Partonic collectivity at RHIC

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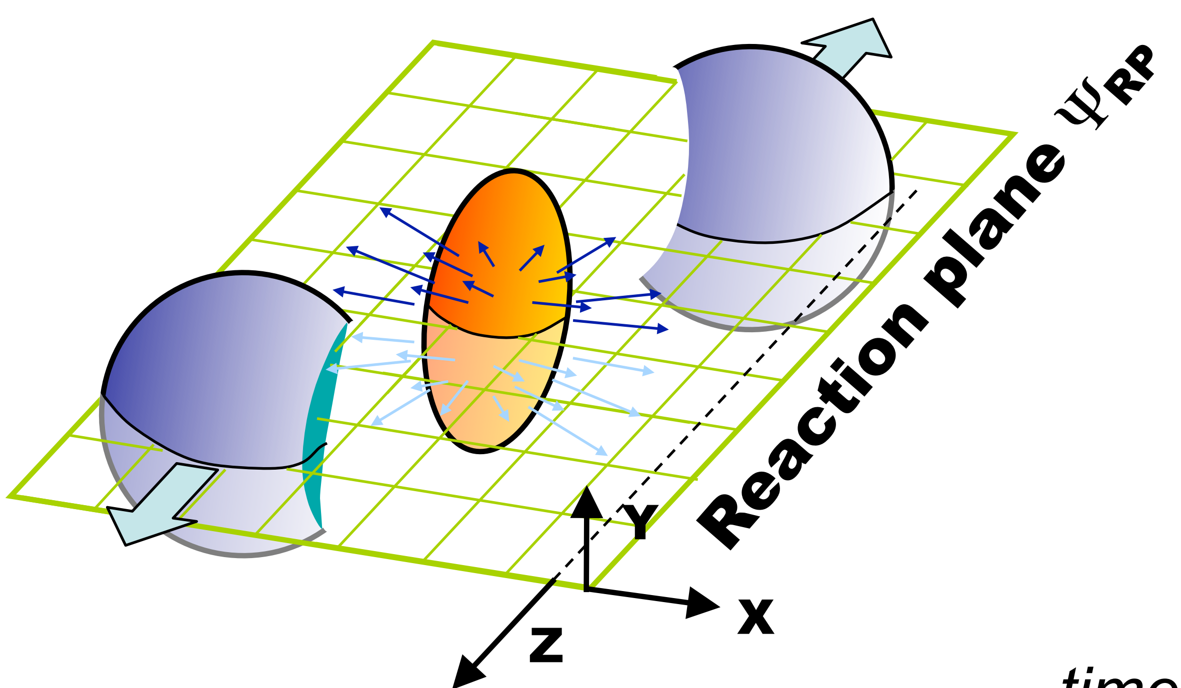
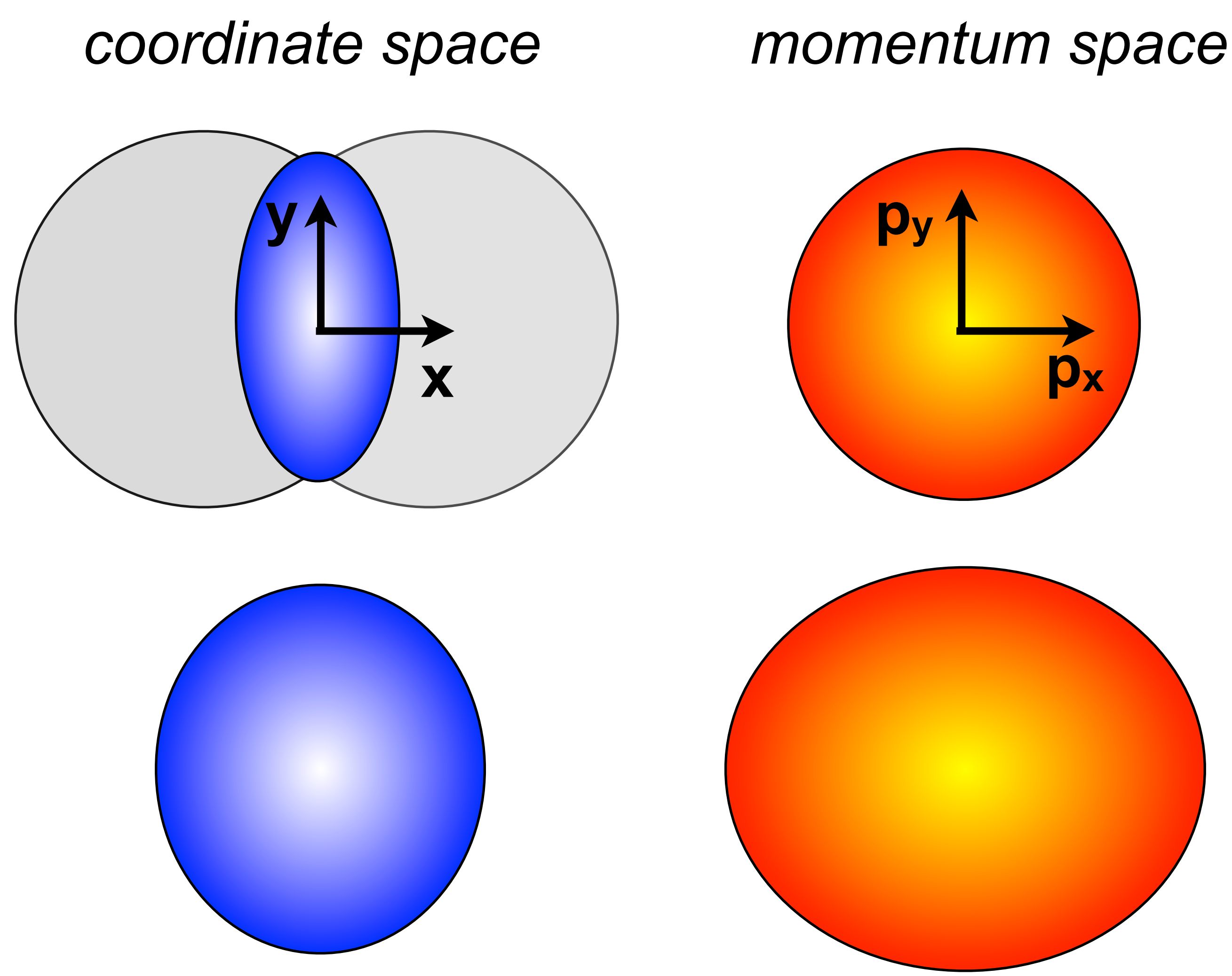
Outline

- Partonic collectivity
  - Recent measurements from RHIC
- Effect of hadronic rescattering on v_2
  - Comparison of v_2 for ϕ meson with protons
- First result of v_2 in U+U collisions
- Summary

Elliptic flow v_2 - bulk probe

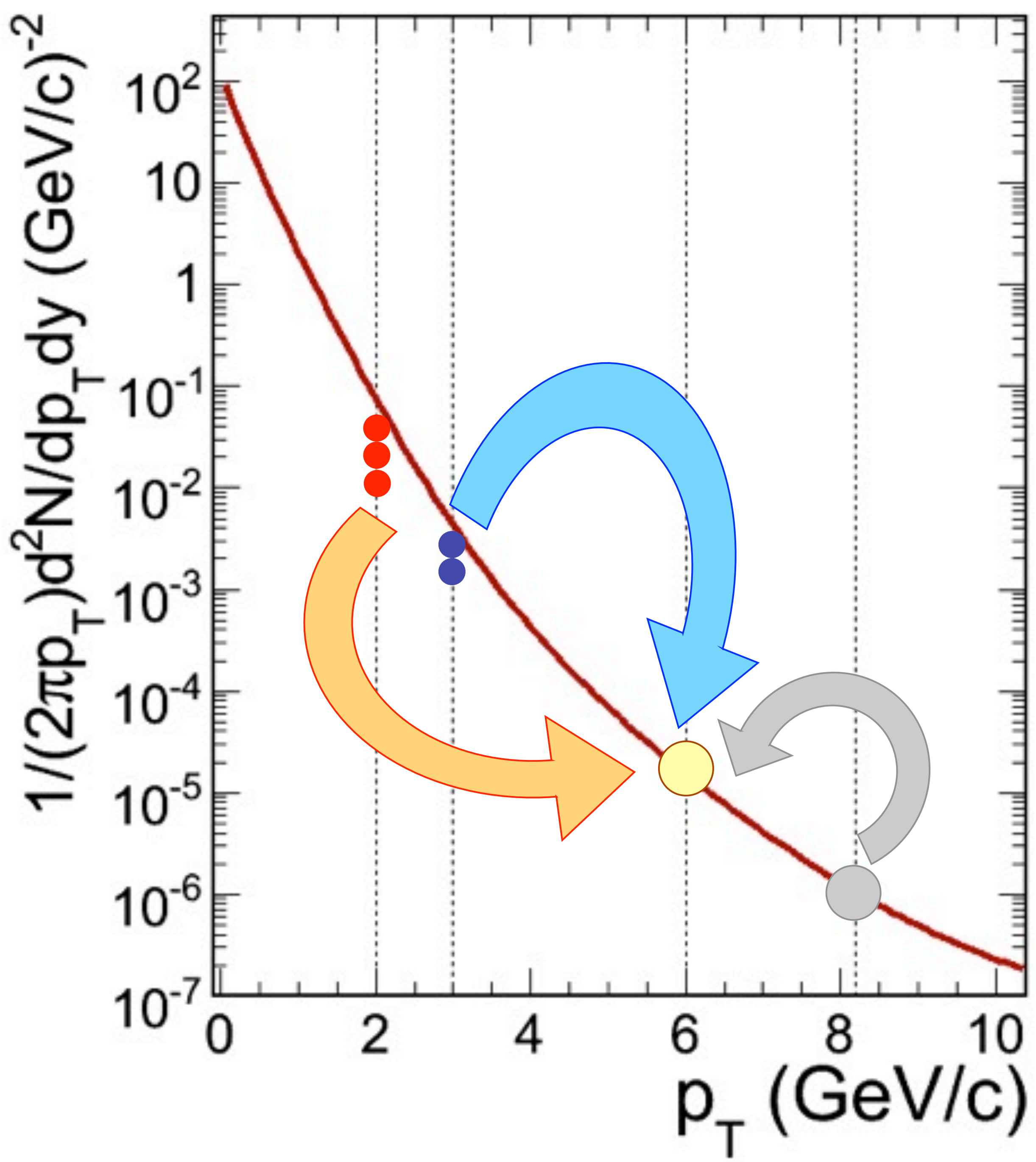




$$v_2 = \langle \cos\left[2(\phi - \Psi_{\mathrm{RP}})\right] \rangle$$

- ***Space-momentum correlation***
  - Interactions convert **initial coordinate space anisotropy** into the **final momentum anisotropy**
- Sensitive to properties of produced matter
  - Equation of state, transport coefficients (η/s)

Constituent quark model + coalescence



*S. A. Voloshin, NPA**715**, 379 (2003)*
*D. Molnar, S. A. Voloshin, PRL**91**, 092301 (2003)*
...

$$\frac{dN_B}{d^2p_\perp}(\vec{p}_\perp) = C_B(p_\perp)\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/3)\right]^3,$$

$$\frac{dN_M}{d^2p_\perp}(\vec{p}_\perp) = C_M(p_\perp)\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/2)\right]^2,$$

$$v_{2,M}(p_\perp) \approx 2v_{2,q}\left(\frac{p_\perp}{2}\right), \quad v_{2,B}(p_\perp) \approx 3v_{2,q}\left(\frac{p_\perp}{3}\right) \quad (\text{if } v_2 \ll 1)$$

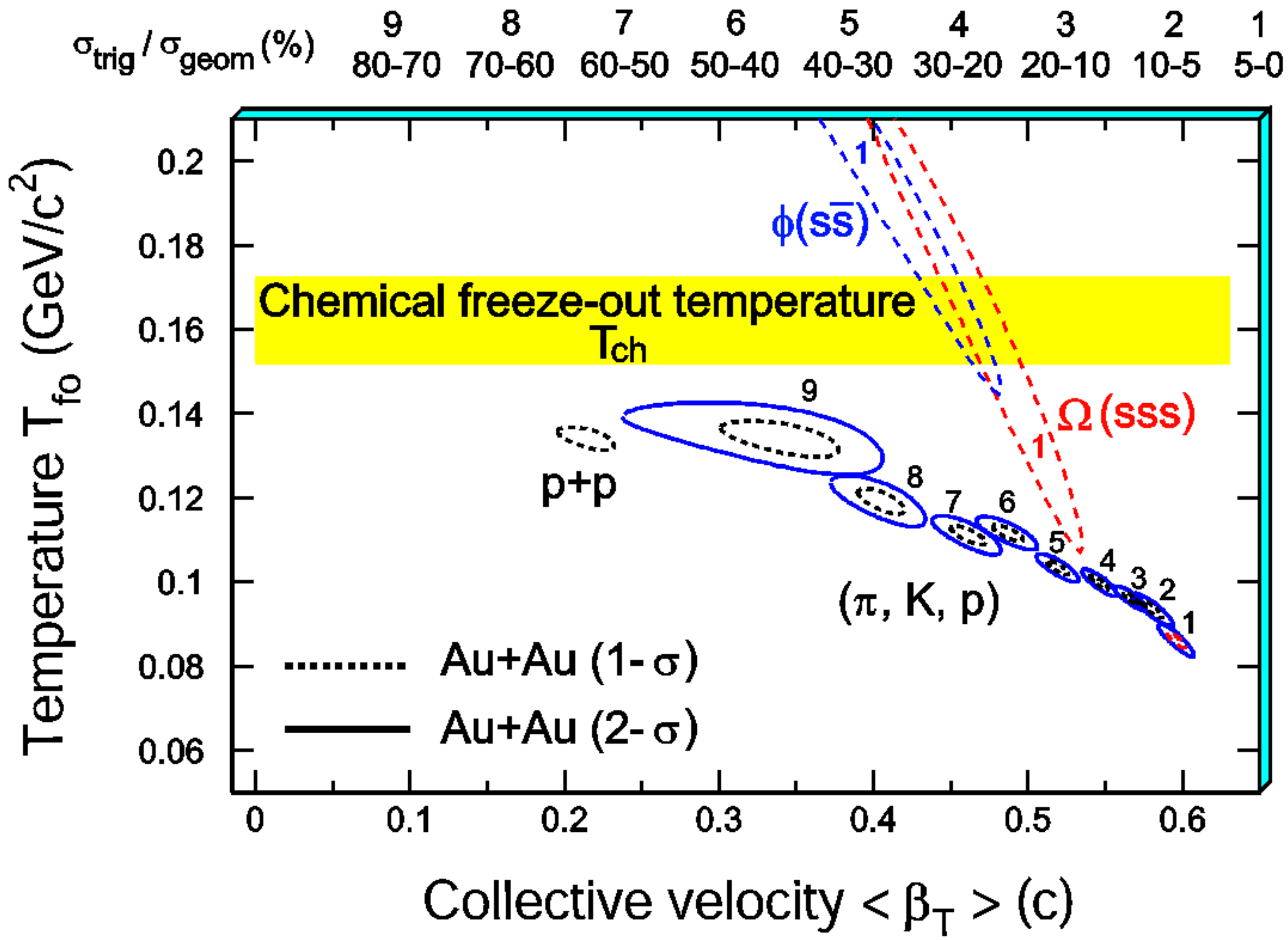
Therefore, in heavy-ion collisions there can be three qualitatively different phase space regions. At very large transverse momenta particle production is dominated by independent parton fragmentation. At lower transverse momenta coalescence prevails, which region can itself be subdivided into two parts: a very low $p_\perp$(high phase space density) region where Eq. (1) is *not* applicable, and a moderate density (higher $p_\perp$) region, where Eq. (1) is valid. Because the density of produced particles depends on the centrality of the collision, the "boundaries" of these regions depend on centrality. Only detailed

*from D. Molnar, S. A. Voloshin, PRL**91**, 092301 (2003)*

- Number of constituent quark (NCQ) scaling of v_2
  - assume quark degrees of freedom is dominant at hadronization

Multi-strange hadrons

*STAR, NPA**757**, 102 (2005)*



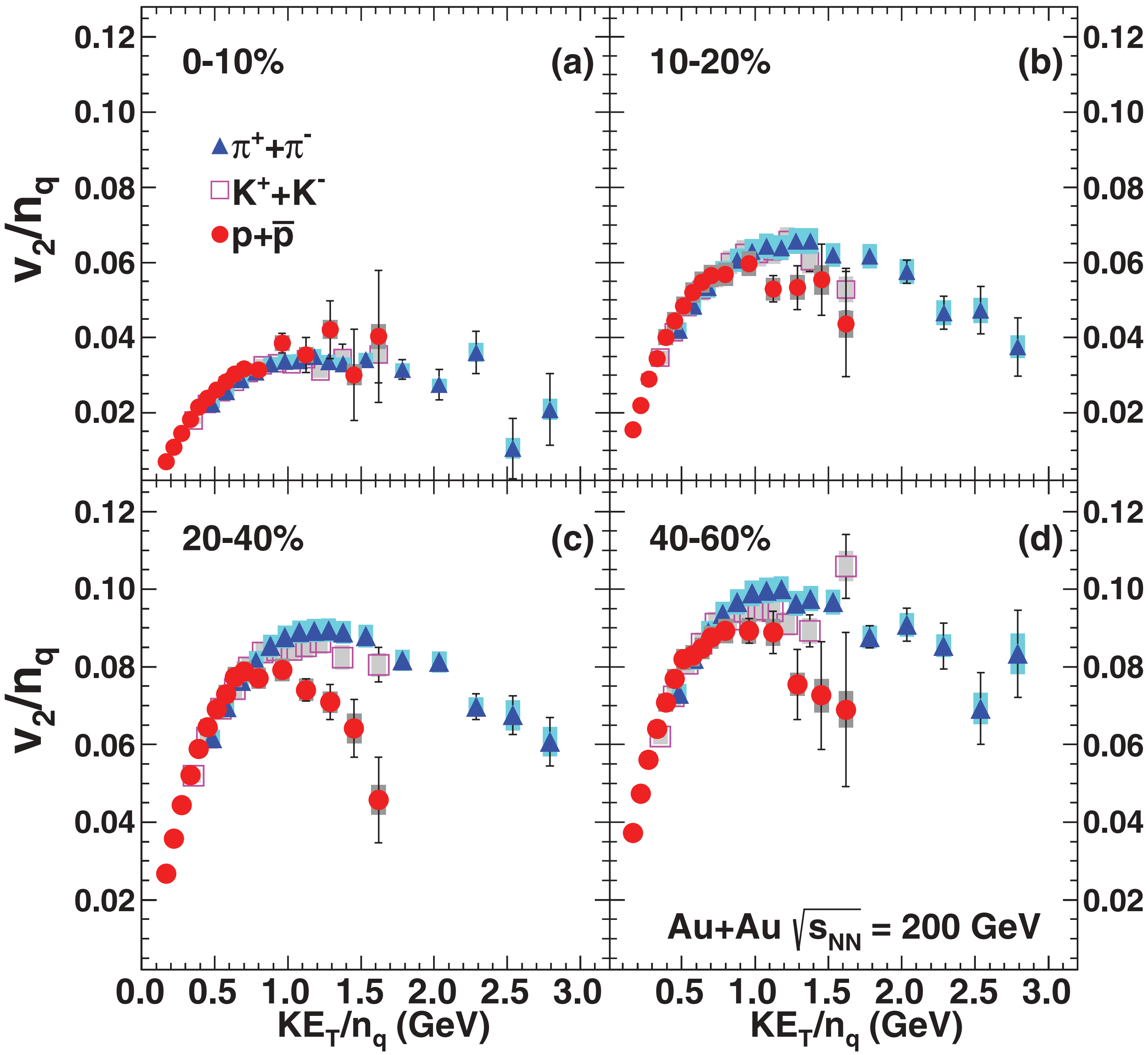
- Probe to early partonic stage
  - Freeze-out earlier than other hadrons within Blast-wave model

➡ less sensitive to hadronic rescattering

  - Good probe to study partonic collectivity

Deviation from NCQ scaling - PHENIX

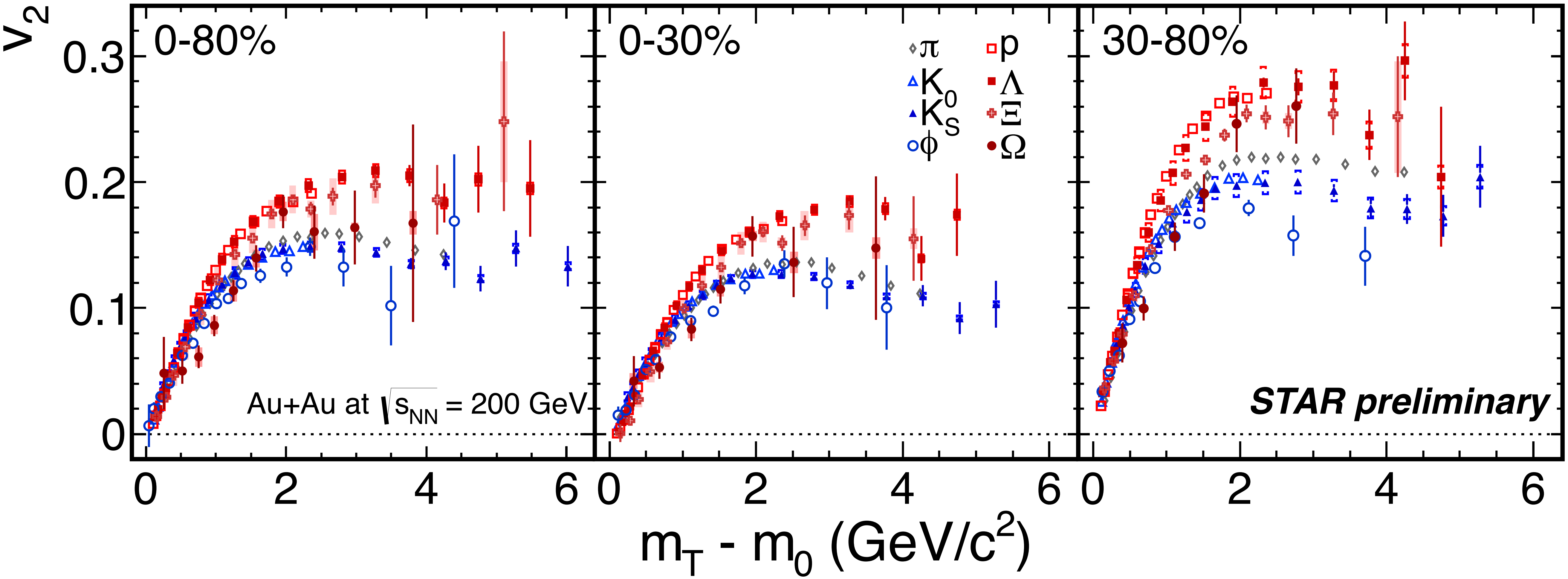
*PHENIX, PRC**85**, 064914 (2012)*



- Scaling holds at 0-10%
- Deviation in non-central collisions
  - KE_T/n_q > 0.7 GeV/c
- Different particle production mechanisms (e.g. jet fragmentation) may dominate over coalescence

Deviation from NCQ scaling - STAR

STAR, QM2012



- Scaling holds better in central
  - similar to what PHENIX observed
- Multi-strange hadrons show smaller v_2 than other strange hadrons
  - $\Omega \sim \Xi < \Lambda$, $\phi < K^0{}_S$

Predictions

$$\text{if } v_2^s < v_2^{u,d}$$

*Z. W. Lin, C. M. Ko, PRL**89**, 202302 (2002)*

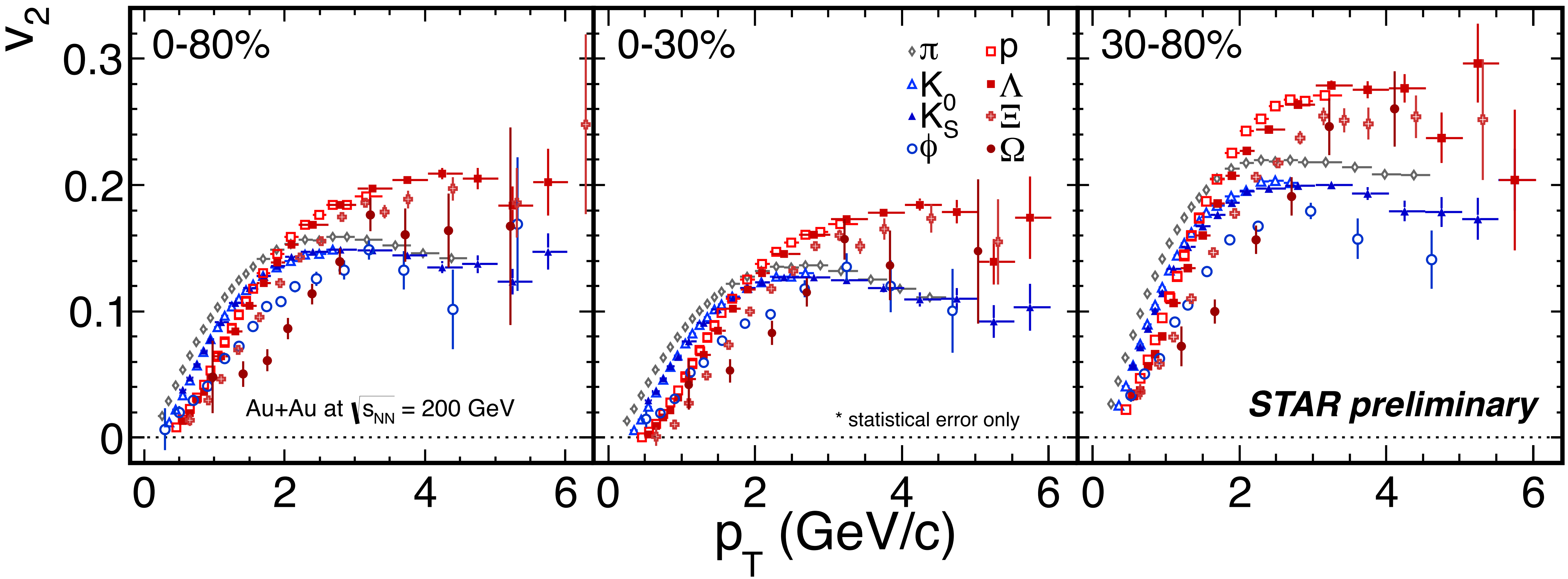
$$(v_2^\pi = v_2^p) > (v_2^\Lambda = v_2^\Sigma) > v_2^K > v_2^\Xi > (v_2^\phi = v_2^\Omega)$$

*D. Molnar, S. A. Voloshin, PRL**91**, 092301 (2003)*

$$v_2^p > v_2^\Lambda \approx v_2^\Sigma > v_2^\pi > v_2^K > v_2^\phi, \quad v_2^{\Lambda,\Sigma} > v_2^\Xi > v_2^\Omega \approx 3v_2^\phi/2$$

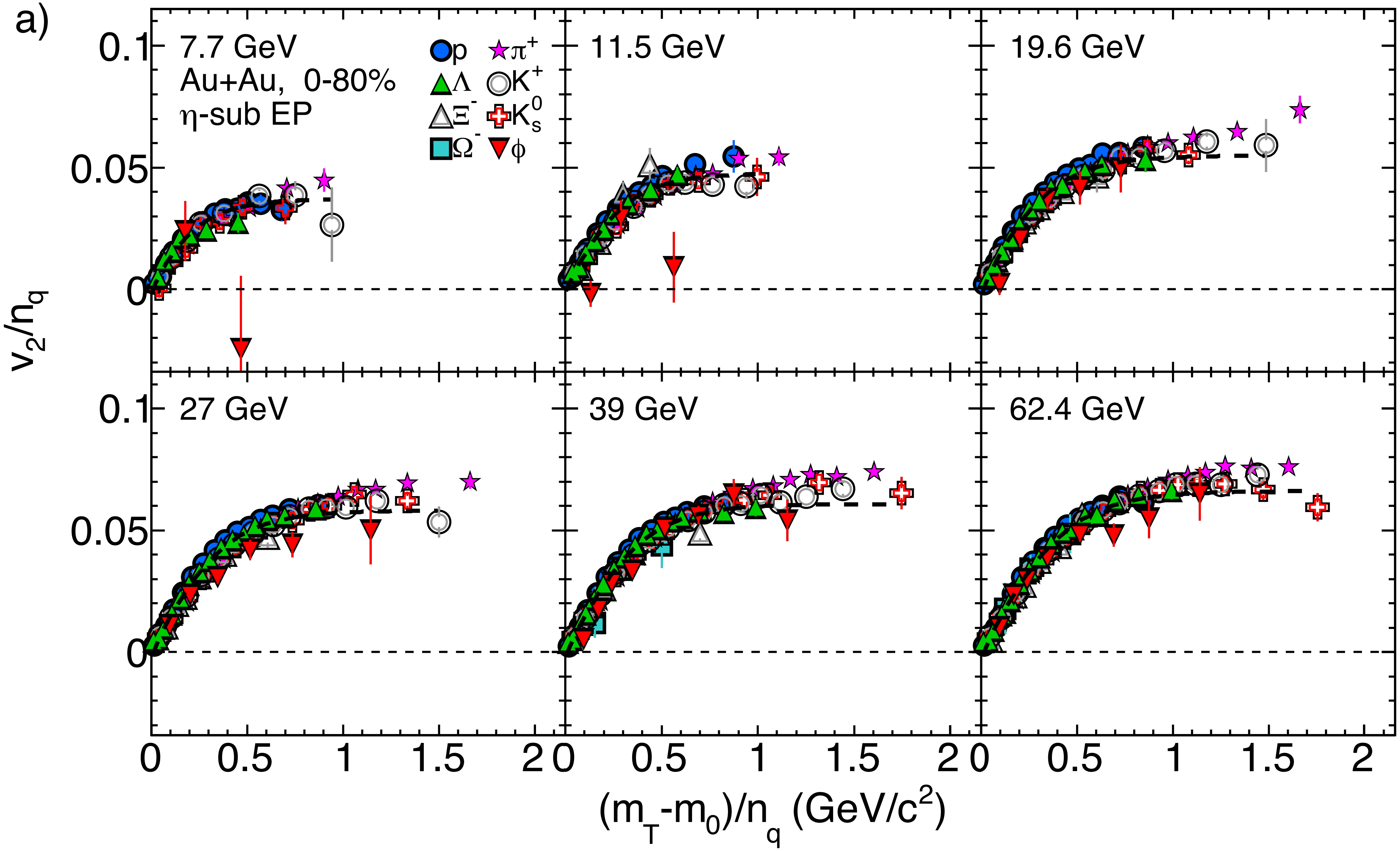
- Different assumptions on relative quark momentum
  - Lin & Co: No constraints, hadron v_2 ~ quark v_2 at high p_T
  - Molnar & Voloshin: strict momentum conservation
- Main difference between two predictions
  - π vs p
  - ϕ vs Ω

Flavor ordering ?



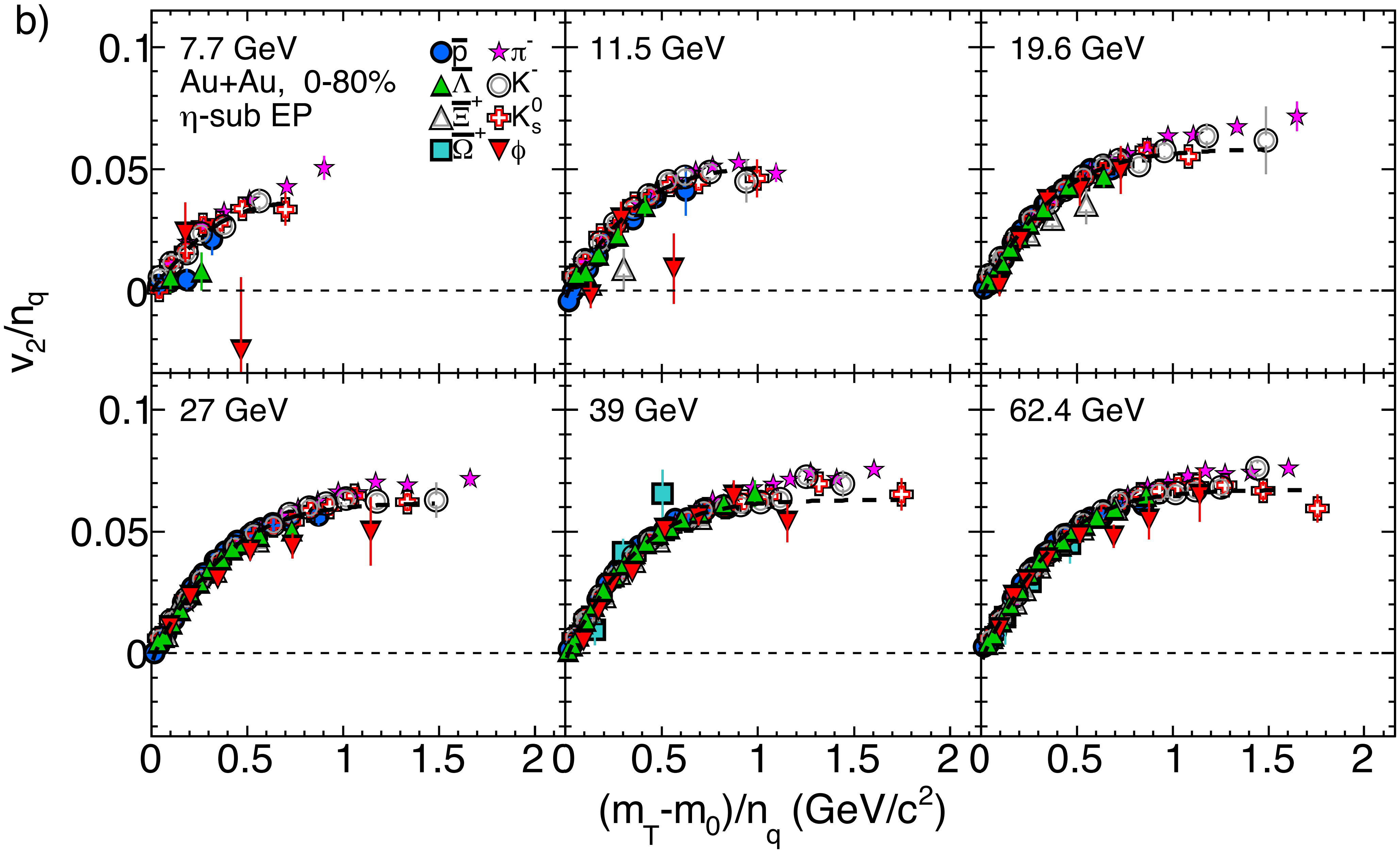
- π vs p: π < p in p_T > 2 GeV/c
- ϕ vs Ω
  - they are consistent within error, except for two high p_T data points in 30-80%

Turn-off partonic collectivity !?



- Important to validate the assumption - small hadronic cross section for multi-strange hadrons
- ϕ meson v_2 show hint for “turn-off” partonic collectivity !

Turn-off partonic collectivity !?



- Important to validate the assumption - small hadronic cross section for multi-strange hadrons
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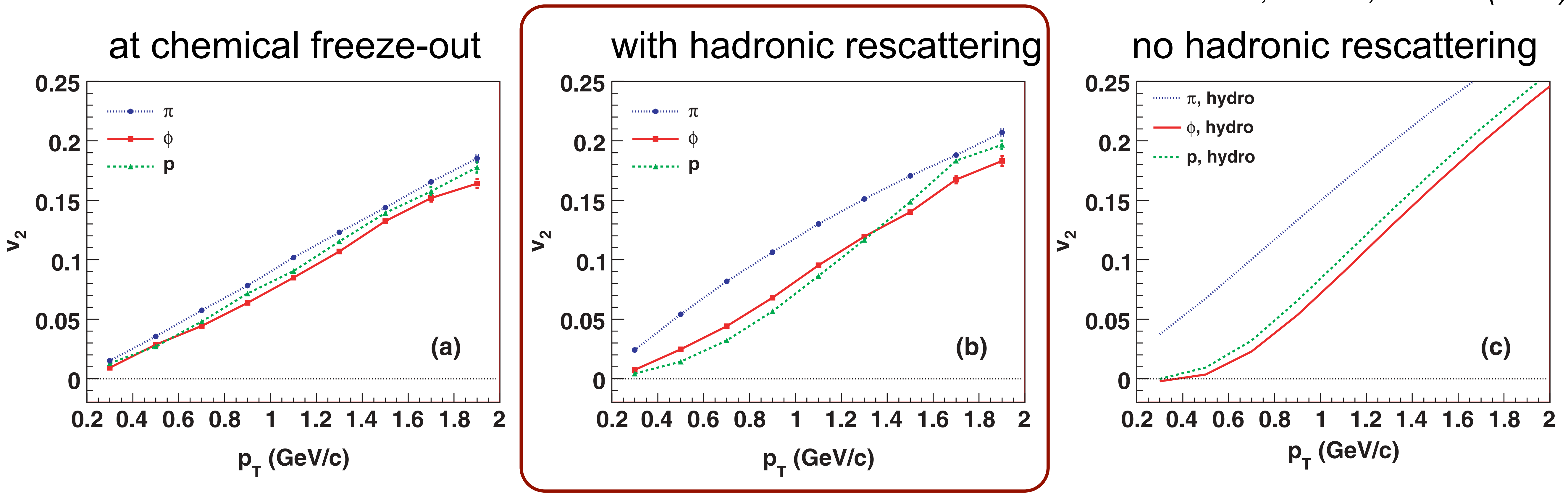
Effect of hadronic rescattering

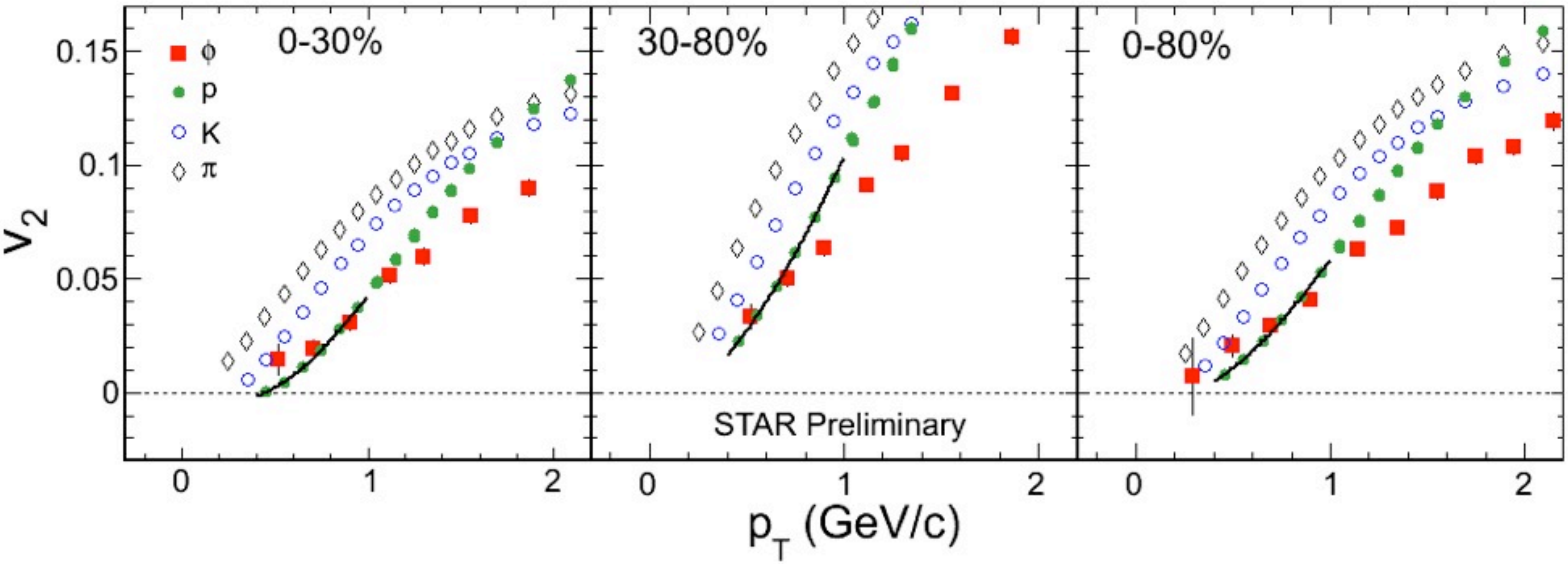
T. Hirano et al, PRC**77**, 044909 (2008)



- Prediction from ideal hydro. model + hadron cascade
  - Glauber initial condition, 1st order phase transition
- Hadrons show similar v_2 at chemical freeze-out
- Violation of mass ordering with hadronic rescattering
  - $v_2(\phi) > v_2(p)$ below p_T=1 GeV/c
  - due to small hadronic cross section of ϕ in hadron cascade JAM

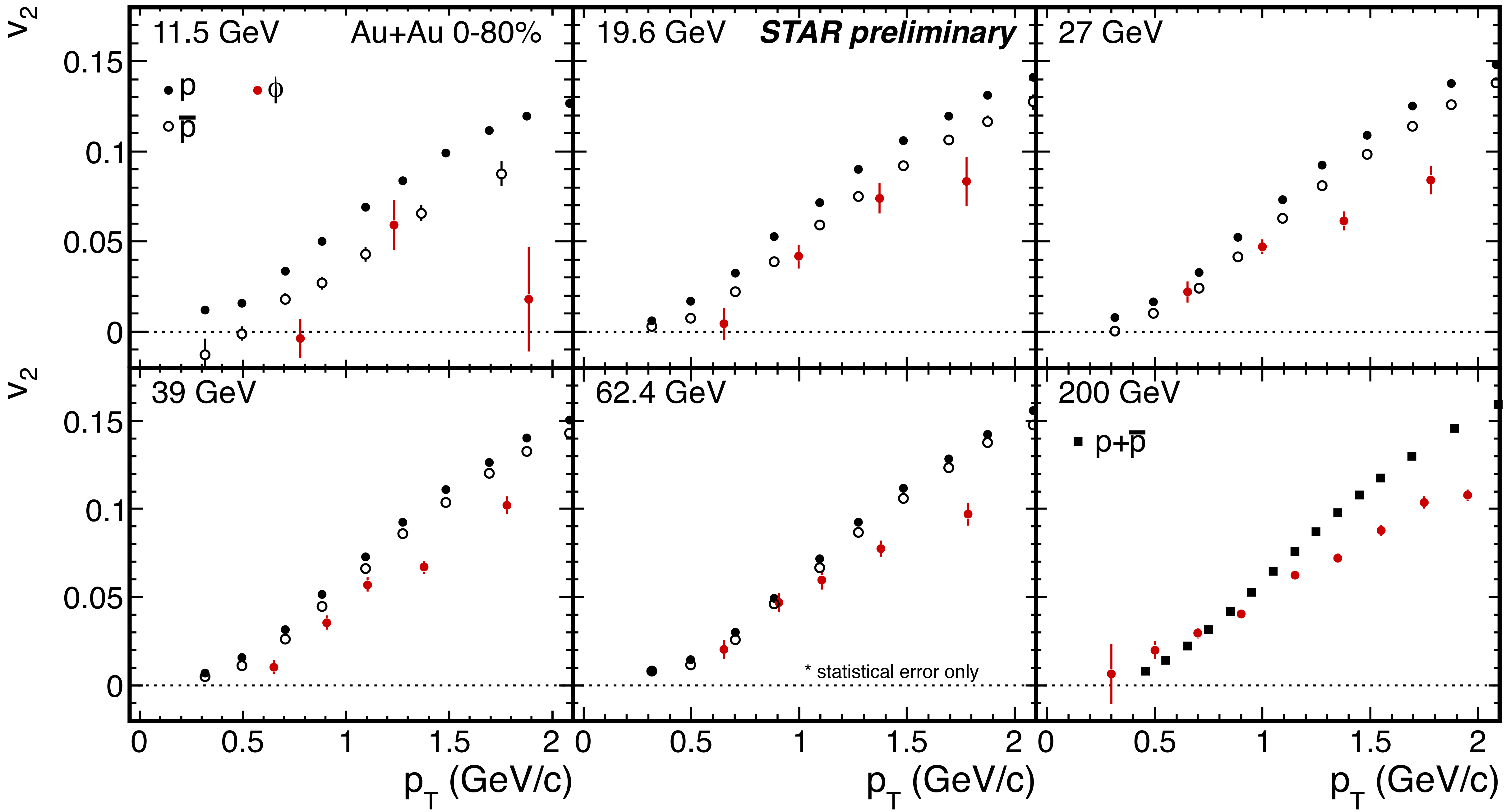
$v_2(\phi)$ vs $v_2(p)$

STAR, QM2012



- $v_2(\phi)$ is slightly higher than $v_2(p)$
  - Effect is stronger in central than peripheral
- Consistent with the scenario with hadronic rescattering effect

Energy dependence



- $v_2(\phi) < v_2(p)$ for low energies ?
  - Need precise measurements & comparison with hydro. models

Deformed nuclei collisions

PHYSICAL REVIEW C, VOLUME 61, 034905

High energy collisions of strongly deformed nuclei: An old idea with a new twist

E. V. Shuryak
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(Received 14 July 1999; published 22 February 2000)

Collisions of deformed nuclei such as U may provide 40% more hard processes and about 30% larger energy densities, compared to central PbPb collisions. They also produce excited systems which are strongly deformed in the transverse plane, which are much larger than possible in peripheral PbPb collisions. We discuss how, even without a polarized target, one can study these phenomena by selecting particular events. Collisions are studied by a simple Monte Carlo model, and it is shown what can be achieved by making cuts in two control parameters—the number of participants and ellipticity. We also discuss how UU collisions may resolve a number of outstanding issues, from corrections to hard processes to elliptic flow (the existence of a quark-gluon plasma), to the mechanism of J/ψ suppression.

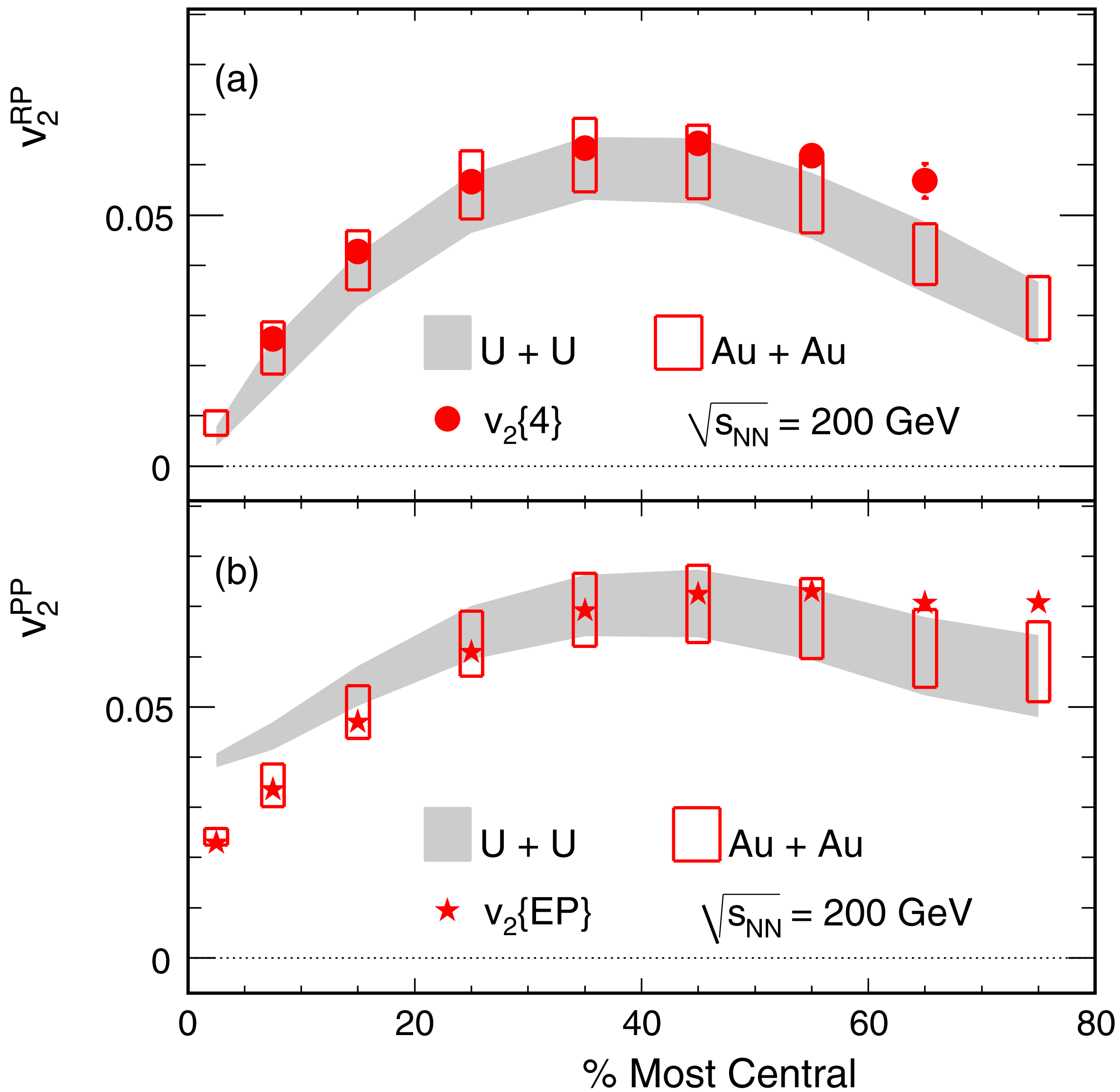
- Can achieve higher density & longer life time of QGP
  - ✓ For body-body U+U at b=0 fm, increase energy density ~20% and ~×2 volume with similar eccentricity in Pb+Pb at b=7fm*

** P. F. Kolb et al, PRC**62**, 054909 (2000)*

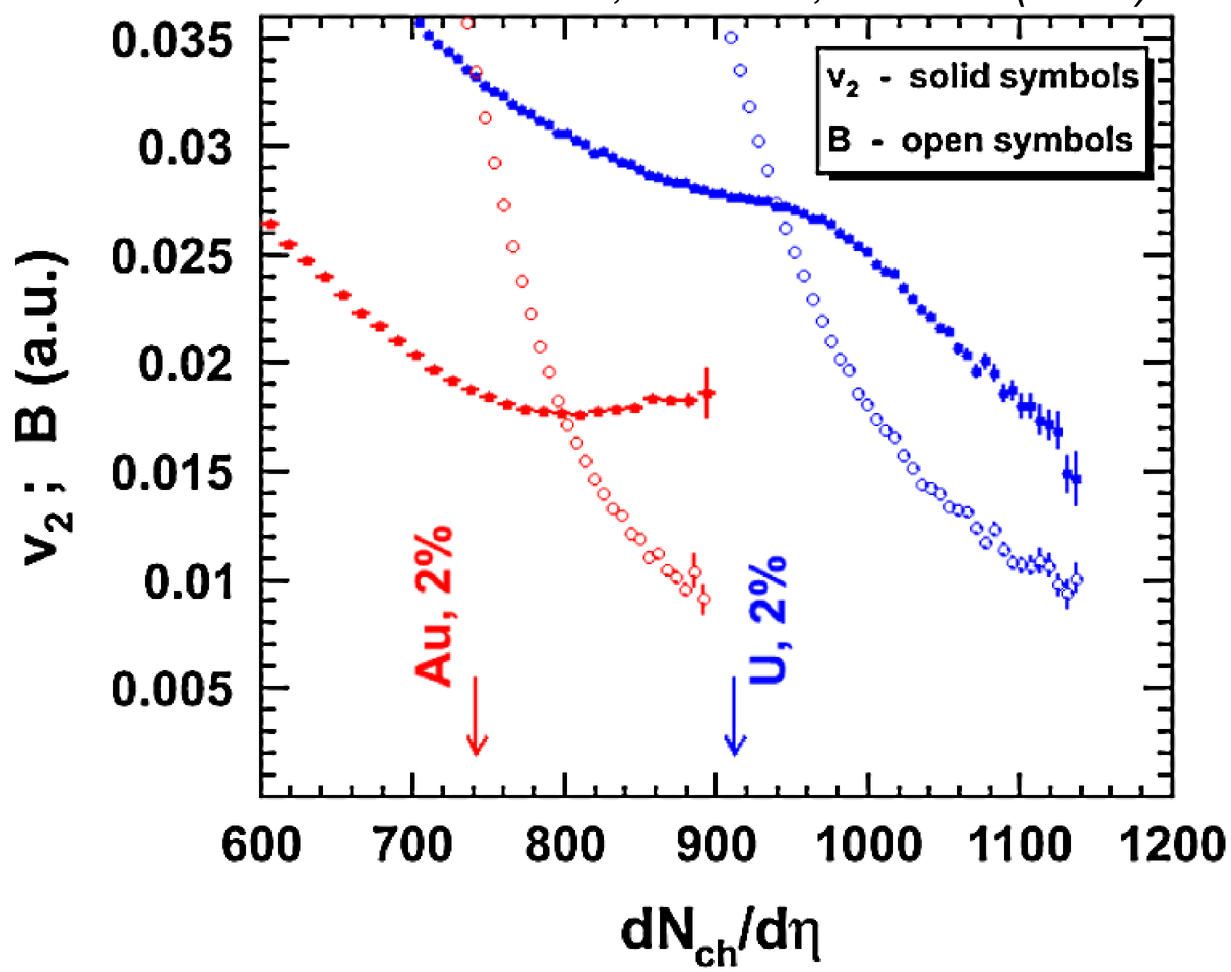
  - ➡ Longer partonic phase
  - ➡ Clear hydrodynamical behavior of elliptic flow (v_2)

Predictions for v_2 in U + U collisions

H. M., B. Mohanty, N. Xu, PLB**679**, 440 (2009)



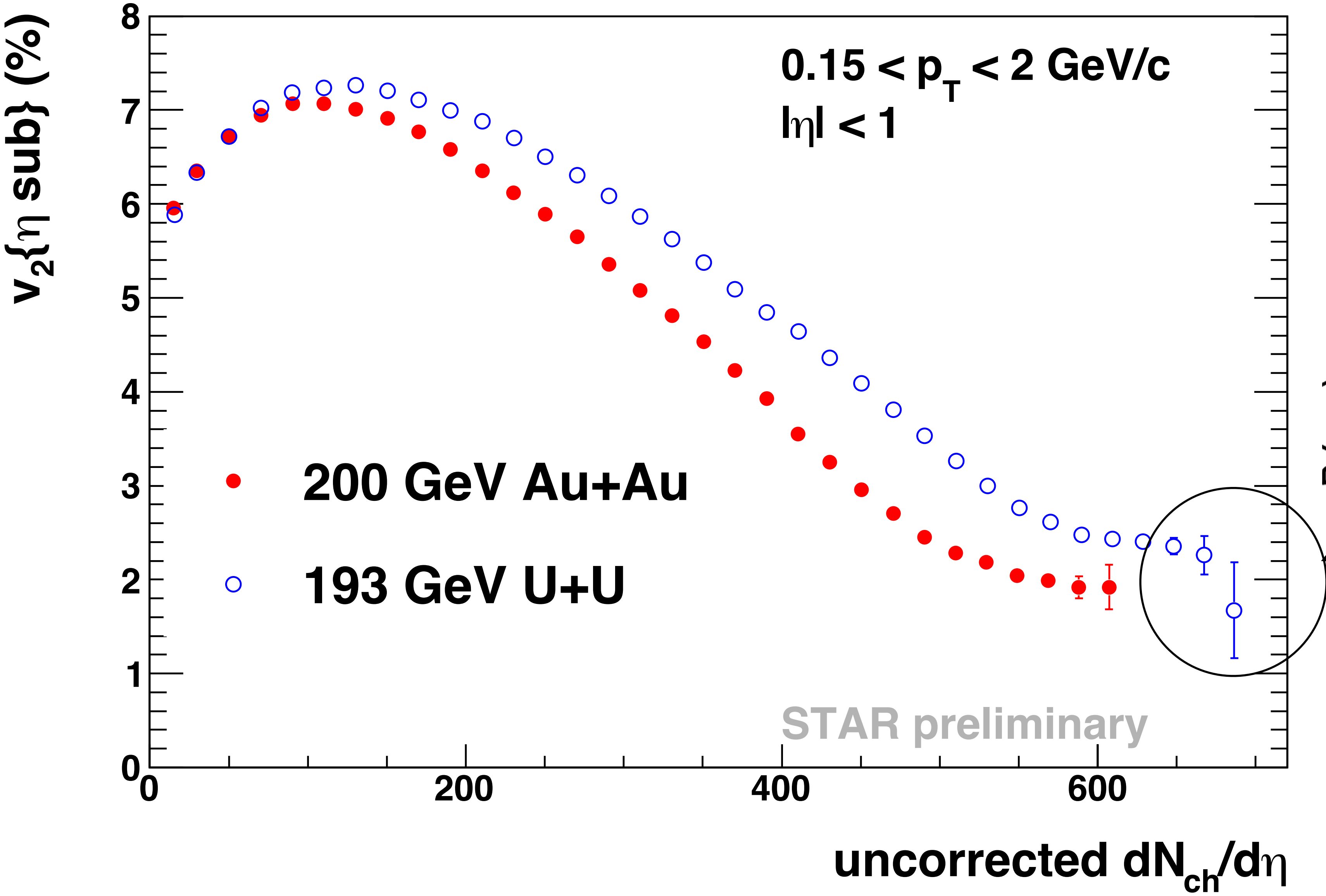
S. Voloshin, PRL**105**, 172301 (2010)

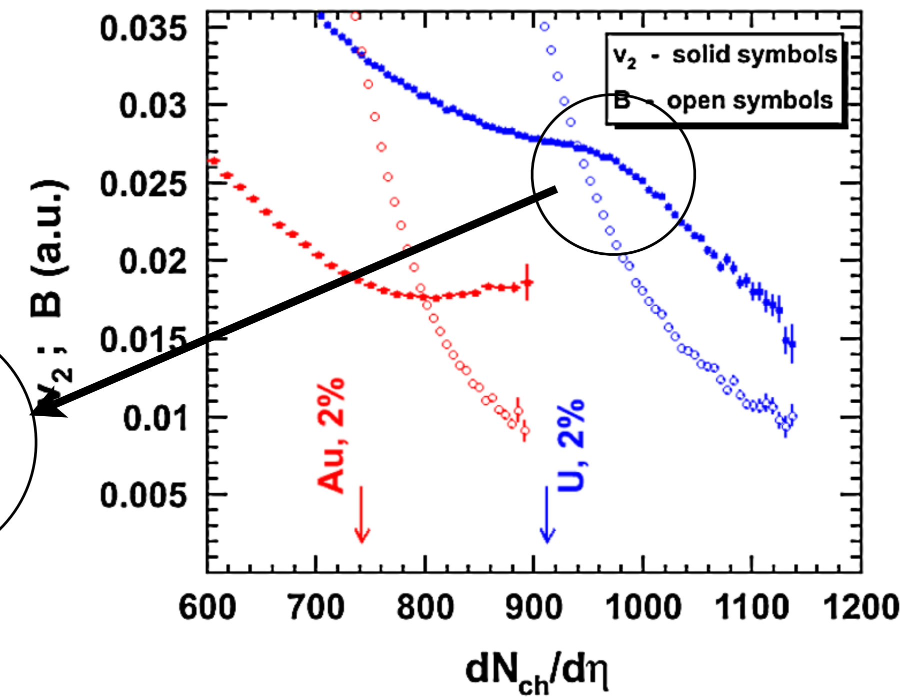


- Expect larger v_2 for a given centrality in most central collisions
  - due to large deformation of uranium

v_2 vs multiplicity

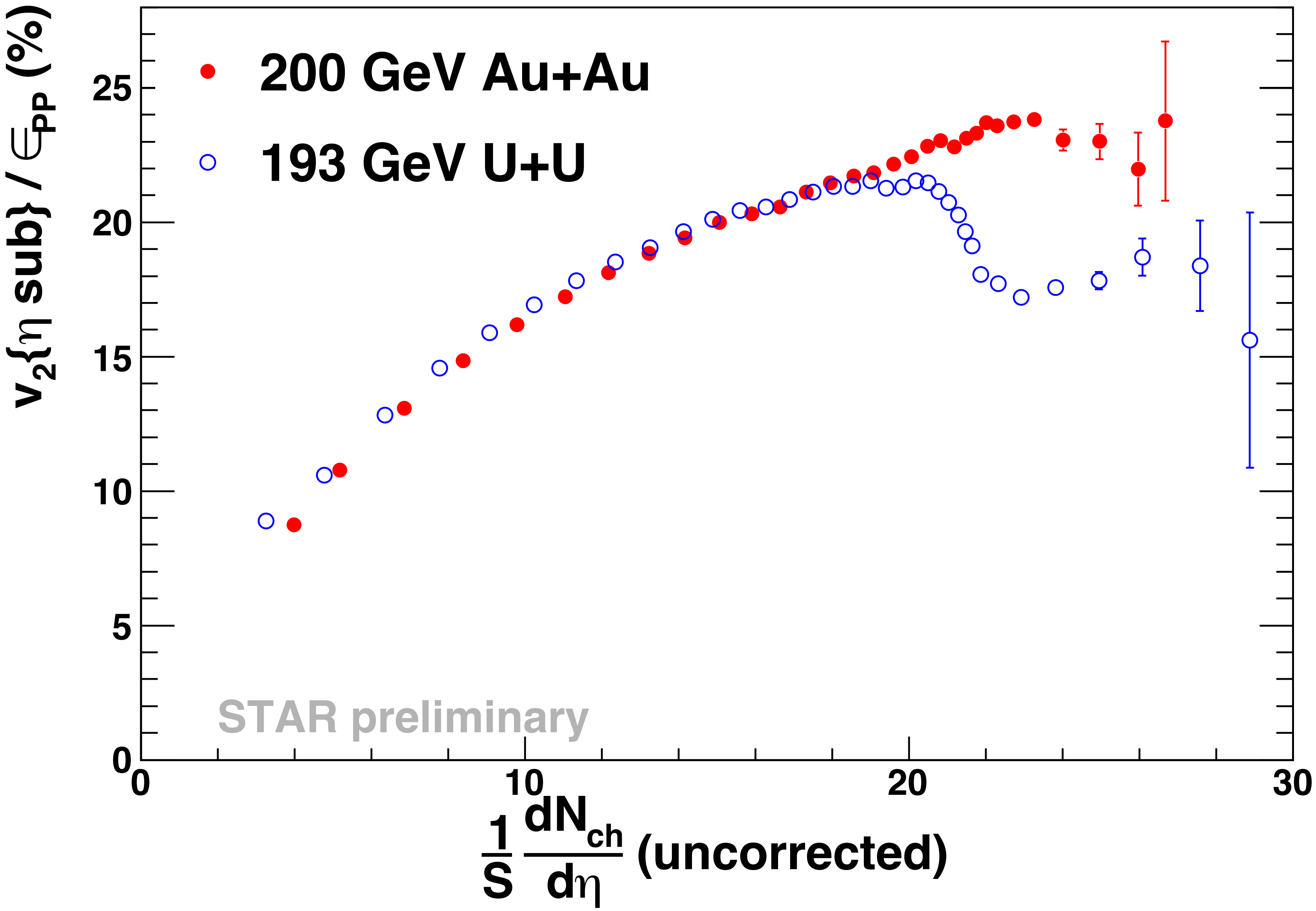
STAR, QM2012





- v_2 in U+U > v_2 in Au+Au in central collisions
- Expected ‘cusp’ structure not observed

Eccentricity scaling of v_2



- Splitting of v_2/ε between Au+Au and U+U
  - Break down of eccentricity scaling ?
  - Artifact of glauber simulation ?

Summary

- Deviation of NCQ scaling of v_2
  - in mid-central, peripheral collisions
  - Flavor ordering ?
  - ϕ meson seems to deviate at low energies (need more statistics)
- Mass ordering of ϕ and p is qualitatively consistent with prediction
  - Hadronic rescattering seems to play important role on v_2 even at top RHIC energy
- v_2 measurements in U+U
  - qualitatively consistent with predictions. Quantitative comparison needs to be done with dynamical models
  - Need more study to understand the eccentricity scaling of v_2