

# $\pi^0$ production in Cu+Au at PHENIX



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Hot Quarks – Las Negras, Spain



# Outline

- Why pions?
  - Path length dependence and energy loss
- Why Cu+Au?
  - Centrality dependence
  - Reaction plane dependence
- Conclusions

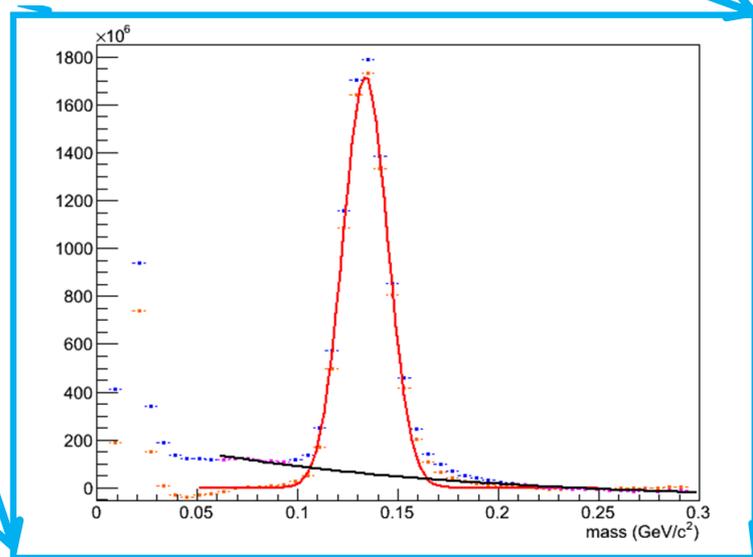
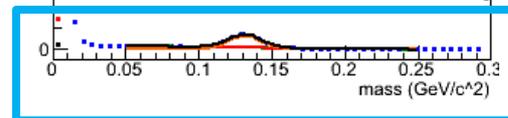
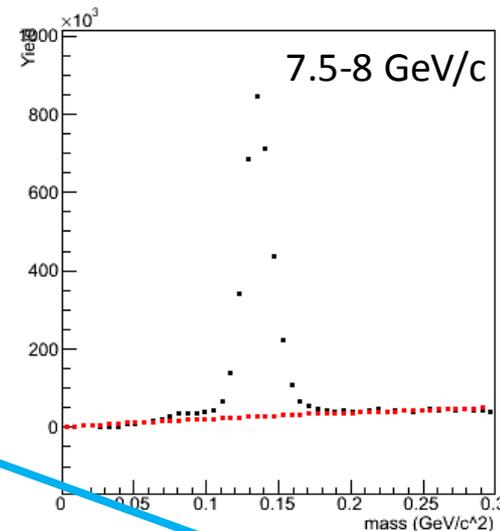
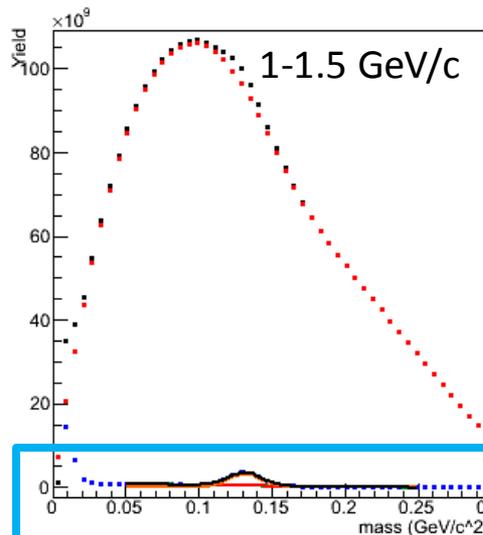
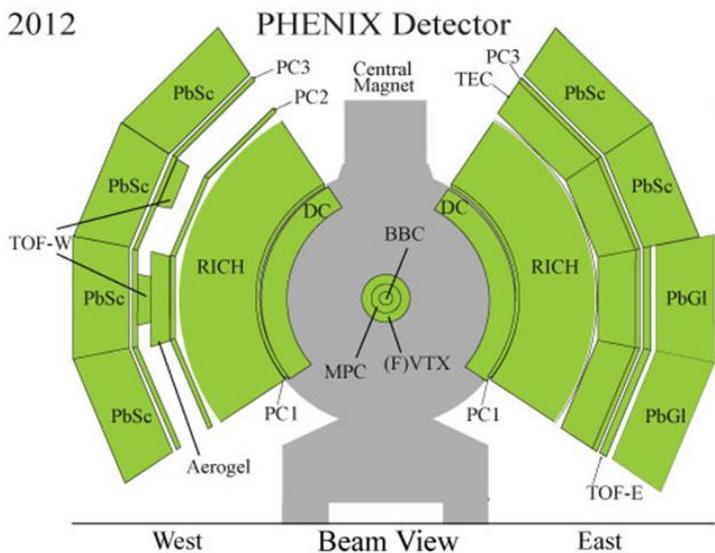
# Why study neutral pions?

- Identified particle with good signal-to-background, lots of statistics
- Low  $p_T \rightarrow$  soft medium effects
  - Experience flow, hadronization
- High  $p_T \rightarrow$  good proxy for a jet
  - Leading particles of a jet are a good measure of the jet energy
  - Can probe the path length dependence of energy loss of the hard parton in the medium
  - Compare to reconstructed jet to learn about fragmentation, modified fragmentation functions

# Measuring $\pi^0$ 's at PHENIX

$$\pi^0 \rightarrow \gamma\gamma$$

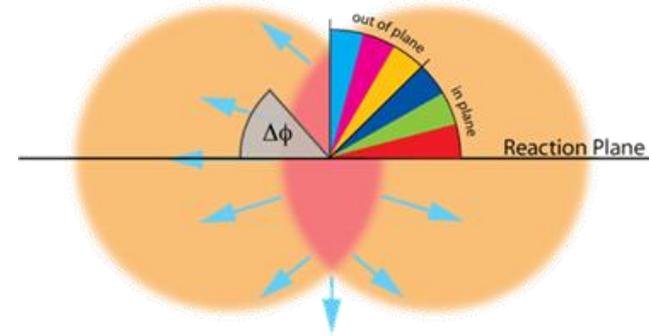
2012



• Cuts:

- $|\text{vertex}| < 30\text{cm}$
- $E > 400 \text{ MeV}$  in PbSc or PbGl
- $\text{Chi}2 < 3$  in PbSc
- Photons in the same sector
- $\alpha = \frac{E_1 - E_2}{E_1 + E_2} < 0.8$

# $R_{AA}(\Delta\phi_i, p_T)$



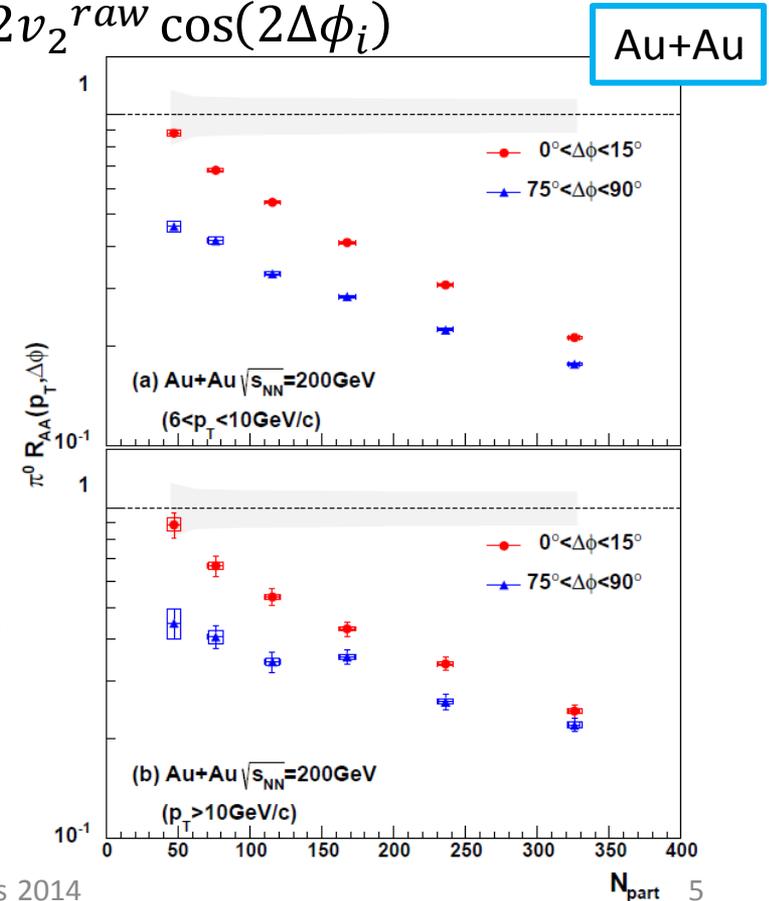
$$R_{AA}(\Delta\phi_i, p_T) = R_{AA}(p_T) F(\Delta\phi_i, p_T)$$

where

$$F(\Delta\phi_i, p_T) = \frac{N(\Delta\phi_i, p_T)}{1/\text{bins} \sum_{i=1}^{\text{bins}} N(\Delta\phi_i, p_T)} \frac{1 + 2v_2^{\text{corr}} \cos(2\Delta\phi_i)}{1 + 2v_2^{\text{raw}} \cos(2\Delta\phi_i)}$$

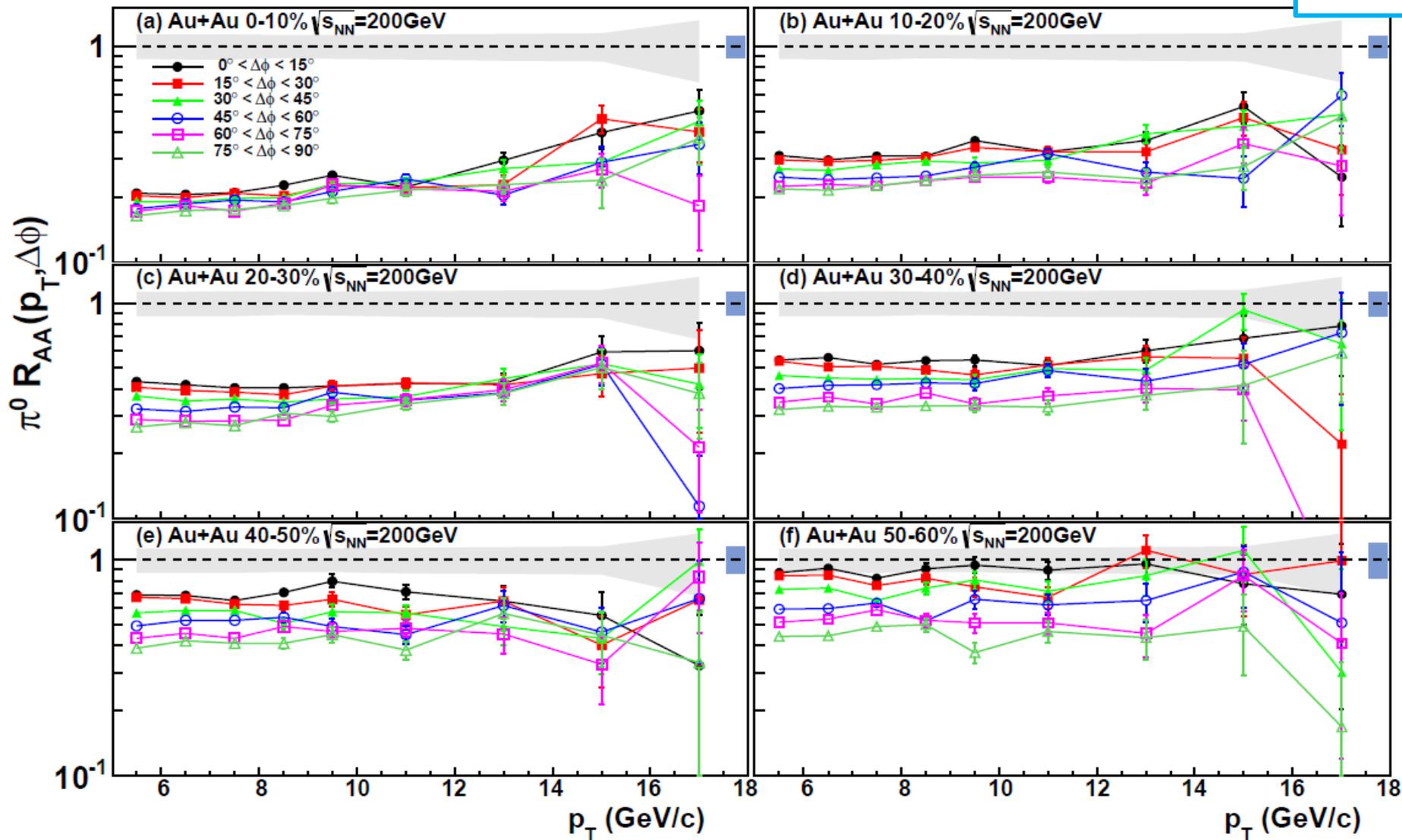
$$R_{AA}(p_T) = \frac{1}{N_{\text{Evt}}} \frac{\partial N_{AA} / \partial p_T \partial y}{\langle T_{AA} \rangle \partial \sigma_{pp} / \partial p_T \partial y}$$

- $R_{AA \text{ in}} > R_{AA \text{ out}}$
- $R_{AA \text{ in}} - R_{AA \text{ out}}$  decreases as  $N_{\text{part}}$  increases,  $\epsilon$  decreases



# $\pi^0 R_{AA}(\Delta\phi_i, p_T)$ in Au+Au

Au+Au

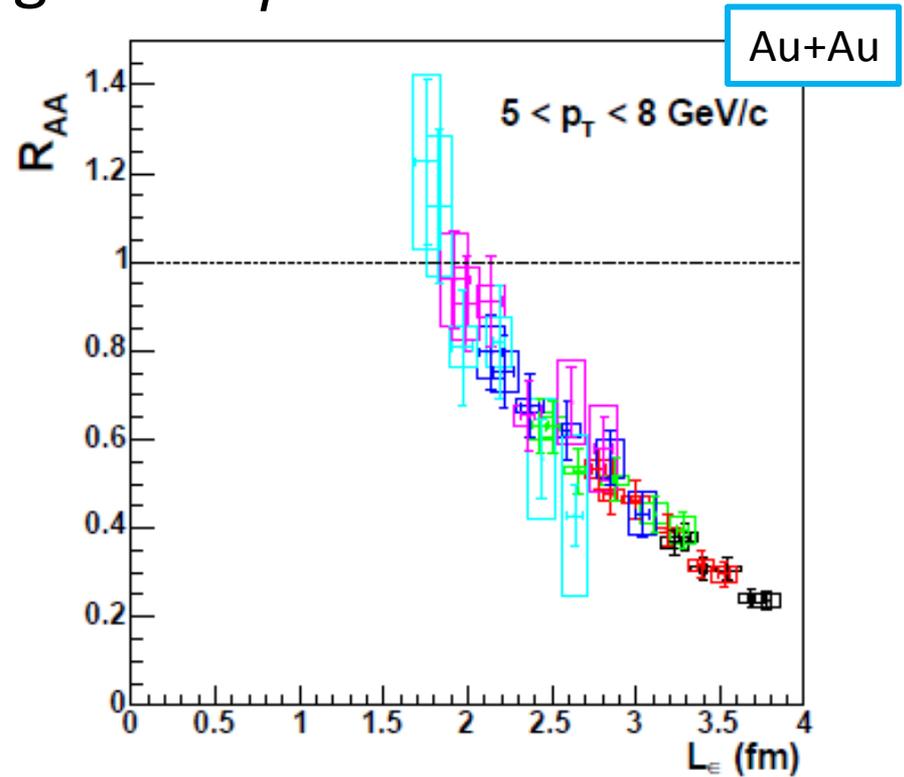
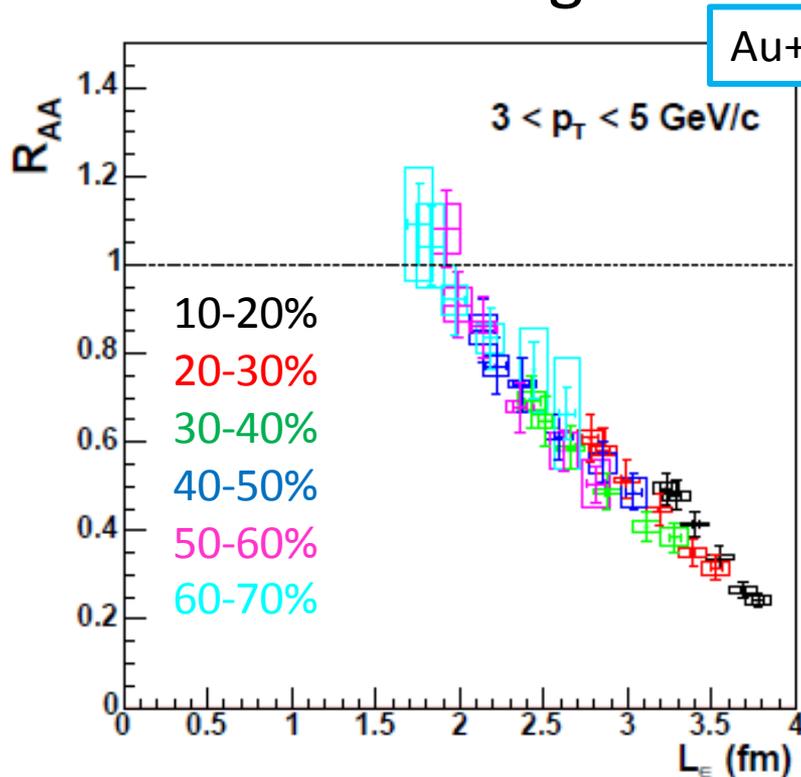


# $R_{AA}$ path length dependence

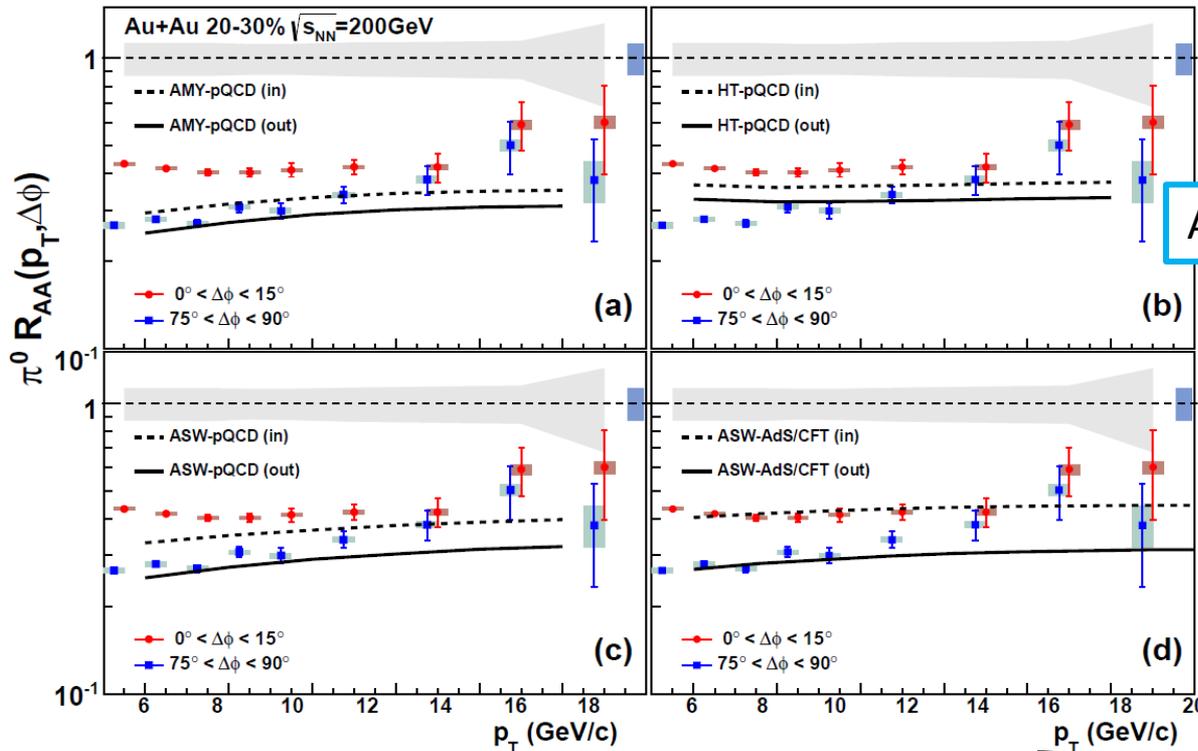
- Simple approximation:

$$L_{\epsilon} = \frac{b\sqrt{1+\epsilon}}{\sqrt{1+\epsilon \cos(2\Delta\phi)}}$$

- Path from center of an ellipse (defined by  $\epsilon$ ,  $b$ ) to the edge for an angle of  $\Delta\phi$



# Models of energy loss



a) AMY: radiative & coll. energy loss, high  $T$

b) HT: higher twist corrections to DIS, radiative processes

c) ASW: radiative processes,  $\lambda \gg r_D$

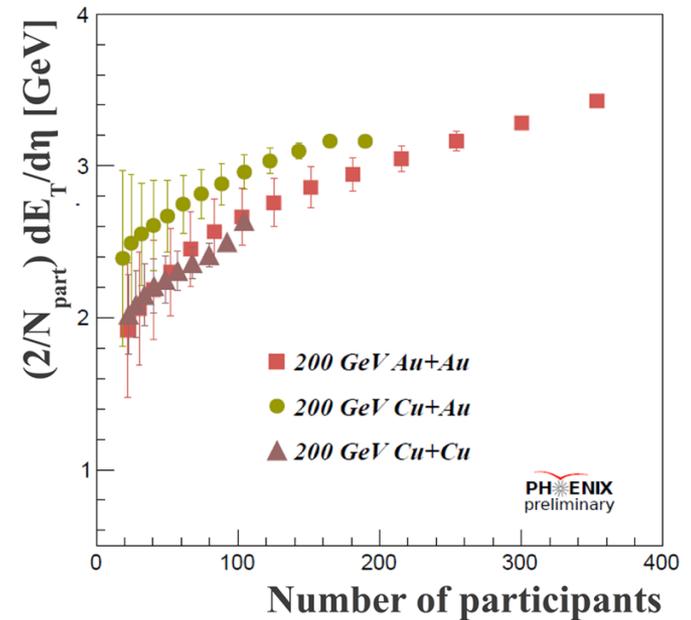
d) ASW-AdS/CFT: ASW-like hard processes, strongly coupled soft processes

}  $L^2$  dependence

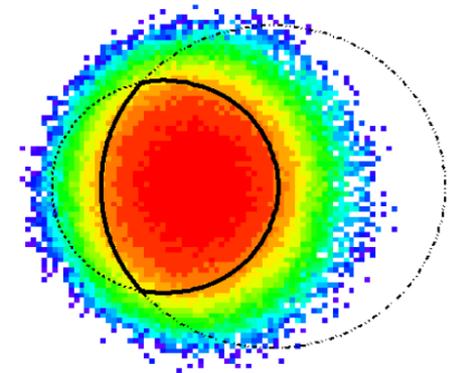
→  $L^3$  dependence

# Why Cu+Au?

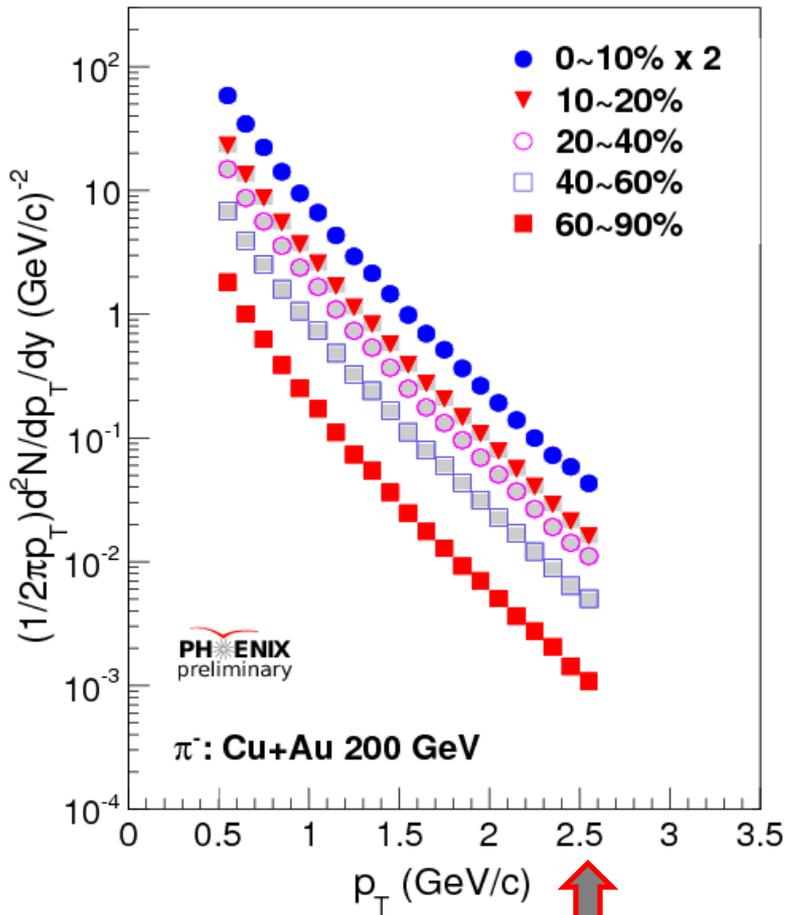
- Asymmetric collisions at RHIC
  - Higher energy densities
  - New collision geometries
    - Asymmetric overlap regions
    - Cu embedded in the Au nucleus
  - Odd flow harmonics not from fluctuations
    - Asymmetric pressure gradients
    - Asymmetric density profiles
    - Asymmetric path lengths



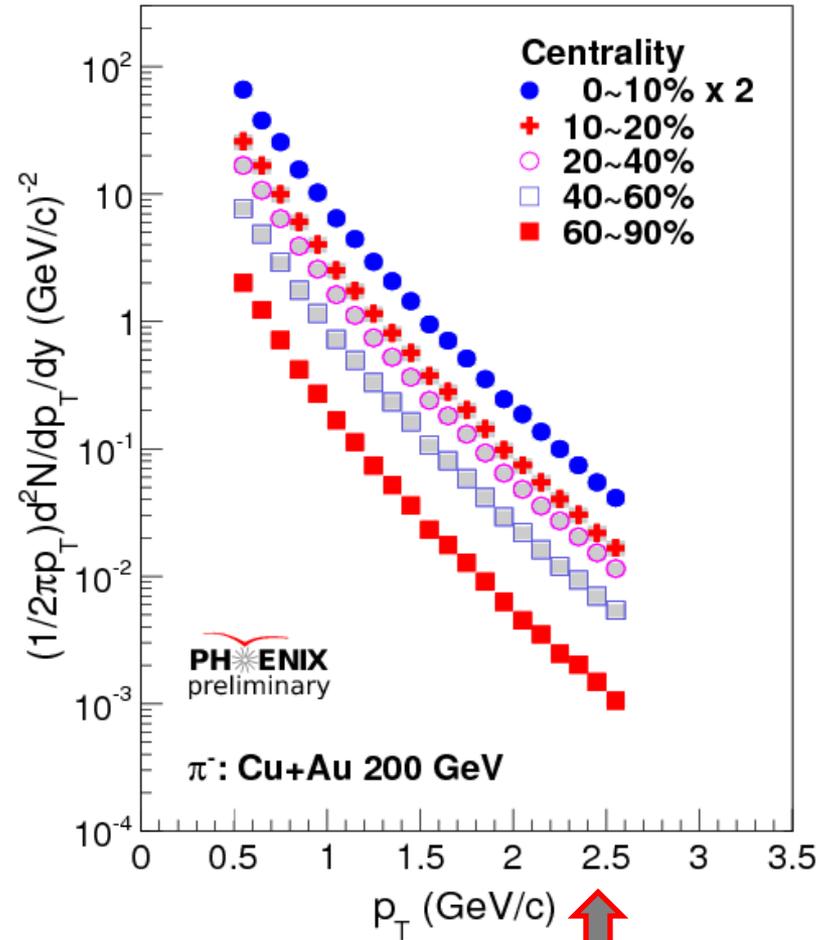
Participant density (log-z scale)



# Charged Pions in Cu+Au

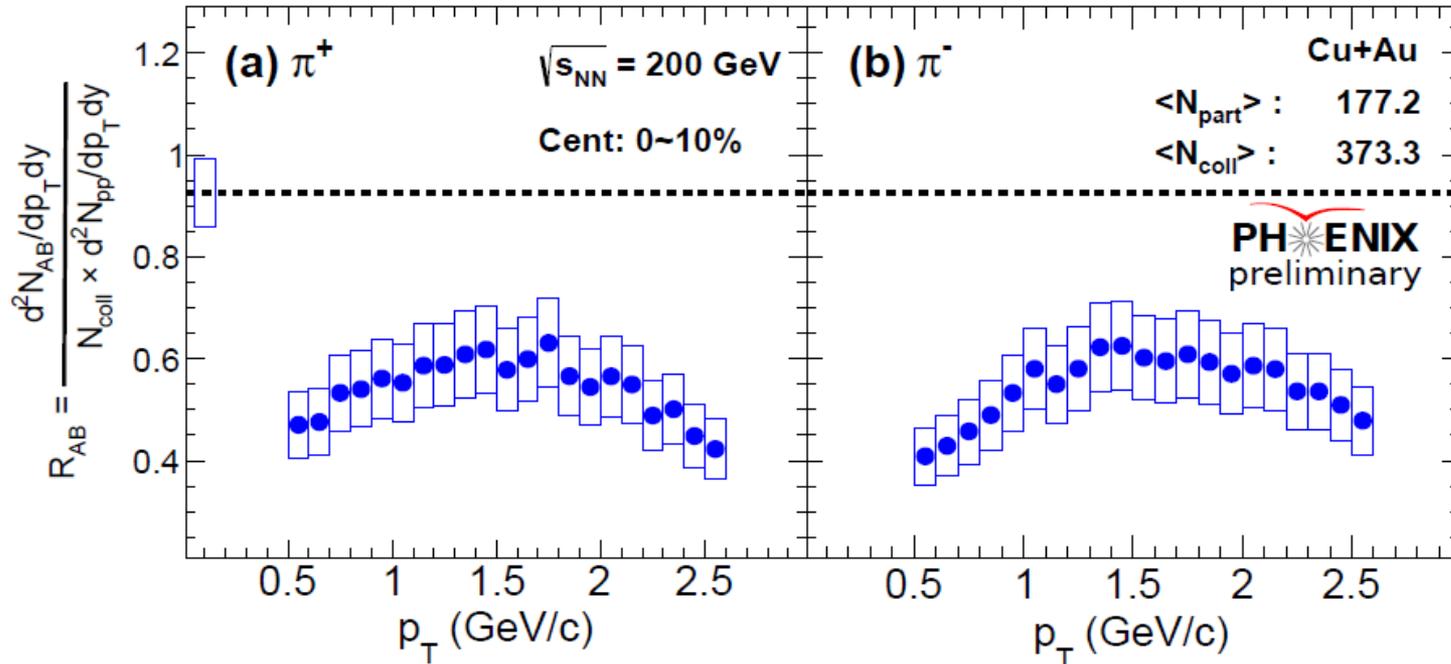


$p_T < 2.5$  GeV/c

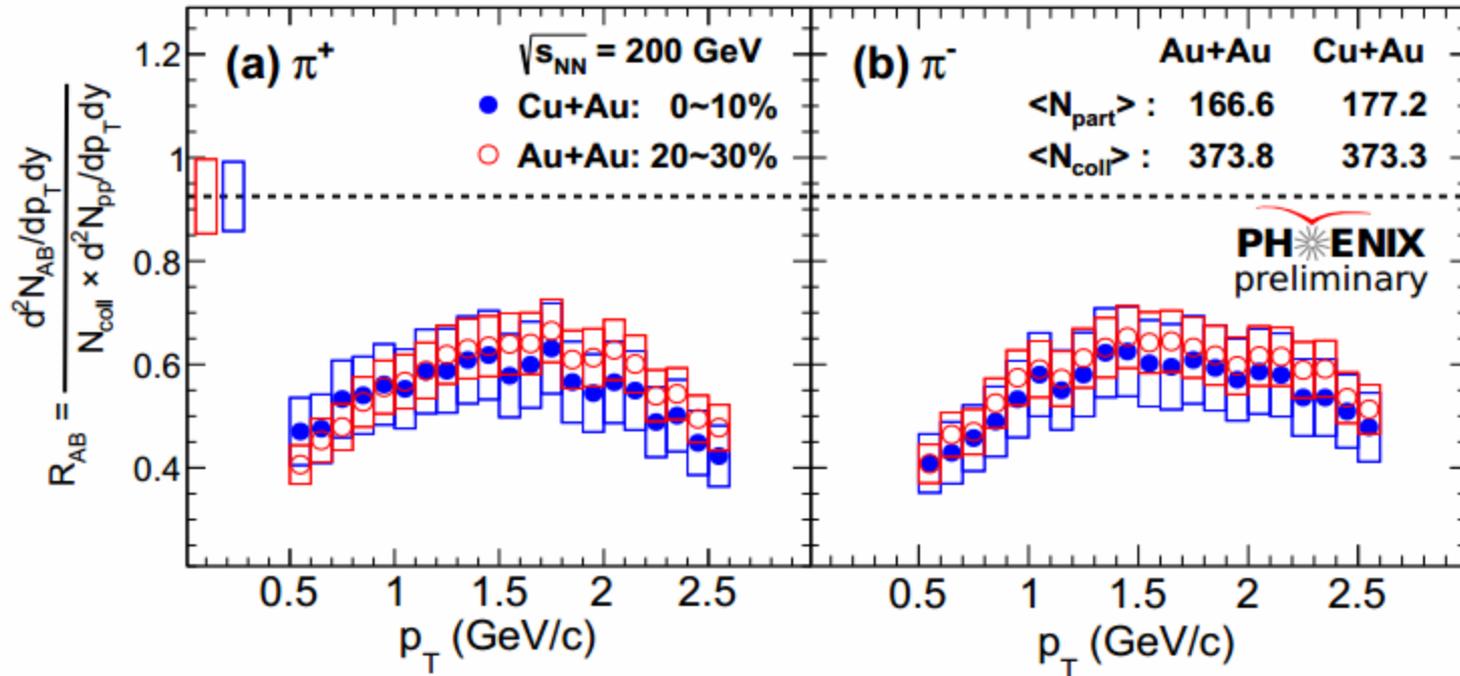


$p_T < 2.5$  GeV/c

# $\pi^\pm$ $R_{AB}$ in Cu+Au

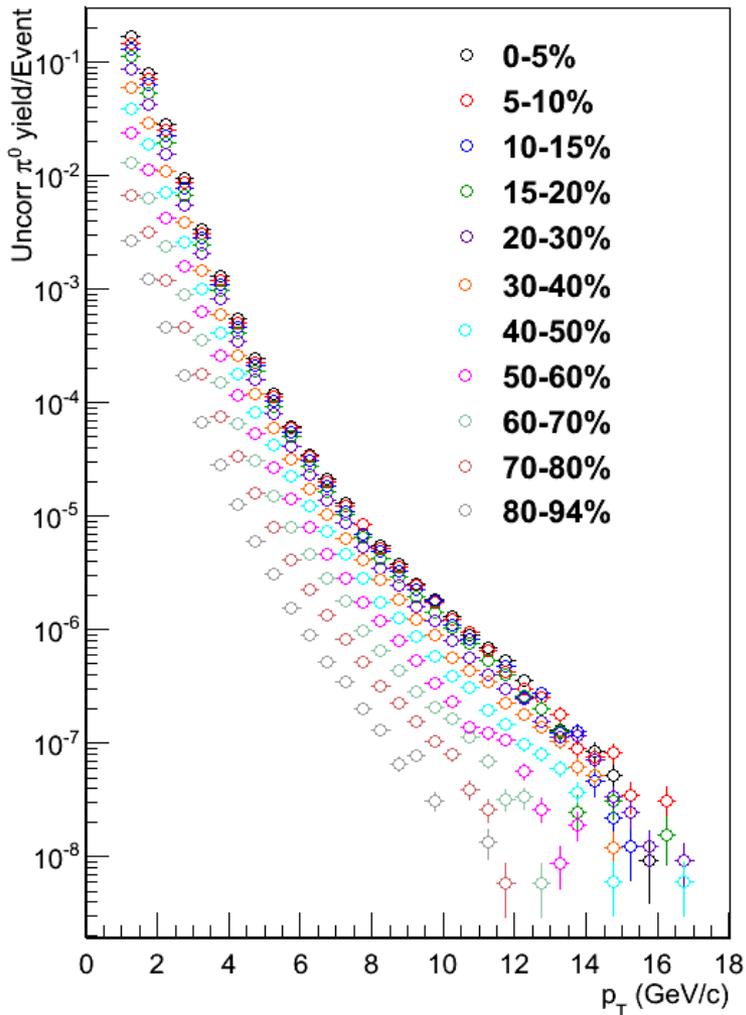


# $\pi^\pm$ $R_{AA}$ in Cu+Au

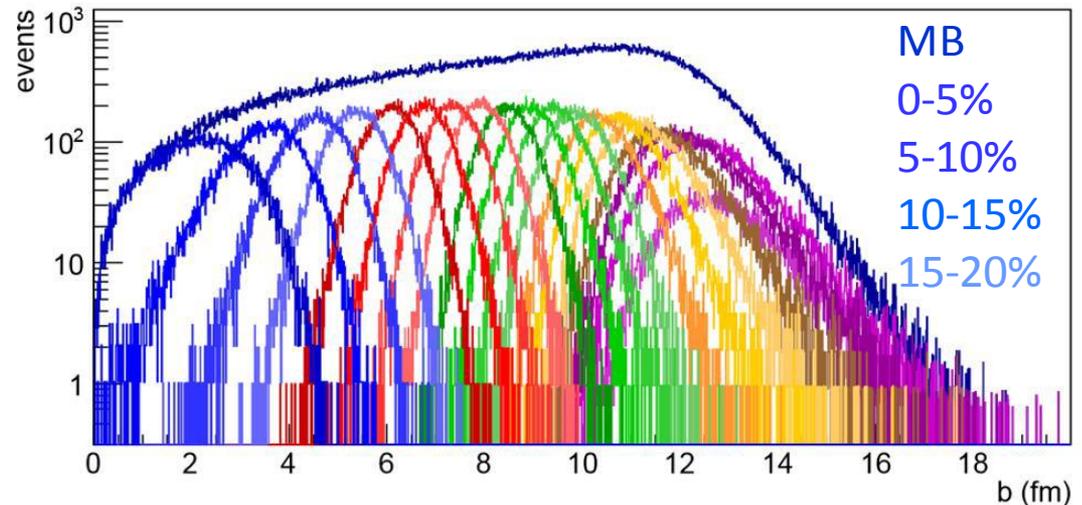


- Cu+Au charged pion  $R_{AB}$  agrees with Au+Au  $R_{AB}$  at similar  $N_{Part}$  or  $N_{Coll}$
- Does this hold at higher  $p_T$ ?

# Uncorrected pion yields in Cu+Au centrality bins

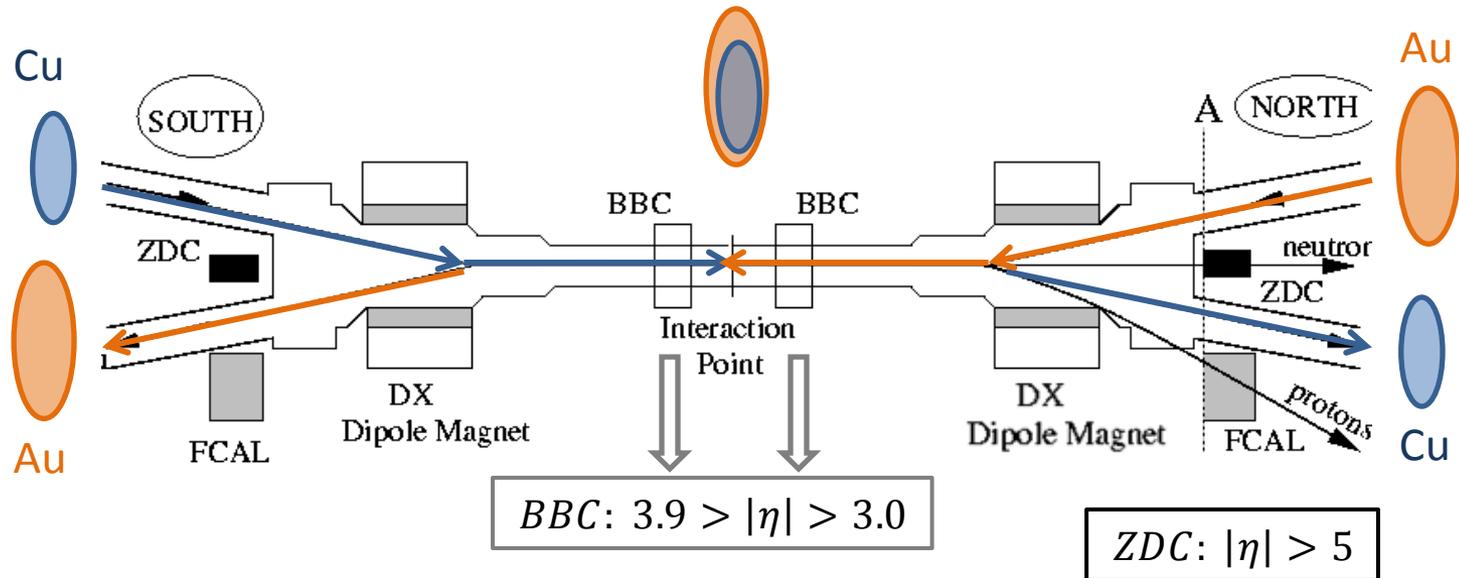


- Able to reach  $p_T \sim 10-15$  GeV/c
- Fine centrality bins



- Efficiency corrections not yet determined

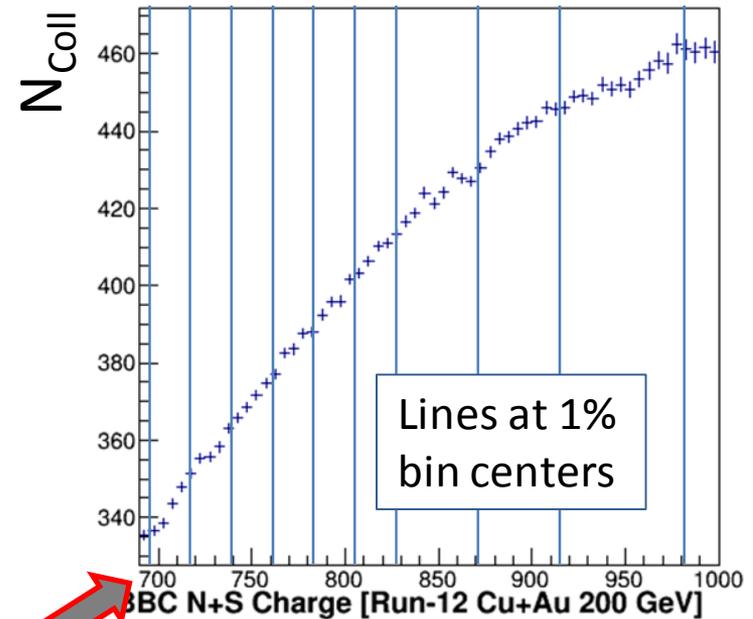
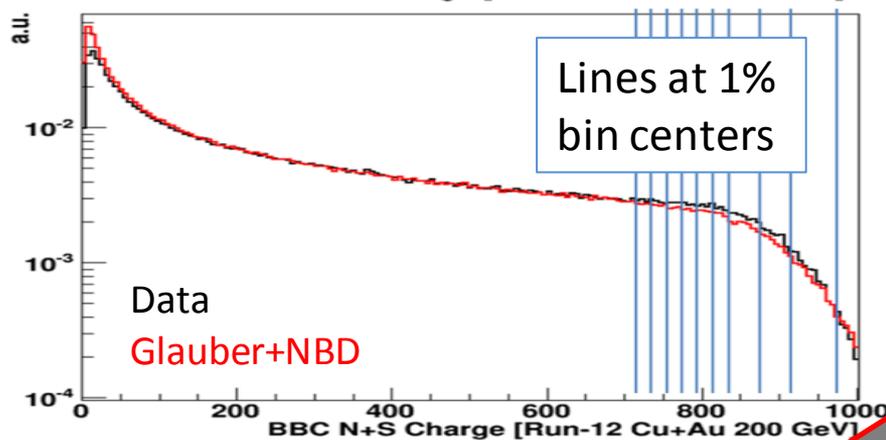
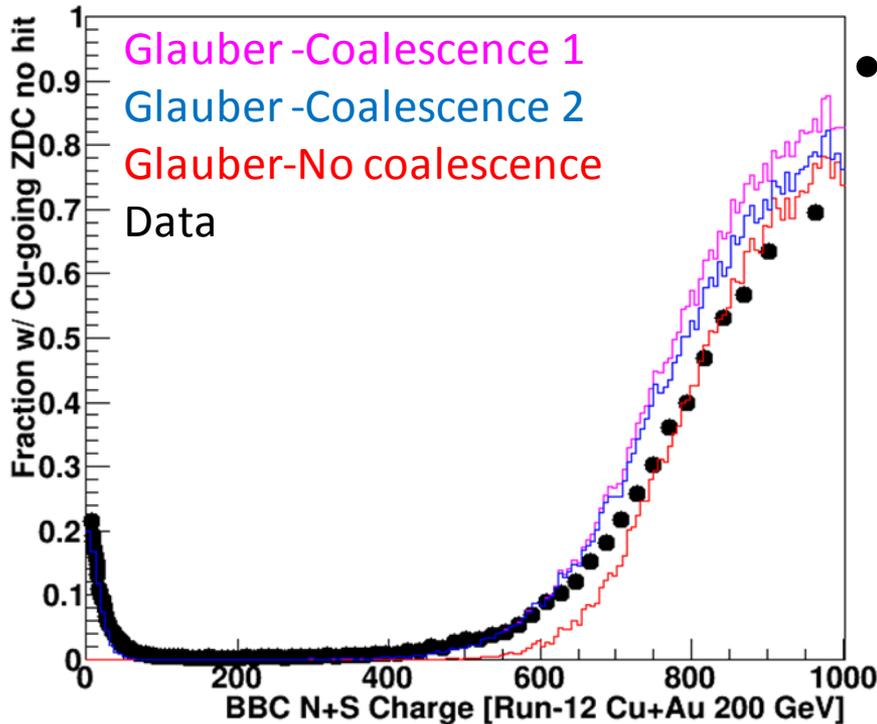
# Cu embedded in the Au-nucleus



- In events where the Cu is embedded in the Au nucleus, there should be very few hits in the North ZDC

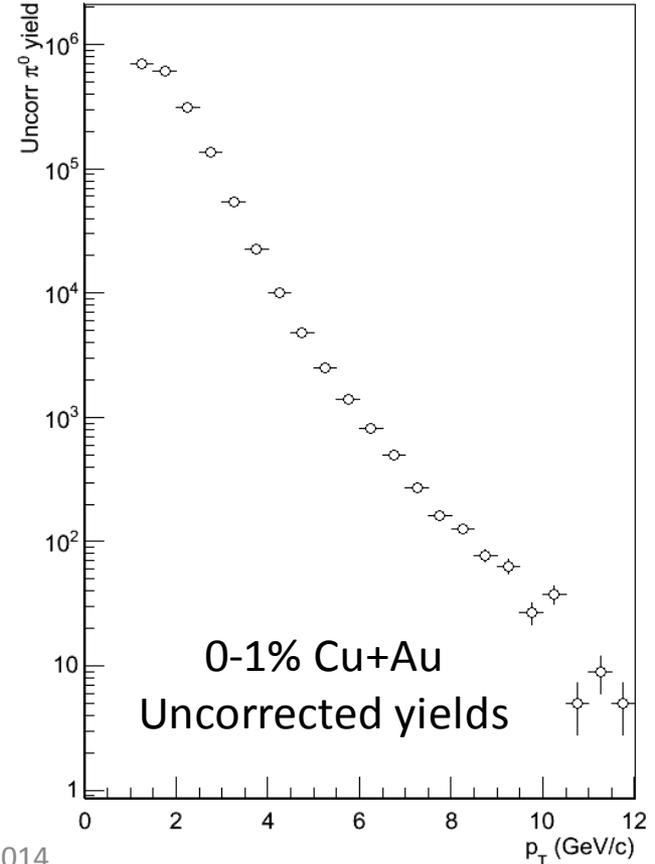
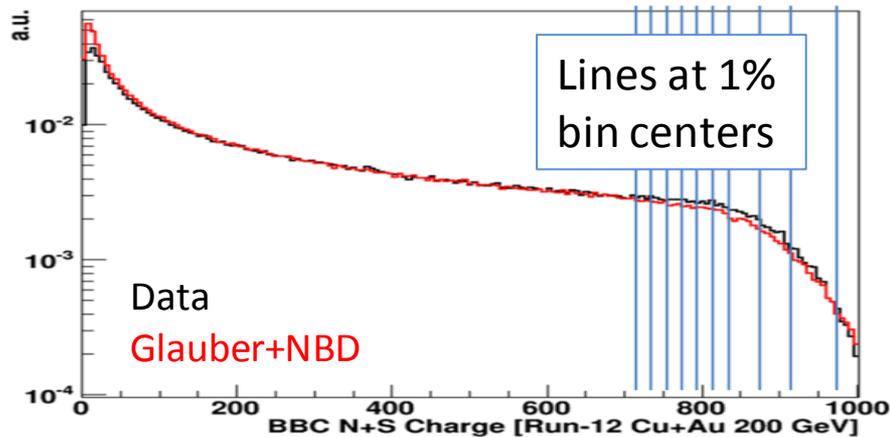
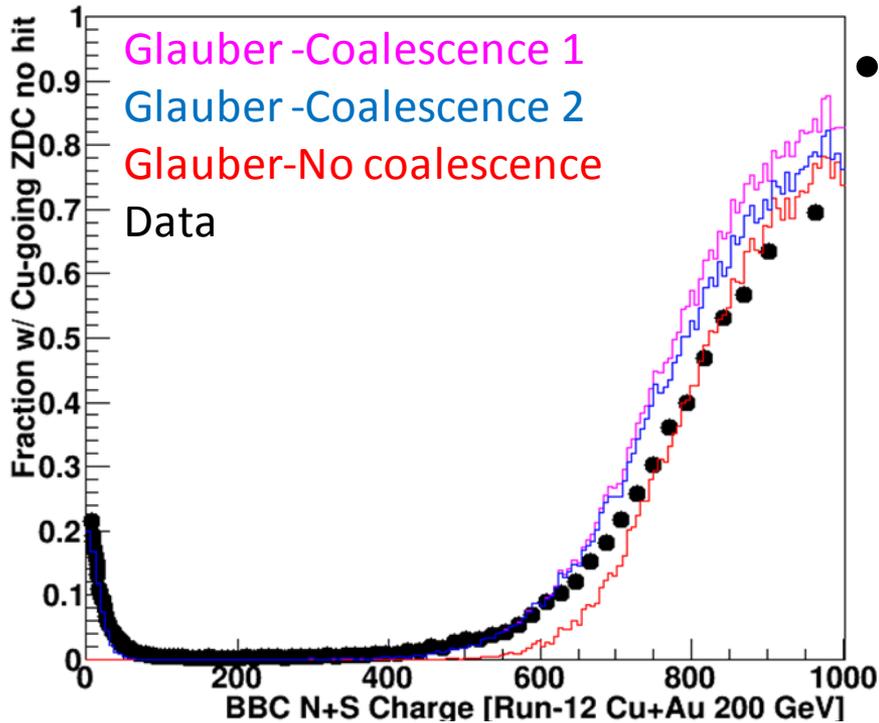
# Cu embedded in the Au-nucleus

- ~70% of events in the 0-1% centrality bin have no hits in the Cu-going ZDC

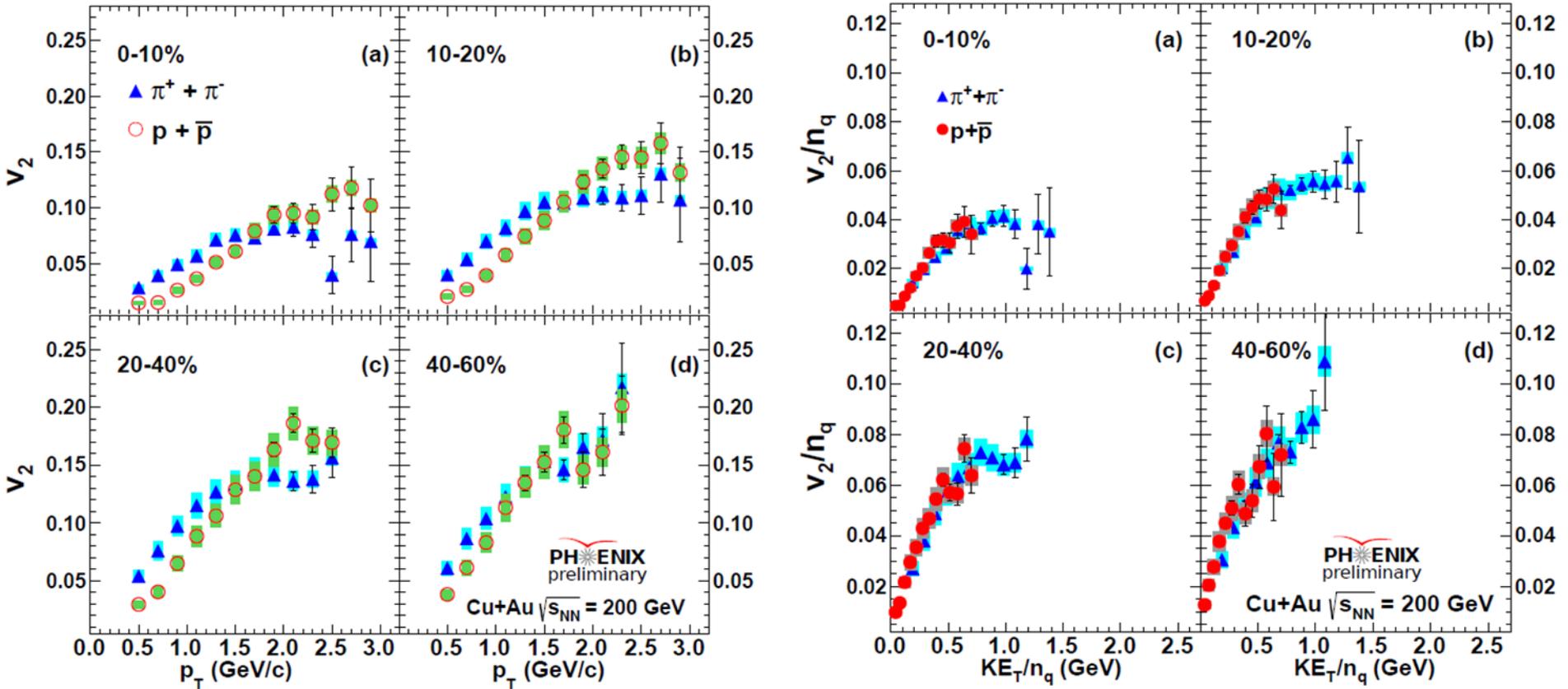


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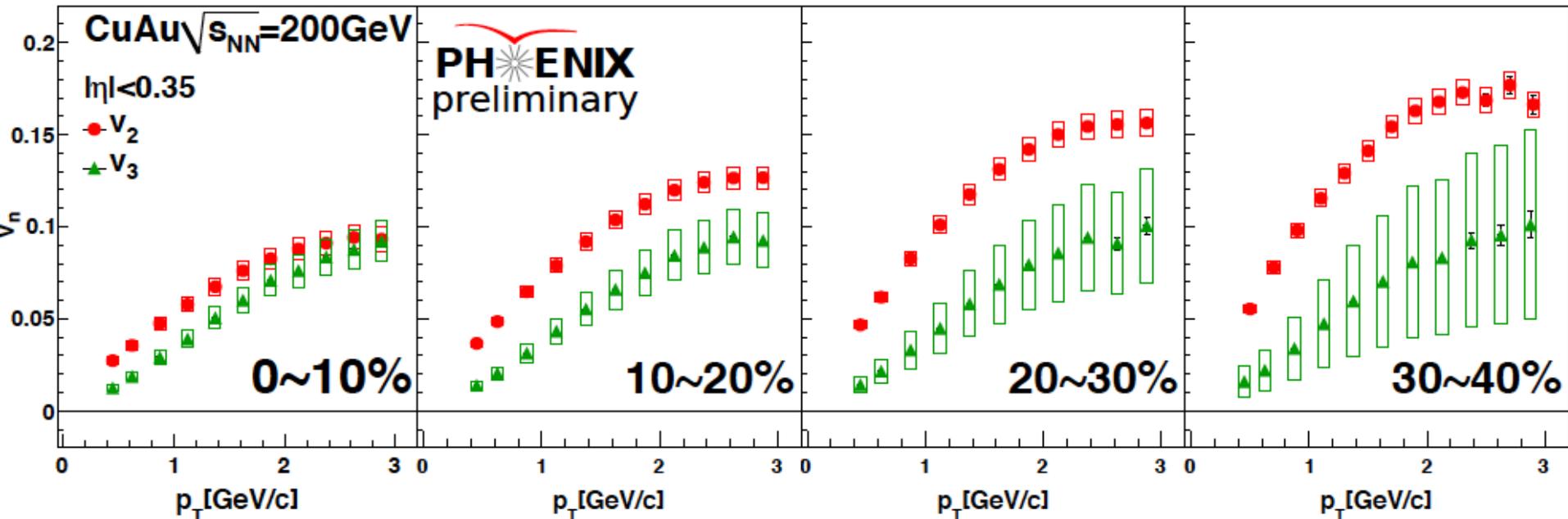


# $\pi^\pm v_2$ in Cu+Au



- $\pi^\pm, p v_2$  follow  $n_q$ -scaling

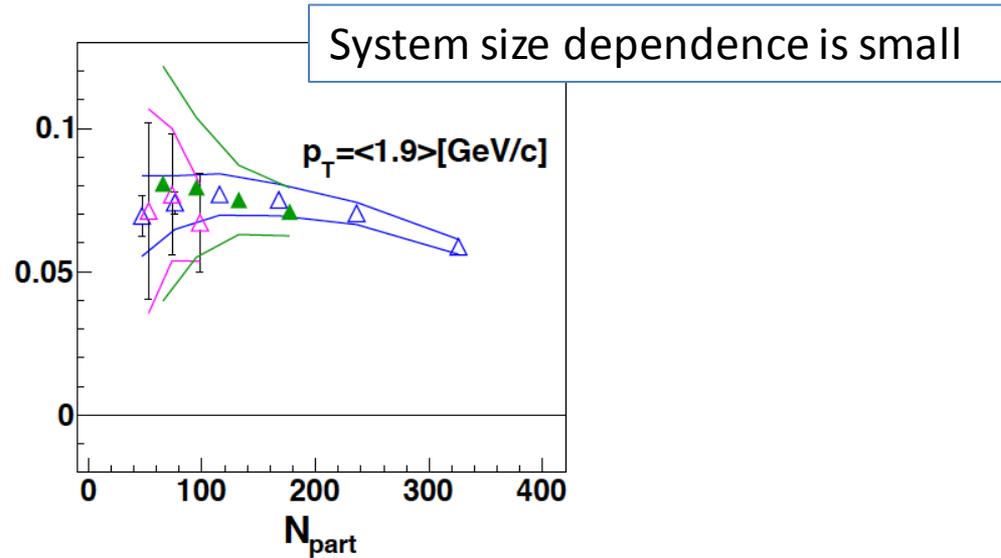
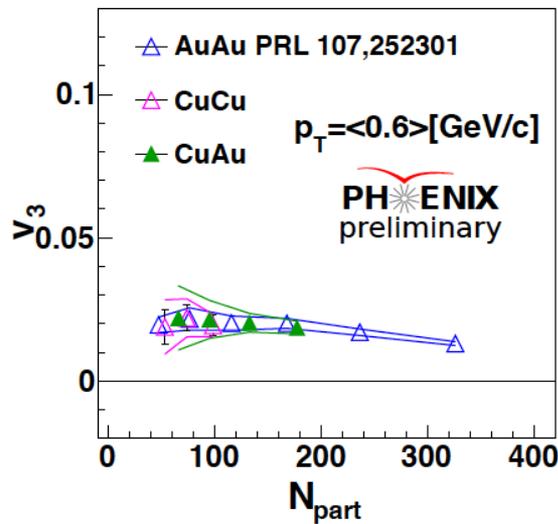
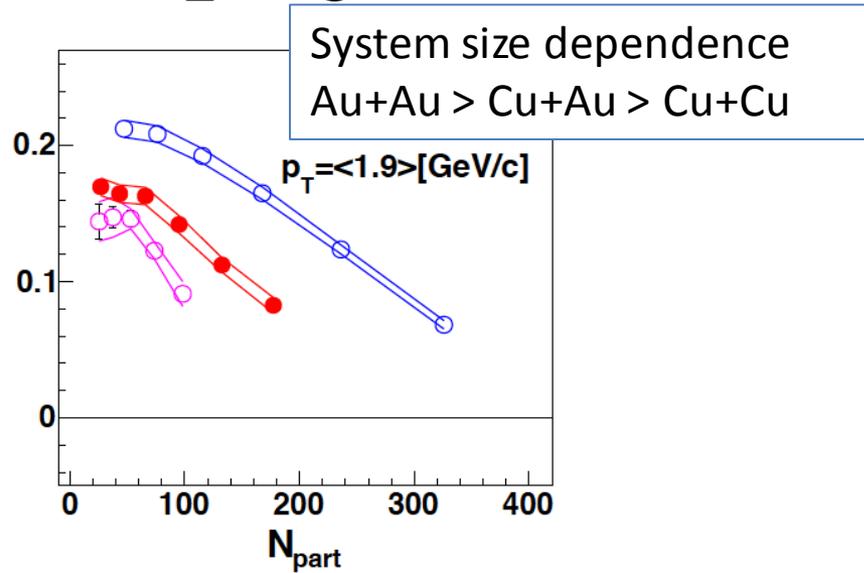
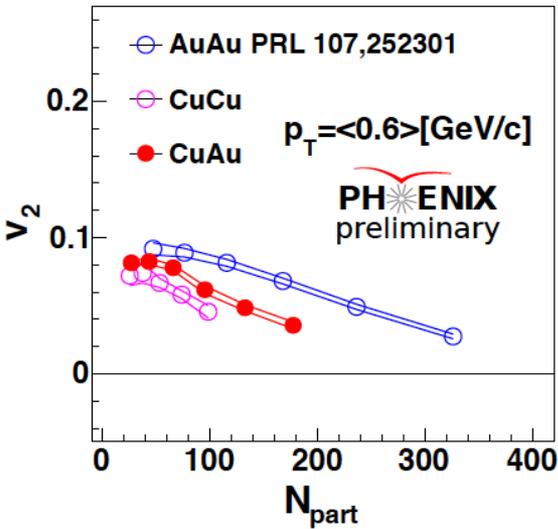
# $h^\pm$ $v_2$ and $v_3$ in Cu+Au



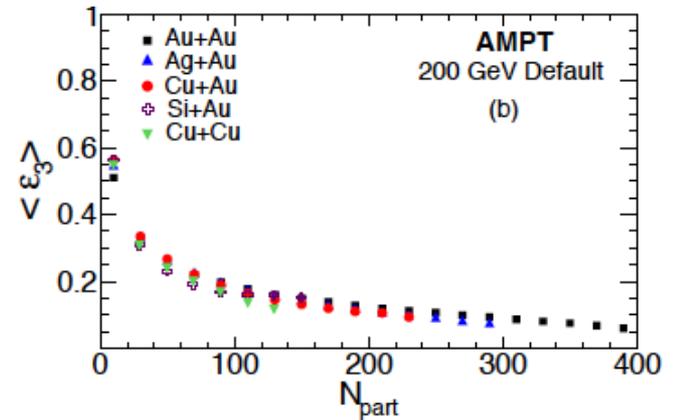
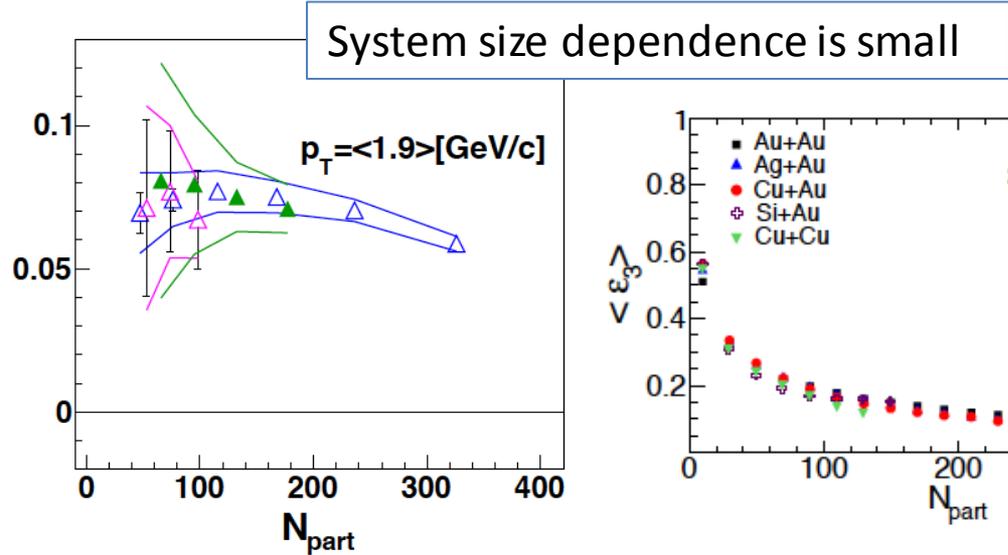
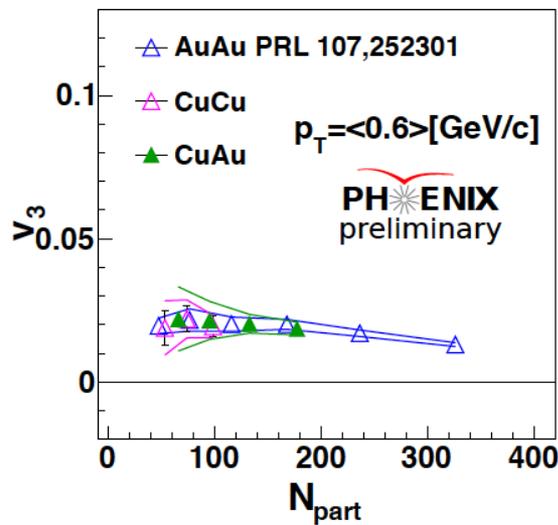
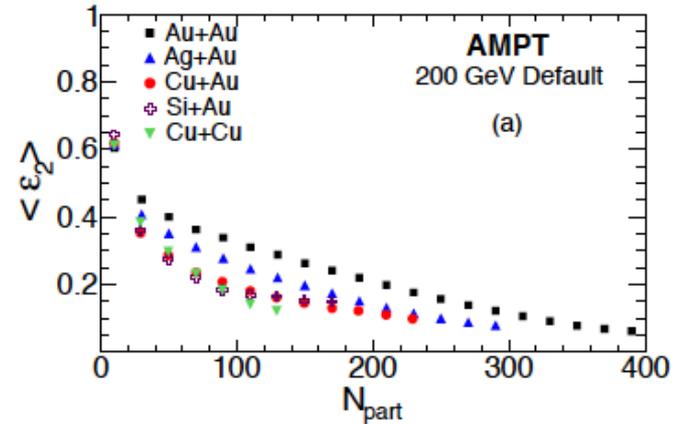
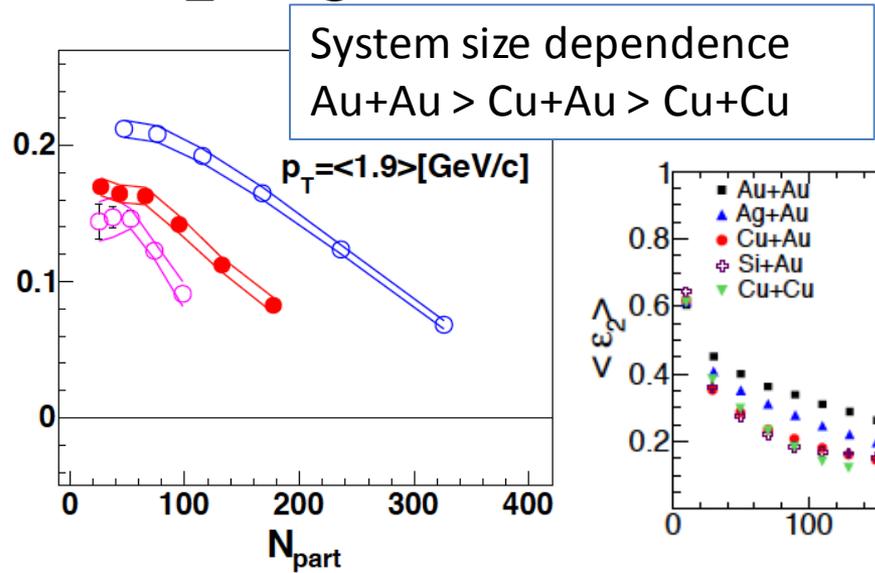
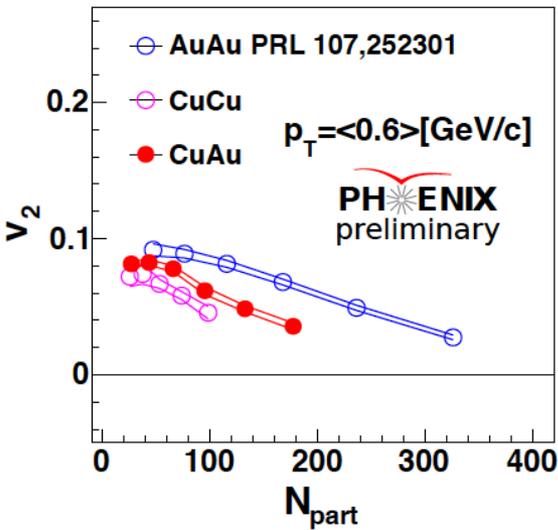
- $v_2 \rightarrow$  clear centrality dependence
- $v_3 \rightarrow$  no significant centrality dependence

Similar to Au+Au behavior

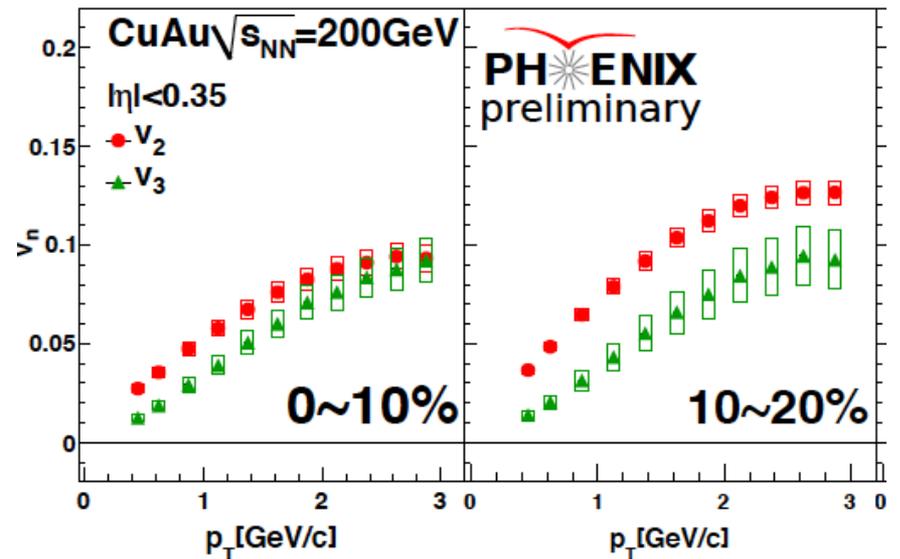
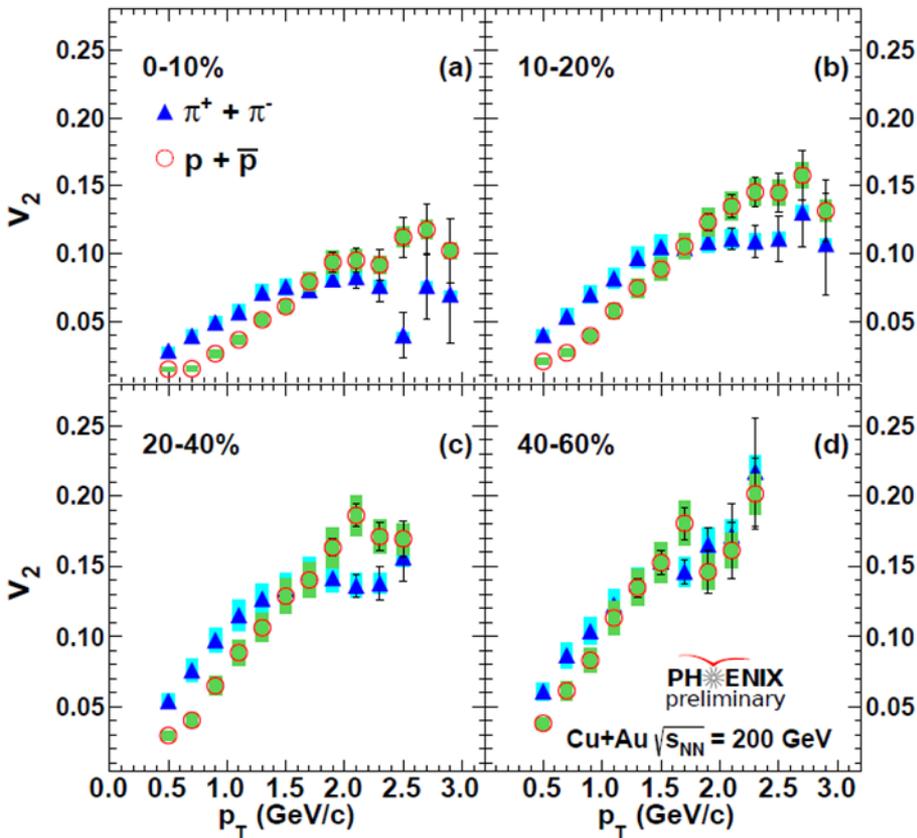
# Comparing $h^\pm v_2, v_3$ to other systems



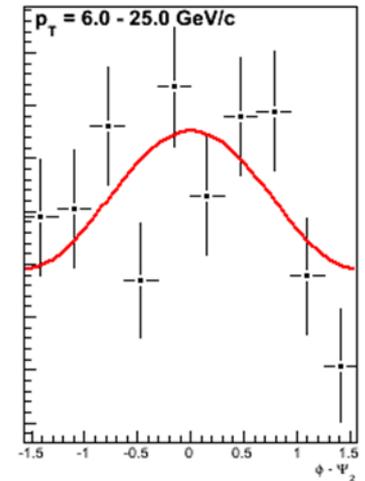
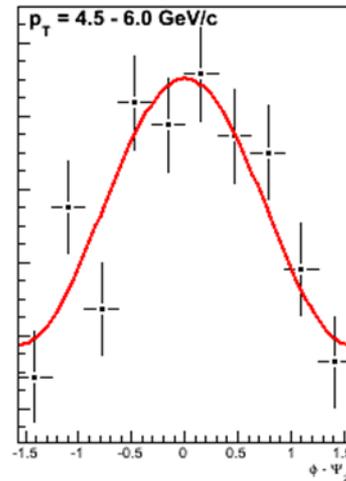
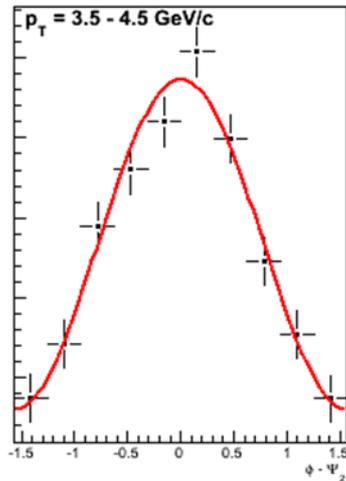
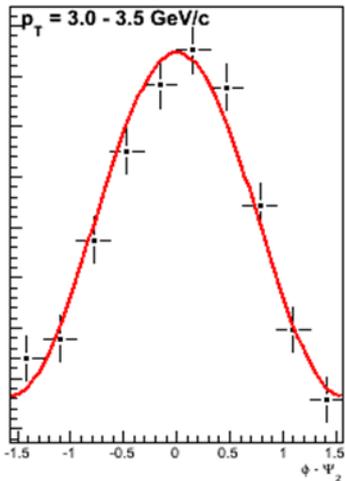
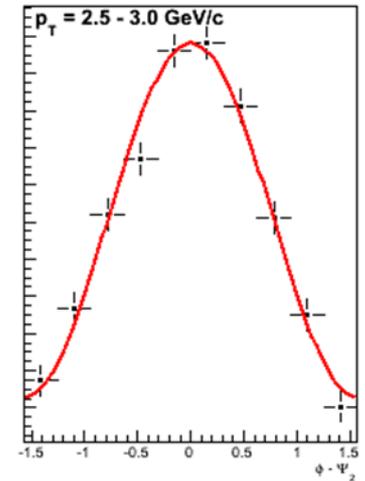
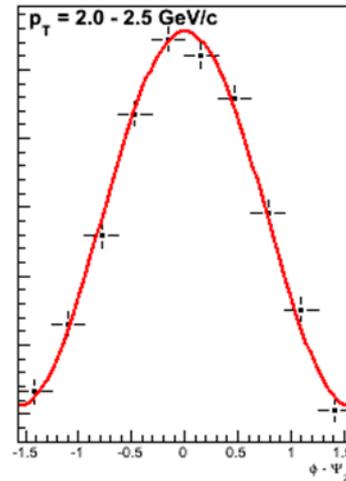
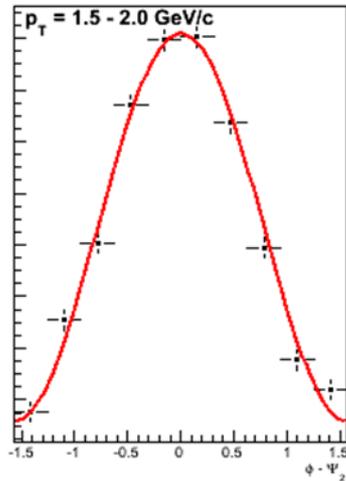
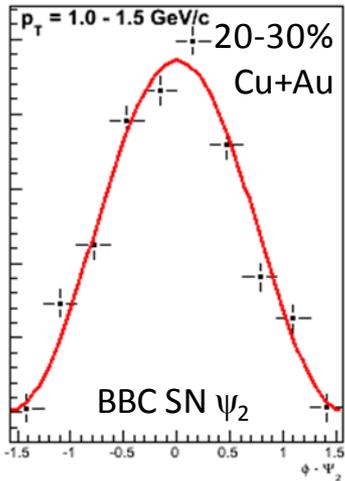
# Comparing $h^\pm v_2, v_3$ to other systems



# $\pi^\pm$ and $h^\pm$ $v_2$ at $p_T < 3$ GeV/c

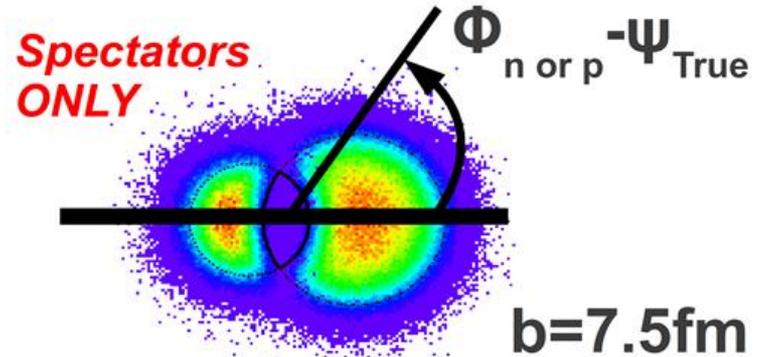
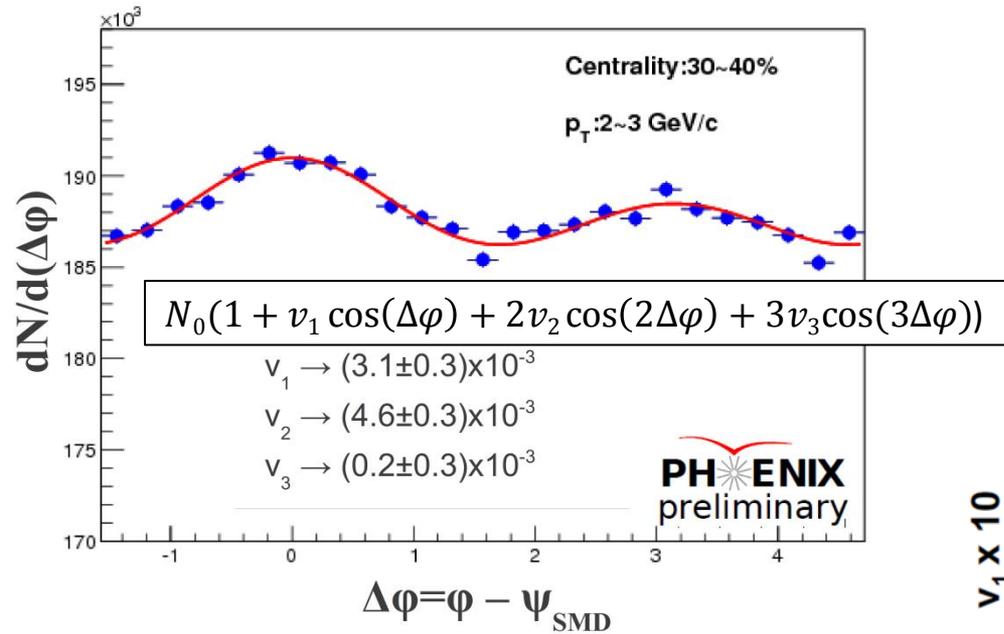


# $\pi^0$ azimuthal distributions w.r.t. $\psi_2$

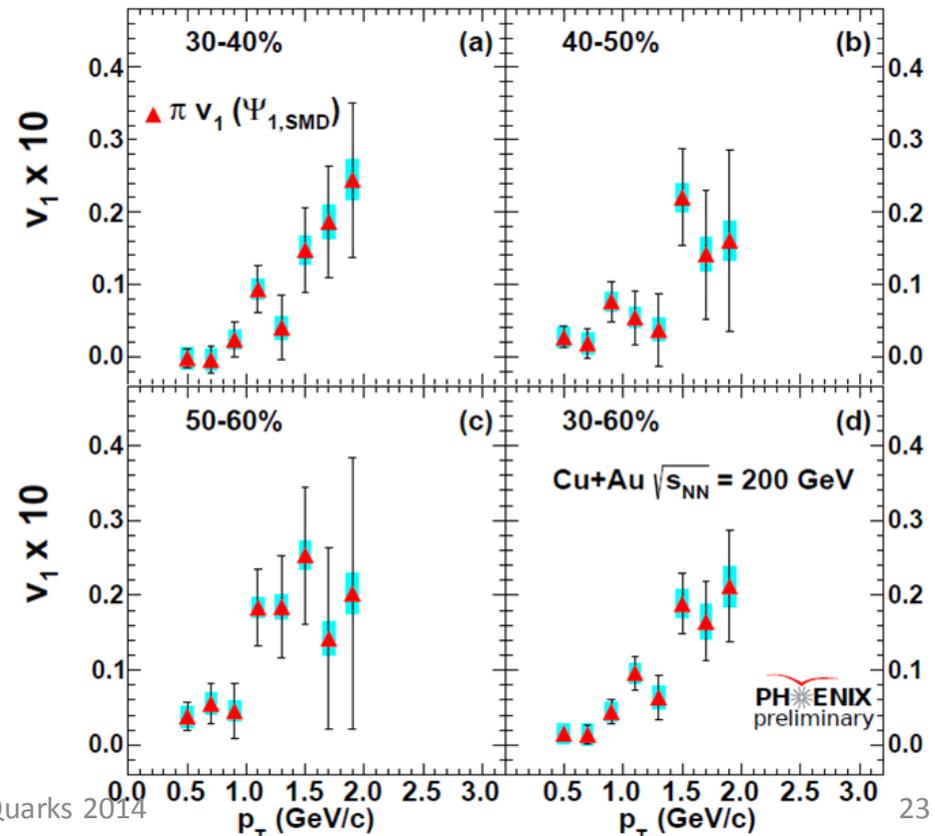


- $p_T$  reach out to  $\sim 6 \text{ GeV}$  in Cu+Au

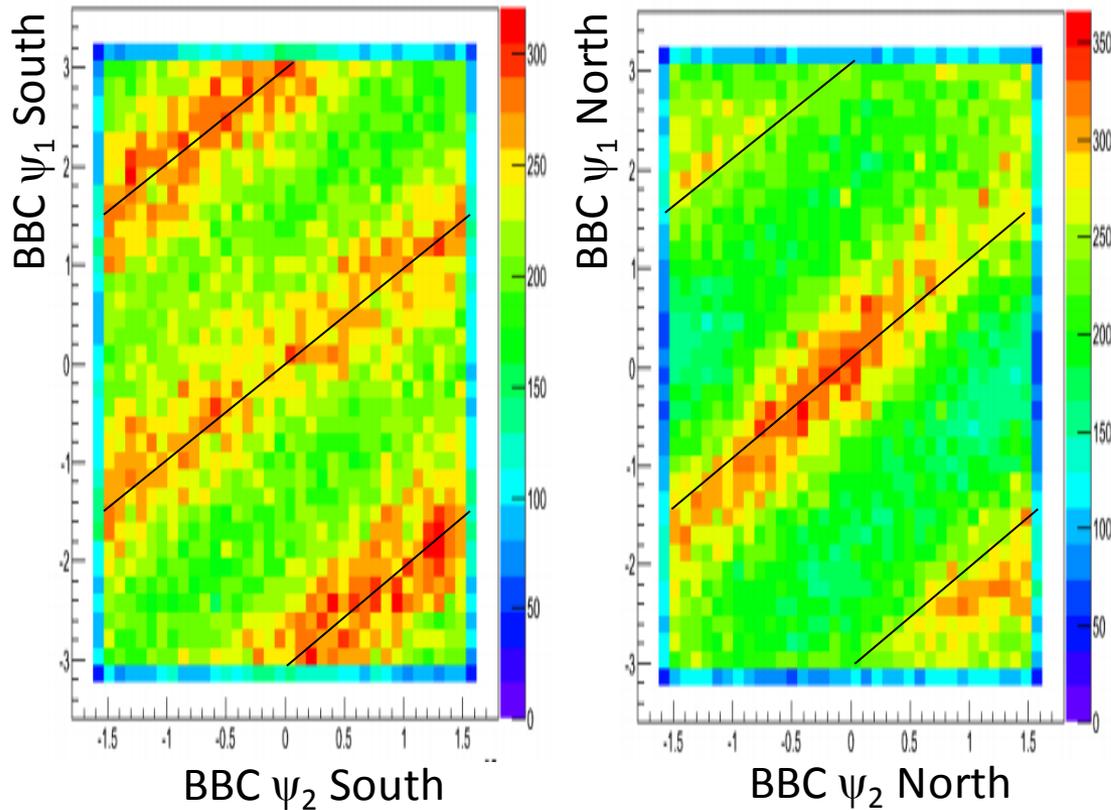
# Odd Harmonics of $\pi^\pm$ in Cu+Au



- Using SMD South  $\psi_1$  plane can measure odd harmonics
- $v_3$  small
- $v_1 > 0 \rightarrow$  More particles emitted from Au-side



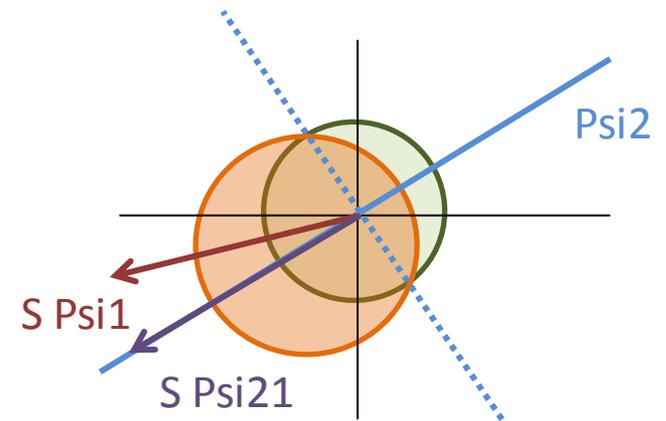
# BBC $\psi_2$ and $\psi_1$ planes



- $\psi_2$  and  $\psi_1$  are correlated:

- $\psi_1 = \psi_2$

- $\psi_1 = \psi_2 \pm \pi$



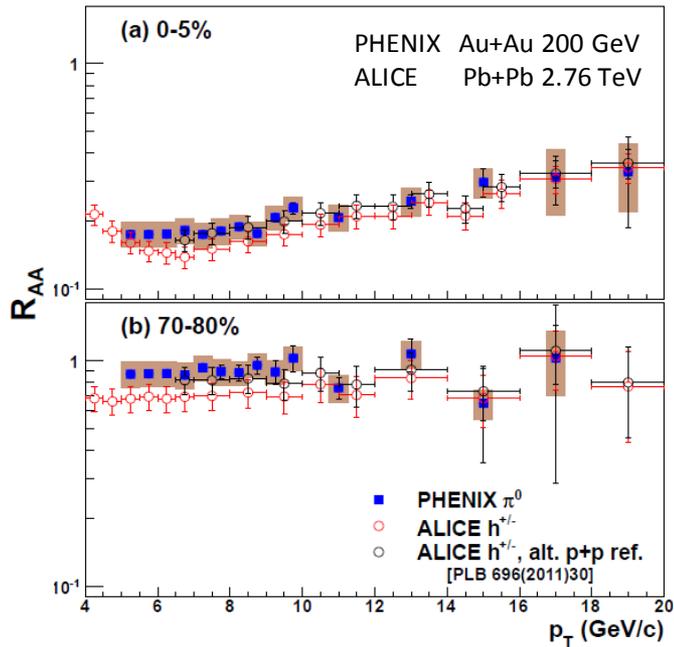
- Create  $\psi_{21}$  to resolve Cu+Au vs Au+Cu left-right asymmetry in  $\psi_2$  plane
  - BBC  $\psi_2$  with BBC  $\psi_1$  South pointing in the Au direction
  - Benefit from good BBC  $\psi_2$  resolution

# Conclusions

- In Au+Au:
  - At RHIC,  $\pi^0$  energy loss has an  $\sim L^3$  dependence
- In Cu+Au:
  - Higher energy densities
  - $\pi^\pm$ ,  $h^\pm$   $v_3$  small and  $\pi^\pm$   $v_1 > 0$  at central rapidity
    - more charged pions emitted from the Au-side
  - $\pi^0$  will extend out to higher  $p_T$ 
    - $\sim 10$  GeV/c in  $R_{AA}$ ,  $\sim 6$  GeV/c in  $v_2$
- Future of  $\pi^0$  analysis
  - Working on simulations
  - Finalizing  $v_2$ , extracting odd harmonics

# Back up

# The limitations of $R_{AA}$



$$R_{AA}^{RHIC} \approx R_{AA}^{LHC}$$

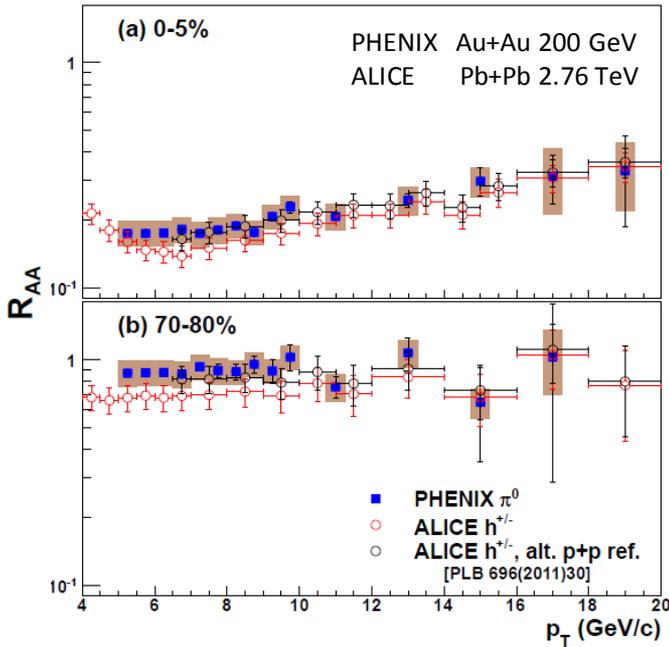
**BUT**

**Energy loss is not the same**

RHIC and LHC  $p_T$  spectra have different shapes, powers

# Fractional momentum loss, $S_{loss}$

- $S_{loss} \rightarrow$  How much does the parton's momentum change in the medium?



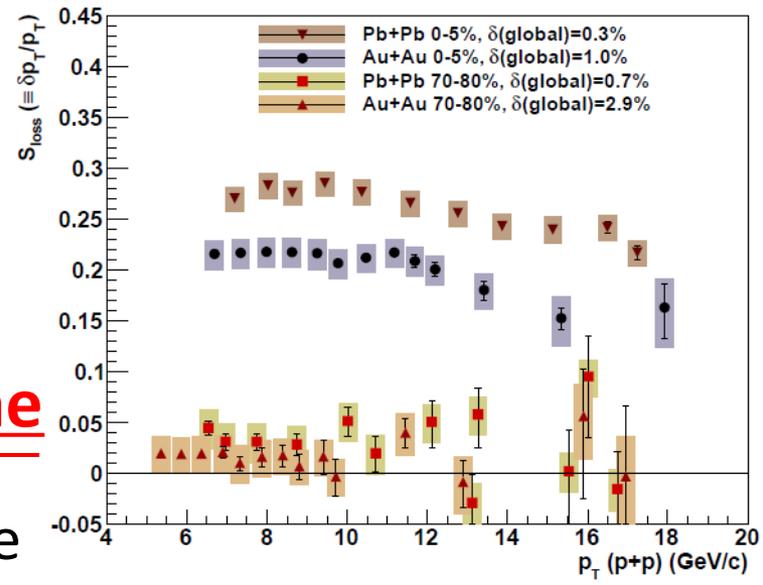
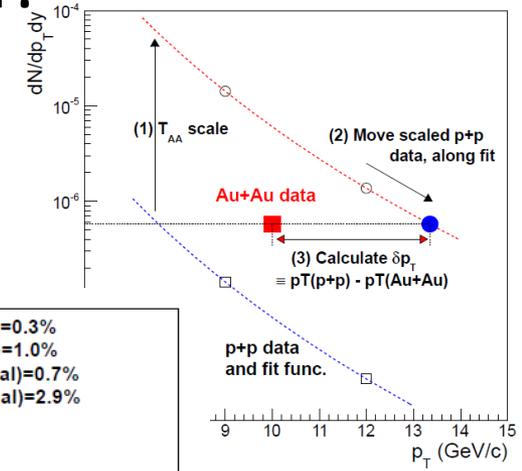
$$R_{AA}^{RHIC} \approx R_{AA}^{LHC}$$

**BUT**

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RHIC and LHC  $p_T$  spectra have different shapes, powers

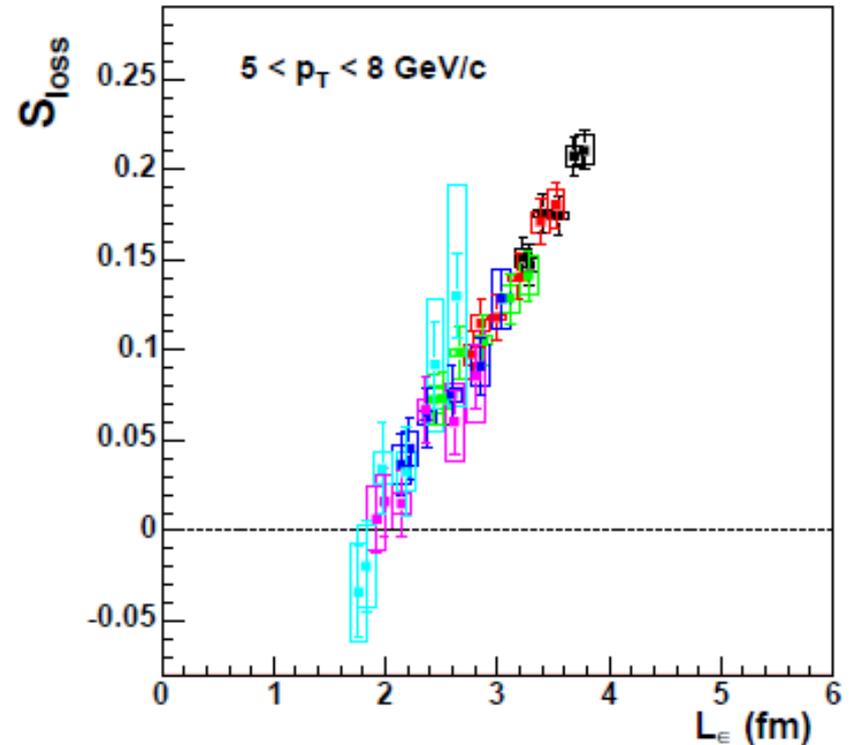
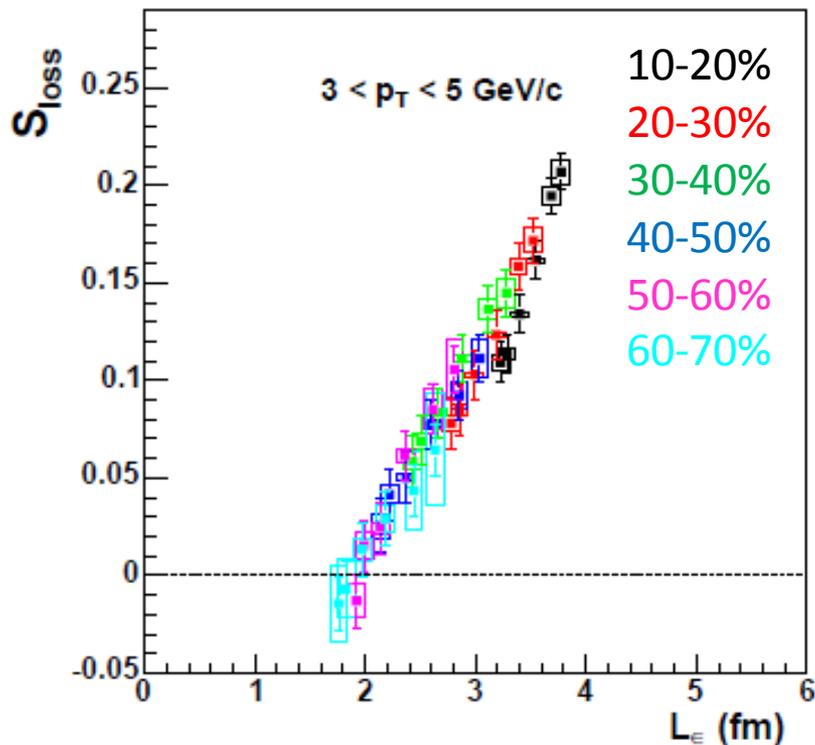
$$S_{loss} = \frac{p_T^{pp} - p_T^{AA}}{p_T^{pp}}$$



# $S_{\text{loss}}$ path length dependence

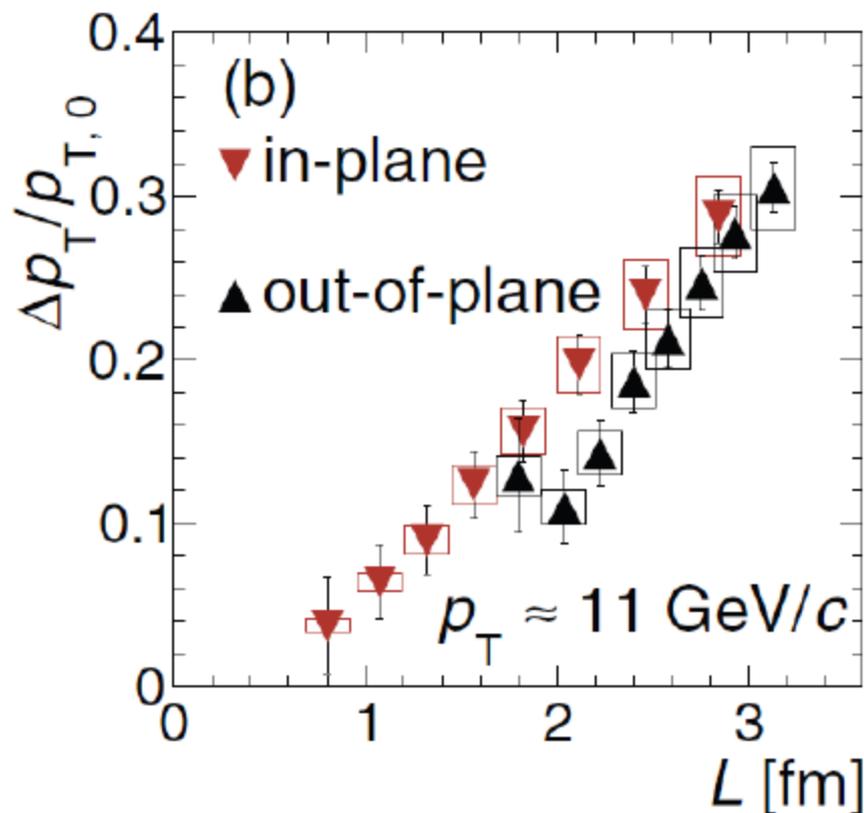
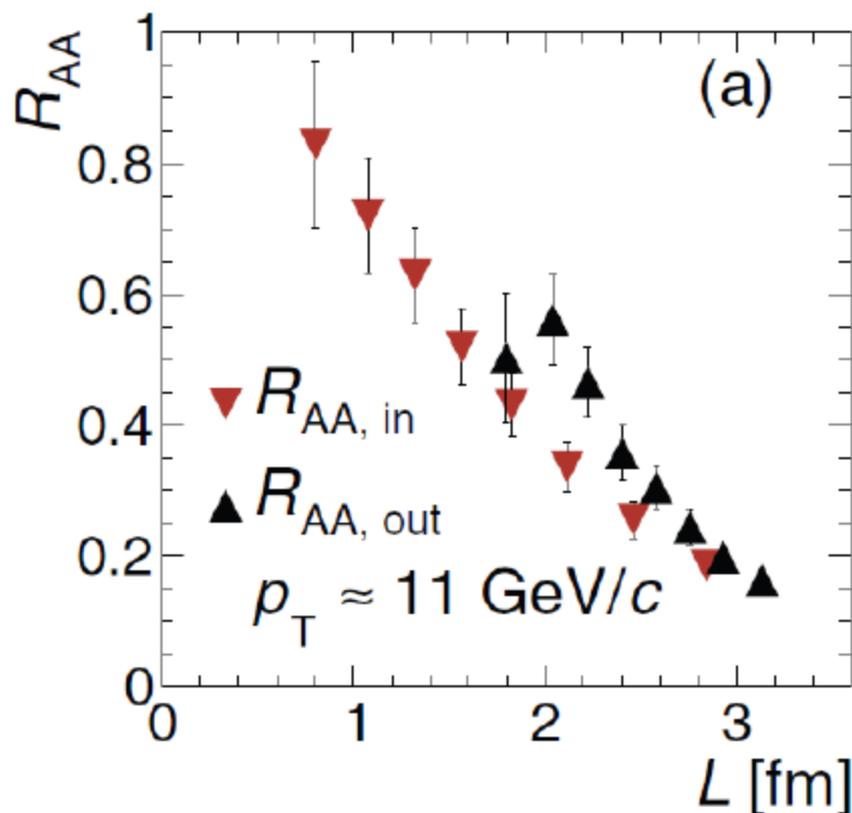
- $L_\epsilon \rightarrow$  path from center of an ellipse (defined by  $\epsilon$ ,  $b$ ) to the edge at an angle of  $\Delta\phi$

$$L_\epsilon = \frac{b\sqrt{1+\epsilon}}{\sqrt{1+\epsilon \cos(2\Delta\phi)}}$$



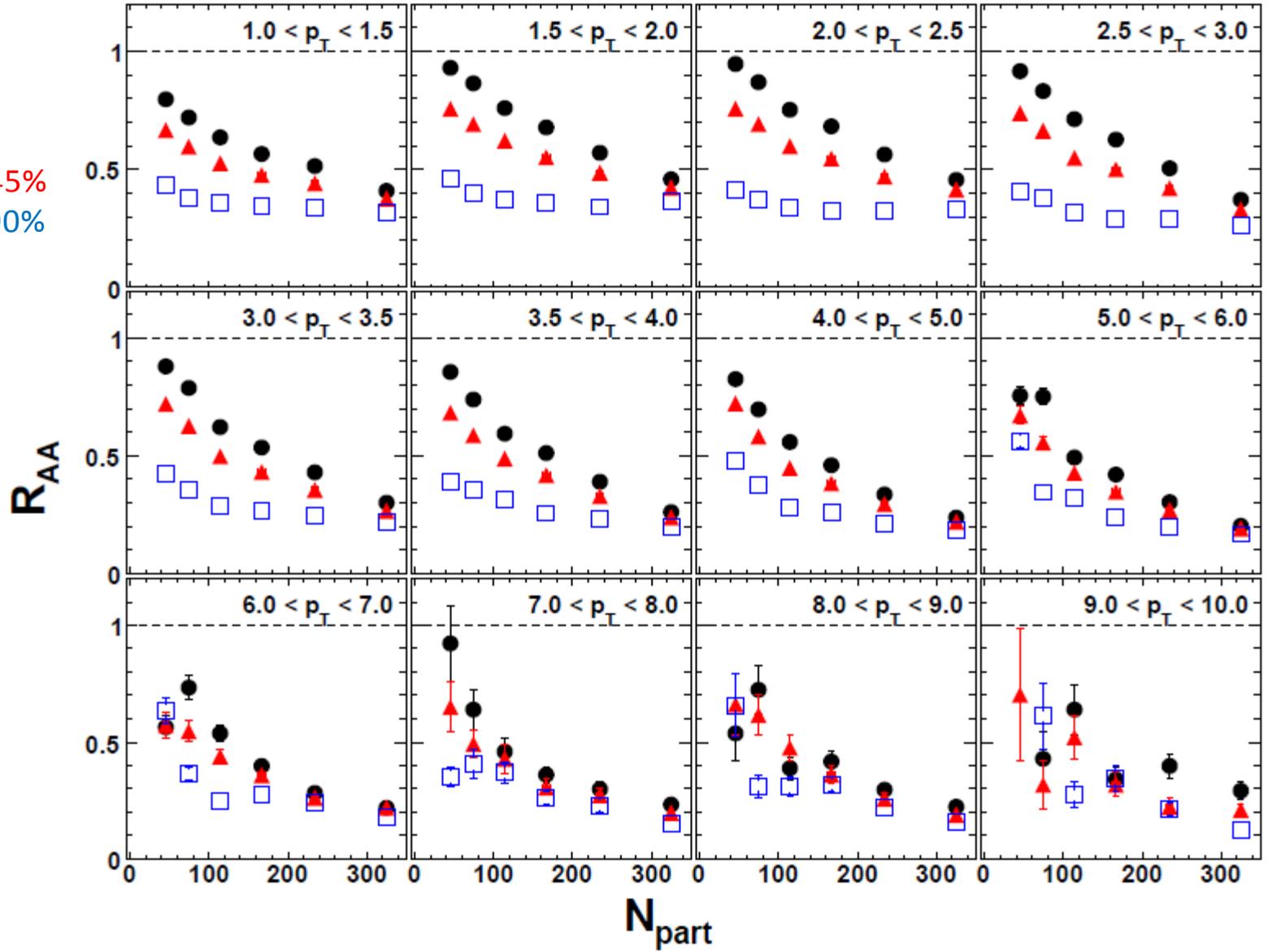
# ALICE recently performed similar study

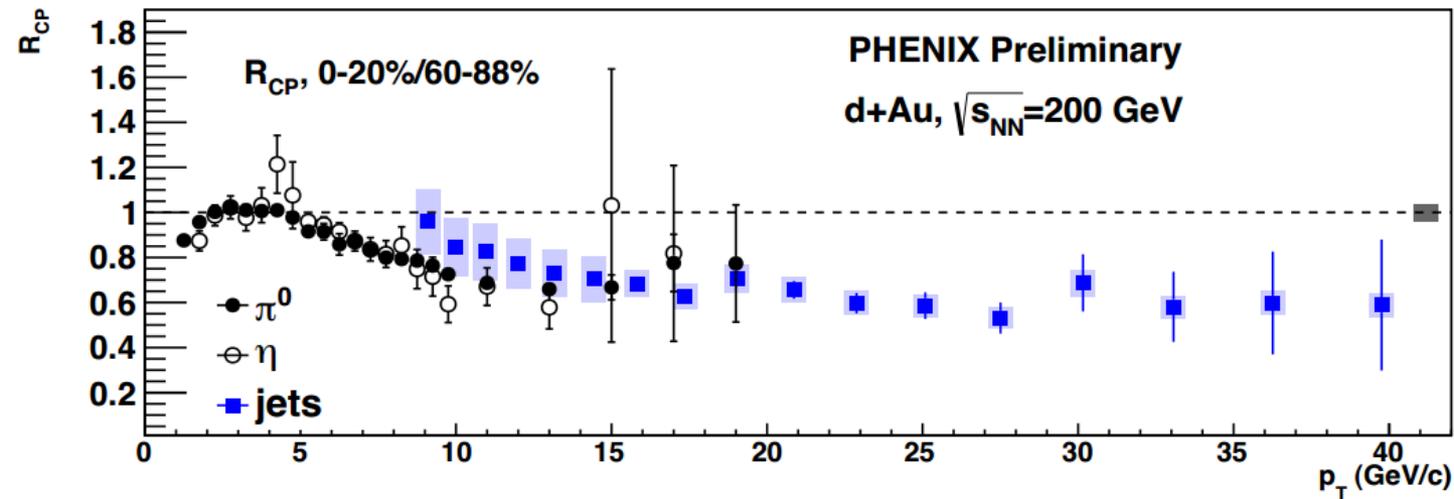
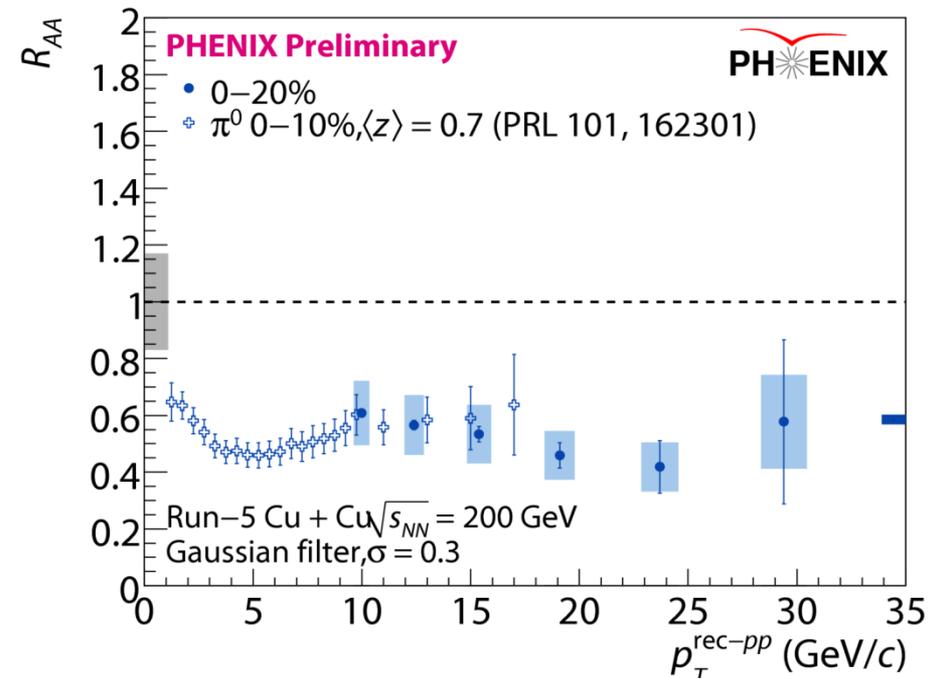
- Using Pb+Pb 2.76TeV data (ALICE).  $L$  should be equivalent to the  $L_\varepsilon$  in the previous slide
- $L$  is not very good at higher  $p_T$ ?



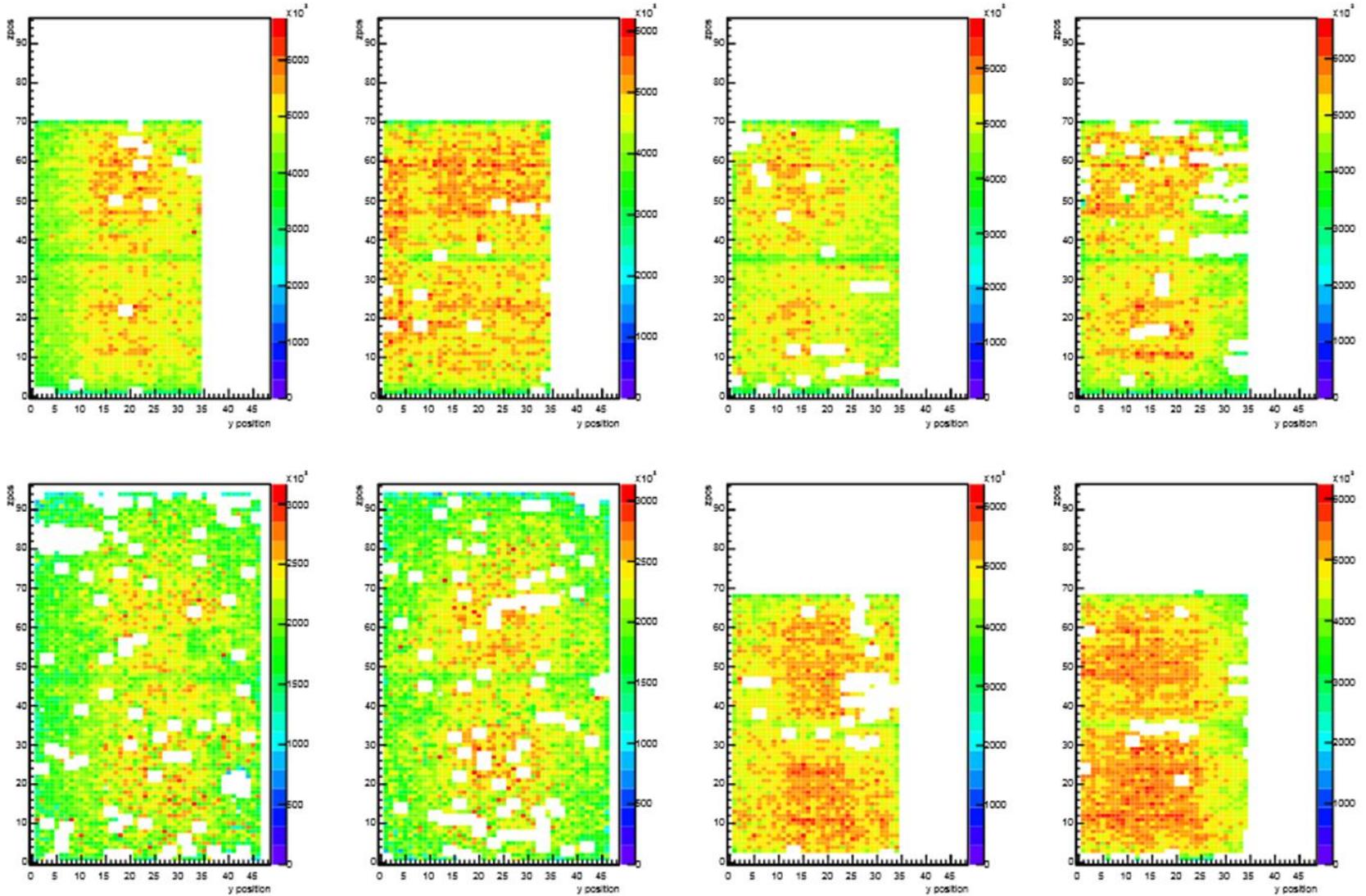
P. Christiansen, K. Tywoniuk, and V. Vislavicius, PRC 89, 034912 (2014)

In plane 0-15%  
 Mid-plane 30-45%  
 Out-plane 75-90%

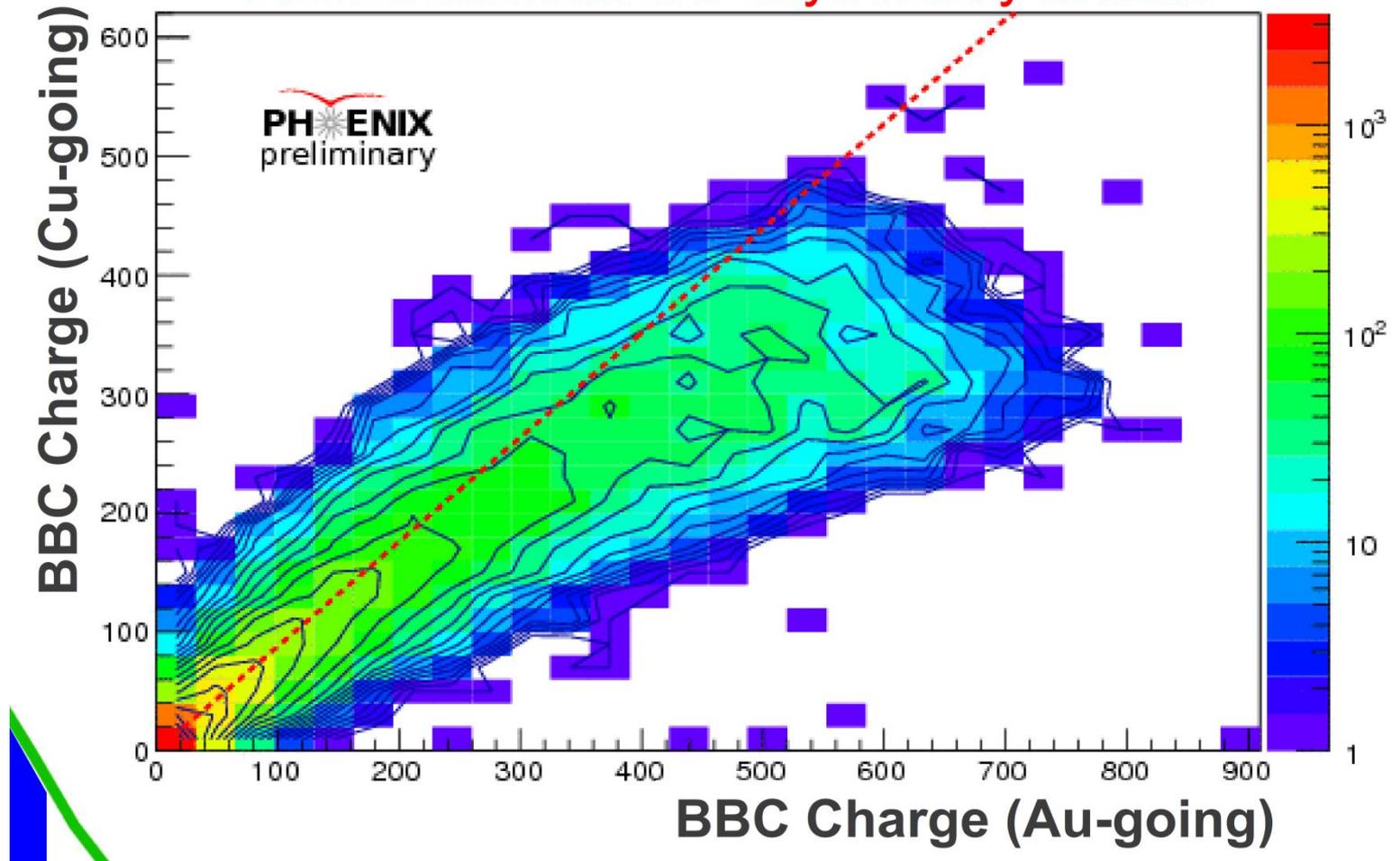


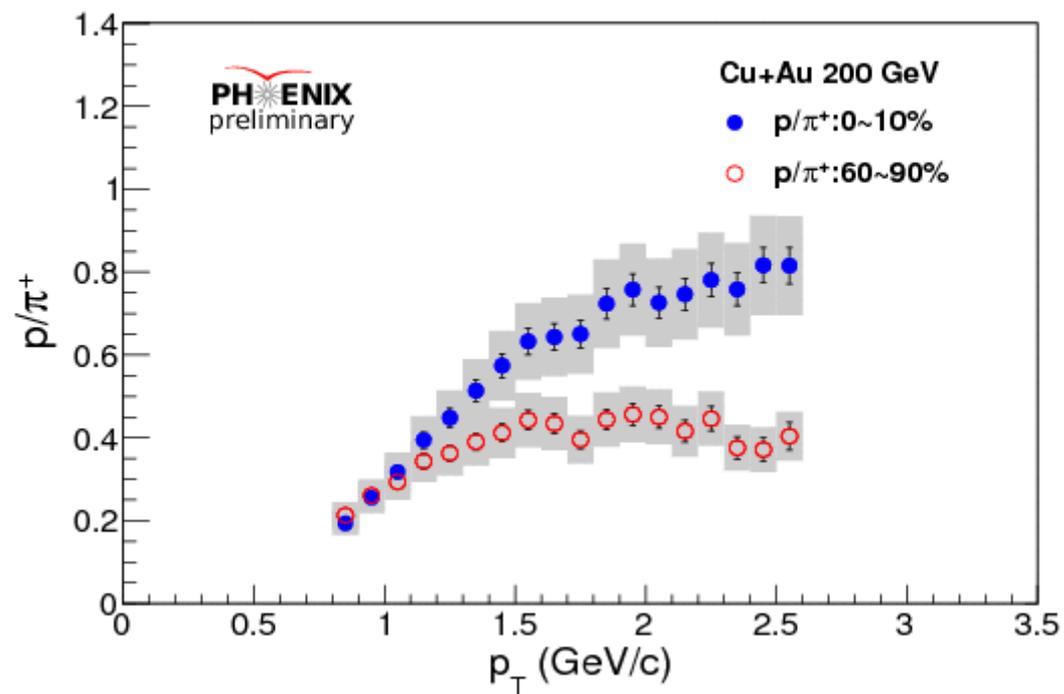
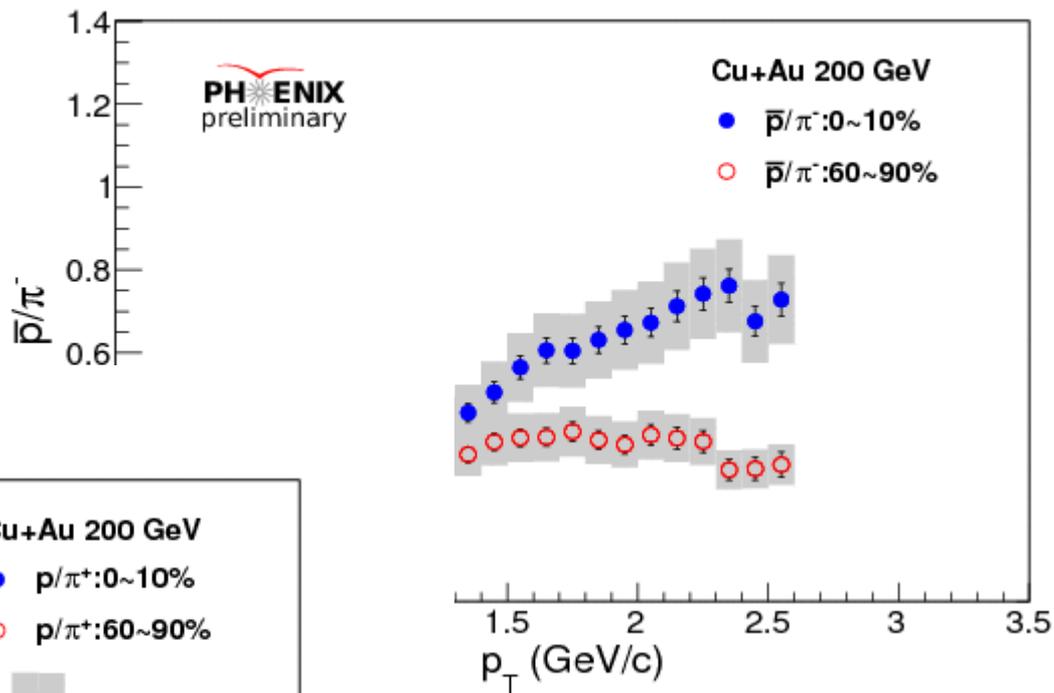


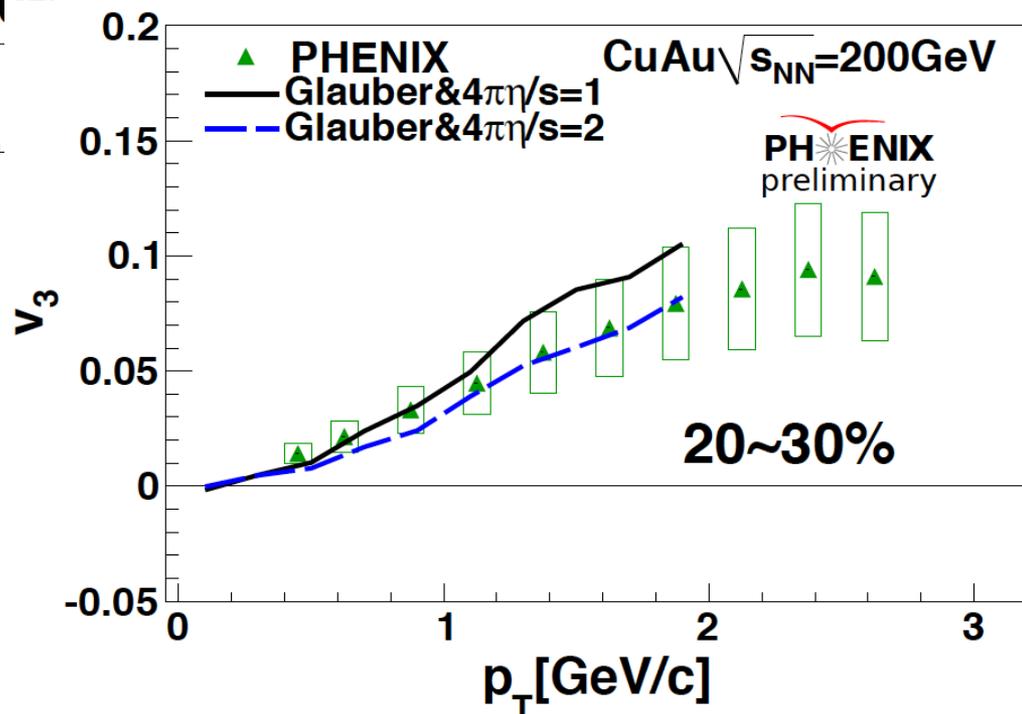
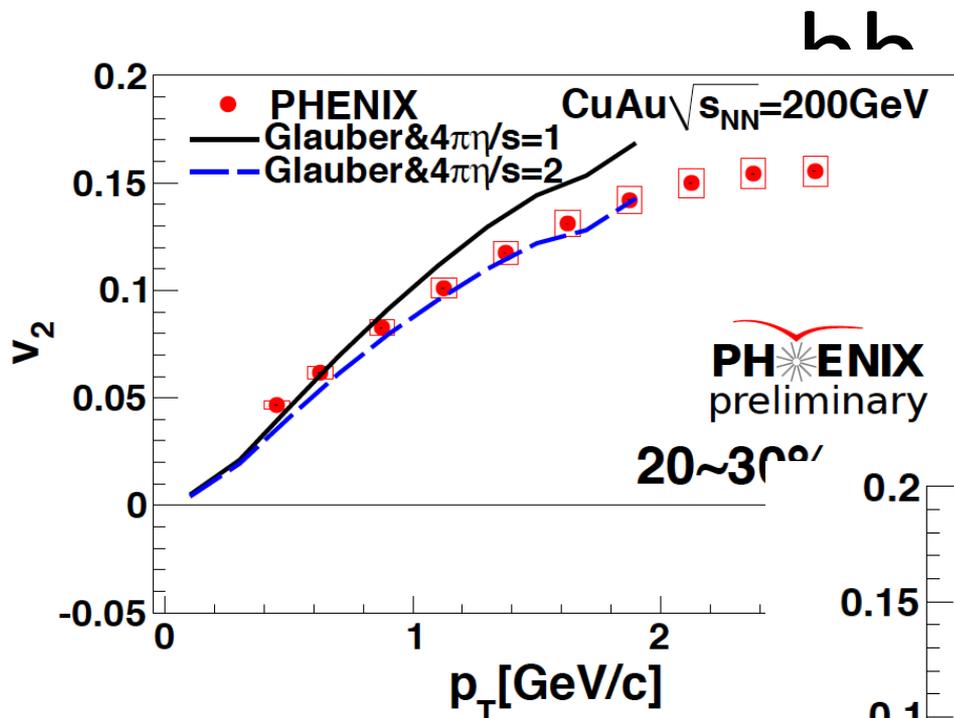
# deadmaps

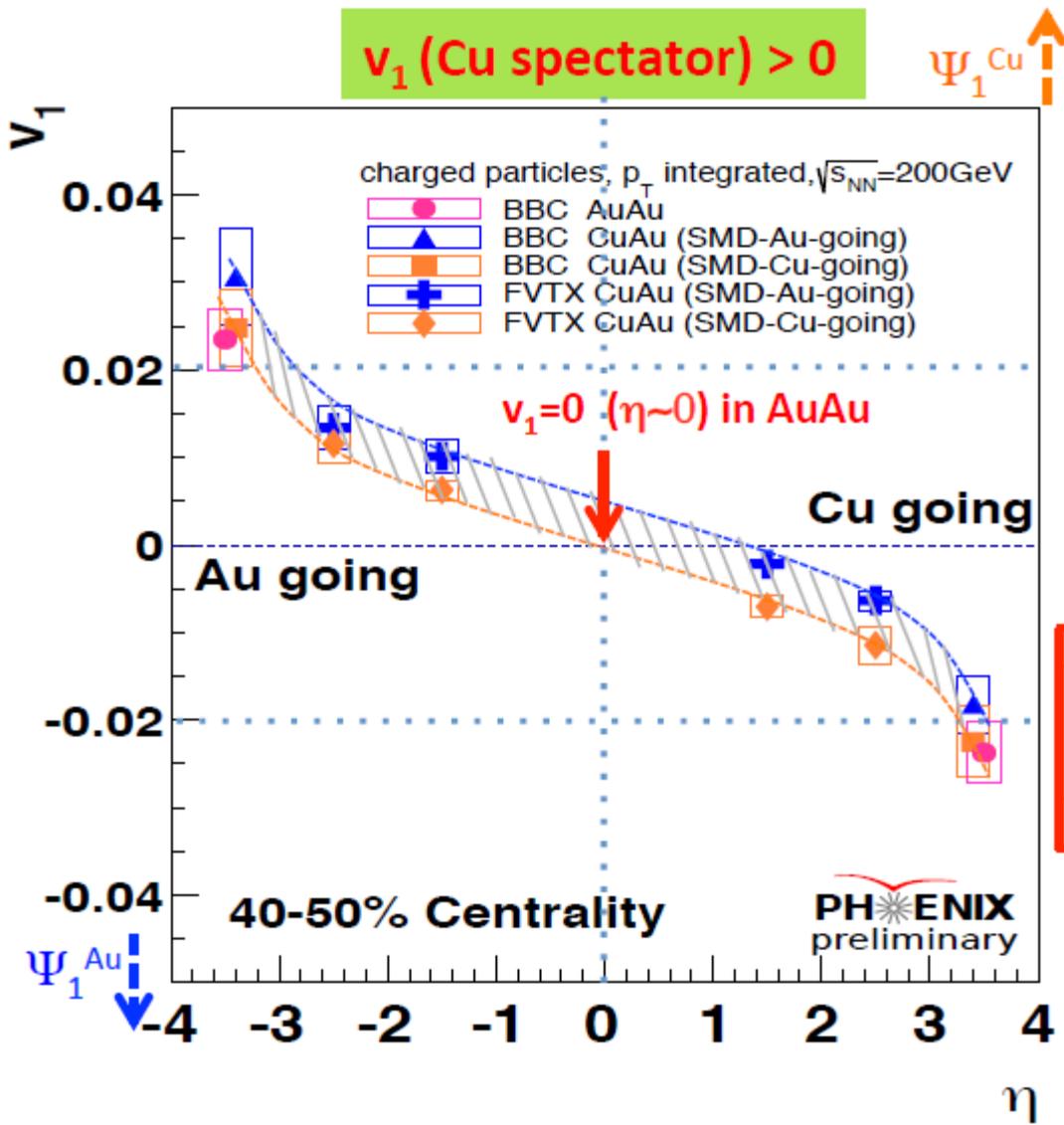


## Forward/backward asymmetry in bulk

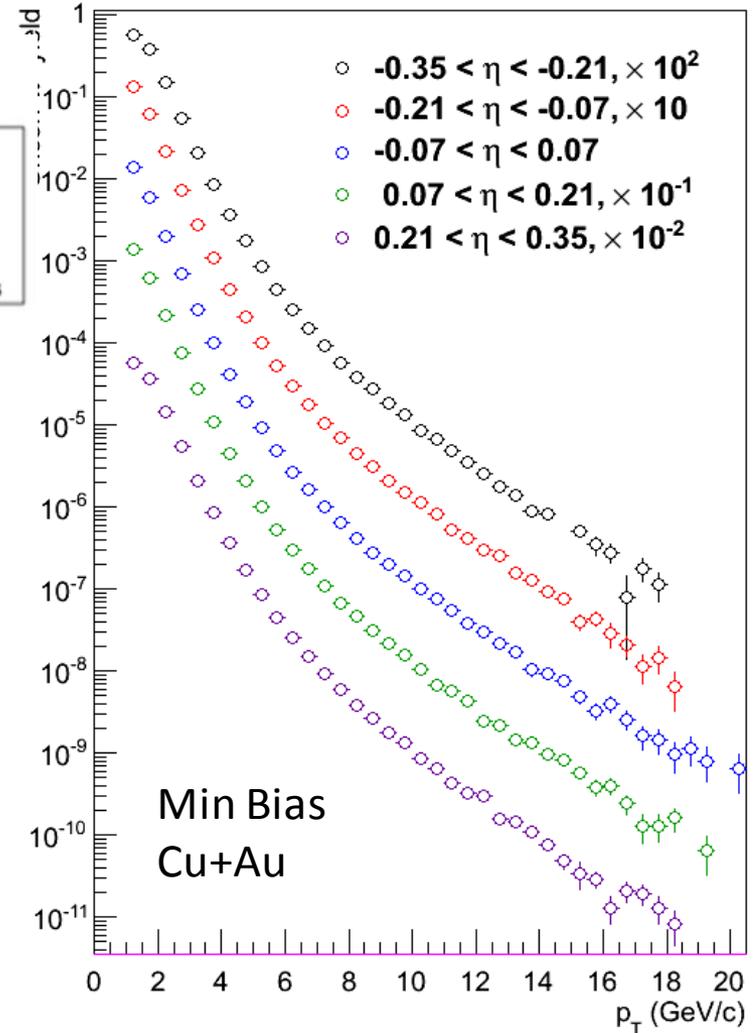
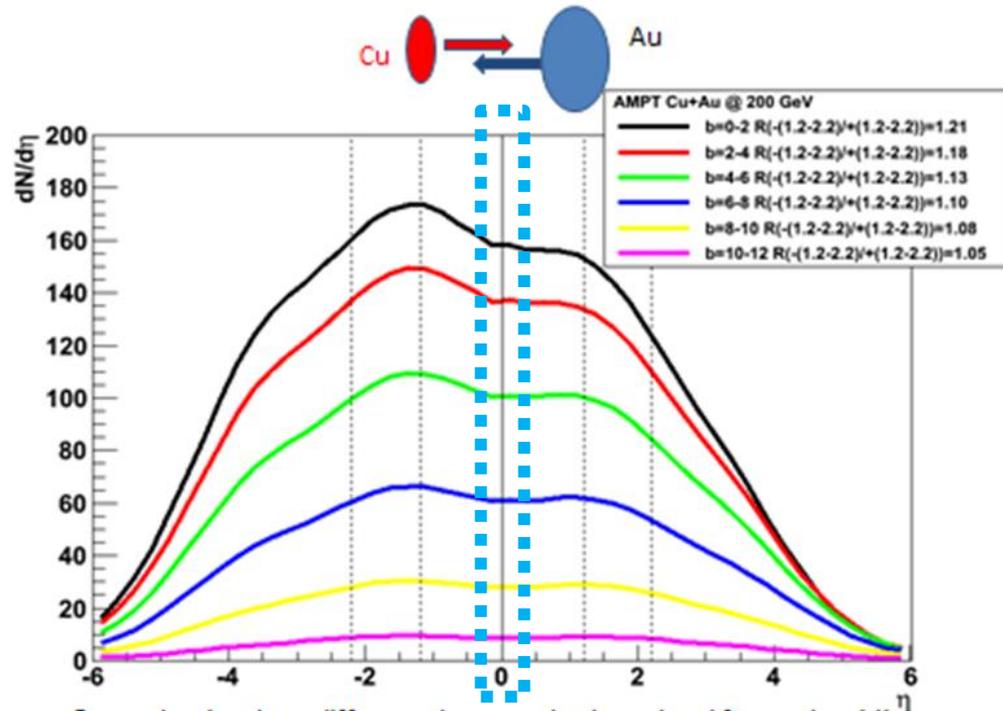






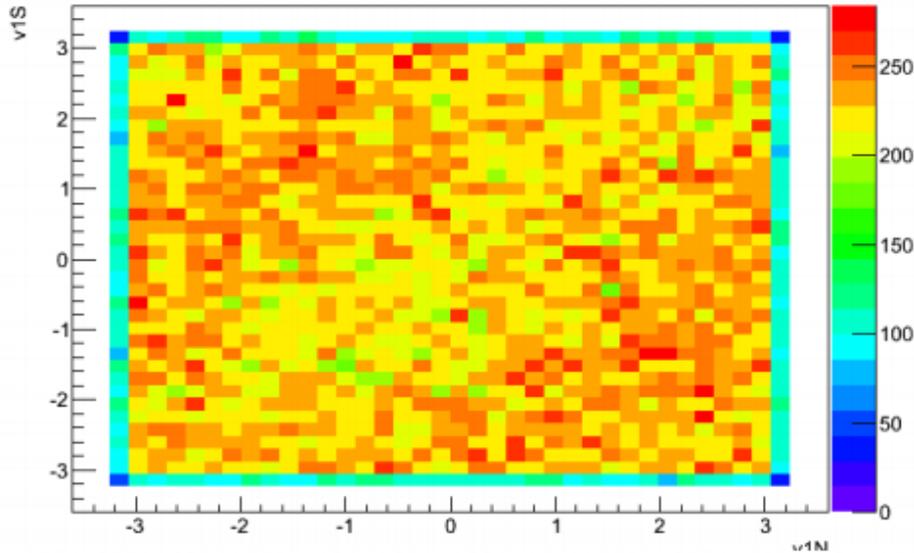


# Pi0 pt vs eta

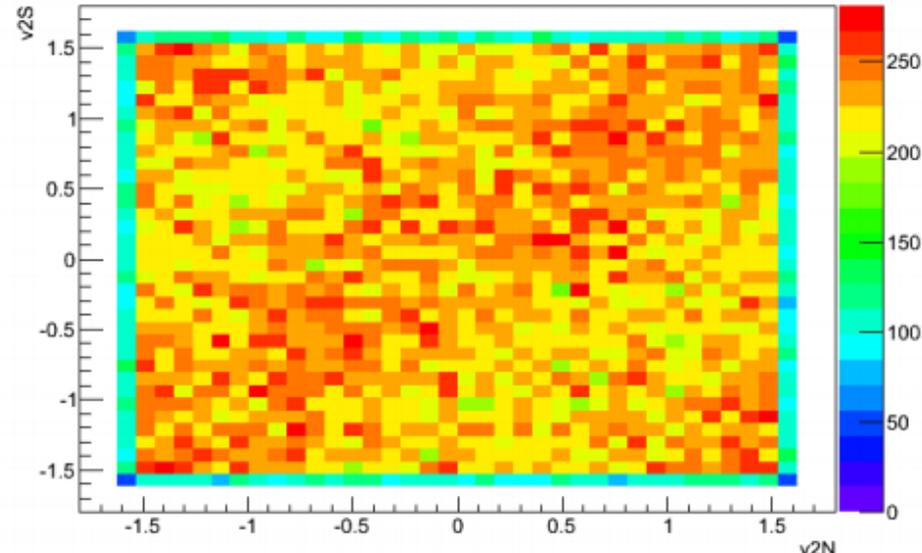


# NEW: BBC Psi1, Psi2 N, S correlations

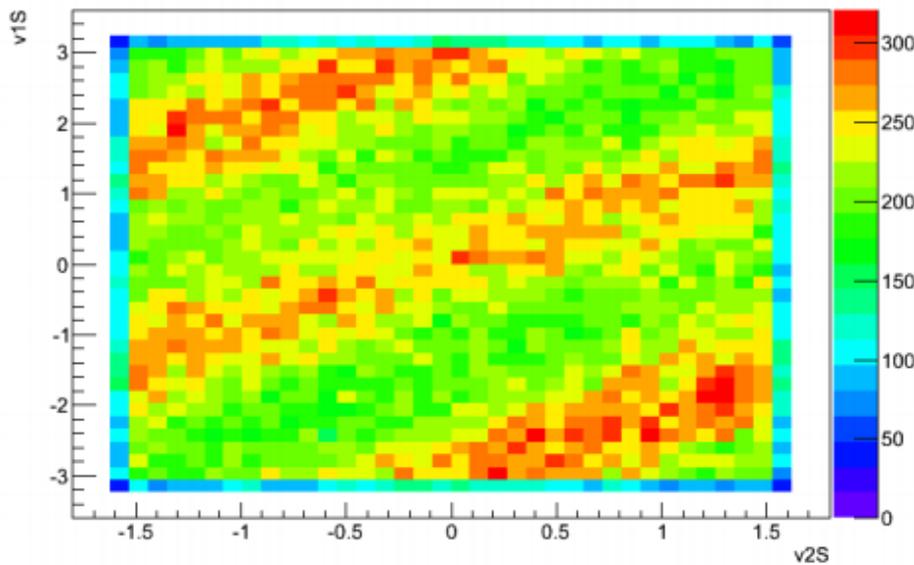
v1S:v1N



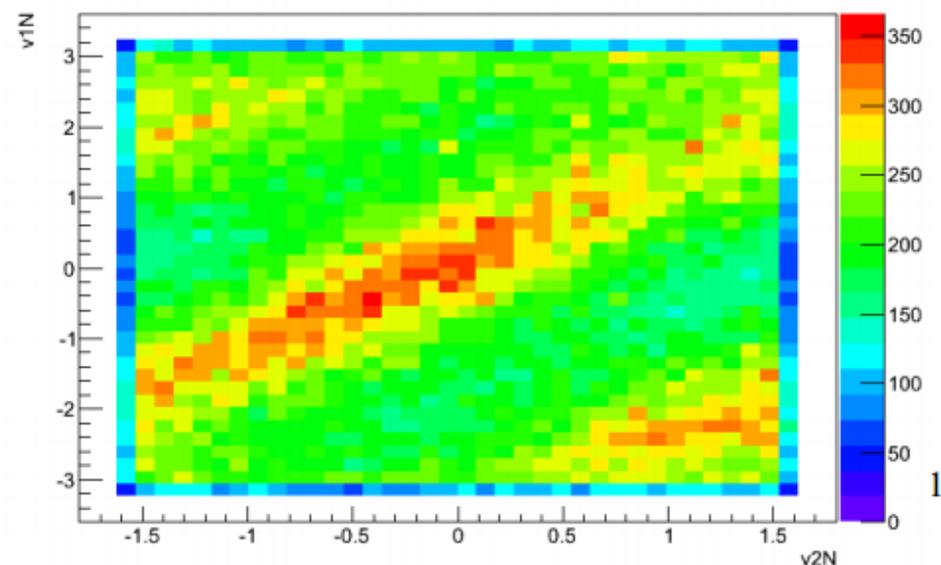
v2S:v2N

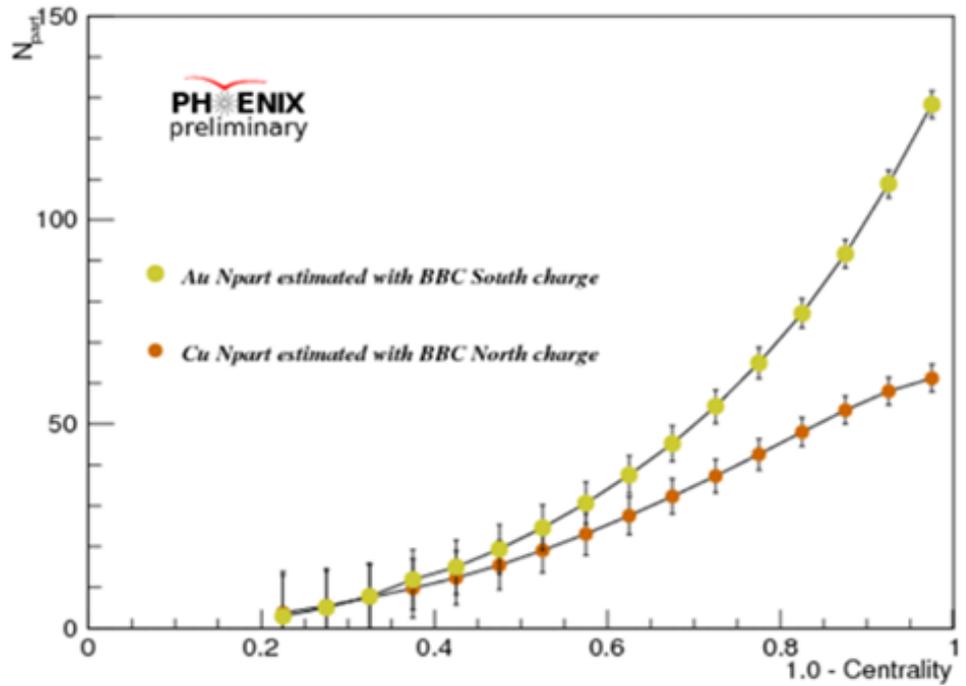
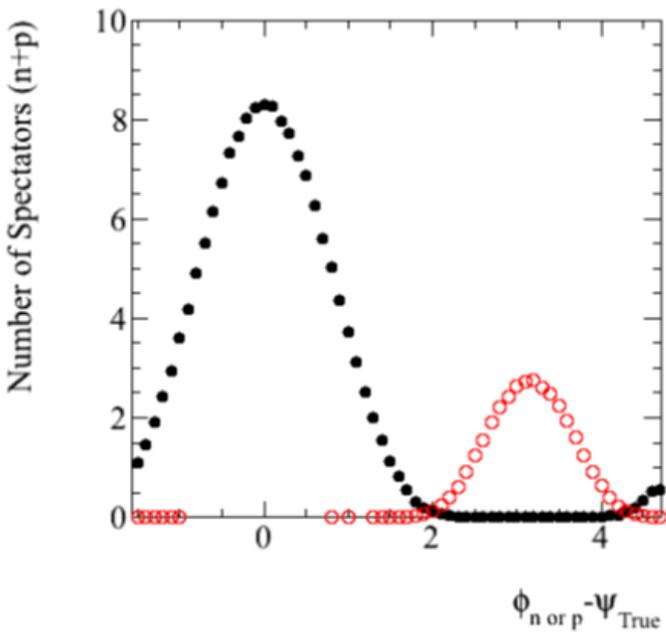


v1S:v2S



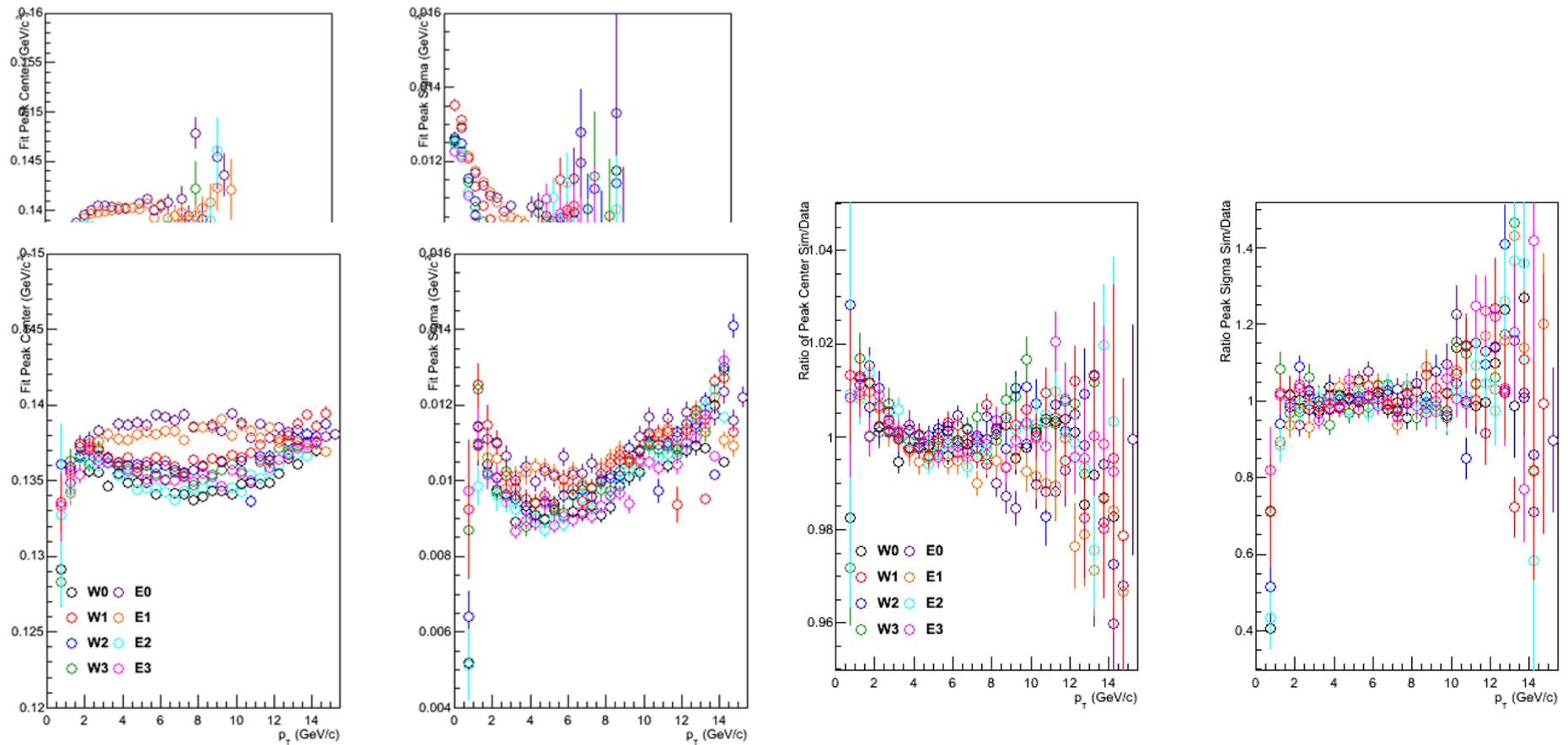
v1N:v2N



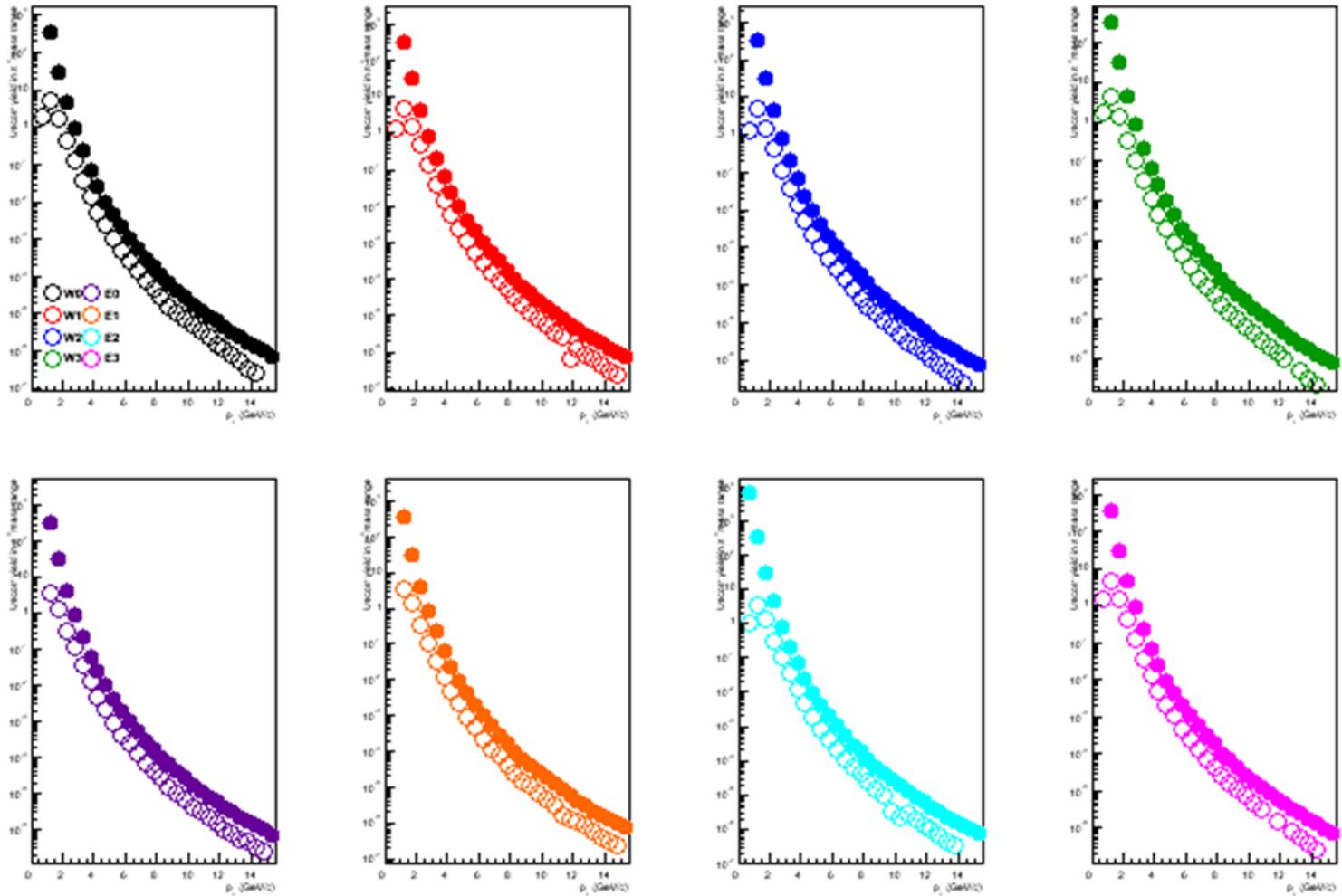


# Simulation

- Calibration to data E scale and resolution



# On the way to efficiency



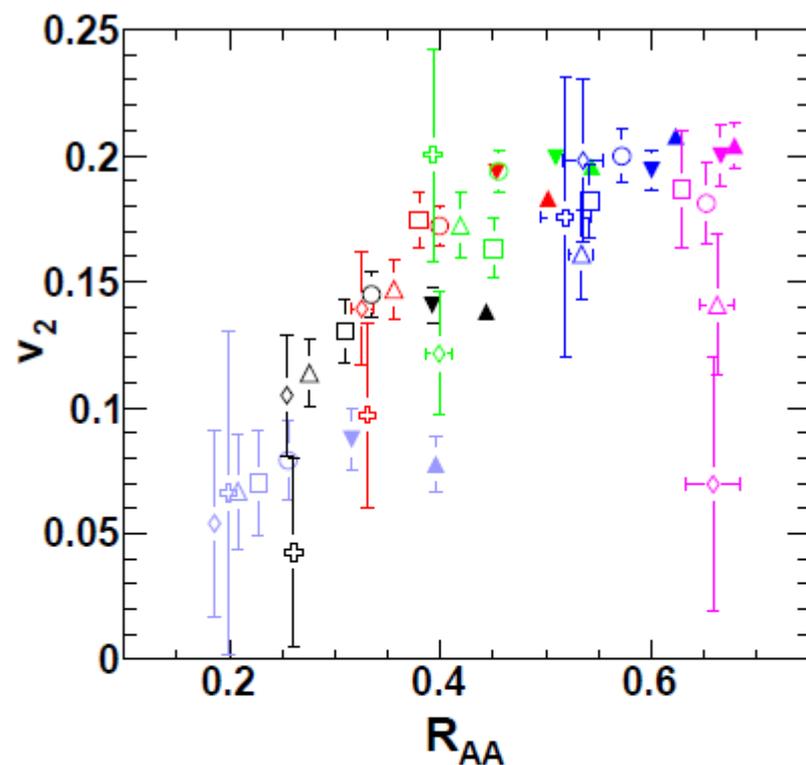


FIG. 20: (Color online)  $\pi^0$   $v_2$  vs. inclusive  $R_{AA}$ . The points denote bins in  $p_T$  as follows: triangles  $2 < p_T < 2.5$  GeV/c, inverted triangles  $2.5 < p_T < 3$  GeV/c, circles,  $3 < p_T < 3.5$  GeV/c; squares,  $3.5 < p_T < 4$  GeV/c; open triangles,  $4.0 < p_T < 4.5$  GeV/c; diamonds,  $4.5 < p_T < 5$  GeV/c; crosses,  $5 < p_T < 6$  GeV/c. Centrality bins are indicated by the colors: light blue, 0-10%; black, 10-20%; red, 20-30%; green, 30-40%; blue, 40-50%; magenta 50-60%.