  - Naive strong magnetic field scenario cannot explain the data
  - Large v_n, blast wave fit (if applicable) could support that direct photons are emitted from late stage