Systematics of Flow Measurements at RHIC

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Thanks to A. Poskanzer and N. Xu for discussions

BERKELEY LAB

Outline

1. Introduction
   - ✓ Why do we study collective flow ?
   - ✓ How to measure anisotropic flow experimentally ?
2. Systematics of v_2
   - ✓ Different methods, different collaborations at RHIC
3. Physics results and discussions
   - ✓ Initial conditions ↔ centrality dependence of v_2
   - ✓ Partonic and hadronic Equation Of State (EOS), hadronization ↔ transverse momentum (p_T) & particle type dependence of v_2

- Conclusions

Physics goals at RHIC

- Study the properties of the matter with partonic degrees of freedom
  - ✓ Anisotropic collective flow is one of the key bulk probes to study early collision dynamics at RHIC
  - ✓ Why do we study collective flow ?

Penetrating probes

- photons, leptons
- jets
- heavy flavors

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Bulk probes

- p_T spectra
- azimuthal anisotropy
- fluctuations

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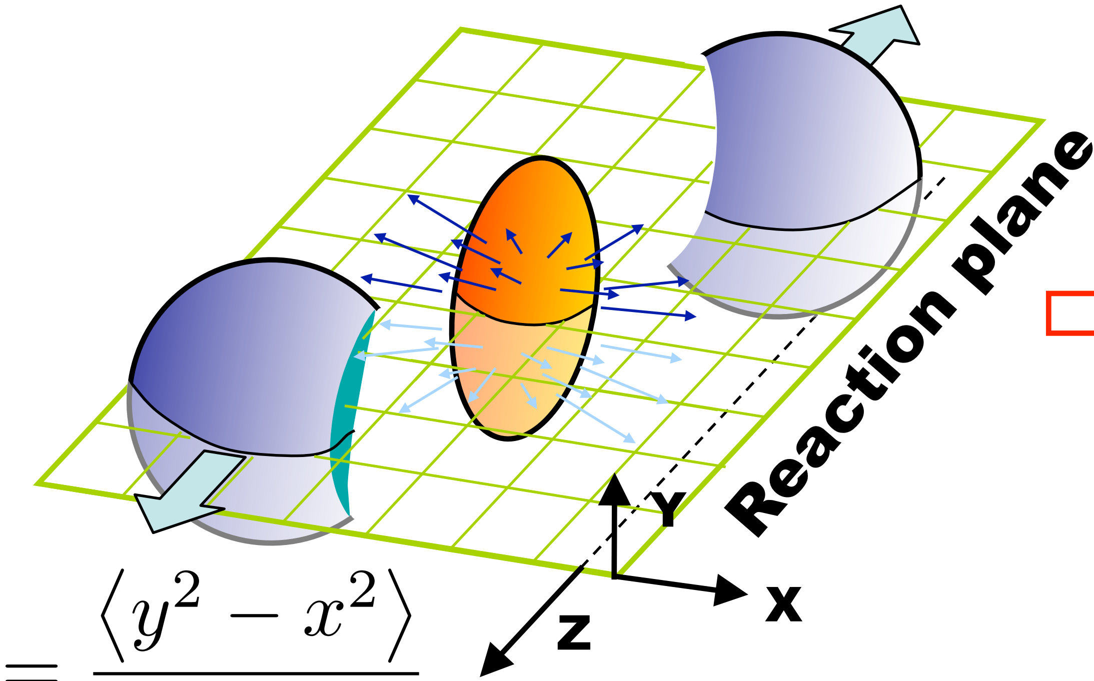
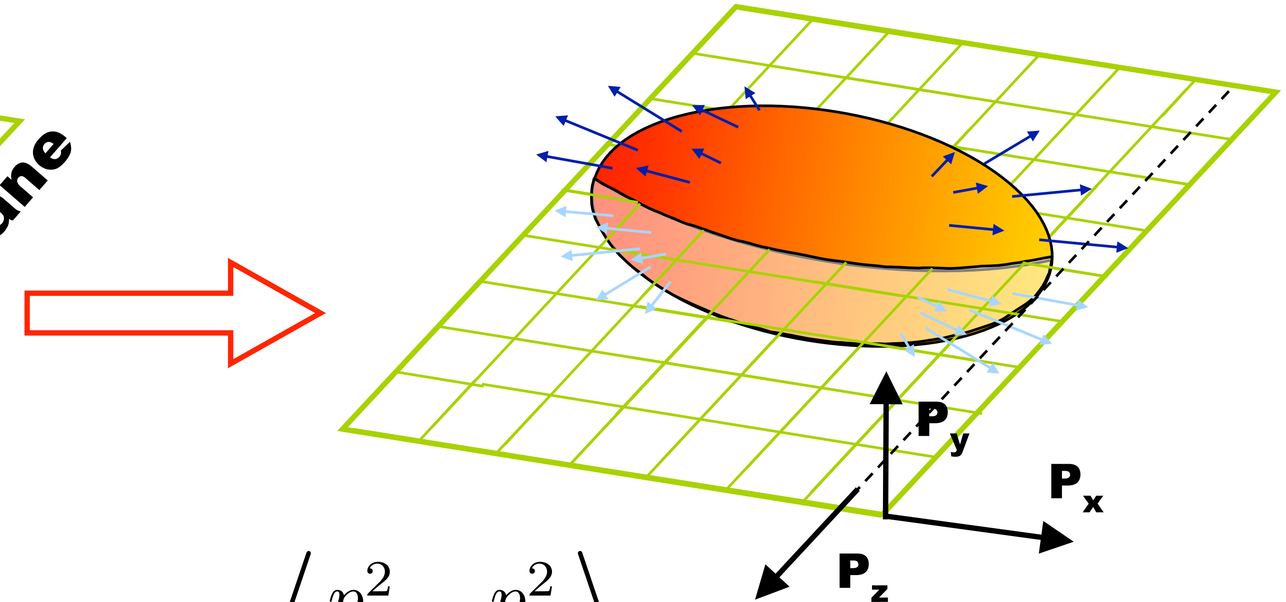
Probe to the partonic EOS



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



$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos \phi' \rangle$$

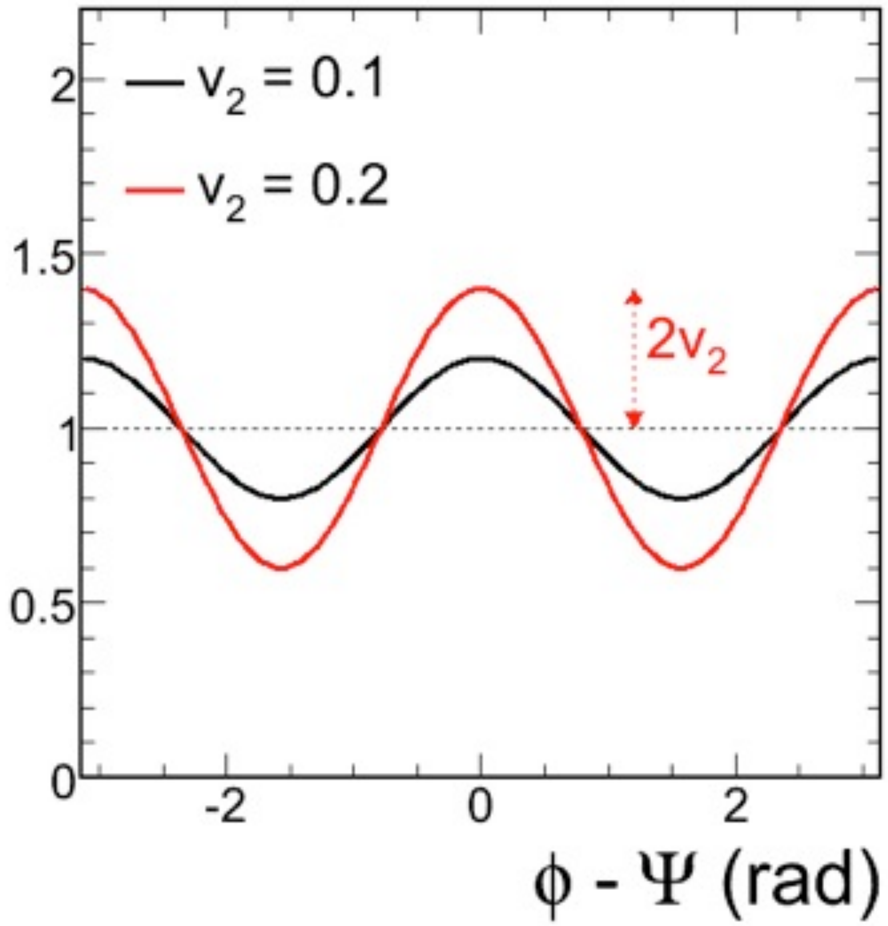
- Anisotropic flow is determined by
  - ✓ (1) initial geometry overlap (eccentricity ε), (2) pressure gradient ← density profile + EOS, EOS ↔ d.o.f, (3) System size
    - Thermalization is not required. It gives stronger scaling of initial and final anisotropies
  - ➡ Space-momentum correlations
- How to measure anisotropic flow experimentally ?

How to measure anisotropic flow ?

$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos(\phi - \Psi_{\mathrm{RP}}) + \boxed{2v_2 \cos(2[\phi - \Psi_{\mathrm{RP}}])} + \ldots$$

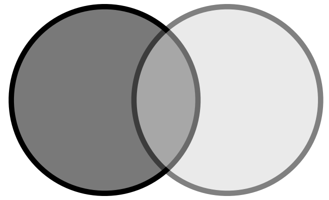
ϕ : azimuthal angle of particles

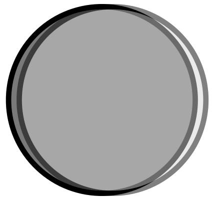
Ψ_{RP} : azimuth of reaction plane

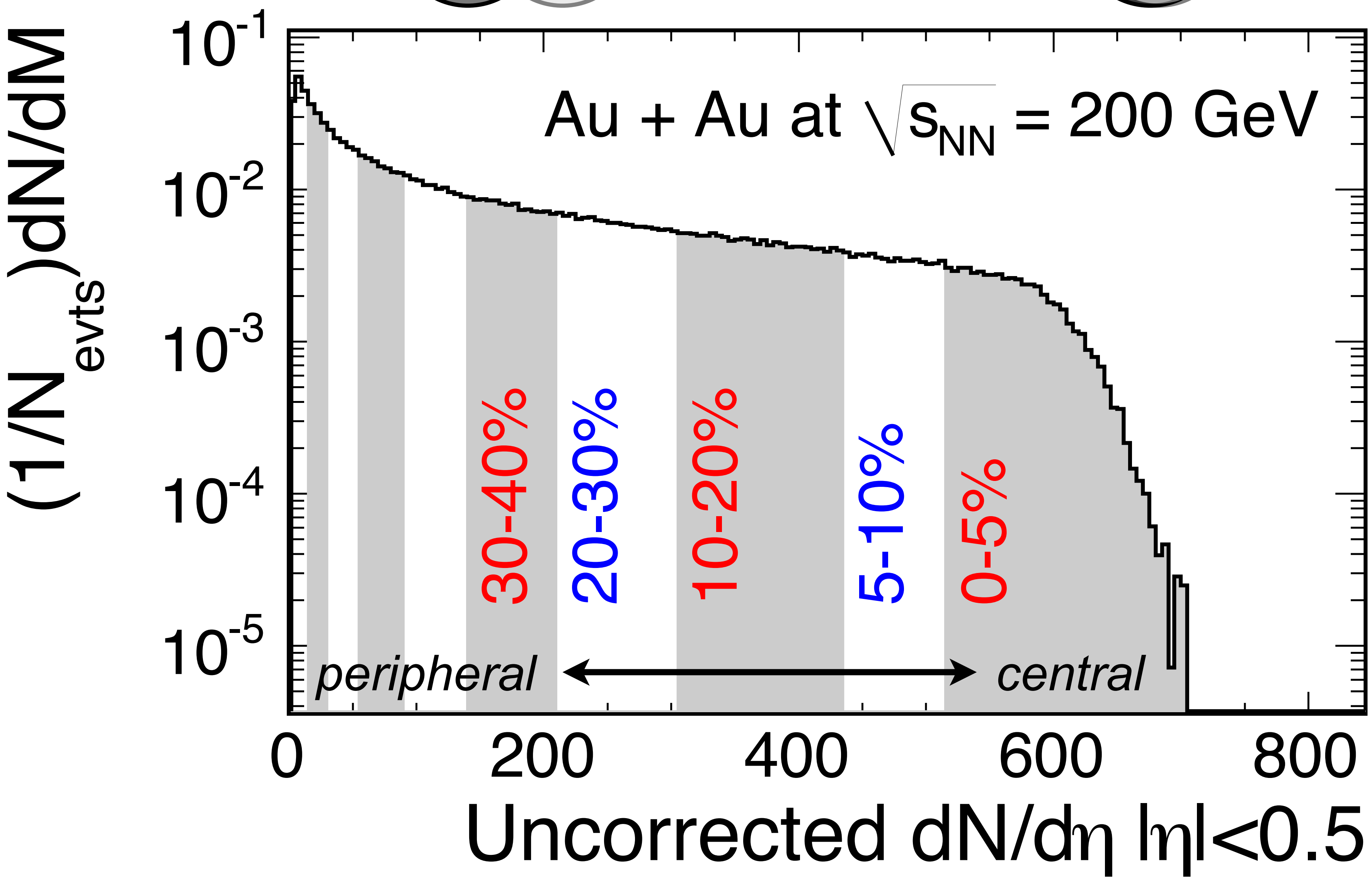


- Azimuthal anisotropy
  - ✓ Fourier expansion of azimuthal particle distributions with respect to the reaction plane
  - ✓ Second coefficient = v_2 is dominant
    - Mean v of odd harmonics vanish in symmetric rapidity
  - ✓ v_2 = 0.1 (10%) → 1.2/0.8 = 50% more particles in “in-plane” direction than in “out-of-plane”

Centrality

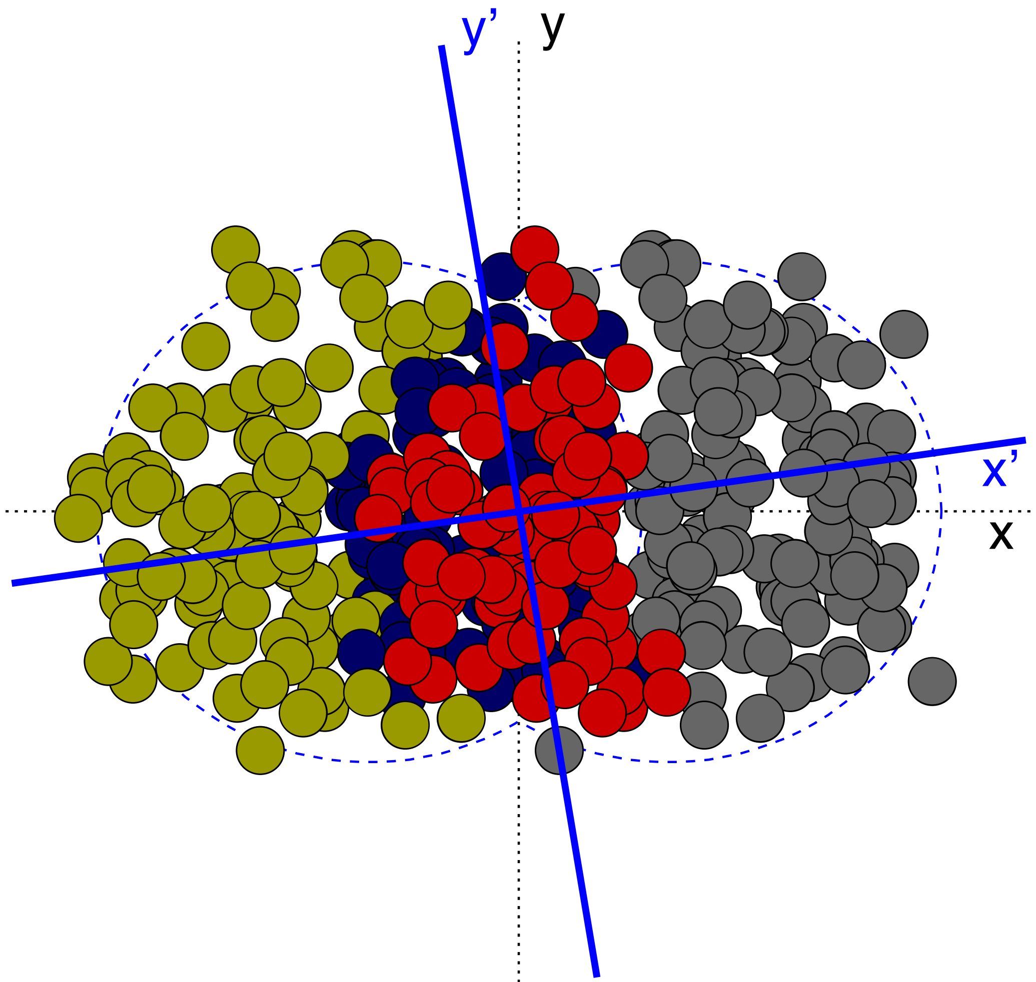


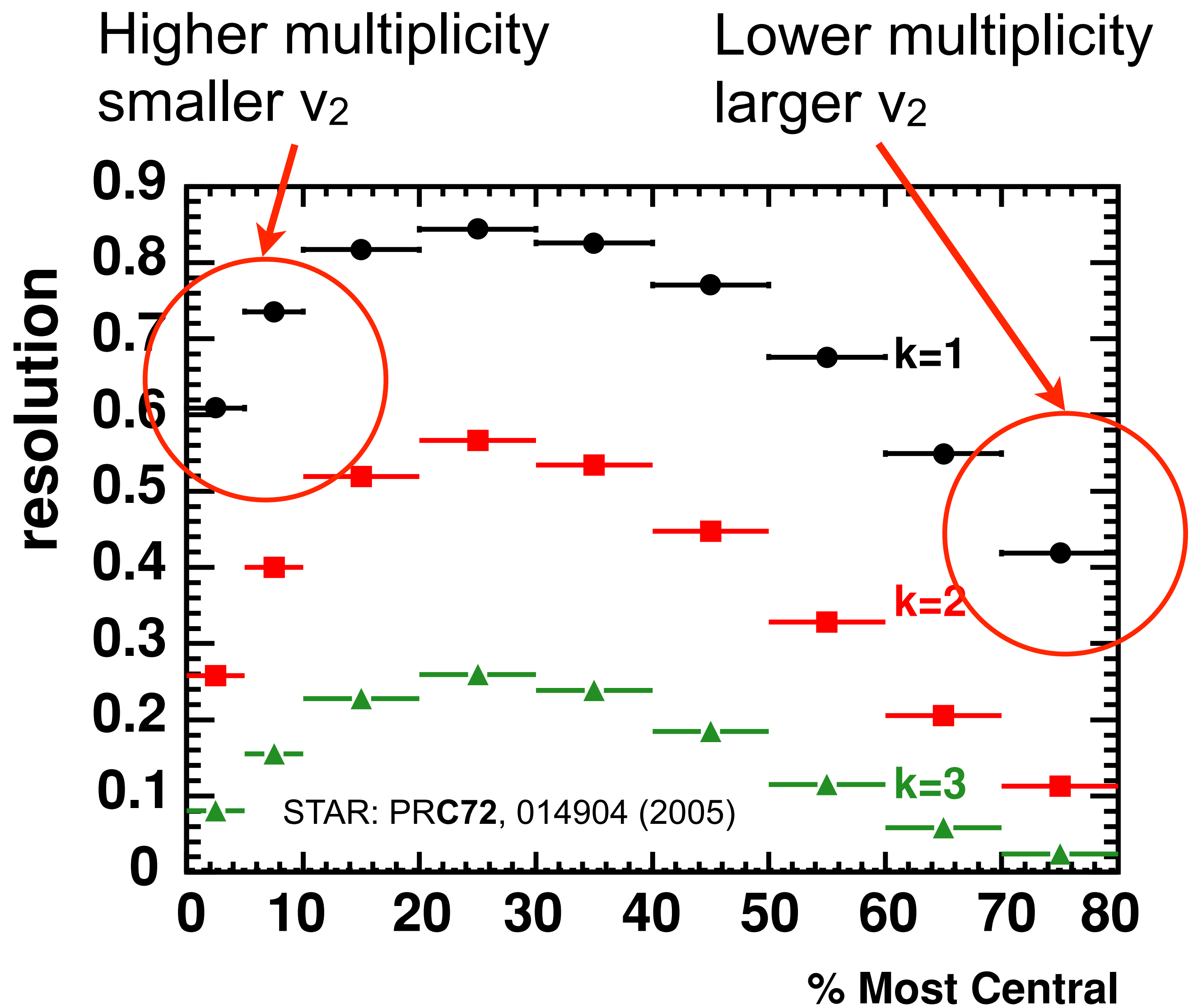




- Centrality determination in heavy ion collisions
  - ✓ Determined by multiplicity distributions
    - with Monte Carlo (MC) Glauber simulation or with event generator (ex. HIJING)
  - ➡ Number of participants, impact parameter, ...

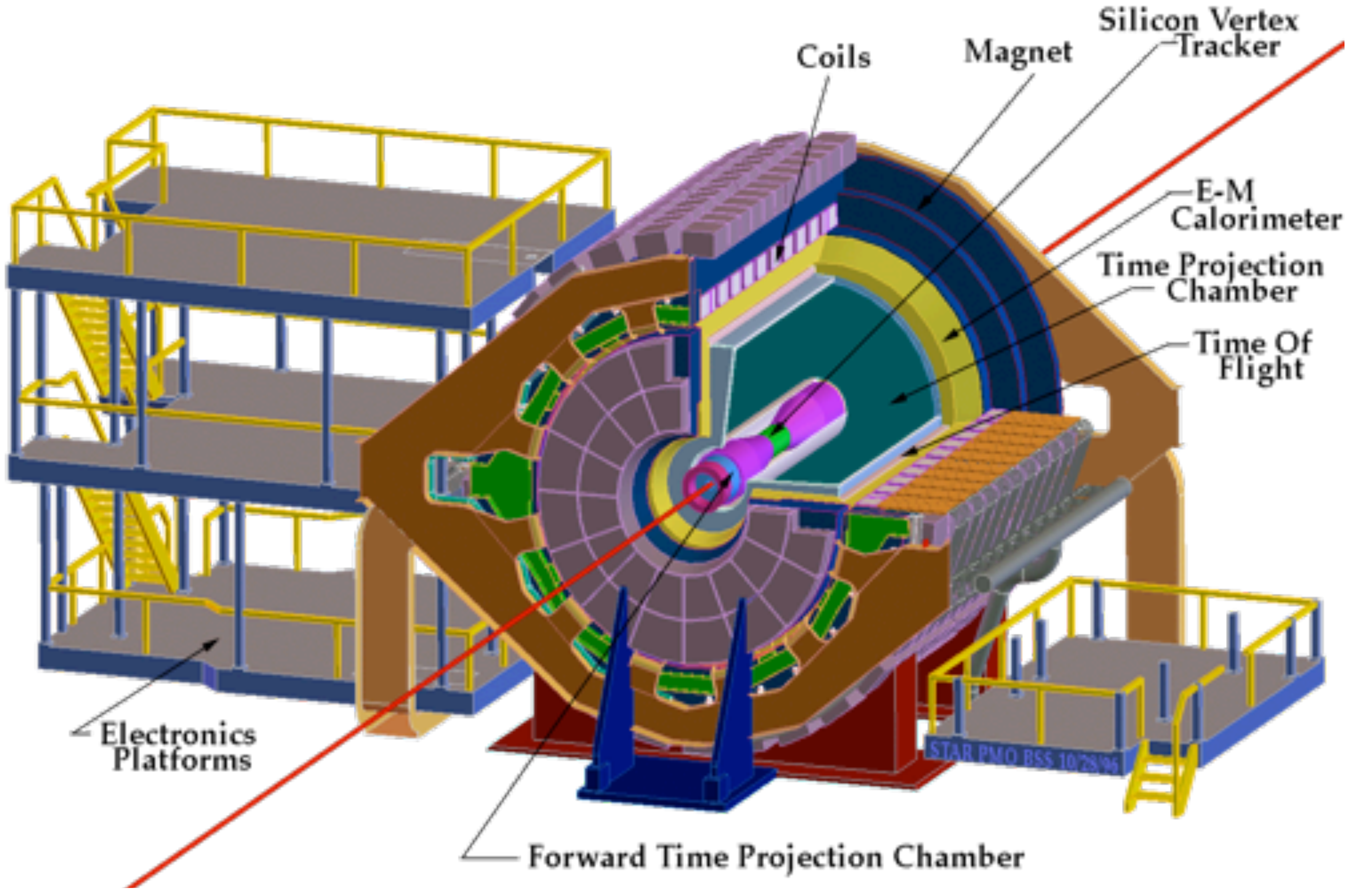
Event plane

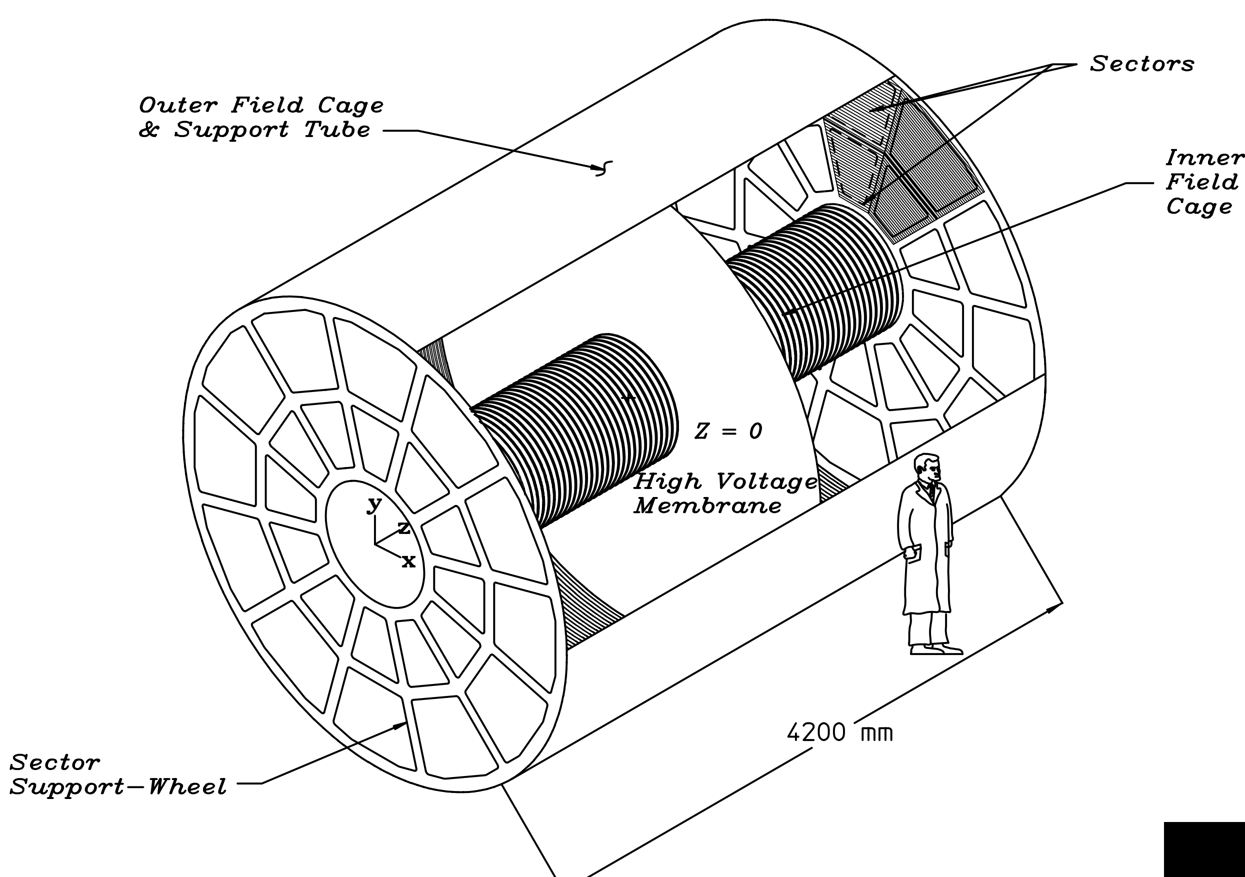




- Event plane ≠ Reaction plane
  - ✓ due to the finite multiplicity
  - ✓ event plane is determined by the flow signal itself
- Event plane resolution $\langle \cos\left(2\Psi_{\mathrm{EP}} - 2\Psi_{\mathrm{RP}}\right)\rangle$
  - ✓ Require at least two independent event planes
  - ✓ depending on multiplicity as well as v_2

Tracking, transverse momentum



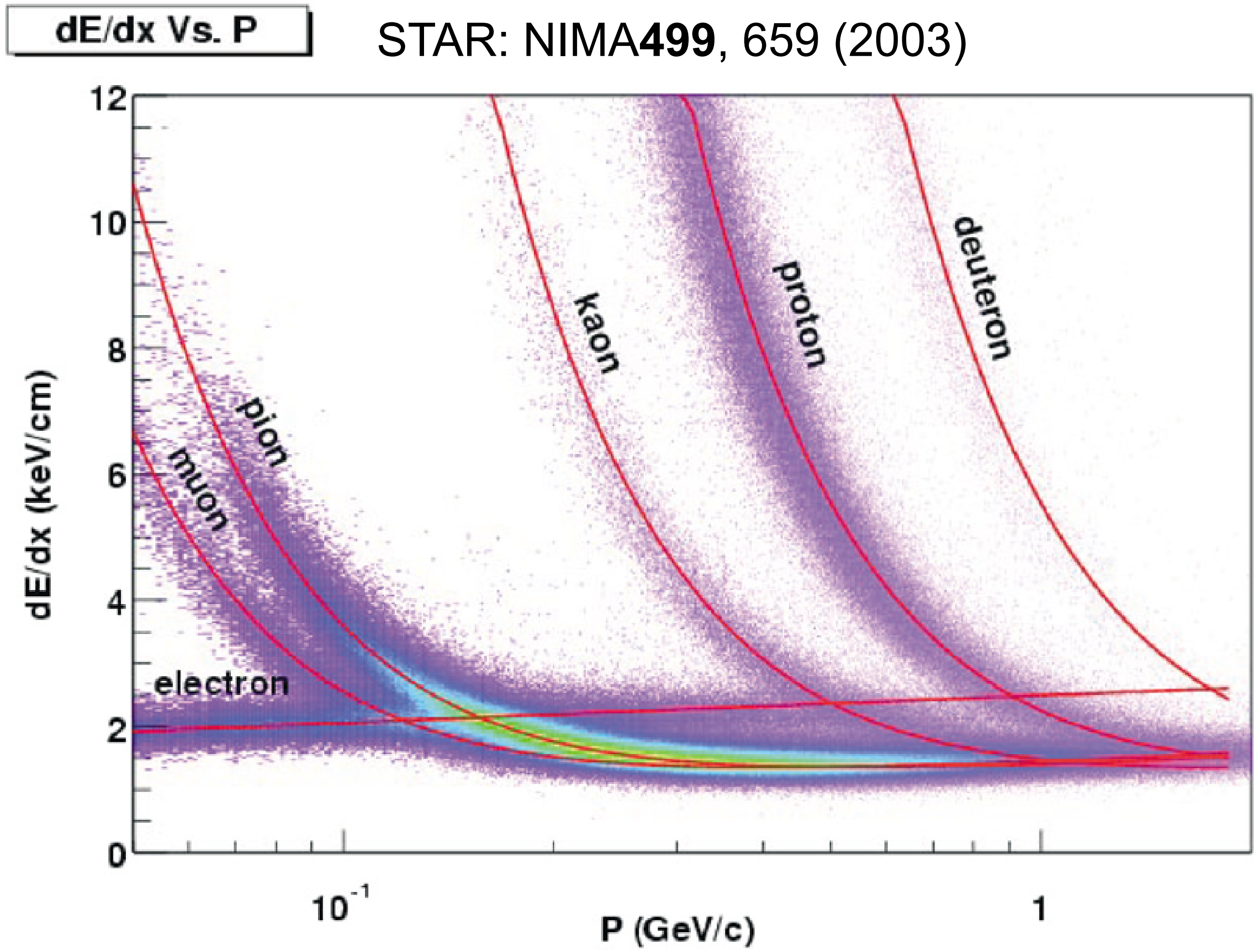


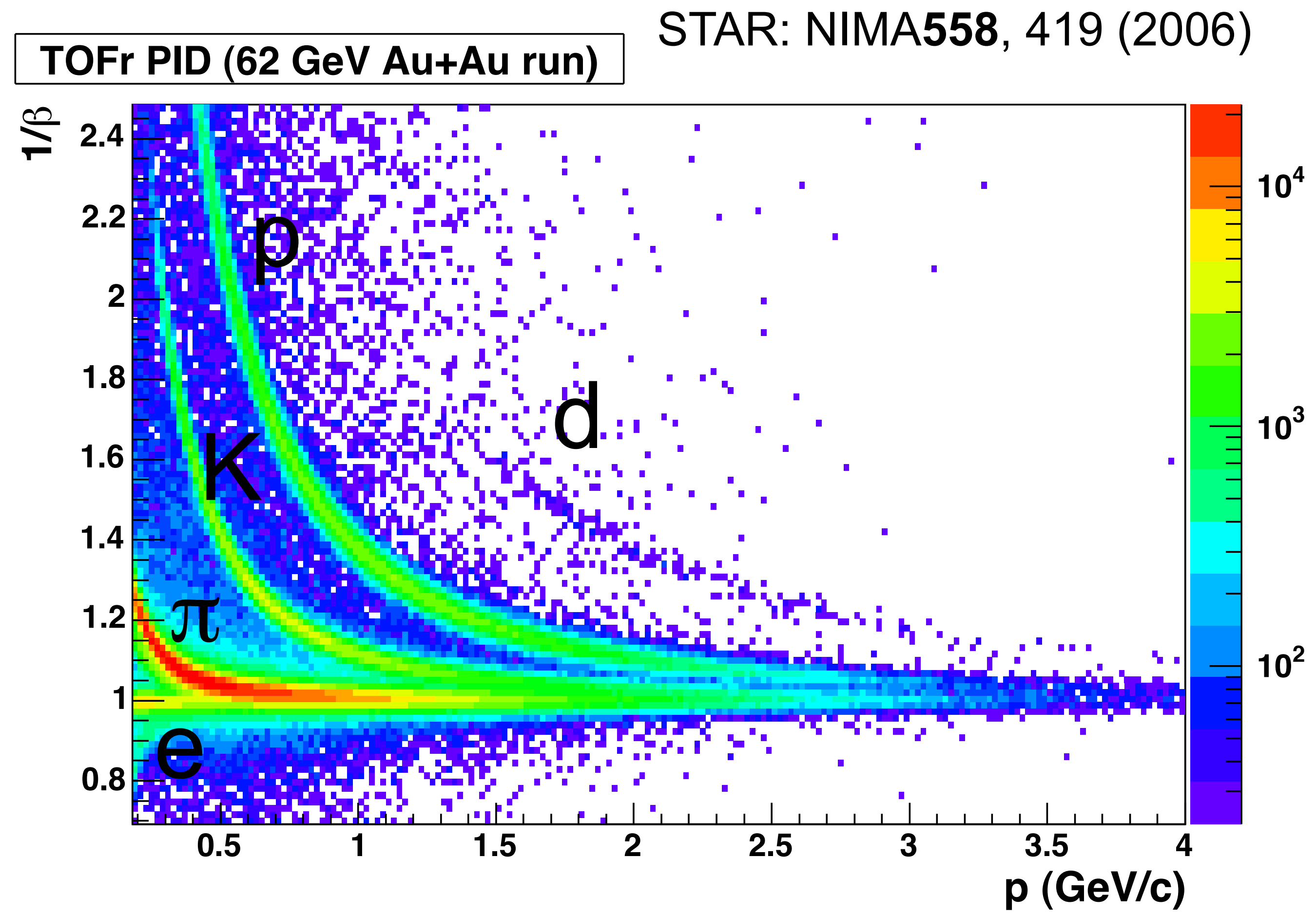
- Tracking
  - ✓ Time projection chamber + magnetic field (0.5 T)
    - (x,y) positions ← hit positions at read out pads
    - z positions ← drift time of secondary electrons
- p_T determination
  - ✓ Magnetic filed + curvature of track

$$p_T \approx 0.3 \times Br \ (\mathrm{GeV}/c)$$

- Typical p_T resolution
  - ✓ $\Delta p_T/(p_T)^2 \sim 1\%$ at $p_T = 1$ GeV/c

Particle identification





- TPC $-dE/dx \propto 1/\beta^2$
  - ✓ Energy loss (dE/dx) in the TPC; up to p_T ~ 1 GeV/c
- Time-Of-Flight detector $\beta = \frac{v}{c} = \frac{l}{tc}, \quad m^2 = p^2\left[\left(\frac{tc}{l}\right)^2 - 1\right]$
  - ✓ Flight time. Typical timing resolution < 100 ps
  - ✓ π/K ~2 GeV/c, K/p ~ 4 GeV/c

Systematics of v_2 measurements

among different methods, different collaborations at RHIC

Methods

Two particle methods

Event plane method: $v_2\{EP\}$, ...

Two particle correlation: $v_2\{2\}$

Large rapidity gap

$v_2\{RXNP\}$, $v_2\{BBC\}$, $v_2\{FTPC\}$, ...

Easy implementation

Large systematic error

Multi particle methods

Mixed harmonic event plane: $v_2\{ZDC\}$

Flow vector distribution: $v_2\{q\}$

Multi-particle cumulant: $v_2\{n\}$, n>2

Lee-Yang zero: $v_2\{LYZ\}$

...

Clean signal

Statistics hungry

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

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

- Two categories: Two and Multi particle methods
  - ✓ Different sensitivity to the ‘non-flow effects’ and ‘v_2 fluctuations’
  - ✓ Basic assumptions are
    - correlations are dominated by collective flow
    - measured particle and event plane (or reference particle) are statistically independent

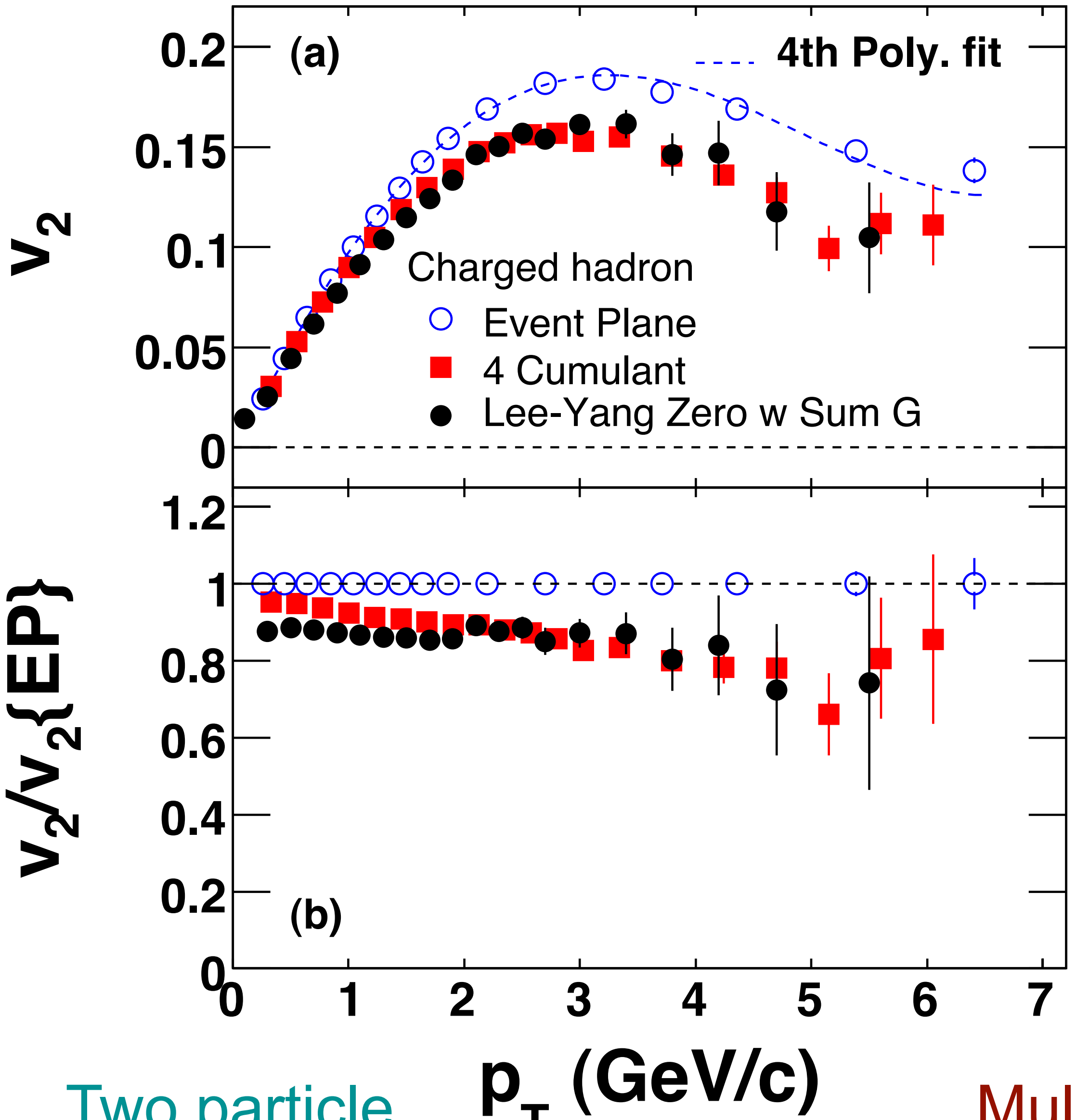
Non-flow and fluctuations

- Non-flow
  - ✓ correlations other than collective flow
    - resonance decays, HBT, momentum conservation, jets, ...
- Fluctuation of v_2
  - ✓ event-by-event fluctuation of v_2 due to the finite multiplicity
  - ✓ contribution of fluctuations to the v_2 $v_2^{measured} = \langle v_2^{\alpha} \rangle^{1/\alpha}, \ \alpha = 1 - 2$
    - α = 2 for two particle correlation
    - α varies 1 - 2 depending on the event plane resolution for v_2\{EP\}
- How do these affect the resulting v_2 from various methods ?

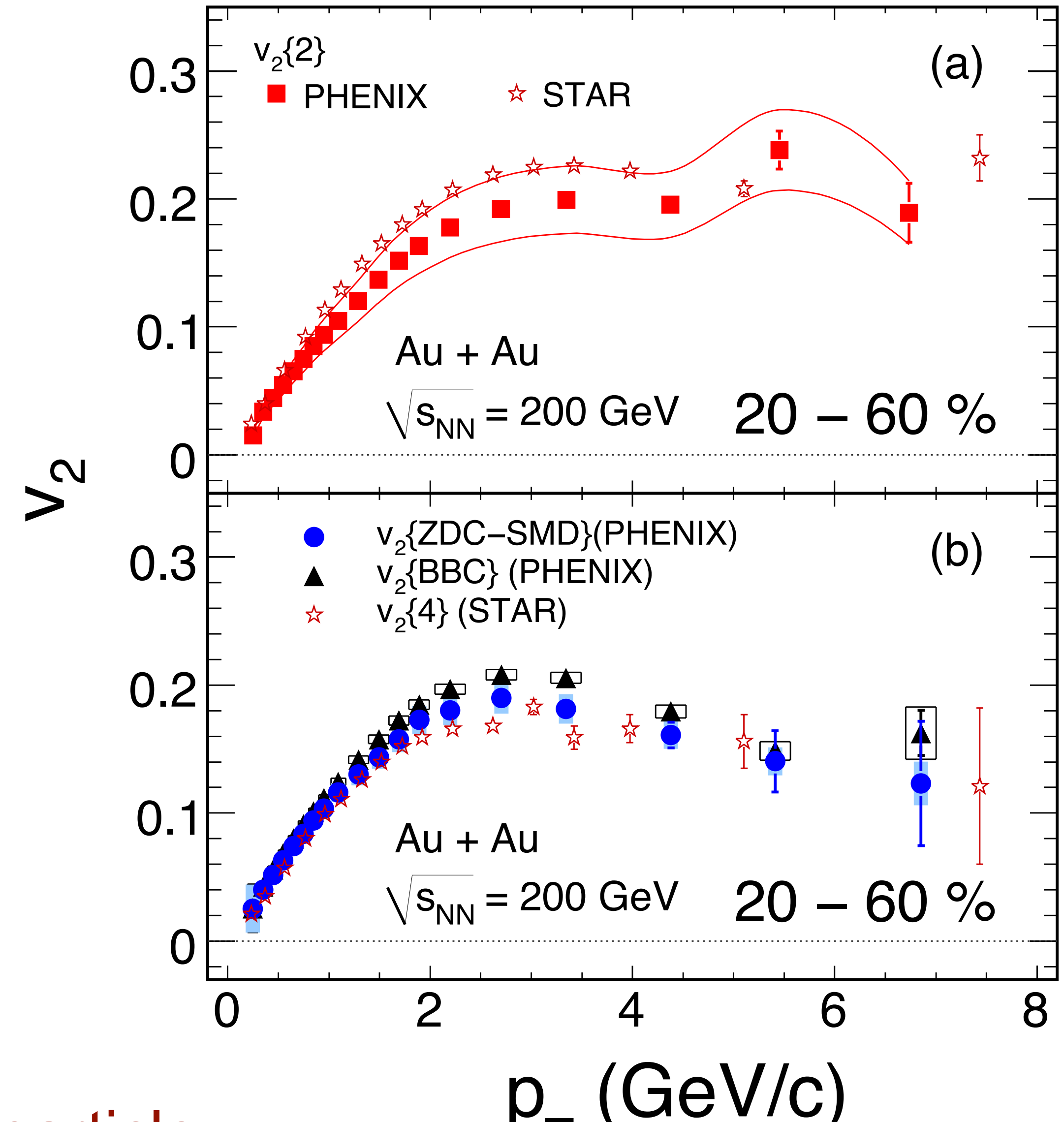
M. Miller and R. Snellings, arXiv:nucl-ex/0312008,
PHOBOS: PR**C77**, 014906 (2008)
J.-Y. Ollitrault, A. M. Poskanzer and S. A. Voloshin, PR**C80**, 014904 (2009)
...

Systematics of v_2 at RHIC

STAR, PRC**77**, 054901 (2008)



PHENIX, PRC**80**, 024909 (2009)



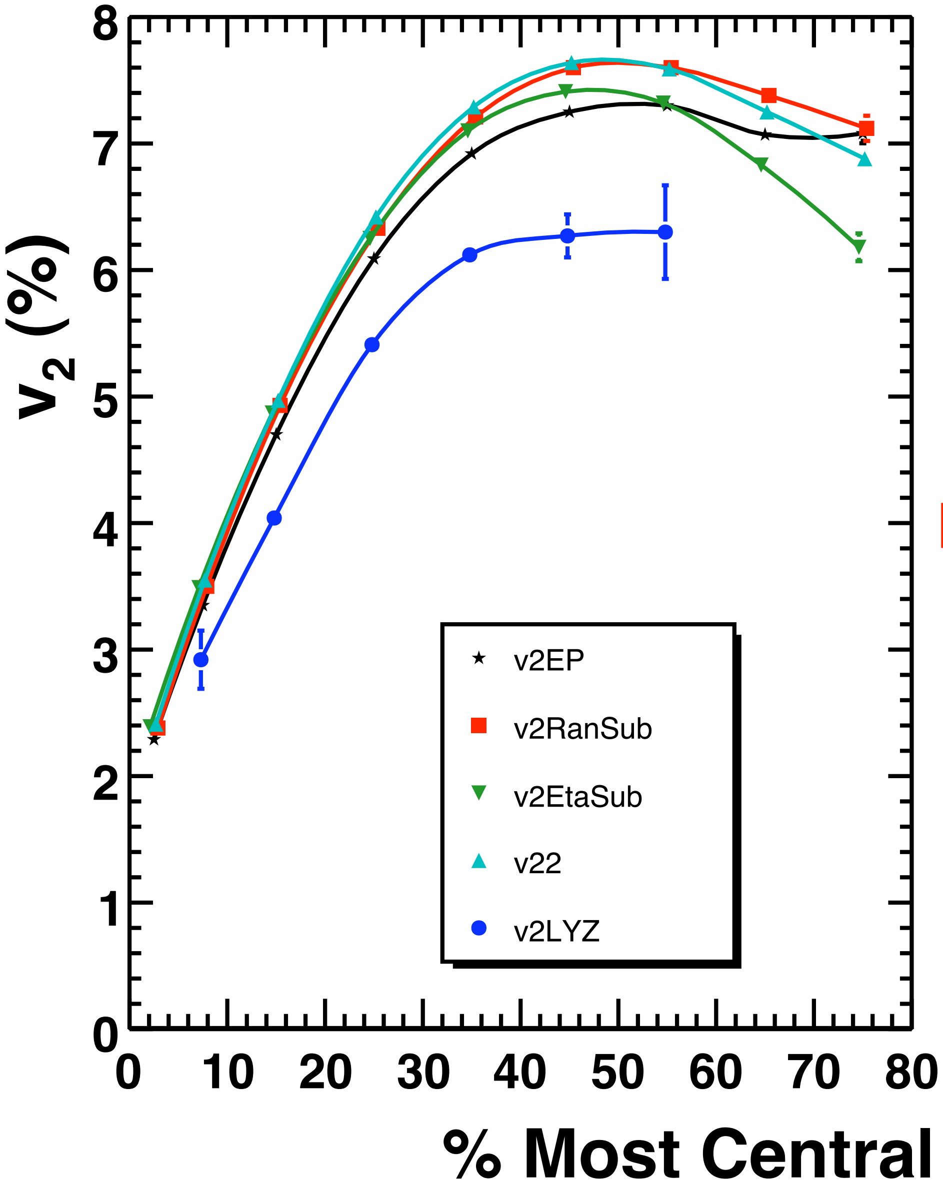
Two particle | Multi-particle

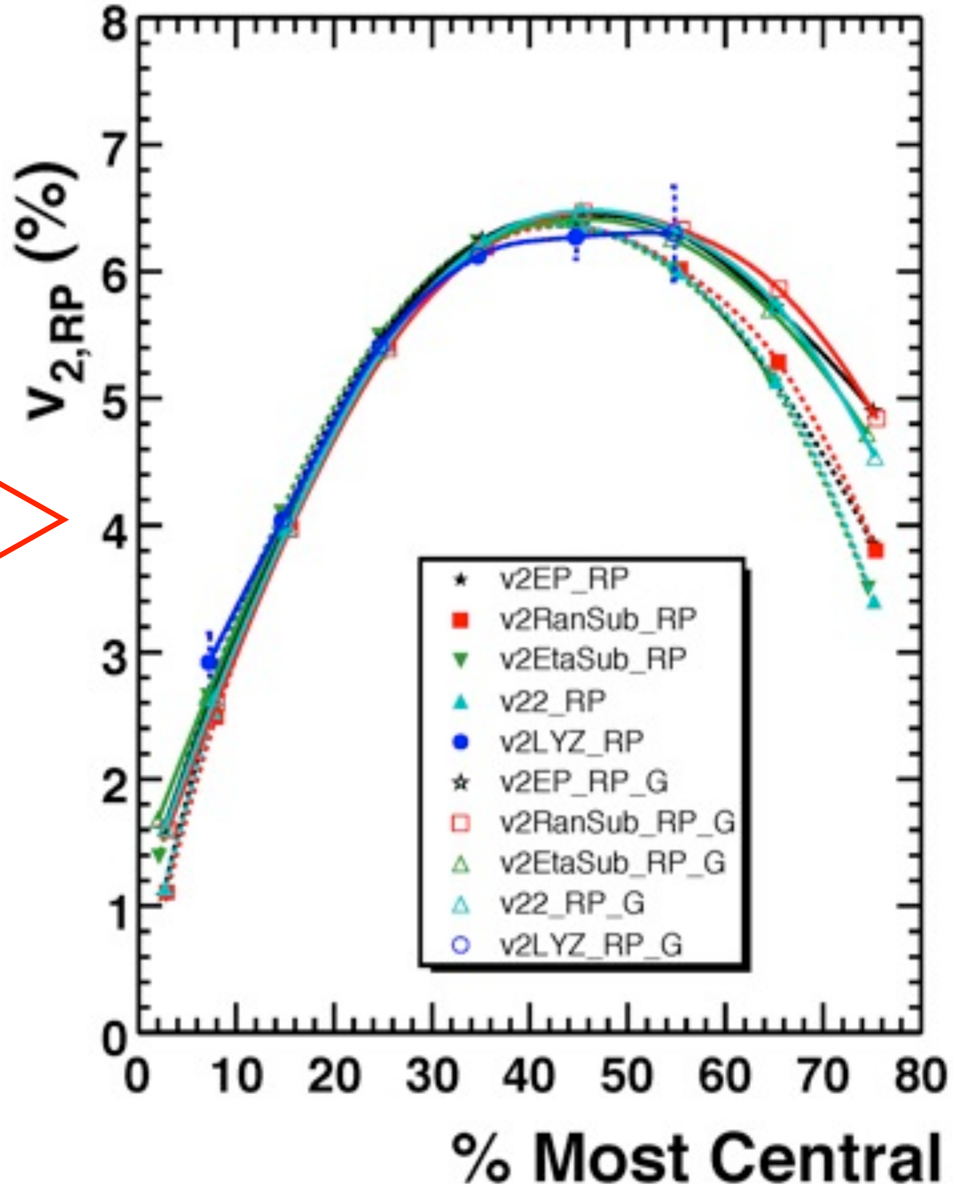
- $v_2\{2\} > v_2\{BBC\}$ $> v_2\{ZDC\text{-}SMD\} \geq v_2\{4\} \sim v_2\{LYZ\}$

  ✓ Can we understand the difference among different methods in terms of non-flow effects and v_2 fluctuations ?

Leading order corrections work

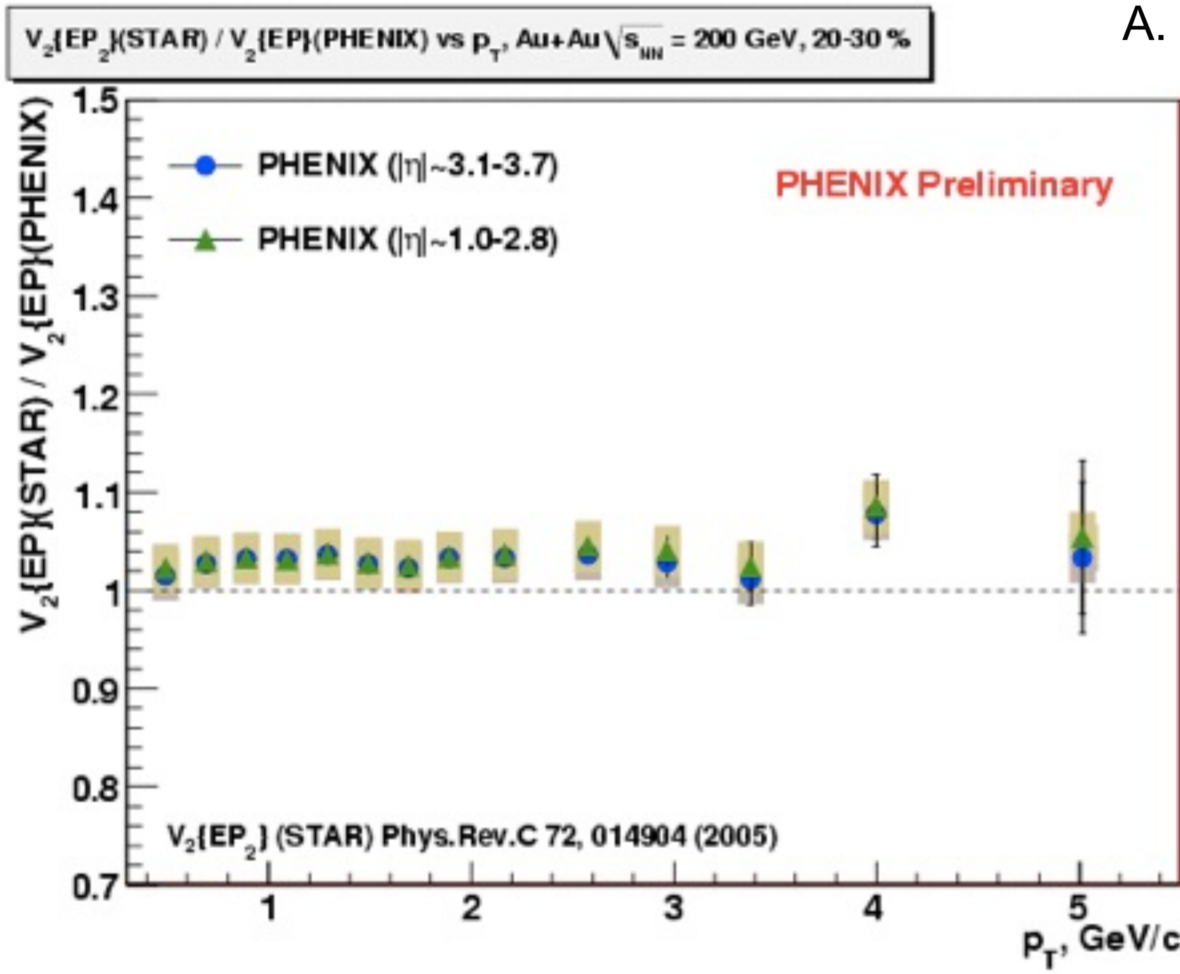
J.-Y. Ollitrault, A. M. Poskanzer and S. A. Voloshin, PR**C80**, 014904 (2009)



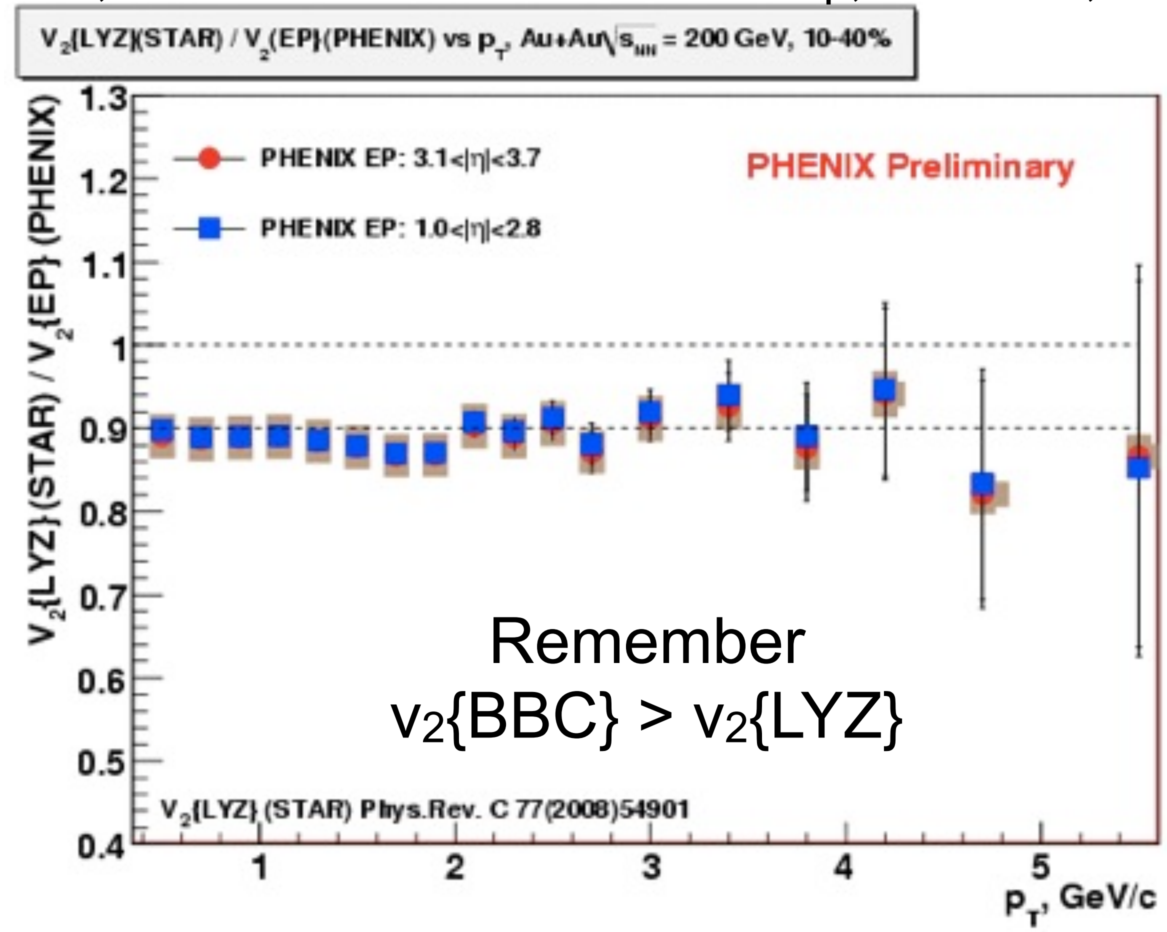


- Understand the non-flow and v_2 fluctuations with reasonable assumptions $\delta \propto \delta_{pp}/N_{part}, \quad \sigma_{v_2} \propto v_2 \times \sigma_\varepsilon/\varepsilon$
  - ✓ caveat: need additional assumptions to separate them

Inter-collaboration comparison

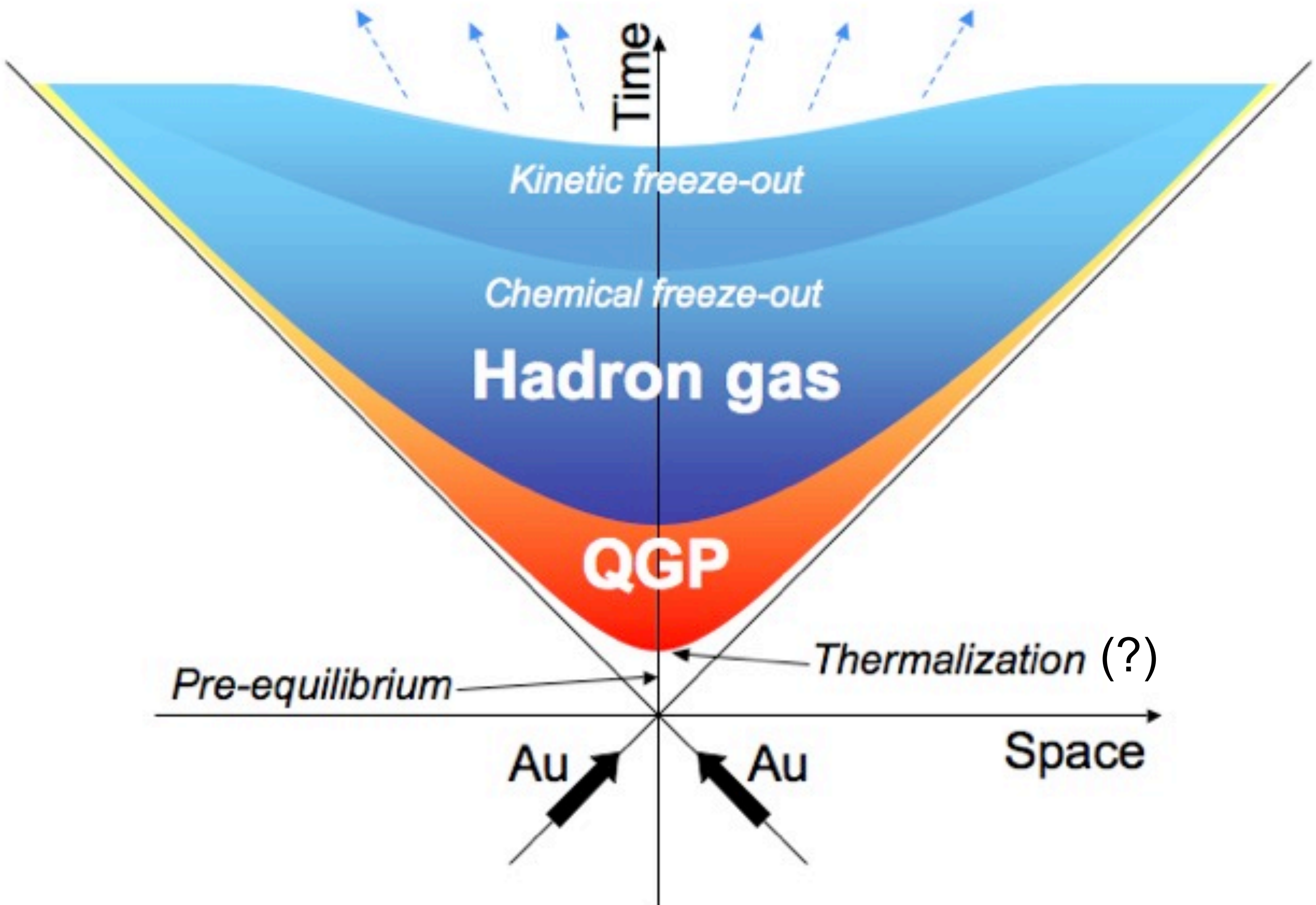


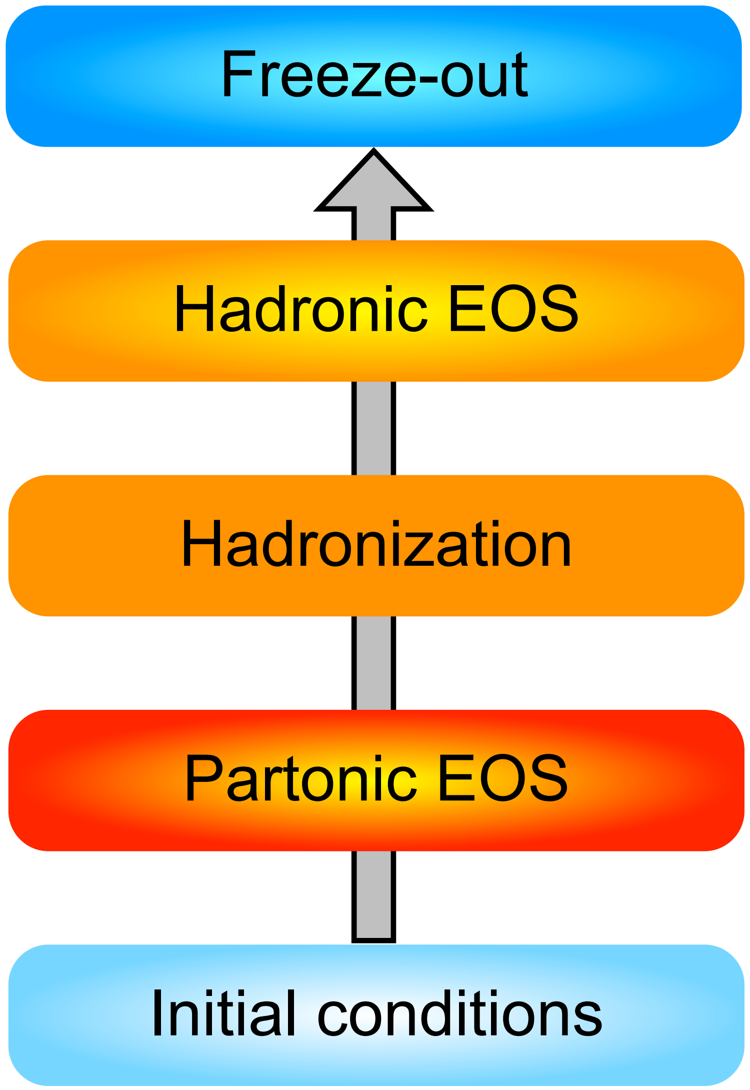
A. Taranenko, Joint CATHIE/TECHQM workshop, Dec14-18, 2009



- Quantitative comparison of v_2 at RHIC
  - ✓ PHENIX, PHOBOS and STAR
    - see more details in A. Taraneko's talk: http://quark.phy.bnl.gov/www/cathie_files/ca-te/Tuesday/TaranenkoV2Compt2009v4.ppt
- Agreement of v_2 is ~ 10%
  - ✓ with possible 1-2% centrality shift between PHENIX and STAR

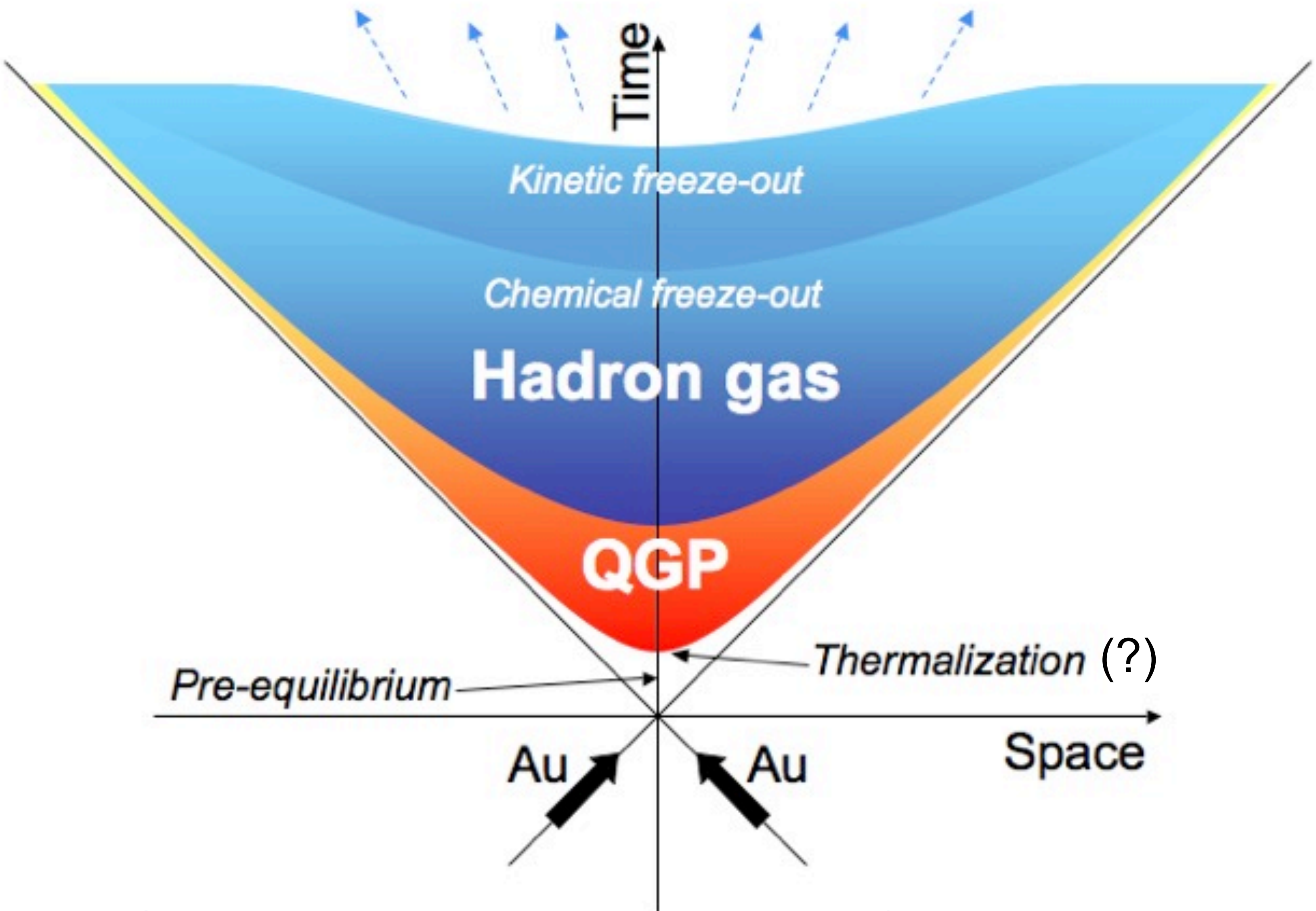
Space-time evolution

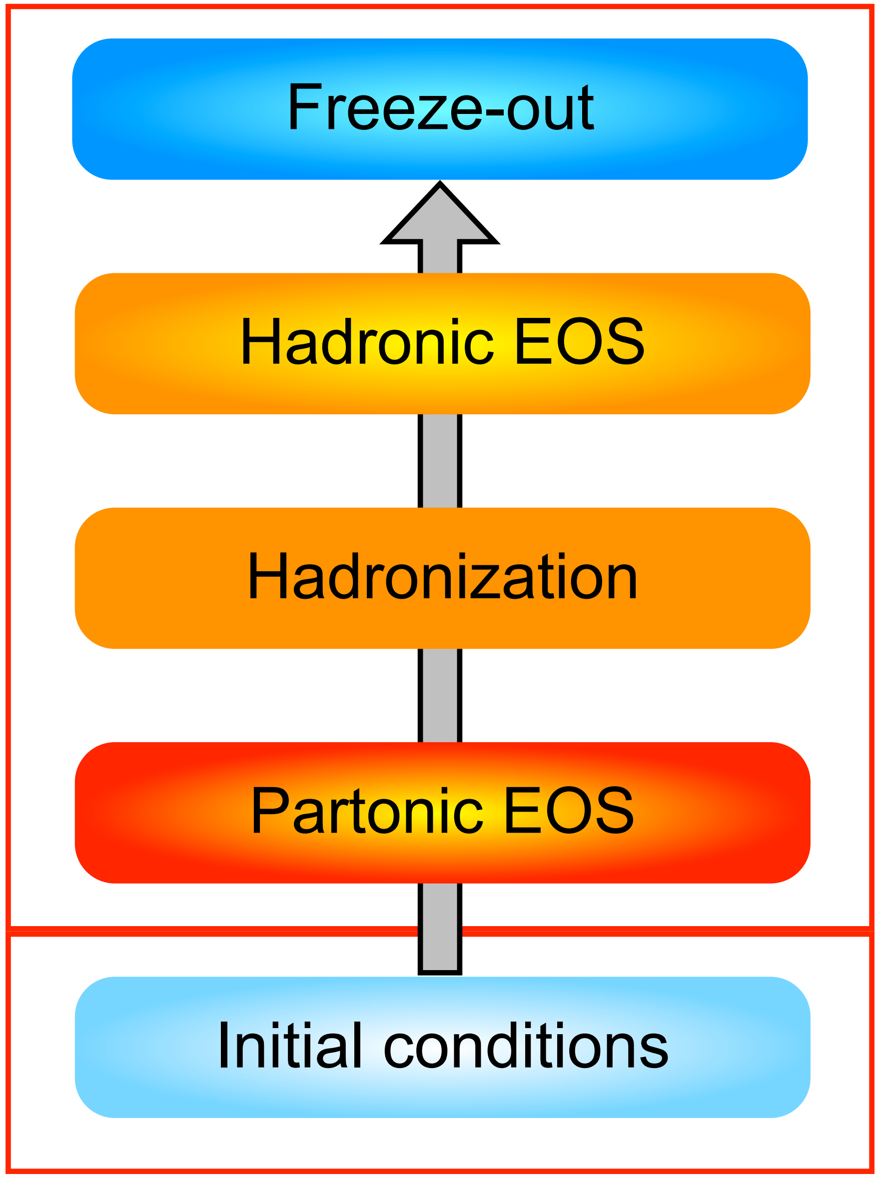




- Collective anisotropic flow is sensitive to all stages
- What kind of v_2 measurements are sensitive to different stages of space-time evolution ?

Space-time evolution





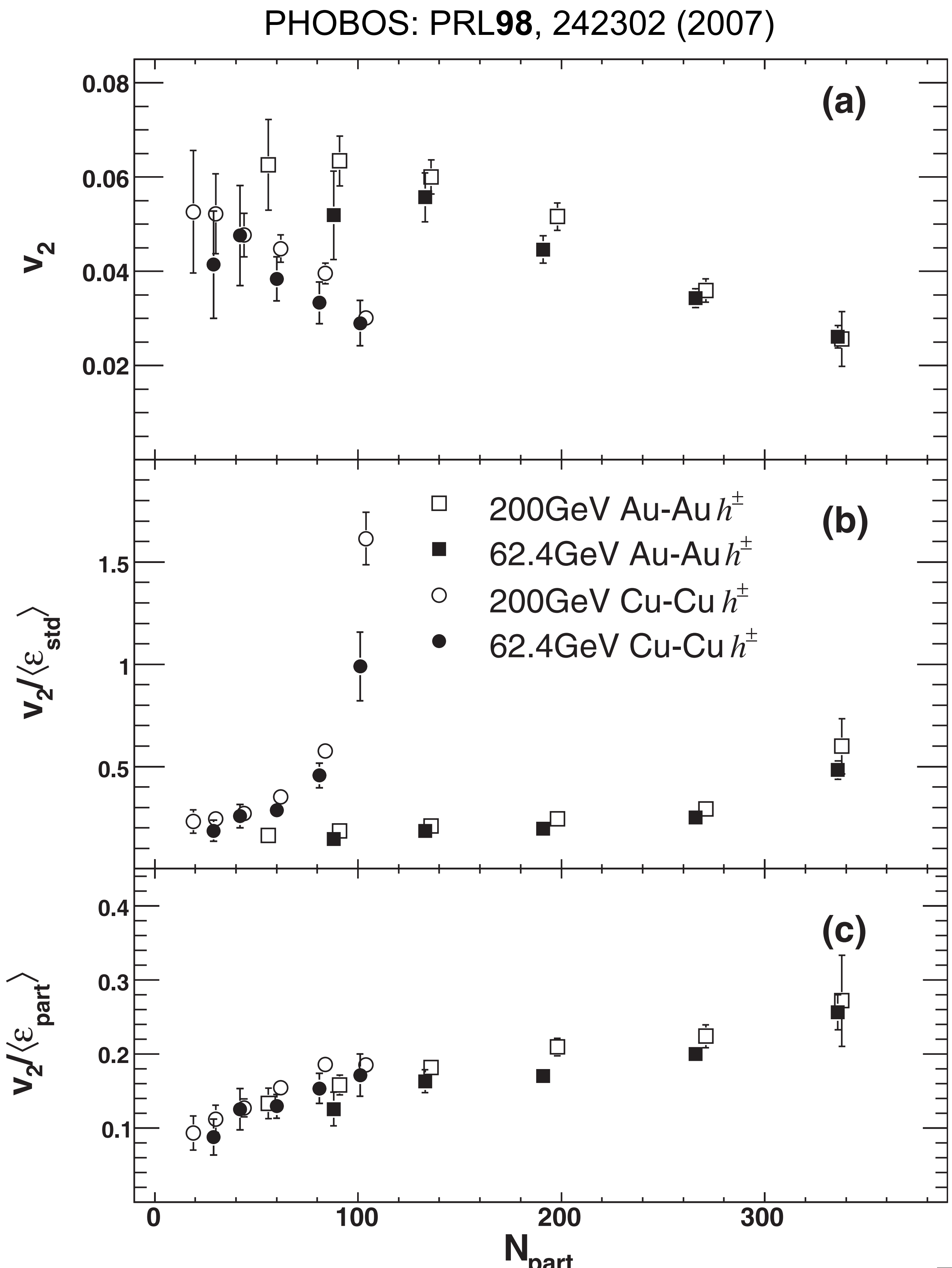
- Collective anisotropic flow is sensitive to all stages
- What kind of v_2 measurements are sensitive to different stages of space-time evolution ?

What have we learned at RHIC ?

Initial conditions

centrality dependence of v_2

Effect of fluctuations



$$\varepsilon_{\text{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

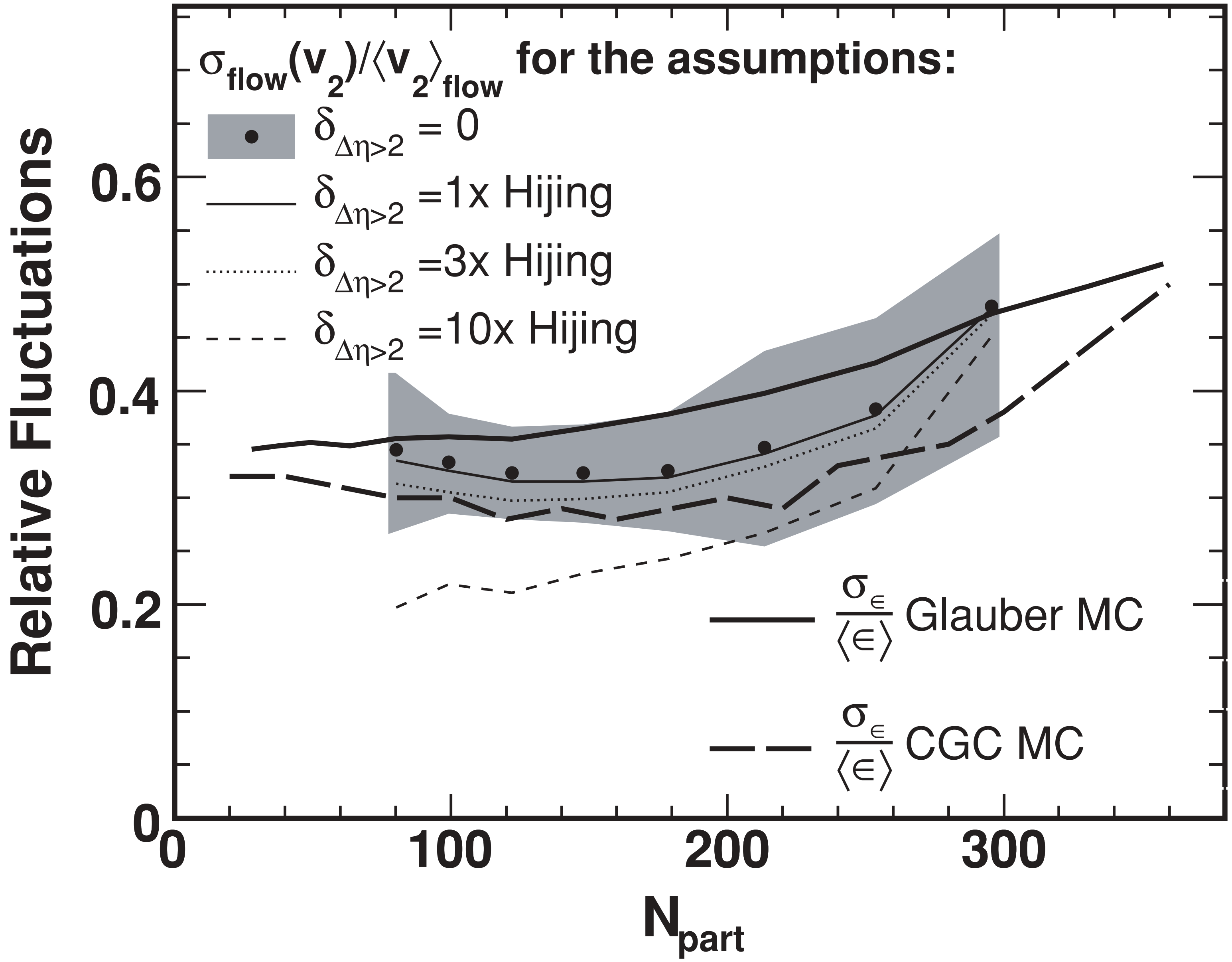
$$\sigma_x^2 = \{x^2\} - \{x\}^2, \sigma_y^2 = \{y^2\} - \{y\}^2$$

$$\sigma_{xy} = \{xy\} - \{x\}\{y\}$$

- Measured v_2 from two particle methods scale with the ‘participant eccentricity’ ε_{part}
  - ✓ take into account the shift/ rotation of frame due to the fluctuations of participant nucleons
- How strong are v_2 fluctuations ?

v_2 fluctuations

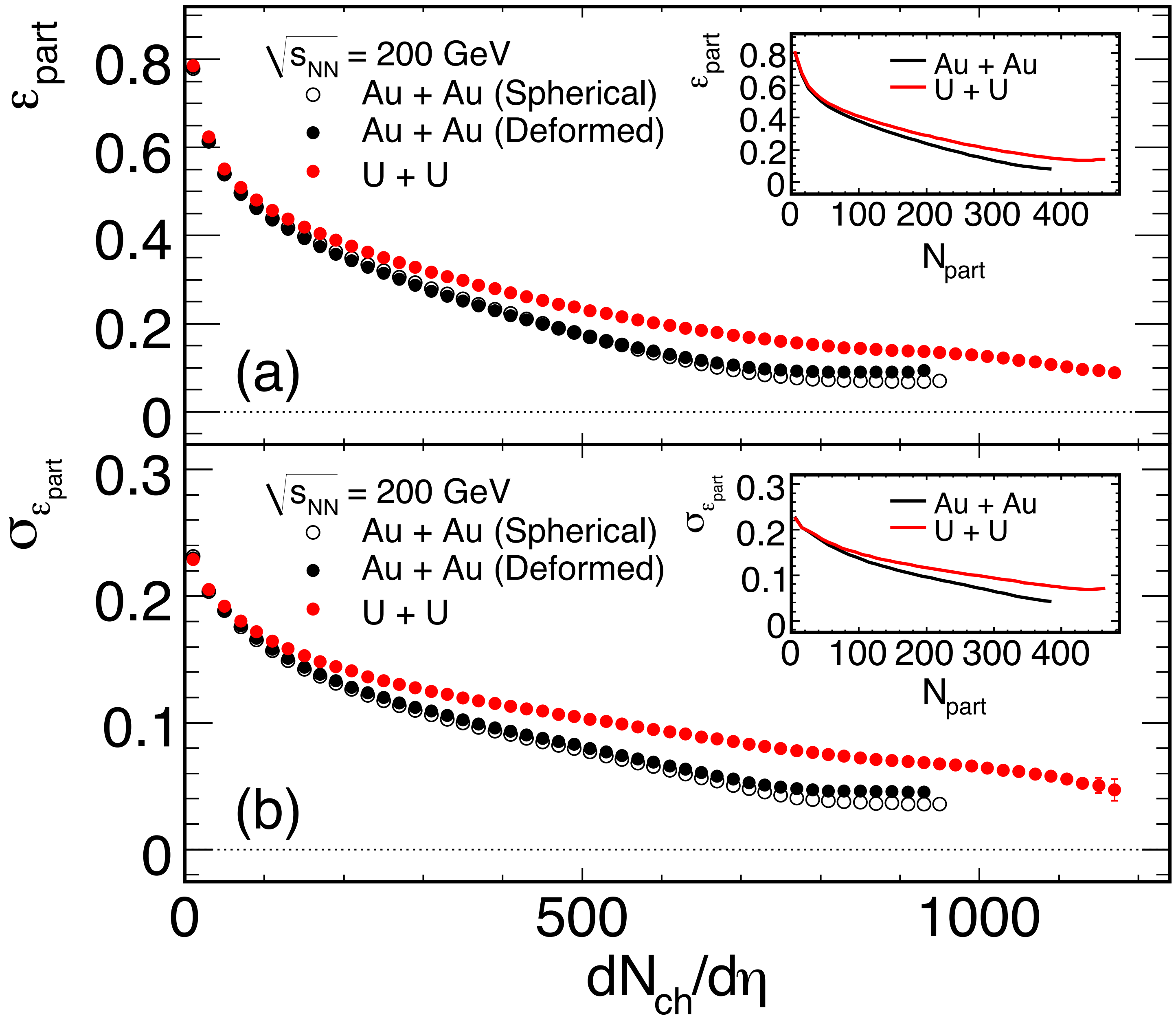
PHOBOS: PRC**81**, 034915 (2010)



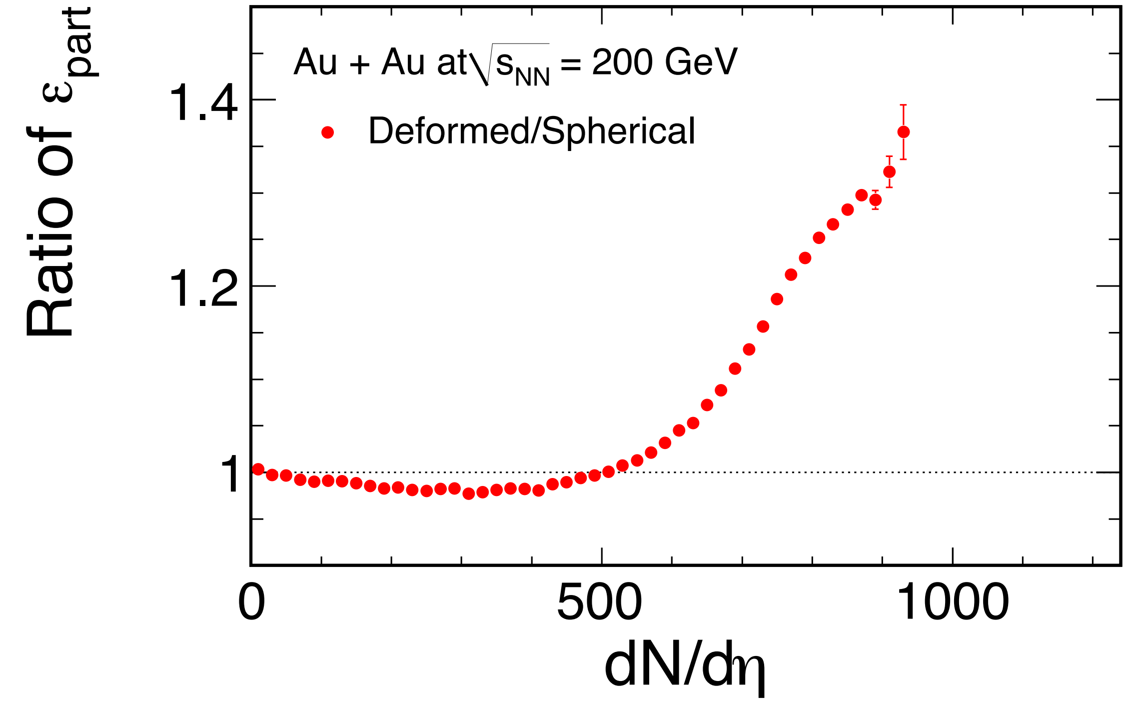
- 6-45% most central
- Measured v_2 and fluctuations event-by-event
- Non-flow is evaluated by superposition of p + p collisions (PYTHIA)

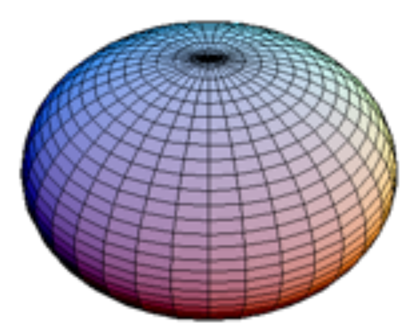
- Relative fluctuations ~ 30-40%
  - ✓ non-flow correlations ~10% of $(v_2)^2$ signal in $|\eta| < 3$
  - ✓ Consistent with both MC Glauber and CGC initial conditions

Effect of deformation



P. Filip, R. Lednicky, H. M., N. Xu
PR**C80**, 054903 (2009)



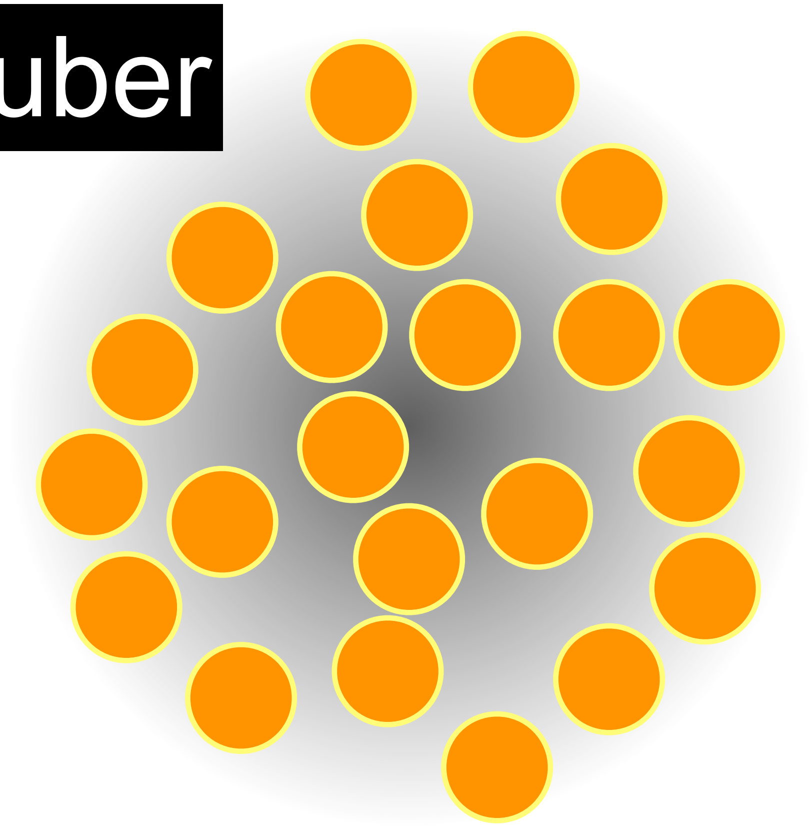


Deformation
$\beta_2 \sim -0.13$

- Possible oblate deformation effects for Au nucleus
  - ✓ ϵ_{part} increases ~30% at central Au+Au collisions
  - ✓ Not affect in mid-central and peripheral collisions

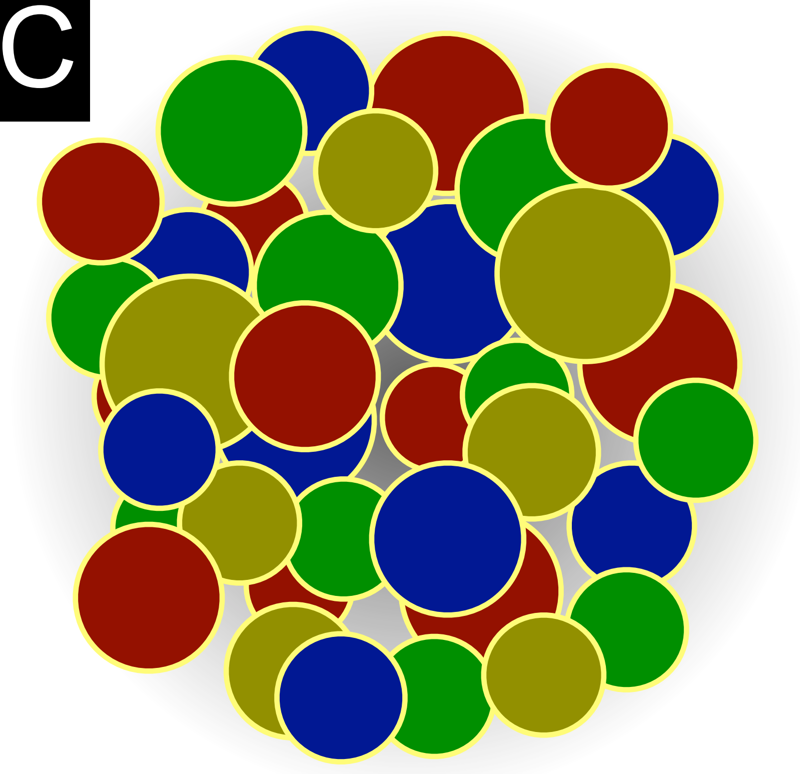
Glauber or CGC ?

Glauber



- Static, nucleons
- No dynamics
- Well defined cross section in p+p

CGC

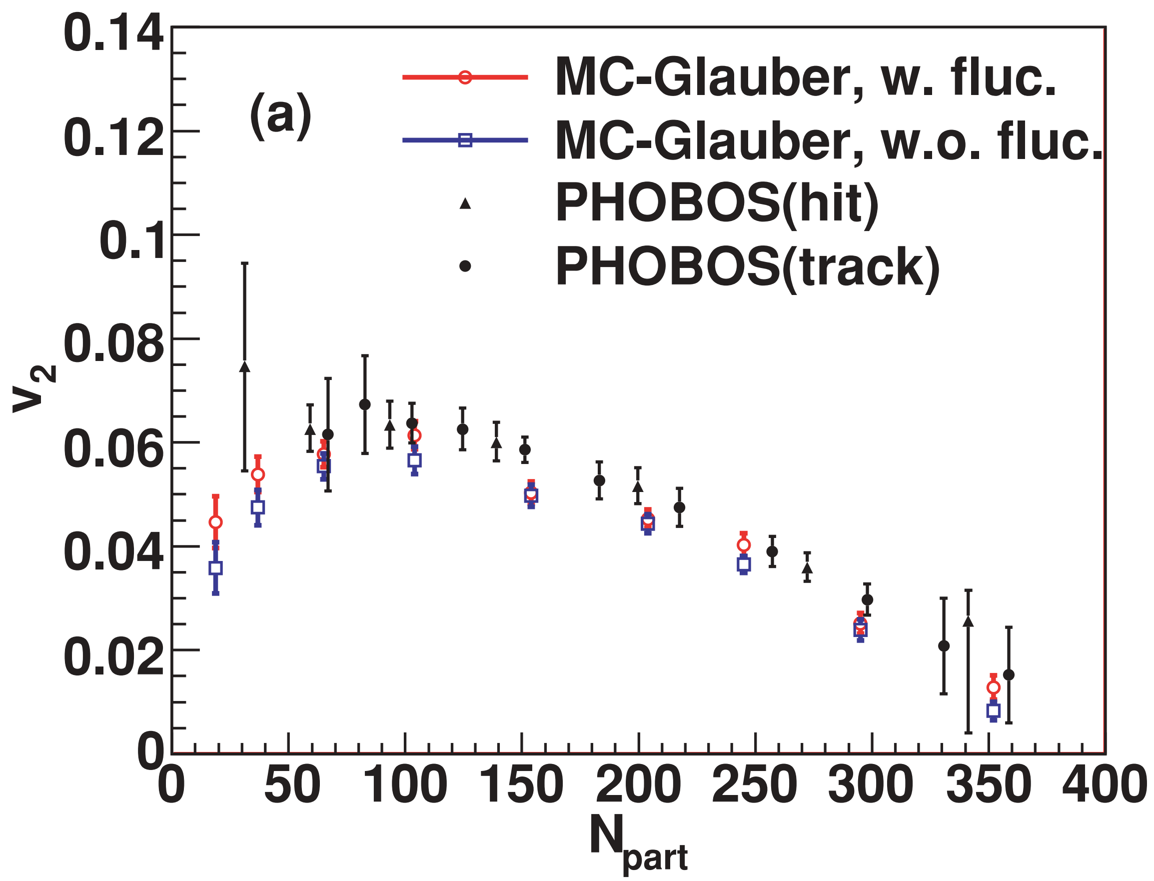


- Dynamical, gluons
- Momentum dependent
- May not be applicable at large x

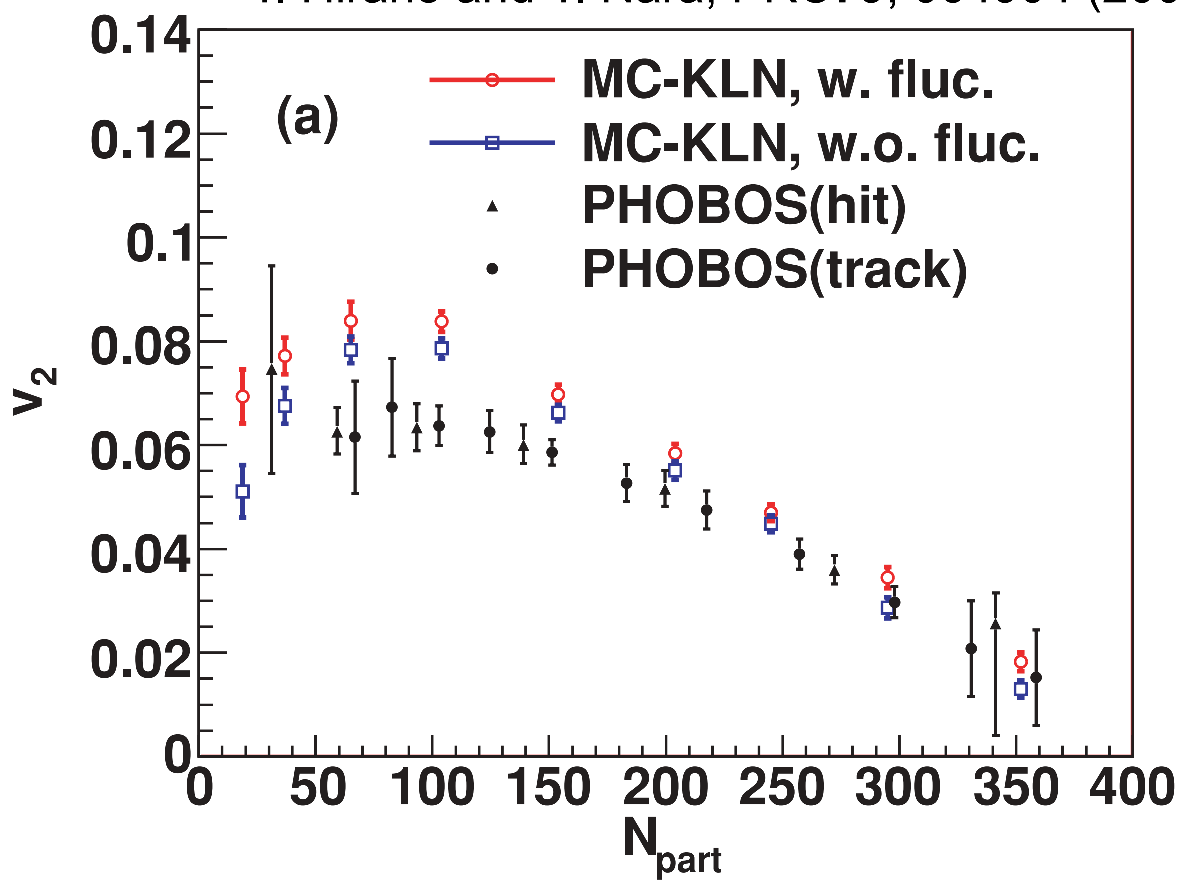
* see for example; H.-J. Drescher, Y. Nara PR**C75**, 034905 (2007)

- Two main initial conditions; Glauber or CGC
  - ✓ Monte Carlo approach to include fluctuations*
  - ✓ How can we constrain the initial conditions from v_2 measurements ?

Glauber or CGC ?



T. Hirano and Y. Nara, PR**C79**, 064904 (2009)



- Comparison with hybrid model, Hydro + hadron cascade with ideal gas EOS

✓ Fluctuation effect is large (Cu+Cu, not shown)

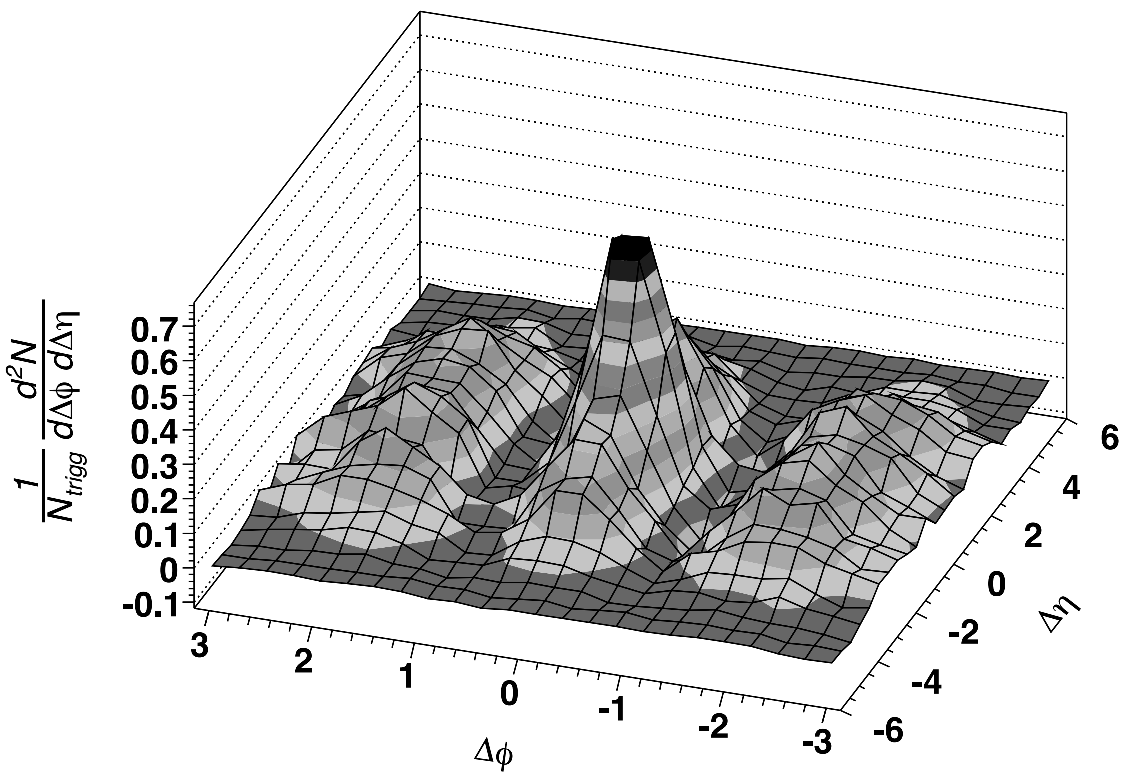
✓ Need QGP viscous effects in CGC ? But data ~ model in Cu+Cu

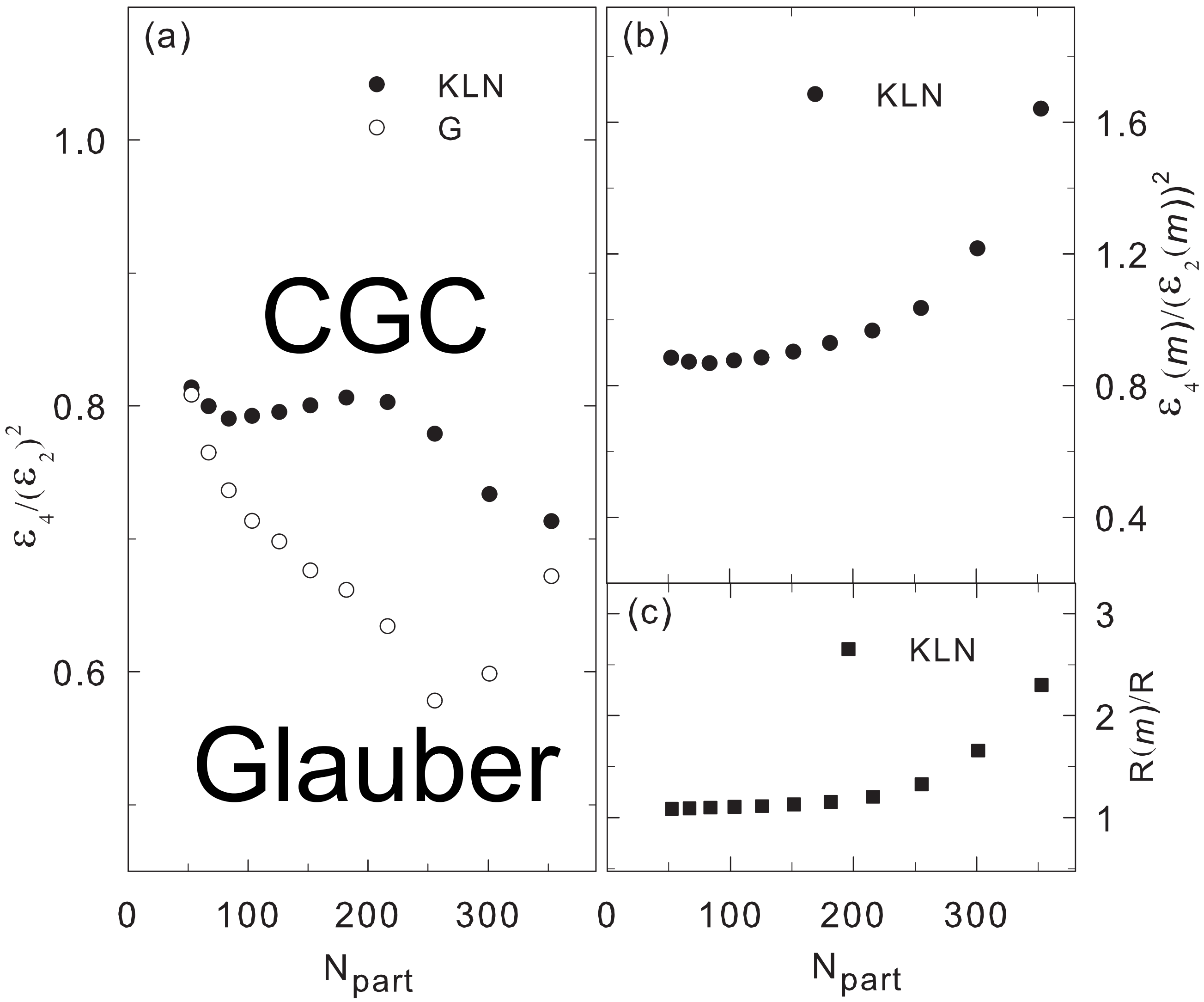
➡ System size dependence of v_2 is important to constrain the model parameters

Initial conditions

J. Takahashi, B. M. Tavares, W. L. Qian, R. Andrade, F. Grassi, Y. Hama, T. Kodama, N. Xu, PRL**103**, 242301 (2009)

R. A. Lacey, R. Wei, N. N. Ajitanand, J. M. Alexander, X. Gong, J. Jia, A. Taranenko, R. Pak, H. Stocker arXiv:1002.0649





- Combined with different measurements would address the initial conditions

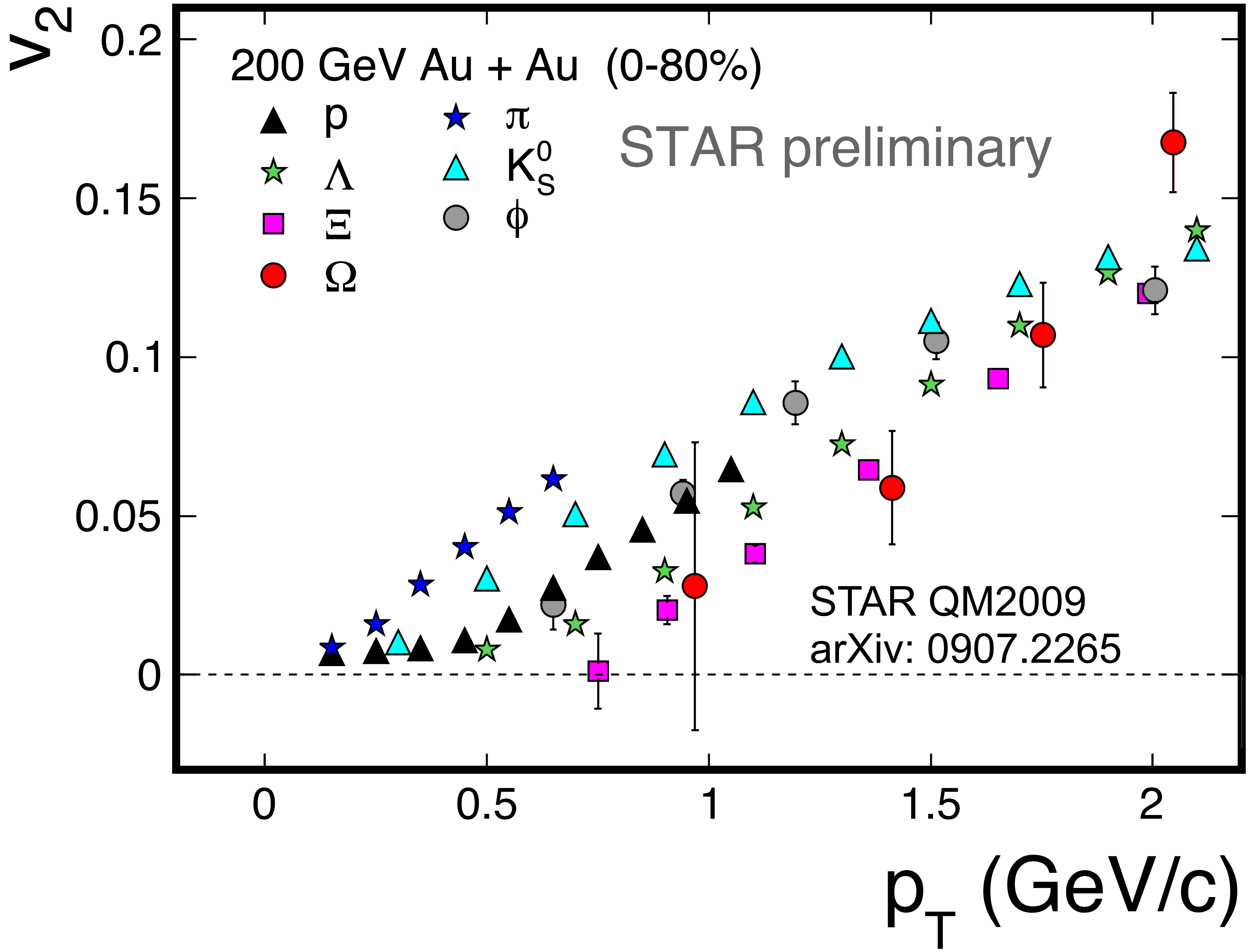
✓ Ridge ? Higher harmonics ?

What have we learned at RHIC ?

EOS, hadronization

p_T and particle type dependence of v_2

Mass ordering at low p_T



Thermal $\oplus$ Collective

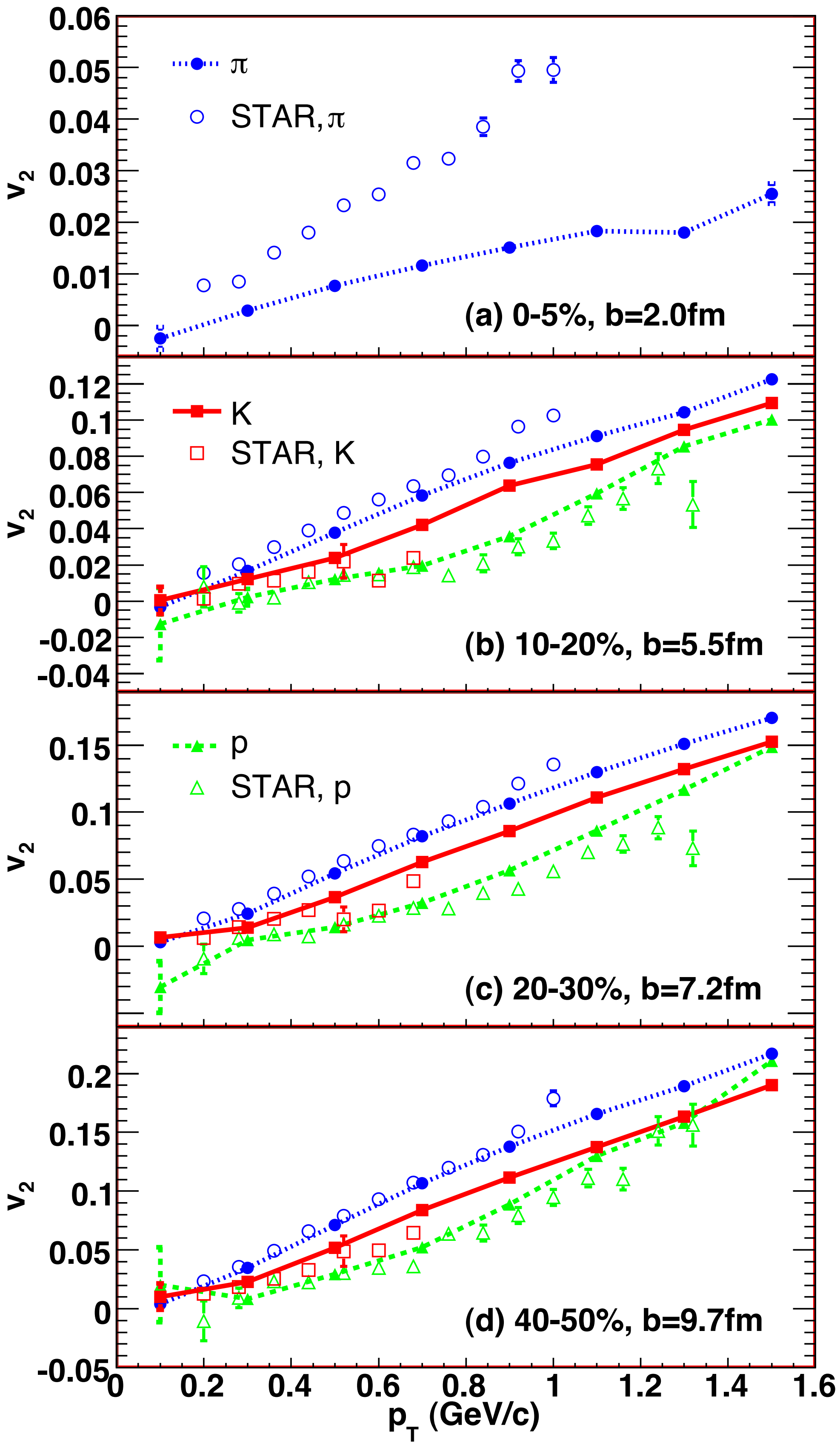
$$T_{eff} \propto T_{thermal} + mass \times \langle v_T \rangle^2$$

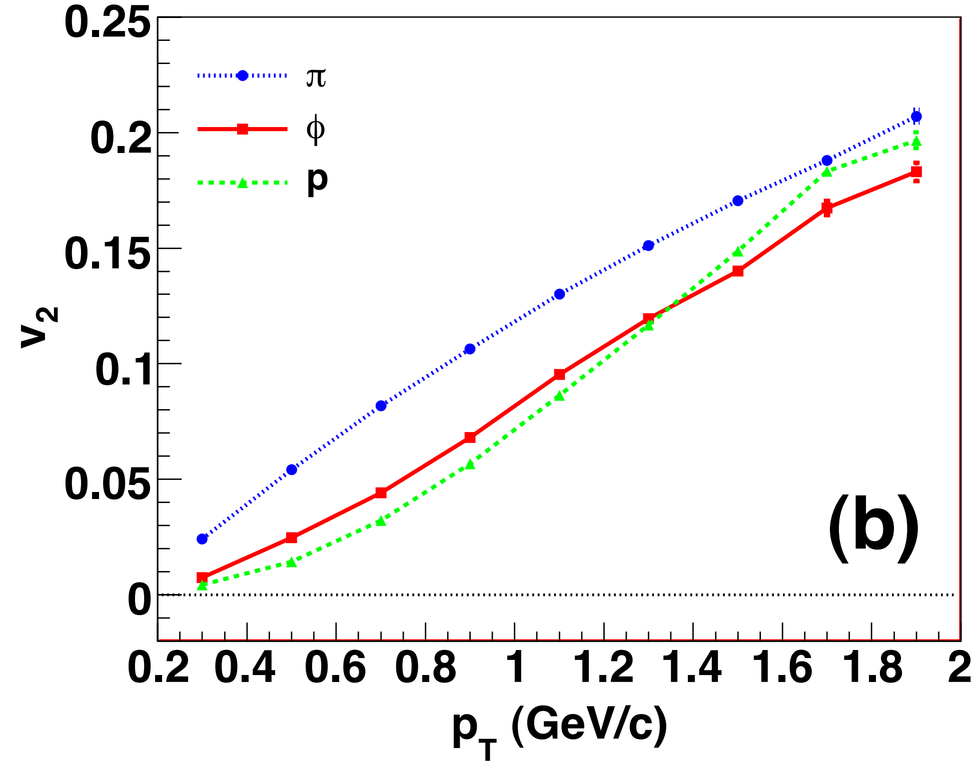
v_T: common velocity among different particles

- Heavier hadrons show lower v_2
  - ✓ Radial flow + eccentricity
  - ✓ Is mass ordering of v_2 a consequence of partonic EOS ?

Hadronic rescattering

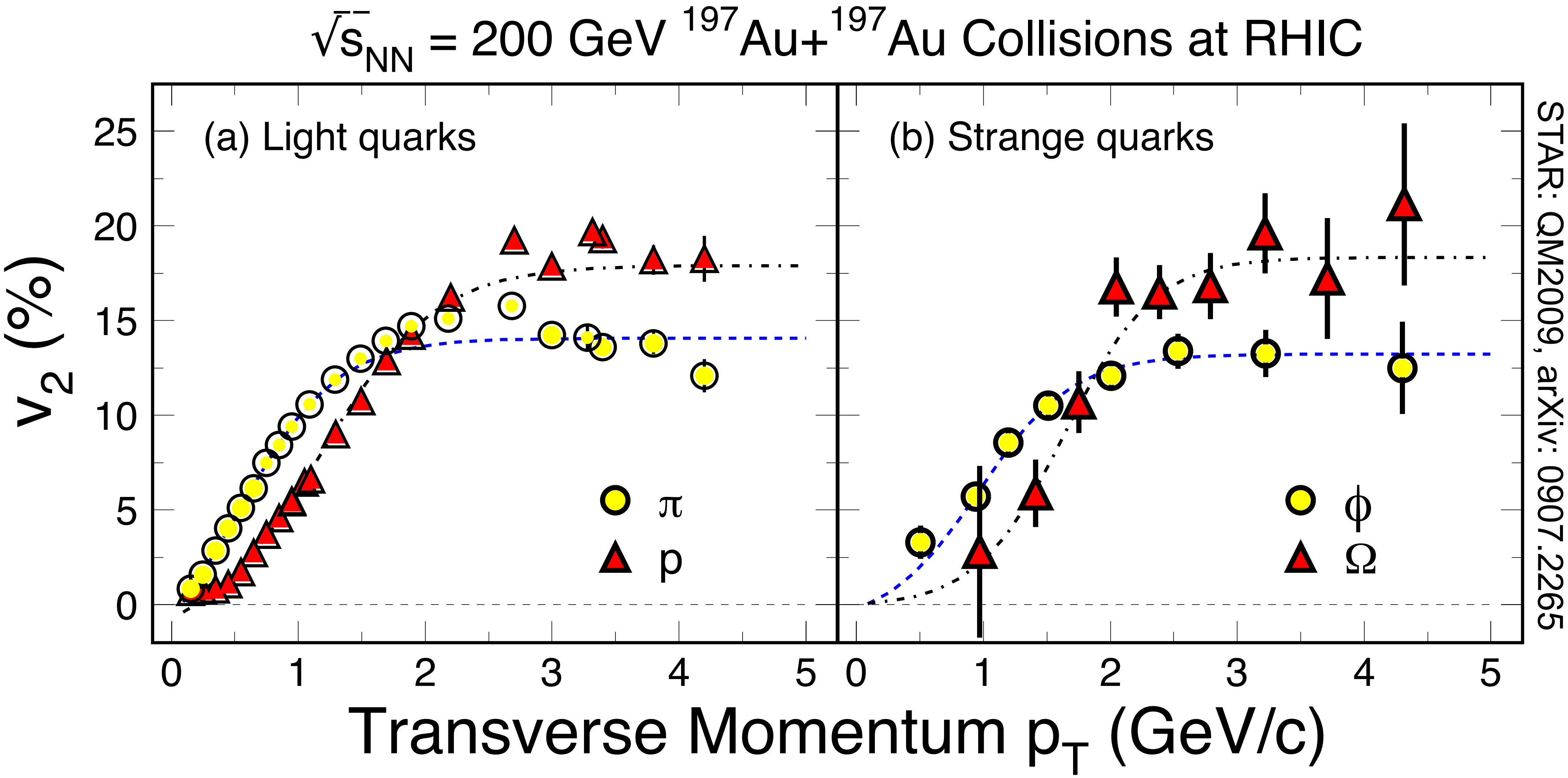
T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, PRC**77**, 044909 (2008)





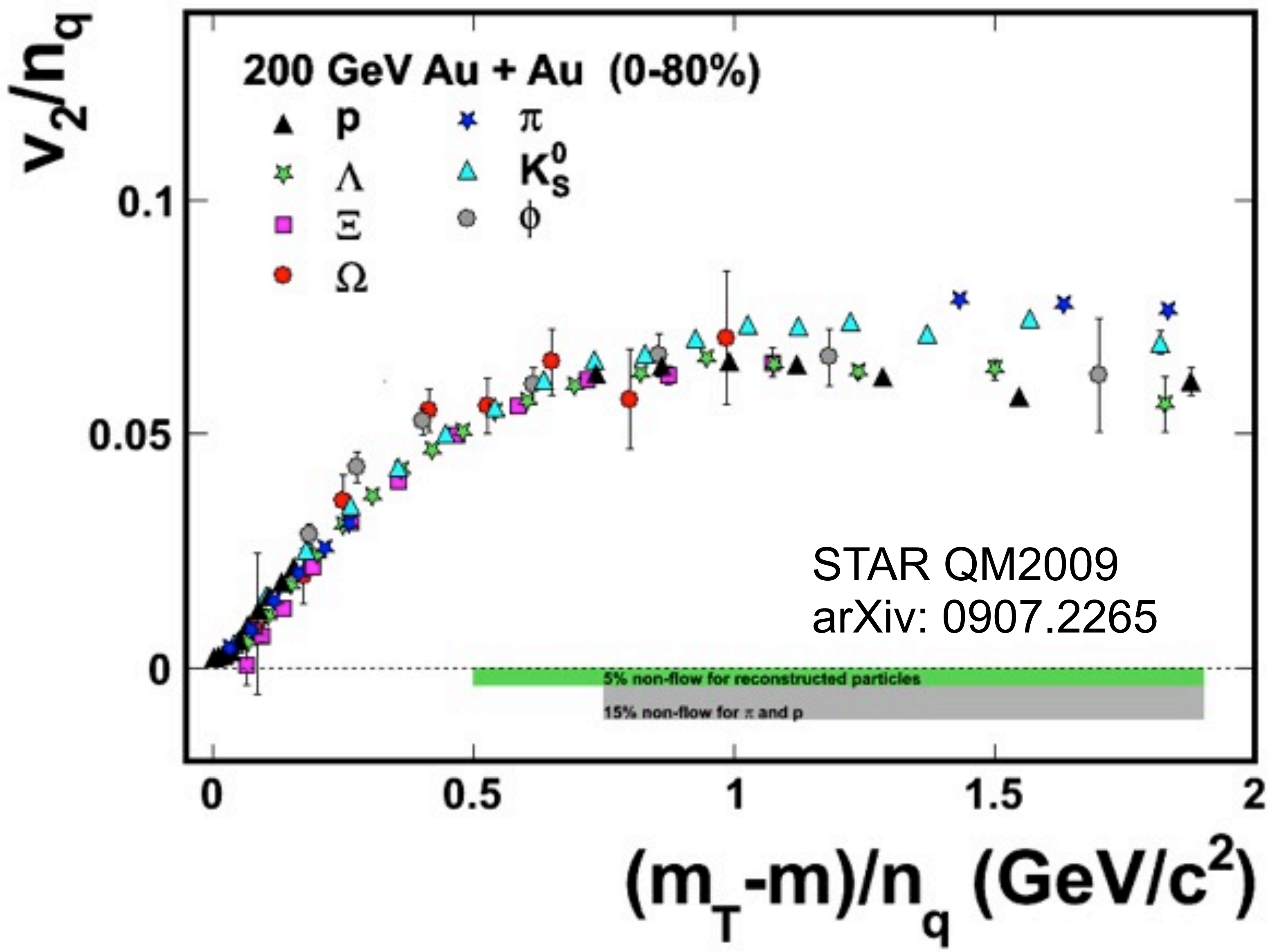
- Hadronic rescattering → mass ordering of v_2
  - ✓ Reproduce mass ordering for π, K and p
  - ✓ $v_2(\phi) > v_2(p)$ below p_T = 1 GeV/c due to early decoupling of φ
  - ✓ Multi-strange hadrons: penetrating probe for early dynamics in HI collisions

Meson/Baryon v_2 at intermediate p_T



- Similar magnitude of v_2 for multi-strange hadrons
  - ✓ most of collectivity is developed at partonic stage
- Clear separation of v_2 between mesons and baryons in p_T = 2 - 5 GeV/c

Number of quark scaling of v_2

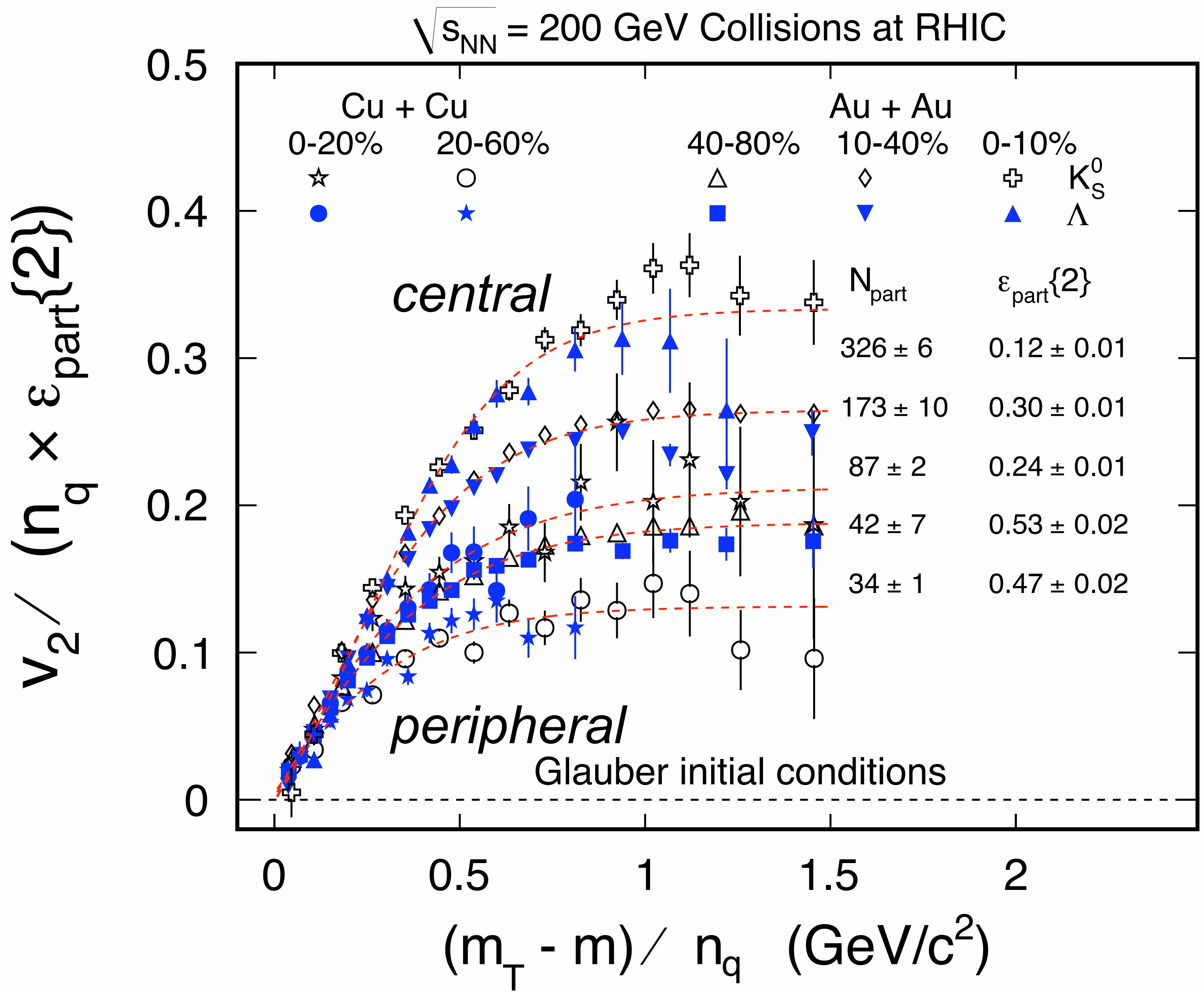


$$v_2^h(p_T) \approx n_q v_2^q(p_T/n_q)$$
$$(v_2^q \ll 1)$$

Quark coalescence/recombination
D. Molnar and S. Voloshi, PRL**91**, 092301 (2003)
V. Greco et al., PRC**68**, 034904 (2003)
R. J. Fries et al., PRC**68**, 044902 (2003)
J. Jia and C. Zhang PRC**75**, 031901(R) (2007)
....

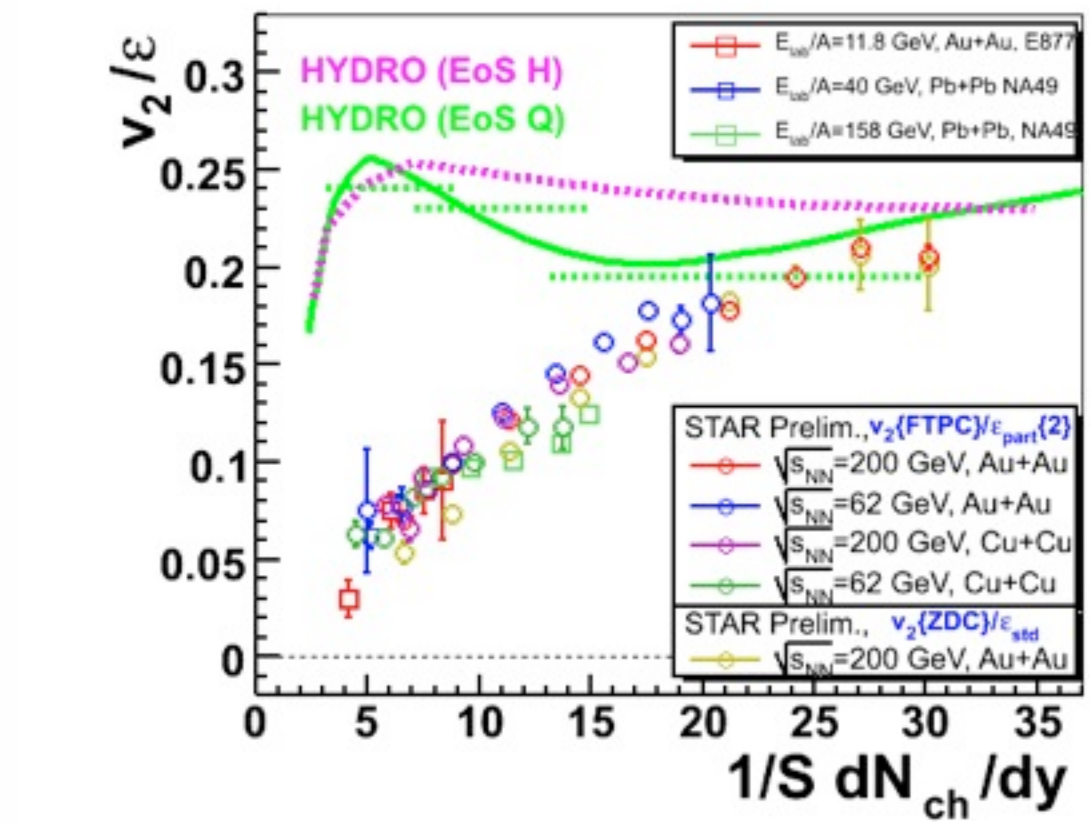
- Empirical m_T - mass scaling at low p_T
- Number of quark scaling holds up to 1 GeV/c in (m_T-mass)/n_q, start splitting above 1 GeV/c
  - ✓ p_T ~ 2 GeV/c for π, ~3.8 GeV/c for protons

Stronger flow at central collisions



Cu + Cu : STAR preliminary
Au + Au : PR**C77**, 054901 (2008)

S. A. Voloshin (STAR) : J. Phys. G**34**, S883 (2007)

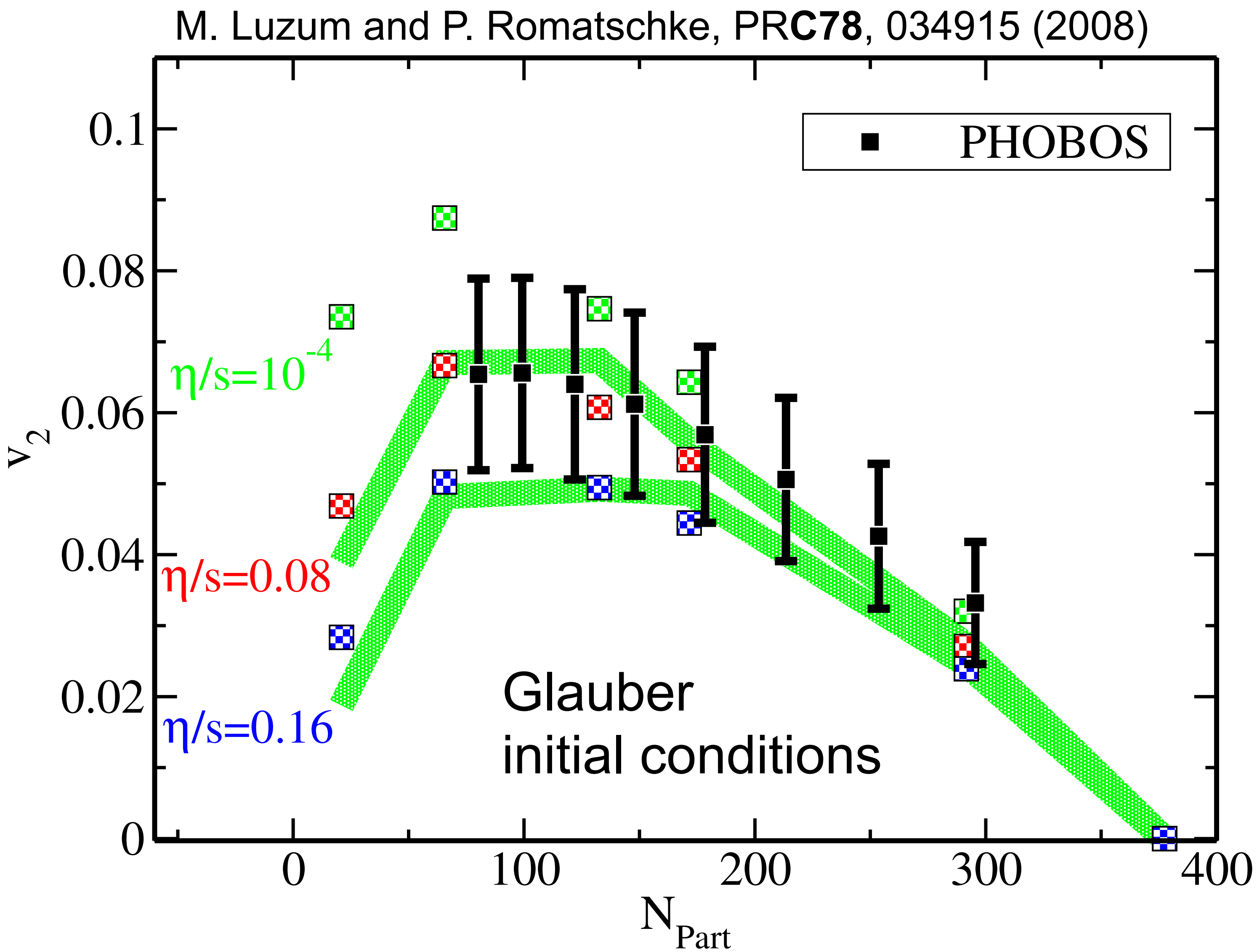


- Number of quark scaling holds for each centrality
- Stronger collectivity in central collisions

✓ Collectivity is driven by the eccentricity and system size

✓ Is hydro. (or thermalization) really applicable in peripheral ?

Extract η/s



Viscous hydrodynamical models
K. Dusling and D. Teaney, PRC**77**, 034905 (2008)
H. Song and U. Heinz, PRC**77**, 064901 (2008)
P. Huovinen and D. Molnar, PRC**79**, 014906 (2009)
....

- Recent developments of viscous hydrodynamical models → Upper limit of QGP viscosity ~ $6 \times 1/(4\pi)$

➡ Need fluctuating initial conditions (+ deformation) + viscous hydro. model + hadronic rescattering

✓ Which initial conditions, Glauber or CGC or something else ?

Other important v_2 measurements

- High p_T v_2 (p_T > 4 - 6 GeV/c)
  - ✓ Number of quark scaling
  - ✓ Parton energy loss
- (Thermal) photon v_2
  - ✓ via direct photon, di-lepton measurements
- charm(onium) (e.x. J/ψ), bottom v_2
  - ✓ Recombination of charm, thermalization
- U + U collisions
  - ✓ Initial conditions, detailed path length dependence (v_2 and R_{AA})
  - ✓ will start in 2011 at RHIC

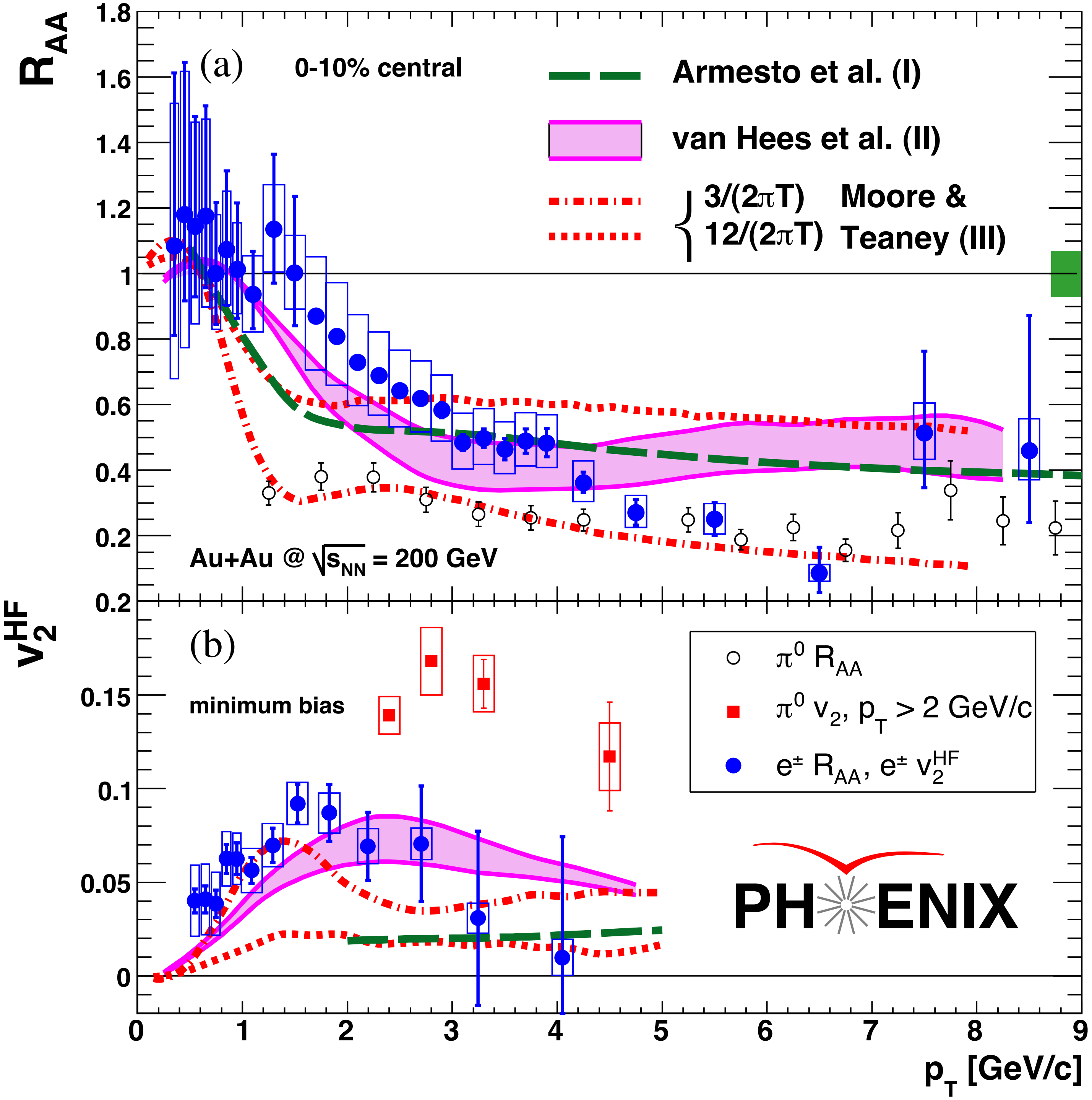
Conclusions

- Azimuthal anisotropy measurements are important for investigating the early collision dynamics at RHIC
  - ✓ Systematics among different methods can be explained with reasonable assumptions of non-flow and fluctuations
  - ✓ Agreement with different RHIC experiments ~10%
  - ✓ Measured v_2 would constrain important model parameters
  - ✓ Quantitative model comparison is crucial
    - Initial fluctuation + (deformation) + viscous hydro. model + hadronic rescattering
- Future v_2 measurements would provide further constraints on medium properties at RHIC
  - ✓ Charm/bottom flow via D/B mesons
  - ✓ Thermal photon flow via low p_T direct photon, di-leptons
  - ✓ U + U collisions, will start in 2011 at RHIC

Back up

Are charm and bottom flowing ?

PHENIX: PRL**98**, 172301 (2007)



- Substantial heavy flavor electron v_2
  - ✓ $\eta/s = (1.3\text{-}2)/(4\pi)$ with model comparison (v_2 and R_{AA})
  - ✓ Significant bottom contribution ~50% at high p_T
    - PHENIX: PRL**103**, 082002 (2009)

➡ Full secondary vertex reconstruction of D/B mesons