PHENIX

BROOKHAVEN NATIONAL LABORATORY

Profiling hot and dense nuclear medium with high transverse momentum hadrons produced in d+Au and Au+Au collisions by the PHENIX experiment at RHIC

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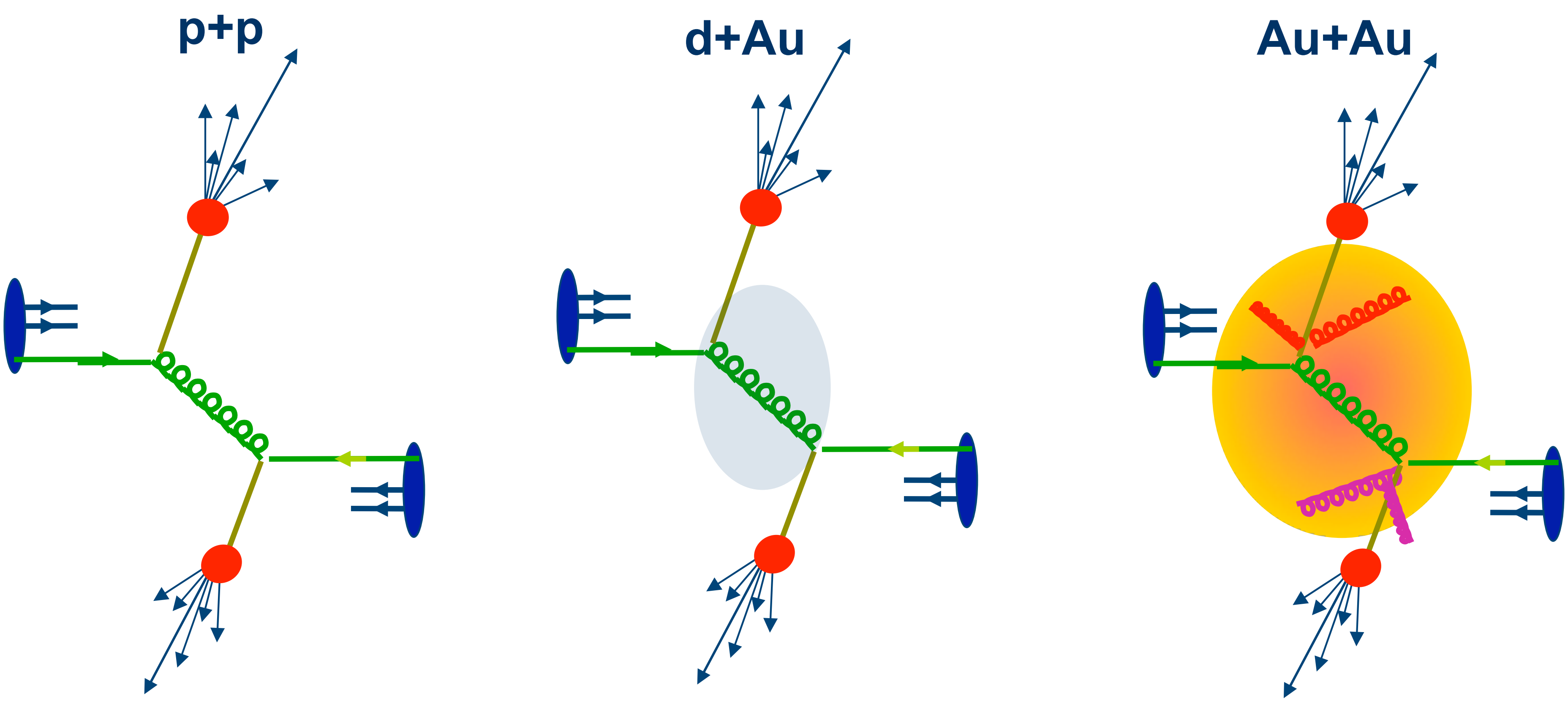
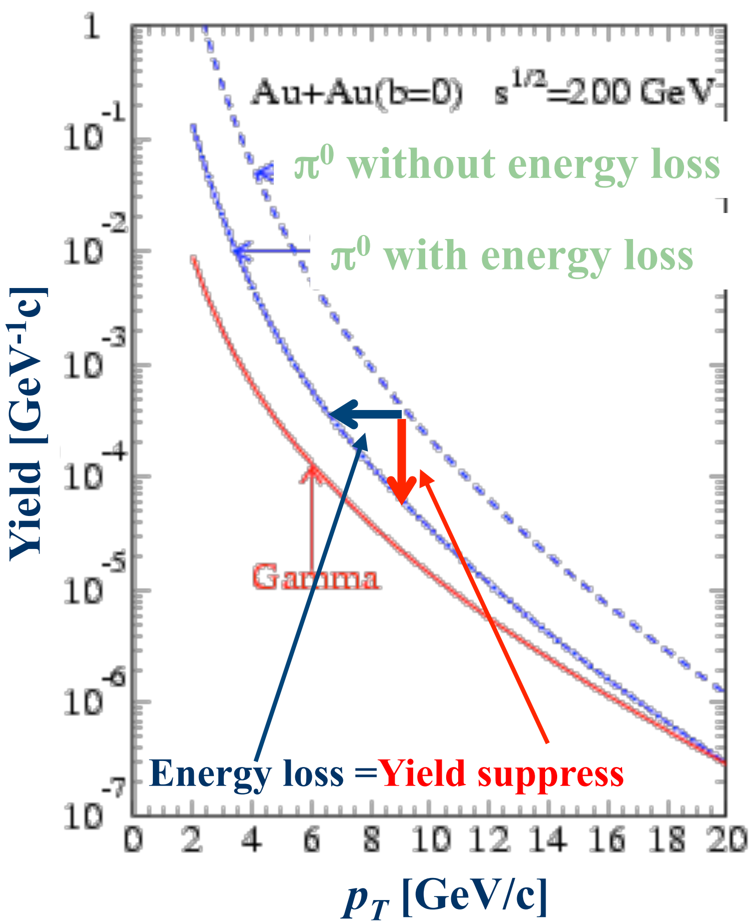
Hard scattering as densimeter

- Parton may change its momentum in the medium
  - Energy loss through Gluon radiation, etc. (A+A)
  - Momentum broadening by multiple scattering in nucleus (p, d+A)
- Effect may be path-length and system dependent
  - A densimeter of the medium



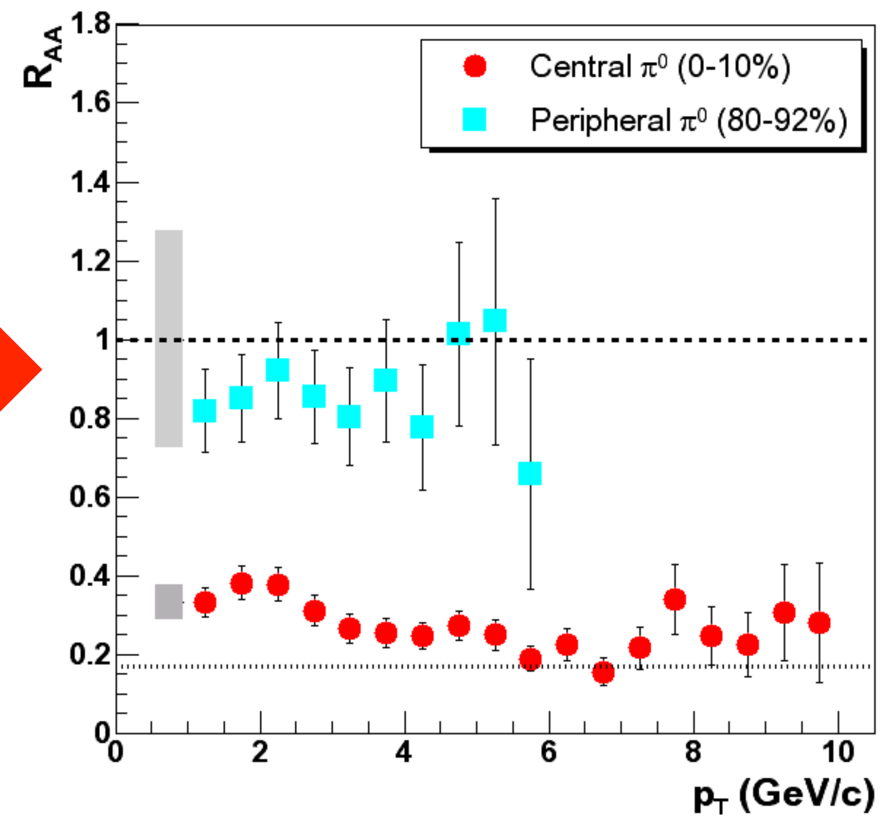
Way to look at jet modification

- Look at leading particles of jet as a measure of jet momentum
- Yield modification. ***We focus on π^0 and η as observables***

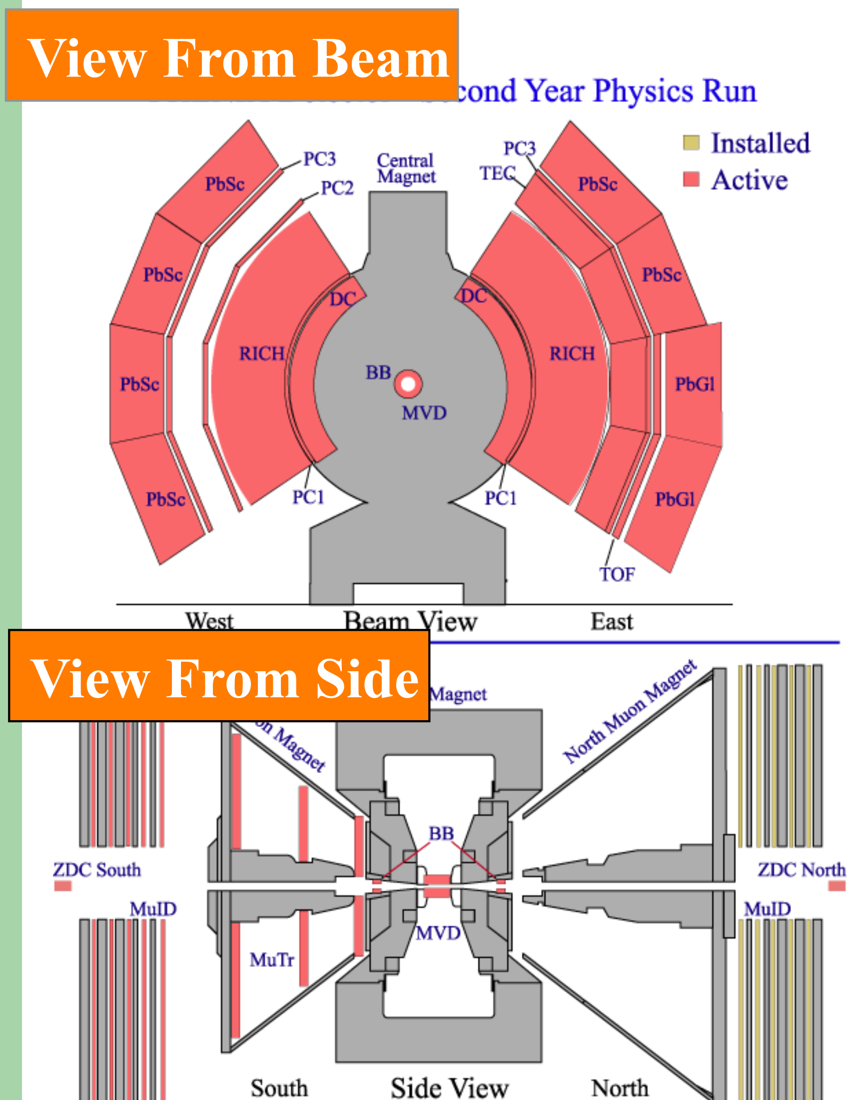


X.-N., Wang, PRC 58 (1998)2321

PHENIX, π^0 in Au+Au, PRL. 91, 072301 (2003)



PHENIX Detector



- Photon measurement
  - EMCal(PbSc, PbGl): Energy measurement and identification of real photons
  - Tracking(DC, PC): Veto to Charged particles

- Event triggered by a coincidence of BBC South and BBC North
  - Sitting in $3.1<|\eta|<3.9$

PHENIX recorded:
d+Au events of 80 nb^{-1} in 2008
Au+Au events of 0.813nb^{-1} in 2007

How we measure π^0, η?

- Reconstruct hadrons via 2γ 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 γs from different events. (mixed-event technique)

PRC87, 034911 (2013)

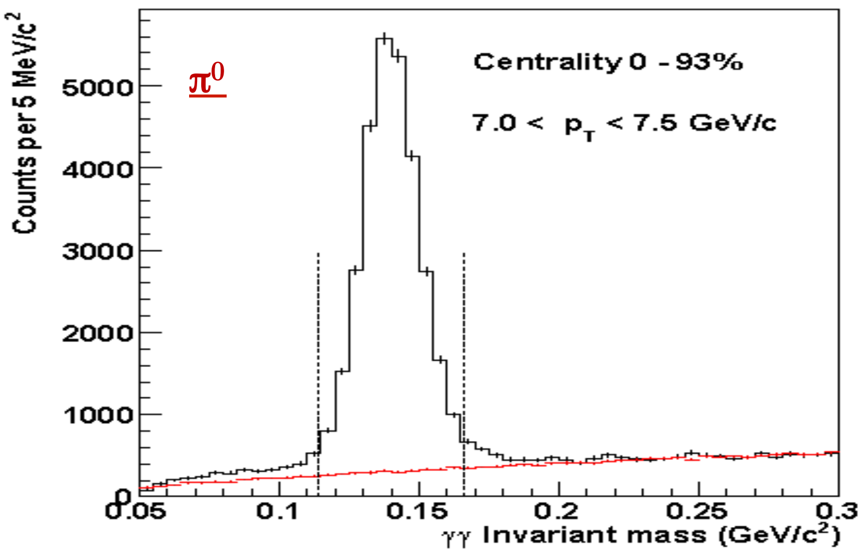
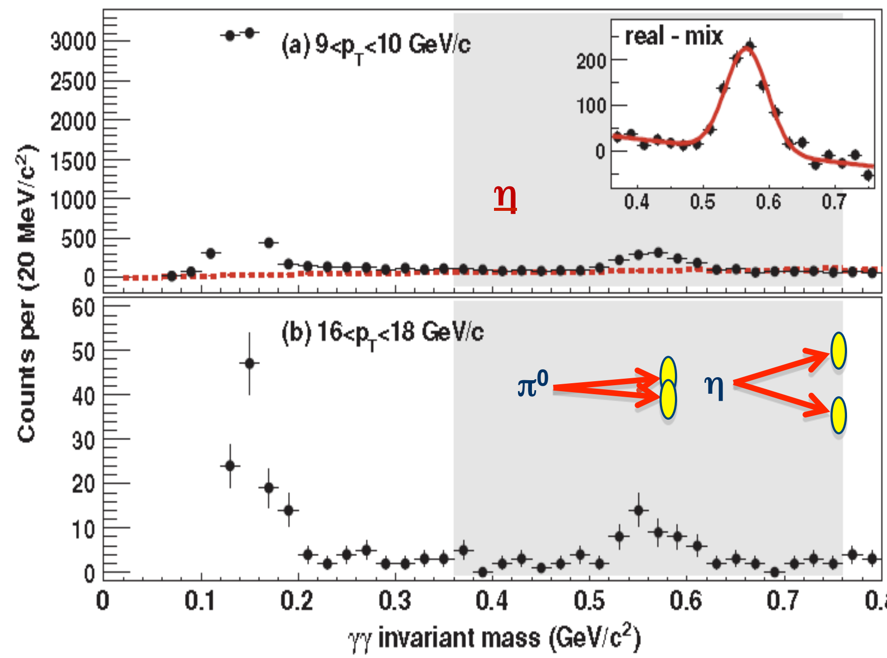


FIG. 3: (Color online) Invariant mass spectrum of two photons (black) and the corresponding mixed events (red) at $7 < p_T < 7.5$ GeV/c in minimum bias collisions. Vertical lines indicate a $\pm 2.5\ \sigma$ integration window.

PRC82, 011902(R) (2010)

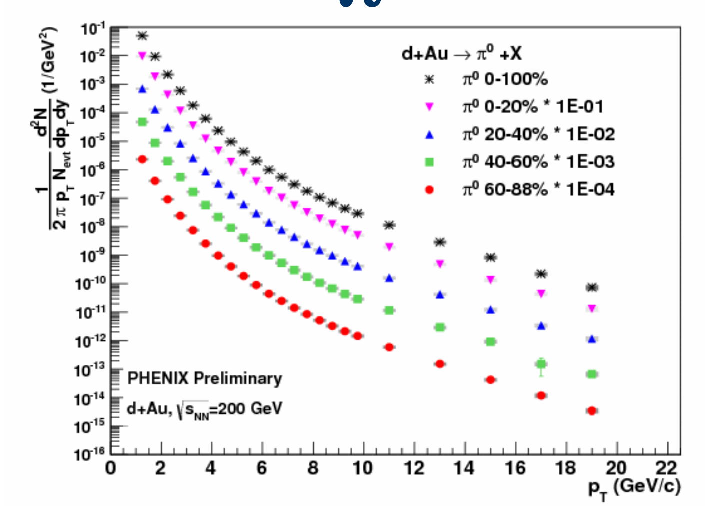


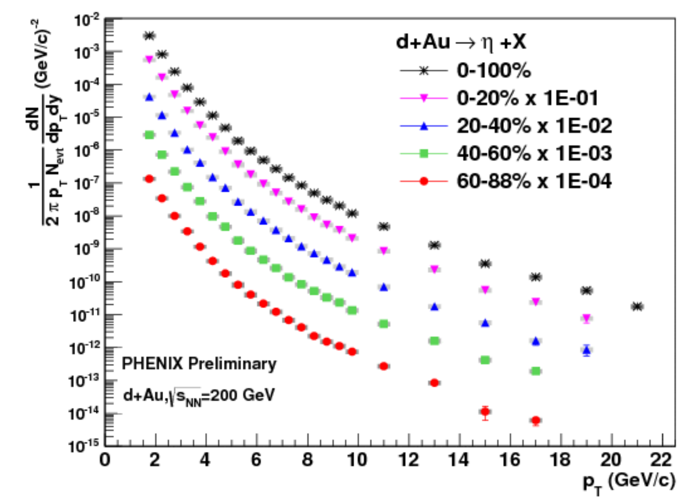
π^0, η spectra in d+Au and Au+Au

- Spectra reached to ~20GeV/c for π^0 and ~22GeV/c for η

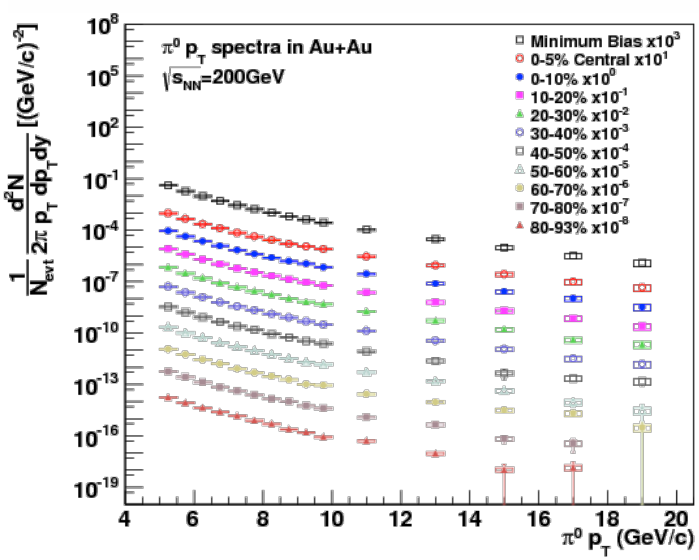
π^0 η

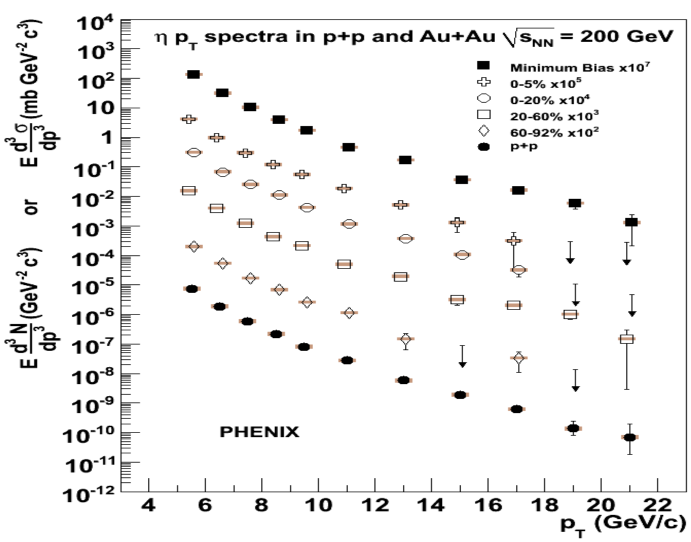
d+Au





Au+Au

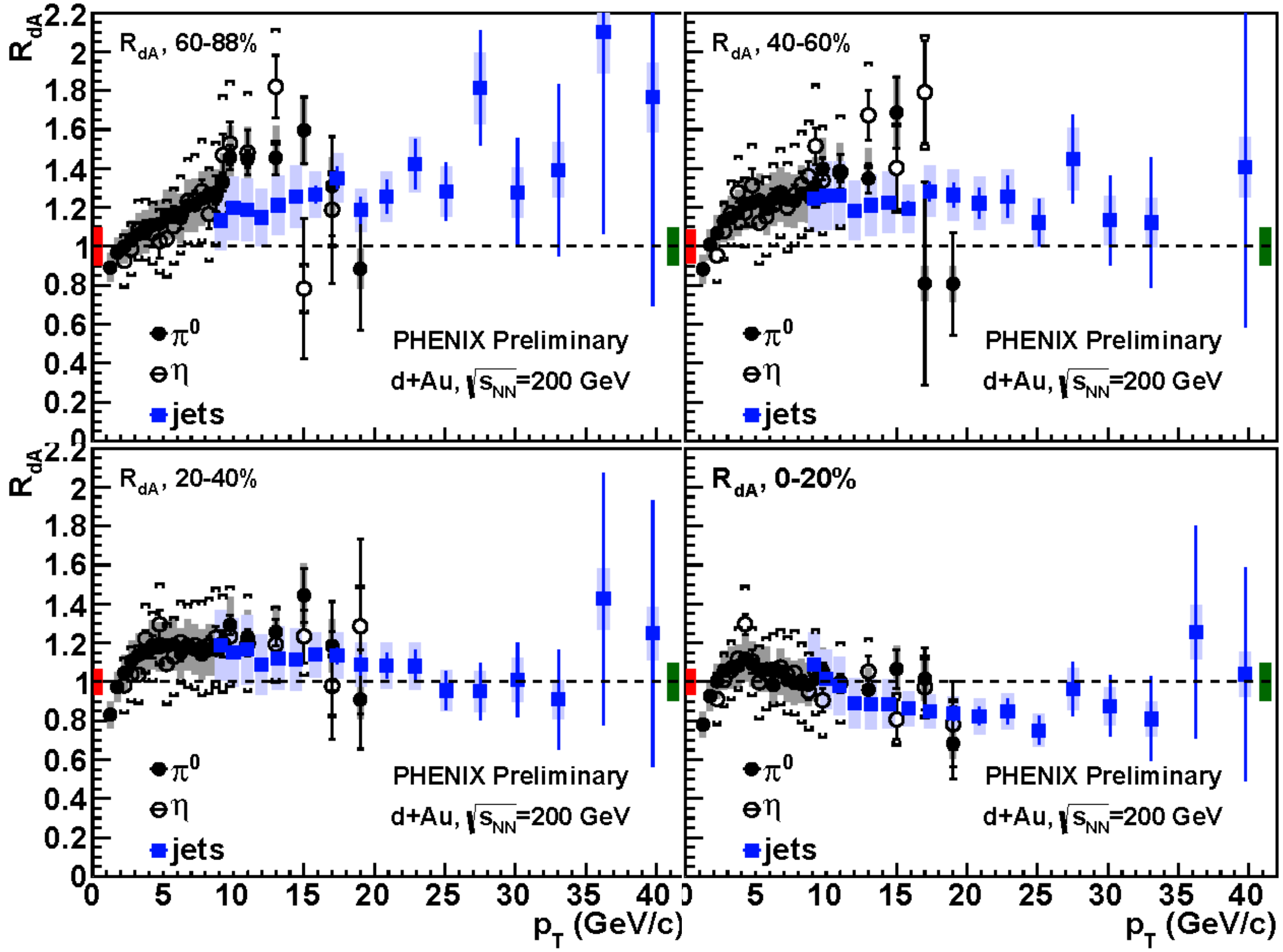




π^0 and η (and jets) R_{dA}

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

- Consistent with 1 for p_T<10GeV for most of centrality class
- Strong centrality dependence is seen



π^0 , η and jets are in good agreement, though the systematics is very different

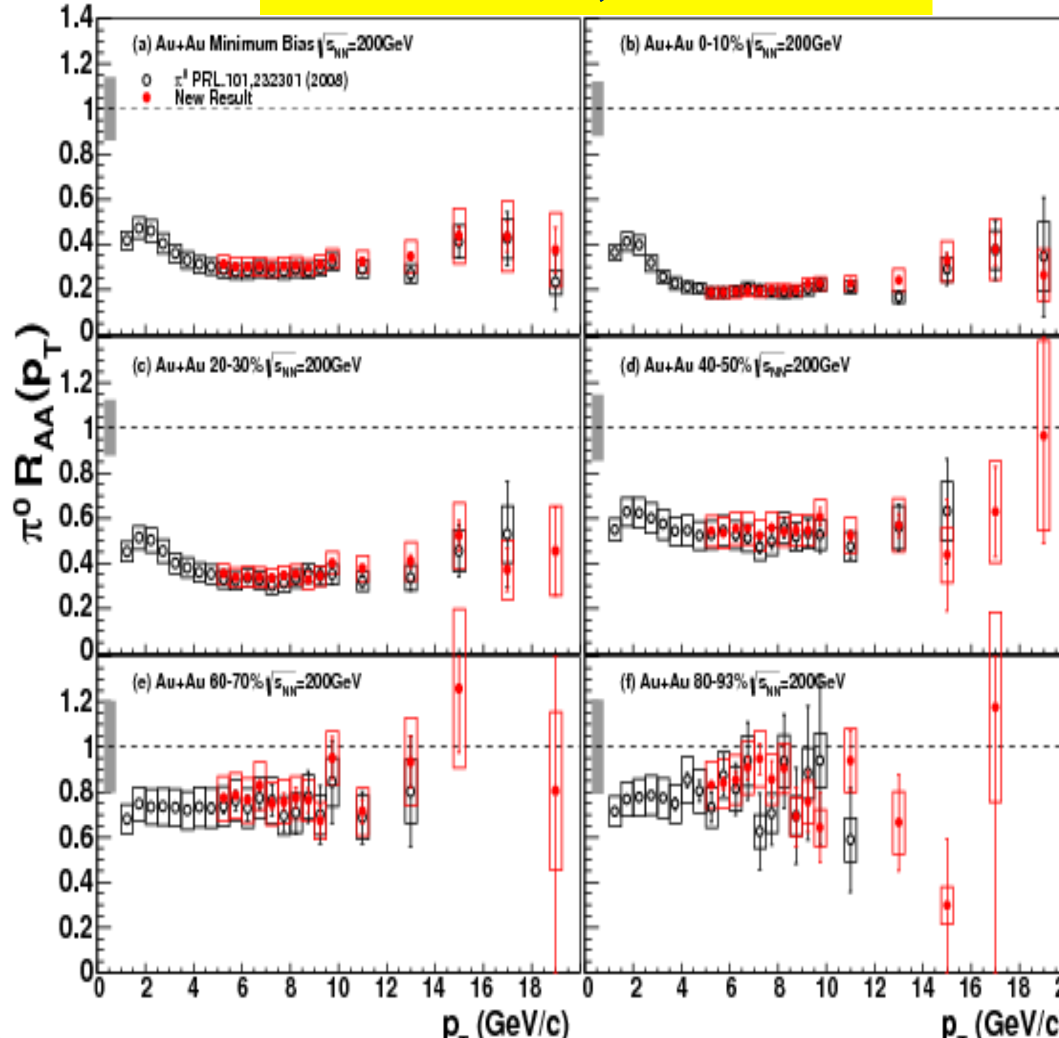
π^0 and η R_{AA}

- 200GeV Au+Au collision system
- π^0 and η nicely agree
- Very nice agreement between RHIC Year-2004 and 2007 results

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

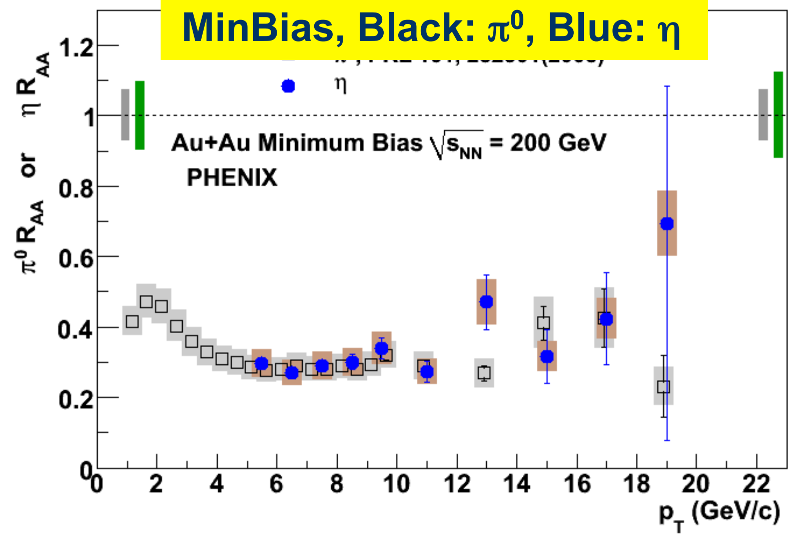
PRC87, 034911 (2013)

Black: Year-2004, Red: Year-2007



PRC82, 011902(R) (2010)

MinBias, Black: π^0, Blue: η

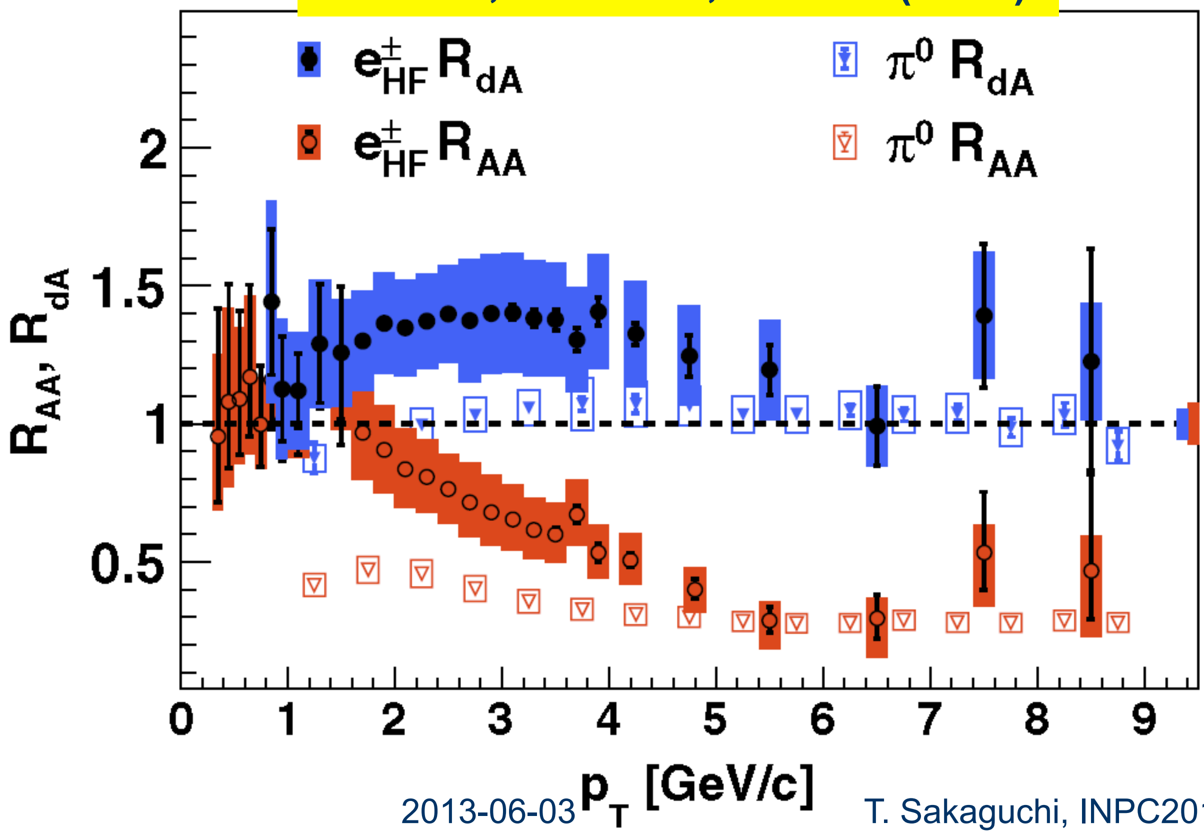


Flavor similarity?

- Different quark flavor may give different interaction
  - Mass ordering (dead-cone effect, etc.)

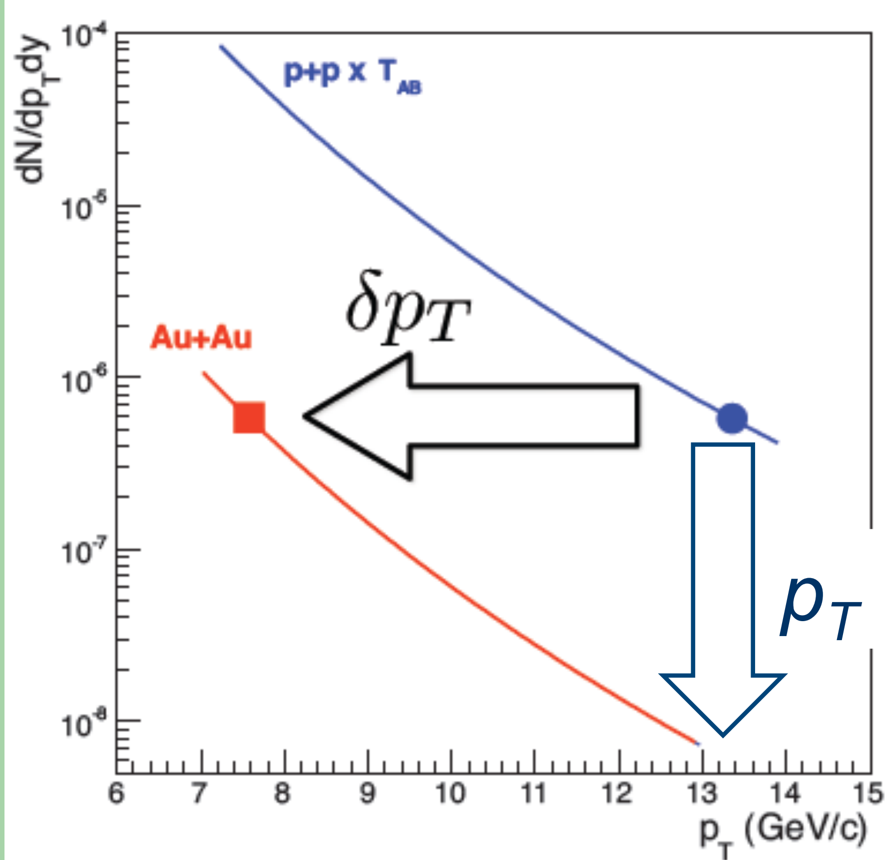
- Electrons from Heavy flavor quark (c,b) show similar R_{AA} and R_{dA} as π^0 decayed from light flavor quark (u,d) or gluons

PHENIX, PRL. 109, 242301 (2012)

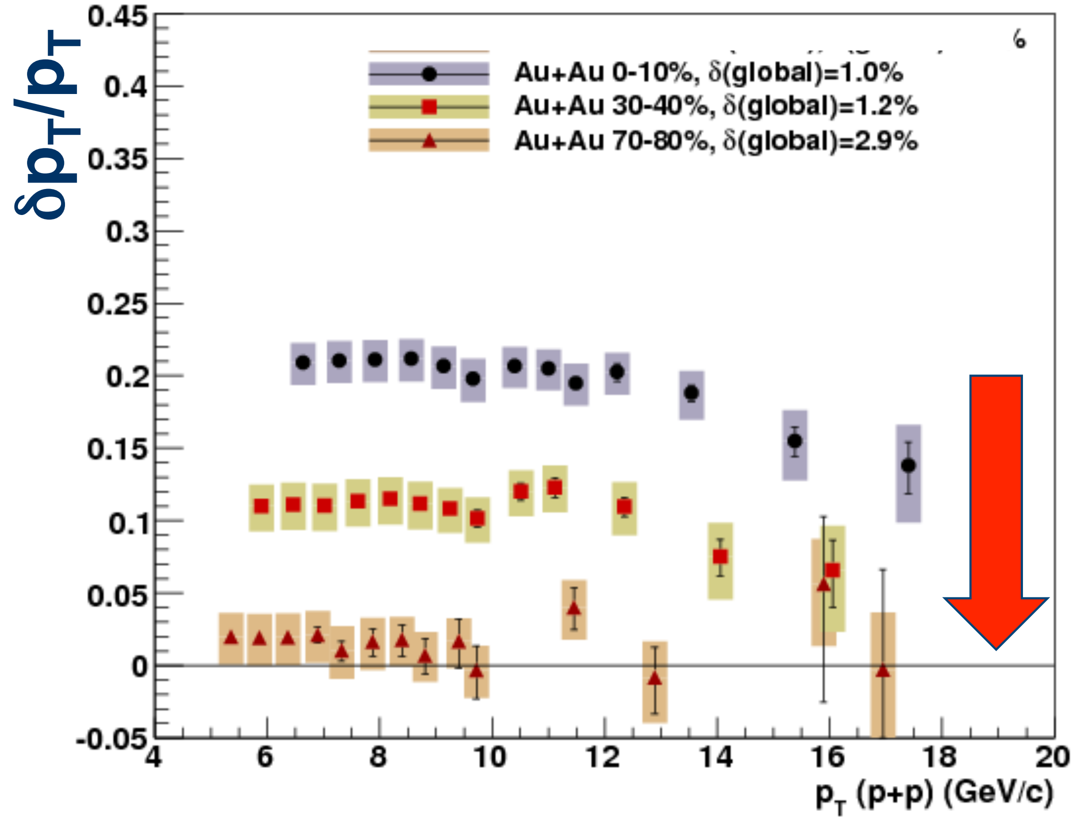


Fractional momentum loss of partons

- 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



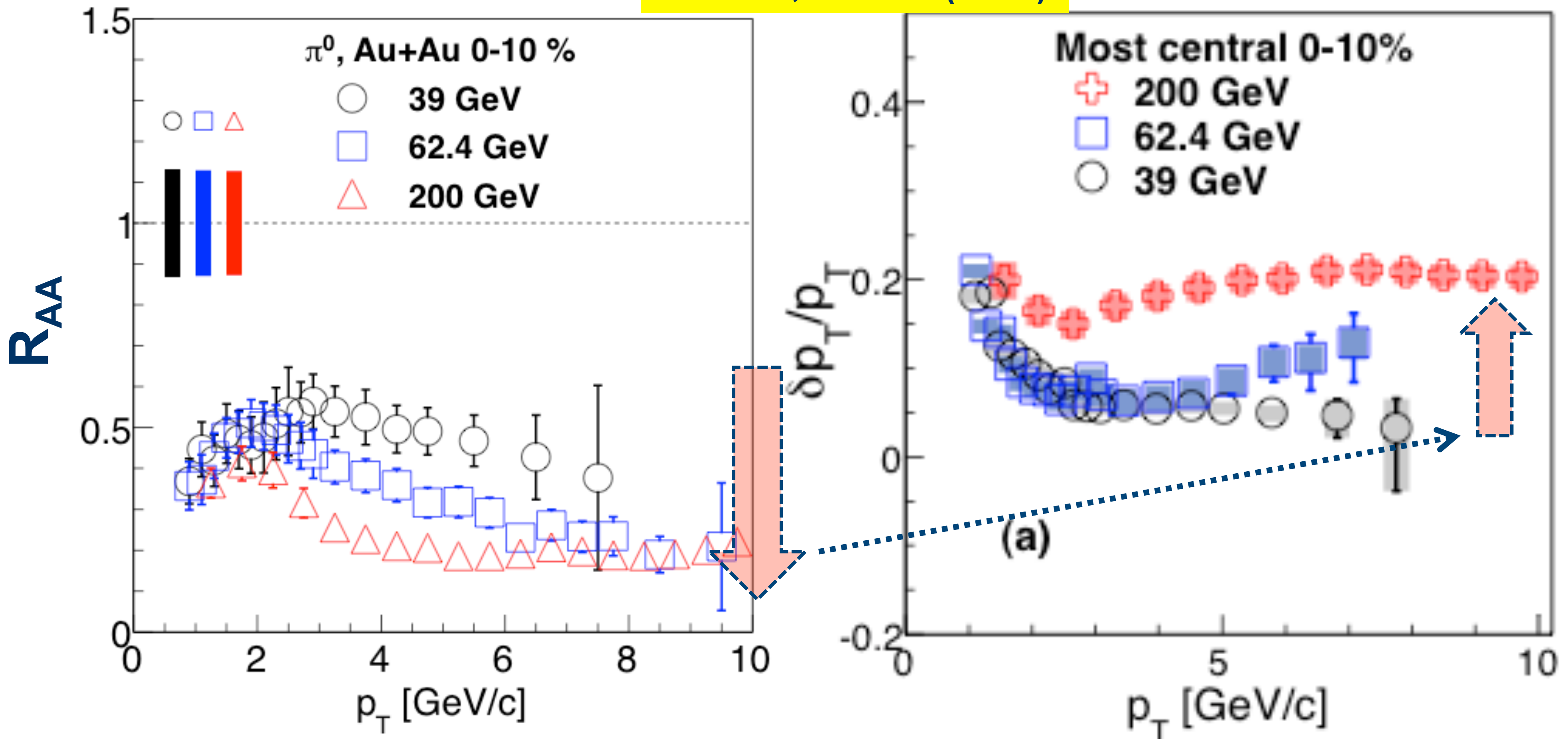
PRC87, 034911 (2013)



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

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

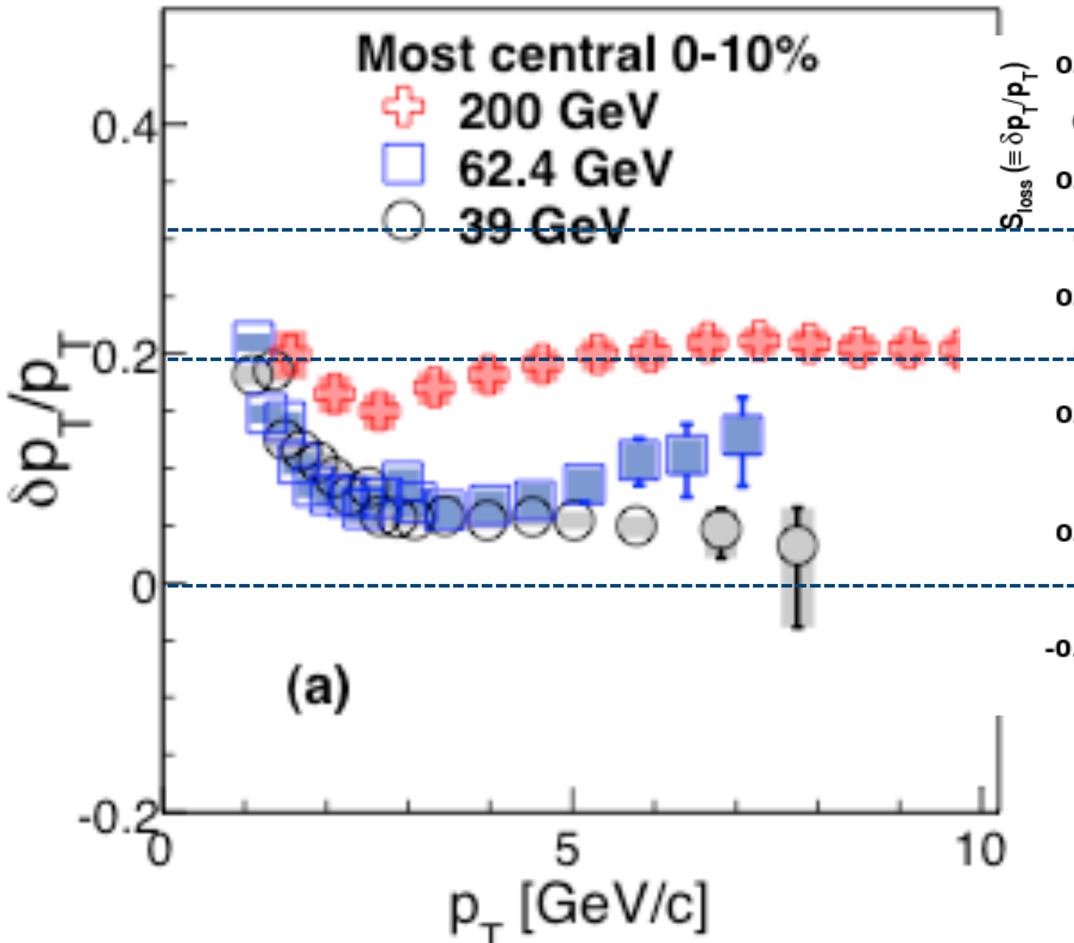
PRL109, 152301 (2012)



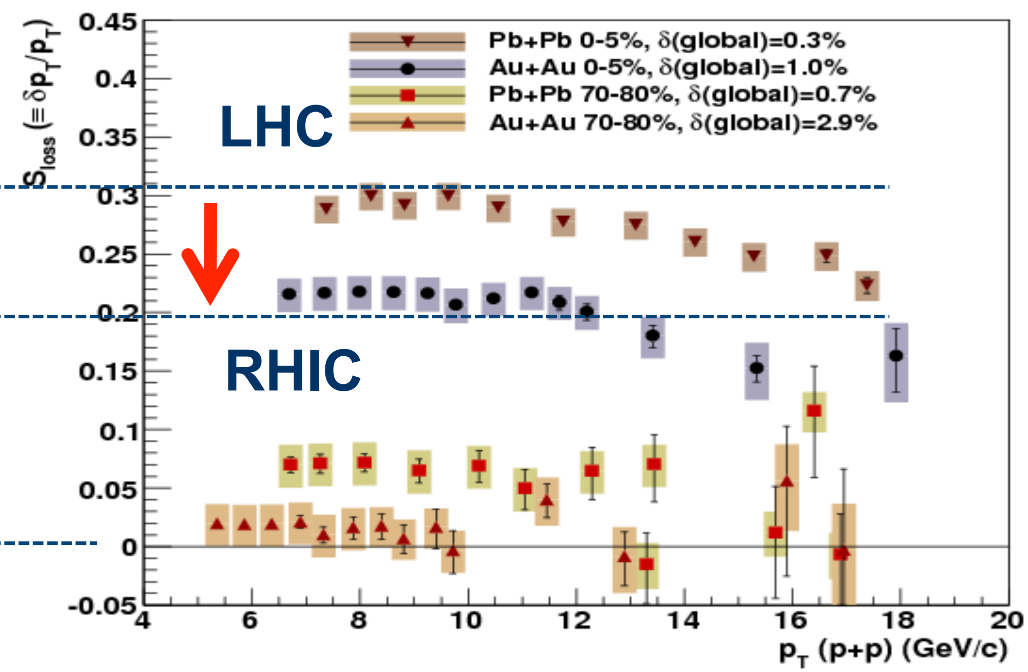
Energy dependence of $\delta p_T/p_T$ (II)

- $\delta p_T/p_T$ from 39GeV to 2.76TeV!: ~0.3 for LHC

PRL109, 152301 (2012)



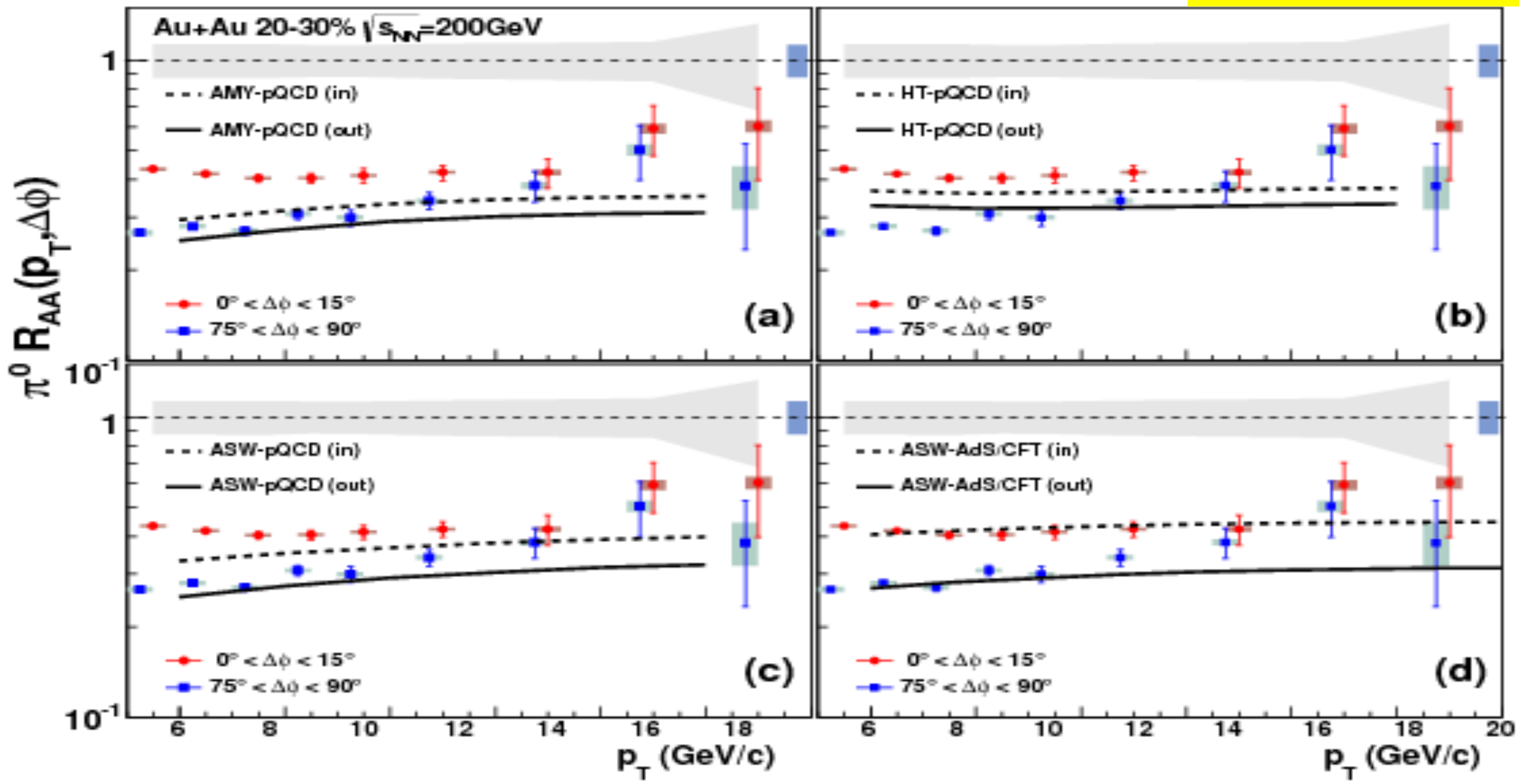
PRC87, 034911 (2013)



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

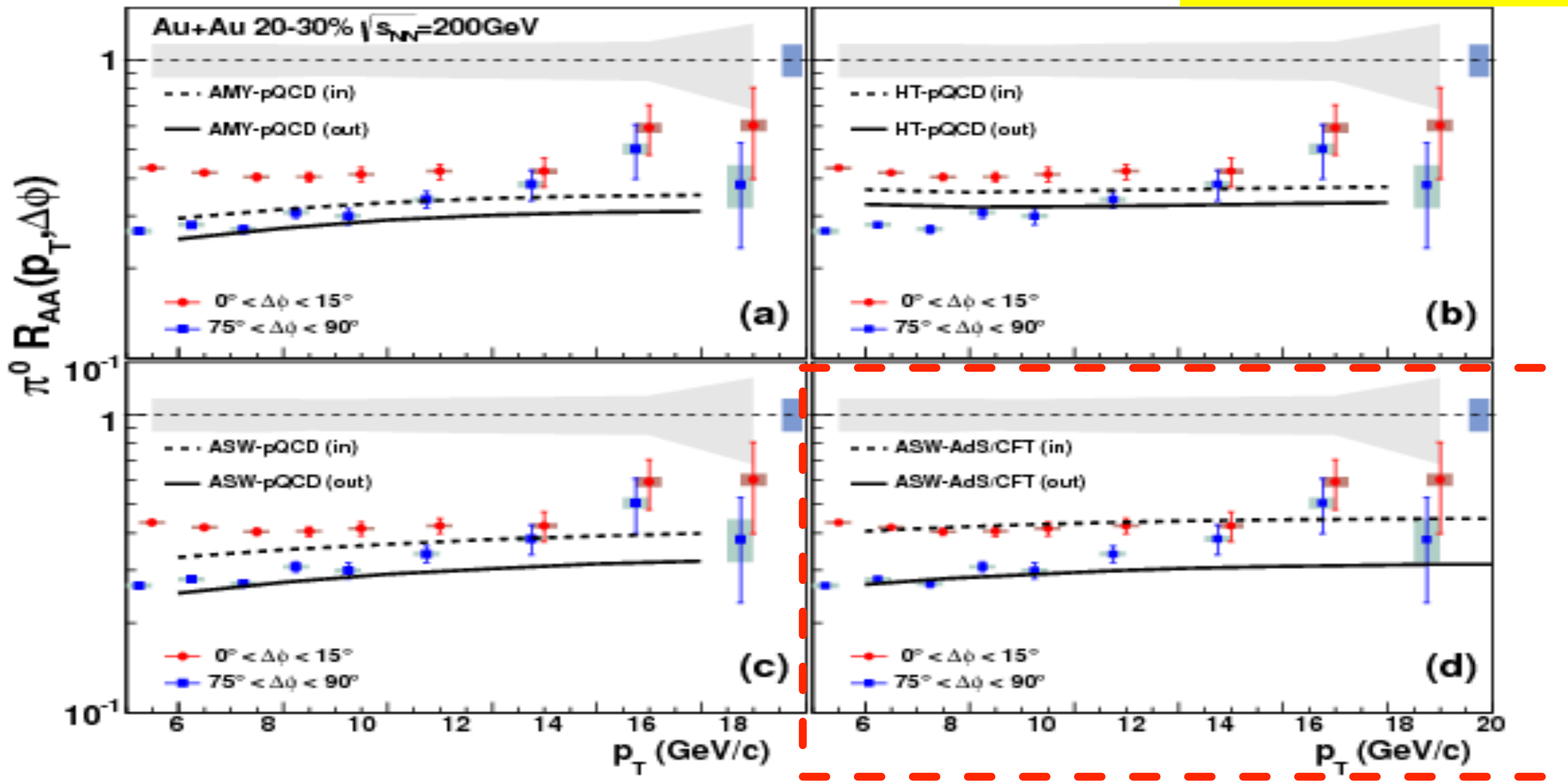
PRC87, 034911 (2013)



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 the Energy loss is L^3 dependent not L^2.

PRC87, 034911 (2013)

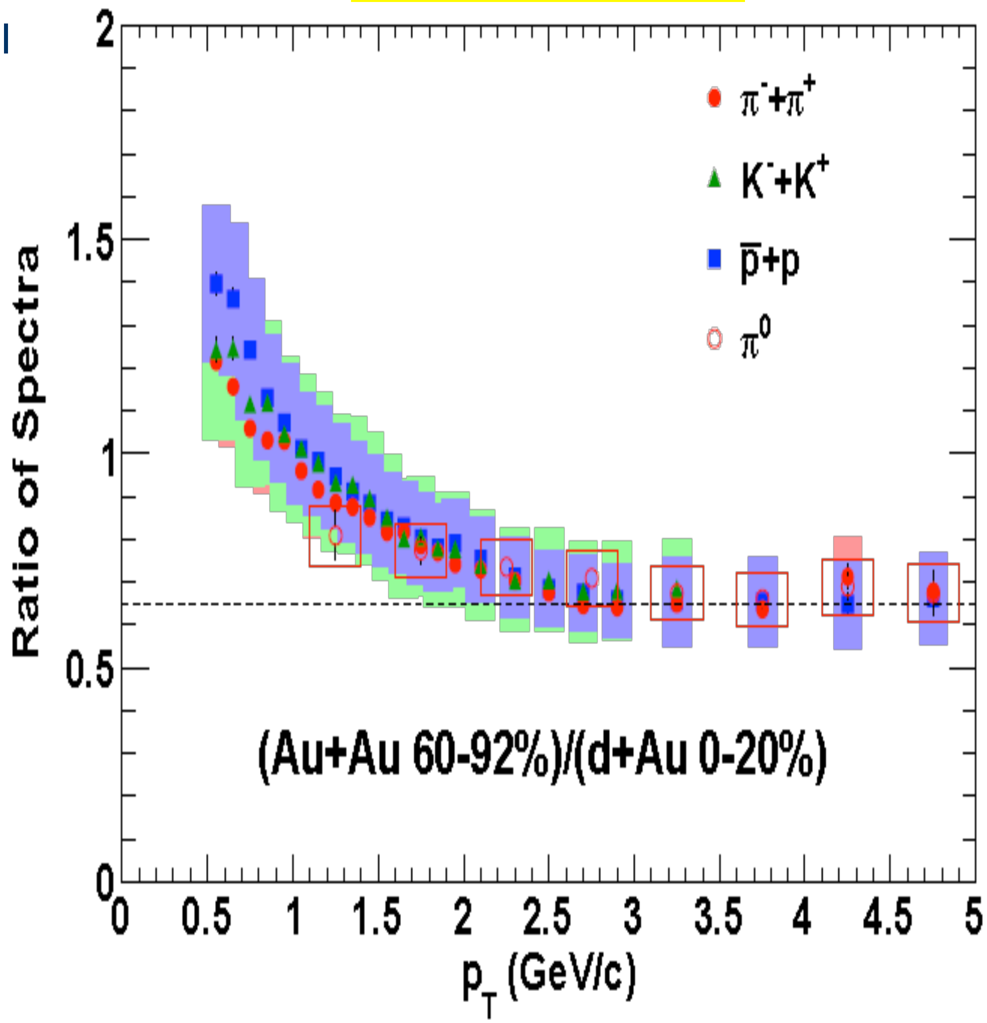


 2013-06-03 T. Sakaguchi, INPC2013@Florence, Italy

d+Au and Au+Au system similarity?

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

arXiv:1304.3410



Summary

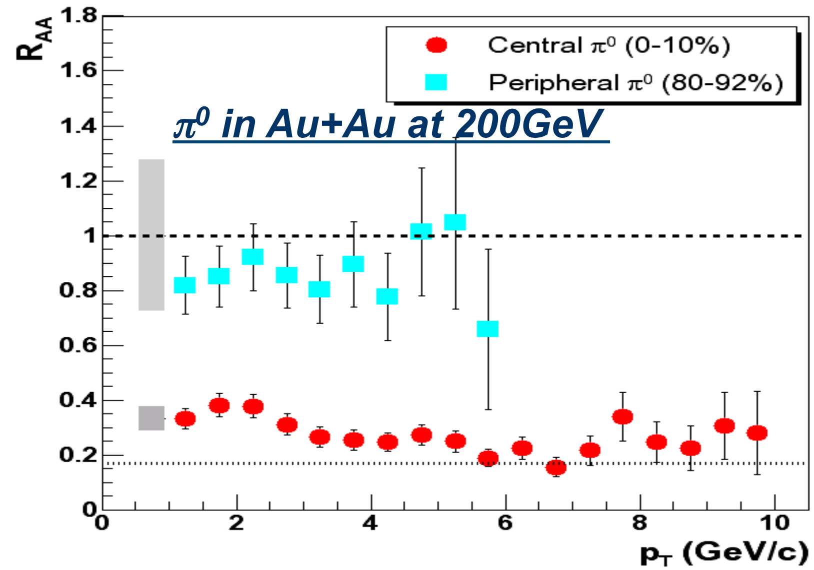
- π^0 and η are measured in 200GeV d+Au and Au+Au collisions
  - π^0 and η give very consistent results in R_{dA} and R_{AA}
- π^0 and HF electrons R_{AA} and R_{dA} have similar trend
  - Similar amount of final state interaction for LF and HF?
- Fractional momentum losses vary a factor of 6, as going from 39GeV Au+Au to 2.76TeV Pb+Pb collisions
- Eloss of partons is L^3 dependent
- Partons may lose their energies in peripheral Au+Au collisions rather than in central d+Au collisions
  - If CNM effects scales with N_{part}

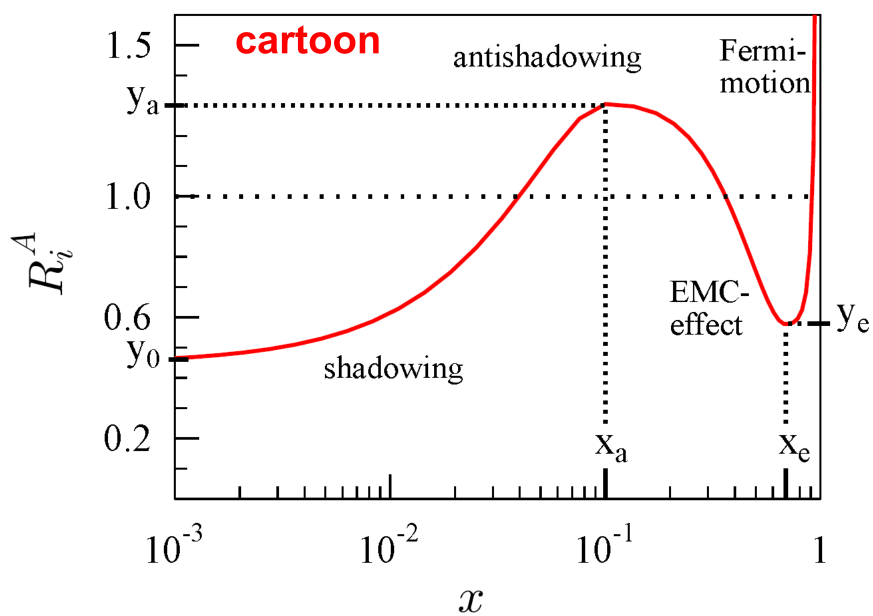
Backup

Why are we interested in d+Au collisions?

- In order to confirm that the high p_T hadron suppression in Au+Au collisions is due to final state effect, and not cold nuclear matter (CNM) effect
  - Need system without additional effects from a hot medium.
- CNM effect include:
  - k_T-broadening (Cronin enhancement at moderate p_T)
  - Shadowing of parton distributions
  - Cold nuclear matter energy loss
  - And possibly more…
- d+Au is more favorable for RHIC operation
  - p+Au becomes feasible now (M.Bai)

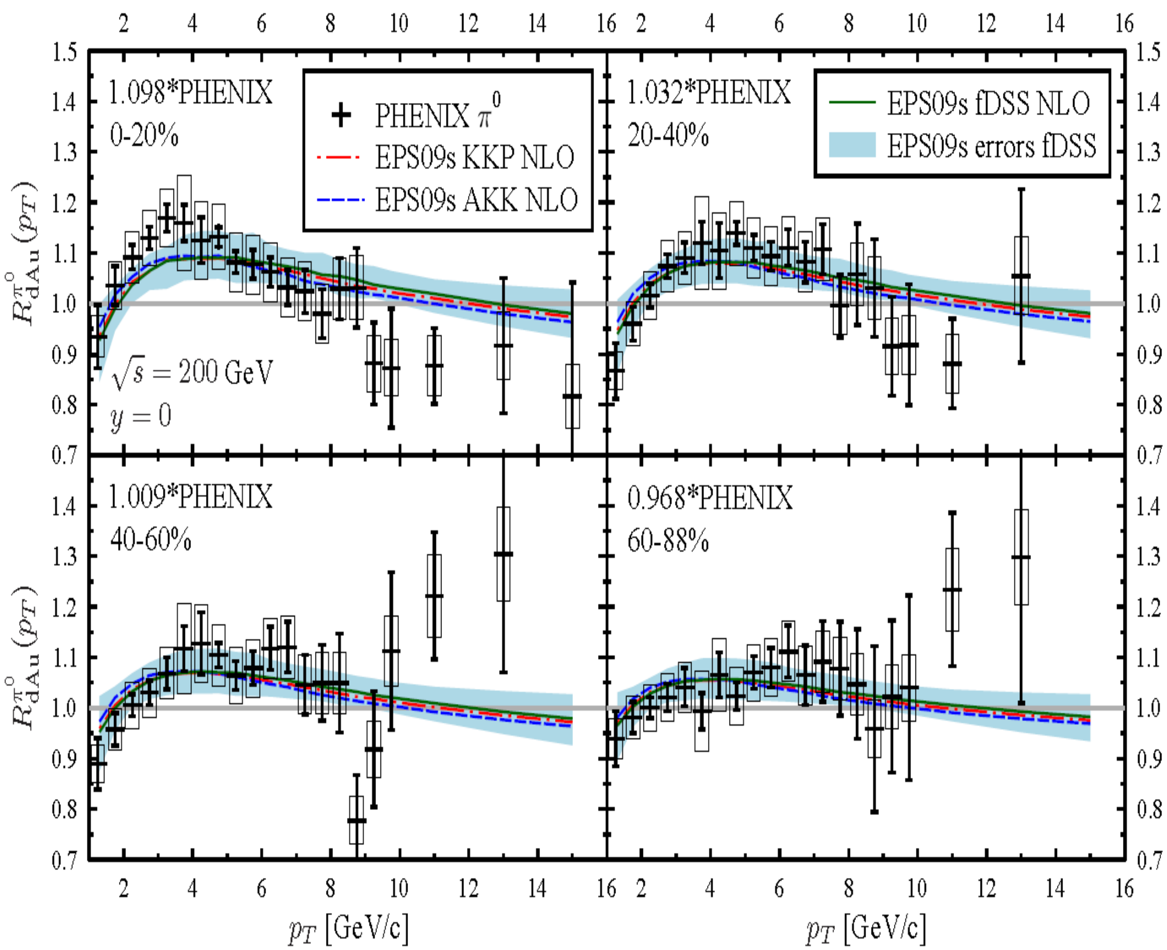
PHENIX, Phys. Rev. Lett. 91, 072301 (2003)





Nuclear PDFs are centrality dependent?

- Helenius, Eskola et.al. published centrality dependent nuclear PDFs (arXiv:1205.5359)
- Compared to PHENIX π^0 R_{dA} published in 2003
- Theory curves are scaled up/down within systematics
- New data can help better constraining nPDFs



Systematic errors

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

π^0 systematic errors

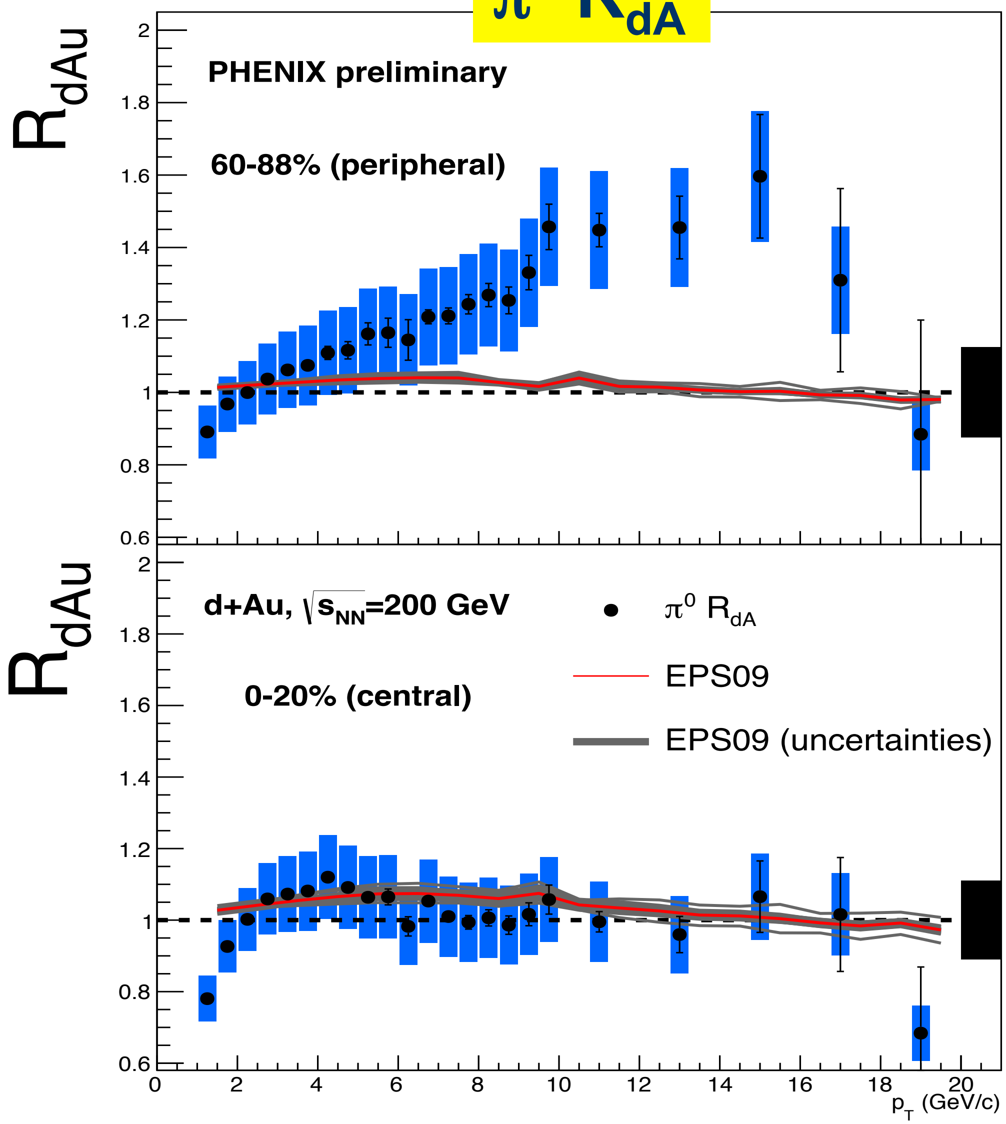
source	type	5GeV	10GeV	15GeV	20GeV
peak extraction	B	2	2	2	2
acceptance	C	2.5	2.5	2.5	2.5
PID efficiency	B	7	8	8.5	9
energy scale	B	7.5	8	8	8
photon conversion	C	2	2	2	2
cluster merging	B	0	0	8	18
total		11	12	15	22

η 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

Comparison to shadowing calculation (I)

π^0 R_{dA}



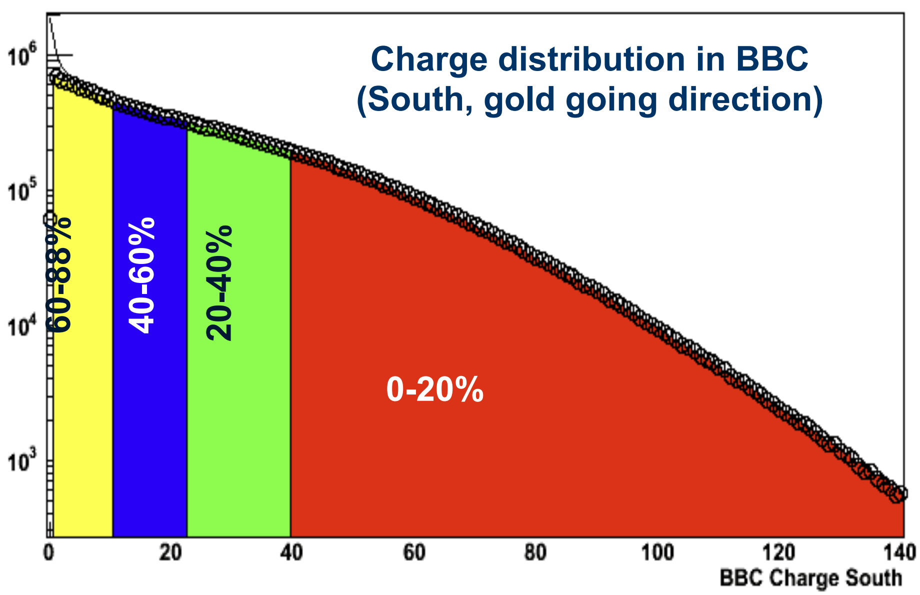
(Very basic) shadowing calculation uses EPS09 PDF modification* + Glauber MC + PYTHIA (x,Q^2) sampling for π^0.

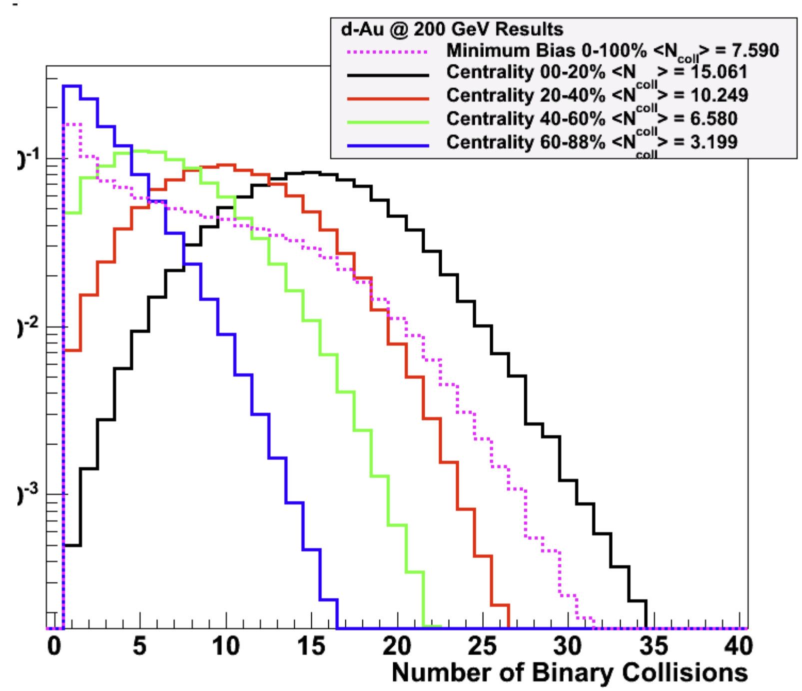
Shadowing effects match reasonably well within the global scale uncertainties in central events (where modification is weak), but is not compatible with the p_T shape in peripheral.

*nPDF modification assumed to scale linearly with longitudinal nuclear thickness.

How we define centralities?

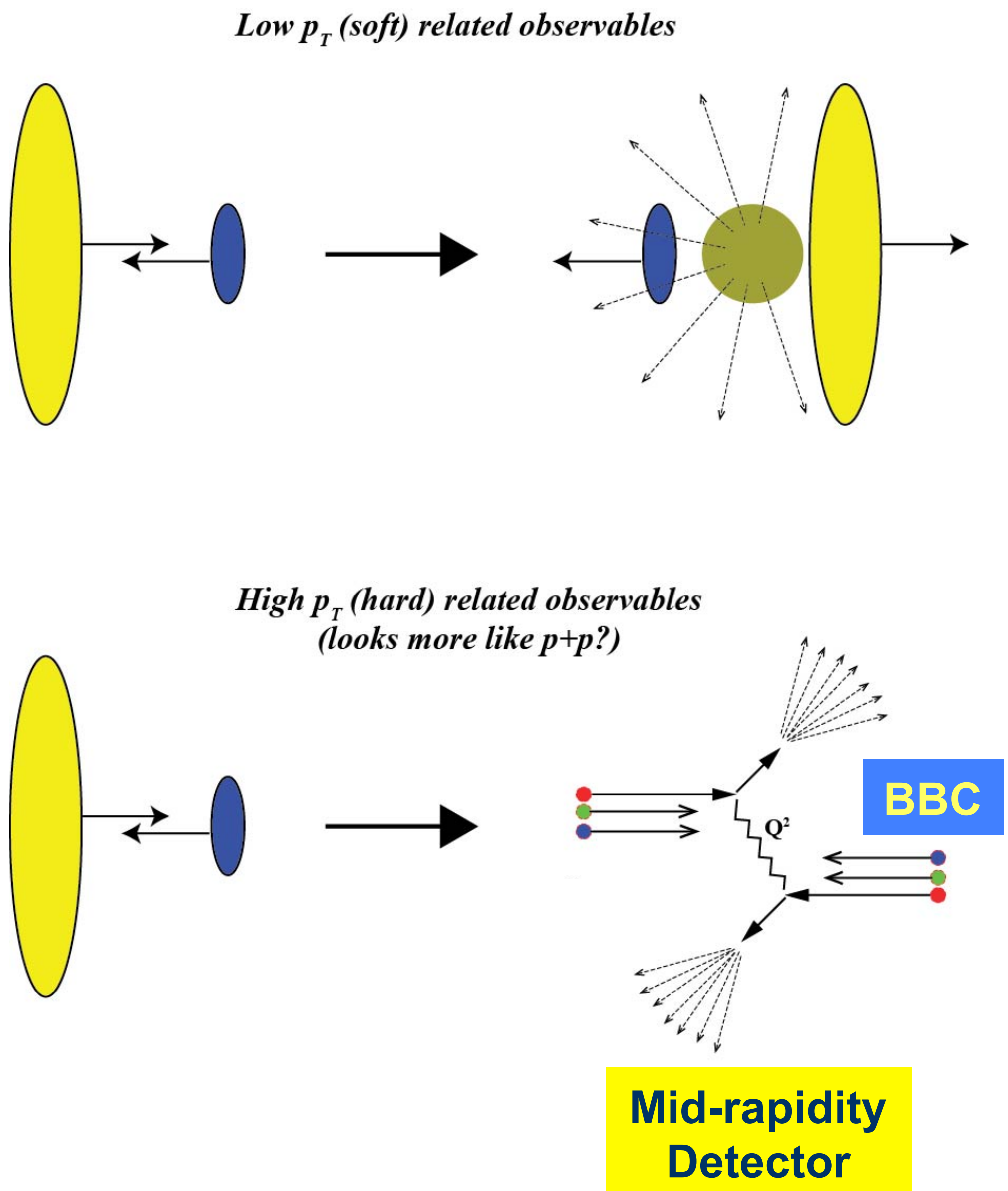
- Use Beam-Beam counter (BBC) installed in $3.1<|\eta|<3.9$
  - Centrality defined by BBC south charge (Gold going direction)
  - Participant region
- Compare with Monte Carlo simulations and determine T_{AB}
  - Glauber calculation folded with negative binominal distributions (NBD)





Possible dynamics in d+Au collisions

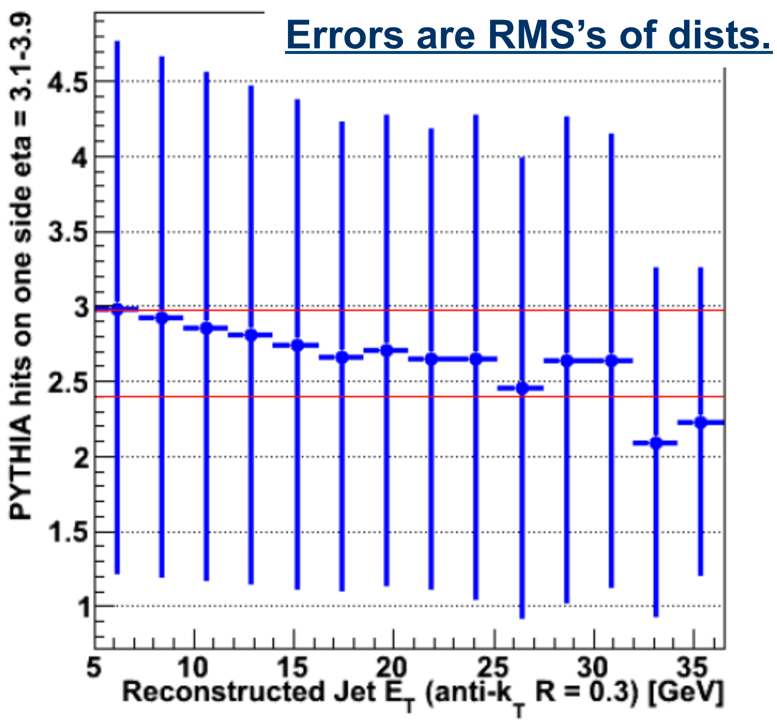
- We talk about ***peripheral*** collision case
- Soft- and hard-dominated events may produce different hit distributions in BBC
- In case that hardest jets are produced, less energy will be available for soft-production at high η
- There could be p_T dependent effect?
  - We use BBC for event triggering as well as centrality definition



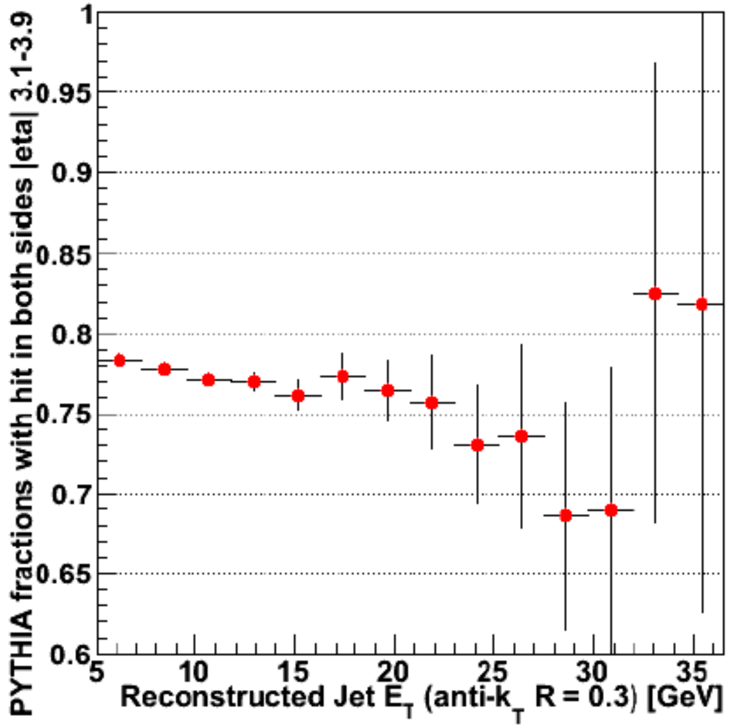
PYTHIA simulation

- Ran PYTHIA and look reconstructed jets in mid-rapidity
- PYTHIA sees a small anti-correlation effect

Number of hits in BBC vs reconstructed jet p_T



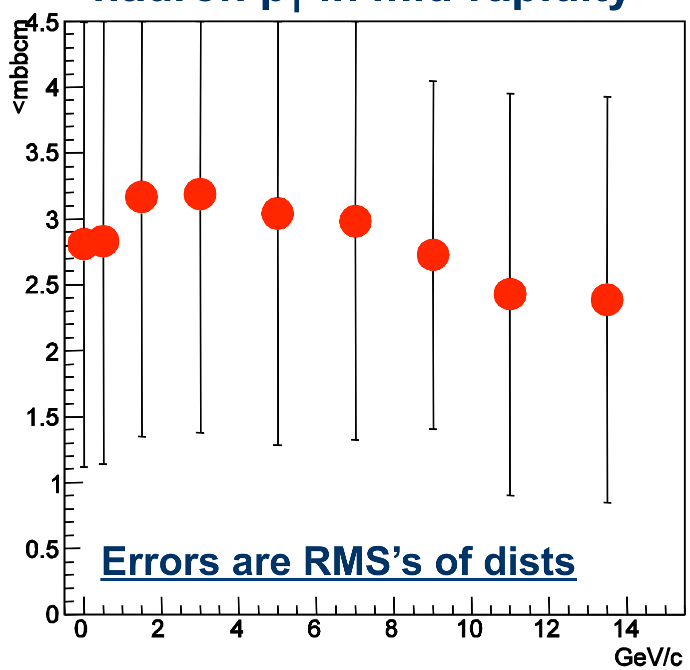
Fraction of reconstructed jets when requiring BBC trigger



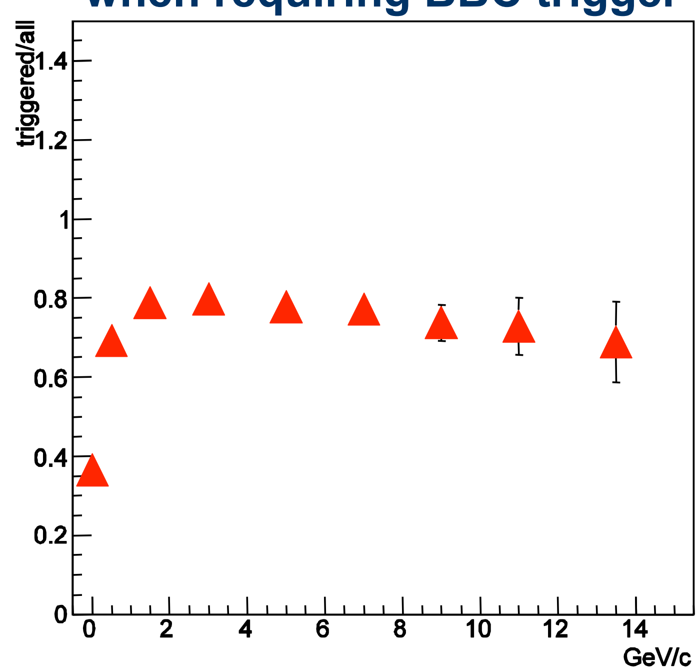
AMPT p+p simulation

- AMPT is a HIJING + hadron cascade event generator
- Plotted as a function of hadron p_T in mid-rapidity
  - Jets are not reconstructed.
  - AMPT also sees similar effect in single hadrons

Number of hits in BBC vs hadron p_T in mid-rapidity

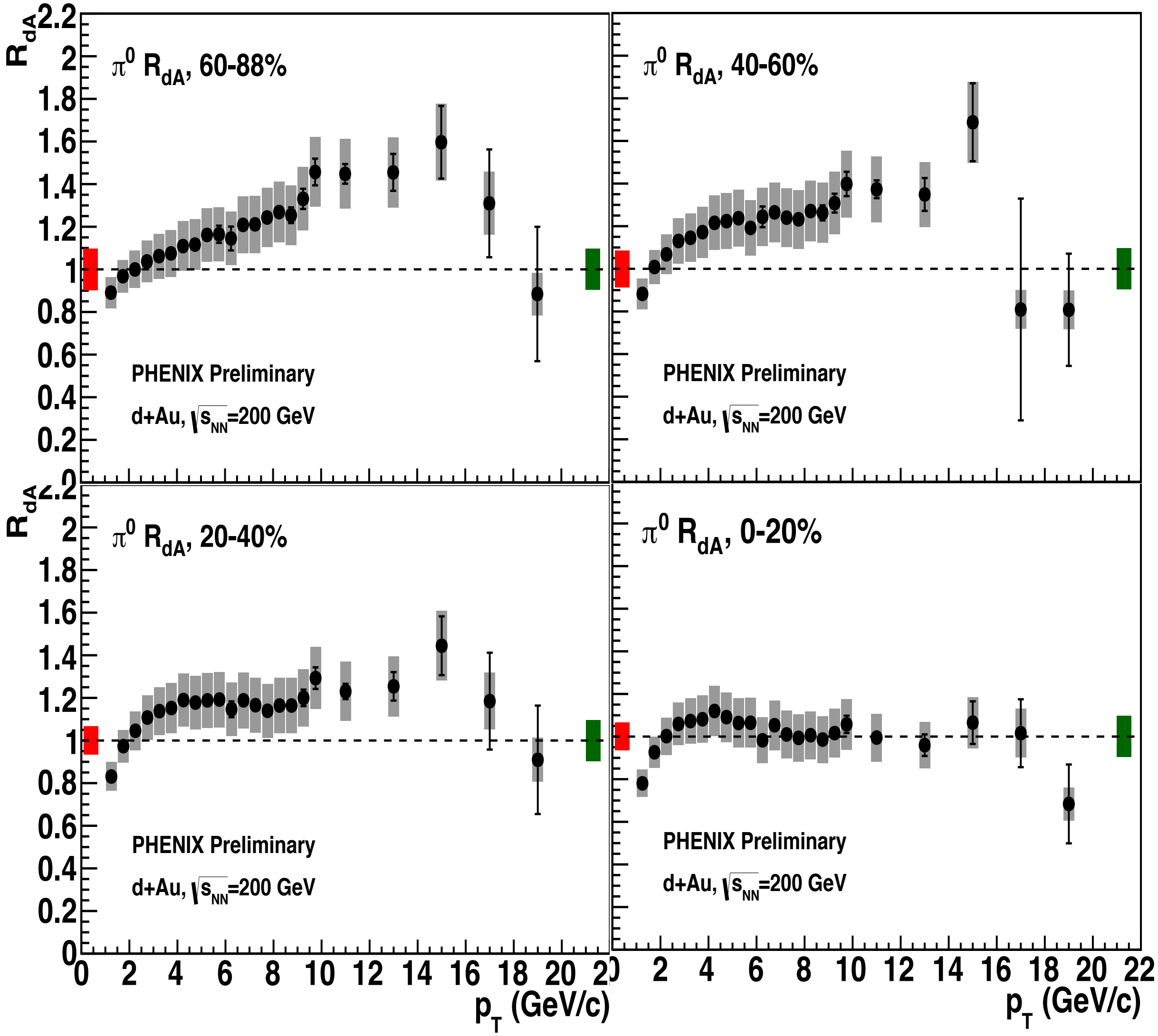


Fraction of hadrons when requiring BBC trigger



π^0 R_{dA} by centrality

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



New π^0 R_{dA} from Run8

- **Better statistics than Run 3**
  - → **Extends p_T reach by 5 GeV/c**
  - → **Better constraint for nPDFs**

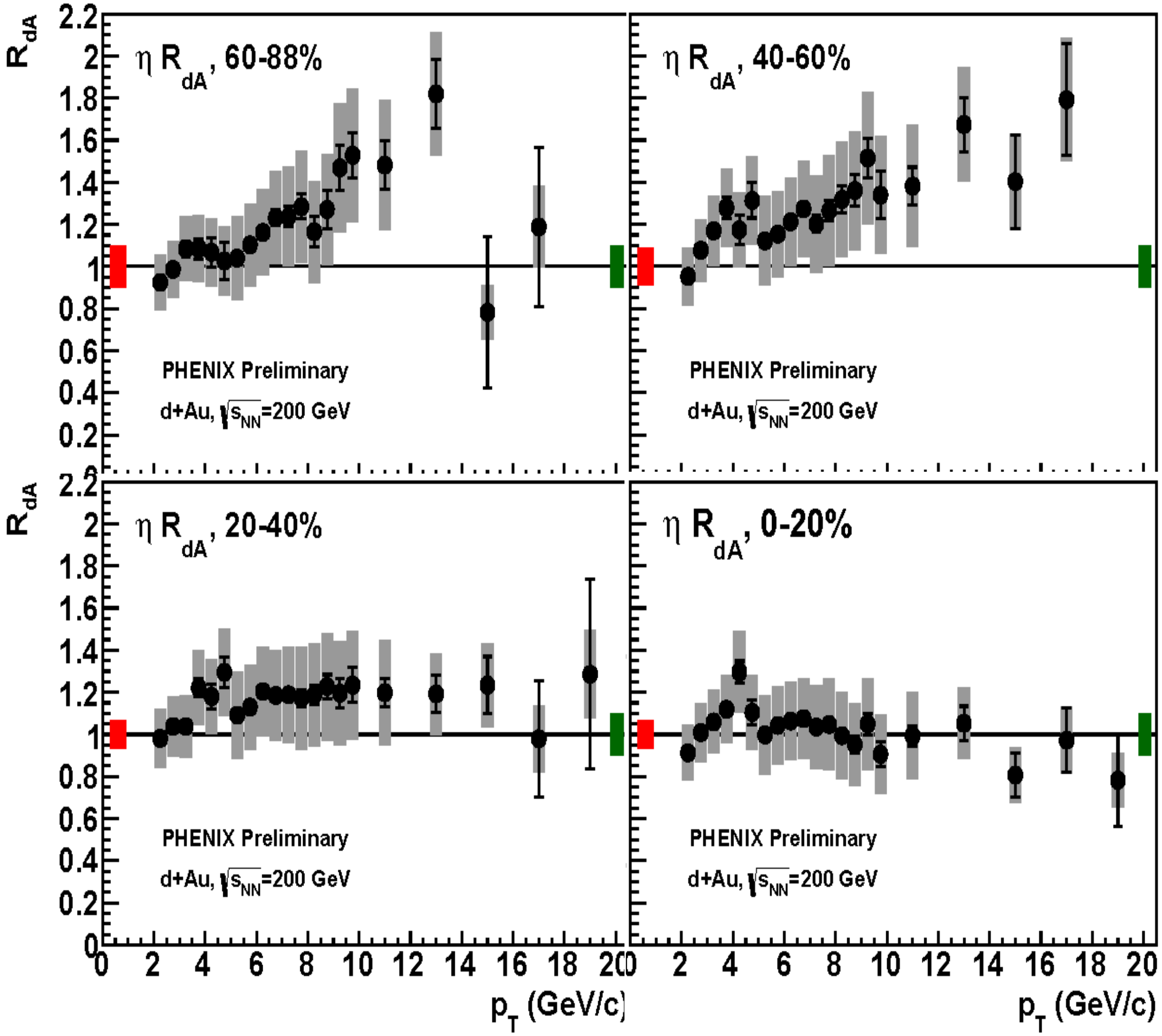
Peripheral is most enhanced

Central consistent with no modification at p_T > 2 GeV/c

How do we understand this? Competing nuclear effects?

η R_{dA} by centrality

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



New η R_{dA} from Run8

- Better statistics than Run 3
  → Extends p_T reach by 5 GeV/*c*
  → Better constraint for nPDFs

Peripheral is most enhanced

Central consistent with no modification at p_T > 2 GeV/*c*

How do we understand this? Competing nuclear effects?

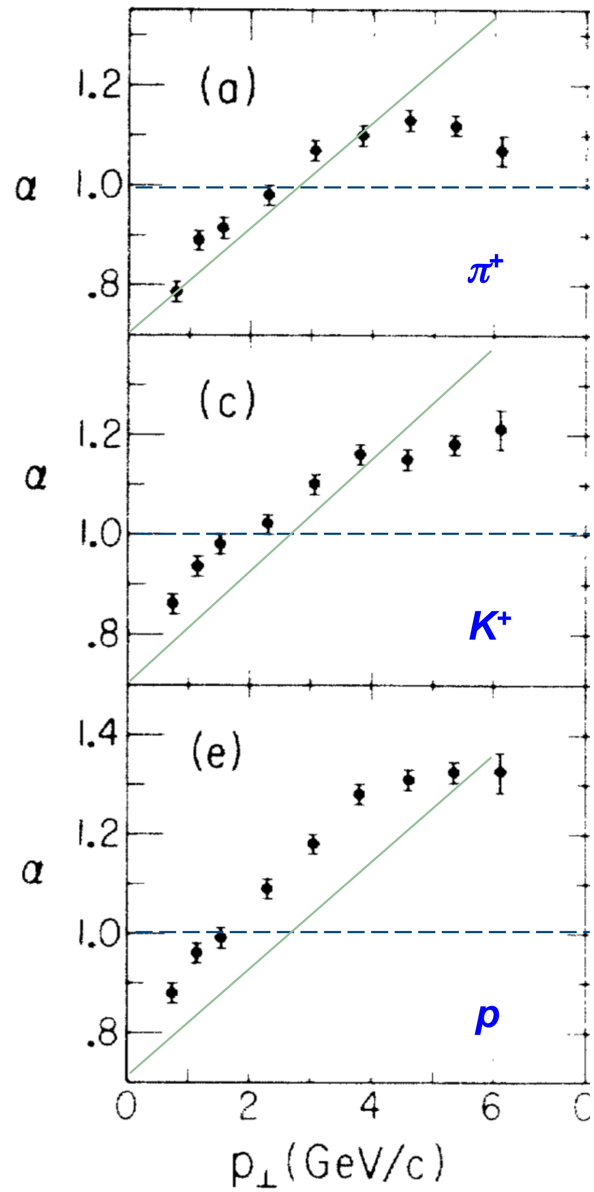
PHYSICAL REVIEW D VOLUME 11, NUMBER 11 1 JUNE 1975

Production of hadrons at large transverse momentum at 200, 300, and 400 GeV *

J. W. Cronin, H. J. Frisch, and M. J. Shochet
The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

J. P. Boymond, P. A. Piroué, and R. L. Sumner
Department of Physics, Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 5 December 1974)

$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$



Enhancement of hadron production in heavy ion collisions

Usually modeled as multiple scattering of the incoming parton on the nucleus.

Most models don't have any PID dependence…

- **However, measured enhancement is larger for protons than pions/kaons.**
- **Originally thought to be due to steeper p_T spectrum of protons and that it would go away at higher energies.**

But proton enhancement is still much larger at RHIC energies!