High-p_T π^0 Production with Respect to the Reaction Plane using the PHENIX Detector at RHIC

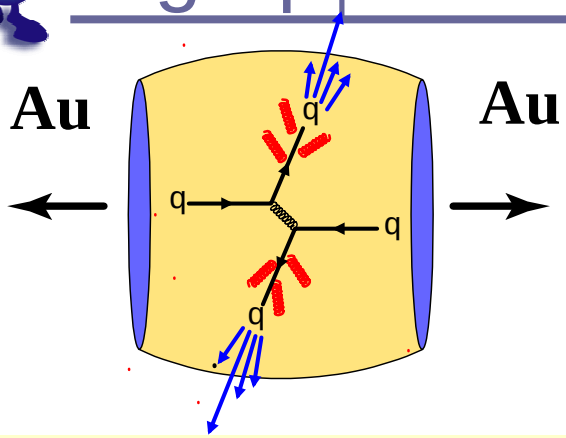
Hot Quarks 2006
Villasimius, Sardinia, Italy
15 – 20 May 2006

David L. Winter
for the PHENIX Collaboration
Columbia University
in the City of New York

Outline

- Motivation
- Measuring π^0s with respect to the Reaction Plane using PHENIX
- Comparison with models
- Summary

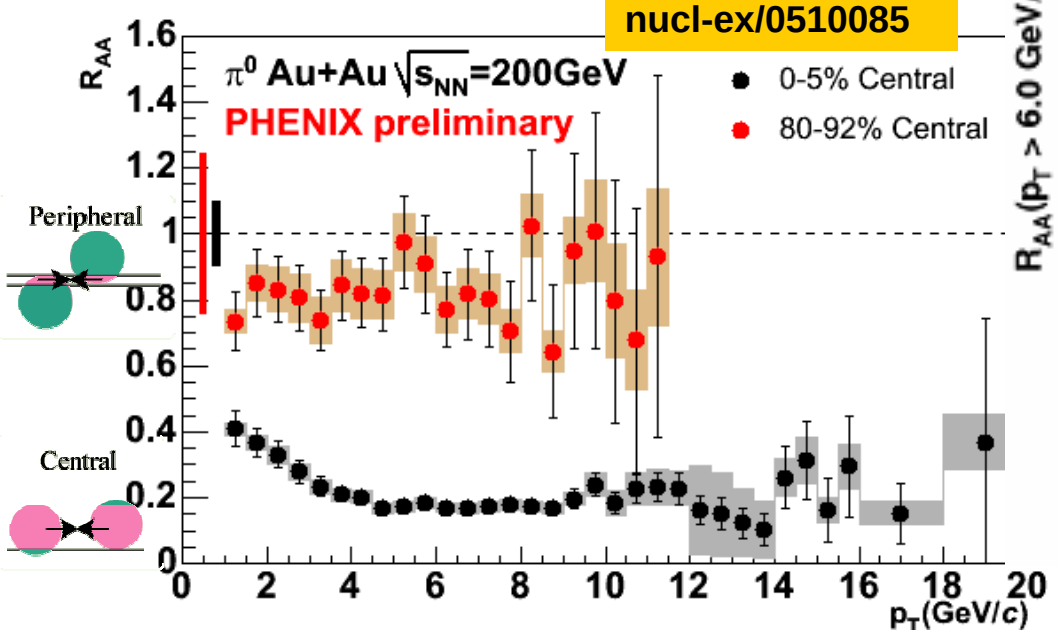
High-p_T mesons as hard probes



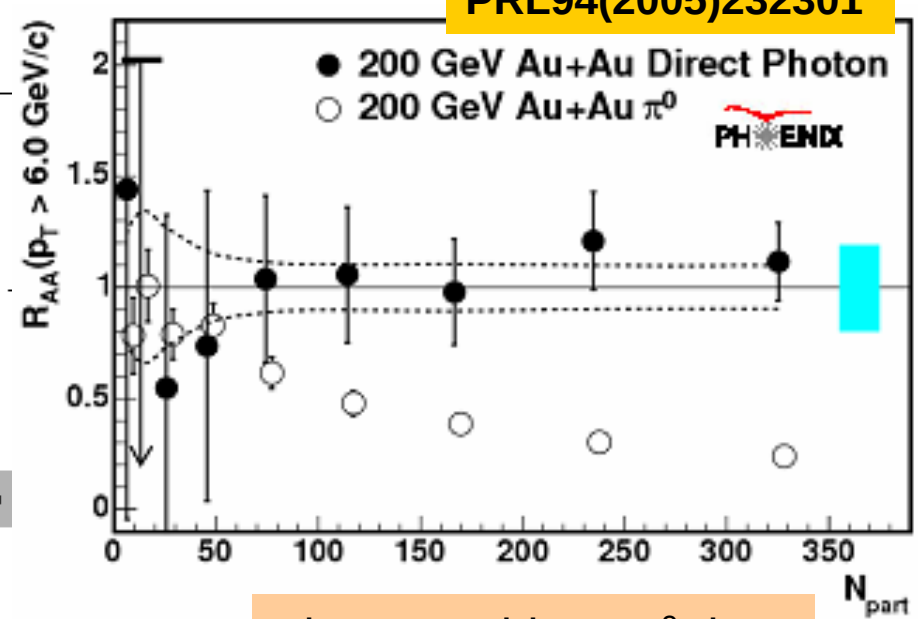
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

- Have access to hard processes
  - High-p_T partons produced by hard scattering
  - Yield scales with N_{coll}
- Study the effects of the medium with the nuclear modification factor
  - absence of nuclear effects: R_{AA}=1
- Suppression of π^0 at high-p_T in central Au+Au collisions (but not photons!)

nucl-ex/0510085



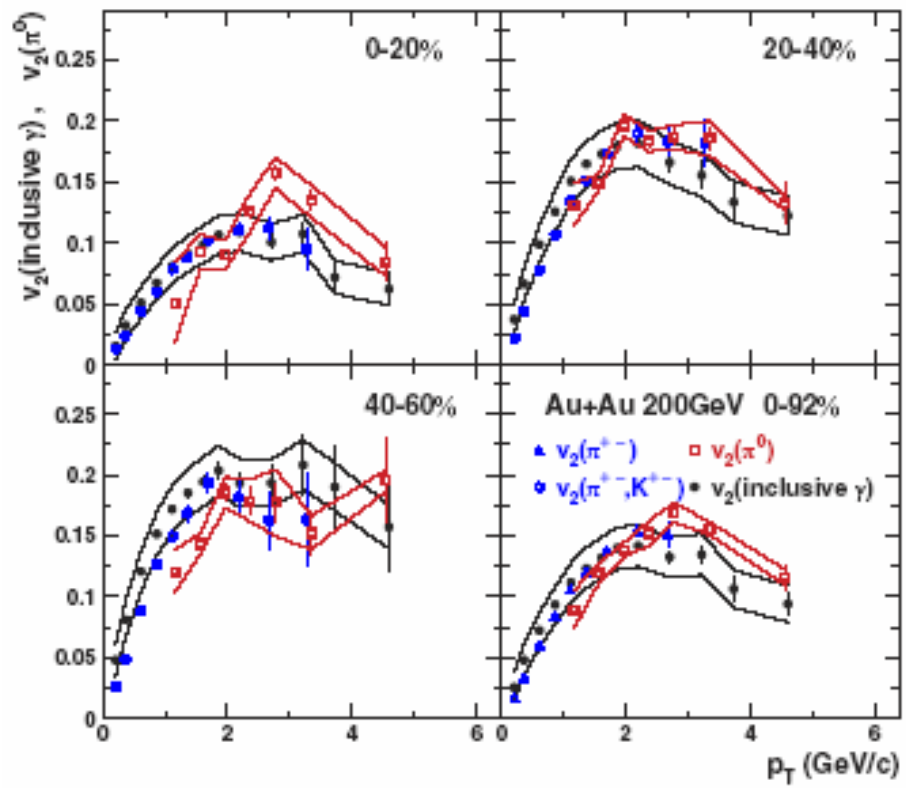
PRL94(2005)232301



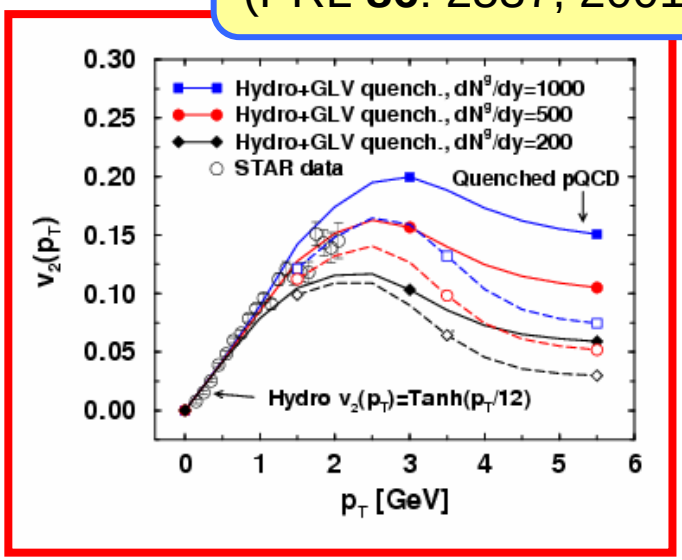
Photons "shine", π^0 don't

Anisotropy parameter v_2

- Large v_2 indicative of high degree of thermalization of produced matter
- (Low p_T) Anisotropic flow can be reasonably described with hydrodynamic models at RHIC...
- But what about at mid to high p_T?



Large v_2 predicted early on (PRL **86**: 2537, 2001)

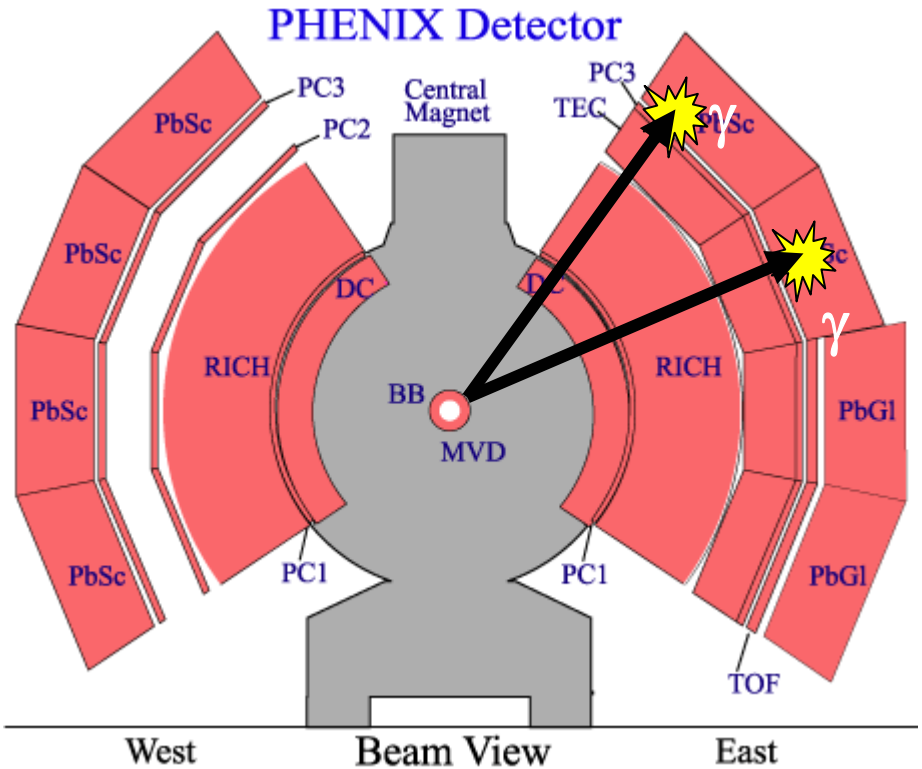


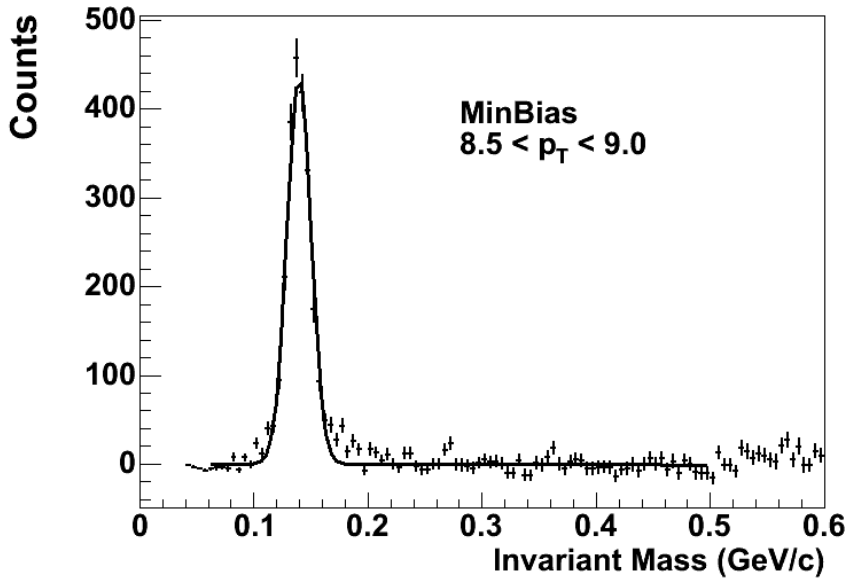
PRL 96, 032302 (2006)

Motivation

- Physics
  - How well do we understand the origin of azimuthal anisotropy (v_2) at high p_T?
  - Can we go beyond or confirm the "usual" explanations of azimuthal energy loss resulting from the geometry of the interaction region?
- π^0s provide ideal "laboratory" to probe the physics at high p_T:
  - (e.g.) Expected to be less subject to effects of recombination
  - PHENIX has high p_T acceptance
- Are there alternative observables that can shed light on what we've observed so far?
  - R_{AA} as function of both p_T and $\Delta\phi$ (wrt RP)

Measuring π^0s in PHENIX



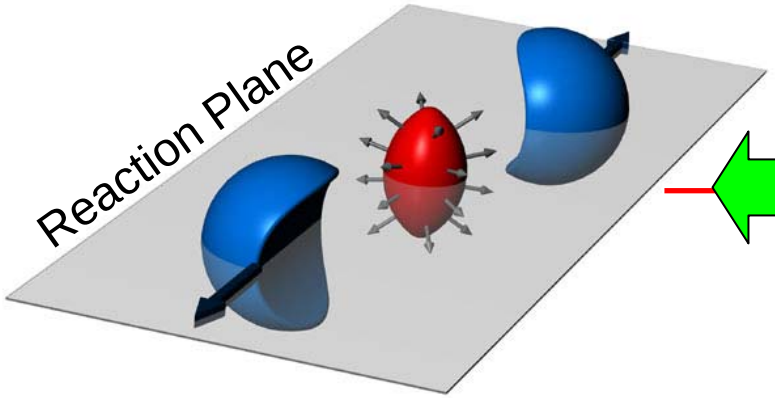


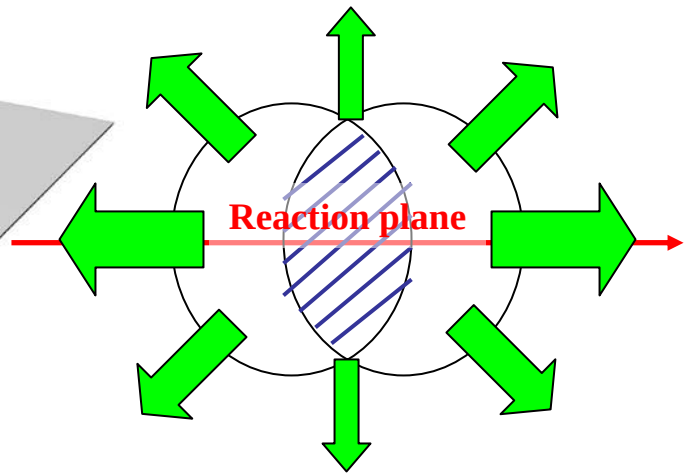
- Run4: recorded 1.5 B AuAu Events
  - This analysis ~ 1B of those events
- For measuring γ, π^0s, we have 8 EmCal sectors
  - 6x: PbSc (Sampling)
  - 2x: PbGl (Cerenkov)

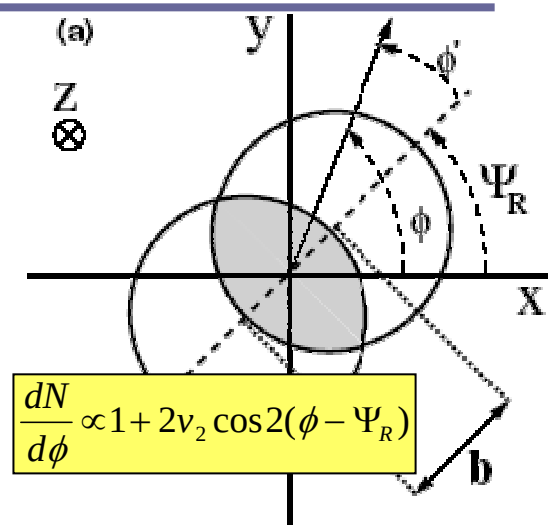
<u>In a given p_T, centrality, and reaction plane bin, we:</u>

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

Measurements wrt the R.P. in PHENIX







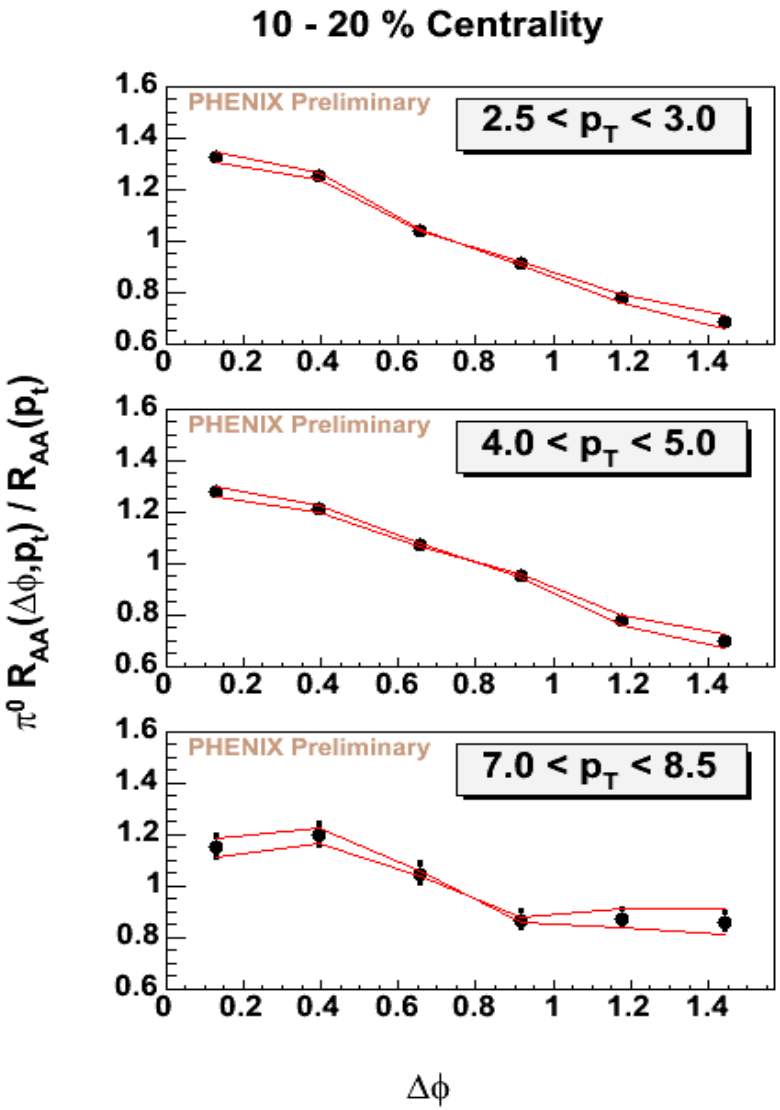
- Reaction Plane determination
  - Use the Beam-Beam Counters @ $3<|\eta|<4$, azimuthally symmetric
  - Measure charged particle multiplicity as function of φ
  - Event-by-event determination
  - 2 independent measurements from N and S counters – estimate of resolution
- Relative Yields as a function of $\Delta\phi$
  - Measure π^0 dN/dp_T in 6 $\Delta\phi$ bins over $[0,\pi/2]$. (corrected for resolution)
  - Multiply the ratio

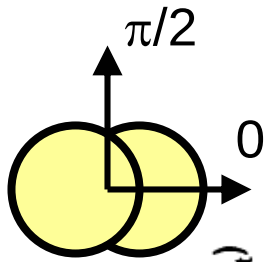
$$r_{\Delta\phi} = \mathrm{Yield}(\Delta\phi)/\mathrm{Yield} \equiv R_{AA}(\Delta\phi)/R_{AA}$$

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

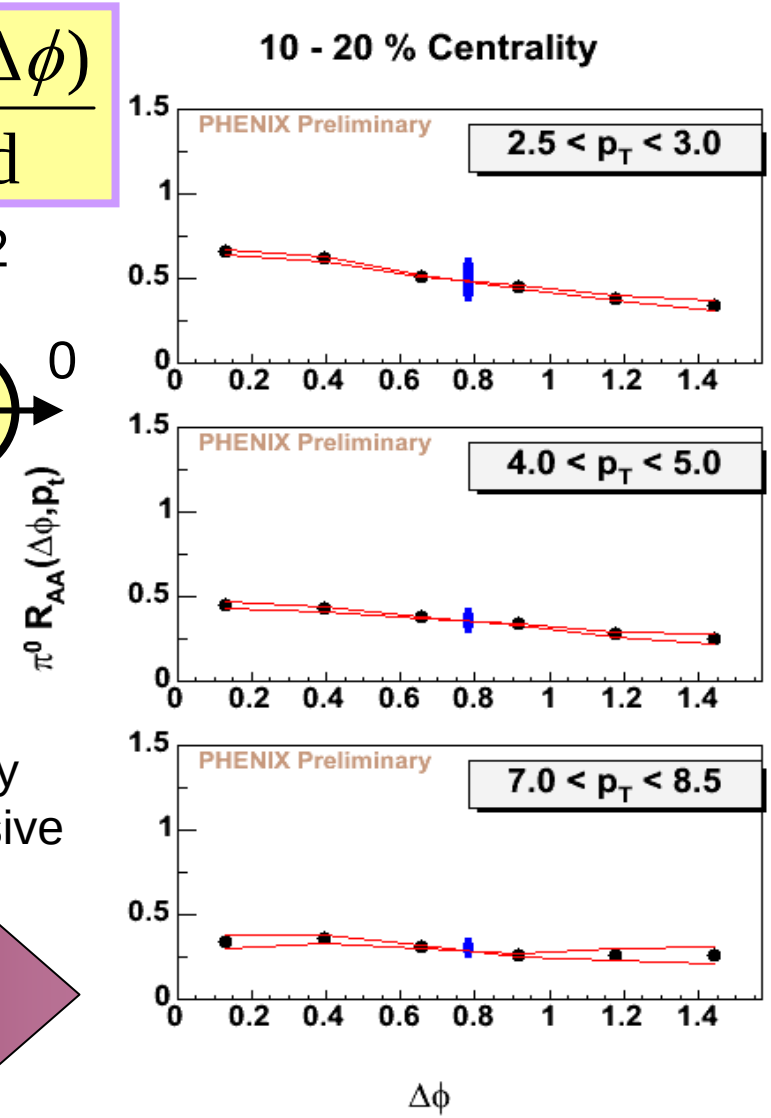
From Relative Yields to R_{AA}

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



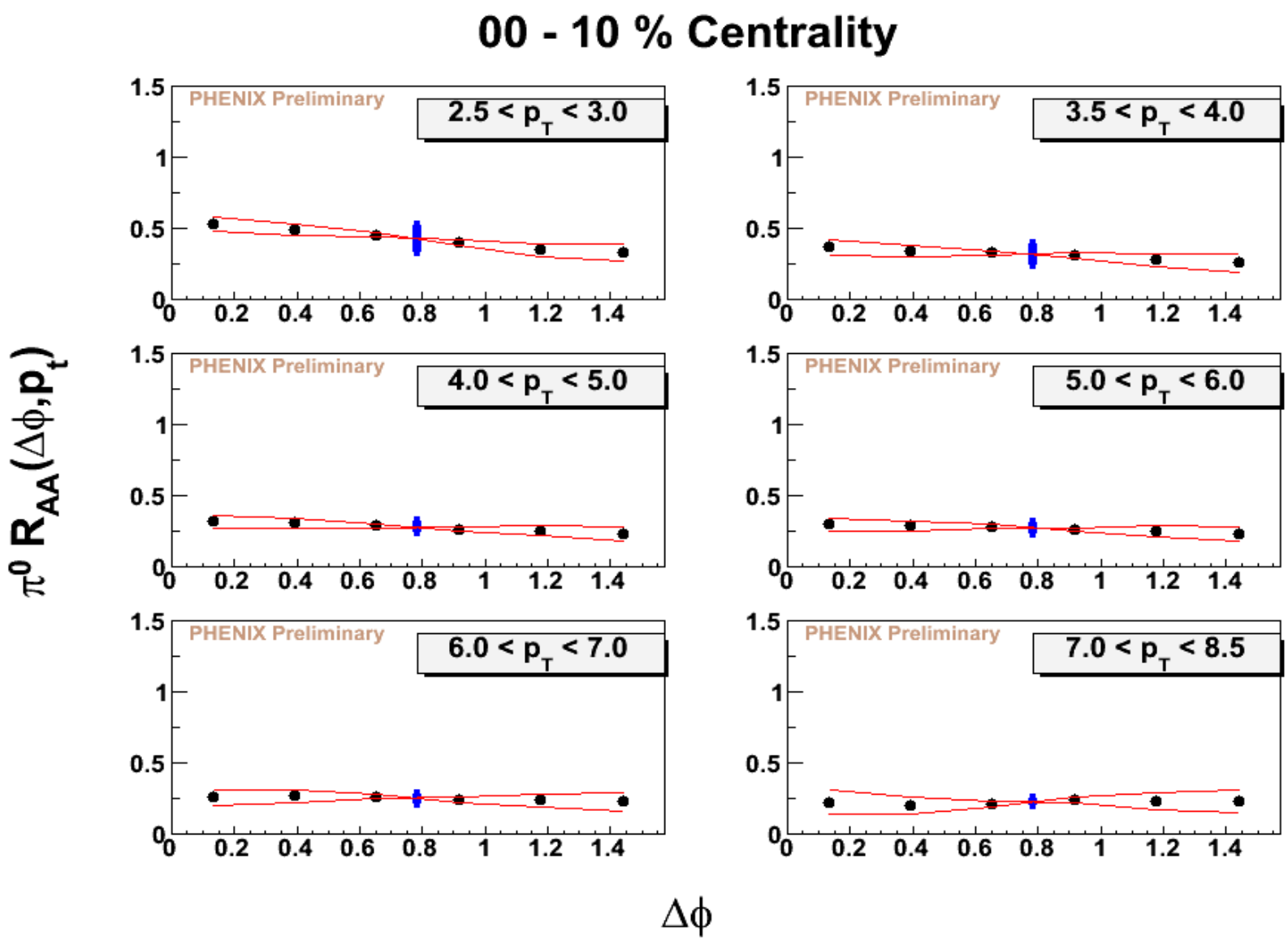


Multiply
By inclusive
R_{AA}

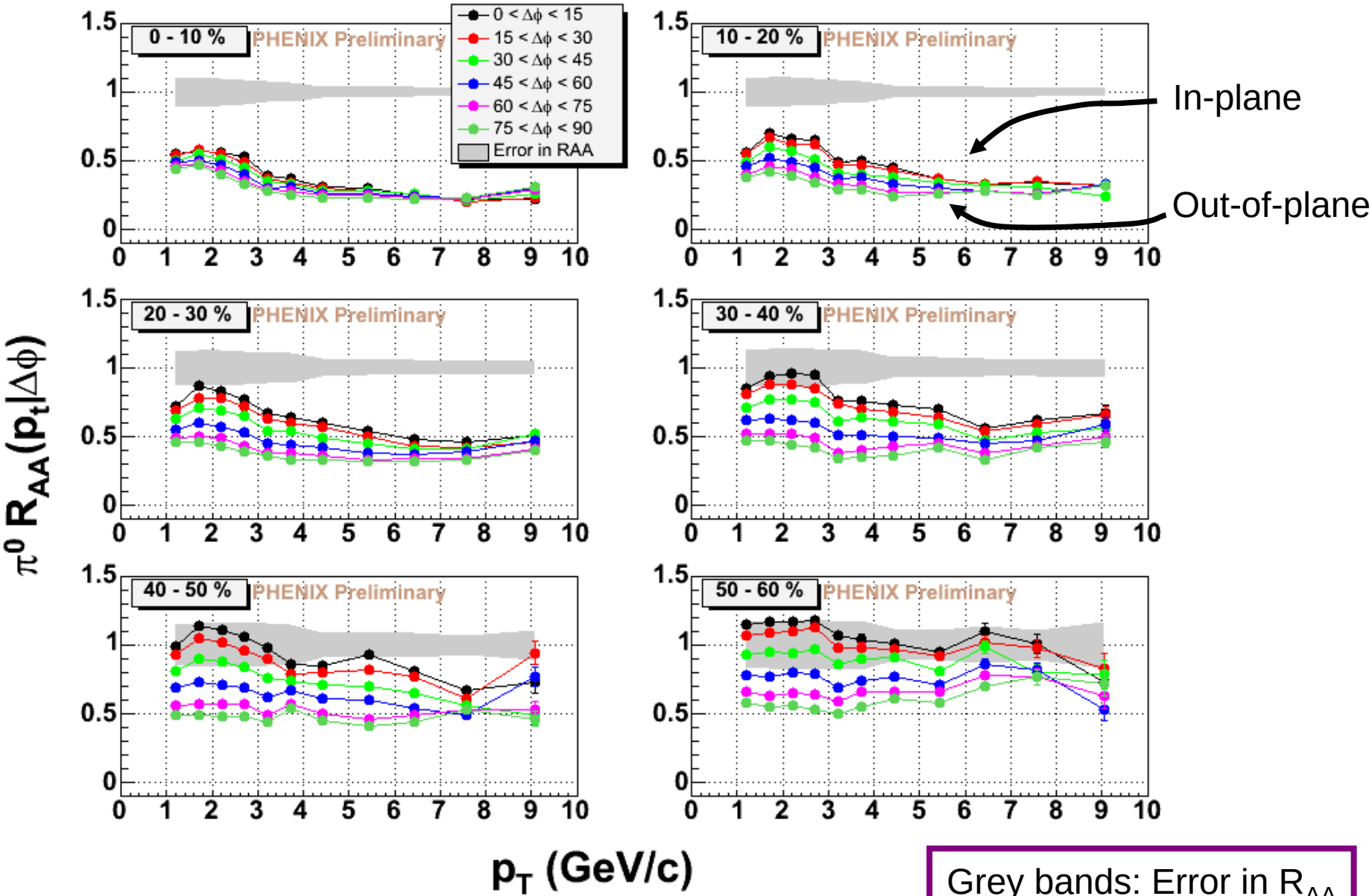


Red: Sys. Due to resolution correction
Blue: Error on R_{AA}

Centrality dependence of π^0 R_{AA}

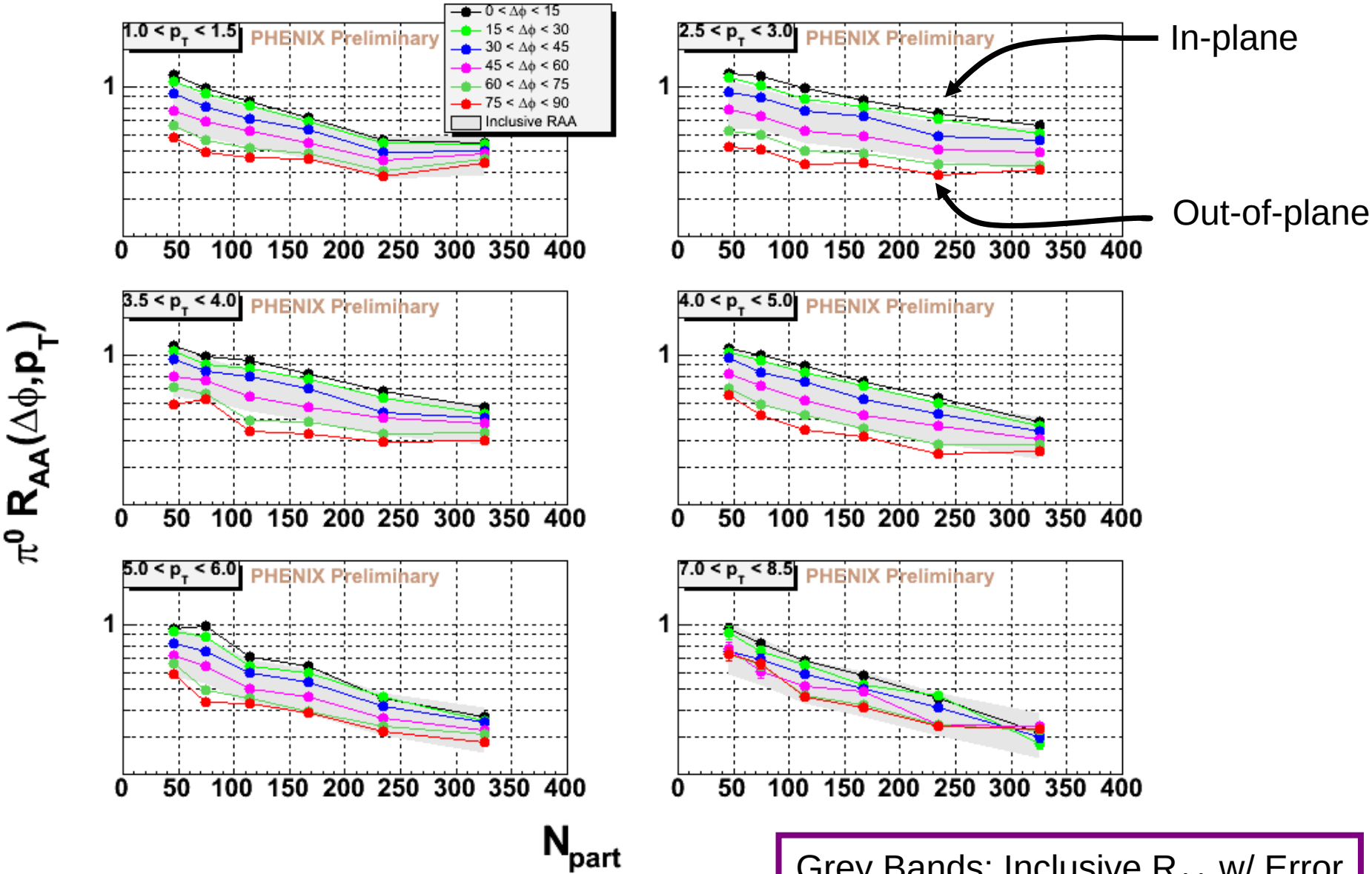


$R_{AA}(\Delta\varphi, p_T)$ vs. p_T (Cent. Dependence)



Grey bands: Error in R_{AA}

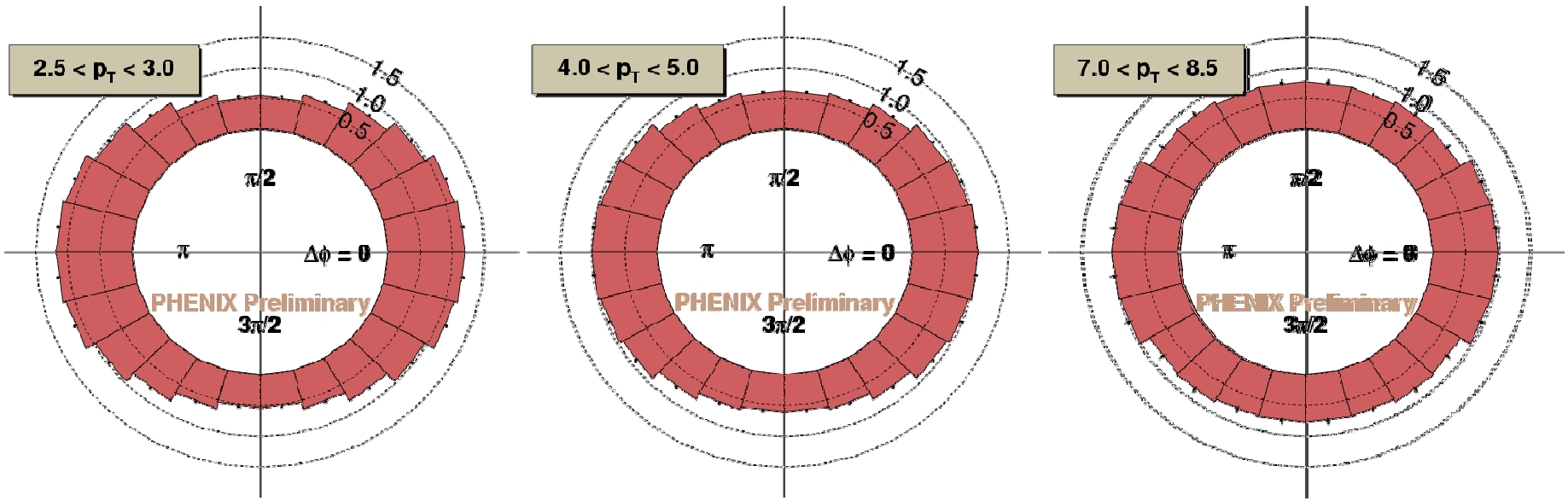
$R_{AA}(\Delta\varphi, p_T)$ vs. N_{part}

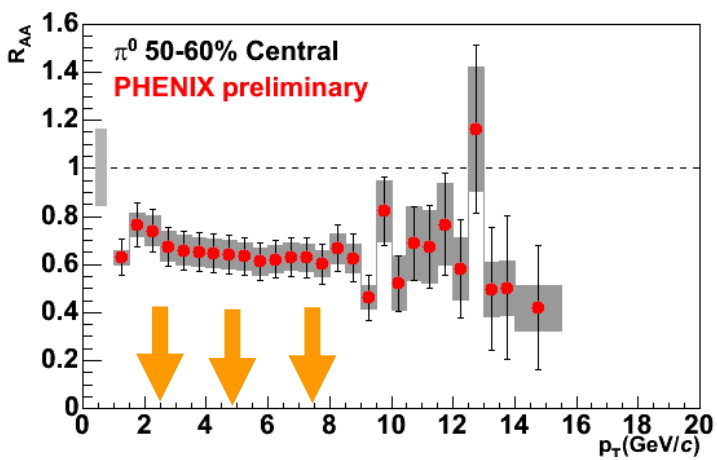


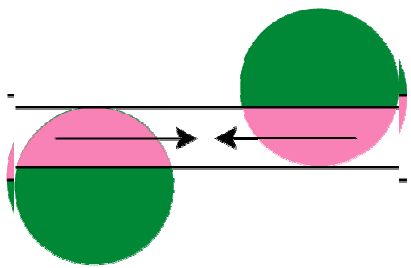
Grey Bands: Inclusive R_{AA} w/ Error

Fun with different perspectives

$R_{AA}(\Delta\phi, p_T)$ plotted in polar coords (folded to 2π)

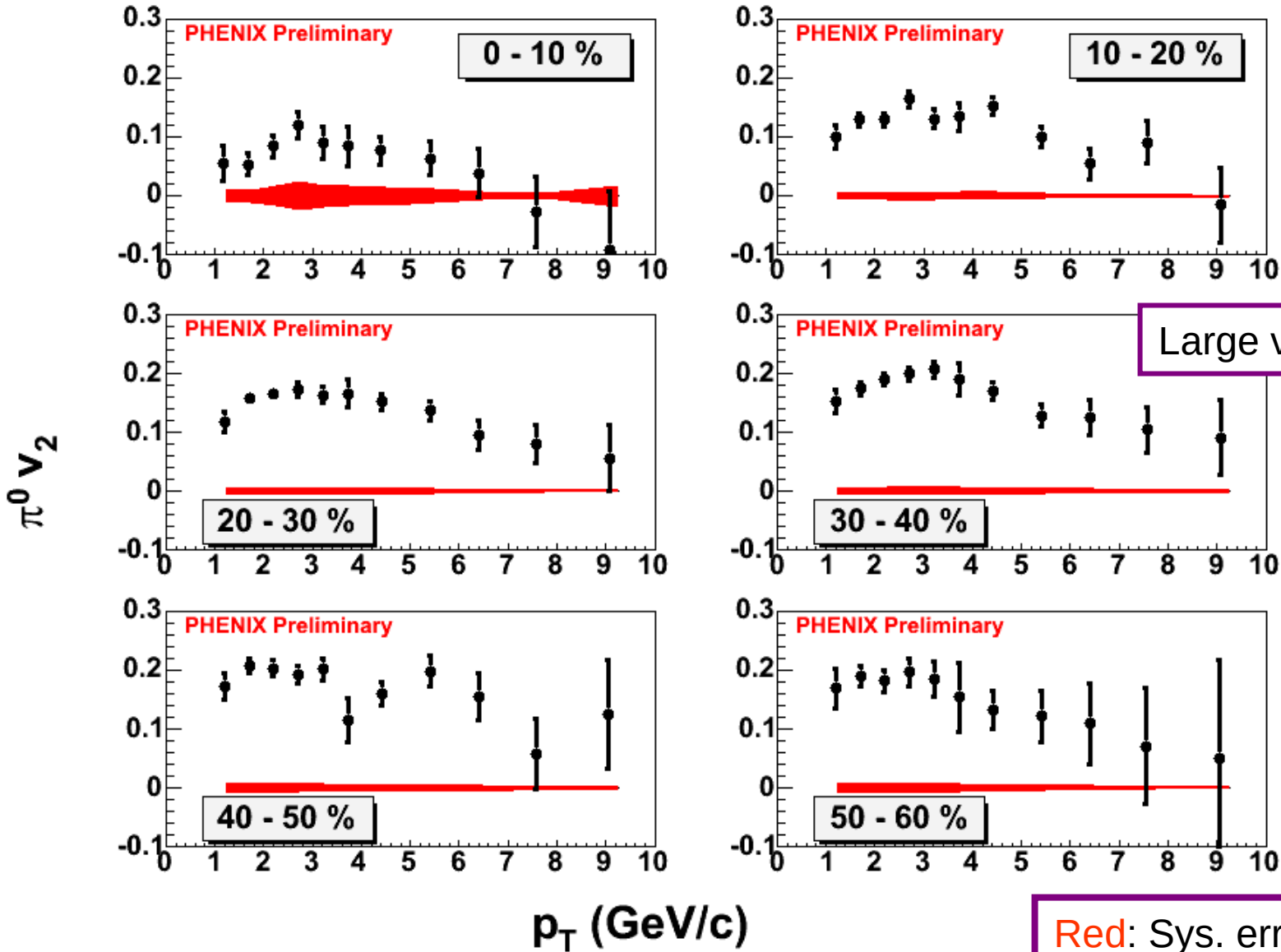






50-60 % Centrality

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 at high p_T
- These two (coupled) parameters both give handles on the parton's path length through medium:
  - Centrality
  - Angle with respect to Reaction Plane
- Is there an equivalent single parameter?
  - Have to depend on density of partons, ρ
  - Need to include time-dependence/formation time in ρ

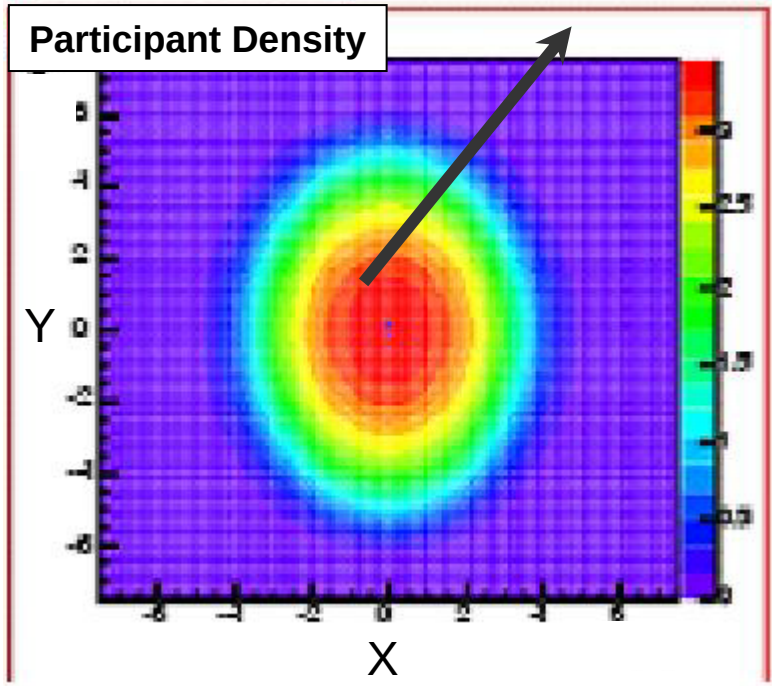
Geometry and "Canonical" Energy Loss

- Initial parton (areal) density

$$\frac{dn_{color}}{dA} \propto \frac{dn_{part}}{dA}$$

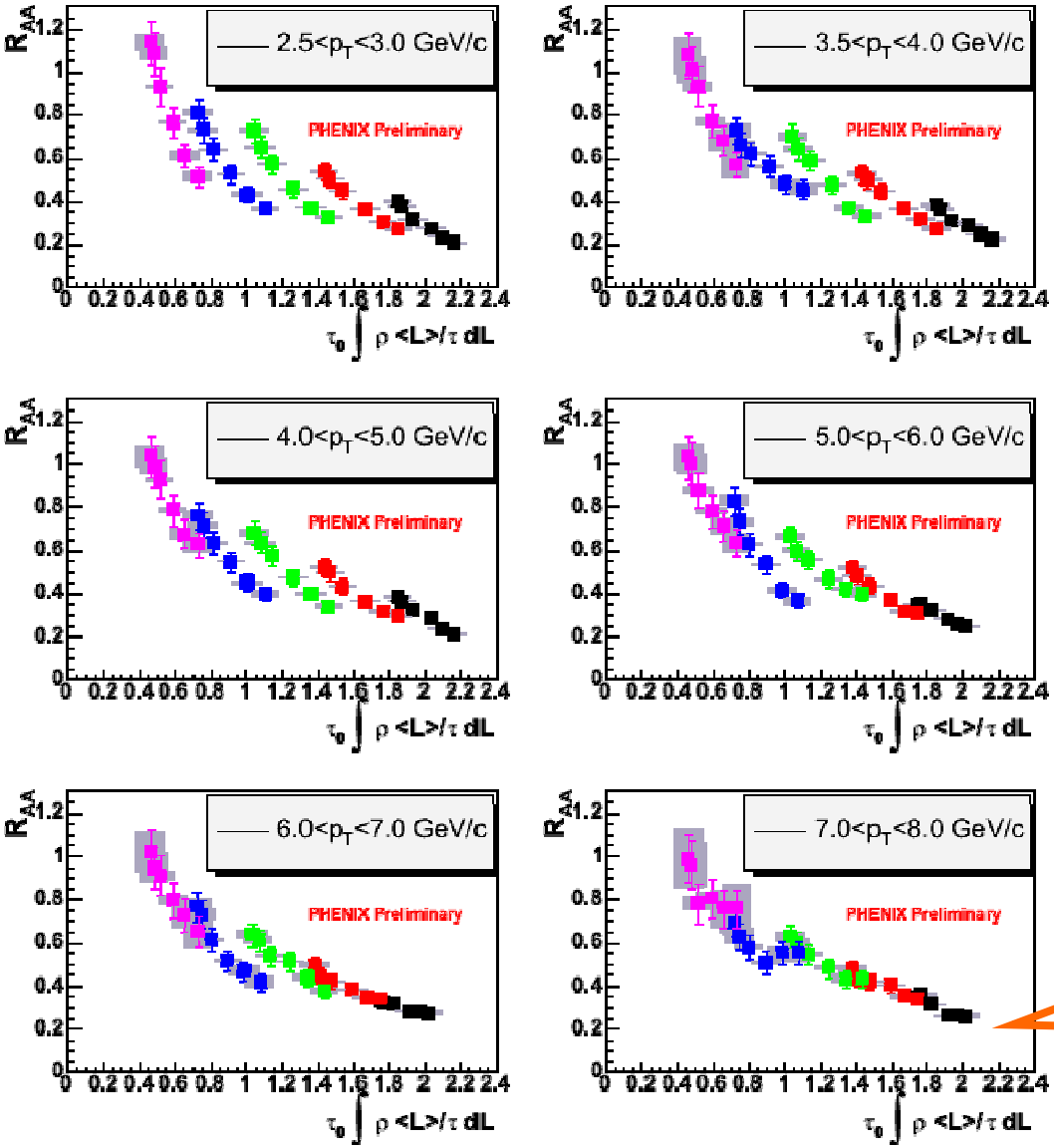
- Intrinsic energy loss: $\Delta E \propto L^2$
- Assume: $\rho_{\text{color}}(\vec{x}_T) = \rho_{\text{color}}^{\text{init}} \frac{\tau_0}{\tau}$
- Calculate:

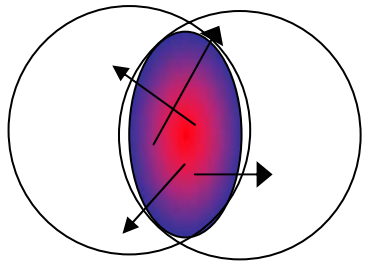
$$\int d\vec{l}\ \rho_{\text{color}}^{\text{init}}(\vec{L}) \frac{L\,\tau_0}{L+\tau_0}$$



- Further refine with Glauber MC sampling of path origin to take into account fluctuations in hard-scattering center
- This quantity should contain all geometric effects, and therefore ΔE should be proportional it.

R_{AA} vs. "ρ L dL"





10-20 % Centrality

20-30 % Centrality

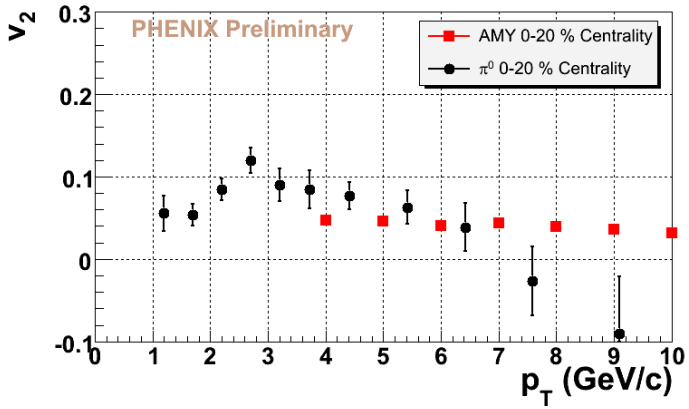
30-40 % Centrality

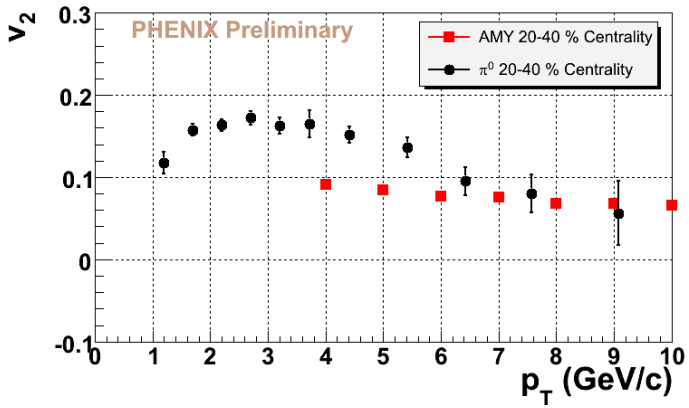
40-50 % Centrality

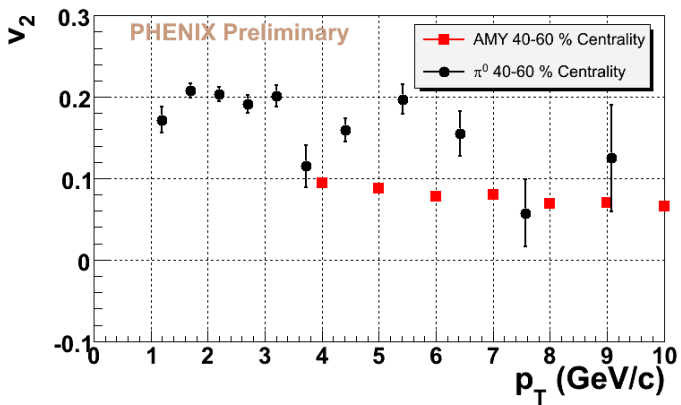
50-60 % Centrality

Angular and centrality dependence described by single curve!!

v_2 Theory Comparison: AMY (Turbide et al.)

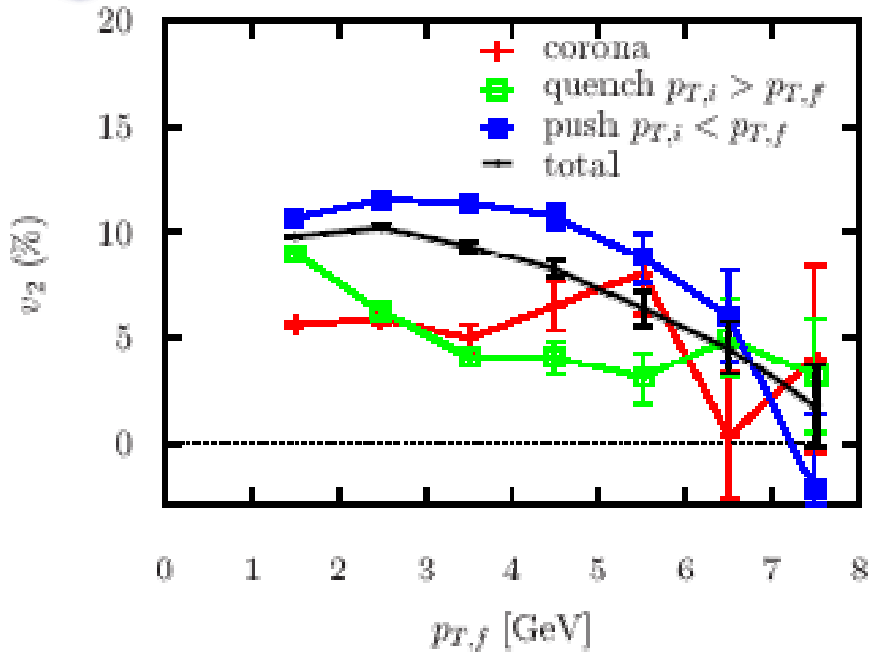




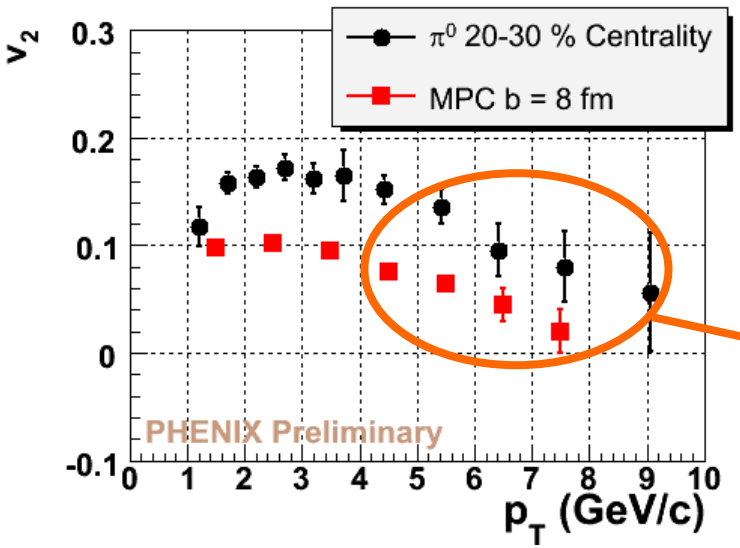


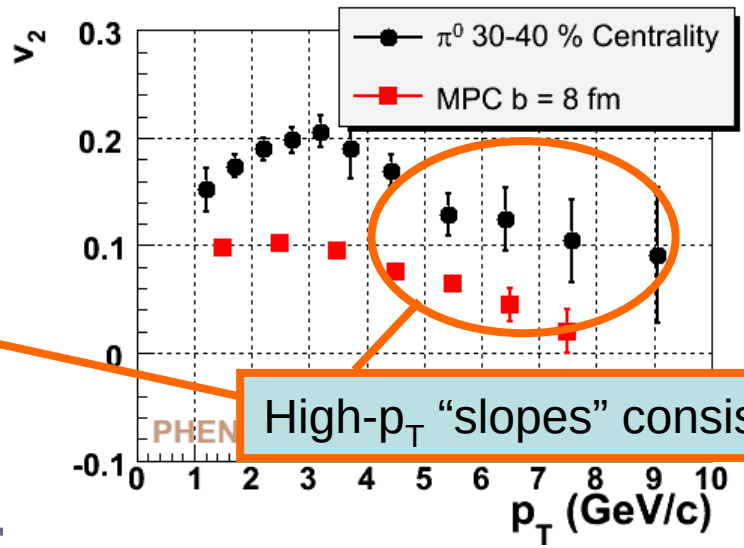
- Calculations based on Arnold, Moore, Yaffe (AMY) formalism
  - JHEP 0305:51 2003
- Energy loss only (BDMS++)
- High-p_T
  - v_2 appears to decrease to energy loss calculation
- Low(er)-p_T
  - Something additional going on…
- While the data appear to approach the energy loss limit at high p_T, there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

Summary

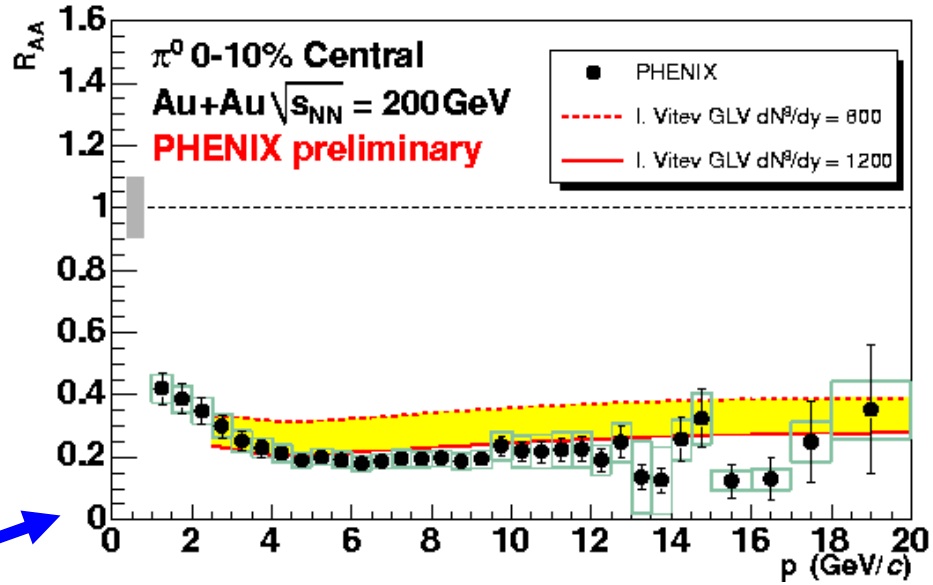
- The observed $R_{AA}(p_T)$ being flat out to very high-p_T is an important and intriguing result from the first several years of RHIC
- However, $R_{AA}(\Delta\varphi,p_T)$ reveals both pt- *and* angle-dependent substructure
- For the first time we see a clear decrease in the π^0 v_2 at high p_T – to a non-zero value!
  - Seems consistent with energy-loss calculations
- Comparison of high-p_T v_2 with models points to pQCD + energy loss as dominant sources
  - How high is high-p_T? (>7 GeV/c)
  - 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?

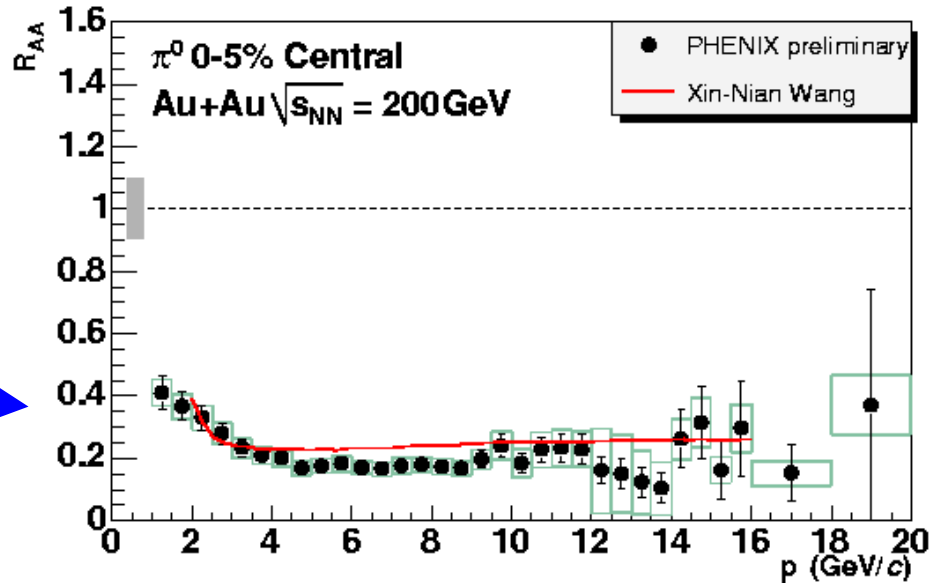
Many thanks to many people…

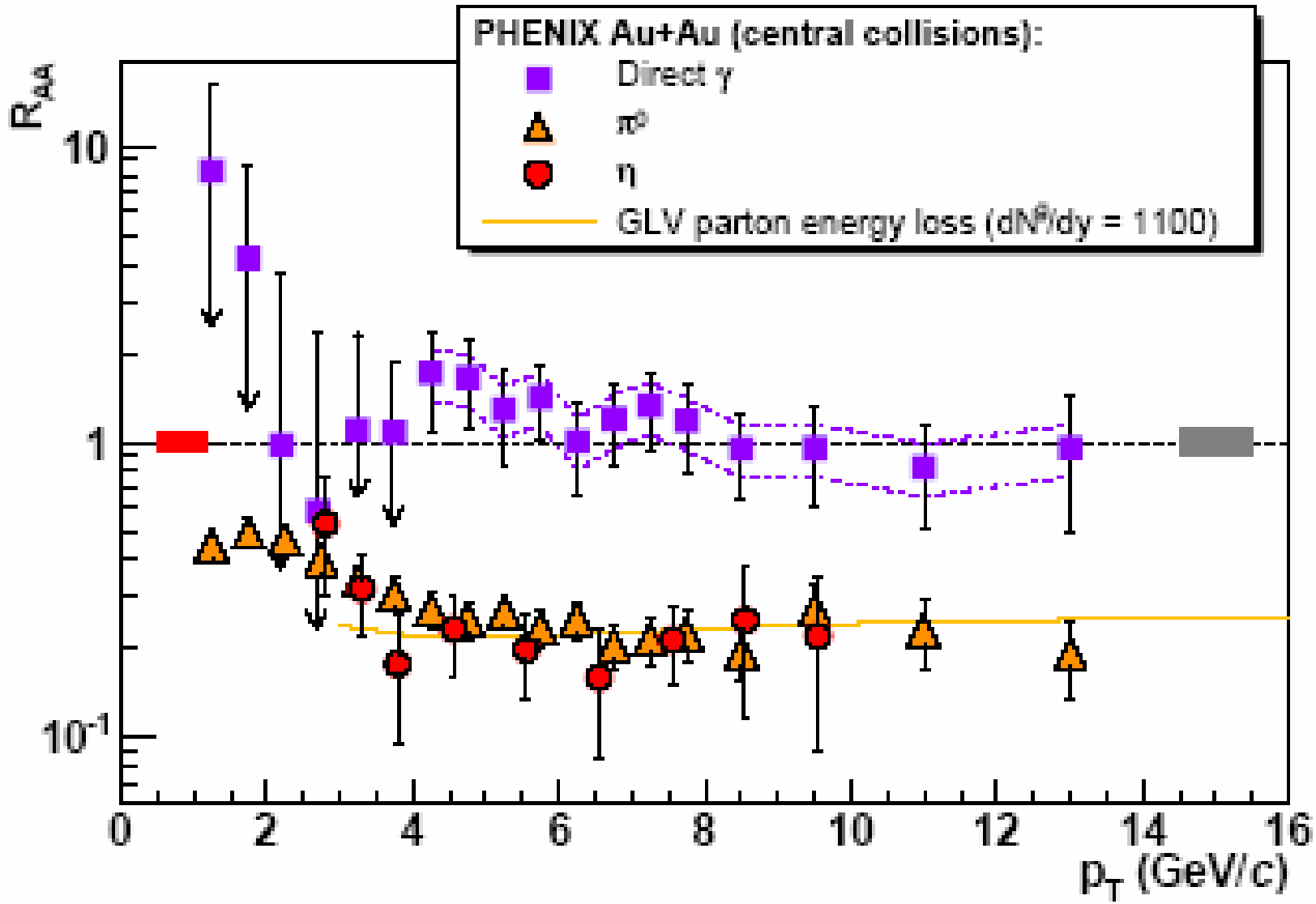
Backup Slides

Theoretical treatment of R_{AA}

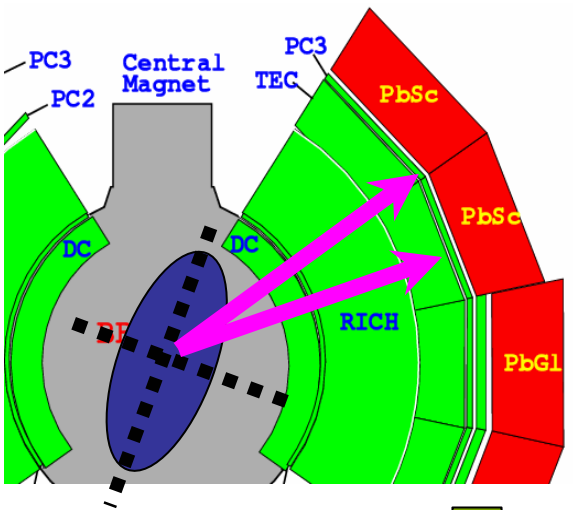
- Flat R_{AA} is mixture of nuclear effects:
  - Jet quenching
  - Cold nuclear effect
    - Nuclear shadowing
    - Cronin effect
- 1+1D Bjorken expansion
- I. Vitev
  - Phys. Rev. Lett. 89, 252301,2002
- X.N. Wang
  - Phys.Lett.B595:165-170,2004



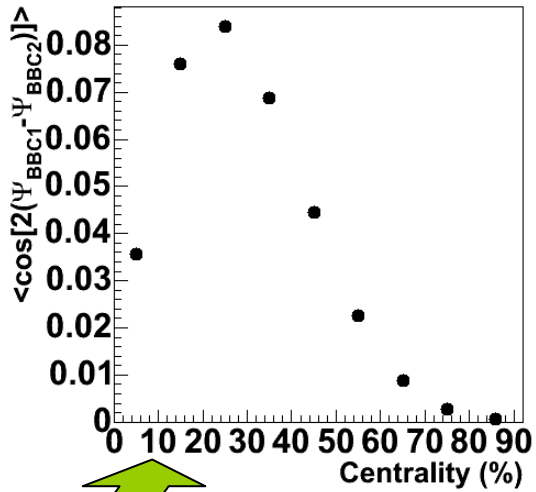


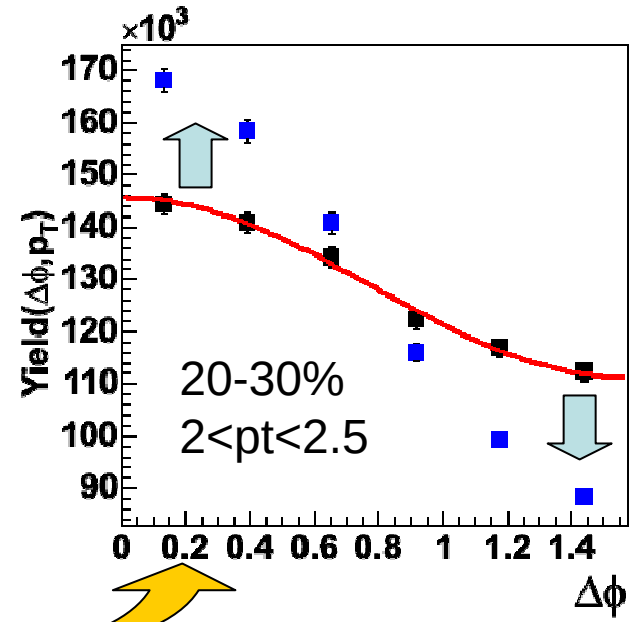

PHENIX Au+Au (central collisions):
Direct γ
π0
η
GLV parton energy loss (dN^g/dy = 1100)
R_AA
10
1
10^-1
0
2
4
6
8
10
12
14
16
p_T (GeV/c)

RP Resolution Correction



Measure RP with Beam-Beam Counters



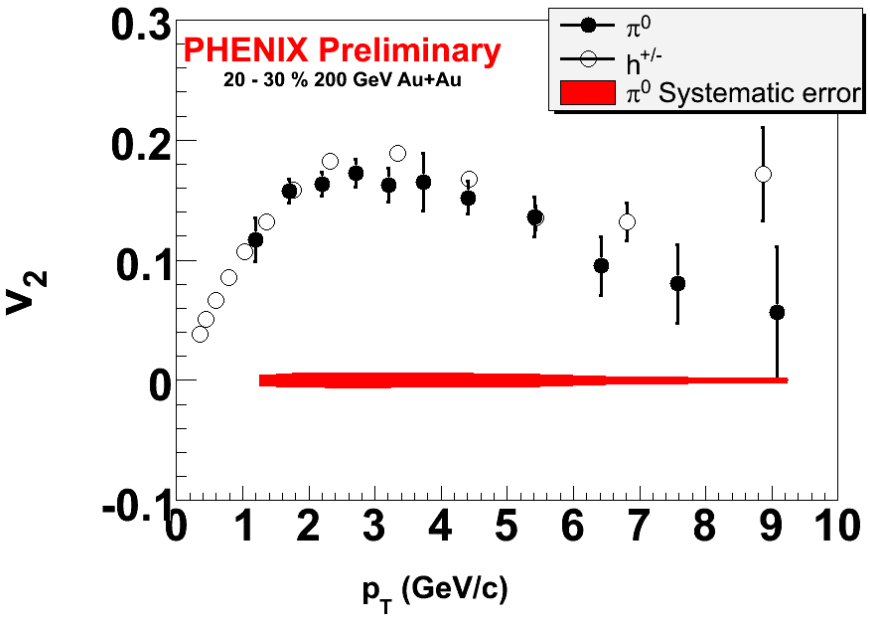


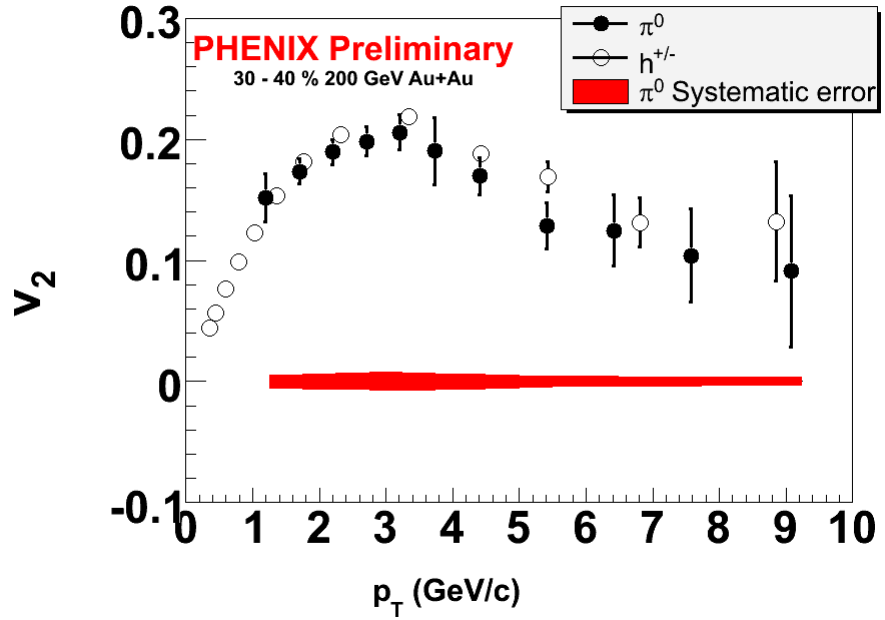
- Reaction Plane as measured has resolution σ
- Fit raw yield($\Delta\varphi$) $\Rightarrow$ raw v_2
- Correct raw v_2 for resolution
- Correct raw yield($\Delta\varphi$) with

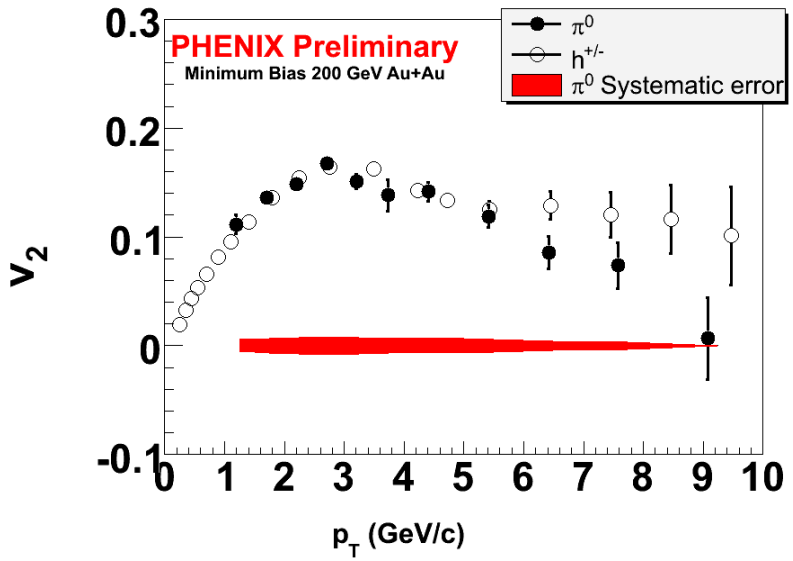
$$\sigma = \sqrt{2\cos(\Psi_{BBC_N} - \Psi_{BBC_S})}$$

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

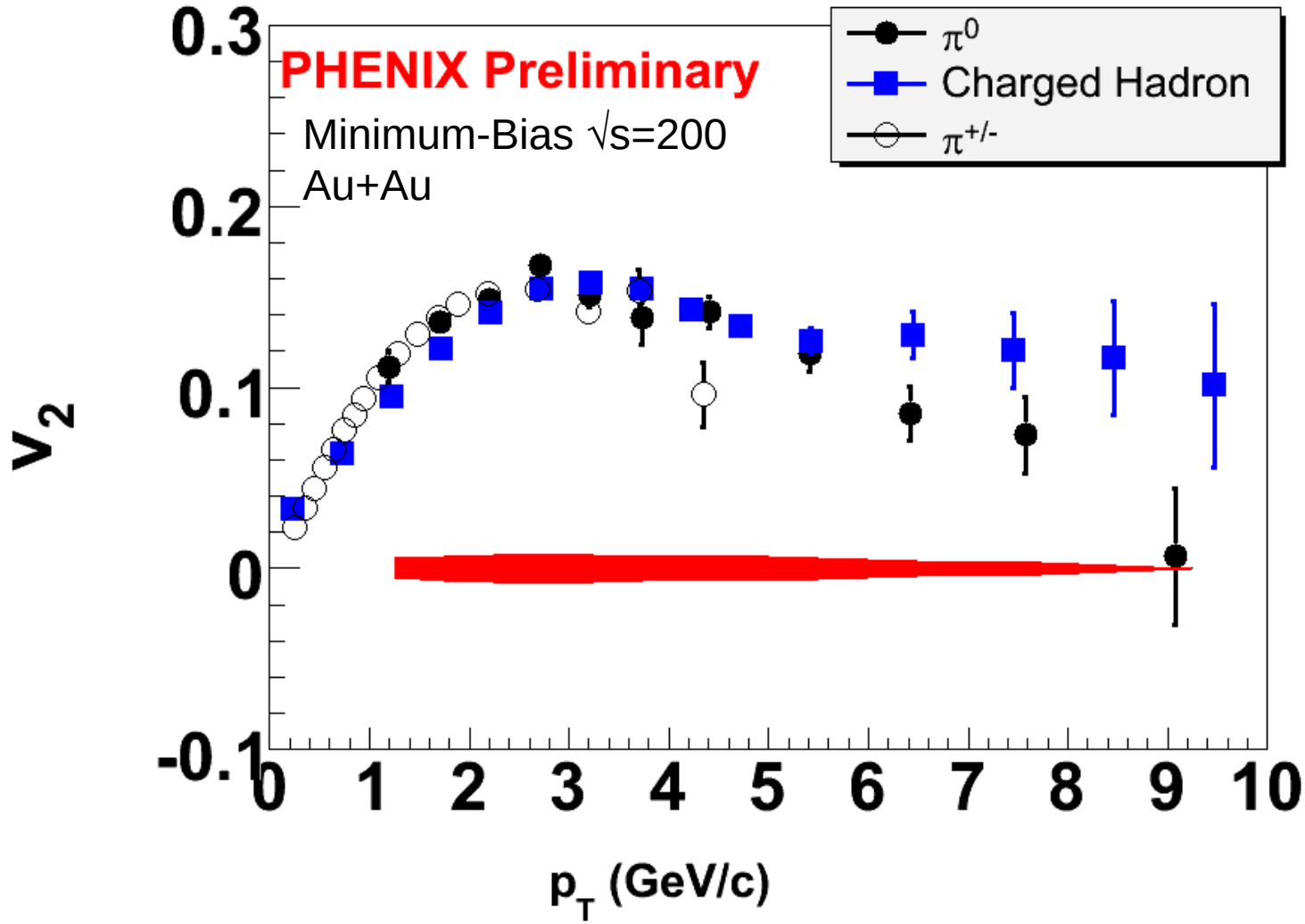
Compare with charged hadrons



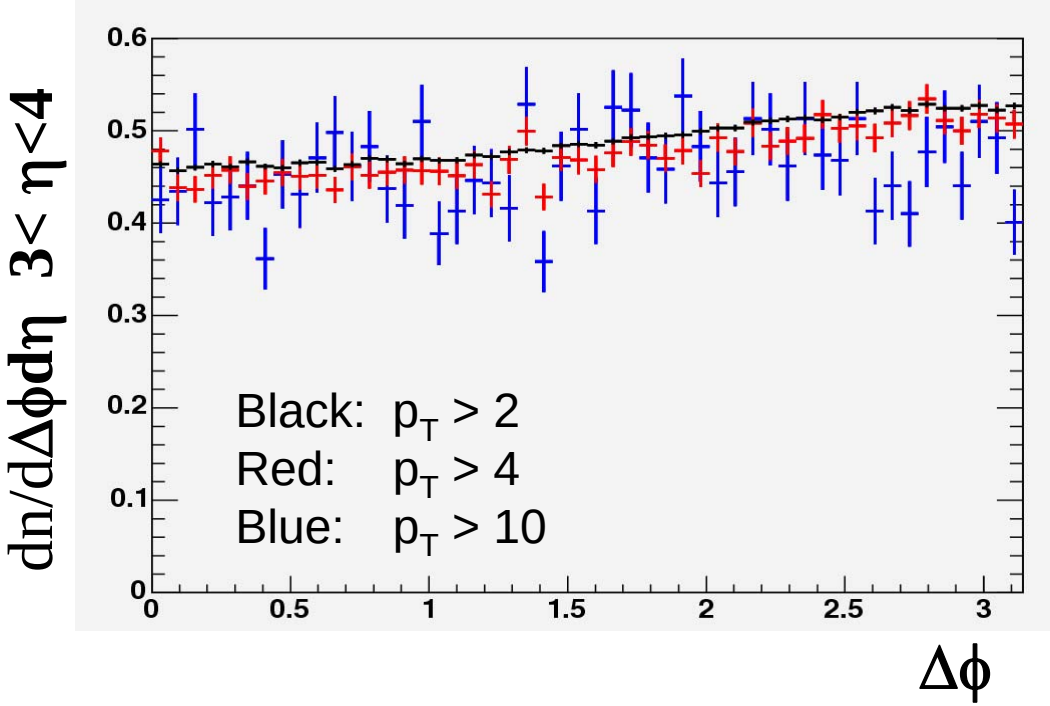




“Zooming in” on MinBias $h^{\pm}$



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.