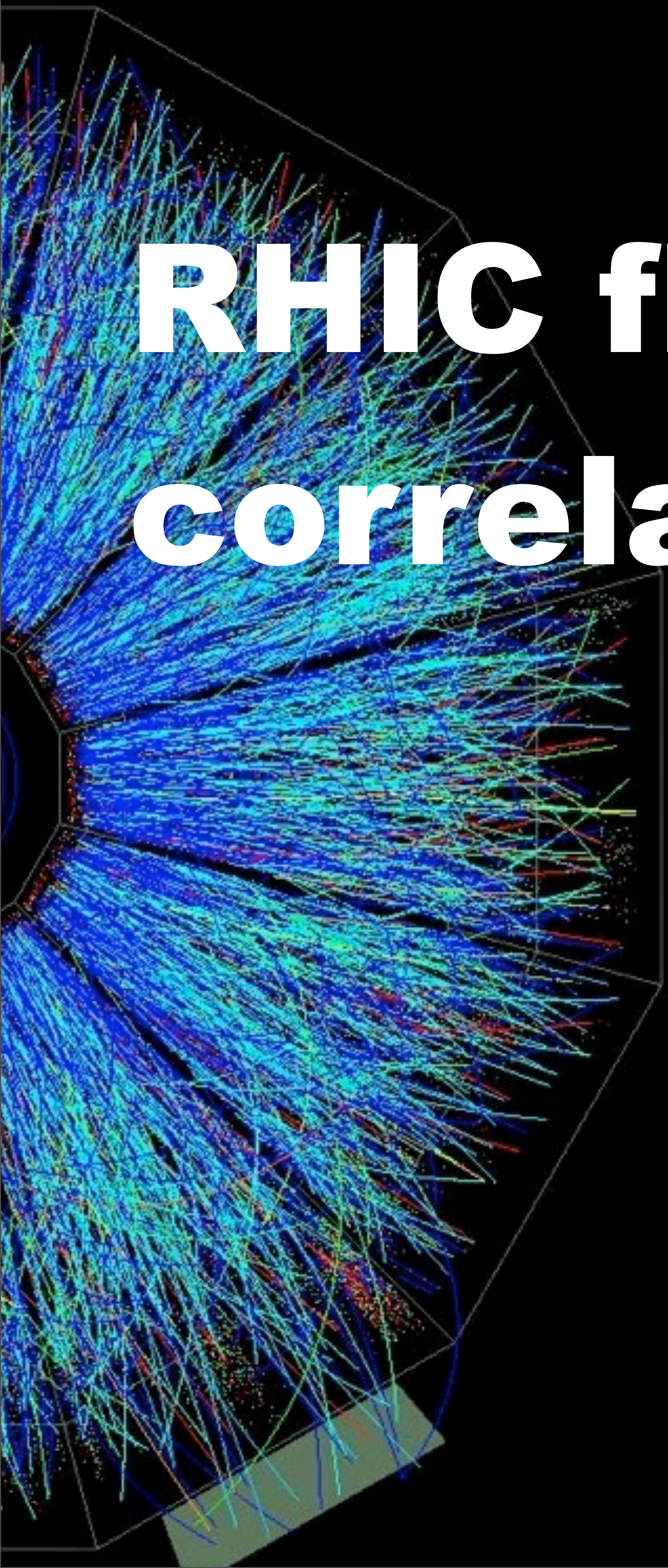
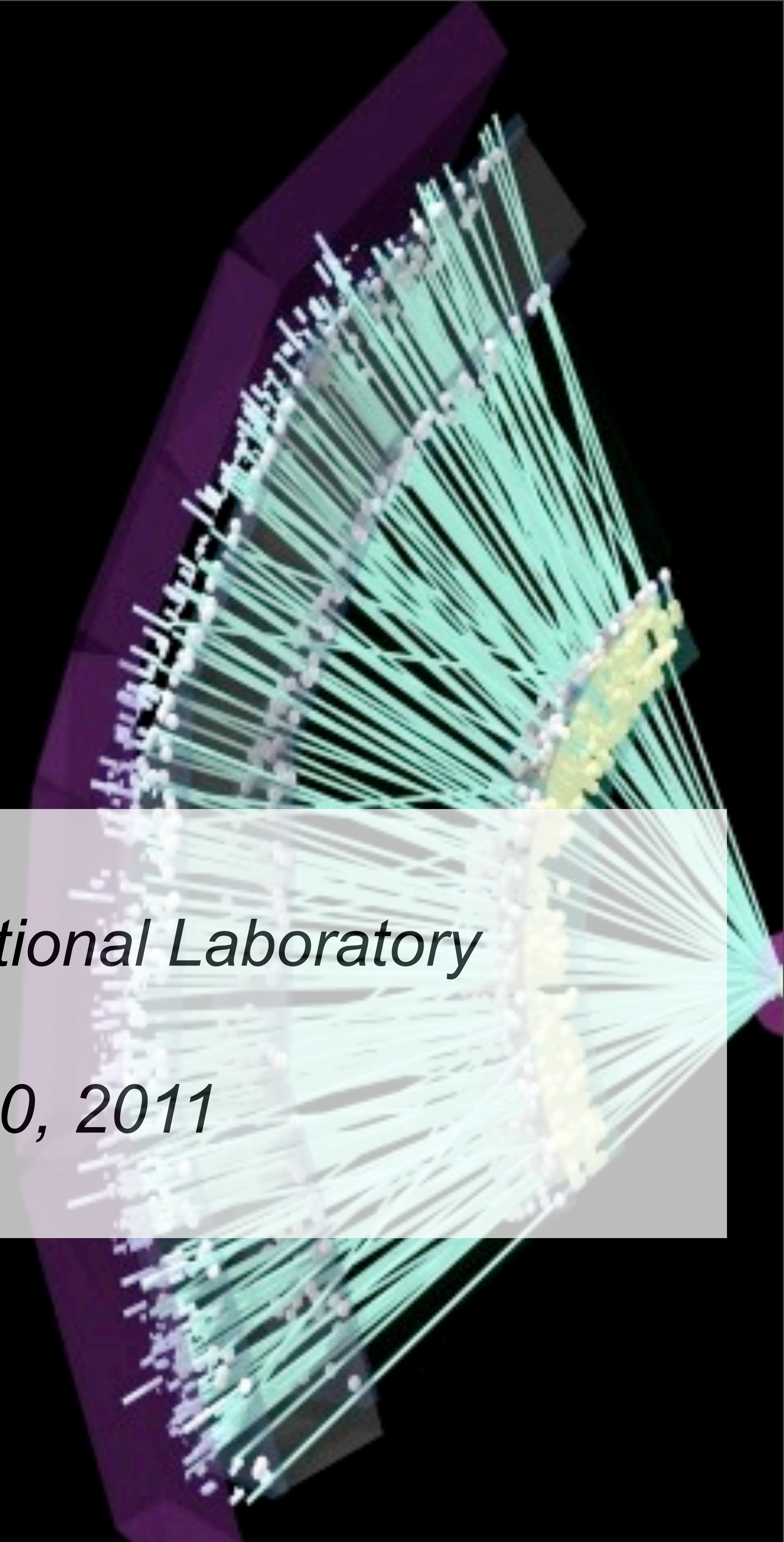
RHIC flow and correlation





Hiroshi Masui
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ISMD 2011, Sep. 25-30, 2011
Hiroshima, Japan

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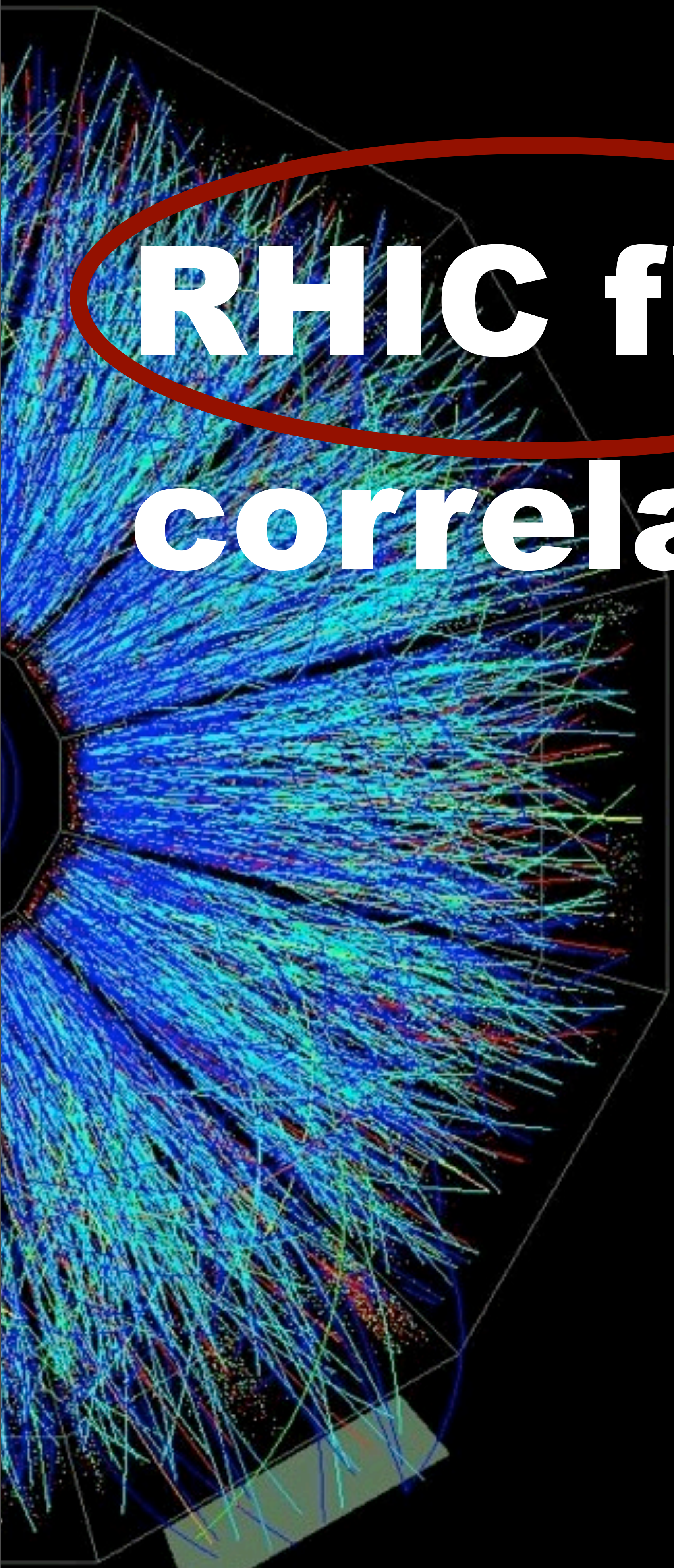

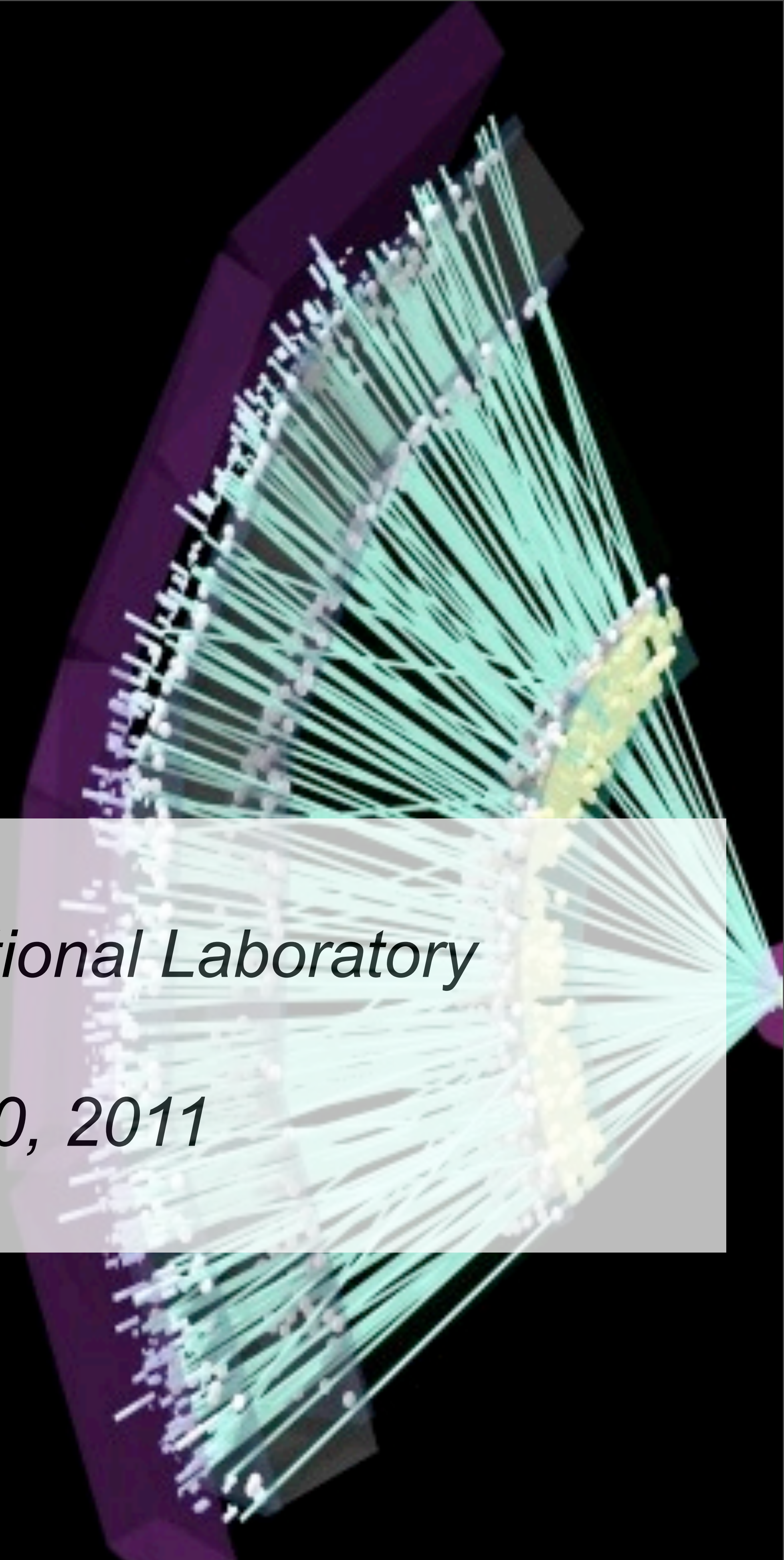

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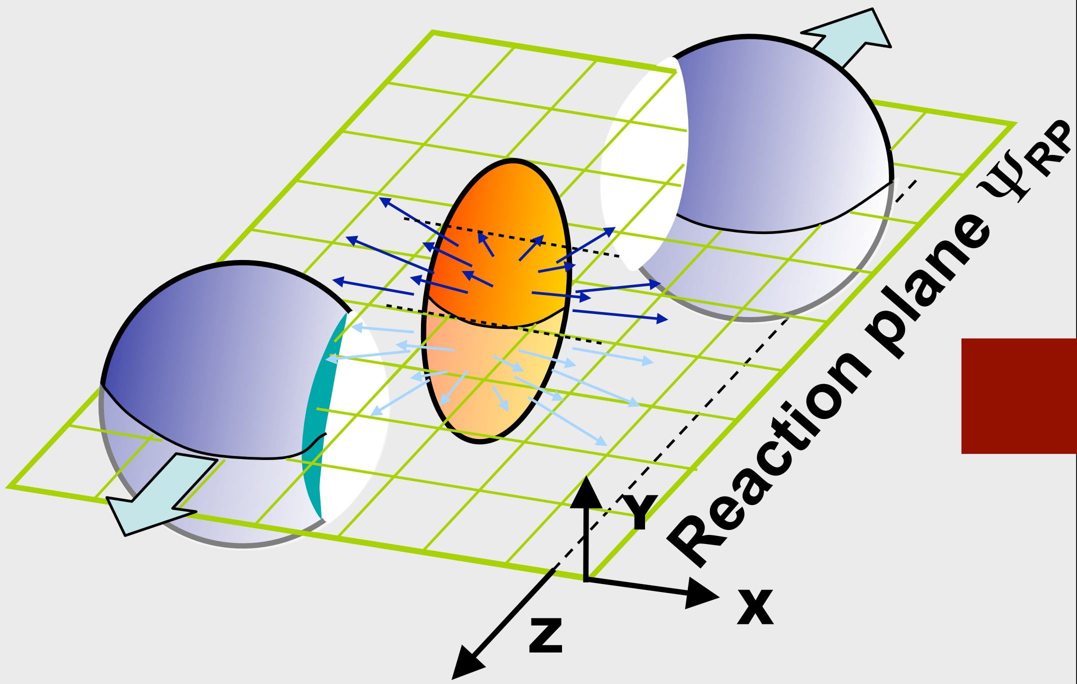
Outline

- Introduction
  - Why do we study anisotropic flow ?
  - How to measure flow ?
- Recent results from STAR and PHENIX at RHIC
  - Partonic collectivity
    - J/ψ v_2, Beam Energy Scan (BES) $\sqrt{s_{NN}}$ = 7.7 - 39 GeV
  - v_2 for direct photons
  - Higher harmonics, v_3
- Conclusions

Anisotropic flow, why ?

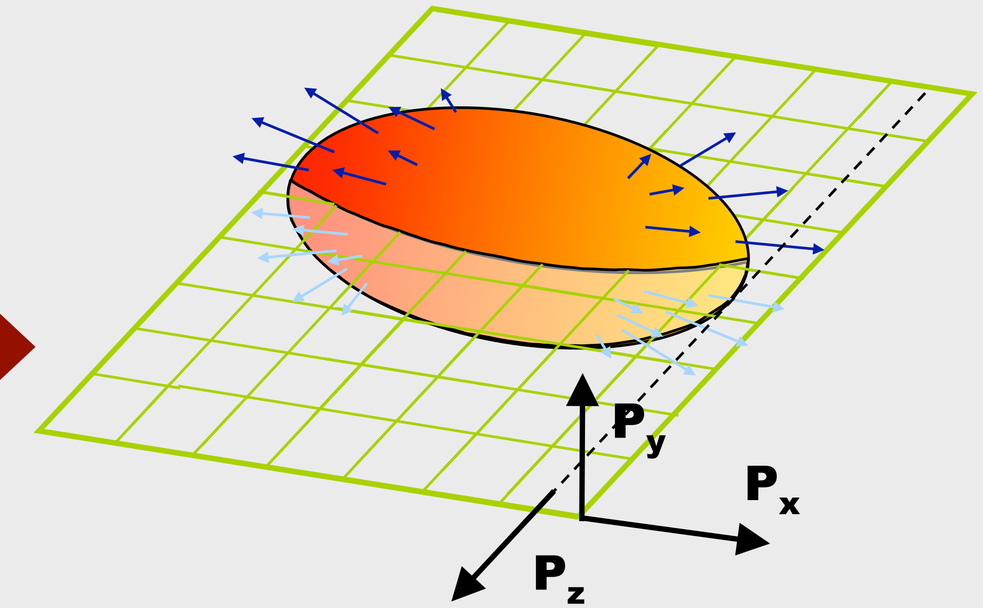
coordinate space



Initial geometry overlap

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

momentum space



final momentum anisotropy

$$\alpha = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

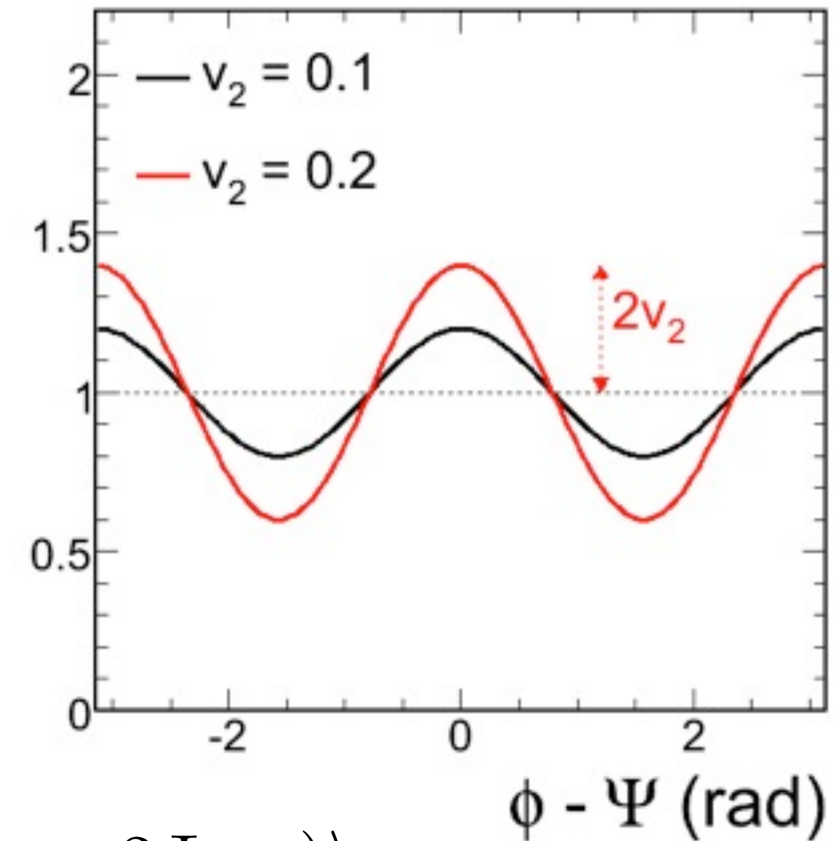
- Space-momentum correlation
  - Conversion efficiency depends on ε, Equation of State, degrees of freedom, transport coefficients, ...
- Sensitive to partonic collision dynamics in early stage

How to measure flow ?

$$\frac{dN}{d(\phi - \Psi_{\mathrm{RP}})} \propto 1 + 2v_2 \cos\left(2\phi - 2\Psi_{\mathrm{RP}}\right)$$

ϕ : azimuthal angle of particles

Ψ_{RP} : azimuthal angle of reaction plane



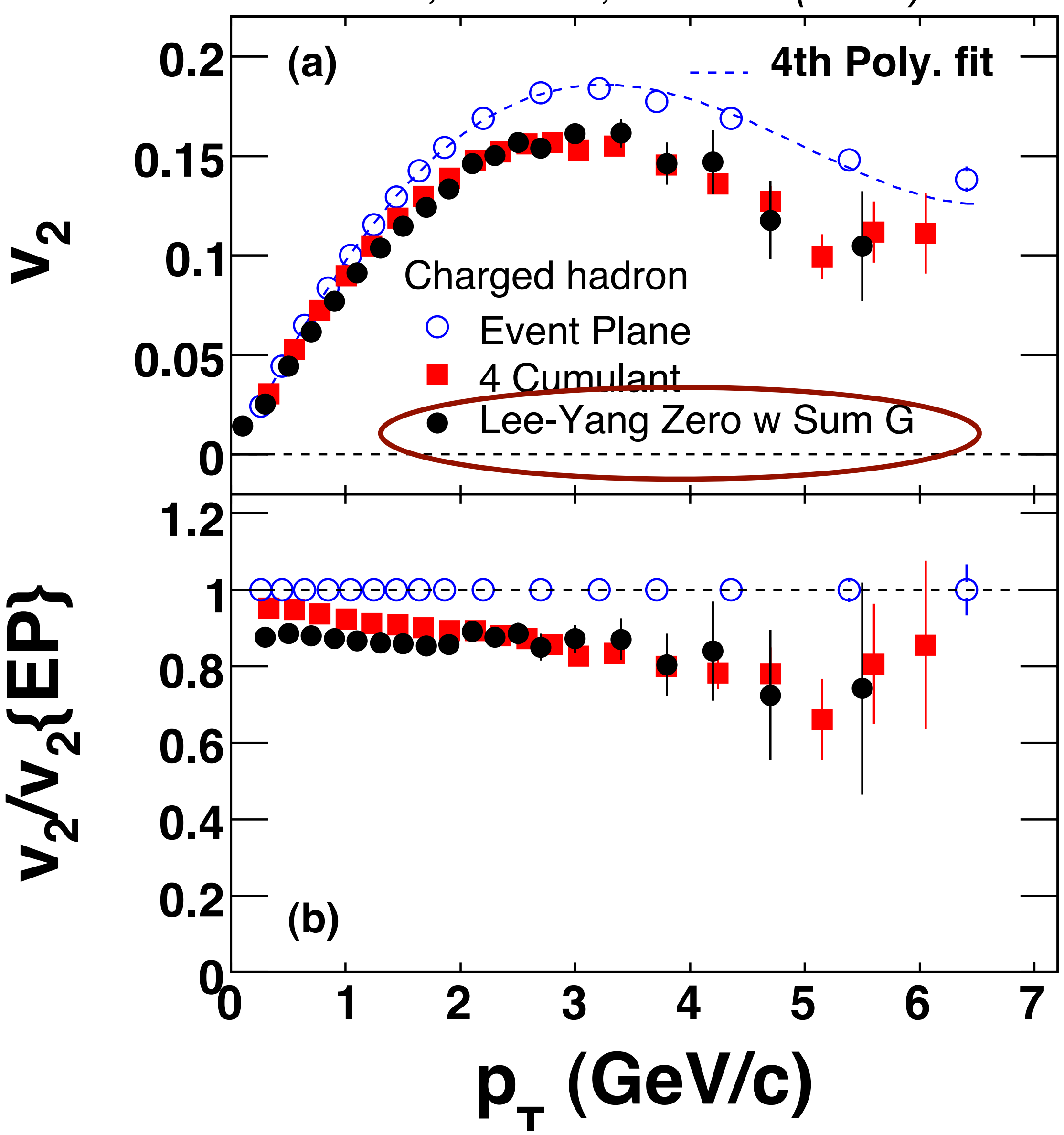
$$v_2^{measured} = \langle \cos\left(2\phi - 2\Psi_{\mathrm{EP}}\right) \rangle = v_2 \times \langle \cos\left(2\Psi_{\mathrm{EP}} - 2\Psi_{\mathrm{RP}}\right) \rangle$$

$$v_2^{measured} = \langle \cos\left(2\phi - 2\phi_{\mathrm{ref}}\right) \rangle = v_2 \times v_2^{\mathrm{ref}}$$

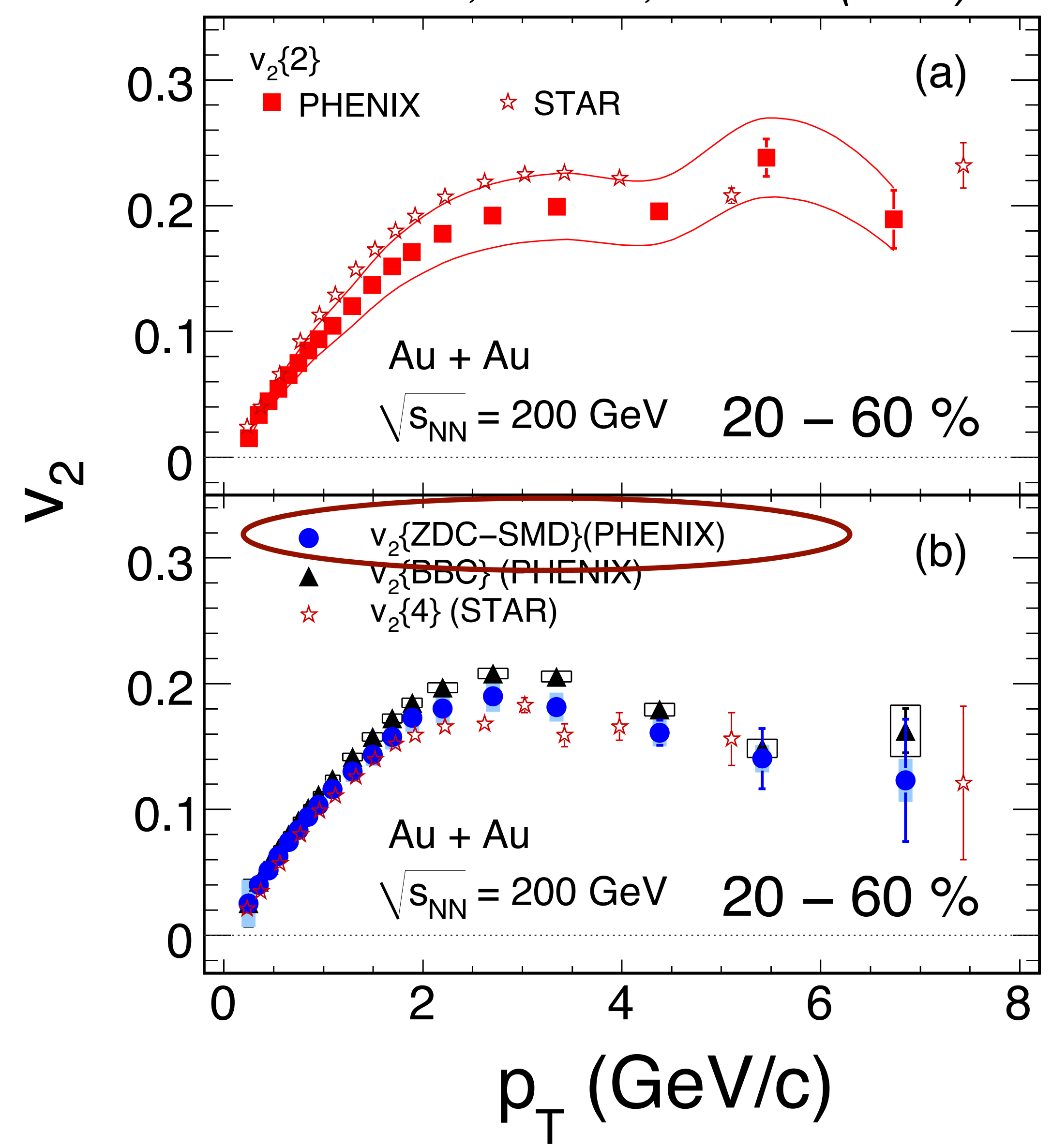
- Fourier decomposition of azimuthal particle distribution
- Reaction plane cannot be measured experimentally
  - Event plane method; estimate reaction plane
  - n-particle correlation; reaction plane is not required

Is v_2 sensitive to anisotropic flow ?

STAR, PRC77, 054901 (2008)

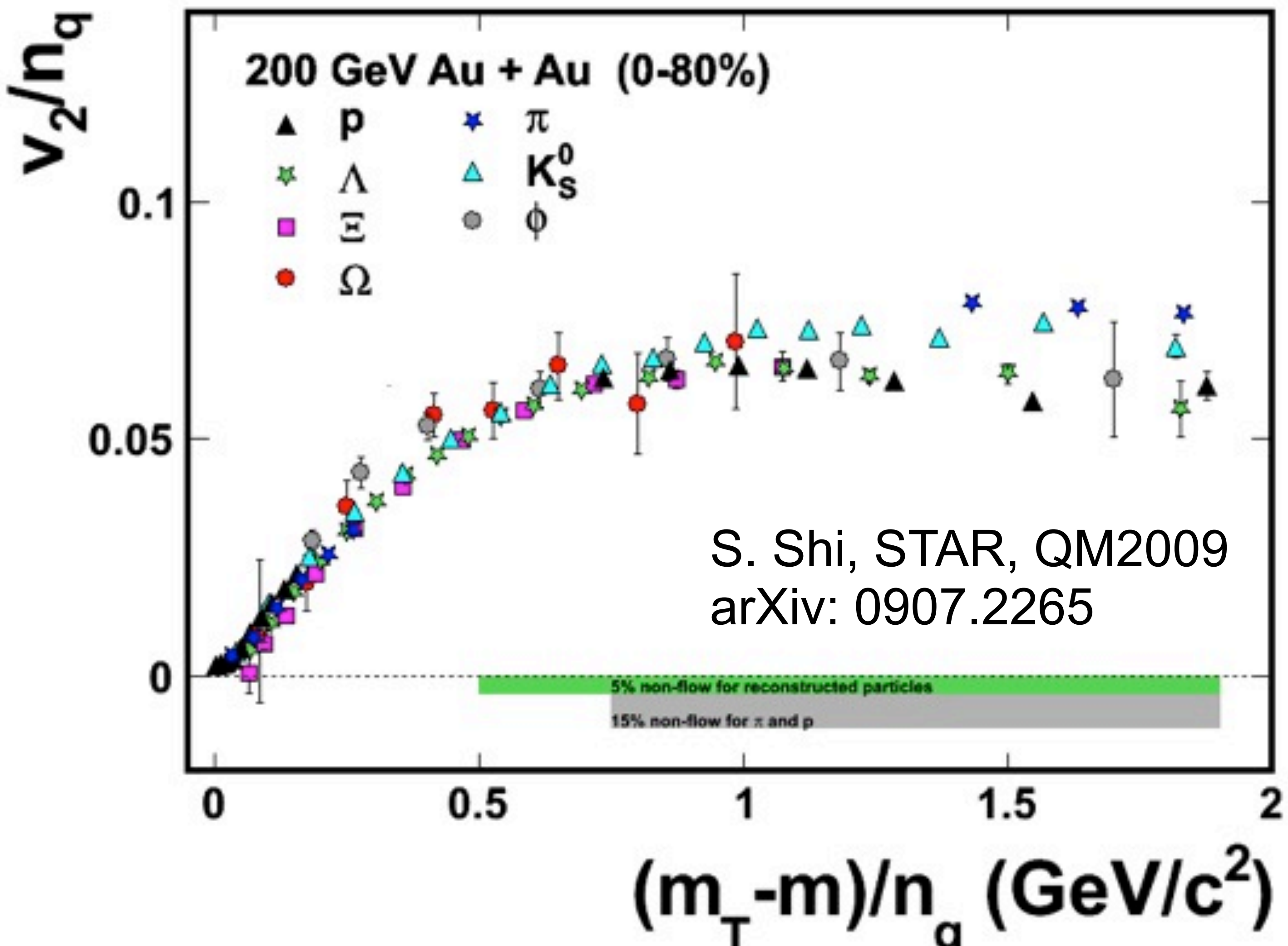


PHENIX, PRC80, 024909 (2009)



- Yes !
  - Correlations among all measured particles (STAR)
  - Correlations with spectator neutrons at $|\eta|>6$ (STAR&PHENIX)

Partonic collectivity



$$v_2^h(p_T) \approx n_q v_2^q(p_T/n_q)$$
$$(v_2^q \ll 1)$$

Quark coalescence/recombination
*D. Molnar and S. Voloshin, **PRL91**, 092301 (2003)*
*V. Greco et al., **PRC68**, 034904 (2003)*
*R. J. Fries et al., **PRC68**, 044902 (2003)*
*J. Jia and C. Zhang **PRC75**, 031901(R) (2007)*
....

p_T ~2 GeV/c for π,
~3.8 GeV/c for protons

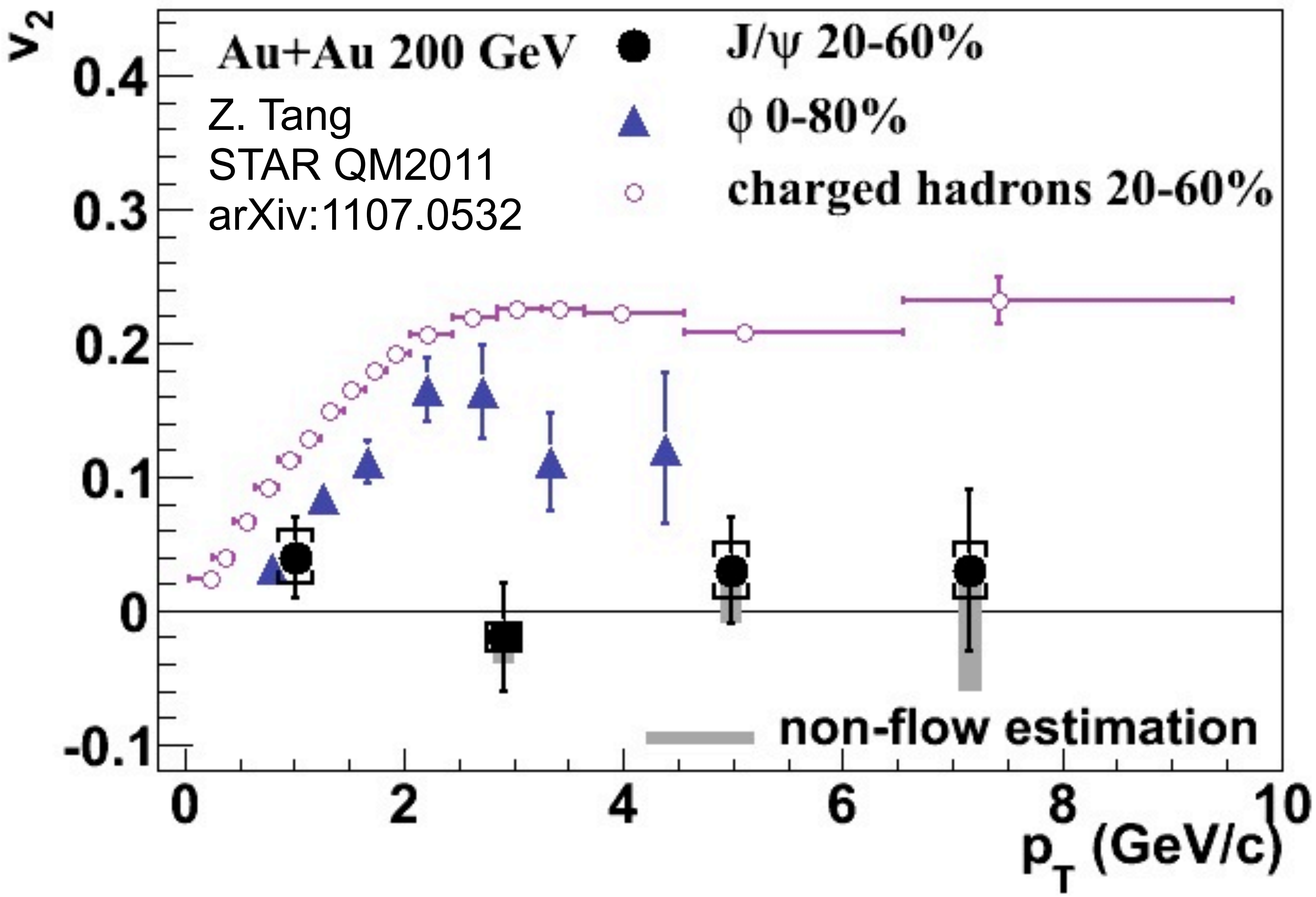
- Number of Quark (NQ) scaling holds up to ~1 GeV/c in (m_T - mass)/n_q
  - φ(ss), Ω(sss) follow the scaling

✓ Most of collectivity developed at early partonic stage

➡ How about charm ? Low energies ?

Less collectivity for J/ψ

*charged hadrons, STAR, **PRL93**, 252301 (2004)*
*ϕ, STAR, **PRL99**, 112301 (2007)*

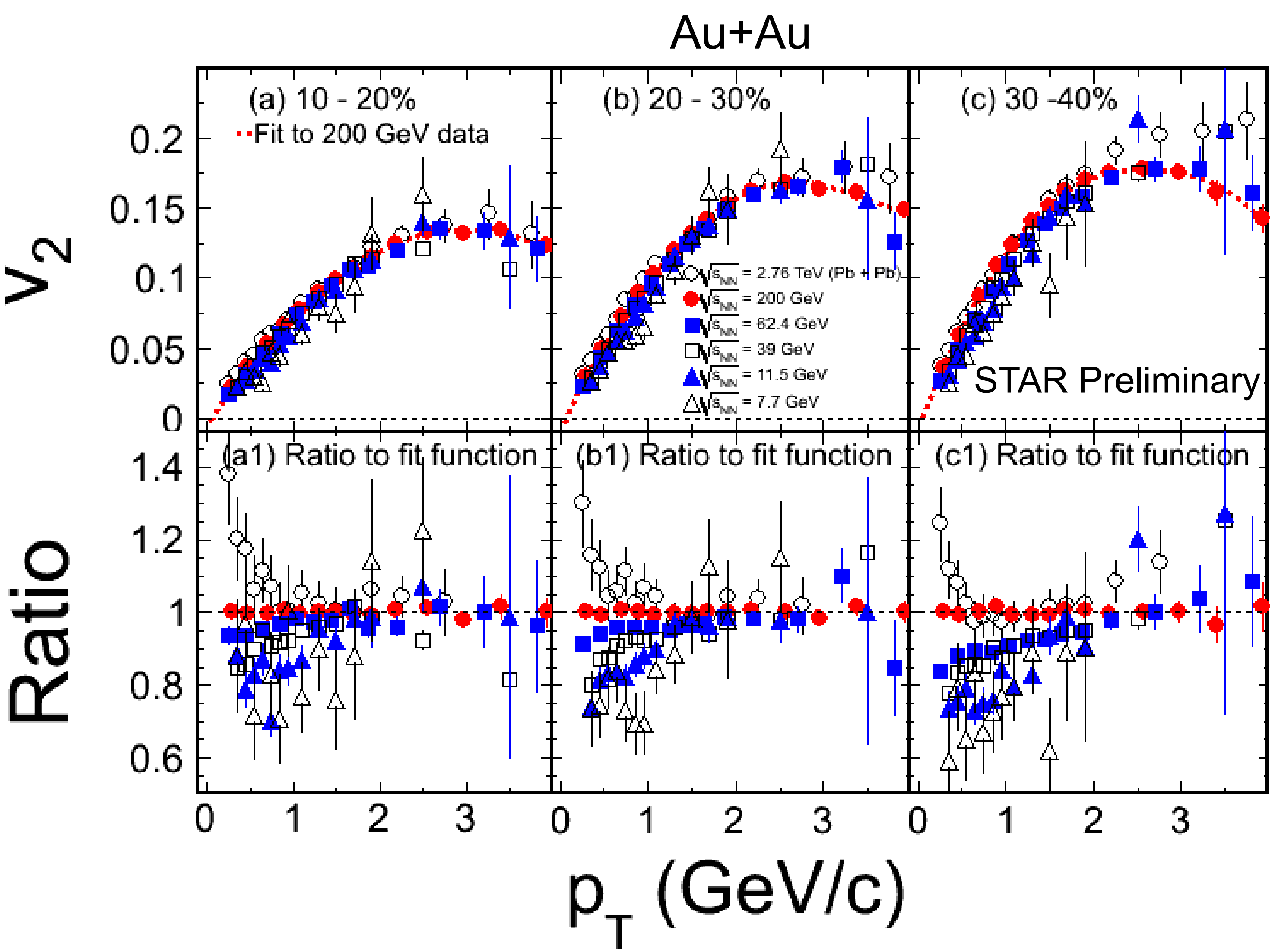


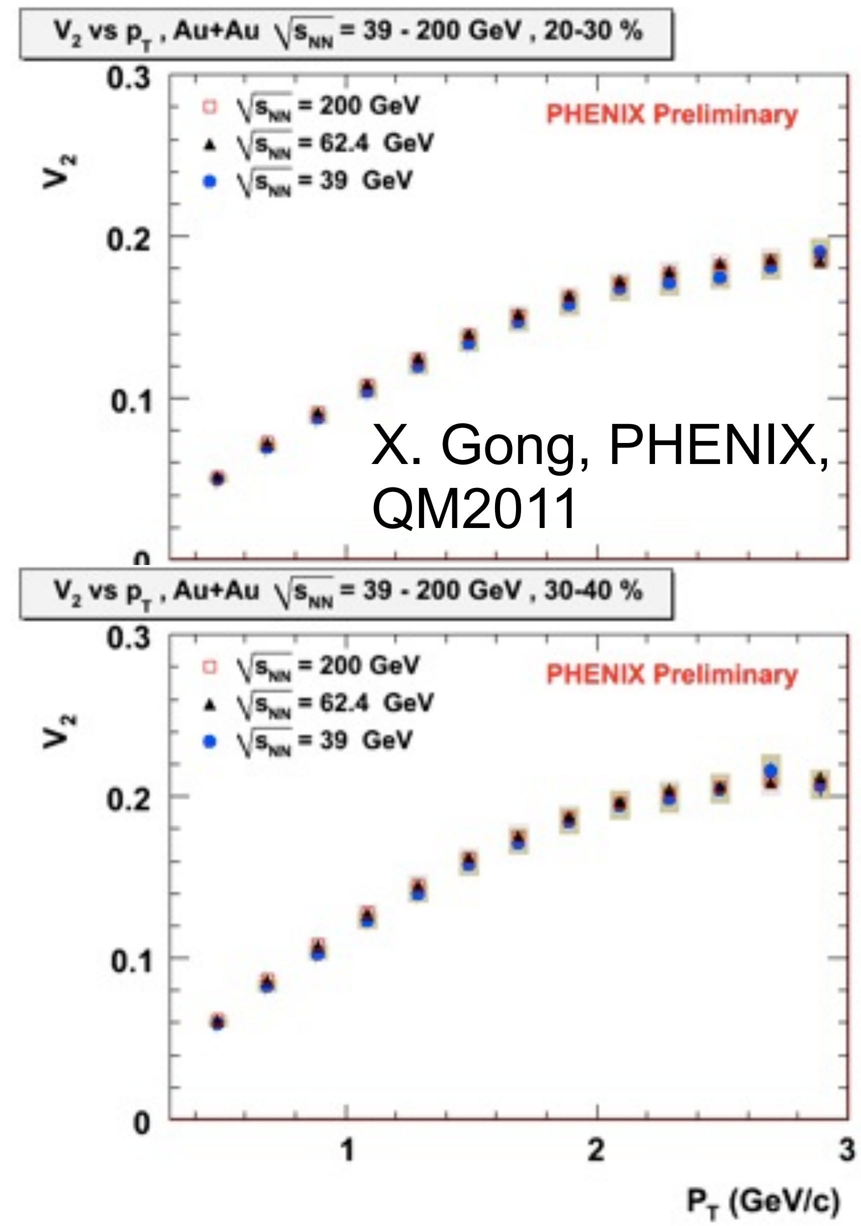
- J/ψ $v_2(p_T)$ is much less than those for other hadrons
  - Disfavors thermalized charm quark coalescence at RHIC
  - LHC ?

v_2 from 7.7 GeV to 2.76 TeV

S. Shi, STAR, QM2011

*ALICE, **PRL105**, 252302 (2010)*

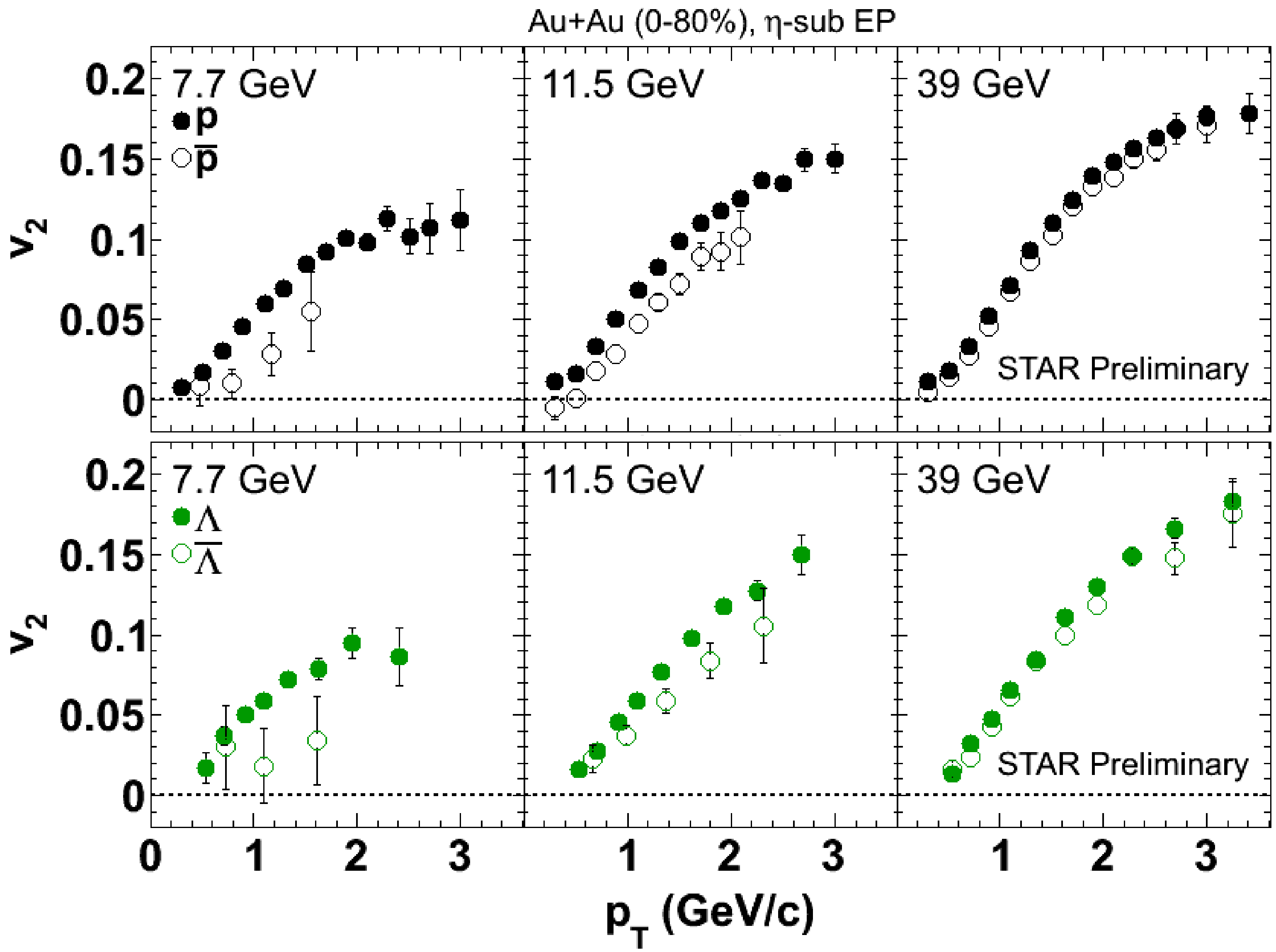


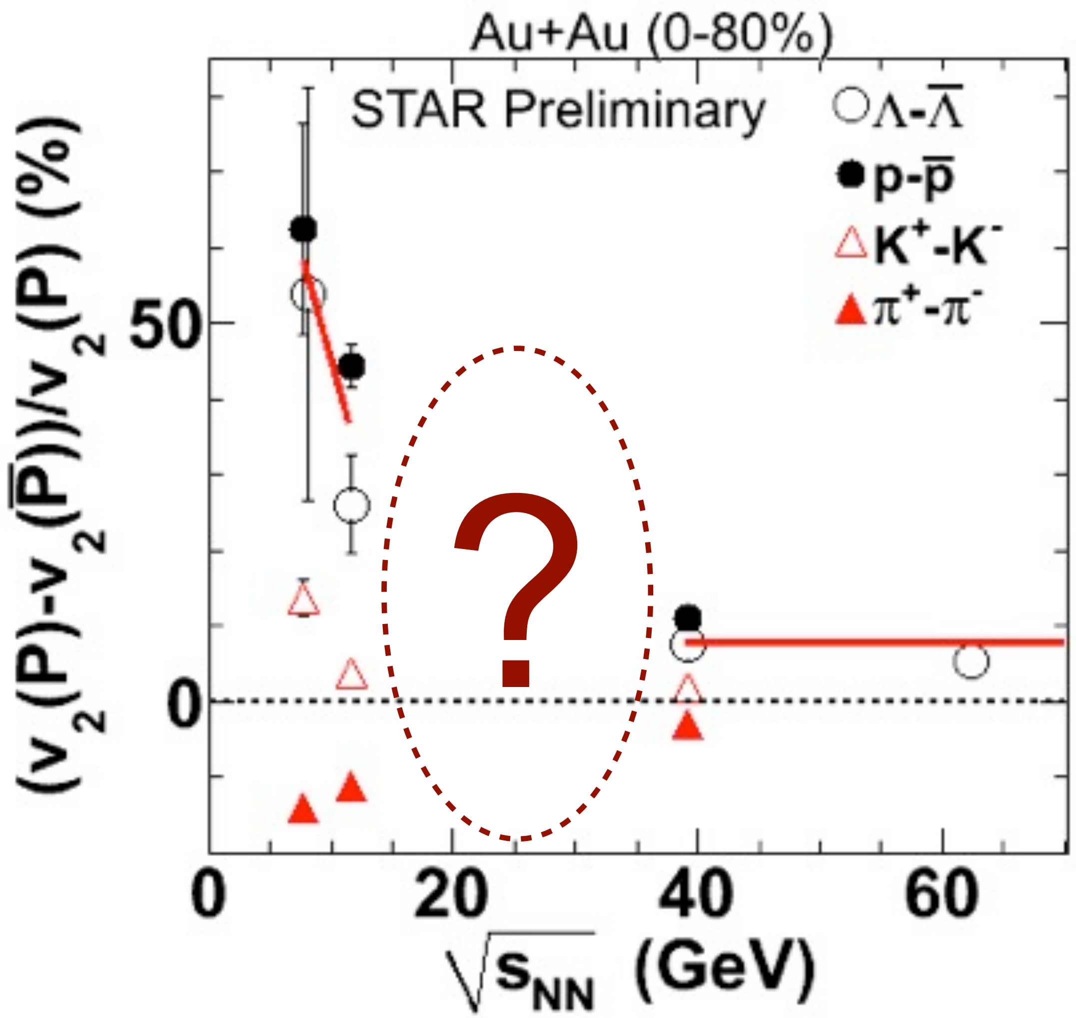


- $v_2(p_T)$ shape is similar over several order of magnitude in energy
  - ~ 30% difference at low p_T → Different particle composition ?
  - Is scaling broken at low energies ?

Is scaling broken at low $\sqrt{s_{NN}}$?

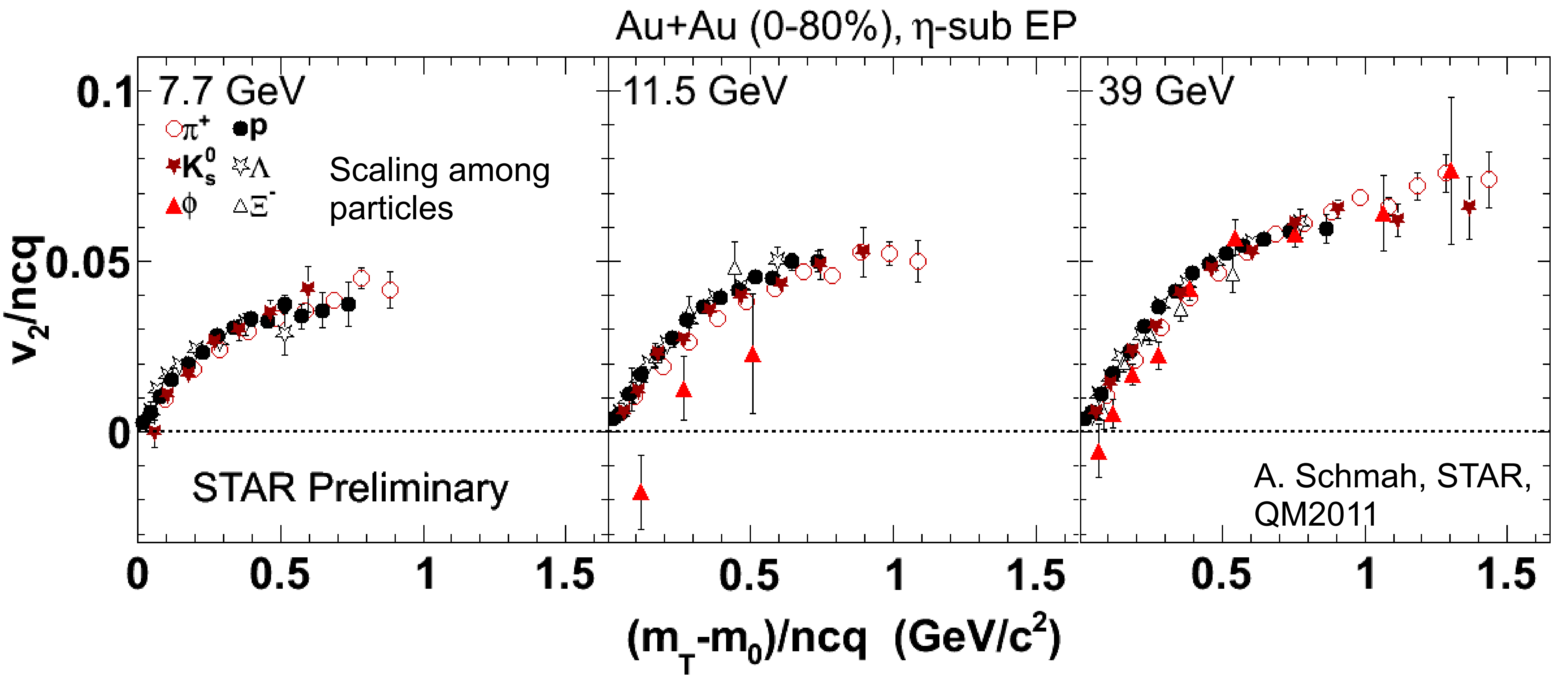
A. Schmah, STAR, QM2011





- Increase the difference of v_2 between baryons and anti-baryons, ~50% at $\sqrt{s_{NN}}$ = 7.7 GeV
  - Scaling is broken between particles and anti-particles at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV → Baryon transport ? Absorption ?

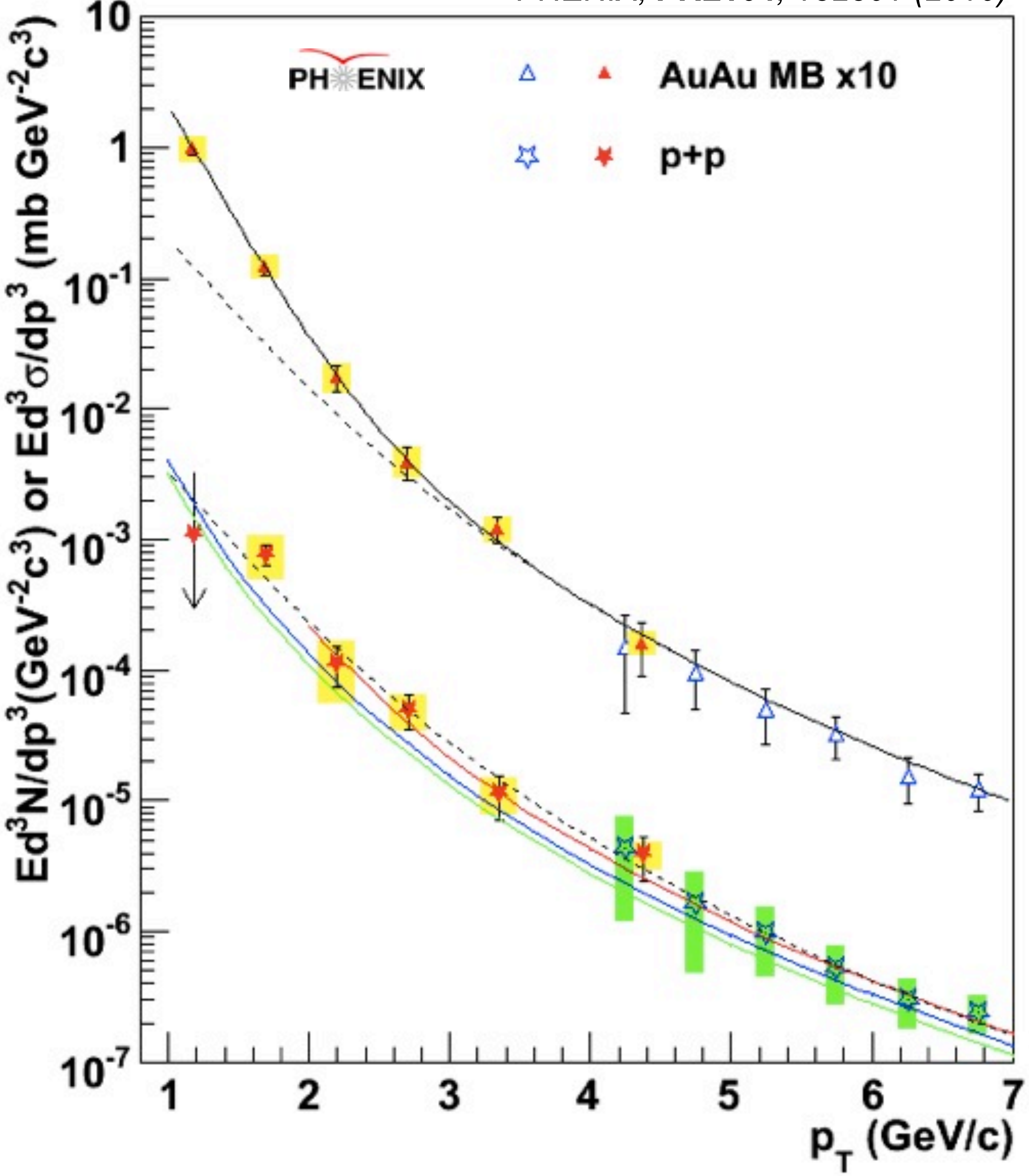
Is scaling broken at low $\sqrt{s_{NN}}$?



- v_2 for φ meson deviates from others at 11.5 GeV
  - Hadronic phase would be dominated at $\sqrt{s_{NN}}$ = 11.5 GeV
- Scaling among other hadrons seems to hold
  - Is hadronic cross section driven scaling ?

Direct photon excess

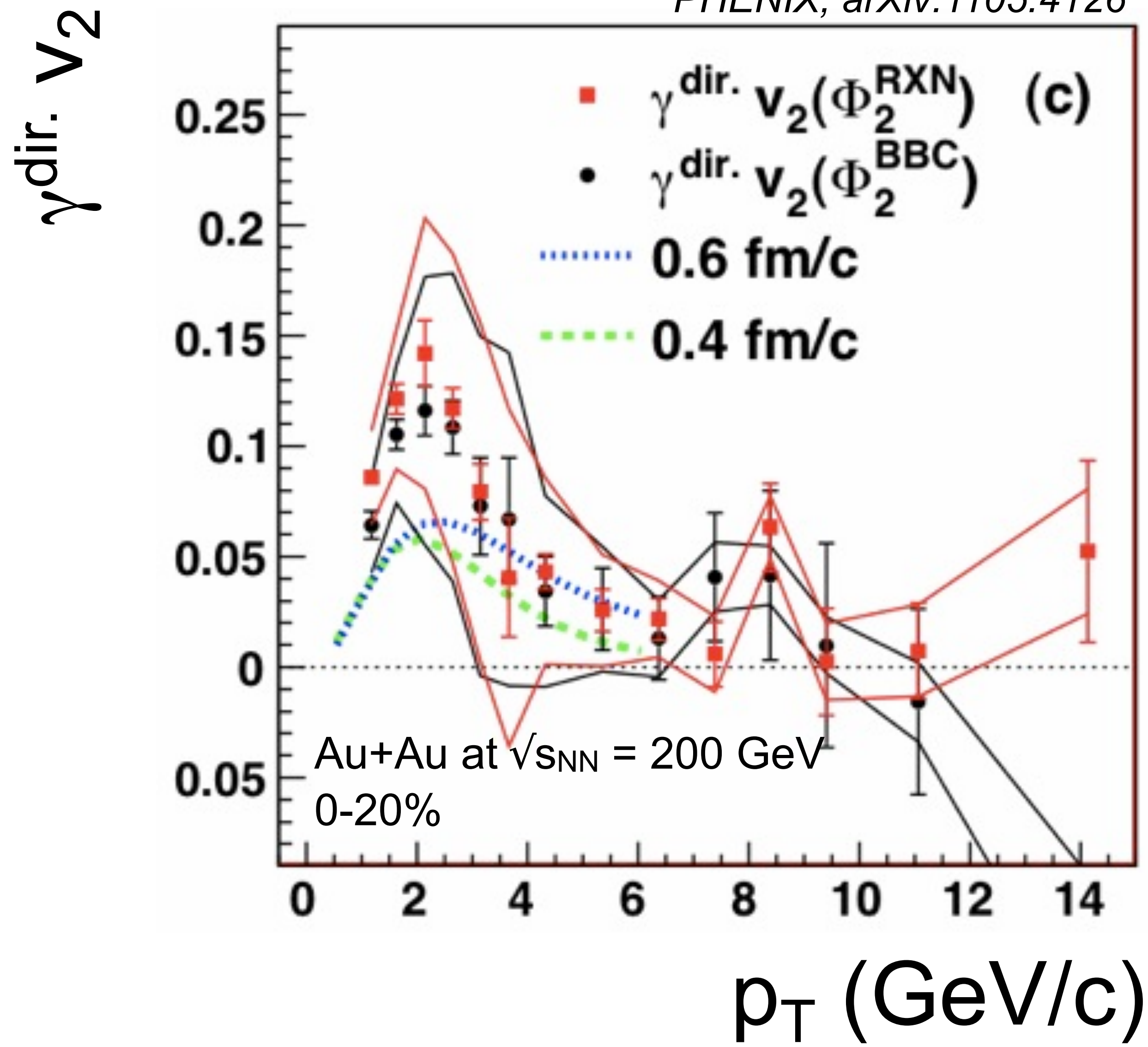
PHENIX, **PRL104**, 132301 (2010)



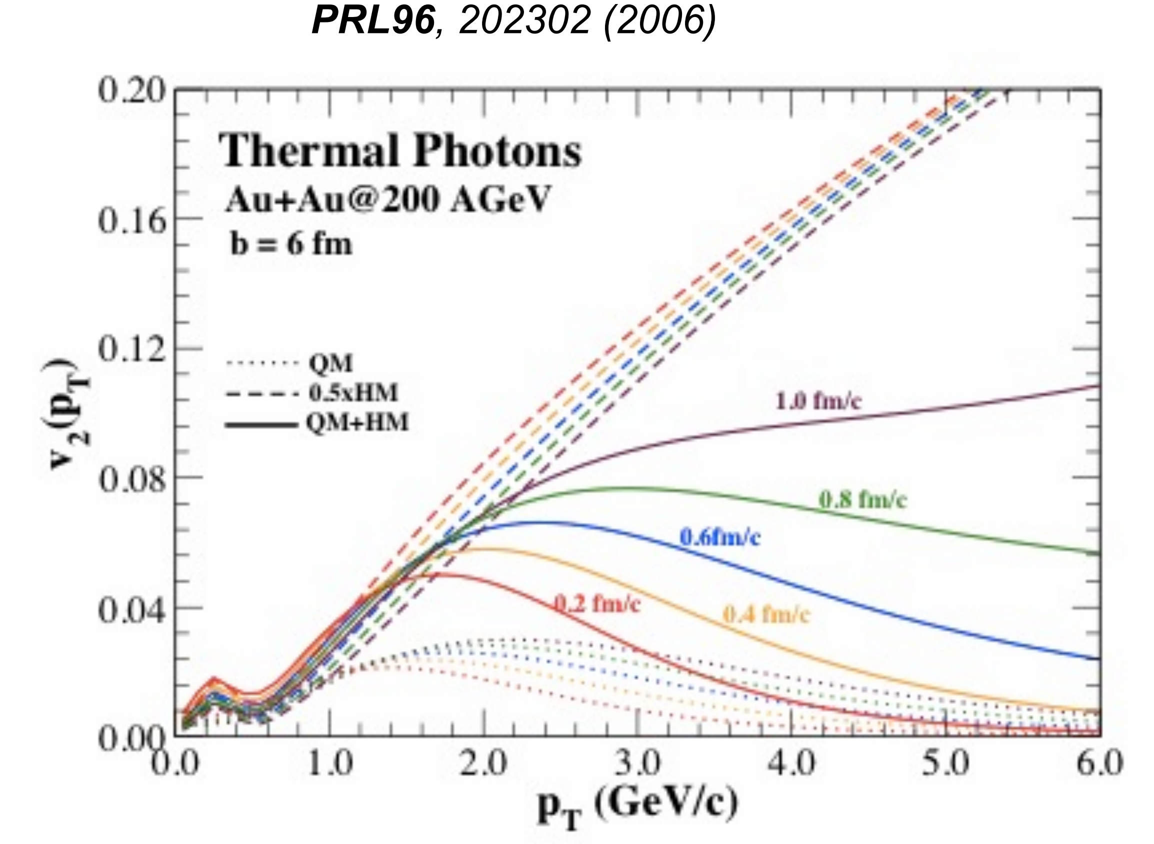
- Direct photon excess in Au + Au above p + p spectrum
- Exponential
  - consistent with thermal
- Inverse slope = 220 ± 19^{stat} ± 19^{sys} MeV
- T_{init} from hydro
  - 300 - 600 MeV, depending on thermalization time
- How about v_2 ?

Direct photon v_2

PHENIX, arXiv:1105.4126

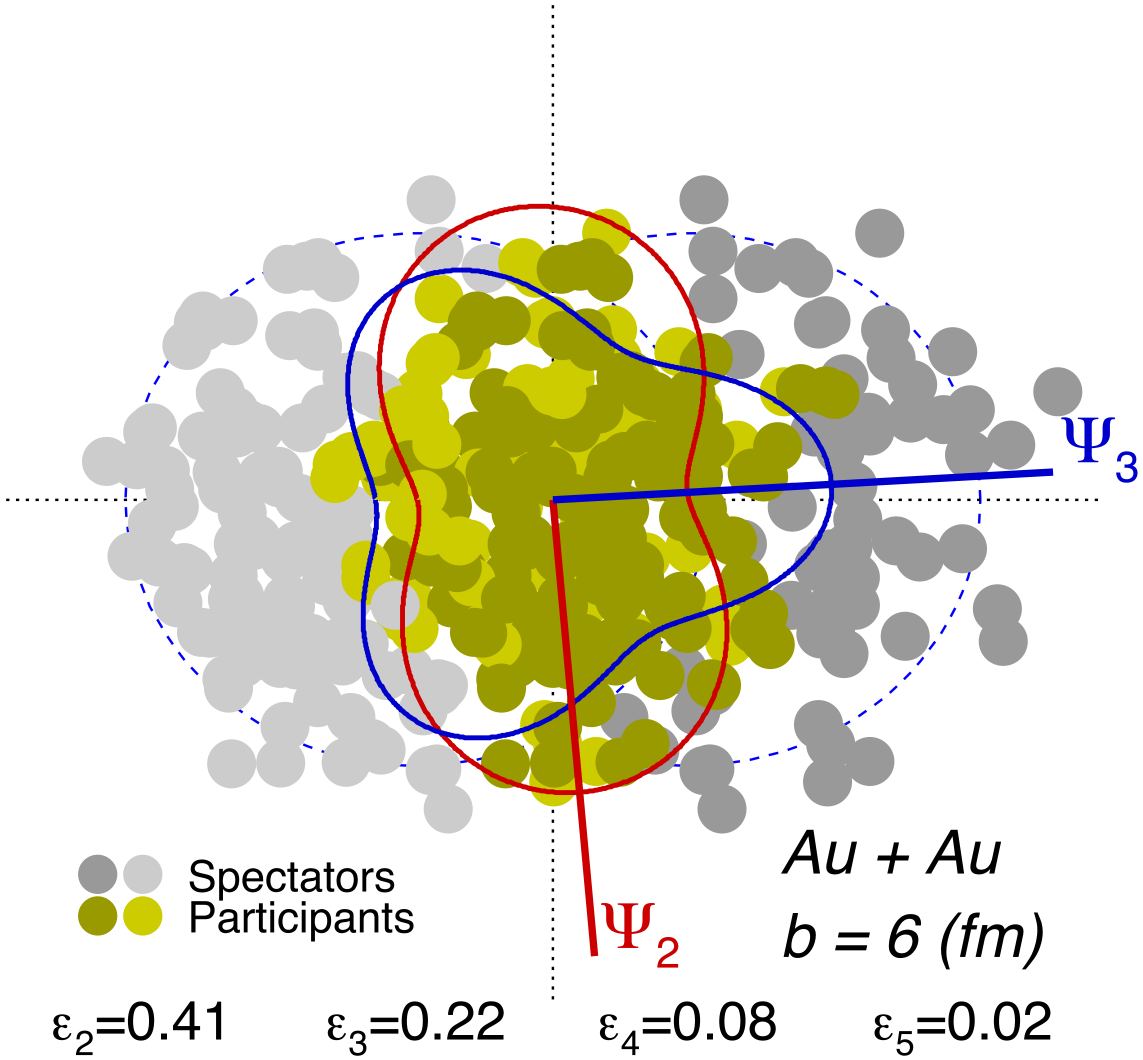


R. Chatterjee and D. K. Srivastava
***PRC79**, 021901(R) (2009)*
***PRL96**, 202302 (2006)*



- Small $\gamma^{dir.}$ v_2 at high p_T → consistent with prompt photon
- Hydro. models under-predict v_2
  - Measured $\gamma^{dir.}$ v_2 is similar to hadron v_2
- Further constraints T_{init} and τ_0 in hydro. calculations

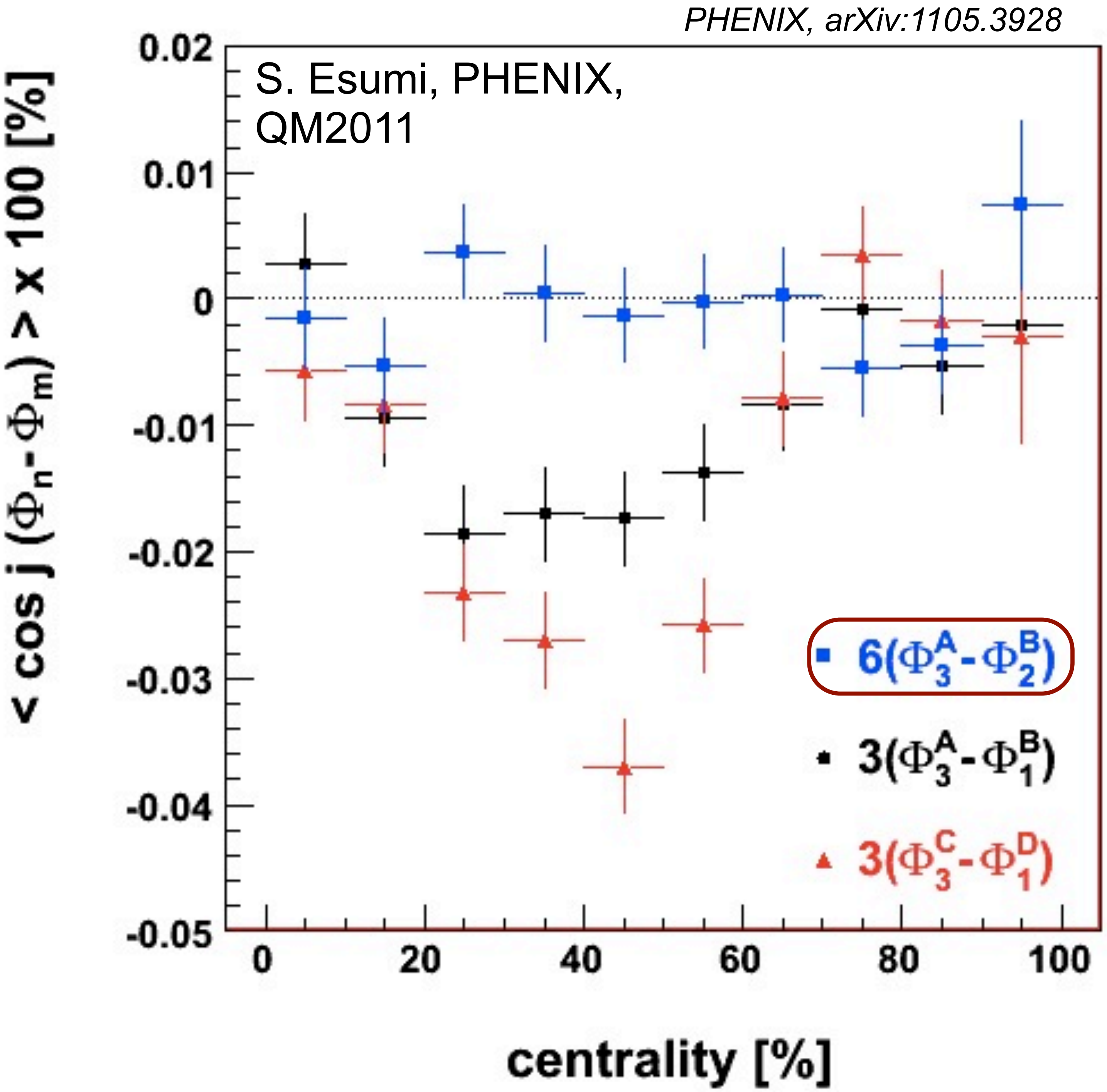
Higher harmonics v_3



- Higher harmonics could be sensitive to the initial geometry fluctuations
- Non-zero ε_3 in Glauber Monte Carlo simulation*
  - with respect to the participant plane Ψ_3
  - uncorrelated with Ψ_2
- AMPT model calculations show significant v_3 at RHIC

* *B. Alver and G. Roland, **PRC81**, 054905 (2010)*
*G. L. Ma and X. N. Wang, **PRL106**, 162301 (2011)*

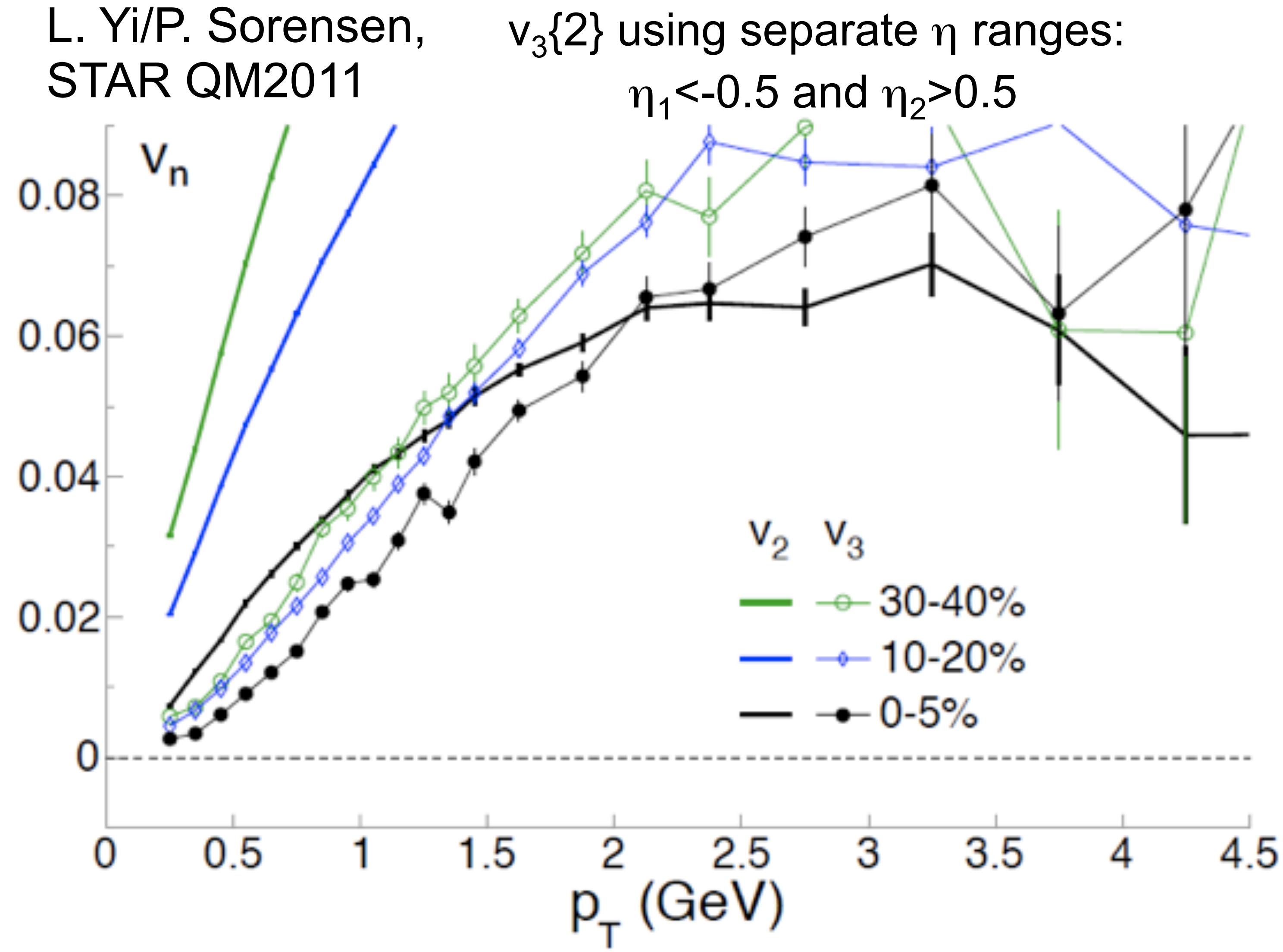
Is Ψ_3 independent of Ψ_2 ?



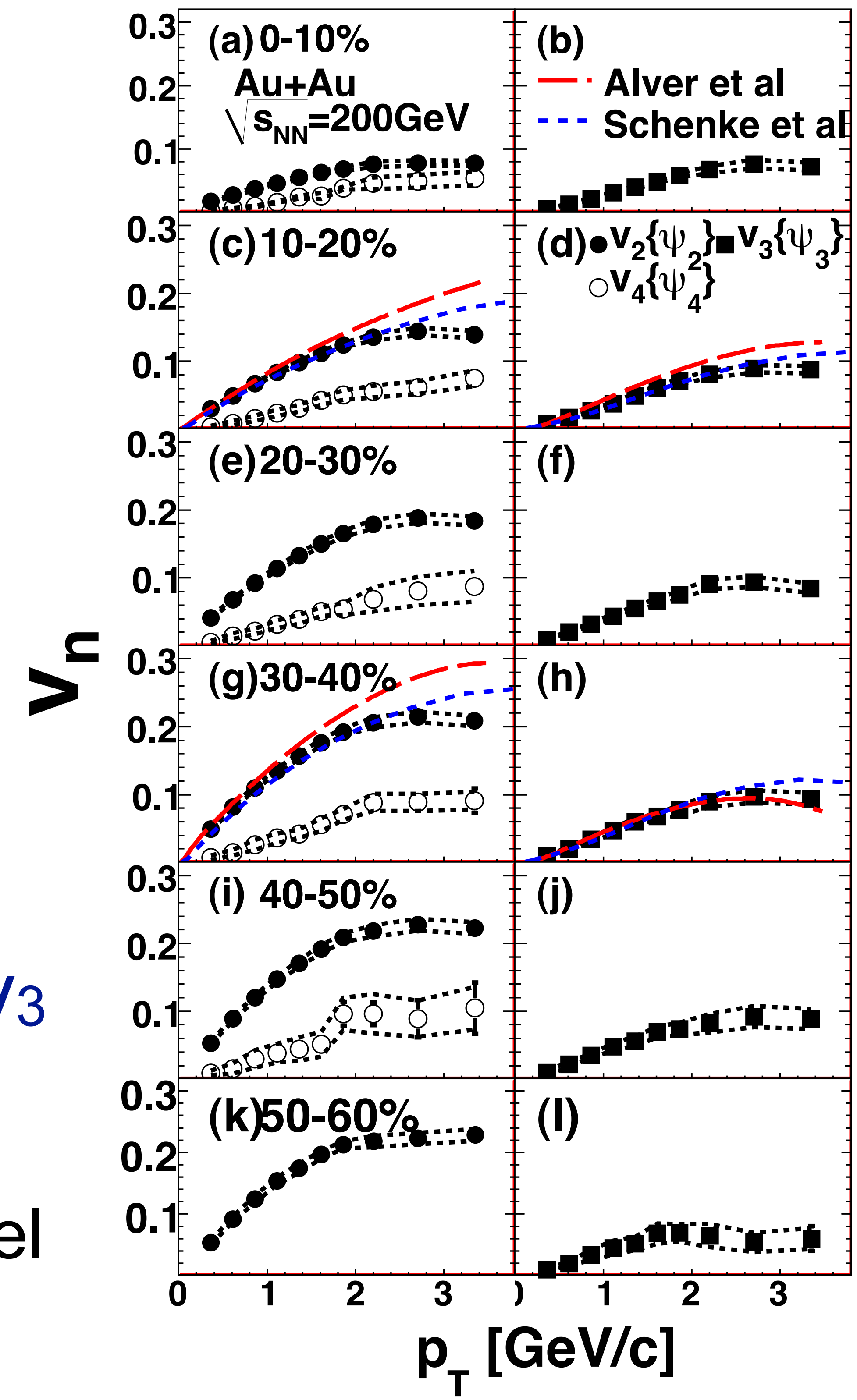
- No visible correlation between Ψ_3 and Ψ_2
  - Initial geometry fluctuation is dominated on Ψ_3

Centrality dependence $v_3(p_T)$

L. Yi/P. Sorensen, STAR QM2011



PHENIX, arXiv:1105.3928

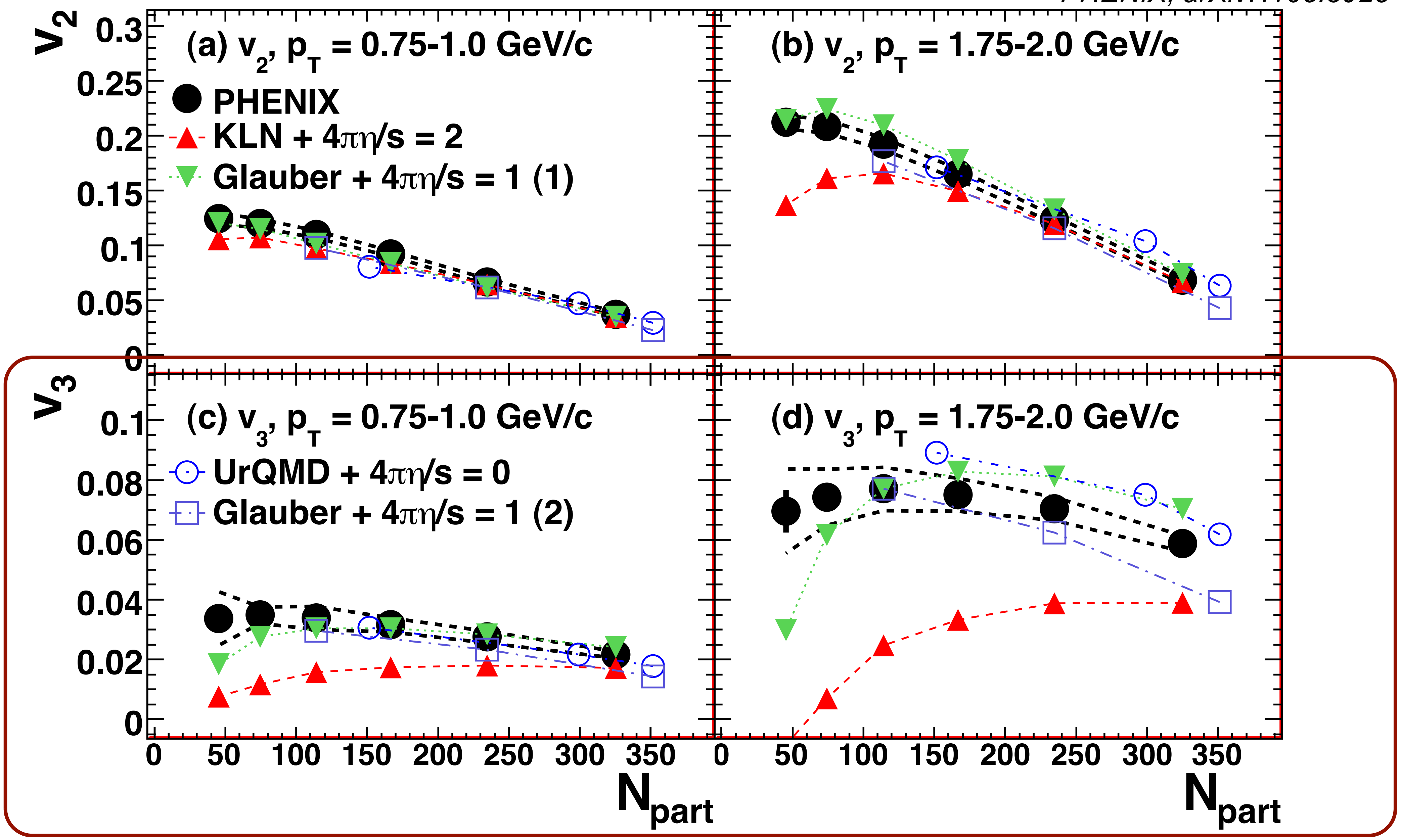


- Weak centrality dependence on v_3
- $v_3(p_T) \sim v_2(p_T)$ at most central
  - Also confirmed in parton cascade model (AMPT)*

* B. Alver and G. Roland, ***PRC81***, *054905 (2010)*
G. L. Ma and X. N. Wang, ***PRL106***, *162301 (2011)*

Extract η/s

PHENIX, arXiv:1105.3928



- Additional constraints on initial conditions as well as transport coefficients

Conclusions

- J/ψ $v_2(p_T)$ is much less than that for other hadrons
  - Is charm not thermalized at RHIC ? LHC ?
    - D meson; HFT(STAR), VTX(PHENIX)
- Dominance of hadronic phase in $\sqrt{s_{NN}}$ = 7.7, 11.5 GeV
  - Number of quark scaling is broken between particles and anti-particles at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV
  - ϕ meson v_2 deviates from other hadrons at $\sqrt{s_{NN}}$ = 11.5 GeV
    - Other hadrons still show scaling down to 7.7 GeV.
- Large $\gamma^{dir.}$ v_2 $\rightarrow$ Constraints T_{init} and τ_0 in hydro. models
- Significant non-zero v_3 observed
  - Consistent with initial geometry fluctuation
  - Additional constraints on initial conditions and transport coefficients