

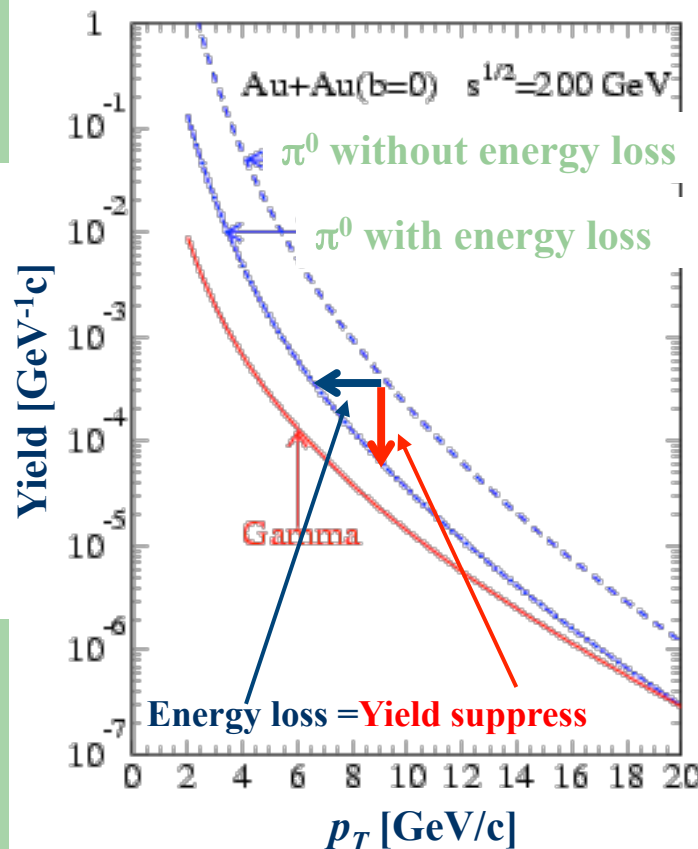
***Detail study of the medium created in  
Au+Au collisions with high  $p_T$  probes  
by the PHENIX experiment at RHIC***



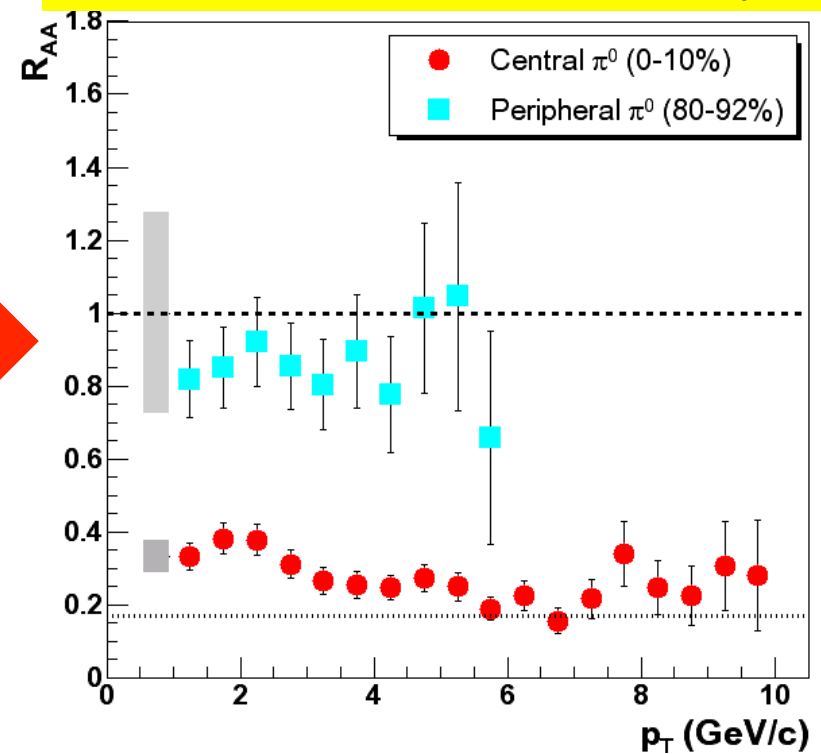
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For the PHENIX Collaboration

# Hard scattering as densimeter

- Parton may change its momentum in the medium.
  - Energy loss through Gluon radiation, etc..
- Effect may be path-length and system dependent ~a densimeter~.
- Look at leading particles of jet as a measure of jet energy.

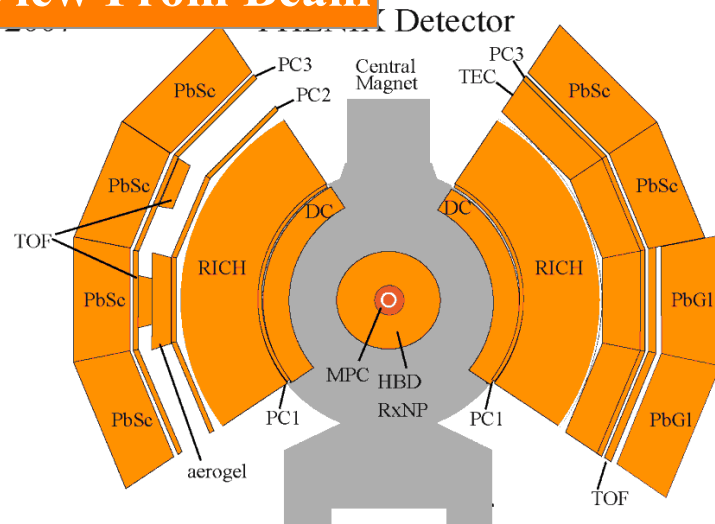


PHENIX,  $\pi^0$  in Au+Au, PRL. 91, 072301 (2003)

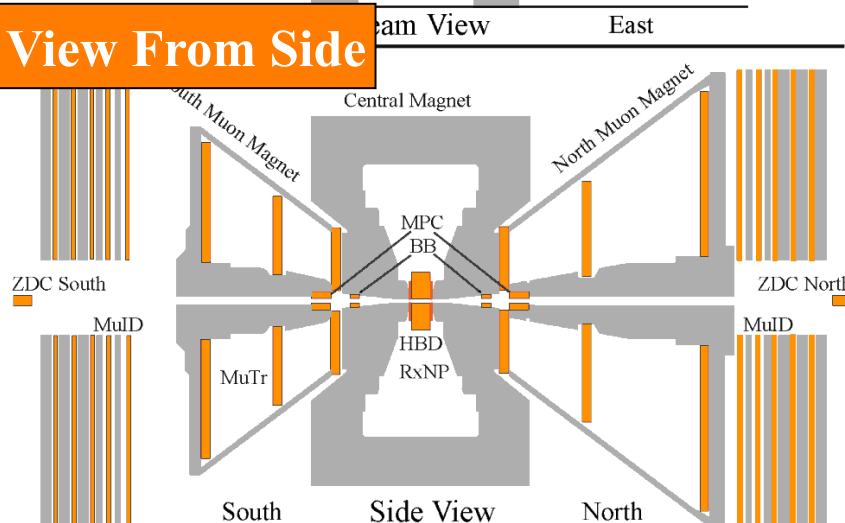


# Setup for measurement

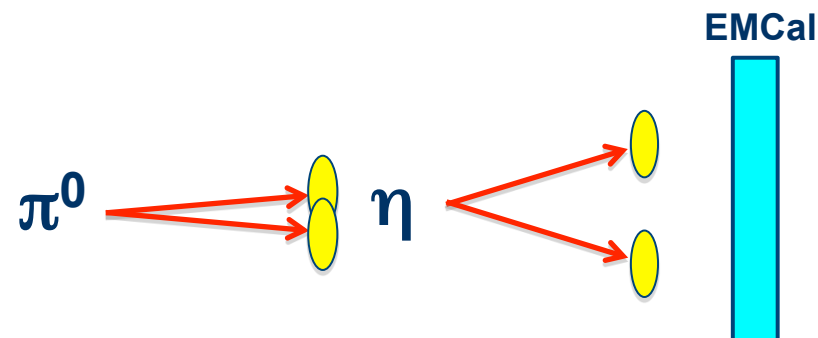
## View From Beam



## View From Side



- Event triggered by a coincidence of BBC South and BBC North.
  - Sitting in  $3.1 < |\eta| < 3.9$
- $\pi^0$  and  $\eta$  measurement
  - EMCal(PbSc, PbGl): Energy measurement and identification of real photons.
  - Tracking(DC, PC): Veto to Charged particles.



Results presented here are obtained from  $0.813 \text{ nb}^{-1}$  Au+Au 200GeV events recorded by PHENIX in 2007.

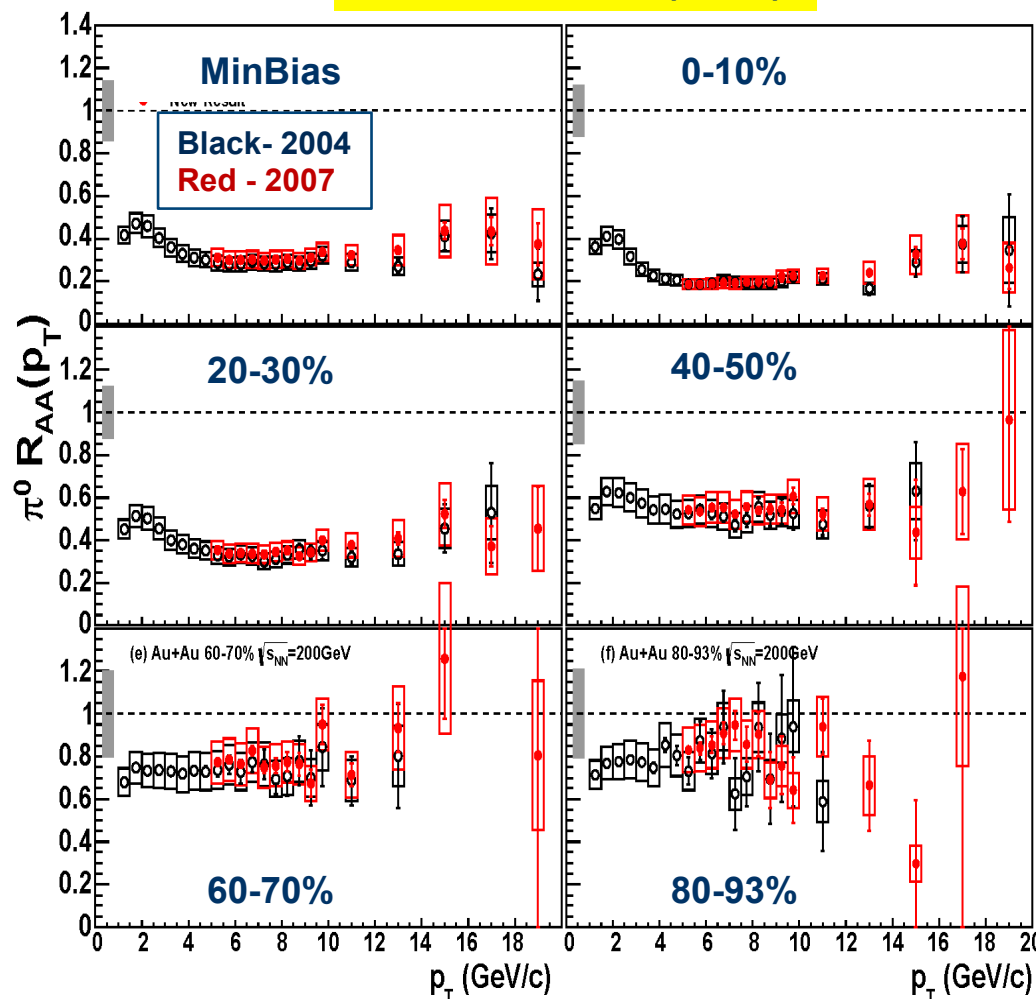
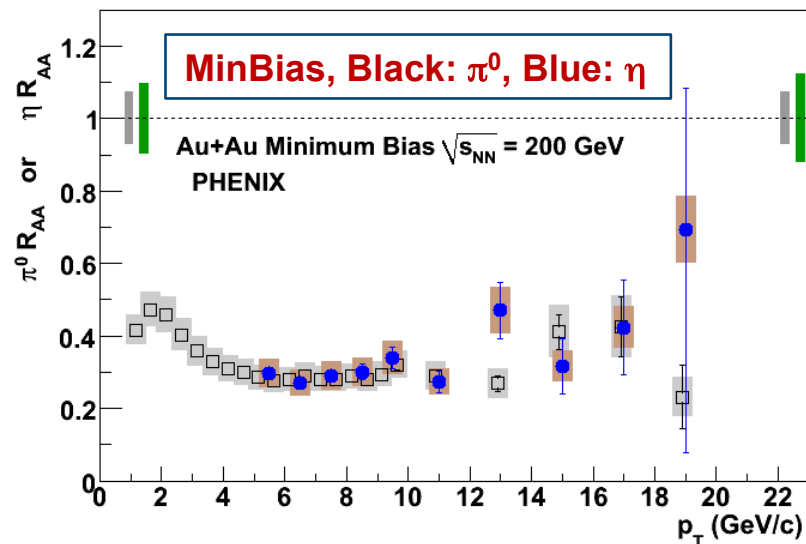
# $\pi^0$ and $\eta$ $R_{AA}$

- 200GeV Au+Au collision system.
- $\pi^0$  and  $\eta$  nicely agree.
- Very nice agreement between RHIC Year-2004 and 2007 results for  $\pi^0$ .

$$R_{AA} = \frac{(1/N_{evt}^{AA})(dN^{AA}/dp_T)}{\langle T_{AA} \rangle (d\sigma^{pp}/dp_T)}$$

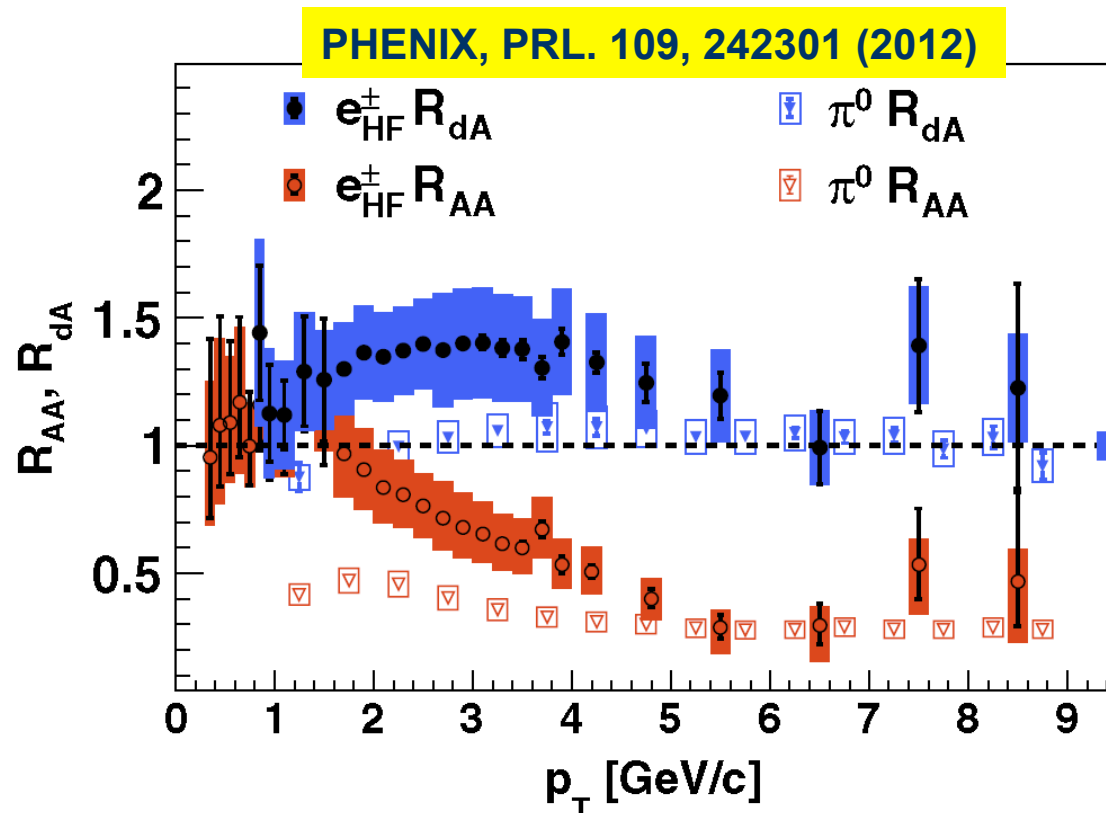
PRC87, 034911 (2013)

PRC82, 011902(R) (2010)



# Flavor similarity?

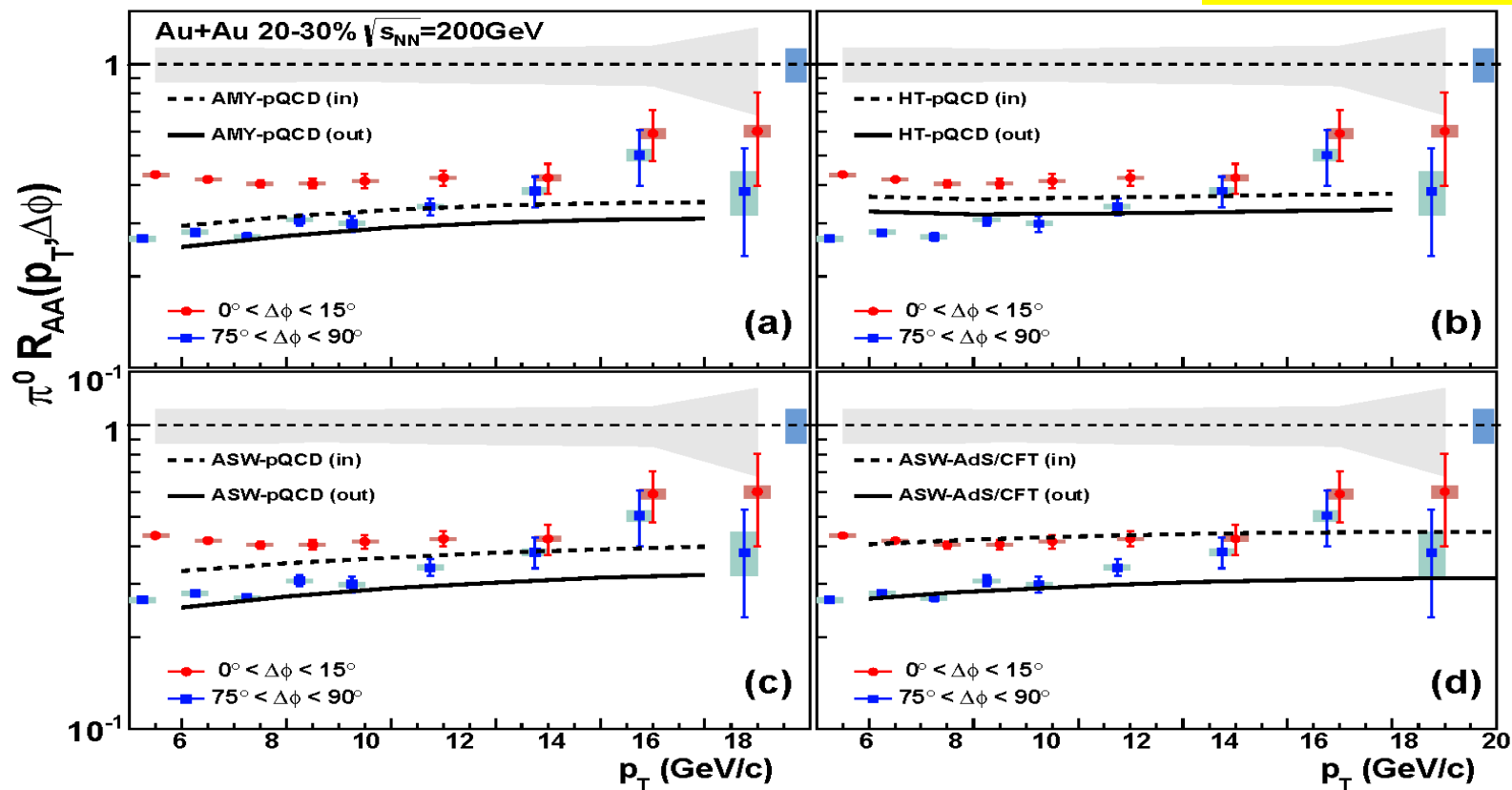
- Different quark flavor may give different interaction.
  - Mass ordering (dead-cone effect, etc.)
- At high  $p_T$  ( $p_T > 5 \text{ GeV}/c$ ), electrons from heavy quark (c,b) show similar  $R_{AA}$  and  $R_{dA}$  as  $\pi^0$ 's from light quark (u,d) or gluons.



# Path-length dependence of energy loss

- Comparison of  $R_{AA}$  between data and models in in- and out-plane
  - Different path-length in in-plane (event plane direction) and out-plane.

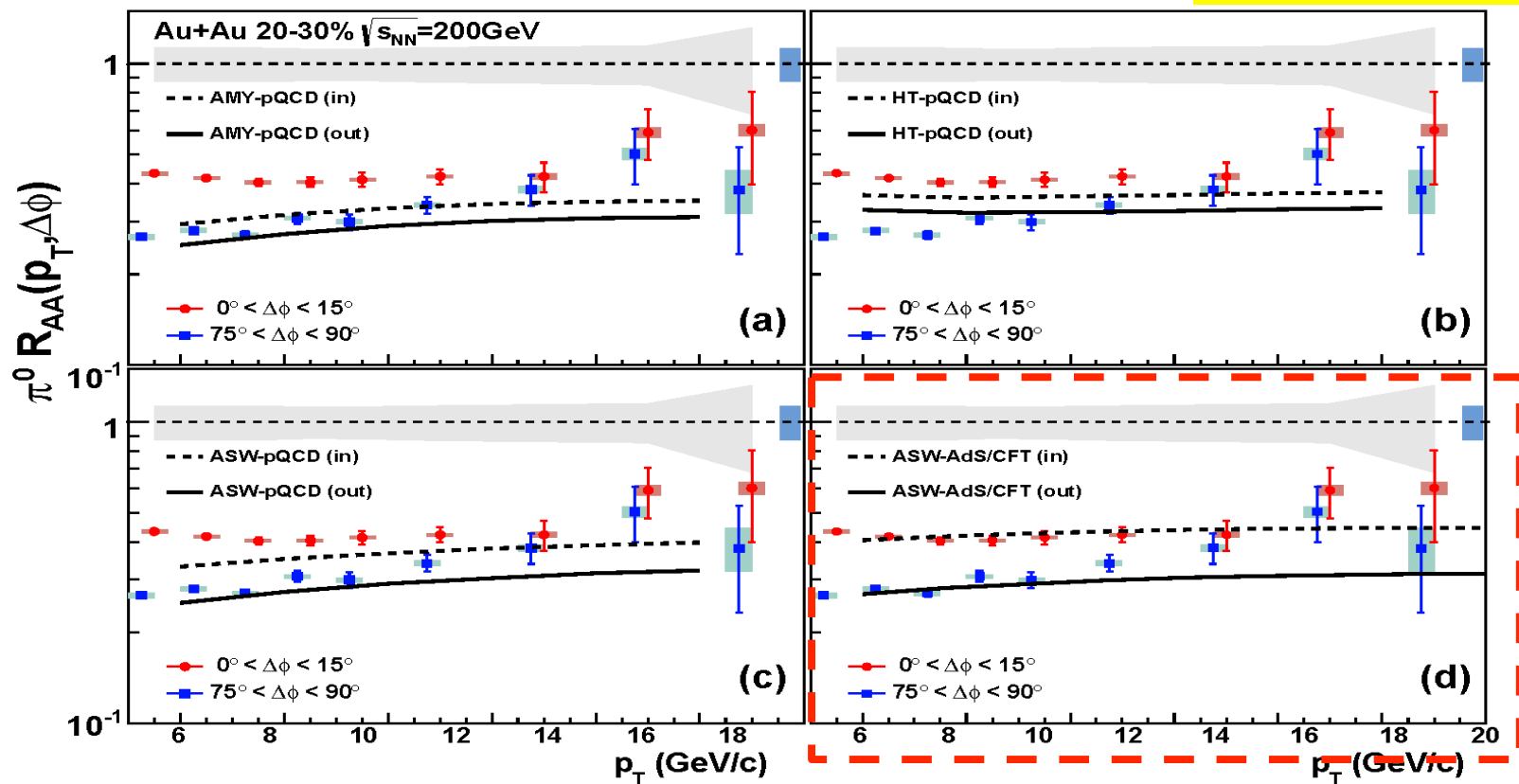
PRC87, 034911 (2013)



# Path-length dependence of energy loss

- Comparison of  $R_{AA}$  between data and models in in- and out-plane
  - Different path-length in in-plane (event plane direction) and out-plane
- Data favor AdS/CFT-inspired model (very strong coupling) rather than pQCD-inspired (suggesting energy loss is  $L^3$  dependent?).

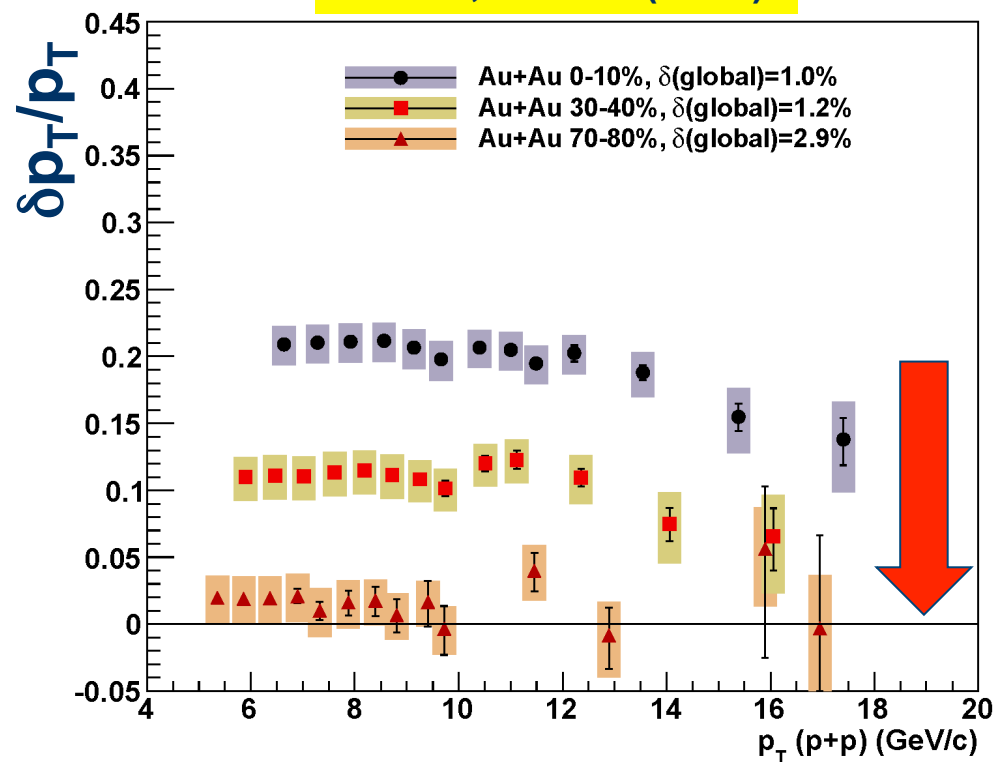
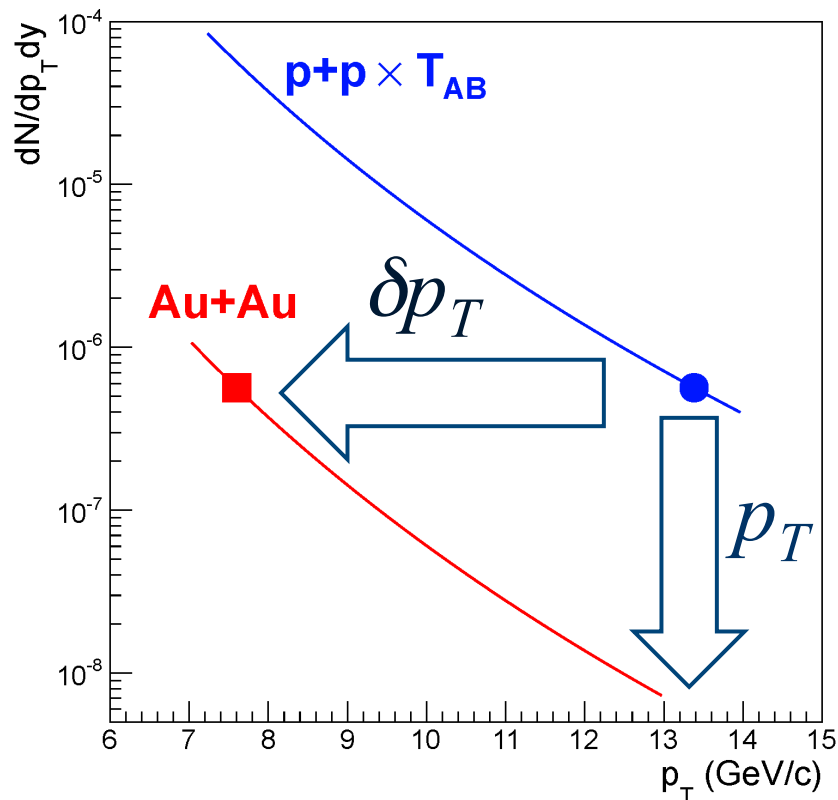
PRC87, 034911 (2013)



# Fractional momentum loss of partons

- Measured fractional momentum loss ( $\delta p_T/p_T$ ) instead of  $R_{AA}$ 
  - In A+A collisions
- $\delta p_T/p_T = 0.2$  in 0-10% centrality,  $= 0.02$  in 70-80% centrality

PRC87, 034911 (2013)

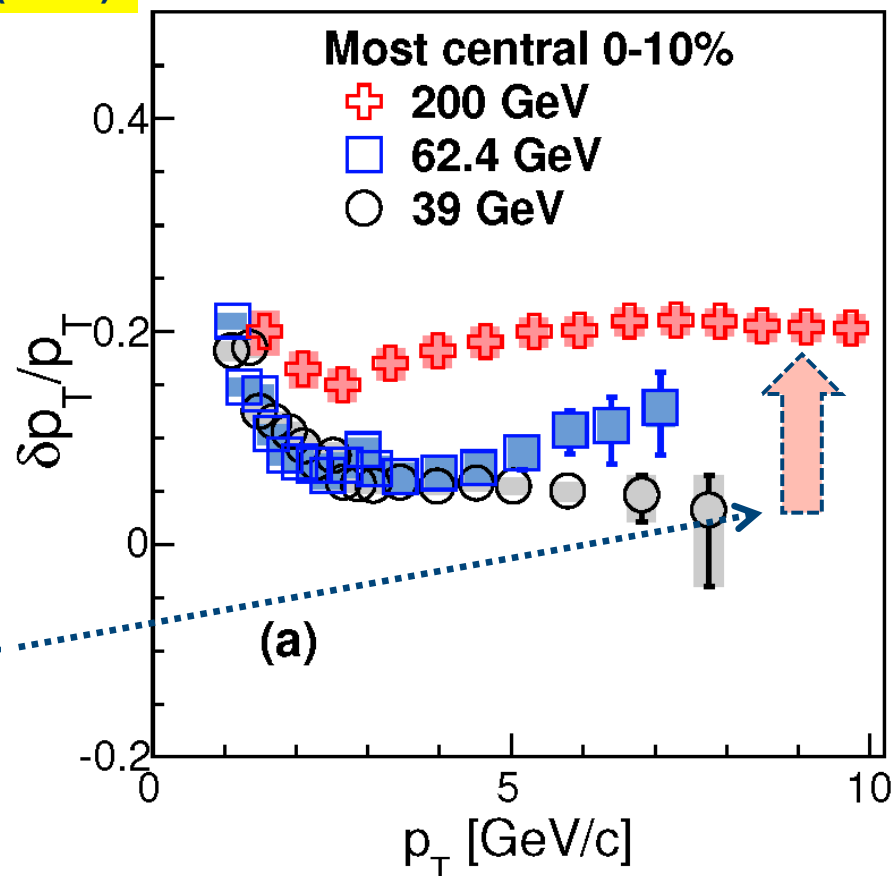
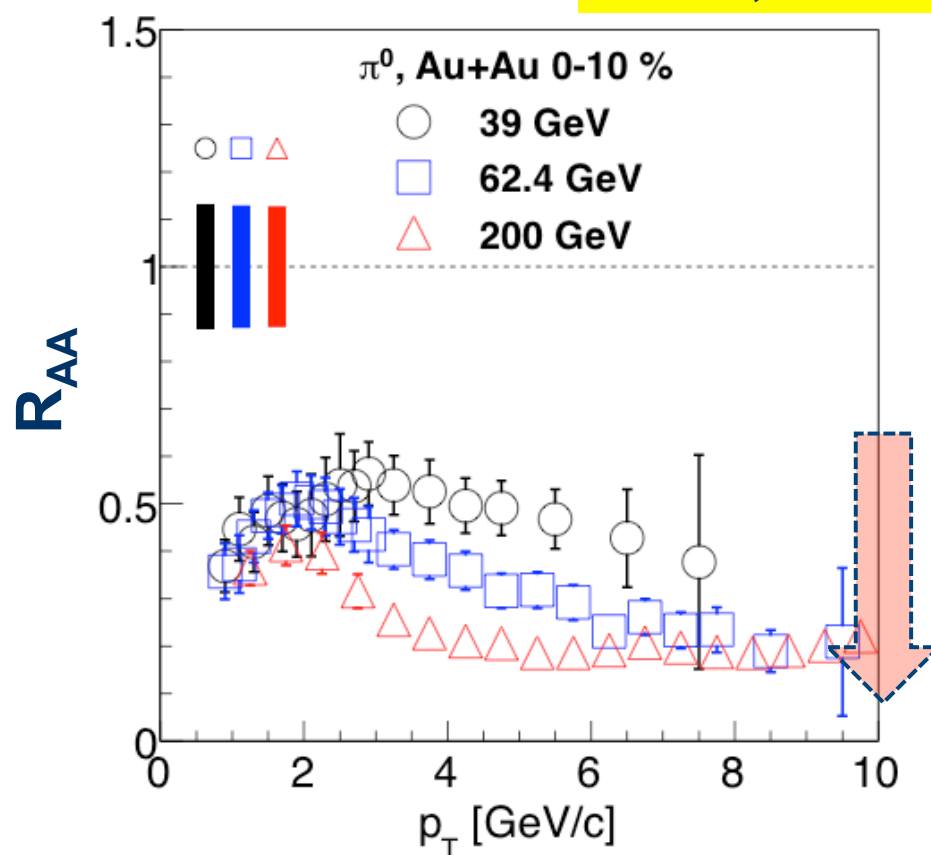




# Energy dependence of $\delta p_T/p_T$ (I)

- $\delta p_T/p_T$  decreases significantly going from 200 to 62, 39 GeV.
- Significantly different  $\delta p_T/p_T$  even the  $R_{AA}$  is similar.

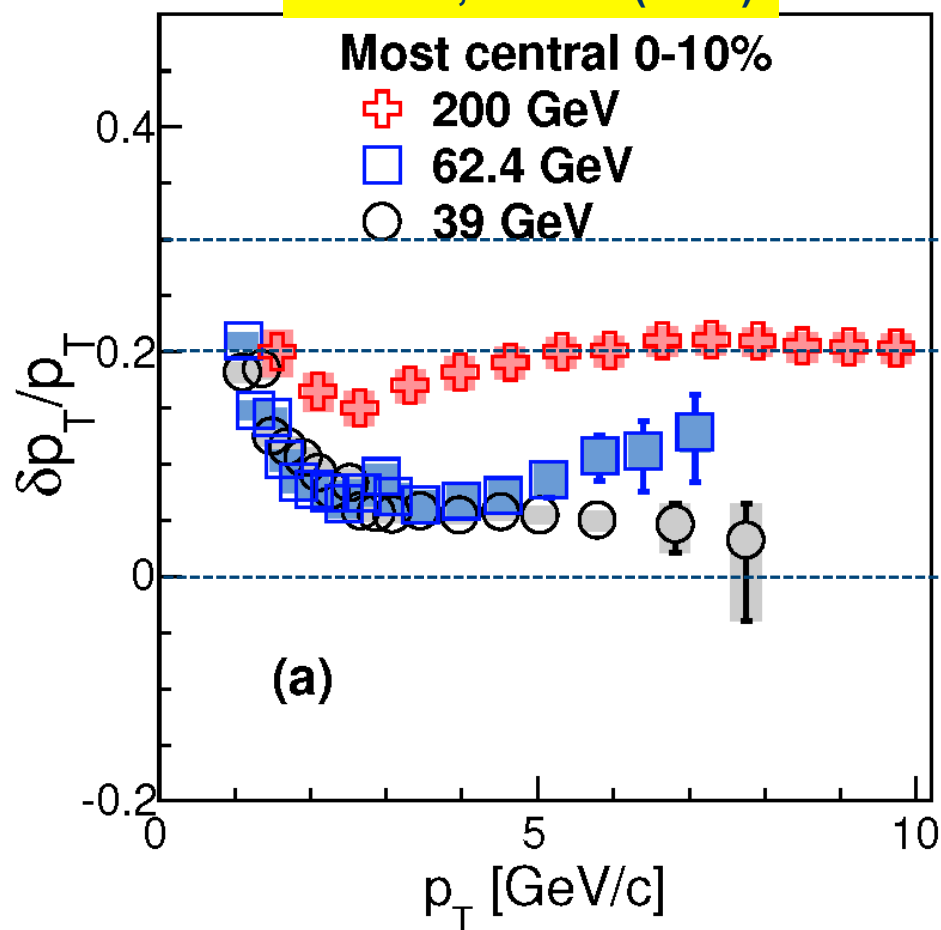
PRL109, 152301 (2012)



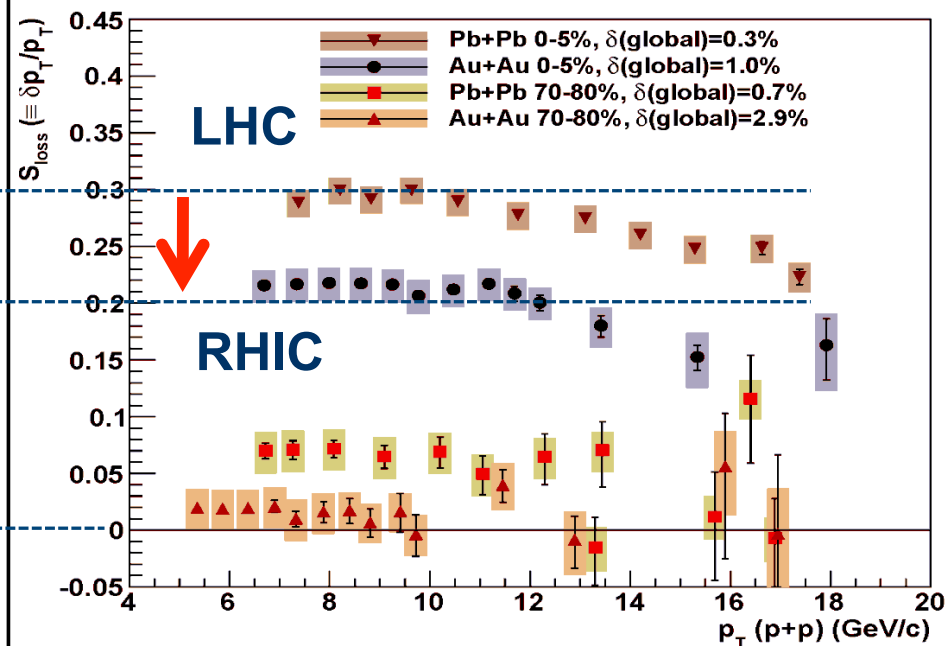
# Energy dependence of $\delta p_T/p_T$ (II)

- $\delta p_T/p_T$  from 62 GeV to 2.76 TeV!:  $\sim 0.3$  for LHC

PRL109, 152301 (2012)

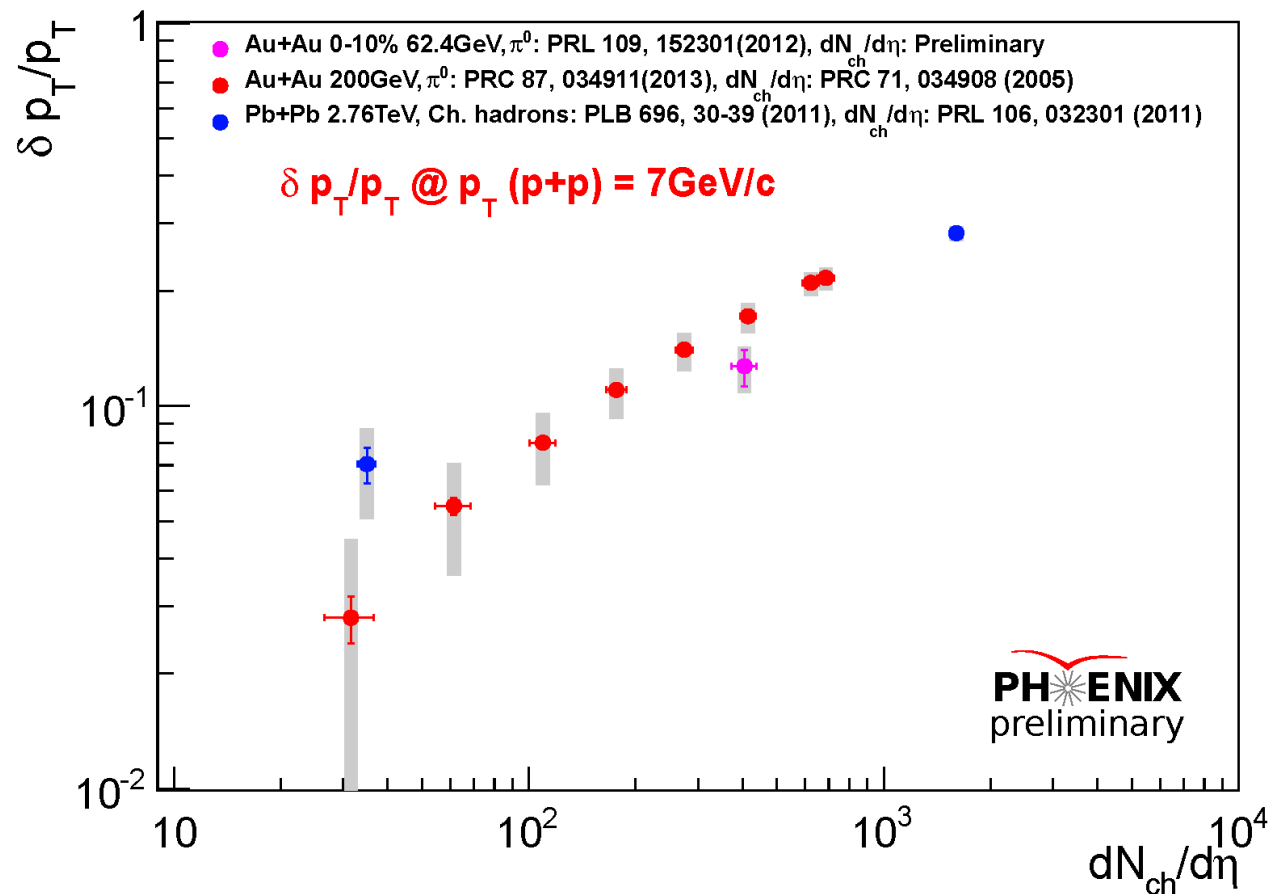


PRC87, 034911 (2013)



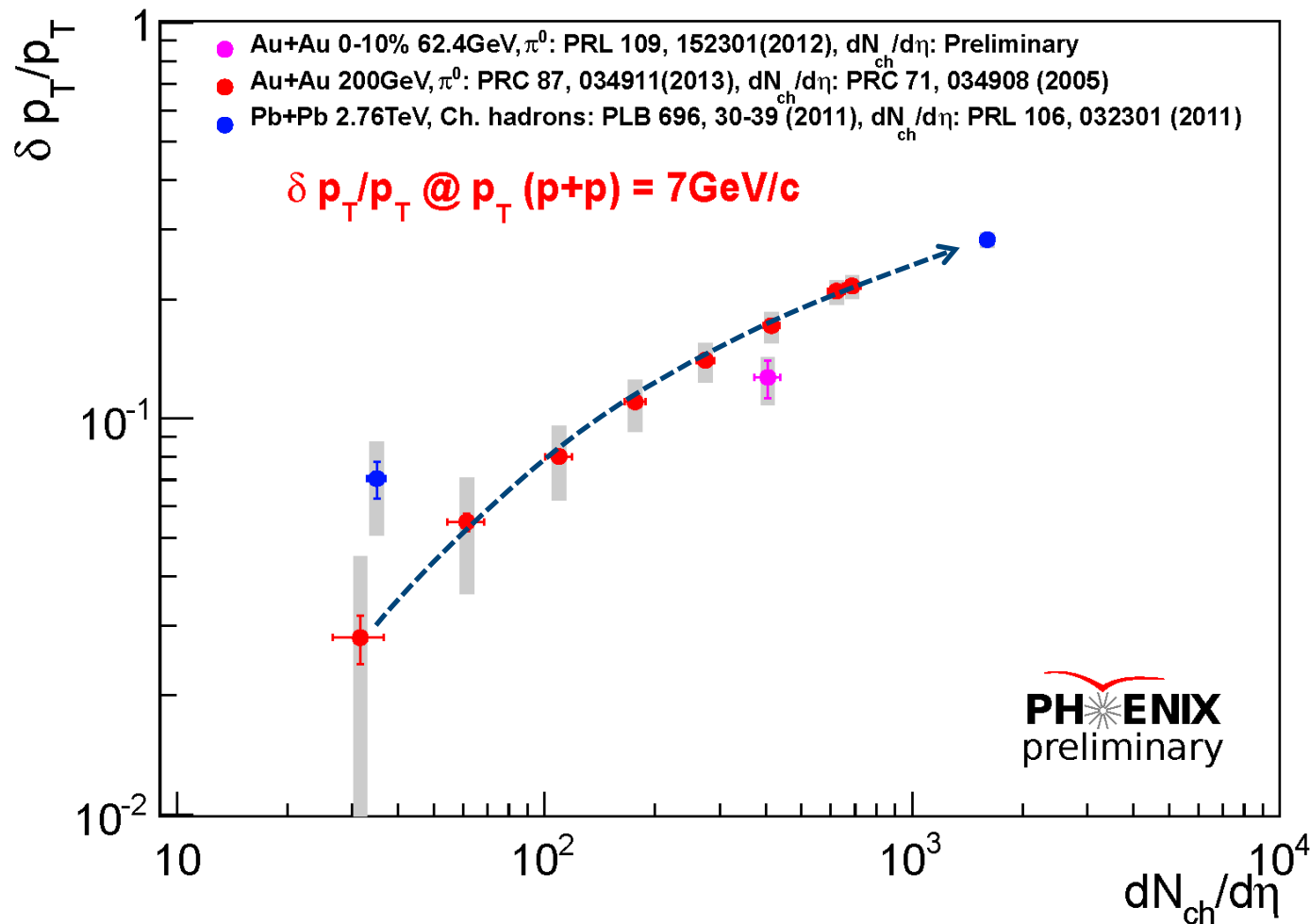
# Detail study of $\delta p_T/p_T$ systematics

- Plotting against  $dN_{ch}/d\eta$  (as a measure of energy density)
  - $dN_{ch}/d\eta$  are obtained in given centrality at given cms energy.
  - $\delta p_T/p_T$ 's at  $p_T=7\text{GeV}/c$  of p+p are plotted.



# Detail study of $\delta p_T/p_T$ systematics

- 200GeV trend points to ALICE 0-5% point?



# Consistency with previous studies

- PHENIX studied fractional momentum loss in two publications
  - PRC76, 034904 (2007), PRL101, 232301 (2008)
  - Assuming the spectra shape is power-law with the power “n”, we can write:

$$S_{loss} \equiv \delta p_T / p_T = \beta N_{part}^\alpha$$
$$R_{AA} = (1 - S_{loss})^{n-2} = (1 - \beta N_{part}^\alpha)^{n-2}$$

- In this study, if we assume  $dN_{ch}/d\eta \propto N_{part}$ , we can write the relationship as follows:  $\delta p_T / p_T = \beta (dN_{ch}/d\eta)^\alpha$

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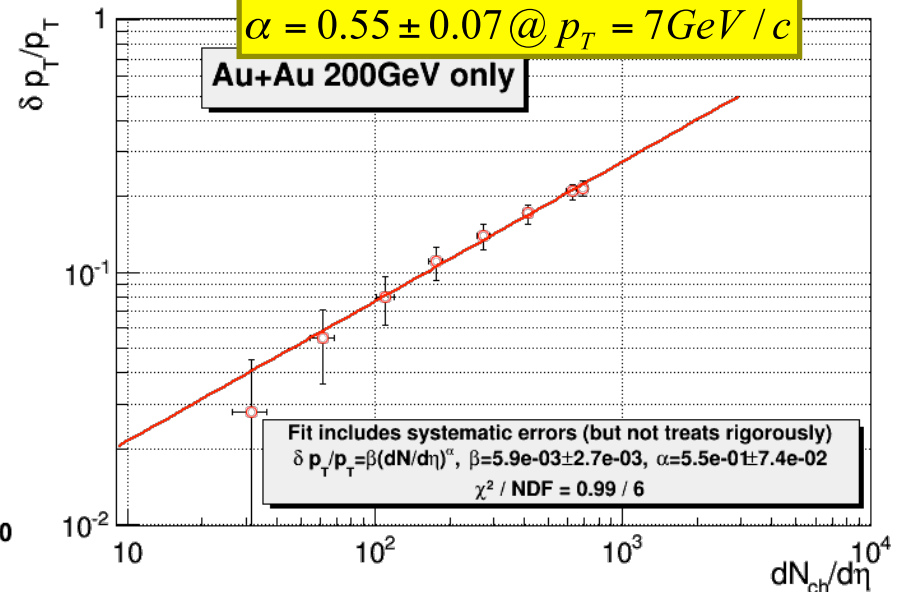
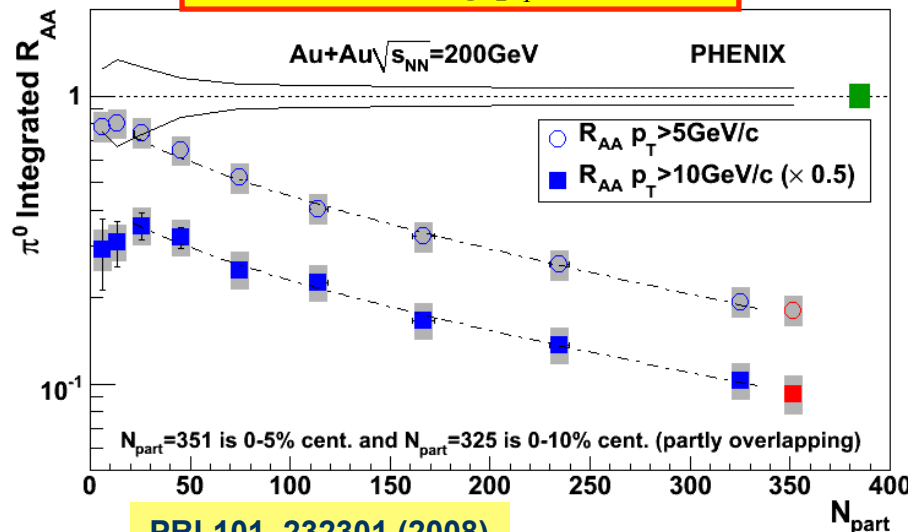
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$$\delta p_T / p_T = \beta (dN_{ch}/d\eta)^\alpha$$

$$\alpha = 0.57 \pm 0.13 @ p_T > 5 \text{ GeV} / c$$

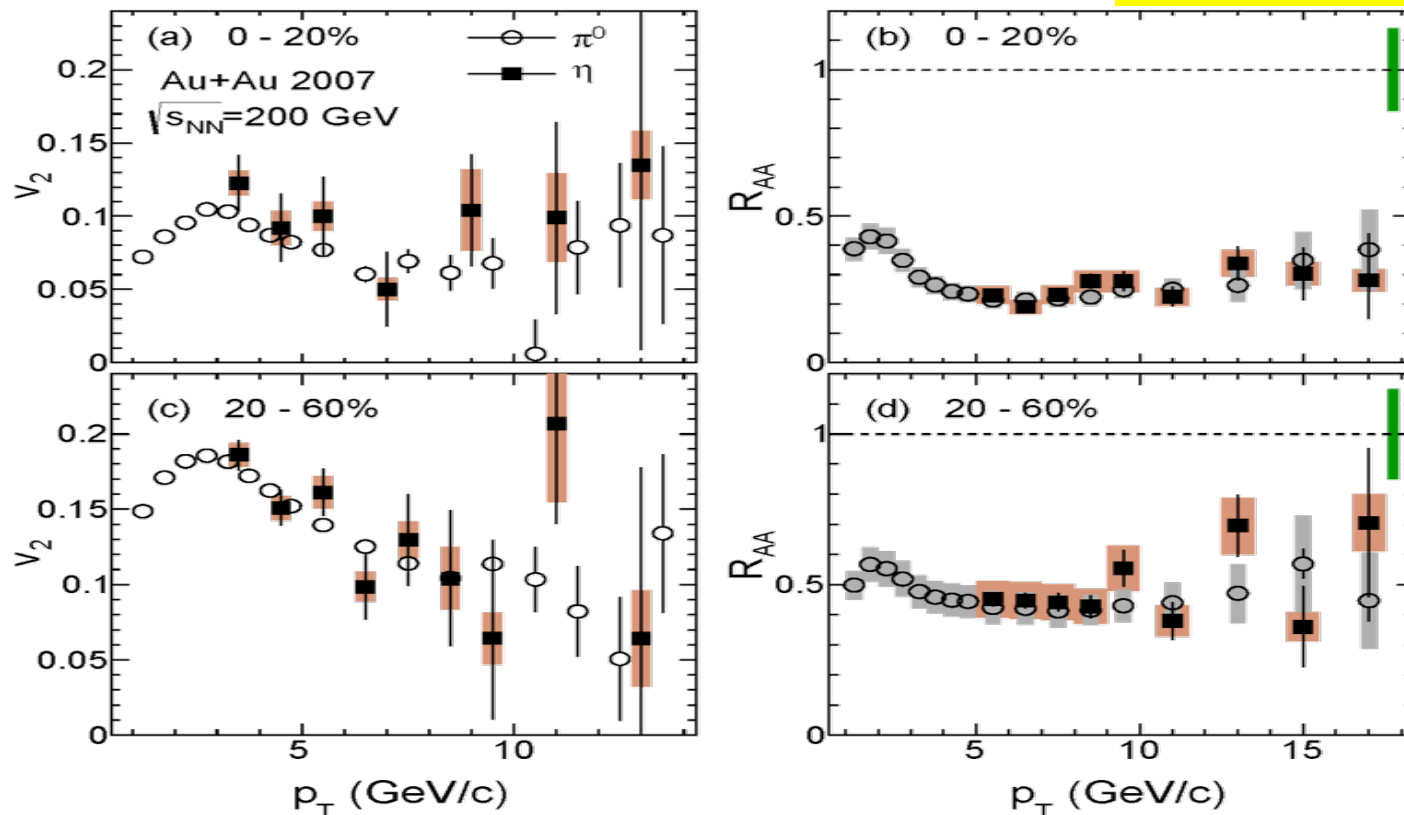


# $v_n$ of high $p_T$ probes

# $v_2$ of high $p_T$ $\pi^0$ and $\eta$

- $v_2$  of  $\pi^0$  and  $\eta$  are measured up to 14 GeV/c.
  - They are very consistent as they are for  $R_{AA}$ .
- We can reach to higher  $p_T$  with  $\eta$  as accumulating more statistics.

PHENIX, arxiv:1309.4437

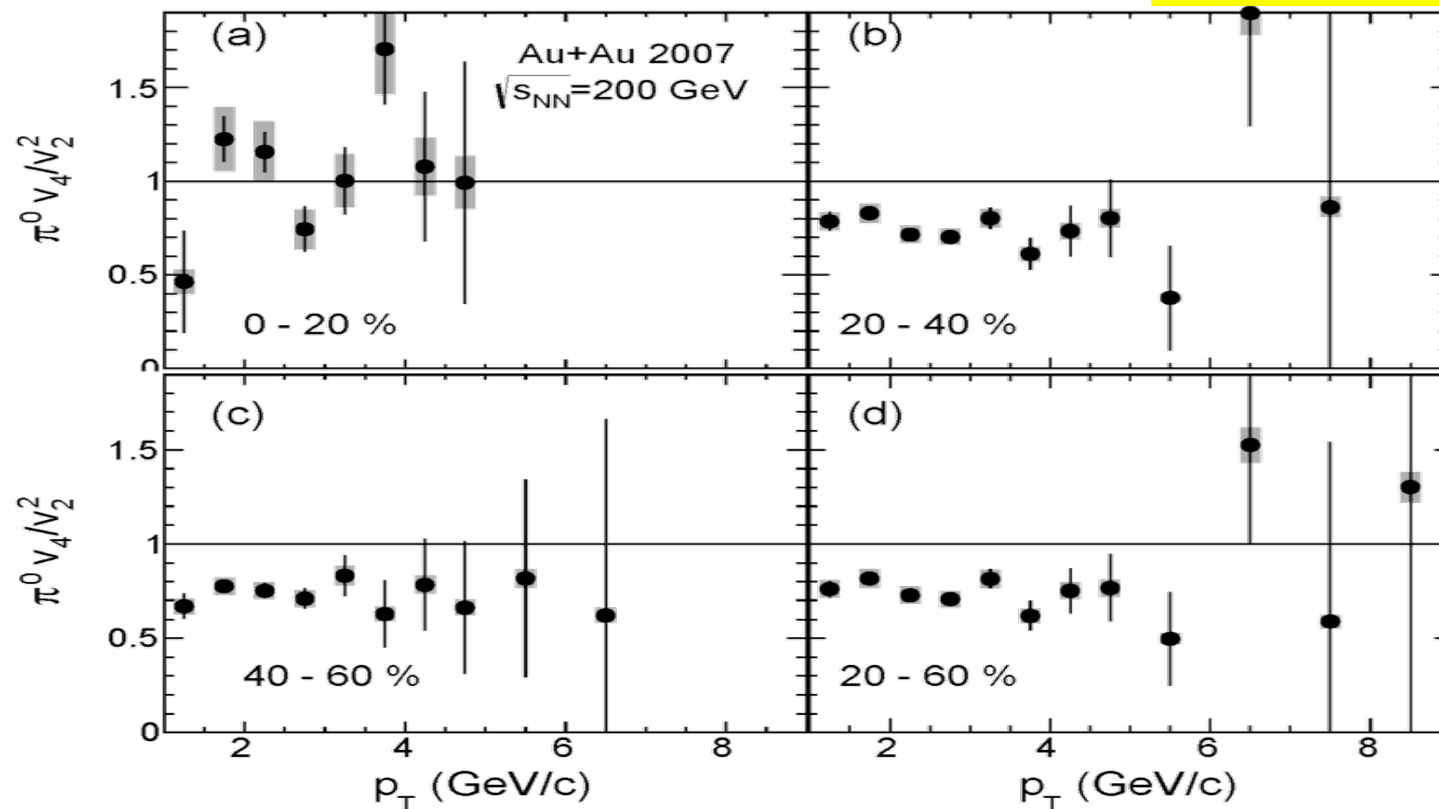




# $v_4$ and $v_2$ of high $p_T$ $\pi^0$

- $v_4$  of  $\pi^0$  is measured up to 10 GeV/c (using  $\Psi_2$  event plane).
- $v_4/v_2^2$  is computed.
  - Flatness of the ratio shows applicability of hydrodynamics..?

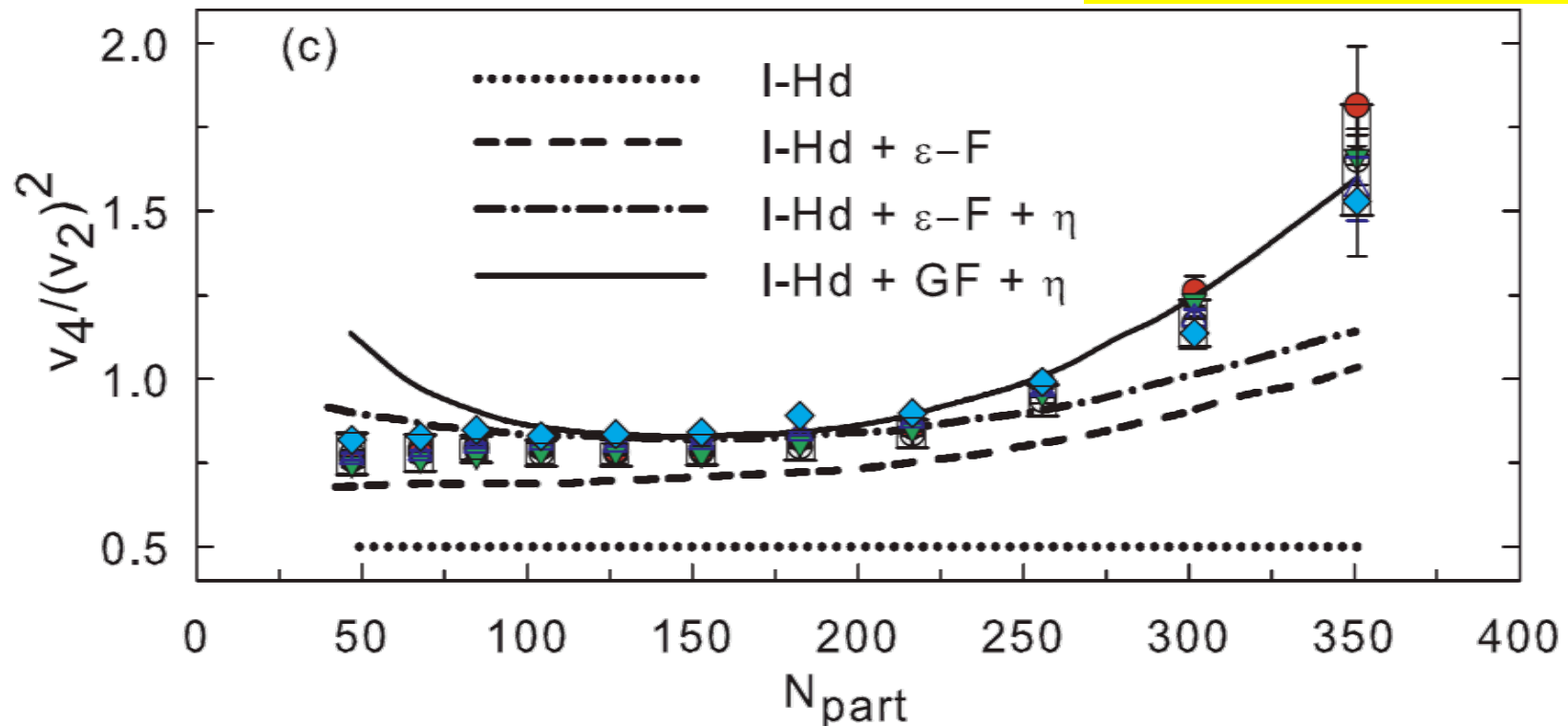
PHENIX, arxiv:1309.4437



# Centrality dependence of $v_4/v_2^2$

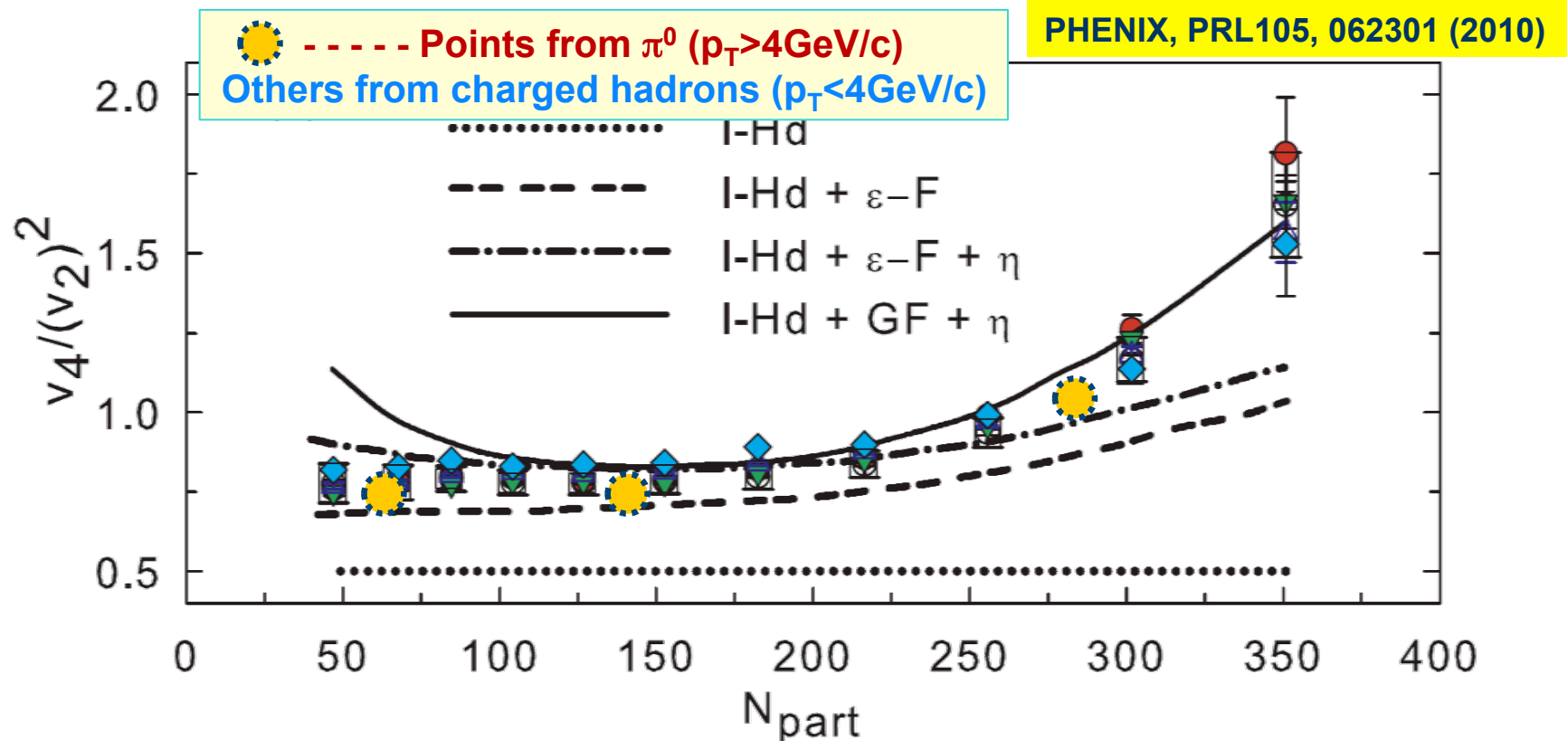
- Charged hadron  $v_4/v_2^2$  compared with models
  - Ideal hydrodynamics only (I-Hd)
  - with eccentricity fluctuation (I-Hd +  $\epsilon$ -F)
  - with viscosity (I-Hd +  $\epsilon$ -F +  $\eta$ ) and Gaussian fluctuation (I-Hd + GF +  $\eta$ )
- Different points correspond to six  $p_T$  ranges in 0.5-3.6 GeV/c

PHENIX, PRL105, 062301 (2010)



# Hydro scaling extends to higher $p_T$ ?

- Plotted  $\pi^0 v_4/v_2^2$  for  $p_T > 4 \text{ GeV}/c$  over charged hadron results.
- Hydro description still holds for this region?
  - Note possible effects from differential energy loss and/or jet bias
  - See prediction, e.g., Bravina et. al., PRC87, 034901(2013)



# Summary

- $\pi^0$  and  $\eta$  are measured in 200GeV Au+Au collisions.
  - $\pi^0$  and  $\eta$  give very consistent results in  $R_{AA}$ .
- $\pi^0$  and HF electrons  $R_{AA}$  and  $R_{dA}$  have similar trend at high  $p_T$ .
  - Similar degree of final state interaction for light and heavy quarks?
- Emission-angle dependent  $\pi^0$  yield favors AdS/CFT-inspired energy loss model.
- Centrality, system, and energy dependence of fractional momentum loss is studied.
  - A trend is seen from 200GeV Au+Au to 2.76TeV Pb+Pb
- Hydro description still holds for  $p_T > 4 \text{ GeV}/c$ ?
  - From  $v_4/v_2^2$  measurement at high  $p_T$
  - Possible effects from differential energy loss and/or jet bias

# Backup

# How we measure $\pi^0$ , $\eta$ ?

- Reconstruct hadrons via  $2\gamma$  invariant mass in EMCal (example is in Au+Au)

$$M^2 = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 = 2E_1E_2(1 - \cos\theta)$$

- Subtract Combinatorial background
  - Compute Mass using  $\gamma$ s from different events. (mixed-event technique)

PRC87, 034911 (2013)

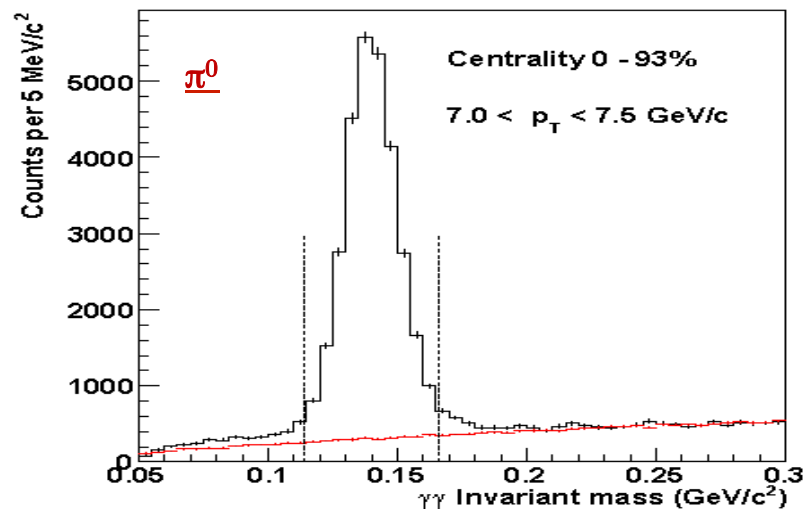
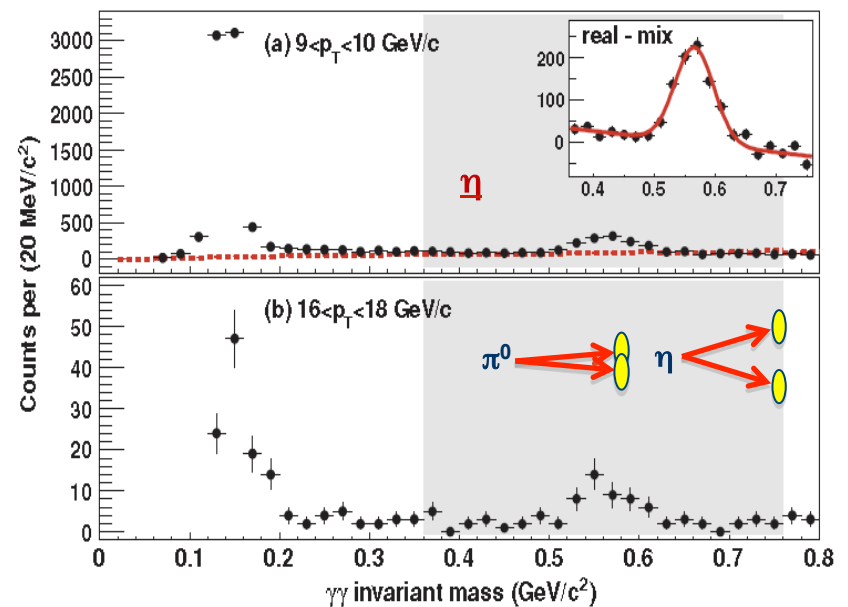


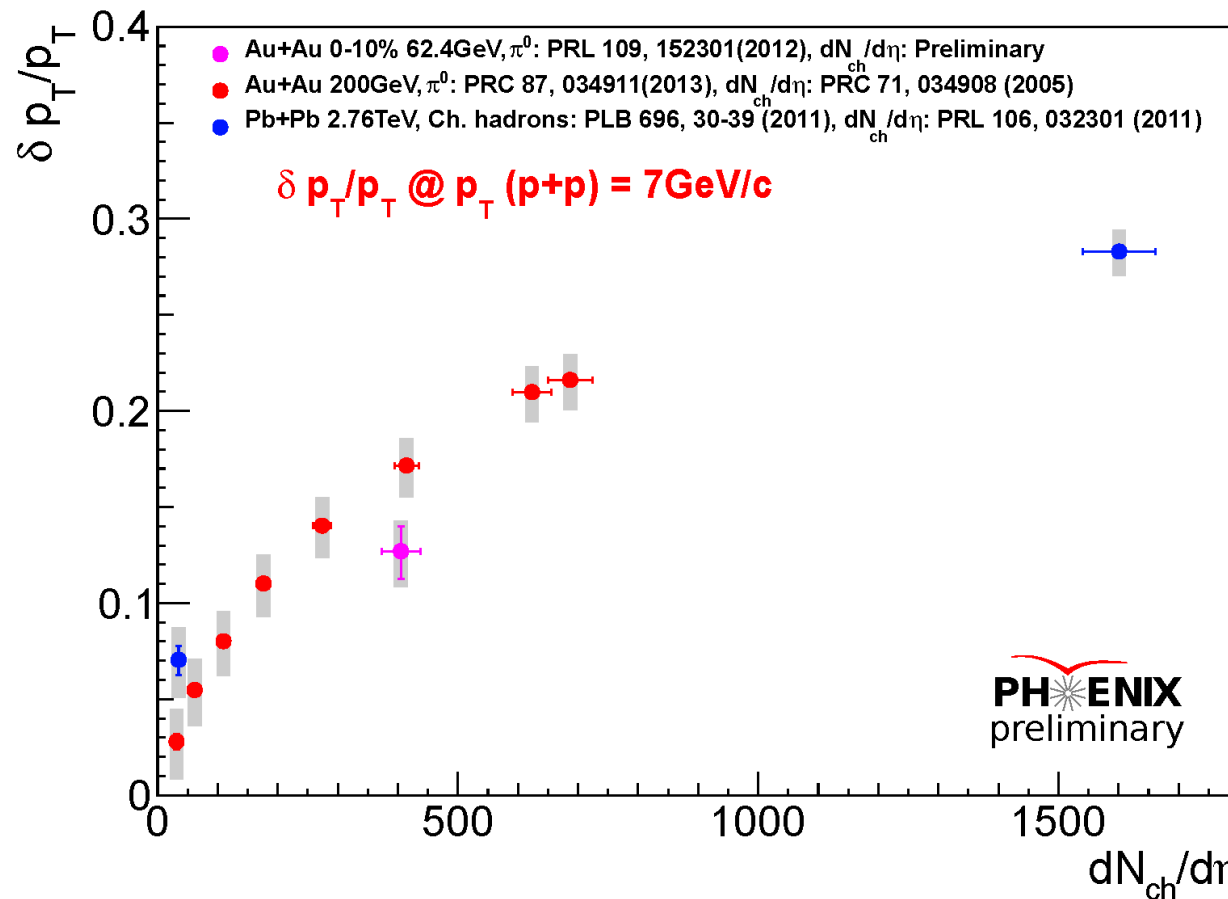
FIG. 3: (Color online) Invariant mass spectrum of two photons (black) and the corresponding mixed events (red) at  $7 < p_T < 7.5$  GeV/c in minimum bias collisions. Vertical lines indicate a  $\pm 2.5\sigma$  integration window.

PRC82, 011902(R) (2010)



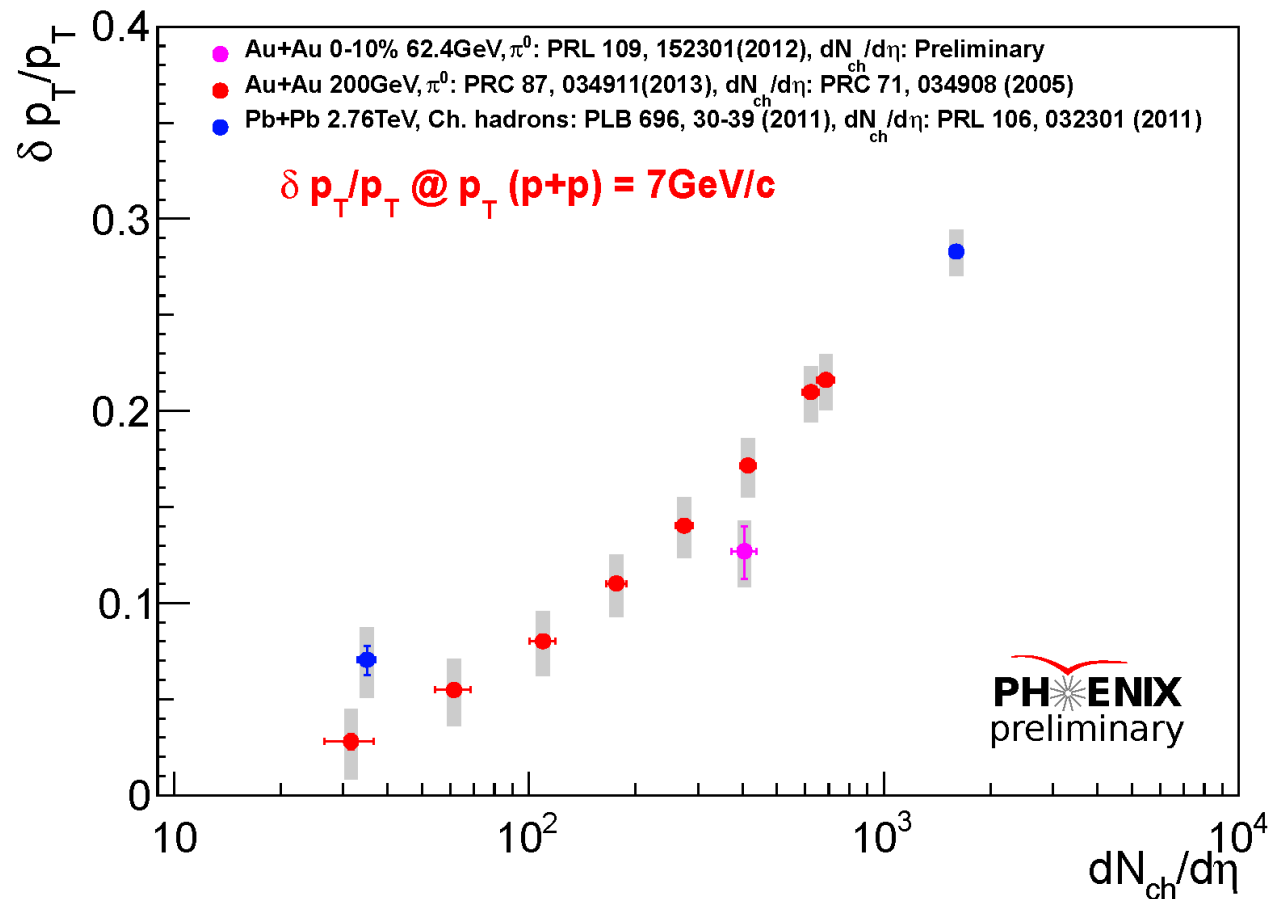
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- Plotting against  $dN_{ch}/d\eta$  (as a measure of energy density)
  - $dN_{ch}/d\eta$  obtained in given centrality at given cms energy
  - $\delta p_T/p_T$ 's at  $p_T=7\text{GeV}/c$  of p+p are plotted



# Detail study of $\delta p_T/p_T$ systematics

- Re-plotted same data points in log-scale for  $dN_{ch}/d\eta$ 
  - $\delta p_T/p_T$ 's at  $p_T=7\text{GeV}/c$  of p+p are plotted

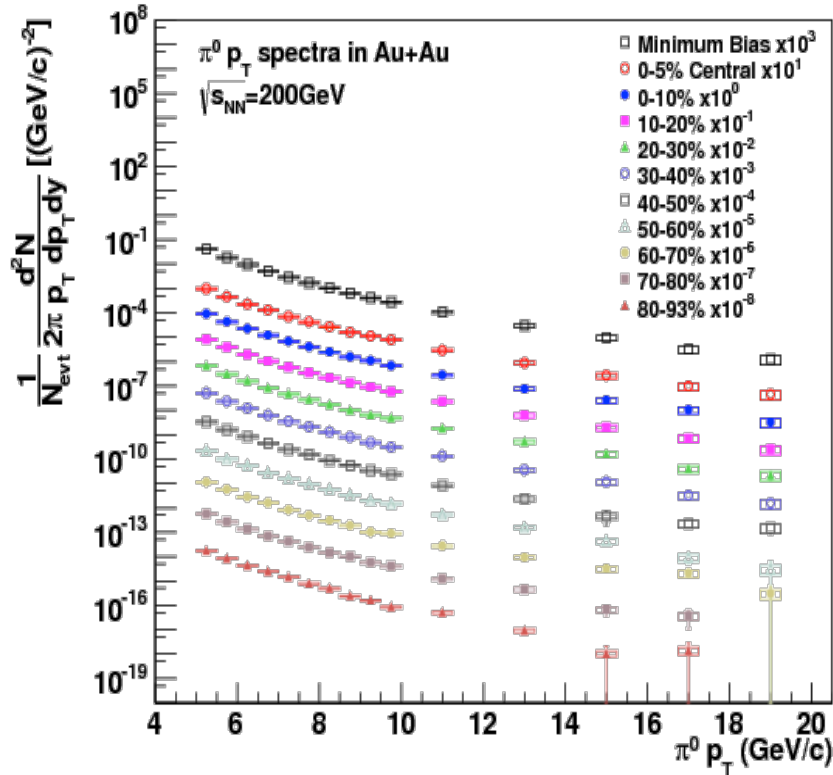




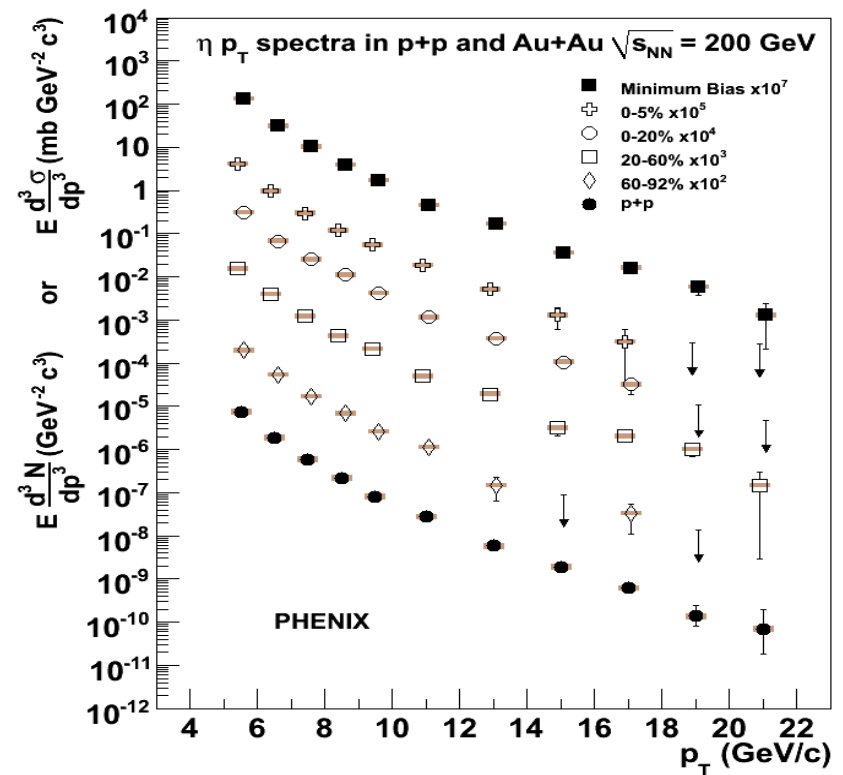
# $\pi^0, \eta$ spectra in Au+Au

- Spectra reached to  $\sim 20 \text{ GeV}/c$  for  $\pi^0$  and  $\sim 22 \text{ GeV}/c$  for  $\eta$

$\pi^0$



$\eta$



# Systematic errors

- Type A: point-by-point fluctuating errors
- Type B:  $p_T$ -correlated errors
- Type C: overall normalization errors

## $\pi^0$ systematic errors

source	type	5GeV	10GeV	15GeV	20GeV
peak extraction	B	2	2	2	2
acceptance	C	2.5	2.5	2.5	2.5
PID efficiency	B	7	8	8.5	9
energy scale	B	7.5	8	8	8
photon conversion	C	2	2	2	2
cluster merging	B	0	0	8	18
total		11	12	15	22

## $\eta$ systematic errors

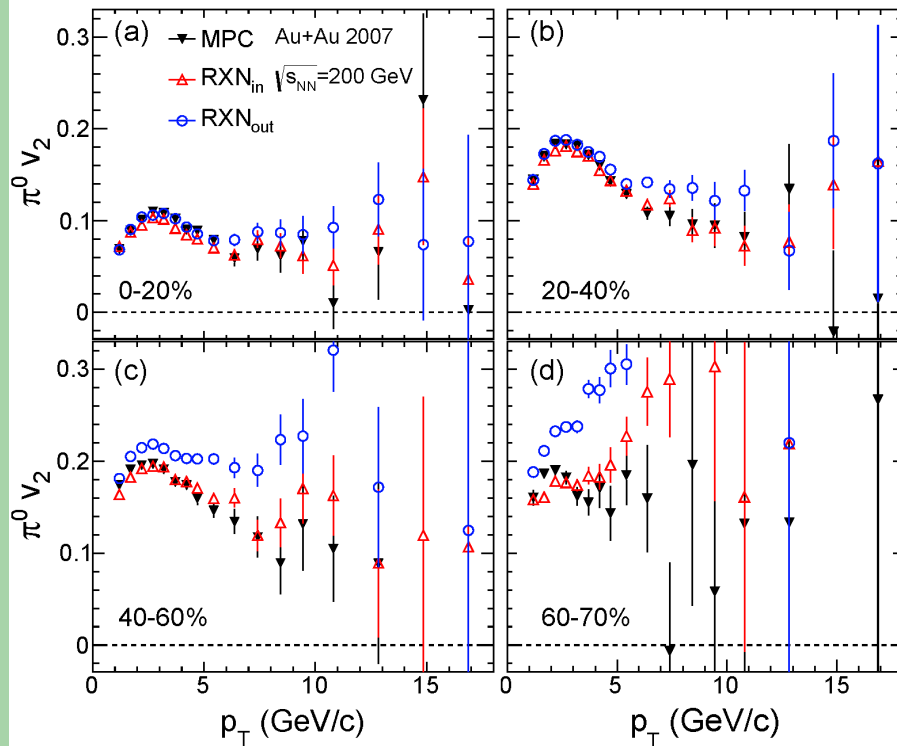
source	type	5GeV	10GeV	15GeV
peak extraction	B	4	3.5	3
acceptance	C	2.5	2.5	2.5
PID efficiency	B	7	8	8.5
energy scale	B	11	12	12
photon conversion	C	2	2	2
total		12	15	15

# $v_4$ and $v_2$ of high $p_T$ $\pi^0$

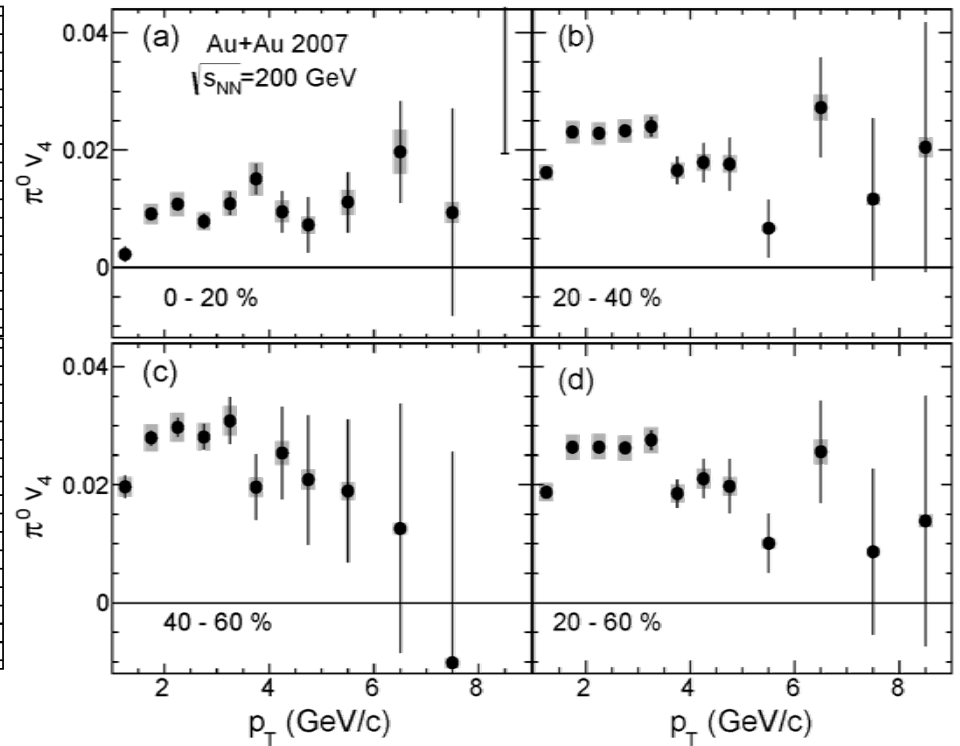
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PHENIX, arxiv:1309.4437

$\pi^0 v_2$



$\pi^0 v_4$



# d+Au and Au+Au system similarity?

- Au+Au 60-92% and d+Au 0-20% have similar  $N_{\text{part}}$ ,  $N_{\text{coll}}$
- Ratios of all ID'ed hadron spectra are on the same curve
- Common production mechanism?
- If all CNM scales with  $N_{\text{part}}$ , ratios may mean  $E_{\text{loss}}$  in the medium in peripheral Au+Au
- Low  $p_T$  increase may rise from rapidity shift in d+Au

arXiv:1304.3410

