PHENIX Measurement of Particle Yields at High p_T with Respect to Reaction Plane in Au+Au collisions at $\sqrt{s}$ = 200 GeV

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Particles and Nuclei International Conference

Santa Fe, NM

25 Oct 2005

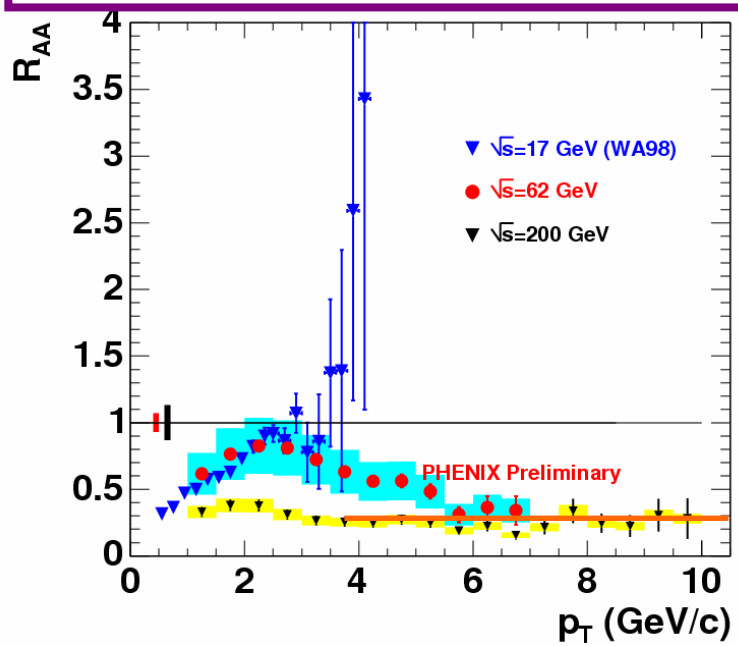
Outline

- Introduction
- Methodology
- Results & Consequences
  - Yields as a function of angle wrt reaction plane
  - $R_{AA}(\Delta\varphi, p_T)$, v_2
- Conclusions

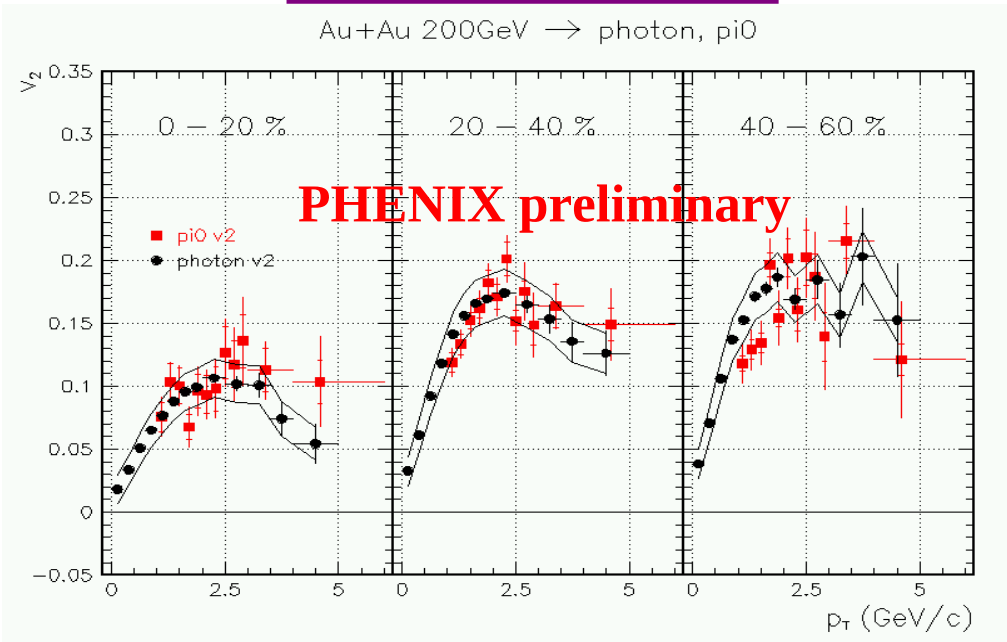
Introduction: R_{AA} and v_2 at high p_T

$$R_{AA} = \frac{\text{Yield}(AA), \text{scaled}}{\text{Yield}(pp), \text{scaled}}$$

π^0 R_{AA} appears flat for p_T>3.0 GeV/c

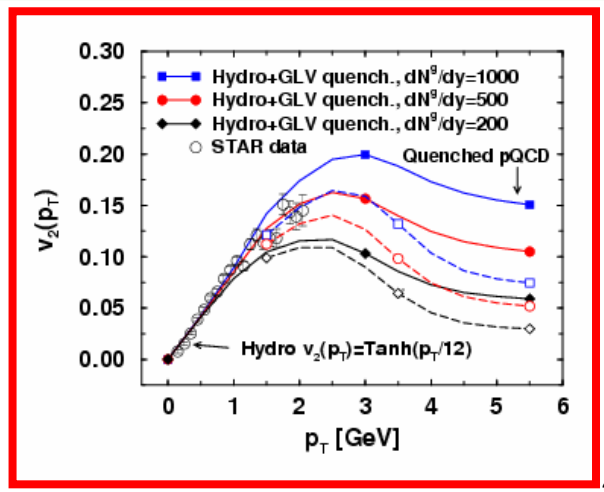


Large v_2 at high p_T



Examples of theoretical studies:

- Gyulassy, Vitev, Wang, **PRL 86**: **2537, 2001**
- Shuryak, Phys. Rev. **C**: **027902 (2002)**
- Drees, Feng, Jia, Phys. Rev. **C:71 034909 (2005)**

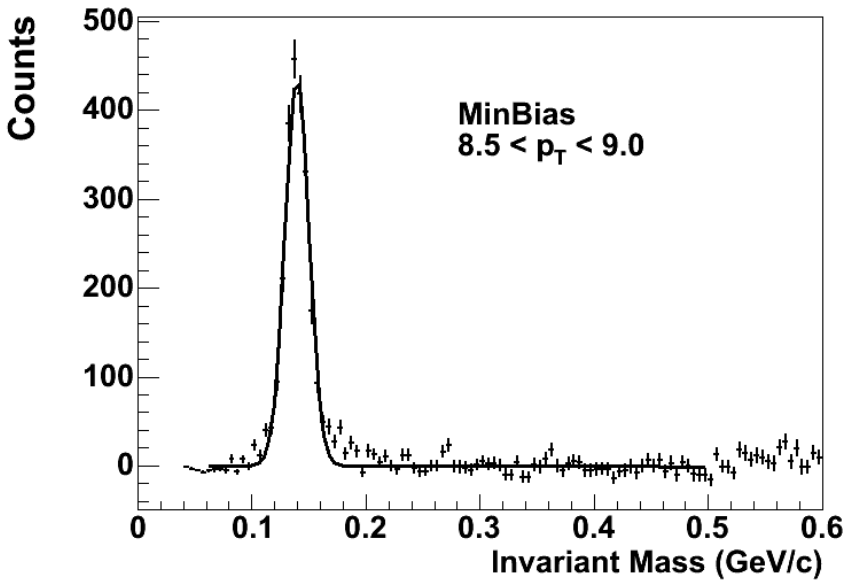


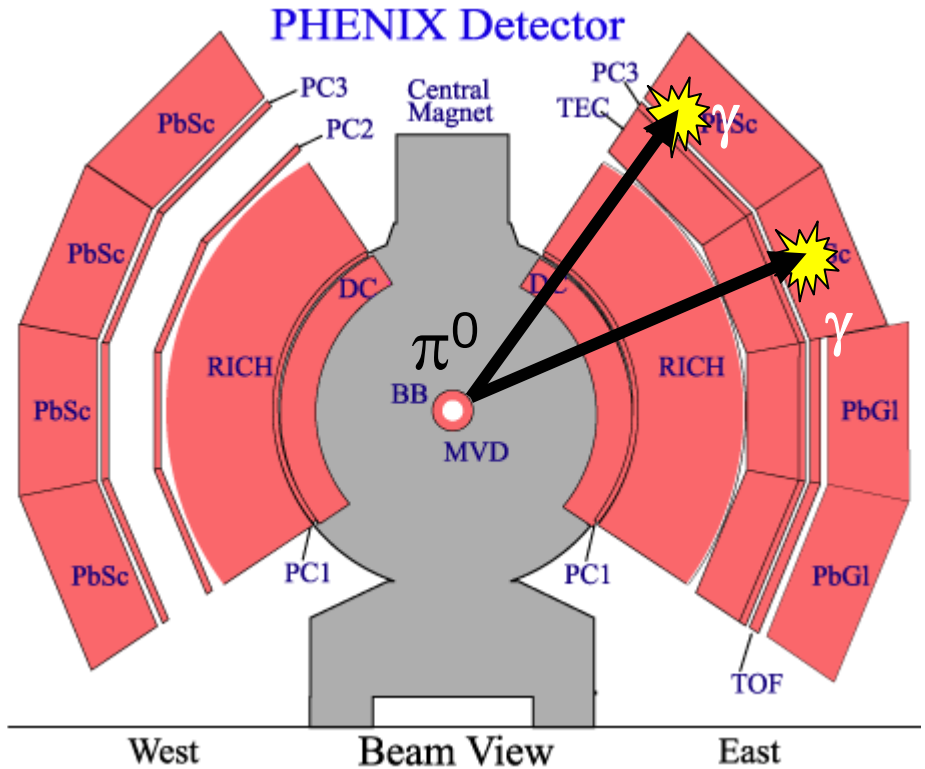
Physics Motivation

- How well do we understand the origin of azimuthal anisotropy (v_2) at high p_T?
- The "usual" explanations
  - Arises from azimuthal variation in energy loss
  - Which is in turn due to geometry: spatial anisotropy of parton density in non-central collisions.
- π^0s provide ideal "laboratory" to probe this physics at high p_T:
  - Possibly less subject to effects of recombination
  - High p_T acceptance
- Studying anisotropy out to high p_T provides powerful tool for studying transition from soft to hard physics at p_T >~ 3 GeV/c

Measuring π^0s in PHENIX

- In Run 4, PHENIX recorded 1.5 Billion AuAu Collisions
  - Data presented here represents ~ 1B of those events
- For measuring γ, π^0s, we have 8 EmCal sectors
- Two technologies
  - PbSc: Sampling
  - PbGl: Cerenkov

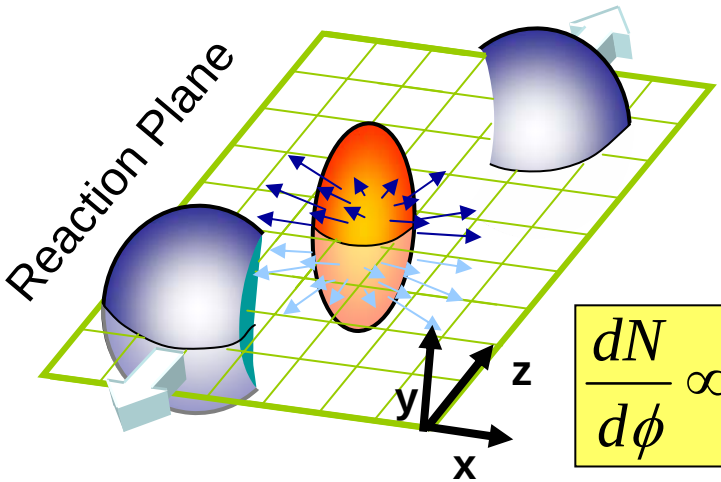




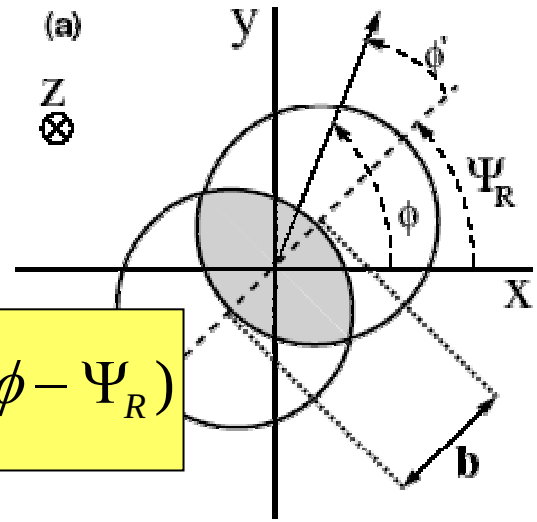
In a given p_T, centrality, and reaction plane bin, we:

- Form pairs of clusters
- Subtract mixed event background
- Integrate counts in mass window
- (Determined by fit to Gaussian)

Relative Yields wrt Reaction Plane



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_R)$$



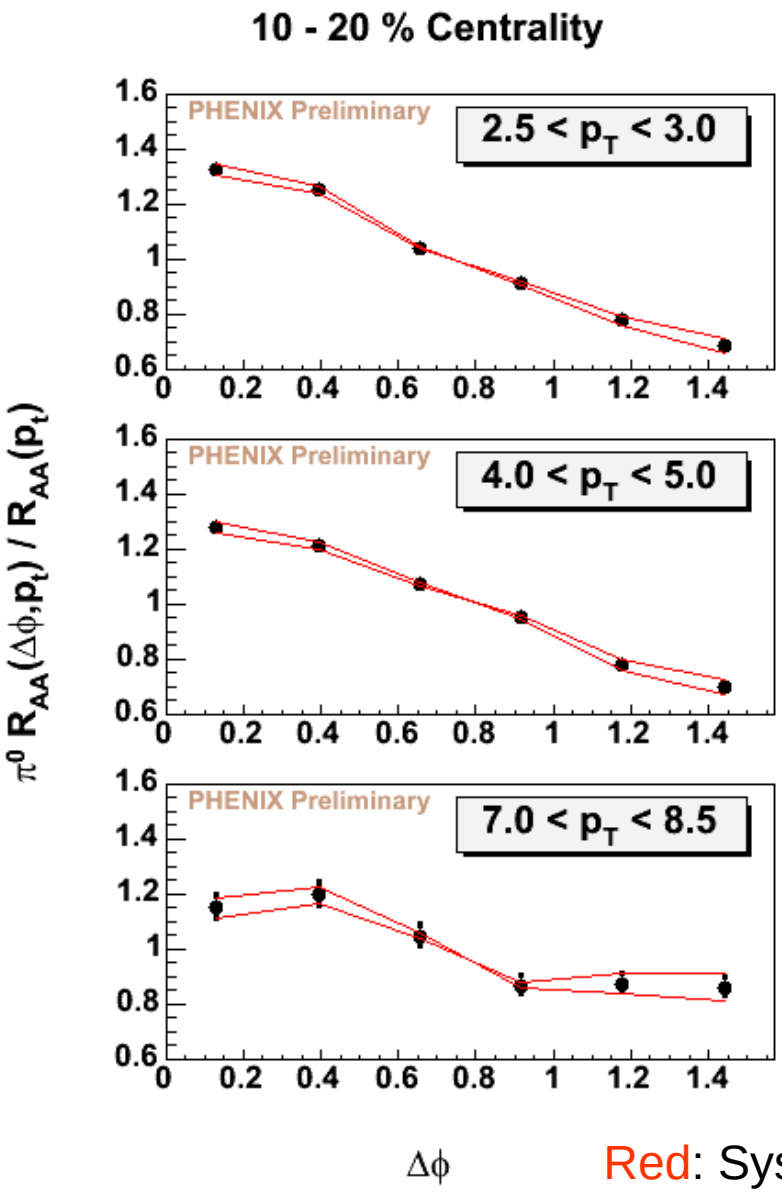
- Measure π^0 dN/dp_T in 6 $\Delta\phi$ bins over $[0,\pi/2]$.
  - Correct yields for reaction plane resolution
- Multiply the ratio

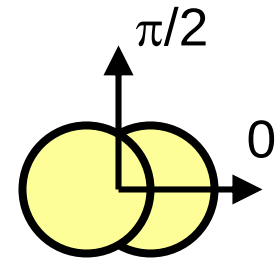
$$R_{\Delta\phi} = \mathrm{Yield}(\Delta\phi)/\mathrm{Yield} \equiv R_{AA}(\Delta\phi)/R_{AA}$$

- With previously measured $R_{AA} \Rightarrow R_{AA}(\Delta\phi)$

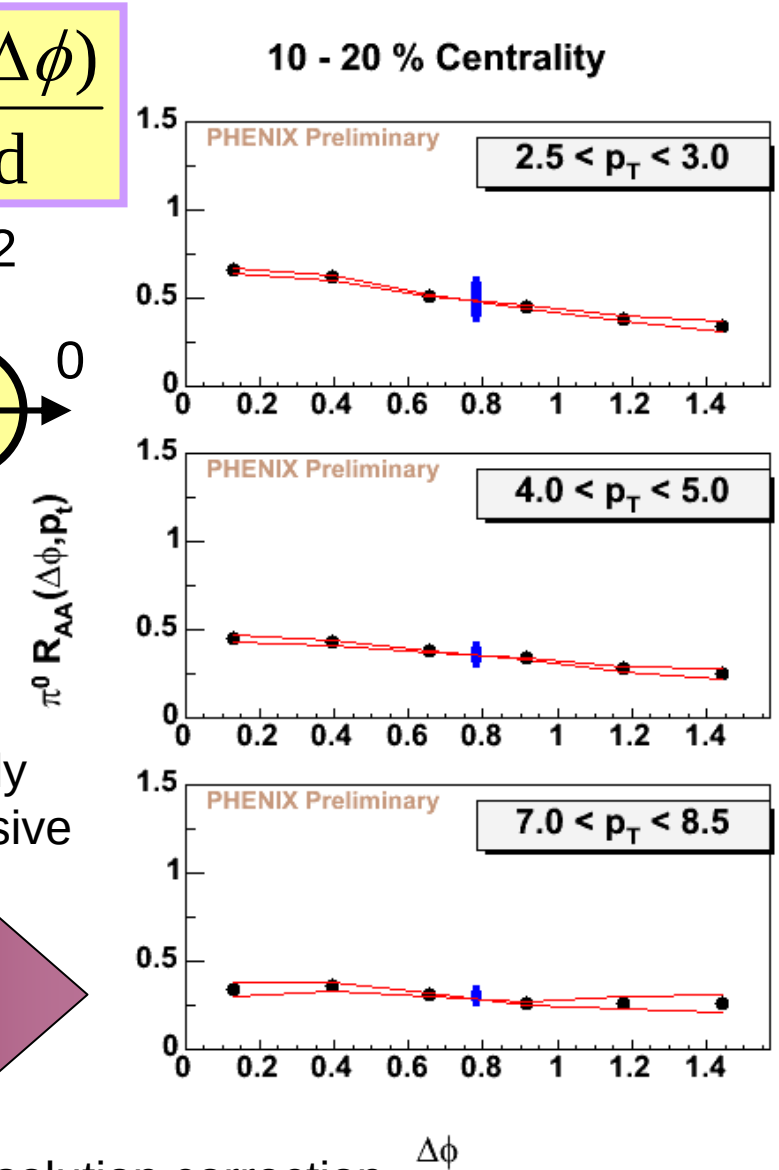
From Relative Yields to R_{AA}

$$\frac{\text{Yield}(\Delta\phi)}{\text{Yield}}$$



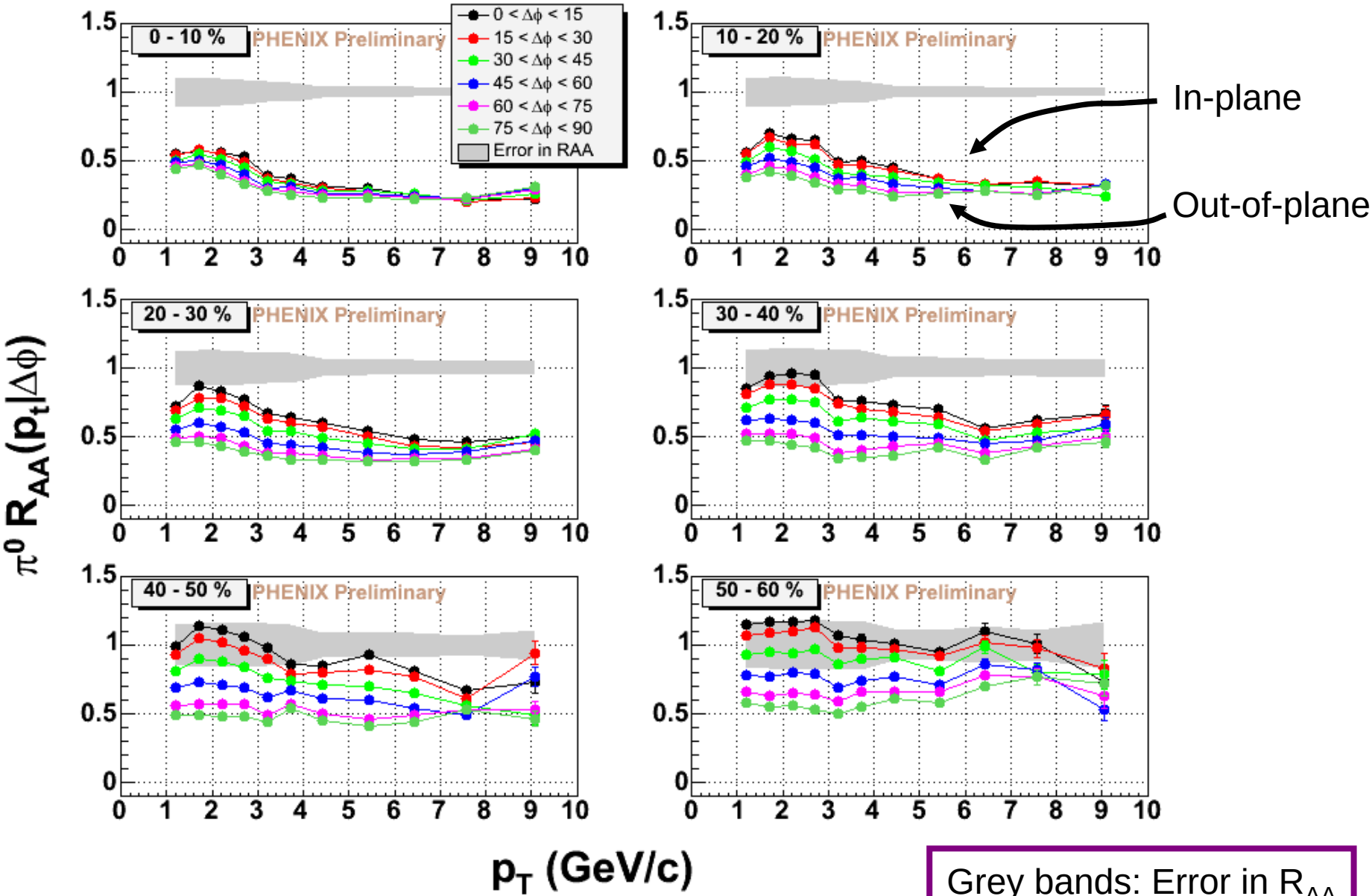


Multiply
By inclusive
R_{AA}



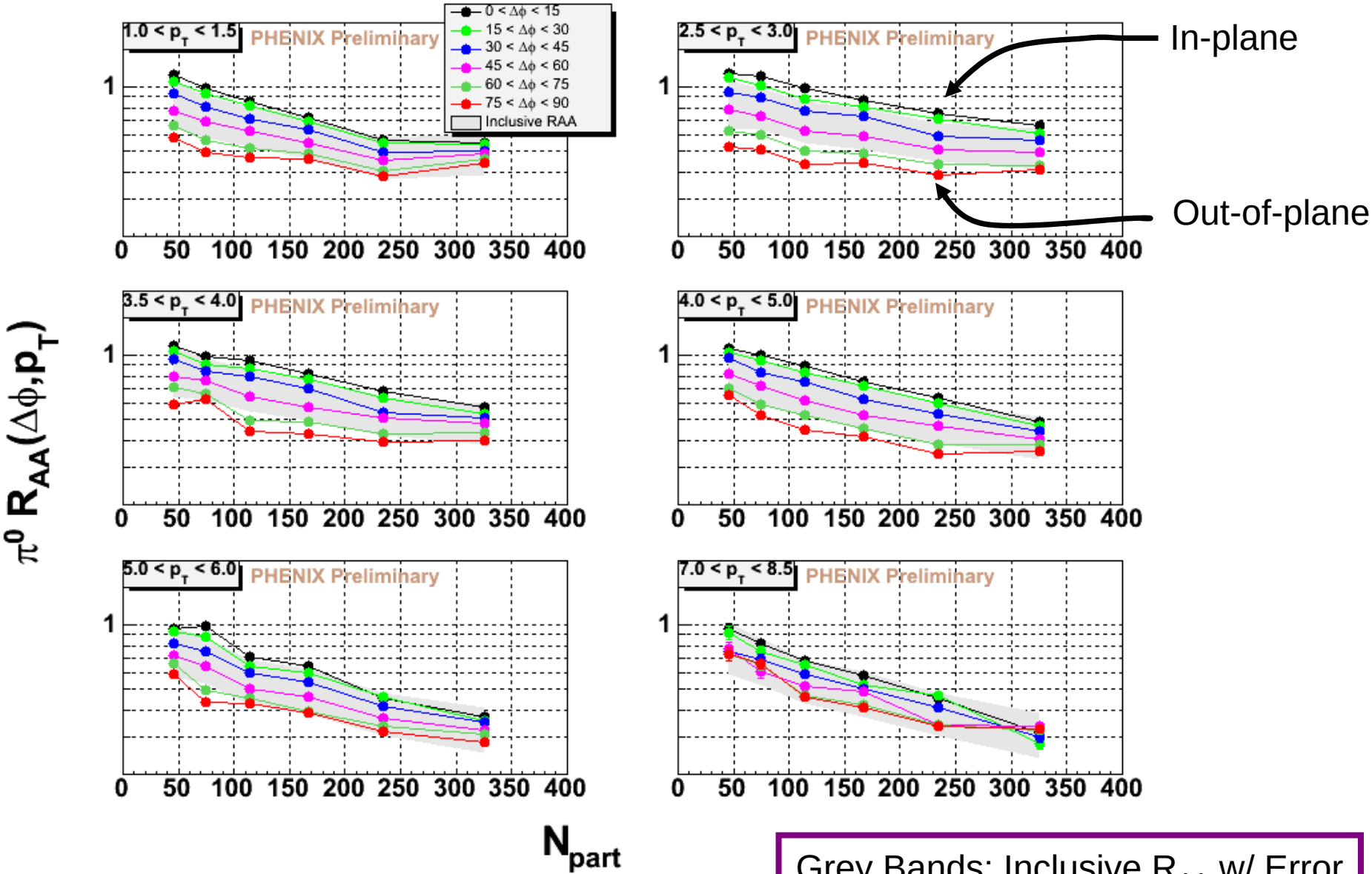
Red: Sys. Due to resolution correction
Blue: Error on R_{AA}

$R_{AA}(\Delta\varphi, p_T)$ vs. p_T (Cent. Dependence)



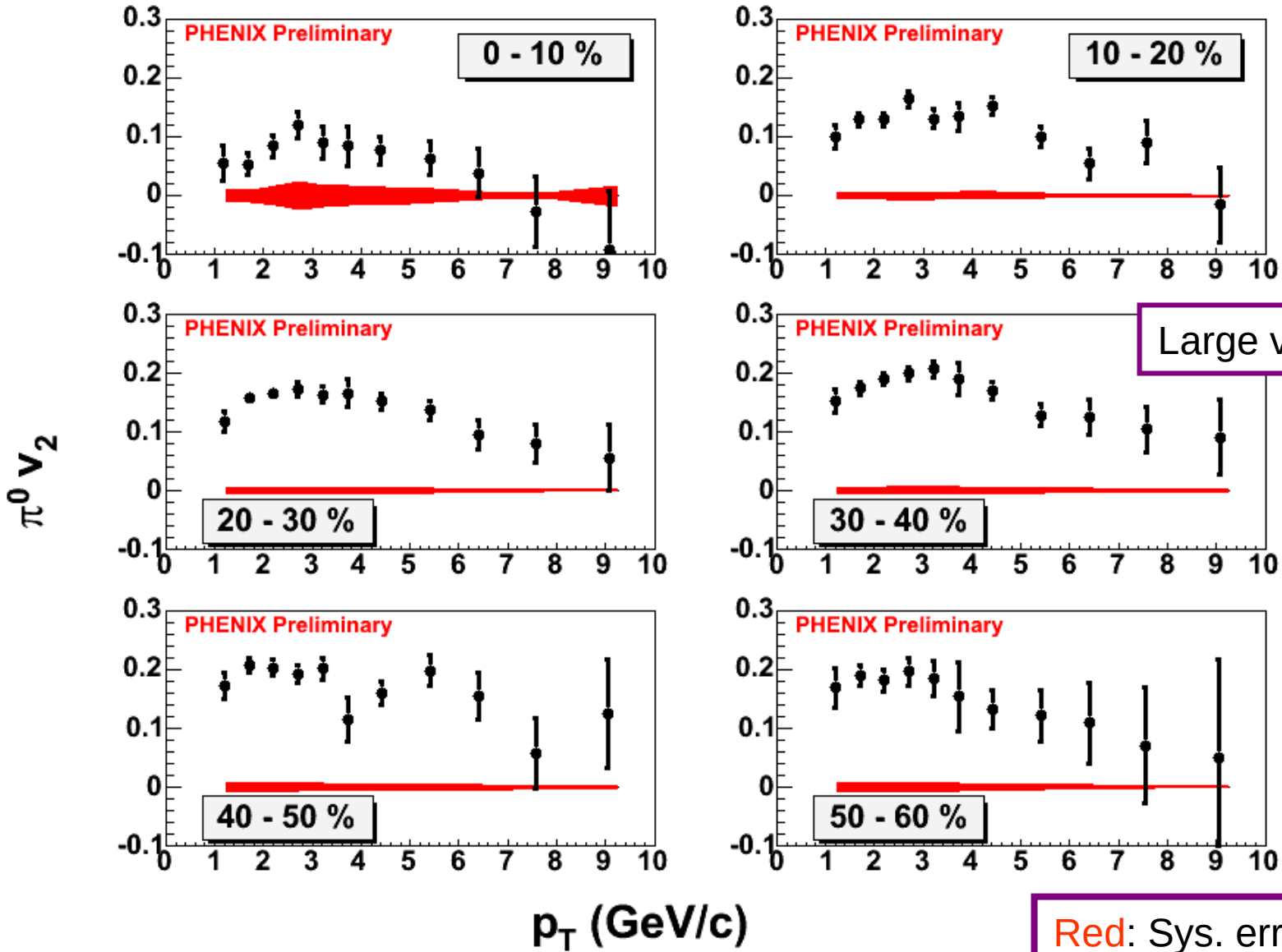
Grey bands: Error in R_{AA}

$R_{AA}(\Delta\varphi, p_T)$ vs. Npart



Grey Bands: Inclusive R_{AA} w/ Error

π^0 v_2



Large v_2 at high p_T!

Red: Sys. error (abs)

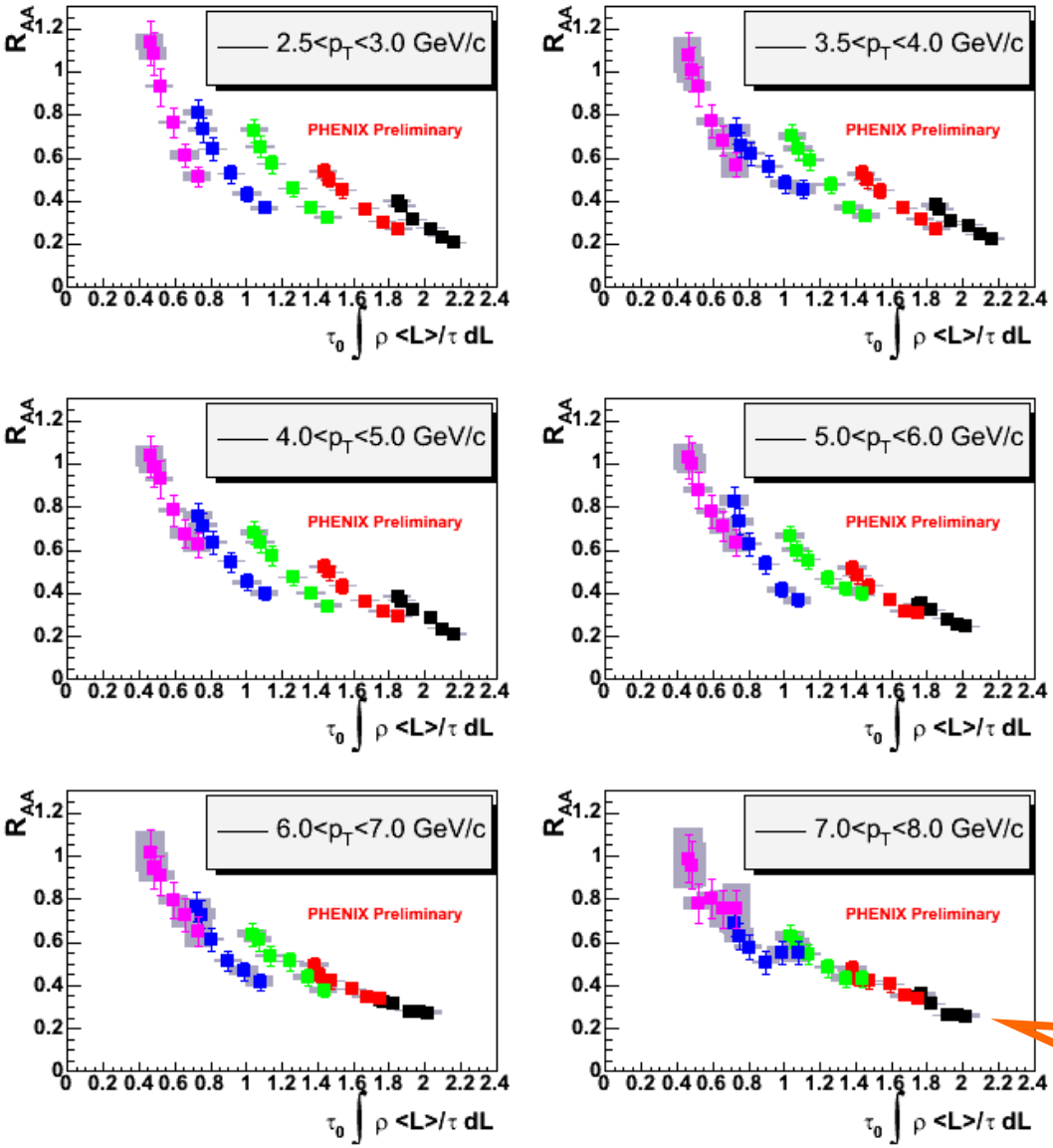
Energy Loss and Path Length

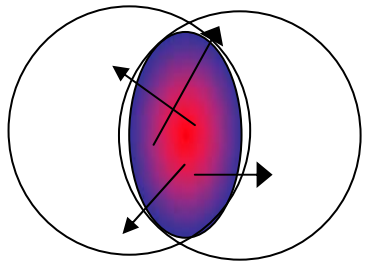
- Suppose energy loss is dominant mechanism
- Two (coupled) parameters give handles on parton's path length through medium
  - Centrality, Angle wrt Reaction Plane
- Can we use an equivalent (single) parameter? Let's call it L_{eff}:

$$L_{eff} \propto \int d\vec{L}\, \rho_{color}^{init}(\vec{L})\, L$$

- Includes time-dependence/formation time in ρ
- Glauber MC sampling of path origin takes into account fluctuations in L_{eff}

R_{AA} vs. Angle+Centrality





Study RAA dependence on density-weighted average pathlength through collision region

10-20 % Centrality

20-30 % Centrality

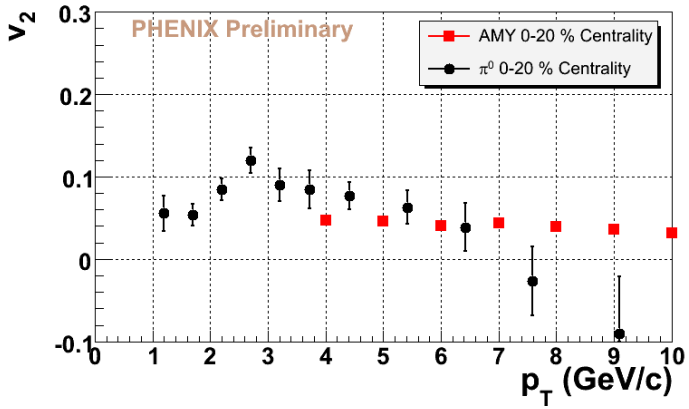
40-50 % Centrality

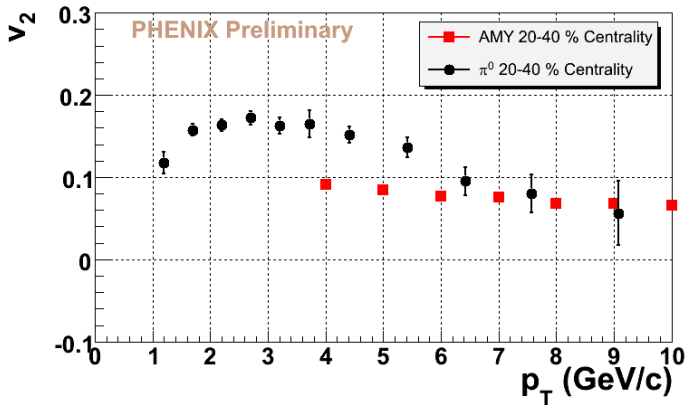
30-40 % Centrality

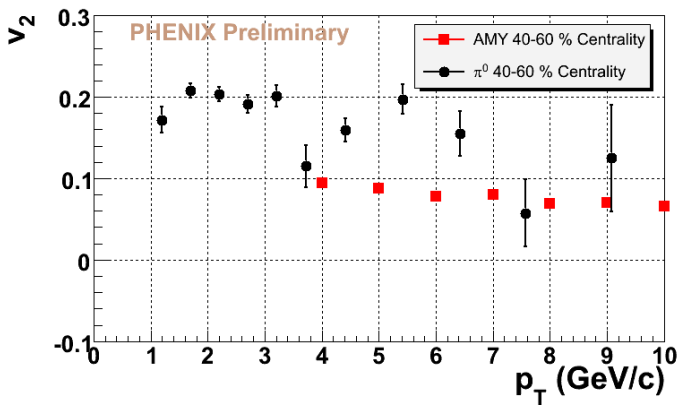
50-60 % Centrality

Angular and centrality dependence described by single curve!!

π^0 v_2 Theory Comparison: AMY (Turbide et al.)

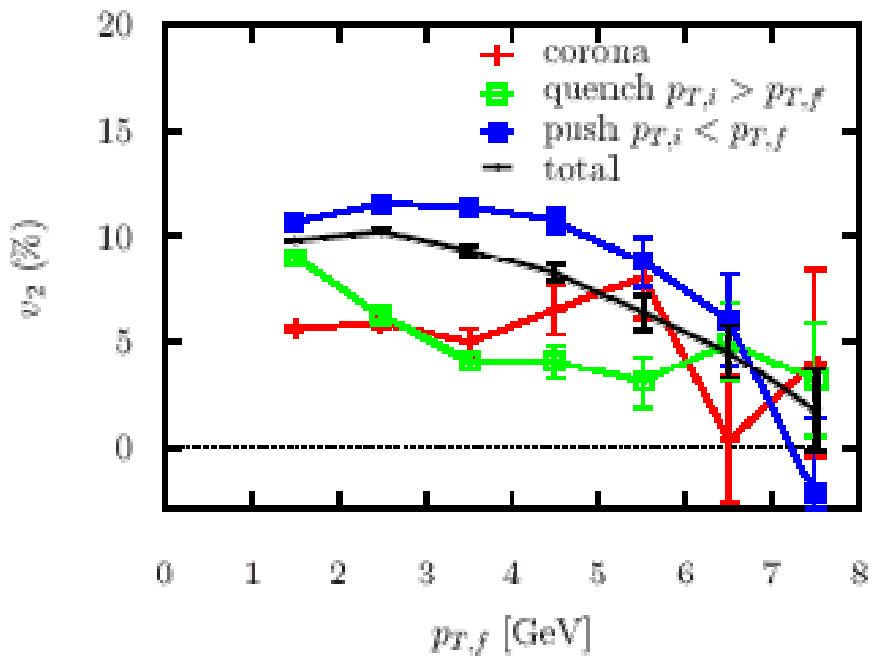




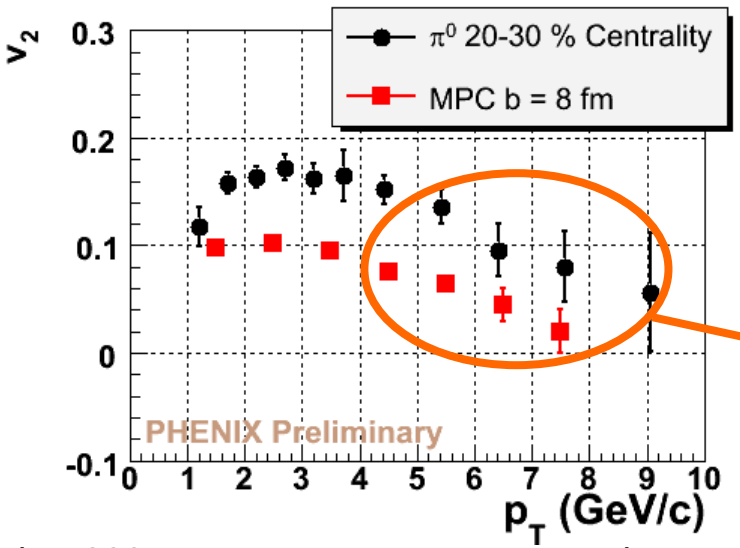


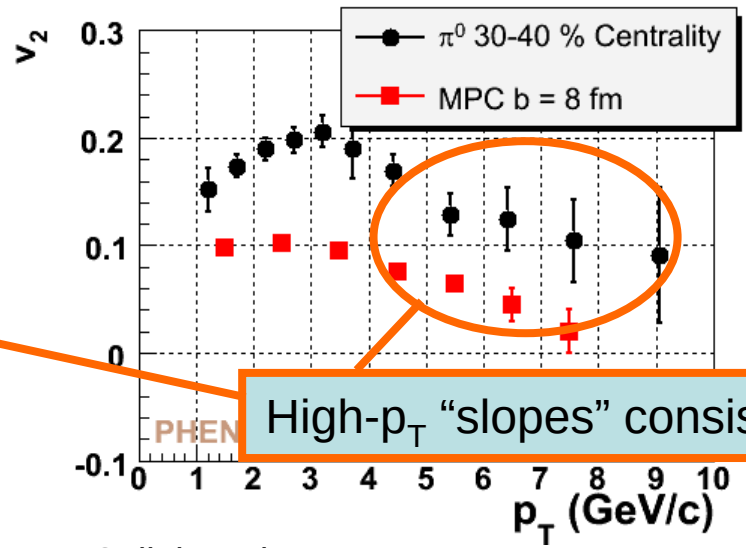
- Calculations based on Arnold, Moore, Yaffe (AMY) formalism
  - JHEP 0305:51 2003
- Energy loss only (BDMS++)
- High-p_T
  - v_2 appears to decrease to energy loss calculation
- Low(er)-p_T
  - Something additional going on…
- While the data appear to approach the energy loss limit at high p_T, there is something extra going on in 3-6 GeV/c region

π^0 v_2 Theory Comparison: D.Molnar



- Molnar Parton Cascade (MPC)
  - nucl-th/0503051
- Contains:
  - Corona effects
  - Energy loss due to interactions
  - p_T boost due to interactions
- Consistency would suggest:
  - QGP?
  - sQGP?
- Model shown here is for one set of parameters
  - Can larger opacity reproduce the v_2?





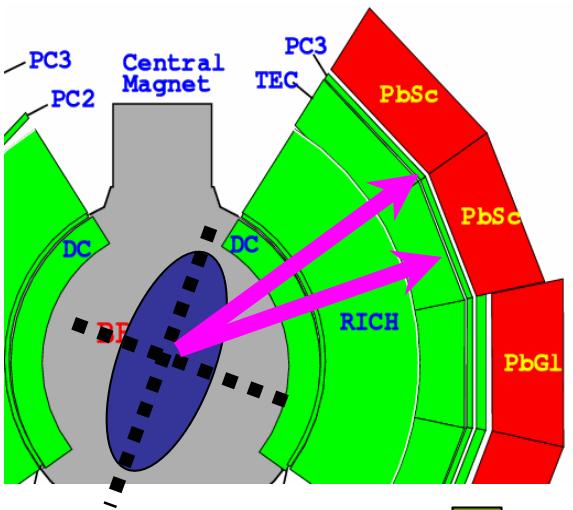
High-p_T "slopes" consistent

Conclusions

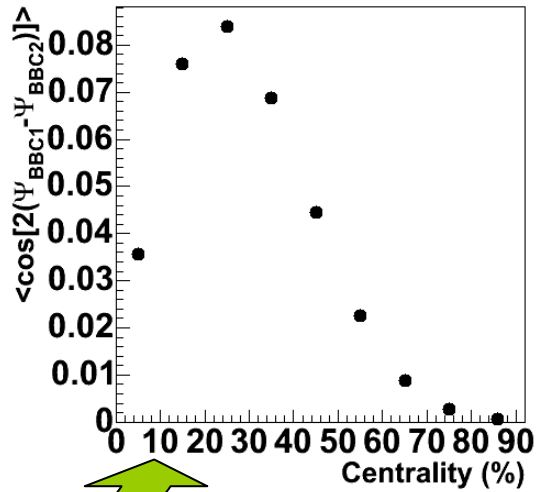
- While $R_{AA}(p_T)$ appears to be flat out to high p_T, $R_{AA}(\Delta\varphi,p_T)$ reveals both pt- *and* angle-dependent substructure
- For the first time we see a clear decrease in the π^0 v_2 at high p_T – to a non-zero value!
- Non-zero high-p_T v_2 is consistent with energy loss calculations
- Comparison of high-p_T (>7.0 GeV/c) behavior of v_2 with models points to pQCD + energy loss as dominant sources
  - What's responsible for larger v_2 at intermediate p_T?
    - Partons pushed to higher p_T (à la Molnar)?
    - Larger energy loss crossing the flow field (Wiedemann et al)?
    - Collisional energy loss?
    - Flow + recombination?

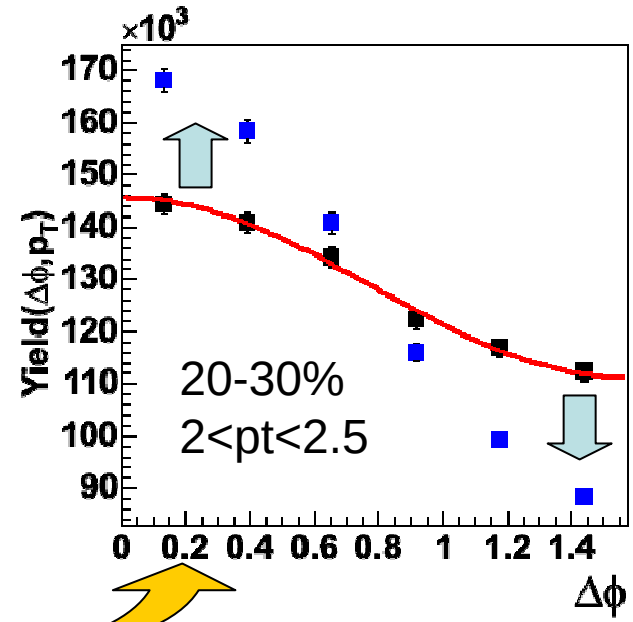
Backup Slides

But first… accounting for the detector



Measure RP with Beam-Beam Counters





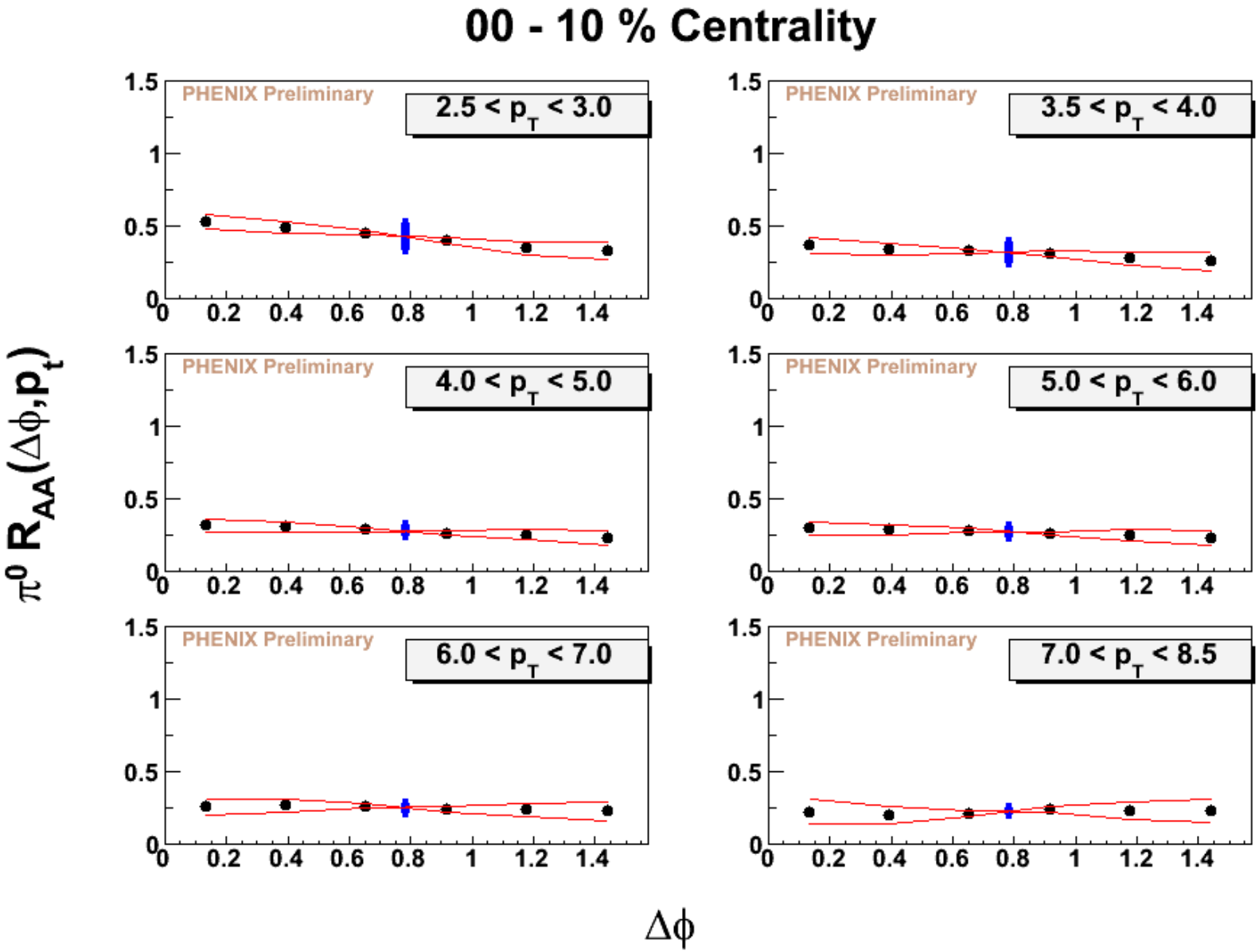
- Reaction Plane as measured has resolution σ

$$\sigma = \sqrt{2\cos(\Psi_{BBC_N} - \Psi_{BBC_S})}$$

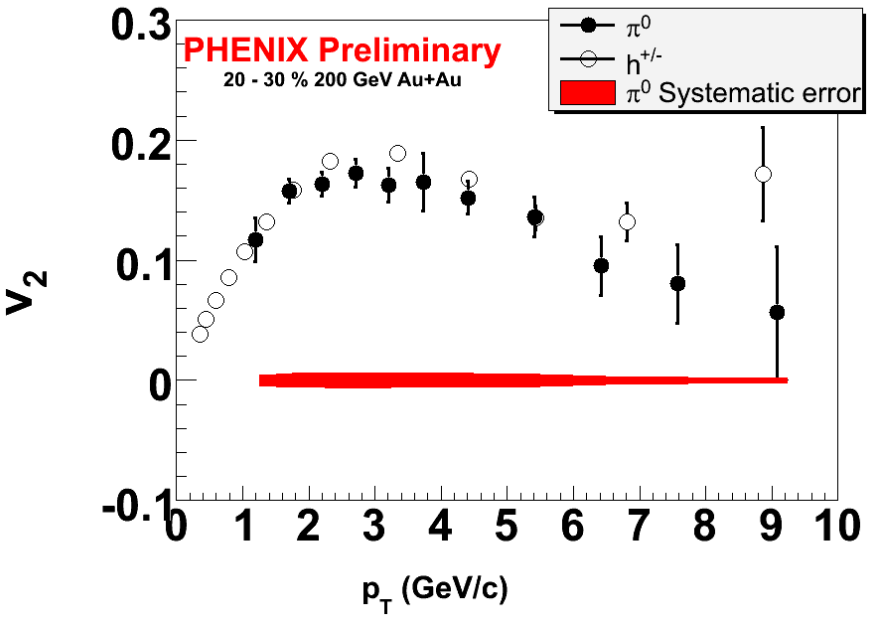
- Fit raw yield(Δφ) ⇒ raw v_2
- Correct raw v_2 for resolution
- Correct raw yield(Δφ) with ⇒

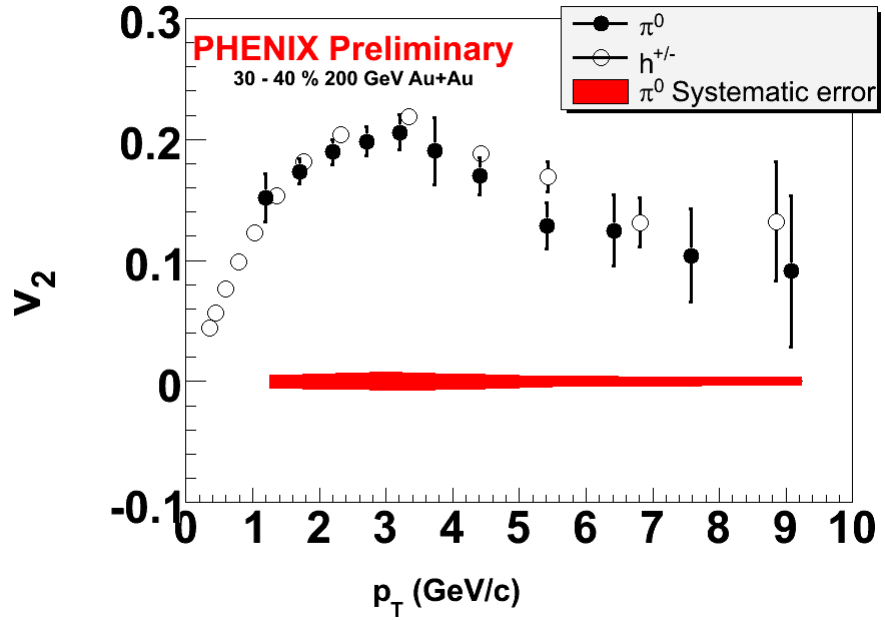
$$\frac{1 + 2v_2^{corr}\cos(2\Delta\phi)}{1 + 2v_2^{raw}\cos(2\Delta\phi)}$$

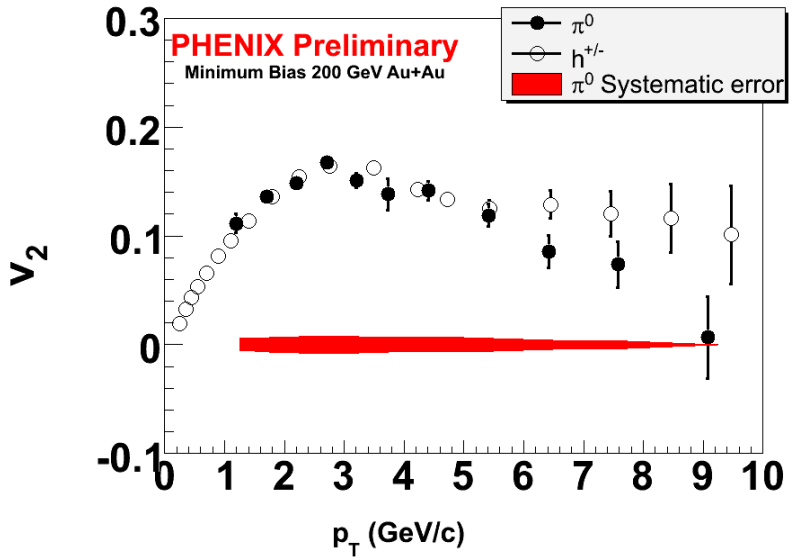
Centrality dependence of π^0 R_{AA}



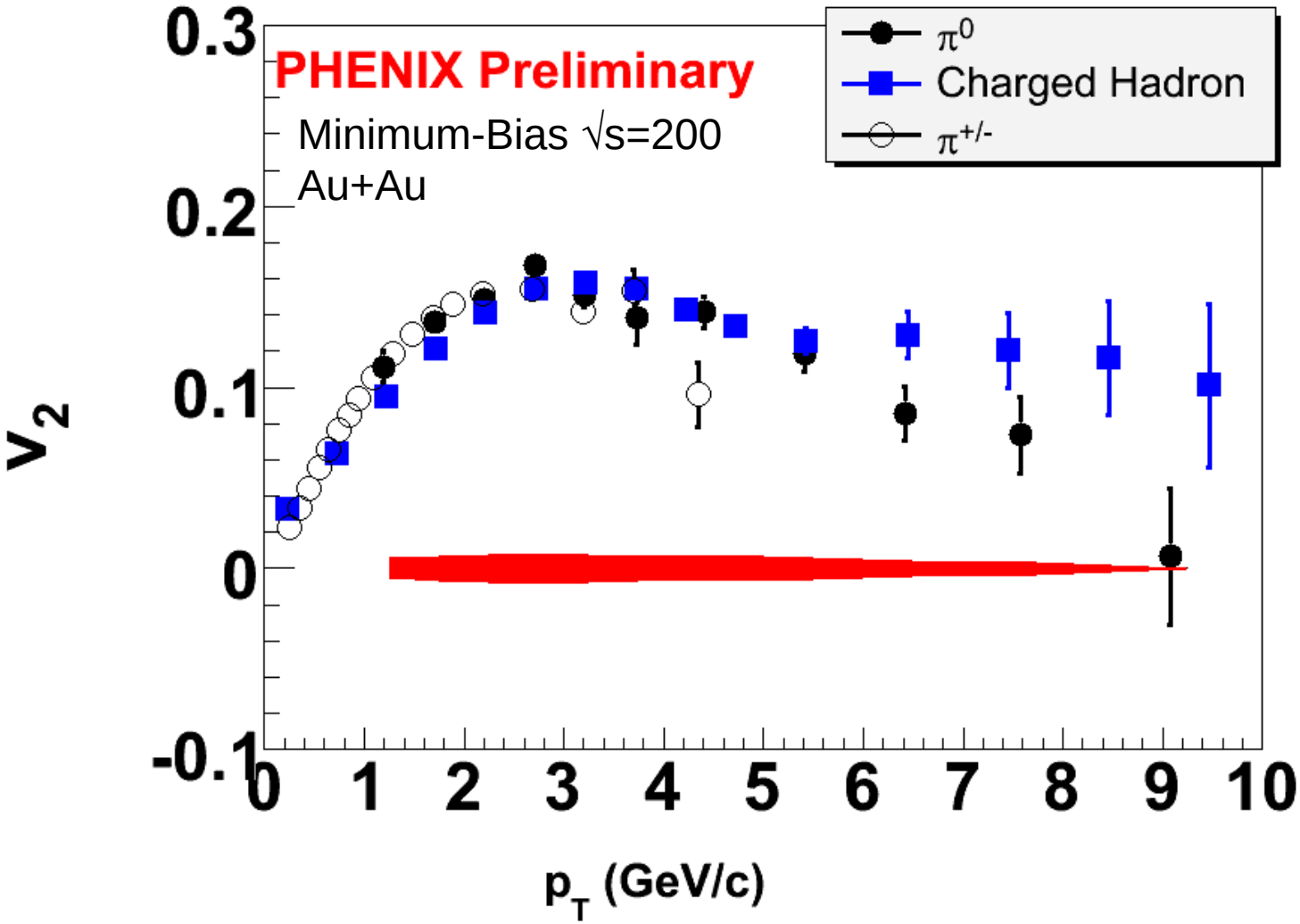
Compare with charged hadrons



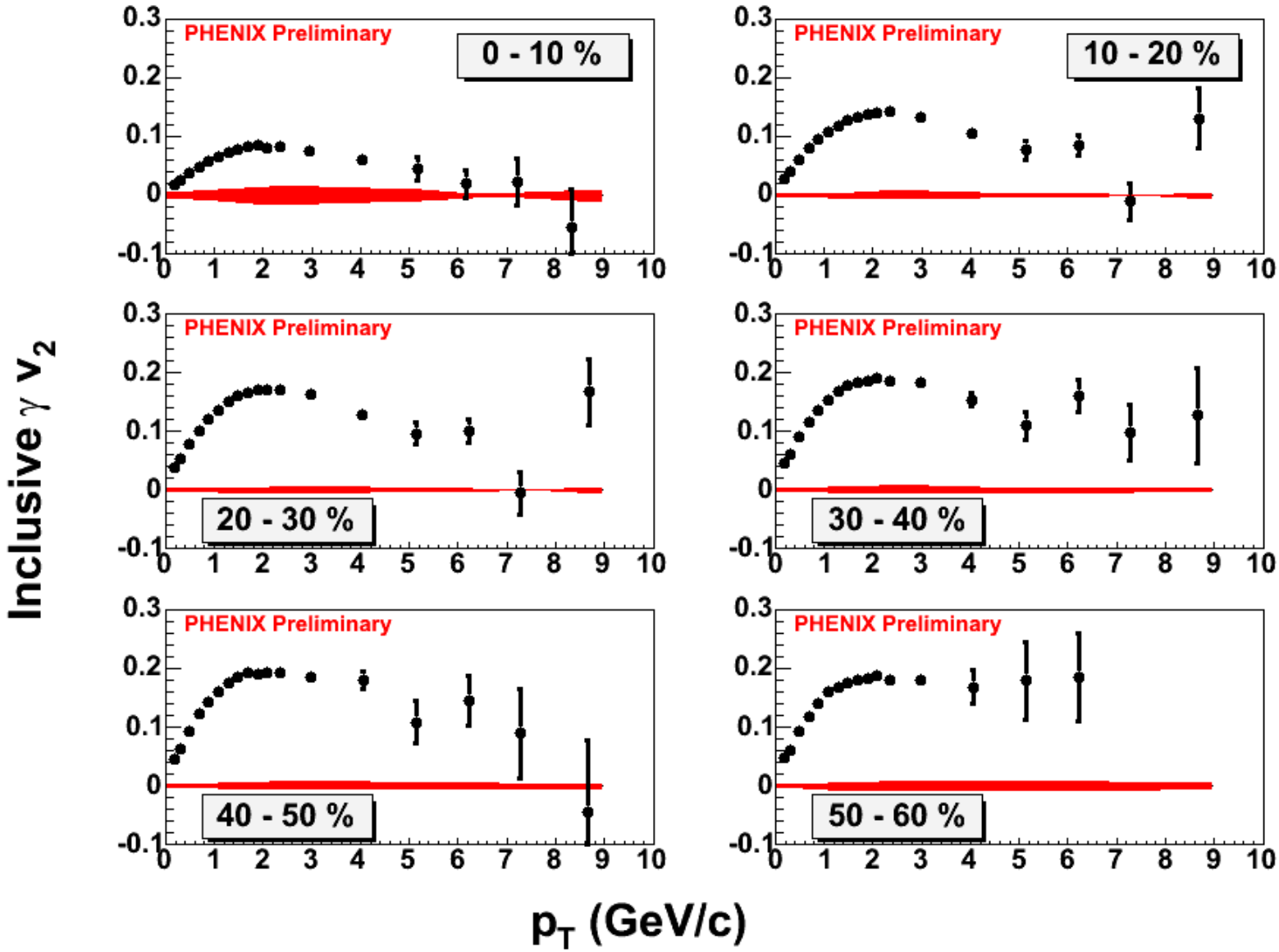




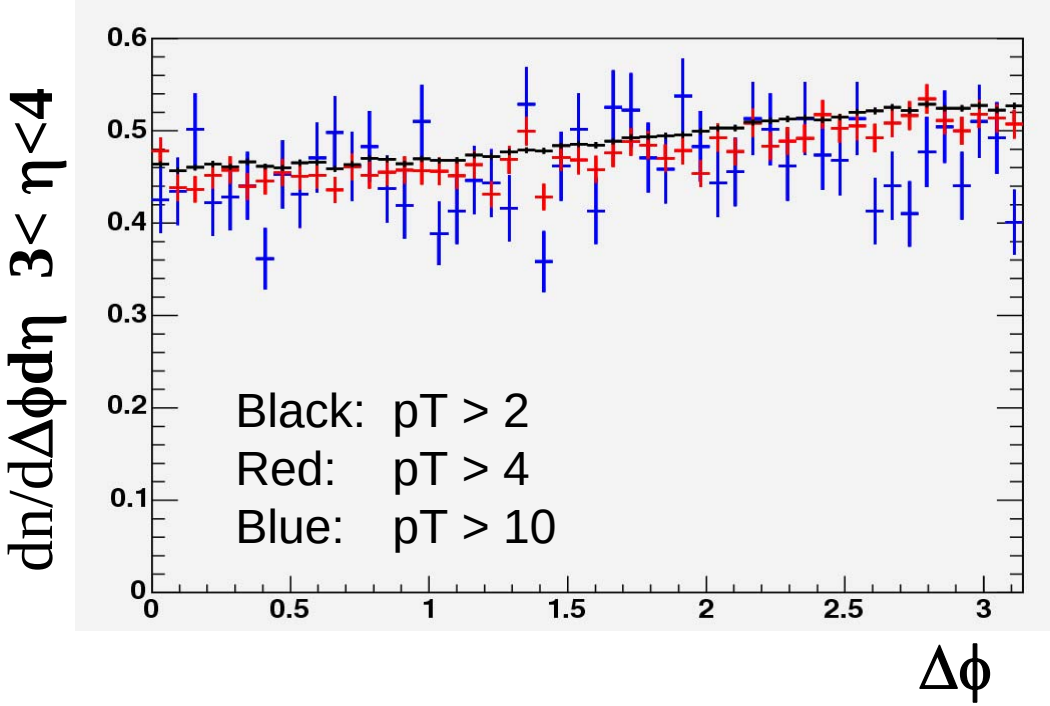
Compare with charged (minbias)



Inclusive γ v_2



Reaction Plane Biases?

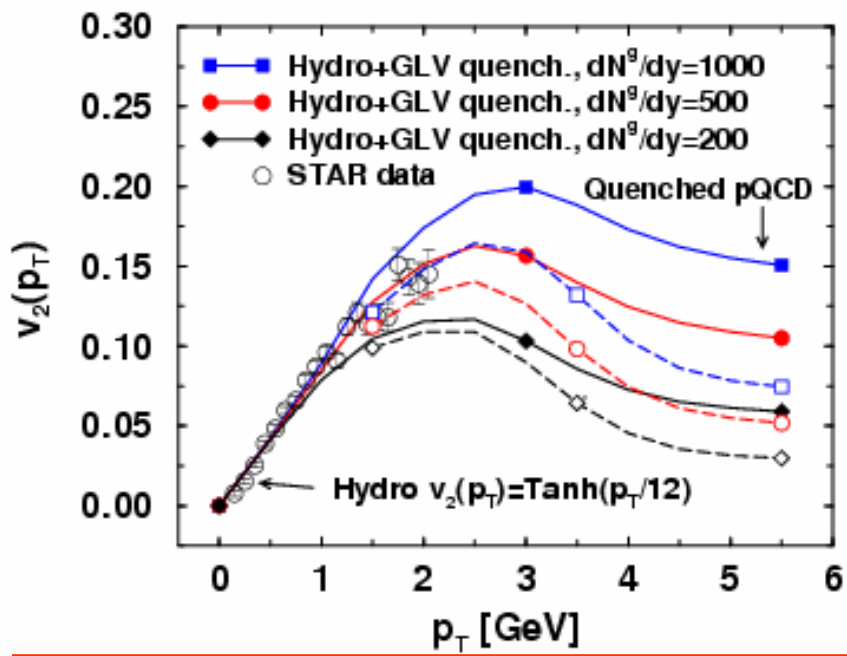


Au-Au **dn/dη*2v$_2$**
10-20% 13±3
20-30% 12±2
30-40% 9±1.6
40-50% 5.8±1.3

⇒ **Much larger than hard scattering correlation.**

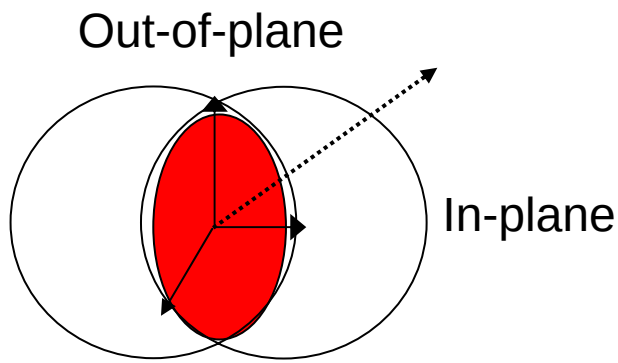
- Can hard scattering bias the reaction plane measurement ?
- Evaluate using Pythia:
  - Calculate Δφ between pions in $|\Delta\eta| < 0.35$ (central arm)
  - And charged particles in $3 < \eta < 4$ (BBC)
  - For different pion p_T bins.

Theoretical Explanation(s) for v_2 at high p_T



Early prediction of decreasing v_2 at High p_T (solid: cylindrical geom, open: WS)

Gyulassy, Vitev, Wang, **PRL 86**: **2537, 2001**



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

Examples of additional studies:

- Shuryak, Phys. Rev. **C**: **027902 (2002)**
- Drees, Feng, Jia, Phys. Rev. **C:71 034909 (2005)**